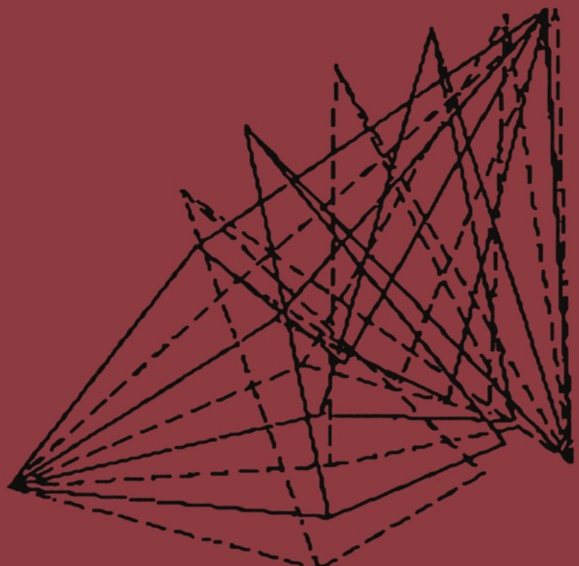
P. CHEDMAIL, J.-C. BOCQUET AND D. DORNFELD (EDS.)

Integrated Design and Manufacturing in Mechanical Engineering



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INTEGRATED DESIGN AND MANUFACTURING
IN MECHANICAL ENGINEERING

Integrated Design and Manufacturing in Mechanical Engineering

Proceedings of the 1st IDMME Conference
held in Nantes, France, 15—17 April 1996

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PREFACE

This volume contains the selected papers of the first *I.D.M.M.E.* conference on 'Integrated Design and Manufacturing in Mechanical Engineering', held in Nantes from 15-17 April 1996. Its objective was to discuss the questions related to the definition of the optimal design and manufacturing processes and to their integration through coherent methodologies in adapted environments.

The initiative of the Conference and the organization thereof, is mainly due to the efforts of the french *PRIMECA* group (Pool of Computer Resources for Mechanics) started eight years ago. We were able to attract the international community with the support of the International Institution for Production Engineering Research (*C.I.R.P.*).

The conference brought together two hundred and fifty specialists from around the world. About ninety papers and twenty posters were presented covering three main topics : optimization and evaluation of the product design process, optimization and evaluation of the manufacturing systems and methodological aspects.

The fifty four contributions contained within this volume have been selected by the following international Scientific Committee :

Chair : P. Chedmail (France)
Co-chairs : J.C. Bocquet (France) and D.A. Dornfeld (U.S.A.)
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H.J.J. Kals	(Netherland)	M. Veron	(France)

These specialists cover a large spectrum in mechanical engineering from applied computer science in mechanics to manufacturing.

Encouraged by the high quantitative and qualitive level of the contributions, the organizers plan to establish ther I.D.M.M.E. conference as a biennal meeting. The second meeting shall take place in Compiegne, France, in June 1998 and the third meeting in Montreal, Canada, in the year 2000.

The Editors, the Scientific Committee and the Organizing Committee hope that they have contributed to the development of Integrated Design and Manufacturing, a new domain of research in Engineering Science.

THE EDITORS

P. Chedmail, J.C. Bocquet, D.A. Dornfeld

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It has received the scientific support of the above contributors and of the C.I.R.P. institution (International Institution for Production Engineering Research), the I.F.I.P. federation (International Federation for Information Processing), the C.E.S.M.A. group (Computational Structural Mechanics Association), the D.G.A. agency (the french agency for research on defense problems).

The Ecole Centrale de Nantes, the I.R.Cy.N. (Institut de Recherche en Cybernétique de Nantes - UMR 6597 C.N.R.S.), the L.M.M. (Laboratoire de Mécanique et Matériaux of the Ecole Centrale de Nantes), the I.U.T. (Institut Universitaire de Technologie of the University of Nantes) and the I.R.I.N. (Institut de Recherche en Informatique de Nantes of the University of Nantes) have directly contributed to the organization of the initial I.D.M.M.E.'96 conference.

INTRODUCTION

Design and manufacturing of products and systems must *satisfy customers' needs*, while *respecting the environment* and *improving companies' profits*.

Under today's marketing constraints, this goal implies reducing *costs*, shortening *lead times*, and strictly respecting *quality* specifications. The customer now has increased power (see figure 1).

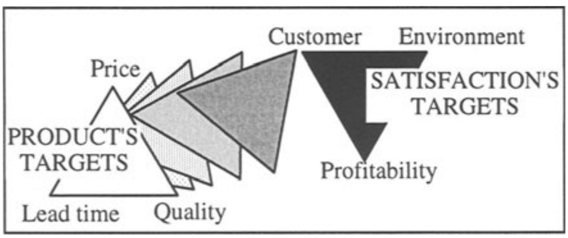

Figure 1. Increasing power of customer

Such an in-depth evolution unsettles all the existing methods and tools for the design and manufacturing of products and systems. This is the main rationale of this book. Our purpose is to take stock of the research results in the domains cited.

A number of internal and external *parameters of the company* define the environment for product development :

- costs,
- lead time,
- logistic reliability,
- international market penetration,
- productivity,
- bio-compatibility of packaging,
- recycling rate, etc.

These *item* must be taken into account from the early phases of the pre-design. They act as constraints on the intrinsic *parameters of product and system*.

The process for design and manufacturing quantifies the two other parameters: company / product.

Economic constraints now prohibit the use of traditional serial engineering methods. These methods are used to manage sequencially all the technologies (mechanical, electrical, etc.), from product design, process planning, manufacturing process design, to packaging and delivery.

Serial Engineering is now too expensive, for all the experts' parameters are defined through a sectorial and sequential process. Experts make decisions locally. Their decisions are isolated in time, space and function :

- in time because the process is sequential,
- in space because each expert sees only his own sector of expertise,
- in function because the fields in product development are separated.

Serial engineering leads to delays in development due to the sequential nature of planned and corrective activities. The corrections are local and the experts are ignorant of their effects on the other activities of the process.

For these reasons, two new strategies have emerged, every one of them are *simultaneous engineering processes* (see figure 2) : the « earliest choice » strategy and the « latest choice » strategy.

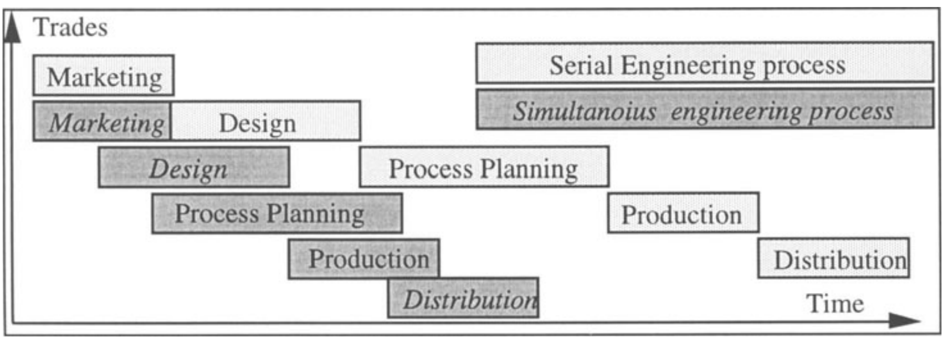

Figure 2. Simultaneous engineering process.

The earliest choice strategy (figure 3) quantifies as soon as possible the values of the parameters. It permits the evaluation of such factors as risk, cost, delays, etc. For this to be feasible, it is absolutely necessary that the decisions take into account the proper constraints of each technology and craft, in which case we must speak of « *integration* ».

New methods, new models, new tools must be deployed, and the present book describes some of them (Tichkiewitch *et al.,* pp. 487-494), (Tournadre. pp. 505-515), (Mognol *et al.* pp. 407-414), (Gao *et al.* pp. 465-474),(Stein *et al.* pp. 367-376).

With an early knowledge of the planned performance parameters, it is easier to control their evolution throughout the projet, and in that way, to guarantee the efficiency of the strategy. But early decisions bring constraints for future actions and increase the risk in delay and cost.

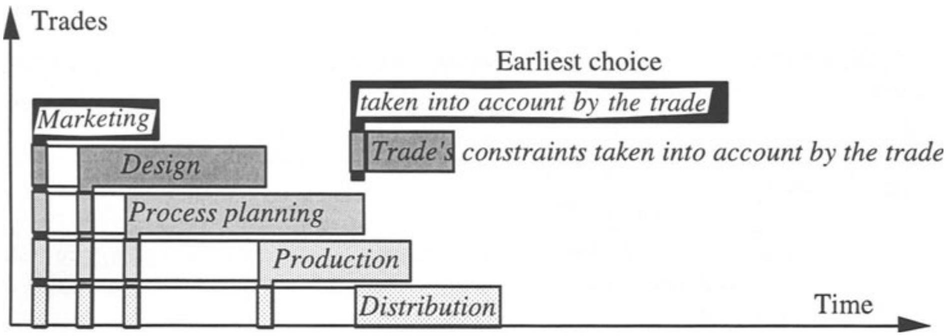

Figure 3. The earliest choice strategy.

The latest choice strategy (see figure 4) quantifies as late as possible the values of the parameters. This is an emerging strategy.

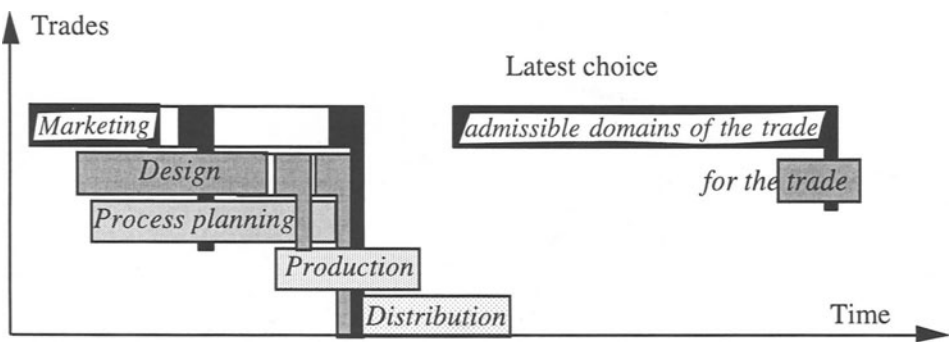

Figure 4. The latest choice strategy.

During the initial phases of product development, this approach leaves large degrees of freedom to the values of the parameters. The concept of *possible values* (associated with the constraints which are linked to the phase) replaces the concept of values. Then the designers set the values at the end of the development process, when all the constraints which appeared at the various development steps may be integrated. This strategy does not lock the parameters for the following participants, but allows a large degree of freedom for their expression, this is a major advantage of the strategy. One might imagine that such an approach would allow the product parameters and the company parameters to reach a global optimum. Unfortunately, this is only theoretical for the time being, since the behaviors and habits of the experts must change dramatically before this goal is reached. Moreover the methods and tools are not yet completely developed. Some results (Petiot *et al.* pp. 3-12), (Cuillere *et al.* pp. 83-92), (Daniel *et al.* pp. 427-436) make a contribution to paving the way, they are presented in this book.

Several research results which are presented herein (De Martino *et al.* pp. 437-444), (Coffignal *et al.* pp. 297-306), (Bocquet pp. 51-60), may be used with both strategies, depending on the context.

The scientific contributions in this book may be presented from several points of view (figure 5) :

- temporal : the development process, i.e., the product life cycle (pre-design, design and size, process planning, manufacturing, assembly, packaging, use then recycling),
- technological : mechanics, physics, automation, data processing,
- professional : project manager, designer, process planner, tool designer,
- systemic : economic, information, production, and logistic systems,
- other : epistemological, knowledge engineering, ontological, etc..

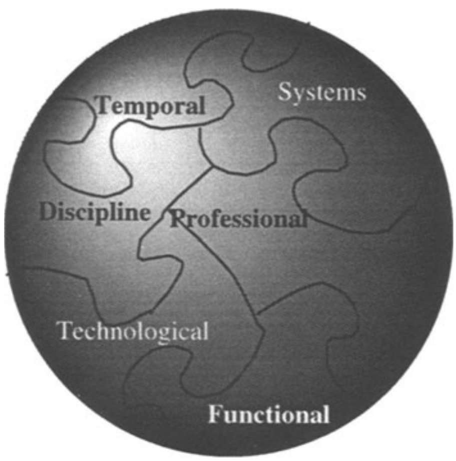

Figure 5. Several points of view.

In fact, each paper contributes at least one improvement to products and systems development. They can be presented from a functional point of view, according to how they improve product and company performance (figure 6).

- *functions which improve the quality* and performance of the product, or of the process for product development,

- *functions which reduce the cost* of the product, of manufacturing, or of investment,
- *functions which reduce the lead time* for design and manufacturing.

Figure 6. Functional points of view.

This presentation permits an easier cross reading of the book. The table of contents lists the methodological themes.

Quality Improvement

We consider three levels of quality, as specified by standards (figure 7) :

- *quality of the product* or quality of the manufacturing system,
- *quality of the process* for design or manufacturing,
- *quality of the design*, management and process organization.

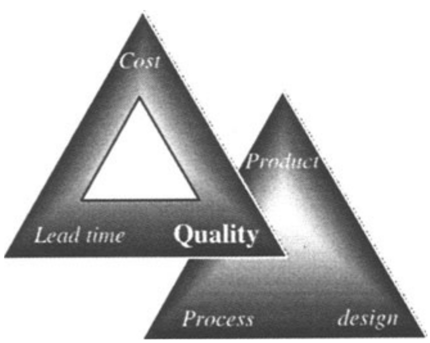

Figure 7. Quality improvement.

Some papers contribute to the evolution of the design process by the integration of disciplines and crafts. They are grouped under the theme « quality of process », although they generally address the improvement of the product or of the manufacturing system.

The improvement of the quality of the product and of the manufacturing system results from (figure 8) :

- a better preliminary knowledge of their behavior, which itself results from the *development of new models and simulation tools*,
- an improvement in managing product fault detection, which requires *great expertise in measurement and computing techniques*,
- an improvement in the analysis of the links between the economic, technological, and temporal parameters of the product and of the manufacturing system, leading to a reduction of uncertainty (error avoidance). *Integration leads to mastery.*

Figure 8. Quality of the product.

Development of new models and new simulation tools:

Nobody's perfect. *Products* may deforme or vibrate when they are manufactured or used. The stability and accuracy of a product are strictly related to the production process.

The improvement of the *product performances* requires new models and new tools (figure 9). For example, for the dynamic behavior of mechanisms, (Abadie *et al.* pp. 255-264) suggests an improvement of the product's accuracy and stability using the development of new algorithms in finite elements space/time. (Gonzales-Palacios *et al.* pp. 205-214) proposes an analysis and synthesis tool for the design of cams. Such methods and tools directly contribute to product improvement. This is the same for *manufacturing systems and toolings* : (Caillaud *et al.* pp. 317-326) models the design process for machining settings using a technological and functional approach of positioning, attaching and bearing. This approach makes possible to structure the knowledge which is necessary for their definition, and gives better control of their performance. (Gaudry *et al.* pp. 399-406) studies the concept of bearer. He proposes a synthesis method for the configuration of bearers for thin parts. Since they are thin, there is a particular risk of warping under machining constraints. The author proposes efficient assistance in clamping configuration in order to reduce the warping at specific points of the workpiece. The workpiece is described in terms of parametric polynomial surfaces, which extend this approach to a broad variety of parts.

Figure 9. Improvement of product performances.

(Paris *et al.* pp. 121-130) addresses the problem of the clamping concept. He models how to grasp the workpiece using the view of the specific machining craft. This allows the automated generation of the process planning. Itherefore, it is possible to verify the efficiency of the clamping.

All these design approaches improve the quality of the mechanical parts manufacturing, and contribute to the improved quality of the products and systems.

In the same time, *the manufacturing and handling processes* need to be improved. The process itself can lead to faults, tolerancy dispersion and lack of quality in the final product.

The global purpose of (Coffignal *et al.* pp. 297-306) is to predict the evolution of machining accuracy. The approach is no longer restricted to the interface tool/material ; it studies the interaction loop workpiece/tool/machine/clamping. This interaction loop generates vibrations and has an influence on the quality of the resulting surface, which is simulated. Machine deformation, cutting behavior resulting from tool/material interaction, workpiece and clamping deformations, are all integrated into a unique model.

Handling processes may unfortunately contribute to a lack of quality and performance of the products. There are various reasons for that lack of quality, such as scratches on the surface of the workpiece due to the robot gripper, uncertainty in the trajectory resulting in the inaccurate positioning of the workpiece on the machine, cycle time too long and not compatible with the necessary rate, etc. For these reasons tools are needed for the design of the handling systems. It is better to prevent problems than to solve them. Two papers illustrate this concept. (Merlet pp. 215-224) and (Chevallereau pp. 235-244) both have studied handling robots. (Merlet pp. 215-224) presents a method for designing parallel robots given the specifications of their workspace and (Chevallereau pp. 235-244) defines feasible trajectories starting at an order 1 singularity with a non zero initial configuration.

These samples of new simulation models and tools for products and processes clearly illustrate the predictive aspect in quality control. There is a wide potential development for this type of research. Indeed, the whole variety of products and processes may be approached in this manner.

Quality management via measurement and computing

There is a number of steps for a product or a system before it is made available to customers or users. It has to be drawn, computed, manufactured, inspected, tested. All of these steps have their own accuracy, their intrinsic expertise. From one step to another it is necessary to exchange data, and these exchanges may cause uncertainty or errors. For controlling the quality of its products, the company must be able to measure and evaluate all these uncertainties (figure 10).

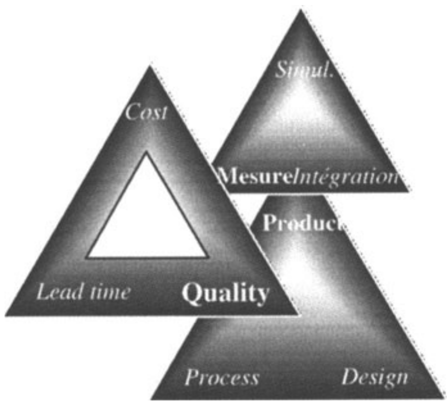

Figure 10. Measuring the quality of products.

It is necessary to provide the customer at the proper level of quality, corresponding to his needs : « Just what's needed ». Too much quality may induce an overcost leading the company to economic inefficiency. A ow level of quality will leave the customer dissatisfied, the company will lose parts of his potential market and may eventually disappear. « Just what's needed » is a difficult target to reach. It generally implies mixing a « lean » prediction (computing), and a « lean » test (measurement).

In the present book, some papers make it possible to study, improve and test the quality which is gained through the generation of several *item* :

- geometry,
- dimensions,
- process-planning,
- manufacturing,
- tests.

One can study the loss of *geometric quality*, more particularly during data exchange between different experts, different companies, different data processing systems. Exchanging representations of complex shapes often leads to inconsistency between the declared topology and the accuracy of the corresponding geometry requested by one of the exchanging systems (continuity of the 2D boundaries, etc.).

Geometric quality is also equivalent to non overlapping. It's a guarantee of continuity and faces tangency. (Boujut *et al.* pp. 277-286) proposes a systematic construction technique of surface models of forged parts which checks the coherence of the generated forms. Compatibility of the construction parameters of the surface is guaranted. More globally, the compatibility of the geometry types with given manufacturing process rules is a broad domain of research in integrated design. This insures that the designed geometry may be obtained via the proposed manufacturing process.

The geometric quality of the product must also be predictable and testable. (Valade *et al.* pp. 339-348) proposes for that purpose a new micro tolerance model for CAD-CAM modelers, which makes possible to evaluate and measure the gap between the geometry which is desired by the designer and the geometry which is obtained with the modeler. Specifications and drawing rules come from traditional industrial drawing domain. Although not adapted to 3D computer geometric representation, they are still used. This is at present a potential domain for research.

The quality of a product or a system is also related to its *performance*. Optimizing the shape generally reduces the quantity of material for a given load. (Abid *et al.* pp. 173-182) proposes an innovative solution to distribute the thickness of beams and shells and minimize the stresses in large displacements analysis. While (Cugnon *et al.* pp. 183-192) elaborates an automatic procedure for shape optimization which ensures the validity of the final design, combining optimization with finite elements error estimation techniques. Quality in computation is a major factor for quality insurance when dimensioning a product. In a finite element context, it is necessary to control errors of discretization and to drive the parameters of the calculation. The purpose of (Coorevits *et al.* pp. 193-202) is to obtain well adapted meshes, with given quality results.

Boundary conditions present some of the actual difficulties in dimensioning calculation. The only way to validate them is still experience. (Cognard *et al.* pp. 495-504) details these difficulties in the design of a specimen for mechanical biaxis tests. Simulations are performed using finite elements, hence the complex structure is calibrated using tests. The authors show the limits of this approach. An example of dimensioning of a metallic cylinder head gasket (Soua *et al.* pp. 535-544) illustrates the difficulties in designing a part with so many constraints. The model is numerical, the behavior is elastoplastic in large deformation, with unilateral contact and friction. Once again tests are needed for validation.

The main trend consists in a continuous improvement of the computing performances in order to reduce the need for tests and eventually to eliminate them. For the development of new vehicles, the aim of some automotive companies is to reduce the number of prototypes from five to two, while the number of pre-serial vehicles needed to adjust the manufacturing system will decrease from fifty to ten.

After the geometric uncertainties (which generate visual defects and difficulties in assembling and use) and the computer unaccuracies (which generate unuseful material or over-quality product and risks in material rupture), the *manufacturing* will bring its own uncertainties. Uncertainties will result from the operating mode, from the process planing, from the mode in positioning the workpiece, from the process itself as in cutting.

(Dupinet *et al.* pp. 329-338) identifies the influence of the process plan onto the accuracy of the manufactured workpiece. The authors propose to compute tridimensional accumulations of dispersions in order to validate process plans of welded sheets of metal. This approach uses tolerance chart analysis.

In processes and in machines, thermal effects may generate dimensional uncertainties. Forecasting and evaluating these effects permits to anticipate and control them. (Le Calvez *et al.* pp. 267-276) proposes an experimental analysis of the cutting process which is based on the use of infrared-CCD camera, and a finite element simulation of temperatures. (Bueno *et al.* pp. 307-316) quantifies the machine-tool dimensional quality using a thermal modal analysis, in order to control their thermal deformations and accuracy.

All these papers open a path toward a better process management, and, as a consequence toward a better quality of the product.

Performance control using integration

In the design process, the various actors, the various crafts, and more generally the various participants (i) generate their own parameters (intrinsic parameters Pi) using as an input the upstream product parameters P(t-dt) which were generated by previous participants. They generate downstream parameters P(t) that further participants will use : P(t+dt). However, the P(t) of any participant may be constrainted by the Pi of another participant (i), upstream or downstream. Product or system parameters are not independant. These dependancies arise from various origins : technical (mechanical, electrical, etc.), technological (machining, casting, etc.), crafts (design, computation, engineering, manufacturing, etc.), tools (CAD, MMS, machine-tool). An important part of the present book is devoted to these different types of coupling (figure 11).

(Tichkiewithch *et al.* pp. 487-494) proposes to *integrate* the electromagnetical and mechanical properties of the material and these of the manufacturing process (permanent deformations) in order to allow compatibility and consistency to the different technologies. A multi-view presentation of an electrical motor illustrates that integration.

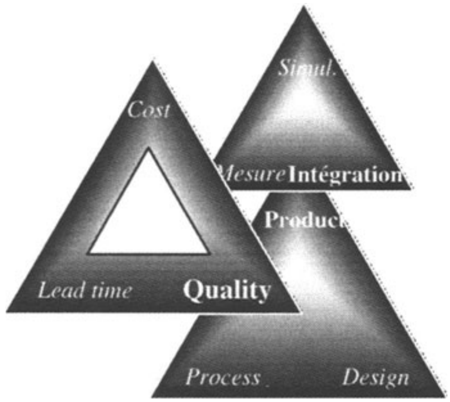

Figure 11. Performance control using integration.

Designing is anticipating. In (Krause *et al.* pp. 13-22), the product failure analysis leads to the identification of the failure design origins. Associating the product structure to the generated failure structure leads to an identification of the wrong solutions which are to be avoided during the design phase. (Samper *et al.* pp. 349-358) integrates the « real behaviour of the product » in order to specify geometrical quality. The authors take into account different defaults in the tolerancing process (perfect mechanism, rigid mechanism with clearance, perfect elastic mechanism without clearance).

Anticipating may also consists in simultaneously designing the product and the manufacturing system. This allows a global optimization of the performances of the product parameters and of the production system, which means a global optimization of the company. A very specific example taking into account the manufacturing burrs is significant. (Stein *et al.* pp. 367-376)] studies *interactions* between design decisions and manufacturing decisions relevant to size and shapes of burrs. With four levels, the authors integrate the impact of the design choices on the process planning, on the manufacturing environment design, on the setting of the manufacturing process, on the computing of the machine trajectories and of the measurements to be achieved. (Lochegnies *et al.* pp. 153-162) integrates computing and metrology tools. Once again this approach consists in a coupled design of the product and of the manufacturing system, herein more particularly applied to glass products. In the manufacturing processes of glass products, finite elements allow to predict temperature evolution. Calculation tools are integrated to CAD and metrology softwares in order to optimize the product and the manufacturing system design.

To insure *consistency* between the manufacturing of the *rough* workpiece and the quality of the *final* workpiece, (Bernard pp. 131-140) proposes an automatic generation of manufacturing data for forge dies (to obtain rough parts), and a determination of the machining process (choice of fixturing and machining operations)of the forged rough parts. It allows an integration of the rough workpiece specifications into the initial conditions of the final workpiece machining.

The crossed expertise which is needed when designing systems may be used for product design. (Valdes *et al.* pp. 515-524) uses the servomechanism design metrology in order to design controlled mechanical systems of machine-tools.

Integration does not mean overlaping nore union. By definition, a product design participant cannot by himself acheive the added value of two or more participants. He has to take into account the other intervenant(s) design processes by communicating and by working simultaneously and respecting constraints.

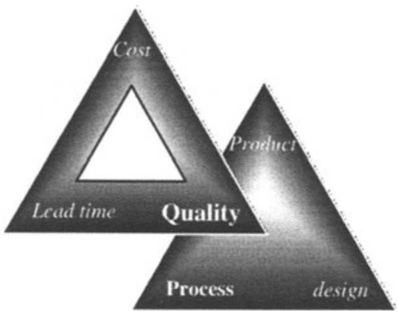

Figure 12. Quality control and design process.

The examples herein are generally relevant to the integration of two participants (technics, crafts, tools) and more rarely three participants. A global approach would need an integration of all of the participants. This gives an image of the volume of researches which still remains to be performed.

Chapter 1
THE DESIGN PROCESS

ANALYSIS OF THE SETTING UP OF A CONCURRENT ENGINEERING SCENARIO

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Abstract : The paper presents the first results of a project called " Scenario for Concurrent Engineering and Communication Analysis in Manufacturing Integrated Systems ". It is supported by the Technical and Scientific Committee (DSPT8) of the French Ministry of Higher Education and Research. The purpose is to study a system production approach within a context of concurrent engineering based on work carried out in various laboratories. Those complementary efforts are channeled towards the study of an assembling system.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 3–12.

1. Introduction

1.1 OBJECTIVES OF THE PROJECT

The Technical and Scientific Committee (DSPT8) of the French Ministry of Higher Education and Research supports research projects in the domain of product development. The aim of these projects is to establish new methods of organization and management of design processes.

Our project is entitled "Scenario for Concurrent Engineering and Communication Analysis in Manufacturing Integrated Systems". Its objective is to implement a concurrent engineering experiment, using the competence of many partners, members of the four laboratories mentioned in the heading.

The interest of this work is to modelise invariant phase during the design process in order to propose a new scenario for the partial design of products. This scenario could be used by laboratories or companies for their projects.

The success of our project rests on the implementation of various procedures whose goals are :

- to allow genuine cooperative work between the many participants in the experimental area,
- to make it possible for this work to be organised along general, structural and functional principles in the methodological area.

A communication framework also needs to exist between the four laboratories.

Beyond the three-monthly meetings, we use electronic mail communication between the laboratories. In the initial specification phase, the Internet/Email network is used. All messages pass through a common mail box managed by the **CRAN**. This allows us to keep track of all exchanges in order to analyse them.

In a further stage, the transfer of models and/or formal data will use a hypermedia server on the Internet network.

1.2 SETTING UP OF THE SCENARIO

The main characteristic of our project is the interaction between the several actors and jobs of the design project. The actors are geographically distributed and they use autonomous systems which intercommunicate in order to work together on a common task. The following steps have then been agreed on. We have first materialised our project by choosing an industrial product. On **LAMIH**'s initiative, we have chosen as medium an assembling bank for an airplane provided by the **DASSAULT Argenteuil** company. In order to replace the present manual assembling device, we have studied an automated assembling device. This system allows us to do the assembly by rivetting the many parts of the fuselage of an airplane.

For the study of this new assembly bank, the design methodology used is a new approach proposed by **LAMIH** (Jacquet *et al.*, 1995a)(Jacquet *et al.*, 1995b). The method consists in doing a functional analysis, then defining the representation structure of the product (Petitdemange, 1987)(Delafolie, 1991)(Tassinari, 1992). The experiment is monitored in terms of quality control at all its designing stages.

In section 2, we present the structure of the design procedure used and its application to the study of our assembly bank.

The analysis of the Quality Control procedures is presented in section 3. Specific procedures, aimed at the elimination of non-quality in the information exchange, are also described.

Finally, section 4 presents our conclusions and future prospects. In this section we also take stock of the decisions taken and the criteria selected to assess the principle solutions. The next stage of our study is the preliminary design of the assembly bank, which will lead to the setting up of the concurrent engineering scenario.

2. Design procedure

2.1 INTRODUCTION

According to Suh (Suh, 1990), there are two types of design methods : Axiomatic and Algorithmic. The axiomatic methods (Yoshikawa, 1989), define several design domains (Client, Functional, Physical...), and a set of rules in order to obtain a good design. The axiomatic methods define the design context but they do not explain what to do in this context. The Algorithmic methods (Pahl *et al.,* 1984) are characterised by a set of phases (Specification, Preliminary design...) and steps which make it possible to define the product progressively. However, the algorithmic methods are sequential and this is opposed to a design integrating the concurrent engineering concepts. Therefore we propose, figure 1, an Algorithmic and non monotonous design method. This method integrates an axiomatic aspect (Functional Independence of service functions).

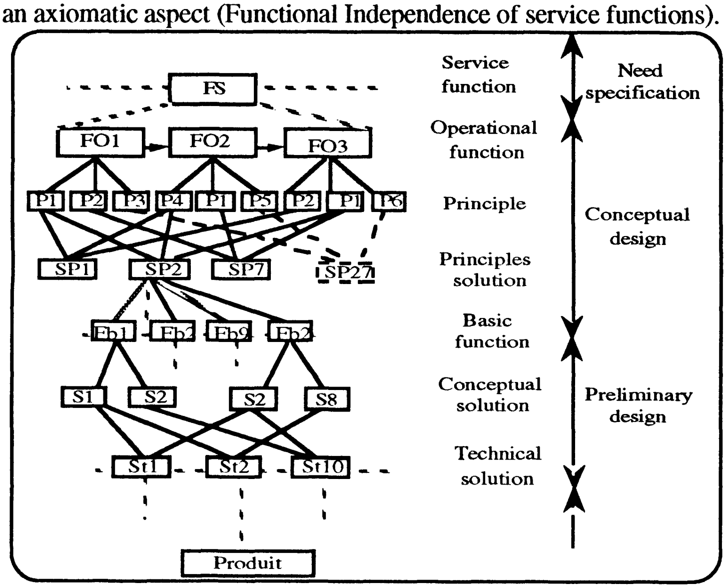

Figure 1 : design procedure

The design procedure is very structured. It makes it possible to define the set of entities (Service functions, Operational functions...) which model the product representation structure during the process design. However, the process design is non monotonous and is then in opposition to the design procedure which is very structured. Therefore, the design process used is relative to the designer culture. The designer can choose between a top-down, bottom-up or mixed design process.

The design procedure which is explained in the following sections is composed of the tasks of "Need specification", "Conceptual design", "Preliminary design"... For each task, we determine the set of entities which permit us to define the product progressively.

2.2. SERVICE FUNCTIONS

This task specifies the requirements that the future product will meet. The functional specification permits us to define **The service functions and the global constraint functions**. The service functions model the need according to a client vision (Petitdemange, 1987)(Delafolie, 1991)(Tassinari, 1992)(Jacquet *et al.*, 1995a). For that purpose, we consider all the material and immaterial elements that can interfere with the system. The global constraint functions model the constraints the product must meet. This task allows us to verify that all the given client informations are coherent and enough for a definition of the needs. Our objective is to define clearly what are the needs to satisfy. The exhaustivity matrix (AFAV, 1989) is used for the representation of the service and global constraint functions. The functional matrix relative to the study of the assembly system, is presented in figure 2.

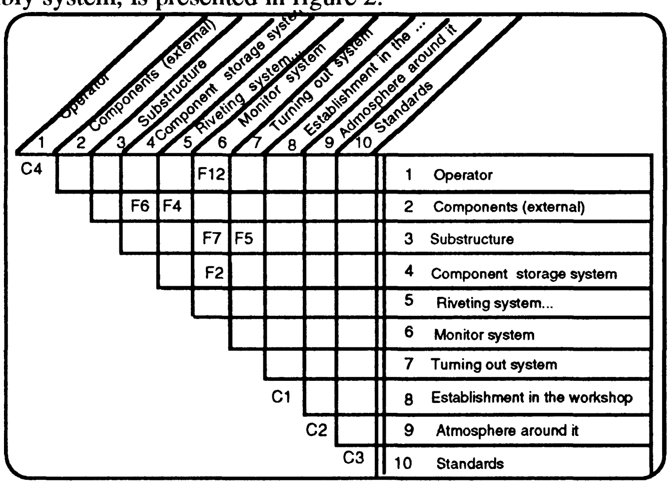

Figure 2 : Functional matrix

The definition of the functional matrix is the result of a common work between the different laboratories. However, in a first stage each laboratory proposed a solution, then the solutions were confronted, and finally the matrix validation led to the functional matrix presented in figure 2.

Each service function is characterised (definition of criteria, value, flexibility), according to the procedures used to define the functional specifications (NF, 1984). In order to use a standard vocabulary in the specification task we defined a glossary which specifies each term used .

The result of the assembly system specification task is presented by the following service functions (the formulation of service functions follows the AFNOR X50-150 standard (NF, 1985)) :

F2 : To indicate the state of the components storage system to the monitoring system,
F4 : To assemble components using the rivetting system,
F5 : To make it possible for the turning out system to extract the substructure,
F6 : To position a component of the component storage system in order to assemble it,
F7 : To indicate the number of substructures to the monitoring system,
F12 : To give information from the human operator to the monitoring system.

2.3 OPERATIONAL FUNCTIONS

The objective of this task is to define "How to" satisfy each need explained in the service function. For this purpose, we first of all define all the operational function sequences capable of supporting each need explained by the first task of the design procedure (Jacquet *et al.,* 1995b). Then, each operational function is broken down into subfunctions down to the definition of **elementary operational functions**. An operational function is “elementary” when its breaking down requires a change of flow. The representation model used to present the operational sequences is the state graph.

Figure 3 presents an exploded view of the assembled components. It shows the shape of the components and the position of each of them when assembled.

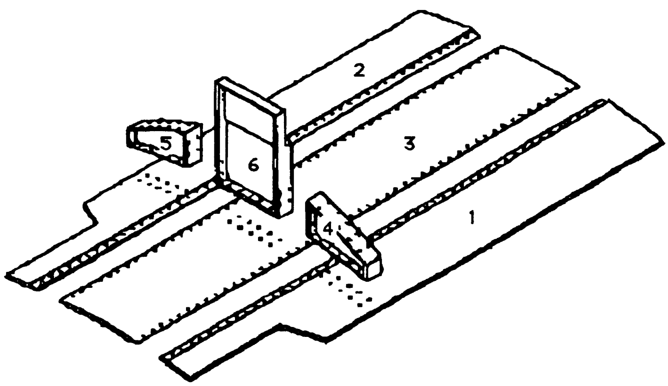

Figure 3 : exploded view of the assembled components

The assembly system can position and maintain the components in position. Its design also allows the extraction of the substructure and is compatible with the working constraints established by **Dassault Aviation.**

The state graph in figure 4 presents the result of the study of the service function "To assemble components using the rivetting system" (F4).

This state graph is obtained from the initial (Component 1 to 6 are not positioned) and the final state (assembled components) of the components to assembly. Then, we define the intermediate states and the operational functions which make it possible to go from one state to another. These intermediate states are defined from the assembly range ((1-2)->3->6->(4-5)) as specified by the client and from the position of the existing external elements (riveting system...).

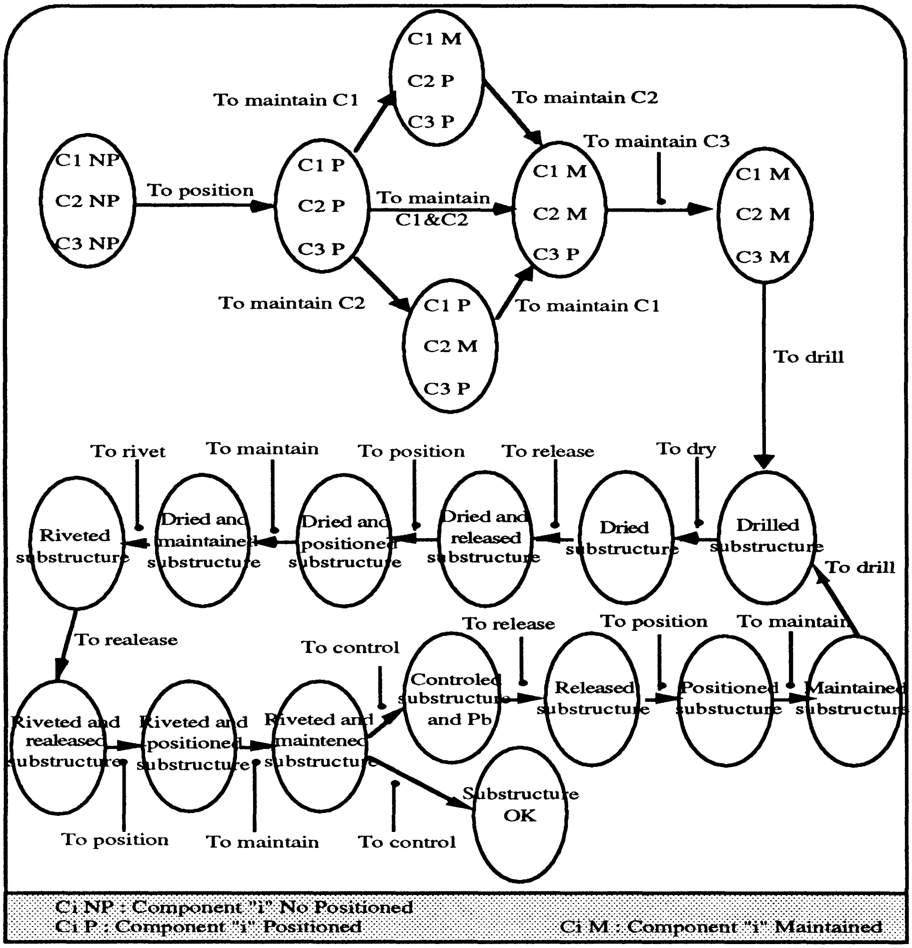

Figure 4 : Operational sequences of the service function "F4"

We then define the admissible principle solutions for each service function. One principle solution is defined as a combination between the admissible principles (Fluid, Electromagnetism, Mechanic) by each elementary operational function. From this set of principle solutions, we select the best solution in accordance to the chosen evaluation criteria. The functional criteria (production criteria like rate, process flexibility....), which are explained during service function characterisation (first step of the design procedure), make it possible to classify the principle solutions. Finally, the task of operational functions definition is completed by the distinction between the static and dynamic operational functions. This step is carried out in order to associate the following **technical functions** to each operational function.

- producing the movement,
- controlling the movement,
- detecting the failure,
- ......

The previous technical functions refer to the design actors (Mechanical actors, Automatical actors, Maintenance actors...) who take part in the design of the product in the preliminary stage.

2.4 PRELIMINARY DESIGN

The objective of this last phase is to determine the global material architecture of the product to design. For that purpose, we carry out the study in a technological perspective, the idea being to identify the possible technological procedures compatible with each technical function. This phase is undertaken by taking into account global constraints (performance, security, existing equipment) and trade constraints. The preliminary design phase marks the beginning of the simultaneous design of the different components of the product. On the one hand, the mechanic begins the design of the mechanical part in order to size and then to position the components.

On the other hand, the automatician carries out an ascending analysis aimed at defining the general control architecture based on the technical components retained ; similarly, he will take into account, in the preliminary design phase, the degraded operative sequences identified during the operative function definition. Finally, among the intervening actors in the design for exploitation, the technician of the maintenance define the maintenance strategy to apply to the future system. This includes the definition of the measure instrumentation to use for the detection of functioning problems and the implementation of intervention procedures for the maintenance of the process.

3. Quality procedures for the scenario

The design of our product cannot be made without a Quality Control approach.

The basic principle of Quality Control is the mastery of the design process. Classically, the process is sequential and the problem is easier than in concurrent engineering where it is necessary to consider activities unfolding simultaneously.

The purpose of the method of design is to give to the customer a satisfactory product "meetings his expressed needs or not" (ISO, 1994a). The integration of Quality Control in the design process is, in this case, intrinsic to the method of design.

"However, technical specifications cannot guarantee in themselves that specifications of a customer will be effectively satisfied. In actual fact, deficiencies can appear in these specifications or in the designing or manufacturing organisational system " (ISO, 1994b).

Our study has therefore been directed initially toward the study of communication between agents belonging to different trades playing a role in design. During the first period of study (between two study seminars), exchanges have been made without particular recommendations. In fact, the communications were of an administrative nature. After this period, the necessity of validation (matrix of service functions) has shown a certain number of non-qualities : losses of information in the utilisation of software (identification of modifications is very difficult when whole files are exchanged), identification of the last current version, problem of message structuring (messages giving information to several partners).

Later on, recommendations following the ISO9001 standard (ISO, 1994a)(ISO, 1994b) were suitable to comply with paragraphs §4.5 Mastery of documents (approval and distribution of documents, change and modification of documents), §4.7 Tracability, §4.16 Recordings relative to Quality.

These recommendations were applied by the installation of exchange procedures as the scenario unfolded :

- Procedure n°1 : "Agent identification". For each message, we transmit a cartridge in which we note the transmitter of the message, the addressee and one or several keywords (Quality, operative functions...).
- Procedure n°2 : "Modifications and validations". To avoid having an inaccurate or outdated document, the following procedure has been implemented :

  => transmission of a document by A

  =>return with modifications from B, C, D

  =>transmission of a new document of reference by A
- Procedure n°3 : "Identification of modifications". To rapidly identify the request for modifications in the documents, these request will be underlined or highlighted.
- Procedure n°4 : "Standard of messages". To avoid being flooded by information and losing essential data, only one type of information will be e-mailed (e.g information bearing on meetings and on design will not be associated).

The aim of these procedures is to classify messages and information with a view to organising and locating those which relate to functions.

In a concurrent engineering context, this allows us to follow the evolution of the product. Furthermore, we can list all the decisions and choices made during the design. We call this process "traceability of the decision's process".

Along the progress of the design scenario, agents follow procedures more and more faithfully. The validation procedure (procedure n°2), although followed by all agents, generated two functioning problems. The first one is the impossibility to question decisions. The second is the possibility for an agent to take a decision by himself, for reasons linked to the technical communication support.

This led us to revise our procedures by structuring them even better.

We completed procedure n°2 by a message discharge process, by means of an emission and reception cartridge. This allows the transmitter of a message to rapidly verify that addressees have received the message under the good format and that it is legible. Following this stage, the receiver study the validation of the content of the message. Furthermore a structured validation procedure, at several levels, has been established (validation between two agents and general validation with all the group). This allows us to take into account the simultaneity of design activity.

Finally, for the identification of modification procedures (procedure n°4), a stricter operative mode is under evaluation. This consists of an author/reader cycle as with the Idef0 method.

4. Conclusion and future work

The work done so far bears on the identification of the different service functions to be satisfied and on the definition of the global constraint functions to be followed (needs specification). Each of these functions has been characterised with a view to assessing the proposed solutions. Likewise, we have defined the operational sequences providing answers to each service function (conceptual design). The functional debasing aspect has been taken into account, which enables us to determine debased operational sequences.

The conceptual design stage must be continued by the definition of the principles that can be associated with each elementary operational function. We must define the criteria enabling us to classify the principle solutions, and establish the technical functions resulting from the best solution.

This stage will make it possible to validate the design methodology chosen as well as the various protocols adopted to solve the communication problems, those associated with quality in a project because of closer client-supplier relationships, and the implementation of a self-controlling procedure.

Lastly, we must determine the material architecture of the product to be designed via the preliminary design phase. In this phase, the system to be designed needs to be modelled according to various viewpoint which involve several trades (automation, mechanics, maintenance, etc).

The global system is the model which integrates all these different viewpoints. Whereas in the specification phase the different trades worked on the same model, in the global system each trade uses its own models.

Three main problems are then to be distinguished.

The first is data exchange. In addition to the problems encountered in the previous phase we find those which relate to the difference in the nature of the data.

The second problem is that of sharing and integrating the different data. It will be necessary to identify the models affected by the introduction of a new data. We must also devise a global model capable of accommodating the "interfacing" between the different models. Lastly, the choices or hypotheses made for a given model having to be compatible with the validity of the global system, the third problem is that of ensuring consistency.

Since our approach, rested so heavily on collaboration between different trades, a concurring aspect naturally derives from the experience. This aspect is reinforced in the second design phase in which not only co-operation between several trades but also work in parallel will occur. This will be made possible through the simultaneous evolution of several models linked to each individual competence. We feel that this particular aspect places our scenario within a concurrent engineering context.

5. Acknowledgements

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FAILURE-SENSITIVE PRODUCT DEVELOPMENT

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Résumé: Dans le cadre de la réalisation d'un management de la qualité qui accompagne le processus de développement d'un produit, l'intégration des applications de la CAO et de la CAQ est l'un de objectifs principaux de la recherche. La communication présente l'amélioration apportée au processus d'élaboration en chaine du produit par des méthodes integrées d'analyse des de l'utilisateur d'un modèle de produit neutre. Simultanément, des informations spécifiques sont utilisées pour accomplir une analyse des dèfaillances qui entraine une amélioration continue du produit pendant le processus de conception.

Abstract: For the realization of product-development-accompanying quality management one of todays research topics is the integration of CAD and CAQ applications. The product development process chain enhanced by integrated failure analysis methods is presented. On the basis of a neutral product model user-requirements are the input for featurebased product development. Simultaneously feature information is used to perform failure analysis leading to a continuous improvement of the product during the design process.

1. Introduction

With respect to the costs needed for the development of a new product on the one hand and the costs fixed during the product development phase on the other hand, it is obvious that the early stages of the product life-cycle should be supported by efficient quality management methods. In order to plan and to analyse the quality of a product and its manufacturing processes preventive quality management (QM) methods, such as failure analysis methods, should be applied as early as possible [KUW93]. Typical failure analysis methods whose origin lie in security technology and that were developed directly for risk evaluation and other quality assurance tasks are:

- Failure Mode and Effects Analysis (FMEA) and
- Fault Tree Analysis (FTA) [VDI94].

FMEA was developed as a form-sheet based application. The form-sheet has two major functions: it is the media for storing and archiving FMEA specific information and it sequences the functional steps of the method logically. There are several software tools available on the market which support FMEA. These tools are stand-alone applications. Because of the closed system architecture the systems do not allow for global information.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 13–22.

The failure-sensitive product development is an approach to avoid these shortcomings by the integration of failure-analysis and product design functionality. It leads to a product developed right the first time.

2. *Quality Features support failure-sensitive Product Development*

For the realization of an integrated system environment to support design as well as quality assurance processes three major aspects need to be considered:

- the functionalities of the several application modules which are needed for efficient integrated product development,
- the model-based information exchange between the CAD- and CAQ- application modules, and
- the control of the development process to have an optimized sequence of the development tasks.

The lack of CAD-systems currently used in the industries is their focus on the later design stages, such as sketching and detailling. Neither other design stages nor QM-methods are supported by CAD-systems. A presupposition for failure-sensitive product development is the feature-based product modelling approach [KsS94]. Features as semantically endowed objects, which can also possess geometric shape, make the representation of information possible required for the support of all development stages [KRC95].

Since design features define the design orientated view of a product, so called quality features define the quality orientated view. Of central interest for the representation of quality features is the quality semantics which can be related to a shape area of the product, Figure 1.

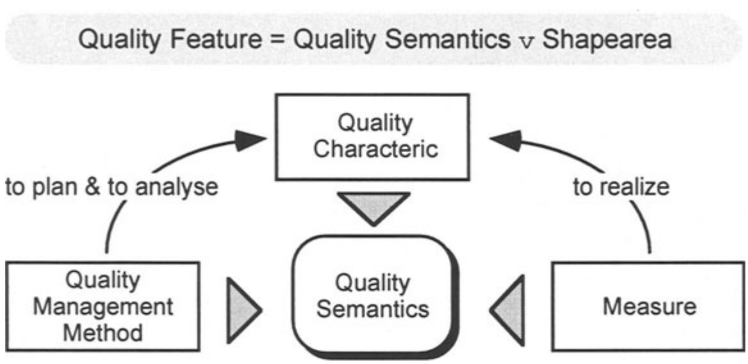

Figure 1: Quality Feature Definition and the Content of the Quality Semantics

The quality features facilitate a computer-internal assignment of quality information to assembly or functional components as well as volume, surface or edge groups as quality semantics. Quality semantics is defined by a quality characteristic, related quality management methods to plan or to evaluate the characteristic and, if necessary, measures which have to be taken to guarantee the certain user-requirements.

3. The Concept for a Failure-sensitive Product Development System

3.1. The Support of the Design Stages

Goal of the concept is the product-development-accompanying failure-analysis. Since user-demands are the input for the product design phase failure information have to be considered for the analysis and optimization of the product. One requirement for the integration of CAD- and CAQ-systems is the need to know the design intent. This means that especially customer demands are considerable during the design process. To represent the user-demands a so called requirement schema was developed. Requirements are specified by characteristics and their related expressions which need to be fulfilled by the new product. The requirement schema is one partial model of the entire product model, Figure 2. It specifies all the information necessary for the representation of user-demands and related information such as objectives of the demands, responsible persons, or weightnings. One example of an application method to access the requirement model is Quality Function Deployment (QFD) [VDI94].

To be the input for the design stages the user-requirements are “translated“ into a company-specific vocabulary via the lexicon-of-characteristics, which is a part of the integrated product model as well. The lexicon-of-characteristics defines lexemes to describe company-specific characteristics. The relationship between these pre-defined company-specific characteristics and the user-specific requirements allow for the description and translation of user-demands into company-specific terms. Further information represented in the lexikon-of-characteristics are the quality-management methods which are related to the characteristics, such as measurement methods for geometrical elements, failure analysis methods for functional objects, or guidelines for experiments. Within the representation of suitable QM-methods, quality management tasks are planned for the following development stages.

As mentioned above the design process requires a feature-based CAD-system which allows for the representation of semantical features. During the design phase generic features which are represented in a feature library, are selected by mapping user-requirements and feature characteristics. For this mapping the lexicon-of-characteristics is of central interest as well. The entity "Concretisation" defines relationships to the requirement schema one the one hand and to the product-characteristic schema on the other hand. Those feature characteristics which are required by a user-demand become a quality characteristic automatically. The features are selected by the mapped characteristics, instantiated, arranged, and assembled to a product.

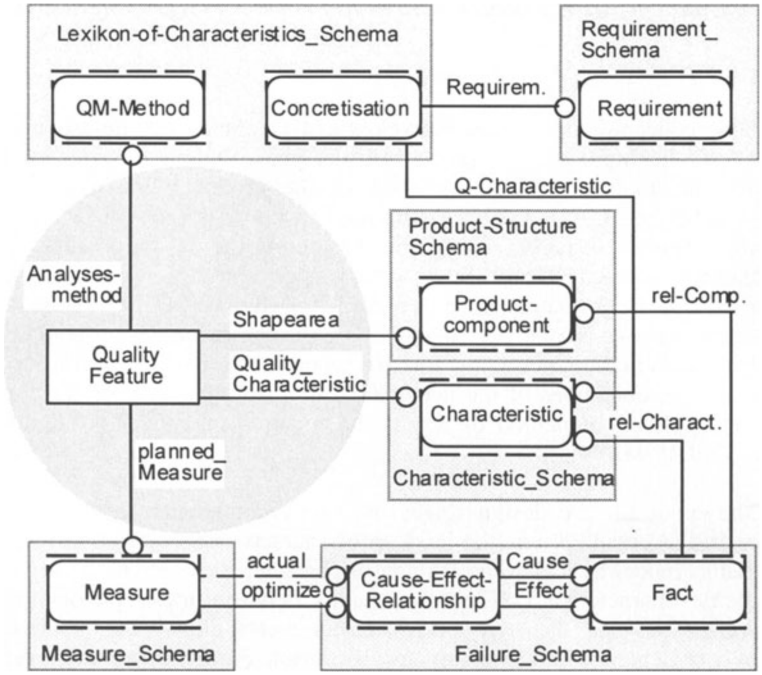

Figure 2: Overview of the entire product model

3.2. Development-accompanying Failure-analysis

The goal of a failure-analysis is to avoid or to reduce risks and to optimize the product during the product development phase by an assessment of the product behaviour of the later life-cycle stages, such as production, use, or recycling. Potential failures are methodically analyzed in regard to their signifiance, the probability of their appearance and the probability of their discovery, and measures for their improvement are monitored.

For provision of already available failure histories or suitable optmization measures it is necessary to collect and to store quality information related to a product in order to conclude that similar products have similar risks. The approach of the failure-sensitive product development allows for the description of failure information related to quality features. For each company-specific feature failure information are represented in the failure model. Central entity of this model is the “Fact”. Facts have to be subtyped to achieve a positive or negative significance. A negative fact will become a failure. Failures can influence each other. The failures described are linked within the model as in a network according to causal connections. These connections, the "cause-effect-relationship", are relations between two facts by identifying one fact as a cause and the other as the effect of the cause. Figure 3 shows the generation of a new product-specific failure network.

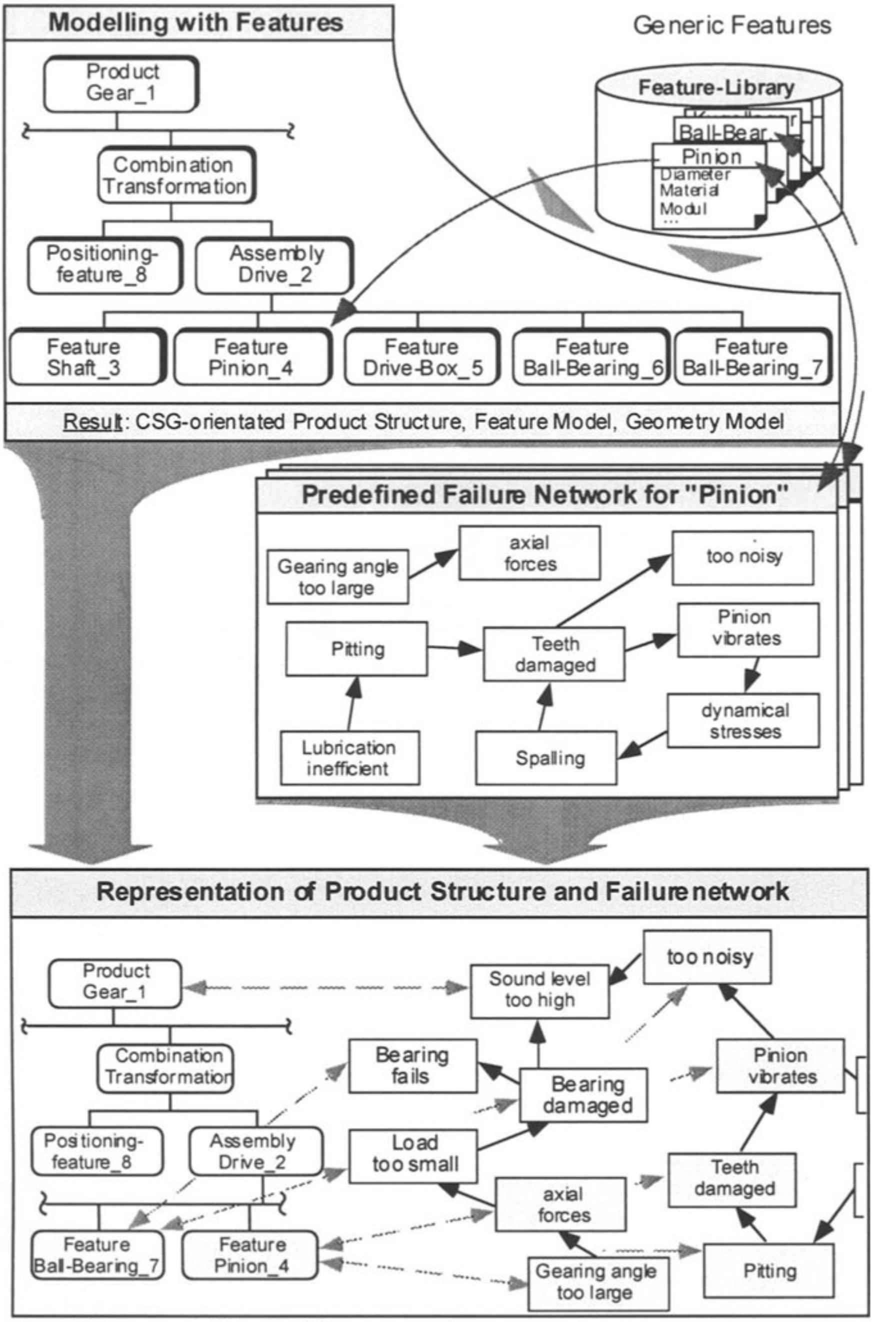

Figure 3: Generation of a new failure network

Starting point is the feature-based product description including the product structure. Figure 3 shows a part of the product structure for the example of a gear. Nodes of the product structure are specific features, whose generic description are represented in the feature library. Within the provision of already available feature histories failure-networks are pre-defined, e.g. for the pinion. To run a failure analysis all failure-networks of the used features are considered. This ensures that all potential failures are under consideration and all risks could be assessed. Interactive management methods allow for the manipulation of relationships between failures of different features in order to build up a new product-specific failure-network.

The relationships between the failure information and the product components lead to the definition of quality feature networks. The entire quality feature network is a basis for a comprehensive failure analysis. The possibilities of the evaluation of quality feature networks go far beyond the possibilities of the well known failure analysis methods. These networks ensure the representation of

- failure-cycles,
- long failure chains of many failures, and
- n:m-relationships between several failures.

Since FMEA is a method to evaluate "Cause-Failure-Effect"-Triples, FTA is a method to represent failures in a top-down manner. Both methods are supported by the quality feature network, but none of these methods support the advantages of a network in an efficient way. In order to avoid resonance catastrophies failure cycles are of special interest to detect relationships between up-building or muffling failures. Long failure chains as well as n:m-relationships need to be represented for high complex products and their failures between several assemblies.

The mathematical calculation of the risk of a failure is supported by a rule-based system module. This module represents rules for the determination of the FMEA-codes and evaluates the risks with FTA-specific methodsusing the theory of probabilities. This ensures that results of the risk evaluation are comprehensible.

If the risk of a failure becomes critical, preventive measures have to be introduced to avoid that the failure occurs. The efficiency of a measure is dependent from the possibility to avoid the causes of the failure. Because of that measures are related to cause-effect-relationships. The computer-internal representation of the measures is designated in the following measure model, Figure 4. It represents actions, the source who is responsible for the definition of the measure, the necessary resources to introduce the measure, and its relationships to the cause-effect-relationships as component of the product model.

If necessary several measures can be introduced by the definition of measure-relationships, whose subtypes specifies additive or alternative measures. Measure are structured by several aspects. The systemrelated point of view identifies the CAx-System which is responsible for the execution of the measure. The statusrelated attribute describes if a measure is required, planned, or already realized. The ISO 8402 describes three types of measures: the disposition of nonconformity, the corrective action and the preventive action. The disposition of nonconformity is an action taken to deal with an existing nonconforming entity in order to resolve the nonconfirmity. Examples are repair or rework. A corrective action is an action to eliminate the causes of an exisiting nonconformity, defect, or other undesirable situation in order to prevent recurrence. A preventive action is an action to eliminate the causes of an potential nonconformity, defect, or other undesirable situation in order to prevent occurence [ISO92].

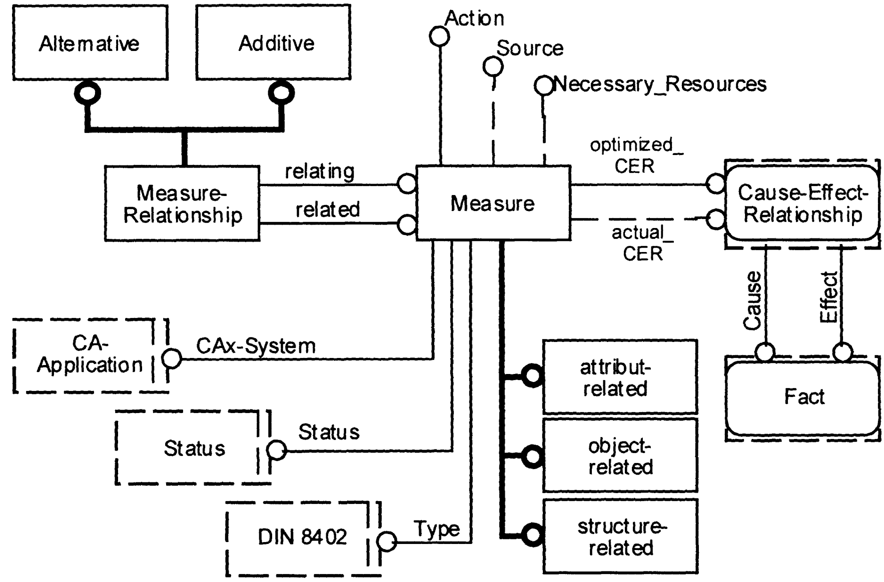

Figure 4: The measure schema

The productrelated measures are of central interest for a CAD-integration and are structured in attribut-related, object-related and productstructure-related measures. Attribut-related measures change the value of a feature characteristic, e.g. it increases the diameter of a shaft. An object-related measure changes the related feature by manipulating the characteristics. The productstructure-related measure changes the productstructure tree by a replacement of the relevant component. An example of a productstructure-related measure is the replacement of a cylinder bearing instead of a ball bearing to increase the load.

4. *The Prototype System for failure-sensitive Product Development*

4.1. The User-Interface

Figure 5 shows the user-interface of the prototype-system for failure-sensitive product development at IPK. In the foreground window the design process based on the CAD-system FEAMOS is presented and in the background window the corresponding failure-analysis process. The given example is the drive-assembly of a two-stepped gear. The failure-analysis process identifiied a potential risk for one of the ball-bearings. This possible failure and its cause is identified and highlighted in the failure-analysis windows. The related shapearea is highlighted in the failure-analysis window as well as in the FEAMOS-window. The graphical representation of the risky shapearea supports the designer to evaluate the possible failure.

As mentioned above the introduction of necessary measures is supported by the failure-analysis process as well. Those measures which became successful in the past and avoided potential failure are presented in an interactive dialog. The FEAMOS-system allows for handling measures as semantical features. Thus measures become modelling objects. The advantages are that measures are processed in FEAMOS automatically and the FEAMOS undo-/redo-mechanisms support the management of the measures. This allows to undo measures if they become contradictory to a later modelling stage.

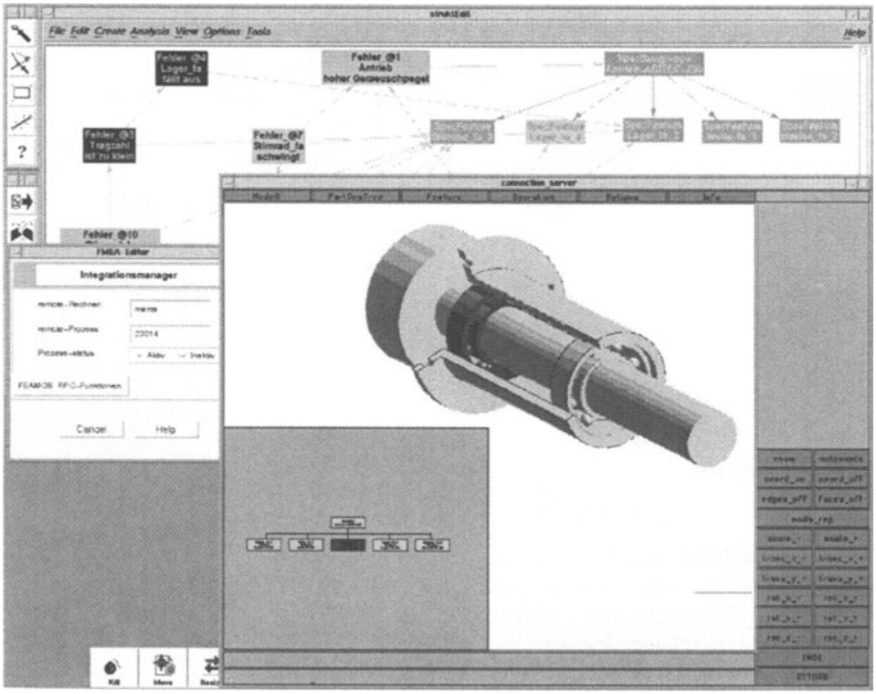

Figure 5: User-interface of the prototype environment for failure-sensitive product development

4.2. The Systemarchitecture

Similar to the systemarchitecture of the CAD-Referencemodel the system for failure-sensitive product modelling is build up in a modular manner [KlM94], Figure 6. The single application modules run as own processes and comunicate via interprocess-communication (IPC). The IPC makes the administrative information exchange between the modules possible, e.g. control information to start a failure analysis for a product or to establish a measure on the basis of an actual analysis. This ensures the most flexible way in order to run a failure-analysis at any time of the development process and leads to a development-accompanying improvement of the product.

The interfaces for the technical information exchange are realized in three well-suited levels: the database level, the application-independent level, and the application-specific level. The database level provide basic funcitonalty to access the information in the database system. To be independent from any specific database, this interface is specified using the SDAI functionality.

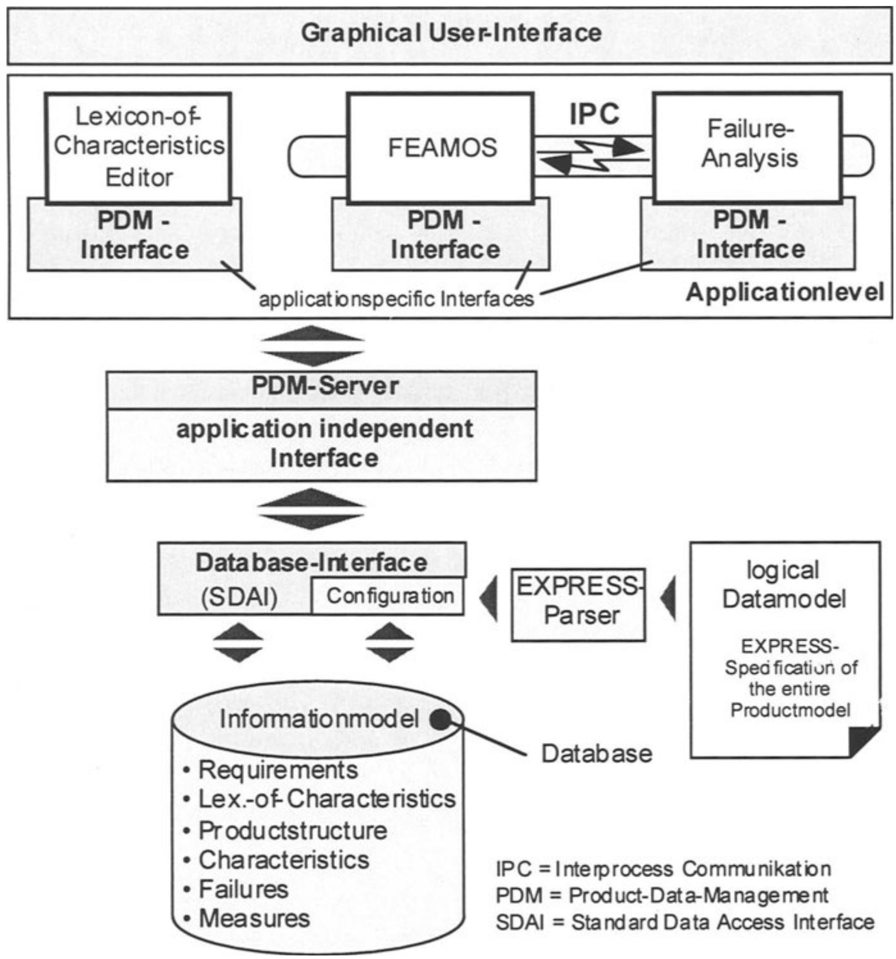

Figure 6: The actual systemarchitecture

The application-independent level provide functionality which allows more complex exchange of information and is used by several application modules. Examples are the exchange of the product structure which is of importance for the CAD- and the FA-module or failure information which is required by several failure-analysis modules.

The application-specific interfaces are the basis to access each module. They provide specific information and are based on the application-independent interface. A typical

5. *Conclusion*

The failure-sensitive prodcut development is a new and efficient approach to integrate feature-based product development and preventive failure analysis methods. The described concept represents one application of a hole framework for the integration of different QA projects at IPK focussing on the goal of quality driven product development. The framework serves as the key concept for various industrial projects dealing with the intergration and implementation of quality control accompanying product development.

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A LANGUAGE FOR THE MODELING OF THE DESIGN PROCESS IN MECHANICAL ENGINEERING

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1. Introduction

Design is a complex activity. It requires the use of several kinds of knowledge and human qualities such as know-how and creativity. It relies as well on theoretical principals as on empirical facts.

On the one hand, design could be defined as an activity which enables the designer the specification of the artefact. On the other hand, the design activity contains the definition of the process applied to build the product.

Presented in this paper is, a model for the representation of design knowledge for mechanical engineering. Our research work deals with routine design and redesign problems.

After a brief presentation of the product model used, a detailed description of our model for the representation of the design activity called " design process model " will be given.

The emphasis is made on the development of the models based on the constraint programming technique. The main part of the model has been implemented inside the European ESPRIT III DEKLARE project involving Ilog, Ikerlan, Copreci and PSA Peugeot Citroën companies and the University of Aberdeen.

A language and its associated tools, for the development of design aided applications, have been implemented. They are based on the constraint propagation technique and linked with traditional CAD/CAM systems such as CATIA and IDEAS products. The

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 23–30.

package has been validated in PSA on a software prototype for the design of cylinder heads.

2. Models for design knowledge

The framework of the Model enables us to represent, on the one hand the family of the product that is to be designed, and on the other hand the design approach to design any product of the family.

This approach is called the " Design Process ".

Therefore, the use of the design process model will lead to the resolution of a set of problems to define a particular product, in accordance with the original specifications.

2.1. THE PRODUCT MODEL. [SAU 94]

2.1.1. Functional Model :

The functional model enables us to represent the functions that are to be satisfied by all of the potential products of the class under a tree-like image. This model gives us as well the opportunity to describe the different possible technical solutions of each elementary function. A technical solution is made up of a set of design features.

The functional model is created by the Knowledge Engineer, from any possible documents regarding design problems. Then, thanks to the functions identified on the documents, he must make a list of the technical solutions belonging to each elementary function.

Finally, he has to computerise every entity defining the technical solutions.

Figure 1 illustrates an example of a functional model. There are several levels of functions. A global function, for example " Compression ", some elementary functions, such as " Seal of Combustion Chamber " or " Valve guide ". This last elementary function should be satisfied by two different technical solutions (only one at one time can be chosen), the first one is " guided by two points " the second one is " guided by three points ". Design features represent the zones of physical parts which characterise the technical solutions.

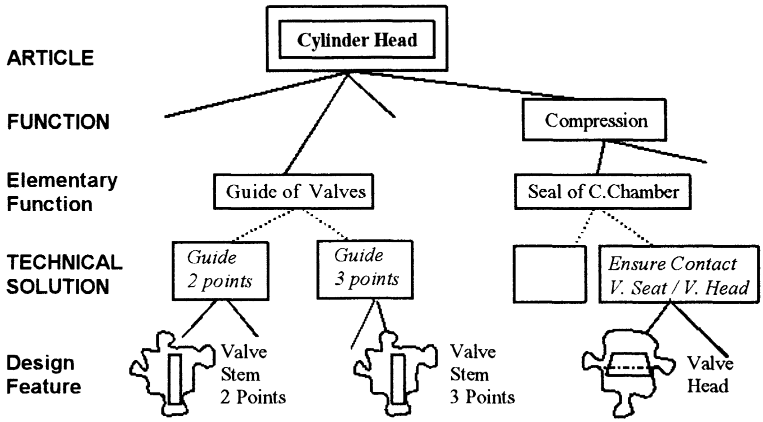

Figure 1. Piece of functional model of a cylinder head.

2.1.2. The physical model:

The physical model enables us to represent the structure of the different product variance. It is based on a tree-like decomposition of assembly parts and sub-assembly parts, in order to obtain basic elements. We can obtain this using documents written by experts, technical plans and pieces of paper (such as nomenclature, case study summaries...).

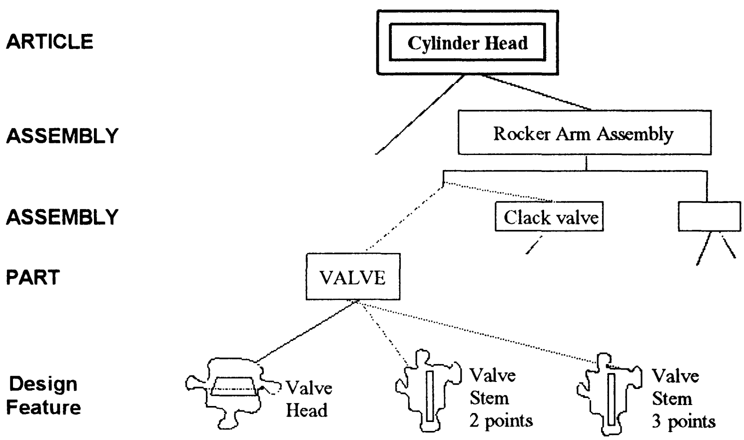

Figure 2. Physical model for a cylinder head.

Figure 2 shows an assembly called " **Rocker Arm Assembly** " which is composed of another assembly called " **Clack Valve** " and a part called " **Valve** ". The valve is itself composed of a set of design features which represent different zones of this part (figure 2). These design features represent a link between this physical model and the functional model where they are connected to the technical solution nodes (figure 1).

2.1.3. The geometric model:

The geometric model links an object to its geometric representation by the intermediary of an object-oriented representation of basic geometric elements available in traditional modelling tools.

ValveHeadGeom = U { Cone1, Cone2, Cylinder1)

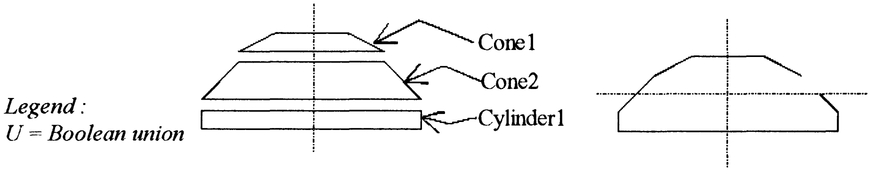

Figure 3. Geometric model for a valve head.

Figure 3 shows a geometric description of a valve head, based on elementary geometric primitives. Thus, the geometric description of the valve head corresponds to a Boolean union between two cones and a cylinder.

2.1.4. The constraints:

They enable us to state specific conditions that have verification between different elements of the physical, functional and geometric models. Consequently, a constraint can be set up between any parameters of different parts. They can be of numerical, symbolic or geometric origins.

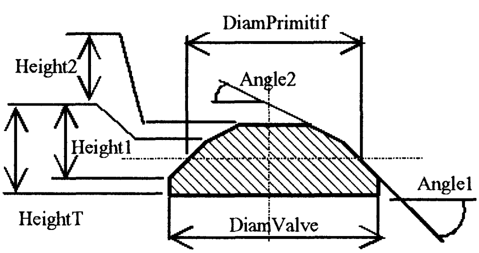

Figure 4. Example of a constraint on a valve head.

The design feature " valve head " is described with a set of parameters (figure 4)
{DiamPrimitif, Angle1 & 2, Height T & 1 & 2}.

An example of a valve head *local constraint* :

DiamValve = DiamPrimitif + 2 ((Height1/ 2) / tan(Angle1))

In this case, parameter " DiamPrimitif " depends on engine characteristics :

$$DiamPrimitif = \frac{DiamAlesage}{1.3*\sqrt{\frac{2100}{Course*N}}}$$

This last expression corresponds to a *global constraint*.

2.2. THE DESIGN PROCESS MODEL.

The design process model represents how the artefact is designed, i.e. the way the object is built. The Design Process Model we would suggest is composed of the following elements :

- Tasks : represented in the drawing here under, they illustrate the different problems to be solved or the goals to be reached during the design.
- Methods : represent a set of possible solutions
- Elementary Methods : allow dialogue with the final user, and ensure queries and links with other programs (except the link with the CAD/CAM)

The Task tree diagram is a static representation of the design process. It provides a detailed structure of problems to be solved (figure 5). A task corresponds to a problem to be solved or a goal to be reach.

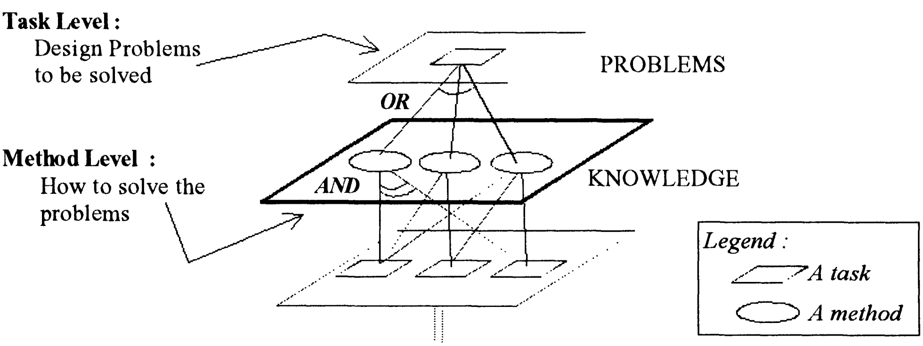

Figure 5. The design process model.

Each task contains several methods. Each method has several tasks. As long as the tasks represent a "problem-subproblem" structure, the methods represent the different potential means to solve each subproblem. The task/method group is then organised under an AND/OR tree-like structure (figure 5).

The setting up of the design process model is achieved by the following steps :

Static definition of problems :

- Make a list of the different problems to be solved.
- Give them a priority : indicate compulsory execution time, when it is clearly defined. The other problems have to appear on the same level (parallel).

Definition of the dynamic associated to the design process model (resolution of problems) :

The dynamic aspects of the model enables the Knowledge Engineer to define his own resolution strategy during a global representation of the different tasks (problems) to be solved.

The different tasks of the process model can be found after analysing the problems explained by the designer. They do not correspond to a description of " how to design each component of the physical or functional model of the product ". Indeed, it is rare in the design of mechanical parts to reduce the design process to the definition of each part or assembly of the artefact. Then, the problems met by the Knowledge Engineer, are linked together.

3. Solving mechanism and development of the approach

The development of an application written in our language will enable the final user to dynamically use the design process model and the product models to solve a design problem. To achieve this goal, we use a solving mechanism based on the constraint propagation technique [Ber 92] [Pug 92].

The artefact could be defined directly from the product model or indirectly from the design process model. The consistency is ensured by the constraint network (figure 6).

The solving mechanism ensures the constraints satisfaction during the whole process.

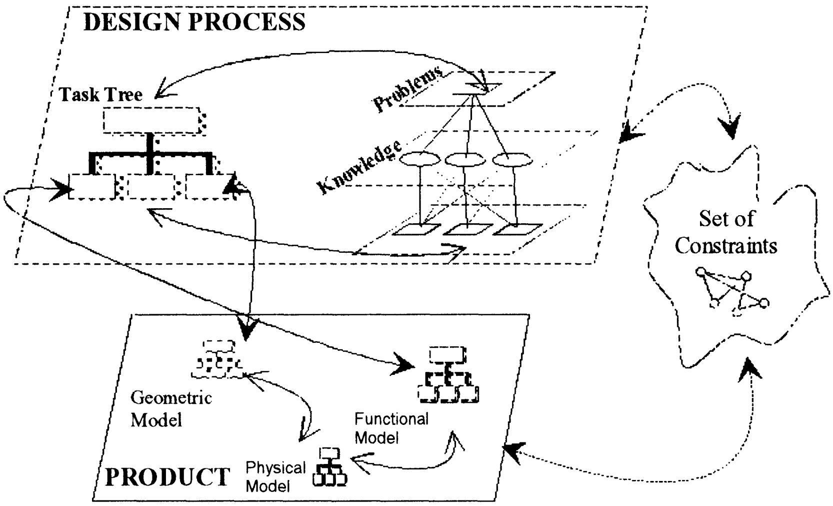

Figure 6. General View of Models.

Throughout the whole design process, the designer has to make decisions : selecting a task, a method or a set of values for a component of the product. Each decision has to be consistent with the set of predefined design constraints. The arc-consistency algorithm [Mac 77] automatically suppresses the unavailable values inside the domain of non instanciated attributes of the product.

Thus, we can switch between the next three cases :

- The physical model is totally instanciated : the designer has fully defined the product
- A domain becomes empty : there is no solution compatible with the designer choices, a backtrack is necessary to search another solution.
- The physical model stays partly instanciated : the designer can go ahead through the design process.

The use of the design process model could be done by two ways :

- Manually : the user takes its own decisions about instanciations and backtrack points
- Automatically : The user is guided by the system via predefined heuristics.

The implementation has been done in C++ with the Ilog Solver constraint programming library [Ilo 95].

4. Conclusion

The set of models presented enables us the representation of the design process of a product or a family of products. These models are the results of knowledge acquisition and structuration. They improve the know-how of the company.

The implementation of such models enables the final user to use a more efficient design aided system, other than the current CAD/CAM systems. Thus, it's possible to guide the user into the several tasks to be treated without making deadlocks in the design process.

The constraint propagation technique enable us to take into account simultaneously all the constraints of the problem. We can also add some constraints in an interactive way during the design process.

The link with CAD systems enables us to deal with several capabilities of the modeler, in real, time during the design; to manage the geometrical results obtained at the end of the session. Therefore, our prototype is completely integrated into the working environment of a designer.

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CAD/ANALYSIS INTEGRATION.

(An object-oriented approach)

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ABSTRACT:
One of the most important problems currently faced by researchers in the CAD/CAM field, is the integration of different design activities in the same product model. The analysis aspect appears at the different stages of design, therefore the integration of the analysis function in the CAD/CAM process is imperative. CAD/Analysis integration has been a crucial problem for many years, motivating a particularly active research. In this paper, we will begin by a state of the art in this field and we make some general remarks about the analysis integration into the CAD/CAM process. Then we introduce the functionalities-based design as an efficient means to integrate several aspects of design, including analysis, into the same dynamic product model. The integration of machanical analysis in functional design will then be detailed along with a presentation of the modelling and implementation aspects. We will finally conclude on the perspectives and the limits of this work.

RÉSUMÉ:
Un des problèmes que tente de résoudre la recherche actuelle en CFAO, est l'intégration des différentes activités de conception dans un même modèle de produit. L'aspect calcul intervient à plusieurs niveaux dans les différentes étapes de conception, d'où la nécessité d'intégrer cette fonction dans le cycle de conception. Cette évidence a d'ailleurs motivé de nombreux travaux de recherche dont nous donnerons dans le début de cet article un état de l'art. Nous montrerons cependant que le niveau d'intégration actuel est insuffisant. Nous présenterons ensuite la conception basée sur les fonctionnalités comme un moyen privilégié pour intégrer plusieurs aspects de la conception, dont le calcul, dans le même modèle dynamique de produit. Les modalités de l'intégration de l'aspect dimensionnement en conception fonctionnelle, telle que nous les préconisons, seront ensuite détaillées, ainsi que l'état actuel de nos réflexions sur la manière de les mettre en oeuvre.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 31–40.

1. Introduction

The notion of dimensioning can cover several domains, such as strength of materials, metal fatigue, fluid mechanics, thermics, etc. In this paper we will only address the search for the minimal dimensions of mechanical parts ensuring a satisfying (functional) behaviour when submitted to specific loads. This domain is characterized by the variety of methods available (strength of material, finite element methods, expert rules, etc.) and the complexity of implementation of the mathematical models that simulate the different phenomena.

The recent evolution of CAD modellers today allows to create the solid model of any kind of solid mechanical part [Zei91]. Parallel to the evolution of modelling techniques, the software tools for simulating the mechanical behaviour of parts using some numerical models under specified loads (referred to f.e.m solvers) have benefited from the increased power of computers, which allows a sensible reduction of the time required to validate a proposition.

However, the evolution of modellers and solvers has been parallel, which means separated. The necessary integration of these two kinds of tools remains difficult because of the difference between the kinds of entities handled by each of them. While modellers manipulate topology, geometry, B_reps, CSG primitives, etc, solvers require nodes, elements, boundary conditions, etc.[Gef91].

The unavoidable conversion of data types from modellers to solvers is thus not only an obvious obstacle to the application of concurrent engineering principles, but also a considerable waste of time, which can represent up to 60% of the time allowed to a complex design project [Afz92]. Actually, the process of analyzing the behaviour of a proposed model until a satisfying solution appears, requires several iterations (trial and error process) and consequently, several conversions.

Much of the research addressing the problem of integration of CAD and analysis is deroted to improving the flow of data during the conversion between two domains (the modeller's one and the solver's one). In this paper, we consider the problem differently, and try to answer the question: "Is it possible to address the analysis aspects right from the modelling stage?"

This leads to consider dimensioning no more as a trial and error process, but from a functional point of view, which is consistent with the requirement of designing functional products. For this purpose, we propose to integrate dimensioning in a functional computer aided design method defined in the LAMIH, in which functions are used to convey information through the different stages of the design cycle and explain the technical choices, thus capturing the design intent.

2. Dimensioning a CAD model

2.1. SET OF PROBLEMS

To analyse parts already modelled in modeller's environment, it is necessary to modelling them again in the solver's one. The use of standards to exchange geometric information has solved this problem. But the interfaces rarely take into account the specific objective of the analysis tool and perform a blind transcoding of the input geometry, resulting in a loss of information (as compared to the designer's intent), following a one-way path that is not compliant with the unavoidable modifications that the project is likely to undergo, and always creating a gap in the continuum of the design cycle. There are many different approaches to address the problem of conversion. We will survey some representative ones.

2.2. SURVEY ON THE INTEGRATION OF CAD AND DIMENSIONING

The use of the well-known CATIA CAD system (Dassault Systemes), opens the possibilities to generate an idealized model for the solver in two steps [Gef91]. An integrated FEM module pre-analyzes the CAD model, allowing the creation of additional concepts (nodes, edges, vertices, boundary conditions, etc.). Then, the result is transcoded for direct exploitation by the solver.

By using EUCLID3 (Matra Datavision), it is possible to pre-process the generated CAD model [Nar92]. An integrated solver called Quicksolver (a subset of Nastran) is available for rapid analysis of simple cases; when the CAD model is altered, Quicksolver proposes some editing facilities to avoid a complete re-meshing of the model. Various interfaces (to Nastran, Systus,...) are also available for more complex cases.

According to Petiau [Pet95], the problem of dimensioning in the aerospace industry can be split into three major steps: computation of the loads, computation of the set of constraints and definition of the admissible constraints. A direct link between a modeller (CATIA) and a solver (ELFINIS) has been implemented by Dassault Aviation, chronologically dealing with the three steps. The main characteristics of this link are the capacity and the performance of the automated mesher and the facility to re-execute a full process on a modified source, using a kind of interactive batch.

Saguez [Sag95] introduces an object-oriented system based on the multi-representation of objects. In such a system, the design model, the solver model and the manufacturing model would co-exist and evolve simultaneously thanks to a set of relations. The problem of a posteriori transferring data between the modeller and the solver would not exist any more. But the chronology of the following operations would still be required: idealizing, discretizing, specifying limits, computing and post processing.

3. Functional design

Functionality-based design [DEN91] [COQ91] is a set of concepts aimed at emphasizing the notion of function in the various design phases that need to be considered, along the design cycle of a new product. The derived design method is based on the fact that in a product of quality, the shapes are present either to satisfy a required function (functional shapes or primary shapes) or to contribute to its manufacturing (wrapping shapes or secondary shapes). Initially inspired by Kimura's product life cycle [Kim90] and by Shah's feature classification [Sha88], the functionalities' approach splits the design cycle into four stages (specification, conceptual design, preliminary design and detailed design), that can be largely investigated in parallel, breaking the traditional barrier of sequential design, and thus facilitating simultaneous engineering.

3.1. SPECIFICATION

This stage consists in specifying the requirements of the future product. Functional specification helps define the service functions and the global constraints functions. Service functions model the requirements from the end-user's point of view. Global constraints functions model the set of constraints with which the product must comply. At the end of this stage, the customer's requirements are validated. These requirements have to be established during the following stages.

Figure 1 shows the organization of the four stages of the design cycle. In the center of each stage representation, constraints are either created, controlled or transmitted to the following stage, which must respect them.

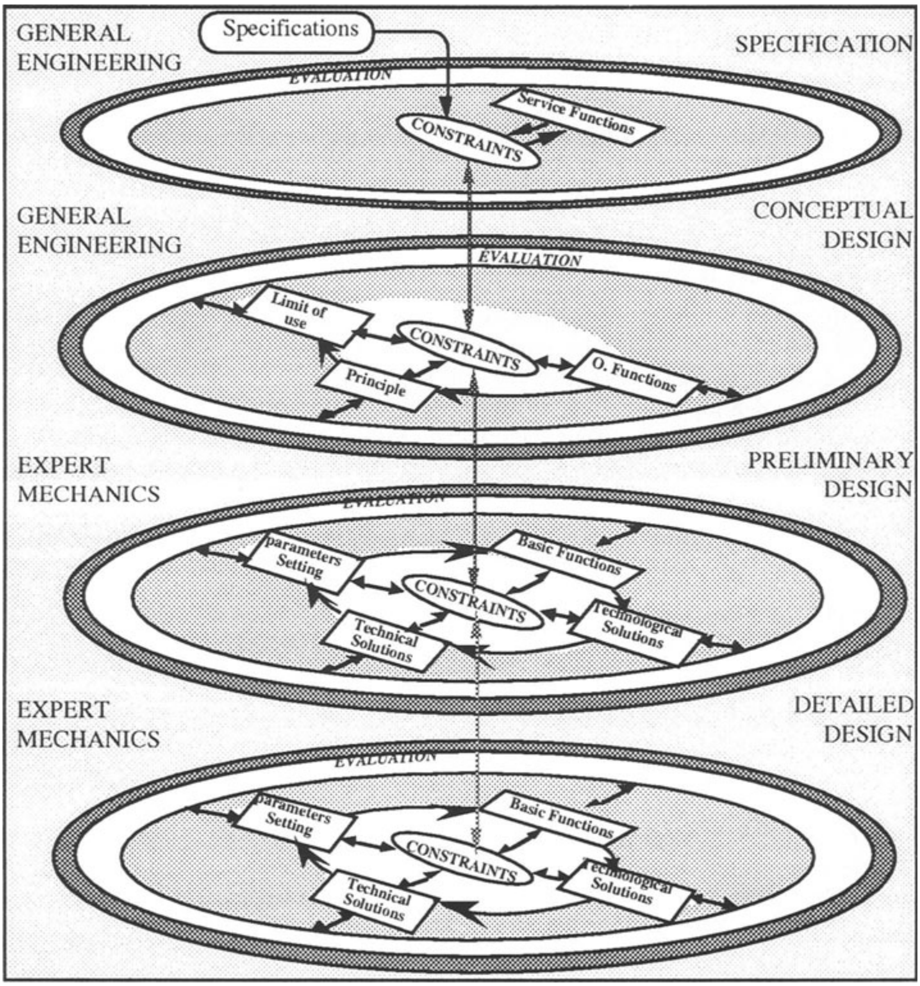

Figure 1: Four-stage design cycle

3.2. CONCEPTUAL DESIGN

The aim of this stage is to define how each requirement is going to be met, from a conceptual point of view. The high level service functions are expressed using a reduced set of known operating functions. Each operating function (control, support, stabilizes, etc.) is in turn decomposed into operating sub-functions, thus further qualifying the requirement. When every operating function of a required service function is identified, known solution principles (mechanics, fluid, electromagnetics, ...) can be associated to them. When a valid reduced set of solution principles is obtained, technical functions can be associated to each operating function. These technical functions implicitly refer to a variety of specialized disciplines (automatics, mechanics, maintenance, etc.). Material aspects only appear during the following stage.

3.3. PRELIMINARY DESIGN

This stage is deroted to determining the material architecture of the product. Known technological solutions are evaluated for each technical function. This task is achieved with respect to the global constraints (cost, performance, ...) and trade specific constraints. Then, refining the criteria again, it is possible to select the technical solutions. Dimensioning of these parameterized solutions (functional dimensioning) is necessary. This stage is characterized by the first possibility to carry out parallel (simultaneous) design. The experts in mechanics can separately evaluate the kinematic behaviour of an assembly and select a particular kinematic chain, while the experts in automatics can use a bottom up approach to specify the architecture of the command of the system, based on the appropriate technologies. The rest of this paper is focused on the dimensioning concerns at this stage.

3.4. DETAILED DESIGN

The aim at this stage is to reveal the final shapes of the parts. Dimensioning here concerns the global shapes. We will not consider this stage in the following.

4. Analysis function in preliminary design

In this paper we will only consider the preliminary design stage, characterized by the potential use of mechanical analysis (Figure 2).

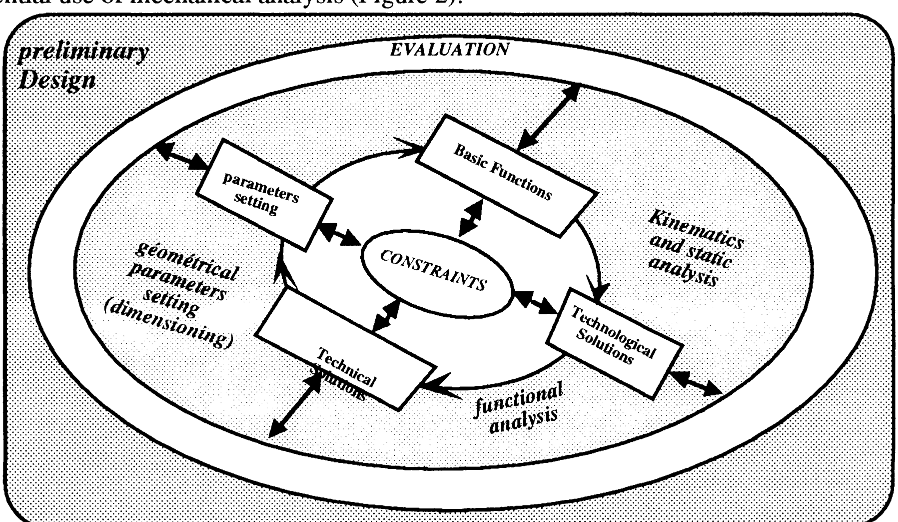

Figure 2 : The analysis function in preliminary design.

We propose to determine the different types of mechanical analysis having a relation with the product definition, in order to study the role of the analysis function at the various steps of preliminary design. At this stage, various types of mechanical analysis are used. In particular, we distinguish:

4.1. KINEMATICS ANALYSIS

Every selected technological solution must be kinematically validated. The kinematics analysis allows for the determination of the input and output laws, the degree of hyperstaticity of the mechanism and the kinematics parameters of basic functions.

4.2. STATICS ANALYSIS

In this stage, the issue is to determine the efforts applied to the inter-parts links. For isostatic systems, it is always possible to determine the resulting efforts applied to each inter-parts link, but for the hyperstatic systems (the number of unknown parameters is superior to the number of equations), other types of rules are used, such as effort-displacement relation (behaviour law).

4.3. DYNAMICS ANALYSIS

Based on the fundamental relation of the dynamics theory, this type of analysis allows to determine the dynamic equilibrium conditions, the vibration stress and distorsion tensors, the kinematic and dynamic moments, the forces of inertia and the frequencies of the different movements (vibrations).

4.4. FUNCTIONAL ANALYSIS

This type of analysis concerns all kind of calculations related to the mechanism. It helps guide the choice of technical solutions such as gearing calculation, the number of teeth, the module, the diameters, the chain of dimensions, the tolerance limits and the rolling bearings selection: such as type, life cycle period, etc.

4.5. MECHANICAL BEHAVIOUR ANALYSIS (DIMENSIONING).

This type of analysis consists in evaluating the stresses applied to the different mechanism parts, so as to determine the appropriate dimensions. The types of calculation used in this phase are the load calculations, the distortion calculations, the dimension calculations and the calculations for evaluation (e.g. : FEM)

5. Functional Dimensioning

After choosing the functional principle and the basic solution, the product can be represented by a kinematics chain (Figure 3).

This schematic representation, expressing a basic idea, constitutes the starting point of the integration in the design prosess (i.e.: how to use known standard components to create a new product). It allows for the idendification of the inter-parts links, hence the kinetic behaviour of each part in the mechanism. We will detail in the following the dimensioning concerns related to this functional design process.

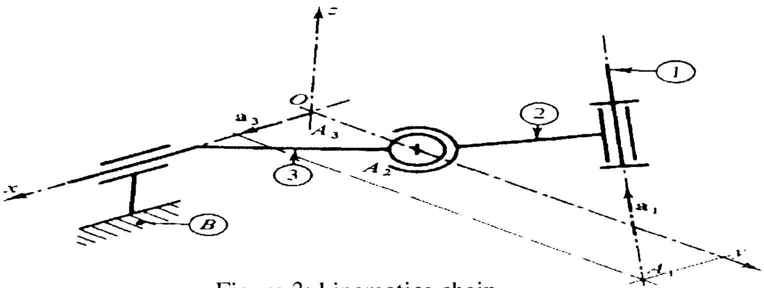

Figure 3: kinematics chain.

The functionalities approach first deals with the functional shapes. One supposes that the design of each mechanism part starts by the definition of its functional shapes. Each inter-parts link constitutes one basic function. The choice of a technical solution, for each basic function, leads to define the set of functional shapes associated to every part. At the end of this process, the product is defined by a set of technical solutions implementing some inter-parts links (Figure 4). Each part may be used in one or more inter-parts links. The technical analysis of every inter-parts link generates part functional shapes.

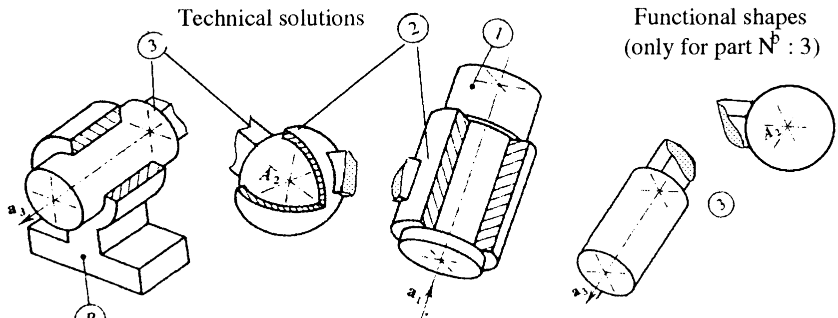

Figure 4: Part functional shapes

In order to ensure the power transfer, the inter-parts links are characterized by a transferable efforts tensor (static tensor). Some static tensor components are intuitively defined, looking at the type of the inter-parts link; the others are determined by application of the fundamental laws of statics. This tensor represents the efforts (in R6) applied to the inter-parts link (Figure 5).

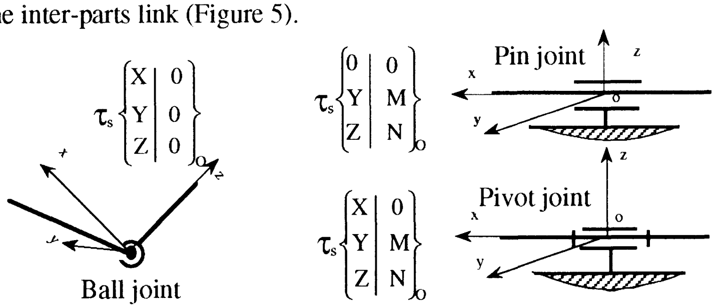

Figure 5: Static tensor applied to inter-parts links.

Each inter-parts link must be dimensioned to support the applied efforts, while respecting the economical constraints. The function-based design considers that the inter-parts links are defined as some parameterized functional shapes.

Investigation models [Aub88] [Lar88] allows to compose the equations containing some parameters that characterize the inter-parts link (dimensions, material ...) and the associated static tensor components. The resolution of these equations allows to determine the parameters of the inter-parts link. This is the main goal of the functional dimensioning function. It is of course necessary to perform a local dimensioning of every functional shape associated to each inter-parts link so as to obtain the functional dimensions of the parts strictly required for the mechanism.
This step of preliminary dimensioning [Ben96] consists in focusing the analysis on a specific aspect of the parts (local analysis): the functional shapes. It results in the definition of the functional shapes correctly dimensioned. This stage may eventually question the choices of the technical or technological solutions.

6. Modelling

The modelling step concerns three basic entities: mechanism, part and inter-parts link.

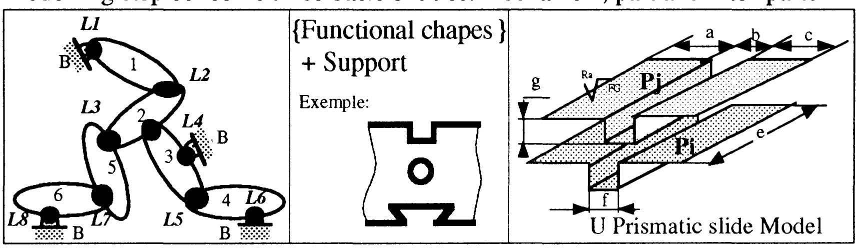

Figure 6.a, 6.b, 6.c : mechanism, part and inter-parts link Models

The model of a mechanism includes a set of parts, related to each other by links called basic functions. The model of the parts is composed of a set of functional surfaces and a support that represents the material flow existing between the different functional surfaces. The inter-parts link model is characterized by form features, precision features, material features, dimensions,...

Figure 6.c shows an example of an inter-parts link (prismatic slide). Since functional design only considers functional shape, the inter-parts link only keeps track of the functional shapes involved in the relationship. The determination of the values of the parameters associated to each link requires different kinds of calculations (FEM, theory of contacts, etc...). The product model must consequently be open to communication with different analysis applications.

7. Implementation

A flexible data structure, able to support the evolution of the dynamic product model is a strong requirement for implementing the concepts previously introduced. The use of object-oriented techniques has provided the application with modularity and rapid prototyping facility. The CAS.CADE platform (Matra Datavision) has been selected, because it provides the possibility to use an extensible set of CAD object classes. Moreover, this platform includes an object oriented data base management system (an encapsulation of Objectivity).

Figure 7 shows how the available classes library can be extended with new packages (set of classes): the dynamical model package, the inter-parts links package and the external communication package.

The dynamic model package is in charge of controlling the design process, dictated by the end-user, who can freely choose to focus design on specific low level problems, question a validated solution, reason about function, using a top down or a bottom up approach, ... Whatever the user's choice, the system must keep track of what part of the problem has been solved so far and what remains to be addressed. It must also store the explanations related to every choice the user has made.
The inter-parts links package maintains pointers to geometry and topology classes and specifies the original product structure which is necessary to control the global assembly model.

The external communication package is an encapsulation of the various analysis tools that may be required to perform the dimensioning of different kinds of parametrerized inter-parts links models (technical solutions). These tools may be either Finite Element Methods, numerical procedures of resistance of materials or expert dimensioning rules implemented using an expert system (Smart Element by Neuron Data Corp.).

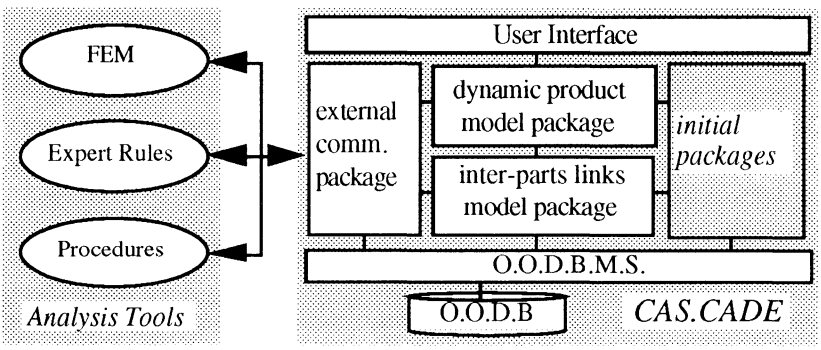

Figure 7 : The development platform.

Through the interface, the end-user can control the dynamic product model and the information model. A significant part of the enrichment made over and beyont the CAS.CADE platform is being devoted to establishing communication means between existing analysis tools and the dynamic product model.

8. Conclusion

Functionality-based design allows to integrate several aspects of analysis, including dimensioning, in a dynamic product model.

The analysis function appears at several levels of functional design and more particularly at the preliminary and detailed design stages. Various types of calculations are likely to appear.

In functional design, the analysis function is used not only for dimensioning, but also for choosing technological and technical solutions. It is also used to evaluate and optimize the globally adopted solution.

The model we introduce in this paper is based on a parameterized representation of inter-parts links; it allows to encapsulate methods and tools of dimensioning. This allows to compute the values of the parameters associated to each inter-parts link. So we can give a positive answer to the initial question: "is it possible to address the analysis aspects right from the modelling stage?"

We think that the approach presented here, based on an object oriented architecture, is an original one. This modelling technique allows to associate different types of information (dimensions, tolerance, surface finish, machining features, etc) to the functional shapes.

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RETHINKING CAD TOOLS THROUGH THEIR USE ?

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Résumé. L'étude des processus de conception du point de vue des objets manipulés et des interactions est très riche d'enseignements sur l'activité de conception telle qu'elle est. A travers une étude de cas menée dans la société Renault Véhicules Industriels (RVI) concernant les pièces forgées, nous proposons dans cet article de poser un regard sur l'activité de conception au plus bas niveau. Nous mettons en évidence des points particuliers qui montrent le caractère imbriqué, distribué et finalement complexe de l'activité. La mise à jours de certains modes de coordination des acteurs à travers la CAO nous permettent de dégager des réflexions sur la structure des nouveaux outils de conception dans une optique de co-conception.

Abstract. Studying the complex interactions of different point of view (i.e. technical, human, economical...) in the mechanical design process activity leads to develop a new approach of the CAD tools structure. The nature of the manipulated objects (i.e. plans, CAD models...) teaches us a lot about the mechanical design activity as it actually is. Through an empirical study done in Renault Vehicules Industriels (RVI) company, regarding the forged-part design process, we propose to look at the design activity at the lowest level. We point out some specific facts which show the task interrelations, the distributed and, eventually, the complex nature of the activity. The actors co-operate in different ways, using tools and objects. The analysis of this activity indicates some research directions in the design of new CAD tools for a co-design environment.

1. Introduction

Improving their competitiveness has become a pressing necessity for companies. This is why they try to improve their productivity. Nevertheless, only the production system has been widely optimised until now. Design departments have been protected

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 41–50.

from these upheavals. Of course, CAD tools and structural analysis programs have allowed companies to improve their performance. But is the product easy to manufacture, to sell or to repair, and, eventually to recycle? Is the design process efficient itself? Drawn up by the market evolution, the concurrent engineering concept was born, translated in terms of project organisations in particular. The goals are to improve the feasibility of the product, the market agreement, while reducing the design cycle. Those project organisations have been widely studied in France [1], the USA and Japan [2], from a human and organisational point of view. All these works show how, task overlaps, team structures, communication and co-operation in the design process are important. This approach have already allowed to reduce drastically design lead times. But through all those upheavals, did the design activity actually change? Are mechanical design engineers so isolated? How does the information come back up from downstream? In a word, what is designing?

Through a case study realised in Renault Vehicules Industriels (RVI) on forged part design, we propose to study the design activity at its lowest level (i.e. the interactions between actors and objects). This work highlights three situations where actors co-ordinate their activity and co-operate through the manipulated objects (e.g. CAD models, plans…). Firstly, we emphasise the constant ambivalence of the process. On one hand their is a trend to institutionalise the practice, while, on the other hand, the activity efficiency mostly depends on local arrangements. Secondly we point out some task overlaps, particularly the co-definition of the functional requirements of some parts. Finally we give an example of a CAD model, built from a functional point of view. We show how the task of the downstream actor is influenced by the lack of communication. The last section is devoted to considerations on computer aided design tools.

2. Process analysis: the E50 axle case

RVI design process is composed of six steps punctuated by five "company meetings" (RVE) and three "quality signals" (TQ) (see figure 1). RVE are project stages where important options, choices are made. They are crucial moments where some irreversibility is introduced in the process. In this situation any mistake could lead to a disaster. "Quality signals" are also an important punctuation of the process. For example, TQ1 is the prototype launching signal, when TQ2 means transition between development and industrialisation… The quality department is the key actor of these TQs, nothing is automatic. Without presenting the details of this global process, one can notice that the schema presented in figure 1 is quite conventional. It illustrates what we call a linear process. Economists learn a lot from this level of refinement. For example, the implication of the market structure on the project organisation, can be studied at this level. On the other hand, this level gives no information on the technical activities , neither on the way people co-operate. This is why we focus on the E50 axle design case. At this level and during the project, three actors are mainly involved: the axle design department, the manufacturing industrial department and the forging industrial department.

The main circulating intermediate objects (according to the concept developed in [3] and [4]) are, for each forged part:

- a 3D volume model,
- a 3D surface model,
- a forged part plan,

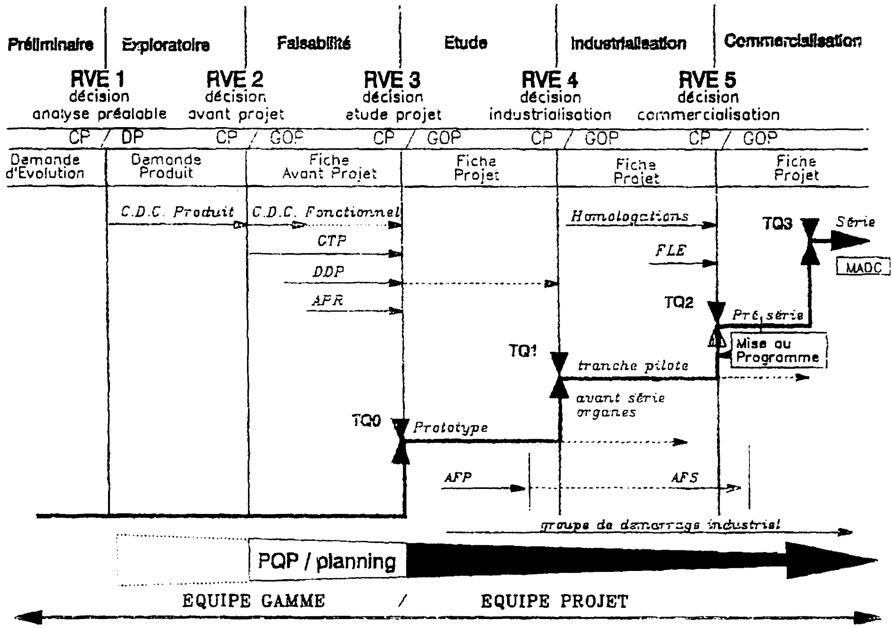


Figure 1 : Global point of view over the design process at RVI.

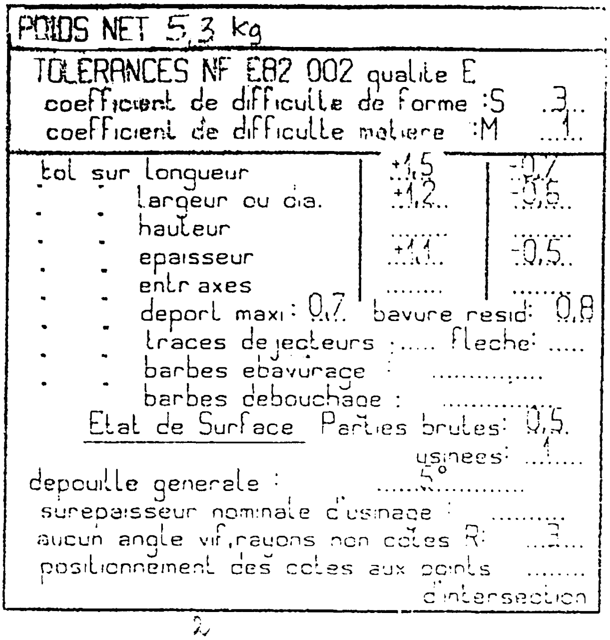
- a tooled part plan,
- an order (for dies, prototypes…),
- prototypes.

Studying some of these objects (how they are generate, by whom, who use them, how...), which are design intermediates, allows to point out interesting process features.

2.1 An activity shaped by agreements, rules…

While looking at forged part plans circulating in the forging plant, we notice the systematic occurrence of a table, on the top right corner of the plan (see figure 3).

It's a summary of the forging allowances, mainly based on Euroforge standard, which is the European forging standard. This table sums up the allowances on the lower and upper die, whatever the part dimensions are. For each new part the values are not revised. People act by habit, to go faster. The economical stress, even the management instructions, inclines to fix as many things as possible, and therefore to keep existing solutions which could have been optimised in a new context. The design process tends to be "institutionalised" by rigid rules without care of the context. Then, local agreements become generic rules just because people have forgotten the story of their creation.



POIDS NET 5,3 kg

TOLERANCES NF E82 002 qualite E
coefficient de difficulte de forme :S ..3..
coefficient de difficulte matiere :M ..1..

tol sur longueur	+1,5	-0,7
largeur ou dia.	+1,2	-0,6
hauteur	....	....
epaisseur	+1,1	-0,5
entr axes	....	....

deport maxi : 0,7 bavure resid: 0,8
traces de jecteurs :..... fleche: .....
barbes ebavurage : ....
barbes debouchage : ....
Etat de Surface Parties brutes: 0,5
usinees: ...1....
depouille generale : ....5°.........
surepaisseur nominale d'usinage : ....
aucun angle vif, rayons non cotes R: ...3...
positionnement des cotes aux points .... d'intersection

Figure 2 : Forging allowances table.

This forging allowances table, contains results of discussions, compromises that may have occurred many years ago. This table is accepted and tacitly extended without being negotiated every time. This is a general feature of the activity. Why discussing or revising what is working properly? This question, a priori striking for an engineer, must be placed in a context of development time reduction. Then, a lack of specification can be discovered, by hazard, when a new supplier produces the part. The latter interprets the specifications in a different way as the former. The part is consistent with the plan, but doesn't fit the mechanism! This true example has revealed a forgotten compromise stated between two actors of the process or an implicit choice made in the past. When actors are moving the organisation forget this implicit knowledge of the context. Of course discussing every choice makes no sense. At this level the good question should be: "What are the points to be discussed and when during the process?"

2.2 A strong tasks interrelation

When analysing in detail the functional tolerancement of a connecting rod (see figure 3), we noticed that some specifications were missing. For example, their was no perpendicularity specification between the fixing hole and the plane surface. This lack of specification may cause assembly problems and even untimely failure of the mechanism. However, the parts were assembled and the mechanism worked properly. What happened? Is this specification actually useful? With an extensive study of the tooling sequences plans we found the missing specification were indirectly met thanks to the manufacturing process (see figure 4).

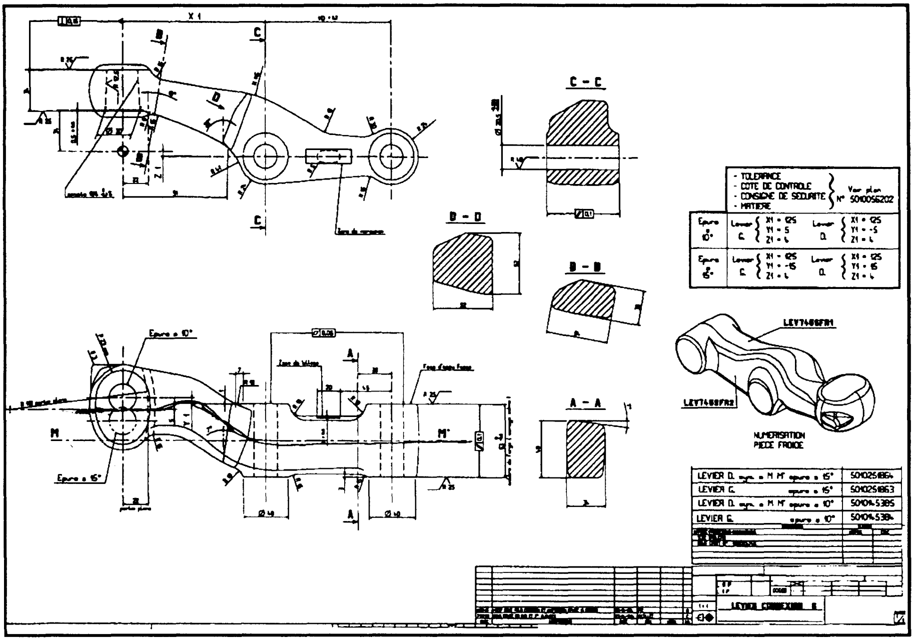


Figure 3 : An intermediate object: a forged part plan.

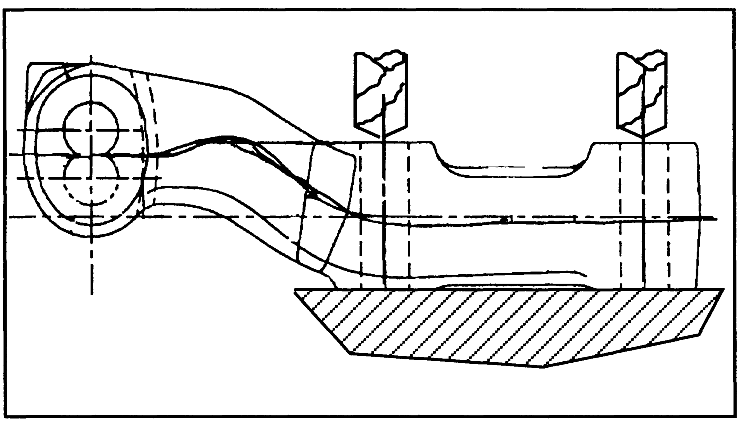


Figure 4 : Implicit definition of the perpendicularity

The plan was clear enough for a professional to translate an implicit (but useful) condition into a tooling sequence. Therefore, in this case, we can say that the manufacturing department helped implicitly the functional definition of the part, without co-ordination with the design department. This example shows that the functional view is also necessary for downstream actors. Some of our academic visions of the different actors' roles sway (the design department owns the functional view...).

2.3 CAD objects, new co-ordinations

The forging department has been one of the first to manipulate surfaces with CAD systems for the dies geometry definition. The surface modelling has a definitive advantage regarding any other representation: it allows tool-paths automatic generation. But it is through the design department that the CAD tools actually arrived. The geometry manipulation and modification facilities together with simulation have widely gain the professionals agreement. The design and forging departments started naturally to exchange CAD models. The plans still exist. We are faced to a twofold representation.

Several hundreds of hours are currently necessary to build a surface model of the forging dies. Therefore, sharing a surface model built by the design department is time saving and economically sound. In this ideal process, the surface model of the part is built by the design department, satisfying its own constraints (i.e. mass reduction, functional requirements...). The forging department, just adds specific forging features (flash land, dies fixturing devices...) to the initial model which is now the model of the mould Almost 80% of the work has already been done. In our case their is no data exchange problem due to eventual heterogeneous CAD systems. A common data base allow an easy sharing.

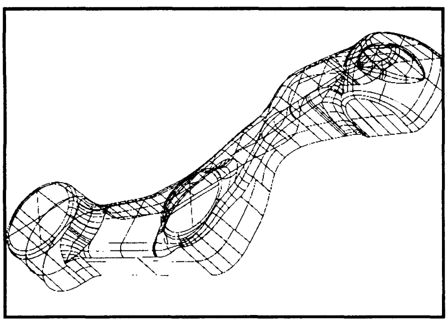


Figure 5 : Surface model of the connecting rod.

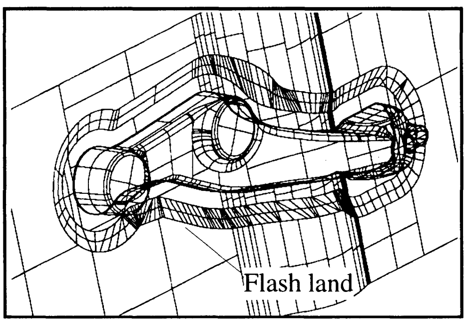


Figure 6: Surface model of one die.

To illustrate the process, let's take the connecting rod example (see figure 3). As we said before, the design department builds the surface model presented figure 5, mainly using a previous design. In fact, this is more a re-design than real creative work. After that, the first operation the forger makes is to build the flash surface (a part of the flash land as shown figure 6). The flash surface is the key entity from which all the die model construction is deduced. This entity uses the flash line of the part model as a supporting line. It is obvious that the result is unacceptable (figure 6). A long and tricky work is necessary to modify the initial model in order to get a proper result. In fact, for the actor in charge of the part modelling task, the flash line is the result the building process, when, for the forger, it is the starting point of the dies modelling process.

This example is a typical situation where different actors' logic do not meet. The notion of actors' logic can be developed at three levels. The first is related to the professional body, its history, rules... It is a common knowledge of the profession. The second level is related to the company where this common knowledge is enriched, shaped by the industrial context. The third level is the level of the individual actor. Each professional builds a specific knowledge from what he learned at school (first level), from the everyday work, from the interactions with other persons and all other interactions with the environment. This last level meets the concept of “object world” developed in [5]. To summarise, the design department logic is mainly oriented toward mass reduction, clearance problems and, more generally, toward the transformation of a functional requirements into a technological structure satisfying the specifications. Finally the design department mainly produces plans and CAD models. On the other hand, the forging plant logic is closer to the material. It is led by the die manufacturing constraints, cost reduction, productivity (the forging plant is competing with external suppliers). The press and hammers are very close, just downstairs…

On the same way, we can say that CAD tools also have their own logic. Indeed, the supported models have a specific format, the surface construction procedures are restrained by a user interface and by the nature of the manipulated entities themselves. The supported entities are mathematical representations of surfaces, pure geometry and not another type of entity (technological features for example). As we can see, a tool (computer aided or not) has a strong logic, translation of the image its creators had from the mechanical design activity. Then, CAD tools widely influence the action. They create a rigid frame for the interactions between actors (design department and forging plant in our case).

When an actor owns the leadership in the system, he tends to impose his logic through the tools he work with. Let’s take the example of the manufacturing industrial department. As we saw in section 2.2, the manufacturing industrial department makes the tooling sequences and the part fixturing device design in order to manufacture the part in the workshop. Its goal is to manufacture the part at the lower cost, ensuring the delivery schedule and the quality required by the plan. The plan? Why not a CAD model? Here, the main intermediate object between the design department and the manufacturing industrial department is a plan defining the part. Here, the exhaustive knowledge of the part geometry is useless, when a precise definition of the functional surfaces through the tolerancement is of prior importance. At this level, the main problem is the capability of the industrial process. In that particular case, the manufacturing engineering department does not use the CAD system as often as it could. The design department (which is traditionally the leader) tends to progressively suppress the plans. This situation could become unbearable by the manufacturing engineering department, because the plan gives the manufacturing engineering department a functional view of the part. The CAD model does not provide this information. This point is well known by the researchers and is at the centre of numerous works about feature based representations for example [6]. Nevertheless, it is too seldom highlighted that an actor can be kept out of the action, only because the tool the leading actor imposes does not fit his logic.

3. Some considerations regarding the CAD tools

Through the presentation of this case study we have shown a situation, however it is not pure, is real. We try in this section to derive some teachings from these observations and in particular we develop several reflections regarding the CAD tools.

The difficulty to make CAD tools accepted by the manufacturing industrialists is symptomatic of the fact the tools are not adapted to their problems. Indeed, it is useful to manipulate complex geometry when only basic geometry is used in 95% of the cases? On the other hand, the lack of tolerancement and more generally the lack of functional information in the CAD models handicap downstream actors heavily, especially the industrialists as we saw. The finding is not new. But this observation is for us the symptom of the absence of matching between the tools and actors' logic. And may be the lack of involvement of the industrialists in the definition of such CAD tools. Or, to finish, the CAD tools designers ignore the downstream actors' logic. Ignoring the different viewpoints and associated logic leads to impose a unique model based on a particular representation of the problem. Typically, today the geometrical logic is dominating. Furthermore, the objects can't fully play their mediating role. Therefore, some actors have difficulties to work with such systems. They undergo the prescription of the other actors. Most of the time the prescription comes from the design department as in the RVI case.

The idea of "virtual space" [7], shared by all the actors is very interesting. This space (materialised in our case by the CAD tools) can be a place where actors can exchange very easily, a kind of neutral field. As we saw in our example, there is not *one* but there are *many* designers in the mechanical design process. Each actor participates, at its own level to the product definition, even indirectly. This is the case, when the manufacturing industrial department implicitly defines a functional requirement (section 2.2). It is impossible to set an exhaustive list of the tasks to be done by a given actor. If a function is define by the tasks, the complete definition is therefore impossible. Then, there is an actual risk to confine the actors in their so called function. This could lead to rigidify the process through too prescriptive tools: "this one must do this, this one have not to do that…". This can lead to the total rejection of the tool as M. Rabardel and Beguin [8] notice:" All design environment development philosophy which a priori rigidify the files structure seems doomed to meet important difficulties , if not a check, because it forbid functional adjustments to specificity of the problem and usage schemes.". This observation definitely meets our point of view over the CAD tools tendency to rigidify the design process, de facto forbidding some interactions with the objects.

Finally, to allow co-design, beyond the simple translation of crafts know-how up to the design phase, there must be a real participation of the downstream actors to the design phase. This requirement is partly met in the project teams and new organisational structures, but not yet in the computer aided tools used in the industry. To avoid taking an excessive position (each actor developing his own specific application), a median way must be found, an information structure allowing multi-viewpoint and giving every actor the possibility to access the data he needs. The idea that consists in taking all the know-how upward in the design process to allow the designer to anticipate the problems is for us an utopia, leading to the concept of an omniscient "super-designer". On the other hand, involving the downstream actors through appropriate devices (i.e. computer aided tools together with appropriate organisational devices), the sooner as possible in the design process is a more realistic option. This is the sense of the work developed about the computer aided design tools for forged parts [9].

4. Intermediate objects, an interdisciplinary approach

The approach we have proposed in this paper is based on a deep study of the interactions between actors and the tools operating conditions (especially the CAD tools). A too macro vision of the process gives information on the design process as it *should be*, when the interest of our viewpoint is in the study of the design process as *it is*.

This scientific program can't be achieved with an engineer or computer scientist approach nor with a social scientist approach [10]. In fact, although the mechanical design of artefacts is mainly a technical activity, it is also a social activity. It is enacted in a social group (a company, a team, between departments...), a human organisation in constant internal and external interrelation. The technical object among the human interactions, it is the artefact being designed... Then, at every moment in the project there are hundreds of objects, from different natures (CAD models, plans, finite element models, administrative documents, prototypes...) which mediate the action. In this constant movement, the artefact is created, the design is processing. This set of objects, mediating the design process, is called "intermediate objects" according to the concepts developed in [10] and [3]. As we saw all along this paper, their form, nature, medium, strongly influences the objects interaction capacity, their ability to be actual mediators [4]. The object also bears the intention of his author and therefore influences its recipient.

This approach has been carried out for four years by a tight collaboration between 3S and CRISTO laboratories. The field studies we jointly make are mainly about the design activity analysis and we use the notion of intermediate objects as an entry point to observe the organisations. The intermediate object concept nature in itself is propitious to the reconciling of the social and design sciences. In fact this notion of intermediate objects mixes mainly technical contents (plans, CAD models...) together with their action on the design process. These interactions can be fully exploited only with sociological sciences knowledge. The object makes sense in its interaction with humans.

5. Conclusion

This case study allowed us to show the mechanical design process from an unusual point of view. We described the process as *it is* and not as *it should be*, and therefore we saw CAD tools in their usage. At this occasion we pointed out the complex character of the activity and the versatility of the interdisciplinary approach regarding this aspect. The repercussions of this kind of studies on our vision of the design activity and therefore on the computer aided tools we develop will be more and more important.

Acknowledgements

We would like here to thank the Renault Vehicules Industriels company for having kindly opened its door to our research and by then provided a very rich field for this work.

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PRODUCT / MANUFACTURING : A SYSTEMIC APPROACH FOR SIMULTANEOUS ENGINEERING

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Abstract. In simultaneous engineering for systems design, one important difficulty is the management of the increasing flows. For the enterprise, the evolution follows the internationalization of both markets and technologies, the reduction of production cycles, and the improvement of competitiveness. In order to reduce this complexity, we have developped a new taxonomy. This taxonomy must permit the structuration, modelisation, simulation and, finally, management the all engineering components of the product development. This paper studies this taxonomy.

1. Introduction

The main difficulty of the system's engineering design resides in its increasing complexity. In fact, for a given product, the number of references, the geometric aspects of components or the corresponding materials are continously evolving (for example, there are 36 front bumper references for 306 Peugeot car, a cover of the yoghurt pot is a four composite materials). For an enterprise, this evolution is depending on the globalization of markets and technologies, the reduction of production cycles, and the reinforcement of competitiveness.
In order to reduce this complexity, it is necessary to implement an appropriated taxonomy of the product development. This taxonomy allows then the structuring, the modelisation, the simulation and the management of the all components of the product development engineering.This paper studies this taxonomy .

2. The system Product/Enterprise

The development of product results from the application of behaviours (functional and operational) to two systems (product and enterprise). This kind of application help to complete the development. See Figure 1 for an overview of this approach.

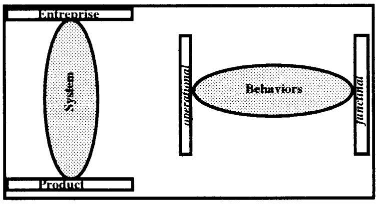


Figure 1. System and behaviours

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 51–59.

The two behaviours are applicable to the two elements of the system
The application of behaviours to the system provides the four fields of the product development; the result is equivalent to the application of the organizational and functionning to both enterprise and product.

-The **Functionning/Enterprise** field must integrate the all necessary and sufficient components to the *enterprise organization*. These components are the strategic, the tactics, and the operational.
-The **Functionning/ Product** field must integrate the all necessary and sufficient components to the *product organization* and its *production tools*. These components are the functional, the structural, and the physics.
-The **Operational/ Enterprise** field must integrate the all necessary and sufficient components to the *enterprise fonctionning*. These components are the means, the ability to act, and the goals.
-The **Operational / Product** field must integrate the all necessary and sufficient components to the *product manufacturing, its use and its production tool*s. These components are the existence, the state, and the value.

As we see, each field is represented by three components what is quite similar to the scientific decomposition into modelization, simulation, exploitation.

The design and the realization:
The enterprise is conceived and realized for the *product*. The product is conceived and realized *by* the enterprise. Under these assumptioms, to be performant to-day, at any time we have a new product to be developped, it is necessary to *adapt the enterprise to those products,* that means to conceive and realize an appropriated project. In fact, three types of acts of design and realization are resulting from the systematic interaction between the four fields of the product development.

The **enterprise realization** resulting from the reciprocal application of the Product Organization (Fon/ Pro) to the functioning of the Enterprise (Opé/ Ent)
The **enterprise design** resulting from the reciprocal application of the Enterprise Organization (Fon/ Ent) to the enterprise functioning (Opé/ Ent)
The **project realization** resulting from the reciprocal application of the Enterprise functioning (Opé/ Ent) to the project elaboration and use (Opé/ Pro)
The **project design** resulting from the reciprocal application of the Enterprise Organization (Fon/Ent) to the product organization (Fon/Pro)
The **product realization** resulting from the reciprocal application of the Enterprise Organization (Fon/ Ent) to the product elaboration and use (Opé/ Pro)
The **product design** resulting from the reciprocal application of the product organization (Fon/Pro) to the elaboration and use of the product (Opé/Pro)
The Engineering of development can be defined by the all fields and interactions intervening in this approach (see figure 2).

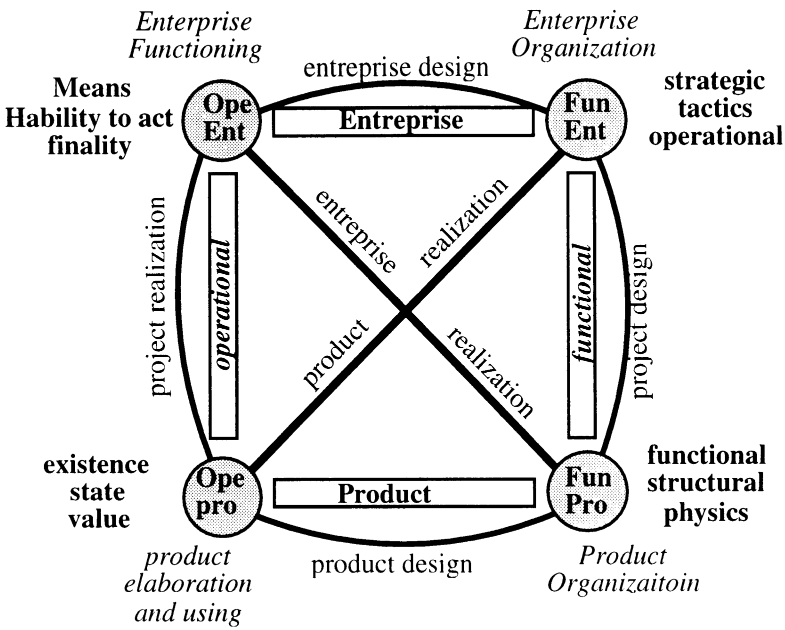


Figure 2. The engineering: project/ product/ enterprise

The "Necessary" of the Entreprise-Product behaviour:
This systemic approach allows us to specify the all set of " necessary " for developping the product and the enterprise.
Thus the design and realization of one product for an enterprise and its corresponding project can be specified. As an example, the enterprise realization is developed.
Example: The enterprise realization :

Entreprise realization	Means	Ability to act	Finality
Functional	Knowledge	Method	Step
Structural	Resource	Process	Goal
Physical	Physical Means	Task	Purpose

Table 1. entreprise realization

The enterprise is realized by its methodes (the injection, the collage...), its processes (manufacturing process, control process...) and its tasks (to inject, paste...). Its activities are expressed in terms of the steps (specification, definition, validation...), objectives and goals (cost, periods, performances, quality...), reaching purposes (produced quantities, client satisfactions...). The enterprises uses generics means such as knowledge (mathematics, physics, economics...), resources (humans, competence...) and physical means (of physical persons, machines...).

The enterprise is realized through its products (functional behaviours). The functional processing of products or its production's tools need knowledges, it is finalized itself in terms of steps and realized itself in terms of methods. The structural processing of the product or its production's tools consommate resources, in order to reach objectives, throughout the production process. The physical processing uses physical means to reach the given objectives by executing the necessary tasks.

A systematic approach concerning each relation of the development engineering allows to build the general taxonomy presented in the table 2.

Entreprise realization	Means	Ability to act	Finality
Functional	Knowledge	Method	Step
Structural	Resource	Process	Goal
Physical	Physical Means	Task	Purpose

Entreprise design	Means	Ability to act	Finality
Stratégic	Context	Choice	Specification
Tactics	Structure	Criterion	Justification
Operational	Trades	Controls	Action

Project Réalisation	Means	Ability to act	Finality
Existence	Organisational means	Decision	Planning
State	Management Means	Commandment	Management
Value	Opérational Means	Execution	Quantification

Projet design	Strategic	Tactics	Operational
Functional	Management function	Service function	Operational Function
Structural	Organization	Logistic	Opérational Structure
Physical	**Décision**	Launching	Real

Product Realization	Strategic	Tactics	Operational
Existence	Organization chart	Schelduling	Planning
State	Direction	Leading	Orders
Valeur	Validation	Method	Realization

Product Design	Fonctional	Structural	Operational
Existence	Creat/Sup Function	Creat/Sup Structure	Creat/Sup Physic
Sate	Fonctional Sate	Structural State	Physical State
Value	Space	Dimension	Data

Table 2 General taxonomy

3. Different views of the simultaneous engineering

The simultaneous engineering is a an approach consisting in committing in parallel activities (and tasks) of the necessary services (and trades) for product development.
This process is, in fact, a commitment at acting time (abilities to act) of the enterprise in order to reach its goals, using its means to do it. The application of this process is translated into an evolution of the product elaboration.
The simultaneous engineering can therefore be represented under five points of views to cover the whole systemic approach of the development of the product as it has been previously elaborated (the view "ability to act of the enterprise", the view "objectives of the enterprise", the view "means of the enterprise", the view "elaboration and use of the product" and, finally, the view "the particular design of the project").

As an example, this paper gives the case of a partial view of "abilities to act of the enterprise".

The present case is a general process and belong to the field of mechanics, and its source is one Japanese document about the new product development, published by Jean-Claude MARTIN [1].

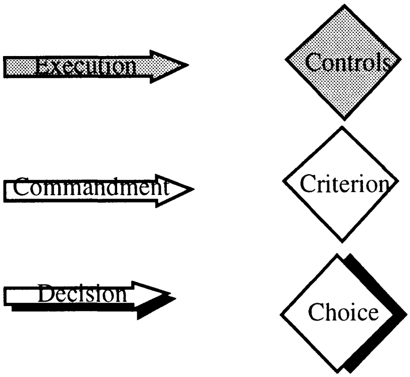
The enterprise must
- determine its goals for action, it concerns; in particular, the ways in which different choices are taken (technological, commercial...),
- the settlement of criterias (indicators of productivité, quality...),
- the building of control methods (of cost, quality...).
One project is realized following decisions (delays, costs, ways...) taken by the management (to determine, to plan...) and the execution (drawing, manufactruring) of actions to be accomplish.

The simultaneous engineering process can be represented under its decisional methods aspects of the *enterprise*, and these *project* decisionnal process.
Methods of the enterprise are generics (independents of the project). They are represented by natures (methods) of choices, criteria of choices and controls. The project processes are specifics to the case study, to one specification; they are represented by decisions, commandments and executions.

Entreprise design	Means	Ability to act	Finality
Stratégic	Context	Choice	Specification
Tactics	Structure	Criterion	Justification
Operational	Trades	Controls	Action

Project Réalisation	Means	Ability to act	Finality
Existence	Organisational means	Decision	Planning
State	Management Means	Commandment	Management
Value	Opérational Means	Execution	Quantification

All these notions (choice, criterion, control, decision, commandment, execution) are represented in the figure 3, following our approach.



The following example show tthe complexity of both choice and decision processes. The choice 1 and the decision 1 in figure 4 are split into intermediary choice i and decisions j. They will be noted 1, i and 1, j.
The initial decision (1,1), that spécifies an action (grow-up), results from the analysis of the first graph. It put forward the evidence of the non-performances in terms of profitability (comparative results of the accounting exploitation 1,1) of company (a), compared with the other companies of this industrial group. The robustness of that decision must be justified comparing, first, inside this company itself (the result at a time 1.2) and, second, with the other competitor companies (1,3).
This way of specification, justification and, finally, action (application) is developed in the next paragraph.
The figure 4 explains the graphs, defines criteria for the decision on these graphs and the links between decisions. They are translated, for example, by specifications such as "product" and they are, provisionnally, estimated in term of "efficiency", "potential of improvement".

The capitalization of know-how in an enterprise needs to be able to represent *decisions* (that means decision, commandment, execution) by models of decision data, duration, and control periodicity (updating) for one *decision* as well as the logic of decision-making by models of processes. These models are studied in works of Oliver Canztler [2] [3] [4].

Others views such as the finality view of the enterprise would have been able to be developed.

Simultanious Engineering : Product processs development "the décisions"

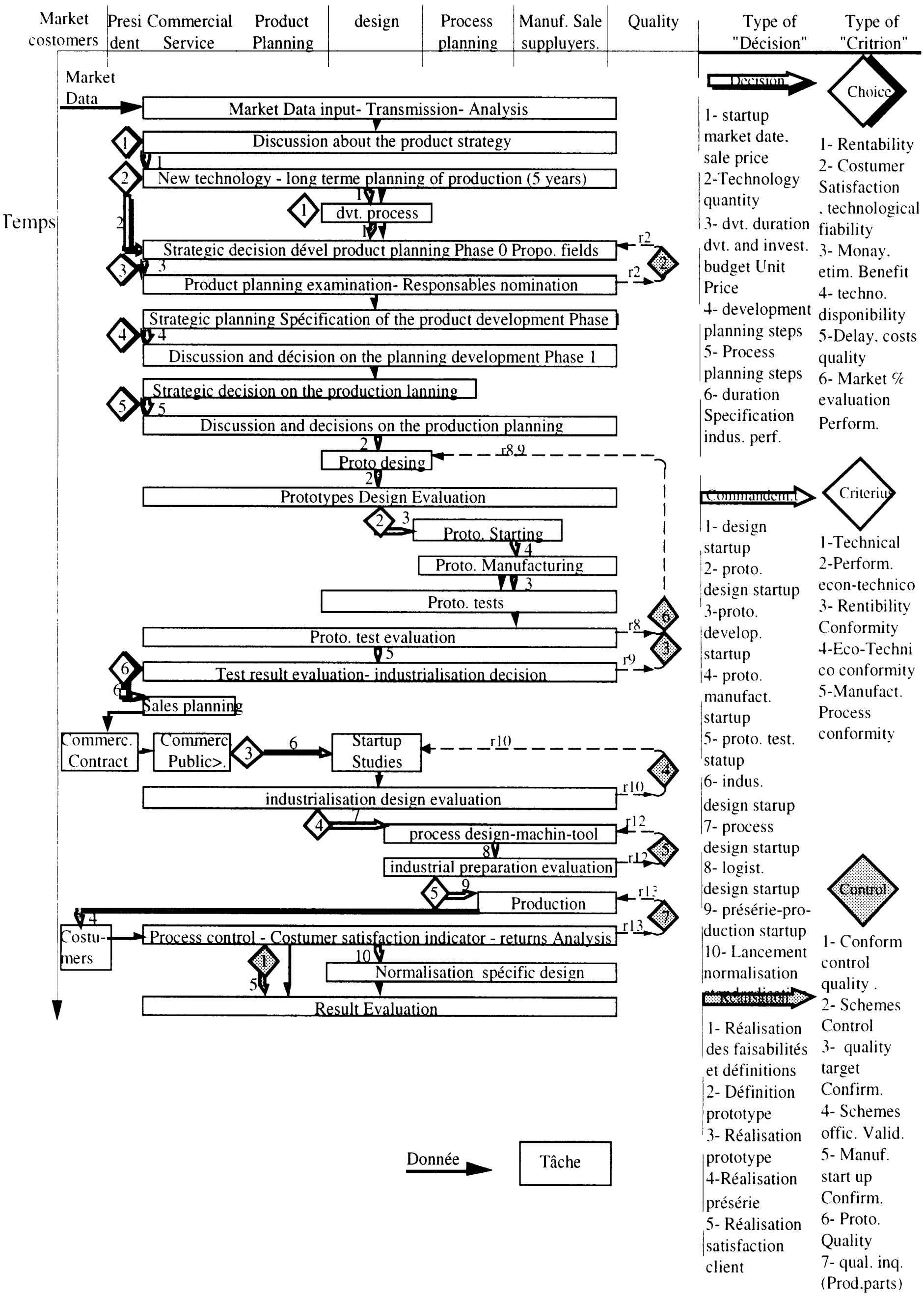


Figure 3. Simultanious engineering process represented by its decisional aspects.

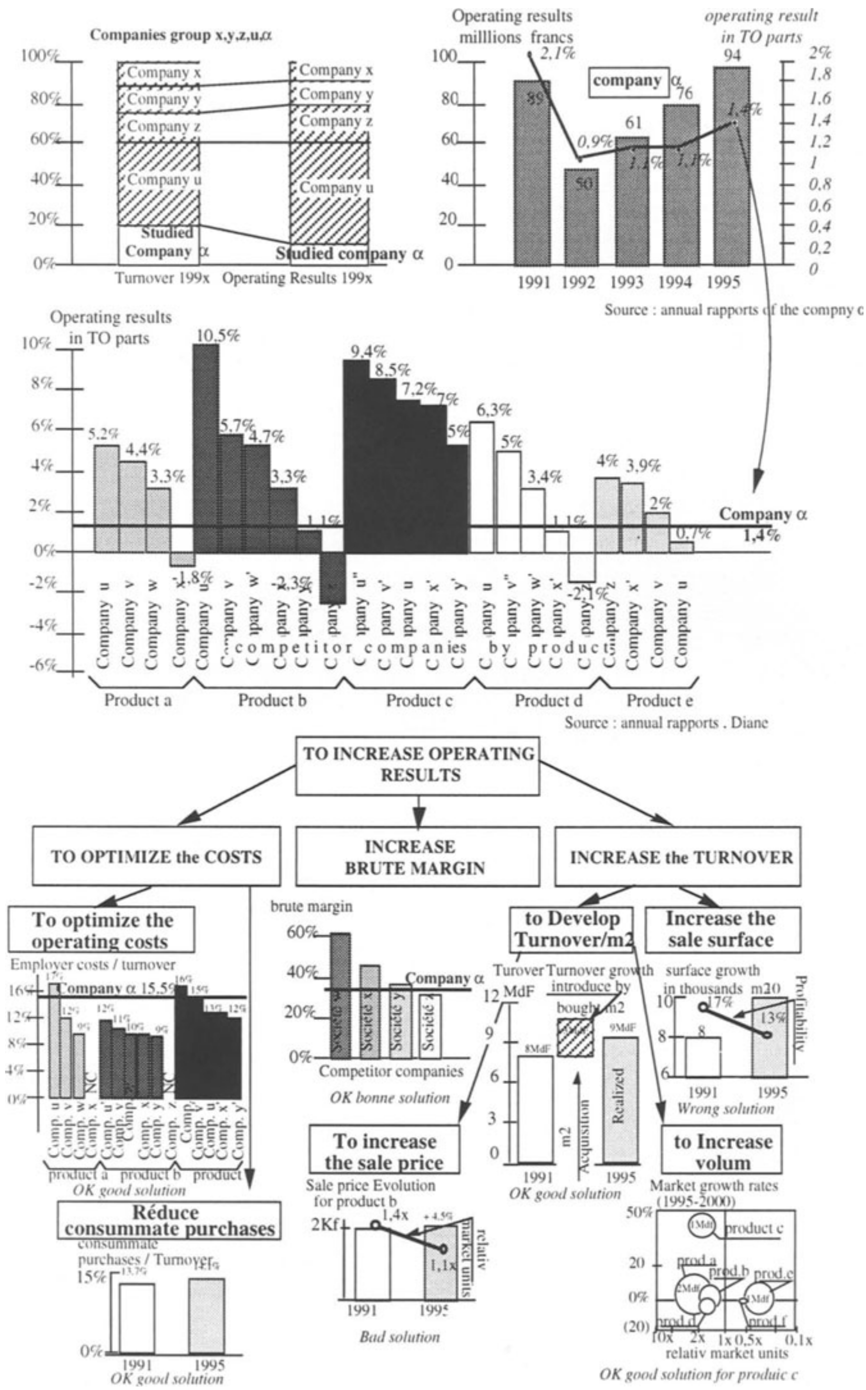


Figure 4. Detailed decisionnal process of the time-to-market, sale price of fitting the profitability criteria.

products opportunity matrix

product type	Product c	Product e	product b
Opportunity	- to buy pattents of new products distribution - good market evolution	- to change the products scale, to buy the technology x - important potential of the market.	- stop the product b (1.5 years) - devel. 1 product with a good profit. and the new comp. y. to arrive on the market Nov 96
Risks	- new products with a good rentability	- real evaluation of the investisment and technology integration	- problems with the supplayers - technical trades
Questions	- potential product? - which turnover and margin ?	- the potential for a new technology ?	- which develop ? - what is the best date for the substitution ?

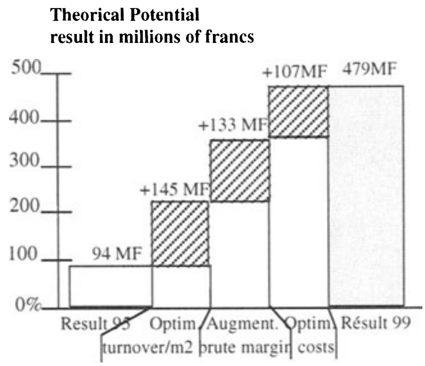


Figure 5. " Product " decision for profitability and estimable of improvement.

4. Conclusion

This paper summarizes some ideas widely explained in the book "The enterprise of products"[5] that will be edited later this year.
It gives the bases for a taxonomy on the product development which allows the comprehension of the engineering product development under many interesting aspects. In addition, it summarizes the necesssary elements for understanding many research themes in the areas such as the elaboration of a representation and the management models of objectives, or even the organization and the management methods of decisional process.

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ON A GENETIC MULTIOBJECTIVE APPROACH FOR THE INTEGRATION AND OPTIMIZATION OF ASSEMBLY PRODUCT DESIGN AND PROCESS PLANNING

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Abstract. This paper presents and discusses a methodology proposed for Computer Aided Design and Computer Aided Assembly Planning integration and for Concurrent Engineering, in order to obtain the generation and selection of optimal assembly sequences and plans with reference to the life-cycle design and redesign of complex mechanical products. The methodology is based on the definition and analysis of suitable assembly product contact relations, dominant element and impediment concept, and on a Multiobjective Optimization approach, that implements a Genetic Algorithm technique.

1. Introduction

The improvement of quality, reduction of cost and time-to-market of mechanical products depend highly on the integration and optimization of product design for ease of assembly and assembly process planning. These functions have deep implications and different aspects strictly correlated to each other. The solution to this problem is a critical task of the implementation of an automated and integrated manufacturing environment. Many procedural and declarative methodologies, techniques and tools have been proposed [1]-[6] for assembly product design and process planning. However, there is still a need for a holistic, simultaneous and concurrent view of the whole product life-cycle design process and manufacturing process planning task, in order to take into consideration the whole manufacturing and post-manufacturing aspects, from design to after-sale servicing, and even to recycling. Moreover the continuously changing production environment, in terms of objectives, capacities, constraints and context, requires the dynamical allocation and reallocation of the tasks

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and the dynamical utilization of the resources actually available. Therefore the problem can be intrinsically defined and structured as the search for a Multiobjective Optimization.

This paper presents and discusses a methodology proposed for Computer Aided Design and Computer Aided Assembly Planning integration and for Concurrent Engineering, in order to obtain the generation and selection of optimal assembly sequences and plans with reference to the design and redesign of complex mechanical products. This methodology is based on the definition of suitable assembly product contact relations, dominant element and impediment concepts, and on a Multiobjective Optimization approach [7], [8], that implements a Genetic Algorithm technique [9] - [11]. On one side the assembly contact relations, the dominant element and impediment concepts are used so as to make possible a quantitative formalization of the feasibility of accomplishing the assembly task of mechanical components. In this phase mechanical constraints are considered and the identification of suitable sub-assemblies is defined [12], [13]. On the other side the Genetic Multiobjective Optimization technique allows the generation and selection of optimal assembly sequences and plans, which are satisfied by suitable objective functions, that are relevant to the whole product life-cycle design process and assembly process planning task. This technique takes into consideration both manufacturing and post-manufacturing aspects, from design to servicing [12], [13]. Therefore the proposed methodology can be seen as a procedure to implement Simulaneous and Concurrent Engineering.

The proposed methodology globally applies the Genetic Multiobjective Optimization to the six main aspects that significantly contribute to the definition of design and manufacturing process of a mechanical system. These aspects are quantified by the definition of six main objective functions, respectively: OB_1, assembly cost objective function; OB_2, assembly cycle-time objective function; OB_3, product reliability objective function; OB_4, maintenance cost objective function; OB_5, production flexibility objective function; OB_6, redesign and/or modification flexibility objective function. OB_1 and OB_2 minimization reduces assembly product cycle time and cost; OB_3 maximization allows the increase of product reliability; OB_4 minimization makes economical all the generic manufacturing and post-manufacturing activities relevant to the product; OB_5 maximization allows optimal utilization of assembly system resources; OB_6 minimization implies the reduction of modifications number to the components, when product needs modifications in order to satisfy specific requirements, different from those previously specified. The concept of dominance of a solution has been adopted as a criterion for the Multiobjective Optimization [7], [8]. Suitable utility functions that reduce the Multiobjective Optimization to a maximization problem have been considered. This problem has been efficiently solved by means of the application of a Genetic Algorithm technique. It works also when these functions are defined as not continuous and discrete.

The proposed approach is implemented and exemplified by a case study applied to a typical industrial assembly product. The proposed genetic Multiobjective Optimization methodology has proved to be capable and suitable to solve assembly product design problems and process planning for mechanical products with a high number of components and complex contact and assembly impediment relations. Moreover, constraints relevant to the assembly process resources and multiobjective functions can be considered. This methodology also allows the parallelization of the assembly process by the introduction of the dominant element concept. Another characteristic of this approach is the possibility to generate a set of optimal feasible assembly plans with an adequate fitness level. These plans could be suitable alternatives to use most optimally the actually available assembly system resources.

2. Multiobjective Optimization Problem Definition

2.1. MULTIOBJECTIVE FUNCTIONS EVALUATION

The Multiobjective Optimization problem definition of the assembly product life-cycle design and process planning is proposed in this paper. Through a simplified case study, the feasibility and the advantage of this approach is demonstrated. It could be virtually applied to more complex cases, closer to industrial practice, if further factors and constraints are examined. In the application study, the selection of a single dominant element has been adopted for assembly planning. Successively, the Multiobjective Optimization problem definition has been decomposed into the definition of the six different aforesaid objective functions OB_i (i=1,2,...,6).

The assembly cost objective function OB_1 to be minimized can be considered equal to CM assembly cost of the product,

$$OB_1 = CM = CP_i + \sum_{j=1, j\neq i}^{n_1} CA_{i,j} + CA_{i,k,l} + \sum_{j=n_1+2, j\neq i}^{n} CA_{i,j} \quad (1)$$

where n is the number of components, n_1 the number of components to be assembled singularly or in subgroups on the dominant element i, n_2 the number of parts to assemble on the system made by n_1+k+l parts, CP_i feeding and orienting costs of the dominant element i. $CA_{i,j}$ and $CA_{i,k,l}$ are respectively the assembly costs of the j and the subassembly k and l on the i component. $CA_{i,j}$ and $CA_{i,k,l}$ costs can be considered as proportional to the times required to assemble together k and l components in a subassembly, to assemble the k,l subassembly on the assembly and to assemble j component on the assembly as follows:

$$CA_{i,j} = K_{i,j} t_{i,j} + C_j \quad (2)$$

$$CA_{i,k,l} = K_{k,l} t_{k,l} + K_{i,k,l} t_{i,k,l} \quad (3)$$

The specific application case regards an automotive steering box composed by 46 components, (see Fig. 1). Costs have been estimated and normalised in a range from 0 to 100. They depend on the available assembly equipment and the connected assembly tasks. The following n_{dom} = 12 suitable dominant elements have been considered (see Fig. 1) as follows:

$$i = 22, 23, 25, 26, 28, 29, 30, 42, 43, 44, 45, 46. \quad (4)$$

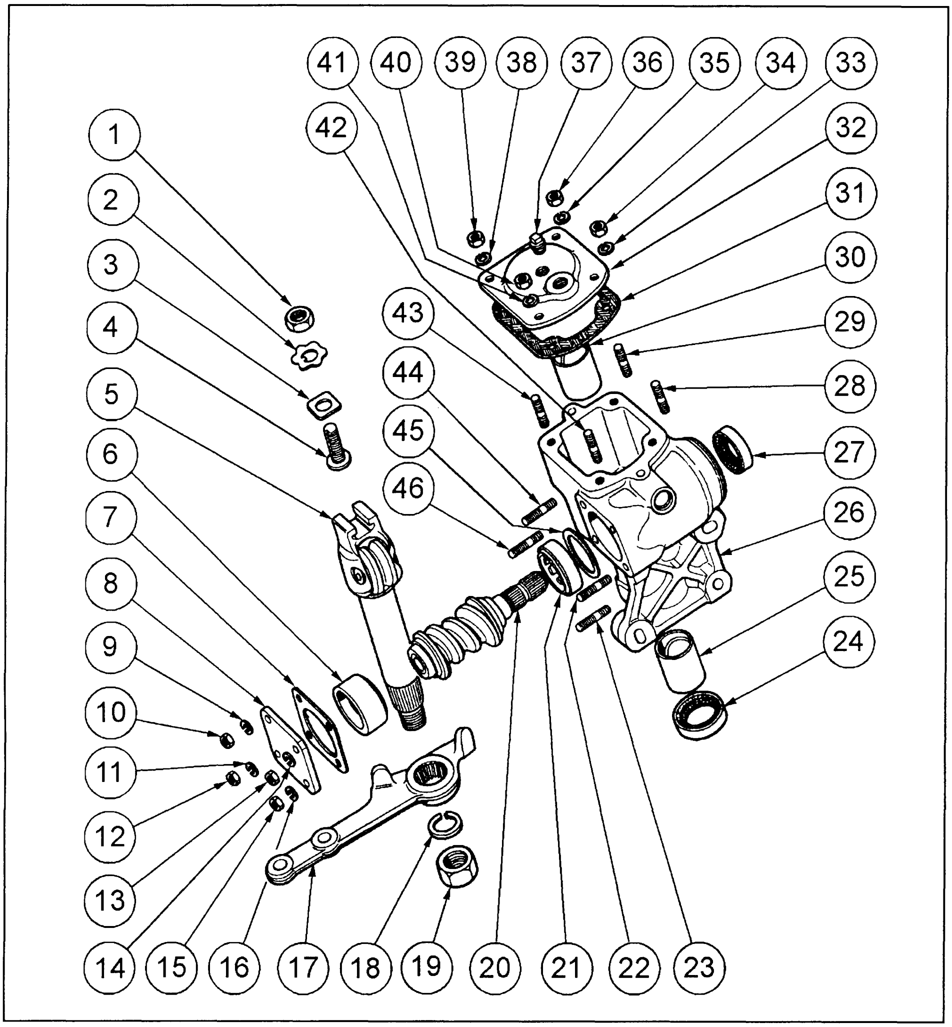

Figure 1. Case study assembly: automotive steering box.

For each dominant element, costs have been evaluated by the previous equations (1)-(3). The assembly cycle-time objective function OB_2 to be minimized can be evaluated as the total time t_{tot},

$$OB_2 = t_{tot} = \sum_{j=1,j\neq i}^{n_1} t_{i,j} + t_{k,l} + t_{i,k,l} + \sum_{j=n_1+2,j\neq i}^{n} t_{i,j} + t_i \qquad (5)$$

where t_i is the time required by a suitable equipment to execute feeding, orienting and inserting operations for the *i* dominant element .
The evaluation of the product reliability objective function OB_3 to be maximized is related to product manufacturing and post-manufacturing reliability R, as follows:

$$OB_3 = R = \prod_{j=1, j\neq i}^{n_1} R_{i,j} \times R_{k,l} \times R_{i,k,l} \times \prod_{j=n_1+3, j\neq i}^{n} R_{i,j} \times R_{d_i} \times R_p \qquad (6)$$

$R_{i,j}$ is the assembly reliability of the *j* component on the dominant element *i*, $R_{k,l}$ is the assembly reliability of the *k* component on the *l* component and vice versa, $R_{i,k,l}$ is the assembly reliability of the component couple (*k,l*) assembled together on the assembly on dominant *i*, $R_{d,i}$ is the assembly/feeding and orienting reliability of the dominant element *i* on the selected workstation/piece of equipment and R_p is the product reliability depending on the assembled components reliability. $R_{k,l}$ is defined as

$$R_{k,l} = R_k R_l \qquad (7)$$

R_k as $R_{d,i}$ is the reliability of feeding and orienting the dominant element *k* relatively to the subassembly *(k,l)* on the workstation. R_l is the assembly reliability of *l* on *k* element. $R_{i,k,l}$ can be evaluated in correspondence to the couple (*k,l*) by means of R_{k_i} and R_{l_i} with the equation

$$R_{i,k,l} = R_{k_i} R_{l_i} \qquad (8)$$

Finally R_p can be evaluated assuming that R_{e_j} is the reliability of the *n* assembled components:

$$R_p = \prod_{j=1}^{n} R_{e_j} \qquad (9)$$

The production flexibility objective function OB_4 is associated to the maintenance costs to be minimized. It can be evaluated as the cost of the planned substitution maintenance C_{sost} like

$$OB_4 = C_{sost} = \sum_{j=1}^{n} t_{sost_j} C_{s_j} \qquad (10)$$

The cost of the planned substitution maintenance C_{sost} of the components can be evaluated by means of $MTBF_j$ of the *j* component, that is, it is function of component reliability as well as of the assembly operation. If product life-time is t_u and

R_{e_j} is the reliability of the j component, by selecting a suitable percentage of reliability reduction p_j at the end of life -time, as it is well known, it is possible to evaluate the corresponding $MTBF_j$. From the knowledge of $MTBF_j$, a constant interval t_{sost_j} of planned maintenance intervention for all the n components is computed:

$$t_{sost_j} = \frac{t_u}{MTBF_j / m} \tag{11}$$

m is an integer and C_{s_j} (see eq. (10)) is the planned substitution cost for the j component. The assembly cost objective function OB_5 to be maximized can be considered equal to production flexibility function NF_{prod} as follows:

$$OB_5 = NF_{prod} = \sum_{s=1}^{n-3} {}_sN_{M_{j,i}} + N_{M_{k,l}} + N_{MGR_{k,l}} + N_{M_i} + N_{MP_i} \tag{12}$$

where:

- ${}_sN_{M_{j,i}}$ the greatest number of alternative devices/workstations/equipment required to assemble j component on i dominant element;
- $N_{M_{k,l}}$ the greatest number of alternative devices/workstations/equipment required to assemble k component on l component that define a subgroup to assemble on the already assembled n_1 components;
- $N_{MGR_{k,l}}$ the greatest number of alternative devices/workstations/equipment required to make up subgroup (k,l) to assemble on the already assembled n_1 components;
- N_{M_i} the greatest number of alternative devices/workstations/equipment required to set dominant element i on feeding and orienting device;
- N_{MP_i} the greatest number of alternative devices/workstations/equipment required to feeding and orienting dominant element i.

The redesign/modification objective function OB_6 to be minimized can be defined as follows:

$$OB_6 = K_{\text{mod}} \tag{13}$$

K_{mod} is a function proportional to the number of product components that must be redesigned and/or modified in order to satisfy different or new specifications. The redesign and/or modification can modify assembly contact and impediment relations. Consequently an assembly plan that was previously convenient for the product before modification and/or redesign, can be no more valid for the modified and/or redesigned product. Therefore maximum flexibility will be reached for a minimum number of modified components.

2.2 IDENTIFICATION OF THE OPTIMAL SOLUTIONS

The identification of the optimal solutions is based on a multiobjective approach that applies the dominance concept of a solution $\overline{x}$ with respect to another one [7], [8]. In the specific case study the global assembly sequences that can be found depend on the values of vector $\overline{x}$. This vector is constituted by 224 elements which define the optimization variables of the problem. The structure of $\overline{x}$ is defined respectively by the selected dominant element (see (4)), the 177 contact relations, which are ordered in a different way as to each component (see Tab. 1) and a random sequence of digits from 1 to 46. Therefore, fixed two vectors $\overline{x}$, namely $\overline{x}_1$ and $\overline{x}_2$, the utility functions have been identified with the specific aforesaid six objective functions. Consequently, a $\overline{x}_1$ solution dominates another $\overline{x}_2$ solution, i.e. $\overline{x}_2$ is better than $\overline{x}_1$ if and only if the following disequations

$$\begin{aligned} OB_i(\overline{x}_1) &\leq OB_i(\overline{x}_2) \qquad i=1,2,4,6 \\ OB_j(\overline{x}_1) &\geq OB_j(\overline{x}_2) \qquad j=3,5 \end{aligned} \tag{14}$$

are satisfied at the same time and if and only if at least for one of them the inequality is true. According to these rules, it has been possible to automatize the search for the more dominant solutions with reference to the feasible solutions generated by the Genetic Algorithm.

3. Multiobjective Optimization Problem Implementation using Genetic Algorithm

The implementation of the methodology has been based on the assembly impediment concept and the Genetic Algorithm [12], [13]. A procedure has been defined in order to make possible the automatic identification and generation of the feasible assembly sequences and plans as soon as vector $\overline{x}$, as it has been defined in the previous paragraph, is fixed. With reference to the steering gear box assembly (Fig.1), the analysis of contact and impediment relations is executed. Using these relations, the procedure identifies i) an assembly sequence of n_1 components to be assembled, ii) a subgroup of two elements (k,l) to be assembled first together and then on the already assembled n_1 components and finally iii) a further sequence of n-n_1-2 components to be assembled singularly on the assembly. When a vector $\overline{x}$ is fixed and consequently a feasible assembly sequence is identified, it is possible to evaluate the six aforesaid objective functions. This procedure has been inserted in the Genetic Algorithm. Executing a Multiobjective Optimization, based on disequations (14), a set of feasible assembly sequences can be generated. The Genetic Algorithm, due to its intrinsical properties [9]-[11] may be used to solve optimization problems formalized by discontinuous discrete functions defined on discontinuous and discrete dominium, typical of specific design and planning application.

TABLE 1. Automotive steering box component description and assembly contact and impediment relations

Corrent element	Description	Assembly relations	
		Contact	Impediment
1	Nut	2, 4	2,3,5,32
2	Safety lockplate	1, 4, 32	32,5
3	Lockplate	4, 5	4
4	Screw adjustment	1, 2, 3, 32	3,5
5	Shaft	3, 30, 20, 25, 24, 17, 18, 19	25,30,20
6	Bearing	20, 7, 8, 26	20,21,45
7	Lockplate	6, 8, 44, 46, 22, 23	22,23,44,46
8	Cover	7, 9, 14, 16, 11, 6, 44, 46, 22,23	7,6,20,21,45,44,46,23,22
9	Lockwasher	8, 10, 44	8,7
10	Nut	9, 44	9,8,7
11	Lockwasher	12, 46, 8	8,7
12	Nut	11, 46	11,8,7
13	Nut	14, 22	14,8,7
14	Lockwasher	13, 22, 8	8,7
15	Nut	16, 23	16,8,7
16	Lockwasher	15, 8, 23	8,7
17	Lever	18, 5	5,24
18	Lockwasher	17, 19, 5	17
19	Nut	18, 5	17,18,5
20	Shaft	6, 5, 21, 27	21,45
21	Bearing	20, 45, 26	45
22	Stud	26, 7, 8, 13, 14	0
23	Stud	26, 7, 8, 15, 16	0
24	Seal	26, 5	25,5
25	Bush	5, 26	0
26	Steering box	24, 27, 28, 29, 42, 43, 44,46,22, 23, 21, 45, 31, 7,30,25	0
27	Seal	26, 20	45, 20
28	Stud	26, 31, 33, 34, 32	0
29	Stud	26, 31, 35, 36, 32	0
30	Bush	5, 26	0
31	Gasket	32, 28, 29, 42, 43, 26	28,29,43,42
32	Cover	33, 35, 38, 41, 31, 37, 28,29, 42, 43,4	31,1,2,3,4,5
33	Lockwasher	32, 34, 28	31,32
34	Nut	33, 28	31,32,33
35	Lockwasher	36, 32, 29	31,32
36	Nut	35, 29	31,32,35
37	Plug	32	0
38	Lockwasher	39, 32, 43	31,32
39	Nut	38, 43	31,32,38
40	Nut	41, 42	31,32,41
41	Lockwasher	40, 32, 42	31,32
42	Stud	26, 31, 32, 41, 40	0
43	Stud	26, 31, 32, 38, 39	0
44	Stud	26, 7, 8, 9, 10	0
45	Ring	26, 21	0
46	Stud	26, 7, 8, 11, 12	0

The complete procedure has been implemented. Three integrated main modules have been made up: i) the Genetic Algorithm, ii) the automatic search of feasible assembly sequences and iii) the corresponding evaluation of the six objective functions. This procedure has been validated on the study case, demonstrating the feasibility of the approach. However further improvements are in progress, in order to make the procedure more user-friendly and less time-consuming from a computational point of view.

4. Conclusions

In this paper a methodology has been proposed for assembly design/redesign and planning with a Concurrent Engineering approach. The aim is to generate and select optimal assembly plans. This methodology is based on the definition of suitable i) assembly product contact relations, ii) dominant element iii) impediment concept, and iv) on a Multiobjective Optimization, that implements a Genetic Algorithm. The Genetic Multiobjective Optimization technique has demonstrated, in a case study applied to an industrial assembly (automotive steering gear box), that it can be usefully employed to the generation and selection of optimal assembly sequences and plans. These results suggest the choice of new suitable objective functions that are relevant to the whole product life-cycle design process. Therefore, not only the assembly process planning task but also some post-manufacturing aspects could be considered. Work is still in progress to include further more detailed aspects in the Genetic Multiobjective Optimization

Acknowledgements

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MANUFACTURING FLEXIBILITY : A NEW EVALUATION

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Abstract. Manufacturing industries have to work under continuously changing circumstances determined by the market and industries. To improve their future competitiveness, they need to develop strategies of flexibility. Decisions of flexibility are made in companies at the highest managerial level, but managers still use questionable recipes based on empirical research to efficiently incorporate flexibility into their strategic decisions. A number of questions have yet to be answered about required manufacturing flexibility and causality between the significant parameters of the system which influence the final cost, delay and performances. The aim of this paper is to give some guidelines to the managers who wants to introduce flexibility.

1. Introduction

Manufacturing industries make profits by satisfying customer needs. Nowadays, for the sake of competitiveness, they must satisfy the changing production demand without generating any extra-cost, nor increasing delivery times. Moreover, customer requirements lead to more and more differentiated products in lower volume and with shorter delivery times. In addition, these recent manufacturing systems must integrate notions of reliability, technical innovations and improvements of working conditions. The above constraints must be taken into account without any significant increase of the product price. The only way to tackle this problem is to optimize the utilization of internal resources (human, machines) by improving *production management techniques*, *product development processes*, *human resource management*, *accounting and information systems or relationships with subcontractors and suppliers* [11].

This ability to change or react with little influence on time, effort, cost or performance defines the flexibility [14].

Consequently, manufacturers have first envisaged transforming dedicated production lines (one product of large volume) into flexible production lines (several products of lower volumes). This implementation of flexibility by flexible production lines and their associated flexible facilities is called *Flexible Manufacturing Systems* (FMS). Although FMS have already proved their great efficiency in a large number of manufacturing industries [11], the best resource optimization is reached in extending the scope of flexibility. So, our paper presents this concept in several different aspects; so-called Manufacturing Flexibility (MF).

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But, despite the popularity of Flexible Manufacturing, managers still use questionable recipes based on empirical research to efficiently incorporate flexibility into their strategic decisions [11]. This lack of a scientific method is due to the great complexity of the industrial reality and the fuzzy causality between the significant parameters which influence the final costs, times and performances. Important studies remain to be done in order to understand the problem in a global concurrent engineering (CE) perspective. Some general questions are listed below:

- Which type of flexibility does the company need to develop to fit to its business plan?
- How should flexibility be used and developed in order to remain competitive when the manufacturing strategy is modified ?
- What kind of compromise must managers make between flexibility, quality, and other performances ?

The aim of this paper is to give some guidelines for these questions which presently represent the major preoccupation of decision makers.

Section 2 of this paper presents a state of the art in MF literature. In section 3, we present our approach which helps situation analysis. In section 4, we take the example of the body construction phase in automotive manufacturing.

2. Manufacturing Flexibility: from Semantics to Evaluation

Presently, flexibility is becoming one of the key objectives of all manufacturing industries, especially in the case of complex industries (automotive, aerospace, defense...). It is the most significant factor for characterizing the concept of "Plant of the future", so this subject is worth thinking about.

2.1. DEFINITIONS OF FLEXIBILITY

Flexibility seems to have been first introduced by Stigler [10]. He studies the influence of production volume on the production cost per unit of product. He proposed to characterize flexibility in terms of slope of the production cost function of the production volume. According to *Stigler*, the flatter the slope, the more flexible the system is (see "*Figure 1.*"). A system is said to be *flexible*, relatively to an interval of foreseen production volume (i.e. a perturbation) when the slope of production cost, inside this internal, is almost flat. The system is said to be *robust* (to the uncertainty of production volume) if this interval is a large one.

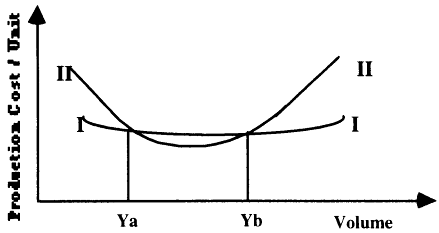

Figure 1. According to Stigler, technology I is more flexible than technology II

Nowadays, in management literature, *Stigler*'s studies characterizes *volume flexibility*. *Volume Flexibility* is one of the various types of flexibility introduced by Browne et al. [2]. Each type of flexibility corresponds to a specific type of perturbation. A type of flexibility is said to be external or internal, depending on the origin of the corresponding perturbation and relatively to the frontier of the plant or the company. These classifications of flexibility (see "*Table 1.*") are useful to provide general types of flexibility that a manager identifies in order to take decisions.

TABLE 1. Browne's taxonomy of flexibility (1984)

Browne's Flexibility	Definition	Nature of perturbations	Origins of perturbations
Machine	Ability to replace worn out or broken tools without perturbing productivity		Internal
Process	Ability to vary the steps necessary to complete a task into several working stations…		External
Product	Ability to easily adapt the existent production system (machines, industrial layouts) to the future products.	Length of product life	External
Routing	Ability to vary machine visitation sequences and to continue producing the given set of part types.	Breakdown	Internal
Volume	Ability for FMS to be robust to volume perturbations…	Aggregate product demand	External
Expansion	Capability of building a system and expanding it as needed, easily and modularly.		External
Process Sequence	Ability to interchange the ordering of several operations for each part type.		External
Production	Ability to quickly and economically vary the part variety for any product that a FMS can produce.	Market acceptance of kinds of products	External

Gupta et al. [8] have provided these different definitions and have found out that in many definitions flexibility is not a self-contained concept. It should be used together with other production data. It is very important to understand the management of uncertainty, in order to take into account flexibility as the system's potential behavior in unforeseen development.

2.1.1. The Management of Uncertainty

Swamidass et al. [12] say that "the competitive value of manufacturing flexibility lies in its ability to neutralize the effects of uncertainty". Many external and internal events, such as a new customer's demand or a breakdown, are expected but their occurrence are not planned. Uncertainties represent unforeseen disturbances or outlooks unforeseeable (new technologies, or material that totally challenge the existing system). So, in any case, they create many disturbances in the manufacturing management. The growing importance of these unforeseen disturbances may sometimes lead to the reconsideration of strategically orientations or tactical choices [3]. Although flexibility is normally considered as an adaptive response to environmental uncertainty [8] (defensive posture), managers may try to redefine market uncertainties (proactive behavior). Consequently, controlling, managing and ideally preventing disturbances are necessary and must be integrated in the global manufacturing management [6].

2.1.2. Compromises between Flexibility and Economic Efficiency

Introducing flexibility in the manufacturing systems requires more important initial investments than traditional manufacturing systems. Consequently, flexibility and cost efficiency have been considered as conflicting objectives. Also, poor optimization can have an effect on the operational cost of a flexible system. The best way to avoid these problems is to give managers adequate guidelines to help them to efficiently incorporate flexibility into their strategic planning.

2.2. FRAMEWORKS FOR FLEXIBILITY ANALYSIS

2.2.1. Background

For the needs of our state of the art we use Suarez et al. [11] classification of the management of MF approaches: *analytical models* and *empirical studies*.

Analytical models of flexibility come exclusively from the field of operational research which generally focus on the flexibility of each production system element. For example, in [13] a one-machine system is used to obtain the *volume flexibility* from *machine flexibility* in the context of a hierarchical structure of flexibility types.

According to Fine's classification scheme, the analytical approaches are divided into four issues: flexibility and life cycle theory, flexibility as a hedge against uncertainty, interactions between flexibility and inventory, flexibility as a strategic variable that influences actions of competitors.

Suarez et al.[11] divided *empirical studies* into four groups:

- A group that has developed taxonomies of flexibility and is represented by the work of [5], [2], [4], [9].
- A group that deals with the relationships between flexibility and performance.
- A group that deals with historical and economic analyses of flexibility.

- A group that has proposed strategic frameworks showing how firms can use or implement flexibility in different competitive situations [11], [12], [5].

  For example, Gerwin [5] proposes a conceptual model which provides a basis for identifying specific flexibility dimensions. But, these dimensions may limit the efficiency of a manufacturing process. Finally, concepts are used for analyzing whether desired amounts of flexibility are achieved and whether the potential for flexibility built into a manufacturing process is used. Swamidass et al. [12] studied how environmental uncertainty influences strategy. They found significant positive relationships between uncertainty and strategy, and strategy and performance. Strategy directly affects performance, but there is no obvious method for generating flexibility. In Suarez et al.'s[11] paper no difference is made between market uncertainties and strategy. Various performance measurements of delivering methods which in turn influence business performance are presented.

In all cases, it is easy to understand that it is always the company's competitiveness that one tries to improve or remain. All these issues tend to complicate the subject and render the study of flexibility a challenging task.

2.2.2. Perspectives

Although much have been written about flexible manufacturing concepts and measures, studies are too empirical and don't exactly meet the requirements of decision makers. So, it is not easy for managers to use these frameworks to justify a required flexibility into their strategic planning. Then, according to Gunasekaran [7], it may be interesting to study the influence of different kinds of flexibility on the performance parameters of manufacturing systems, under the aspect of different loading strategies and various system configurations based on the organization of internal resources.

In the next section, we introduce a decision support framework, that consists of four separate phases, for MF selection. This framework makes easier the causality description between required flexibility and others parameters which influence the final cost, times and performances.

3. Concepts for Analyzing Manufacturing Flexibility

This section describes a decision support framework which allows managers to efficiently decide on Manufacturing Flexibility. Moreover, it describes paths that help using and controlling evolution of each required flexibility in order to always remain competitive. The next paragraph examines this framework.

3.1. NEEDS, REQUIREMENTS AND MEASUREMENTS FOR FLEXIBILITY

Our analysis framework is structured in four separate phases (see "*Figure 2.*")

- When considering flexibility it is essential to understand what type of flexibility the company needs to develop according its business plan?

For that purpose, it is necessary to define:

- * Environmental uncertainties which are associated.

  Enumerating the types of events and uncertainties faced by manufacturing managers provides a basis for identifying *specific flexibility dimensions.*

- * Internal resources of the company

- Clarify manufacturing objectives by determining what is going to be produced or decide whether the same facilities will be used for new products. We clarify *why flexibility is required* ? The answer to this will influence the extent of *required flexibility* and whether flexibility is needed at all.

- When needs and requirements are formulated, a working plan can be defined. It describes the requirements for tooling, facilities, technology, human resources by an optimization of internal resources.

- The performance measures can be defined to provide the best way to obtain and to use flexibility in order to remain competitive.

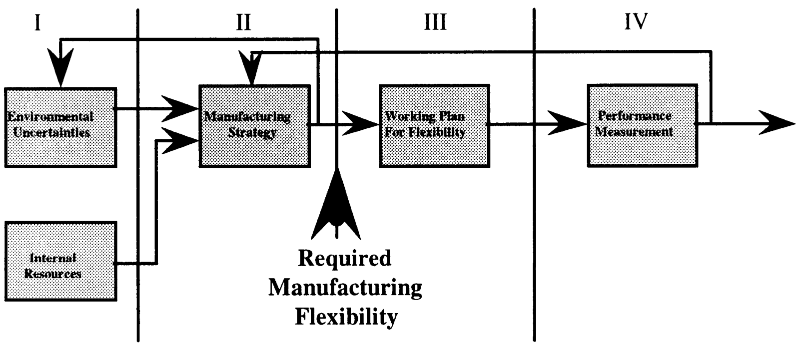

Figure 2. Framework analysis for flexibility

The path from Required Manufacturing Flexibility to Performance Measurement exposes the causality between the significant parameters of the system which influence the final performance. Moreover, a feedback loop exists to take into account a proactive strategic posture.

3.2. CONCEPTS AND ANALYSIS

3.2.1. Conceptual Model to Evaluate Requirements for Flexibility

The great complexity of the industrial system leads to address flexibility at different *levels in a manufacturing organization* and different *levels of the flexibility life-cycle* (development, implementation and utilization, destruction).

Consequently, in order to define for *required flexibility* (Phase I of the framework), it is important to *localize* it and next to ask about its *formulation.*

The localization must be explored according to the *level of the system* where one operates (multiplants, plants, manufacturing systems or machines) and the level of flexibility life-cycle. Localization answers to the questions Where ? and When ?

According to the definition of flexibility used in this paper and introduced by Upton [14], *formulation* allows to justify internal flexibility with regards to external flexibility. *Formulation* is based on the three following sub-models:

- e*nvironment uncertainties sub-model* which models environment uncertainties and the corresponding external flexibility
- *resource sub-model* which models resources and internal abilities of the system: the corresponding external flexibility
- *justification sub-model* which justifies internal flexibility with regards to external flexibility in terms of requirements of flexibility (cost, quality…).

This conceptual model (see "*Figure 3.*") allows the identification of the real kinds of flexibility that the company needs to develop, according to its strategic objectives and to its proper resources.

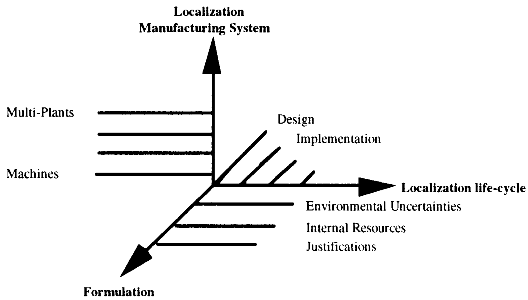

Figure 3. Conceptual model for required flexibility definition

3.2.2. Evaluation of performances and non-performances of flexibility

From parameters of required flexibility justification, this analysis exposes the causality between significant parameters of the system which influences the final cost, delay and performances. It is possible to use both quantitative and qualitative performance information. Using the previous framework, *working plan for flexibility* may use factors which affect flexibility implementation such the *production technology*, *production management techniques*, *relationships with subcontractors and suppliers*, *human resource management*, *product development processes*, and *accounting and information systems* [11]. From the *required flexibility*, the analysis tested impacts on the implementation factors. So, the system's potential behavior in unforeseen development is estimated (see "*Figure 4.*").

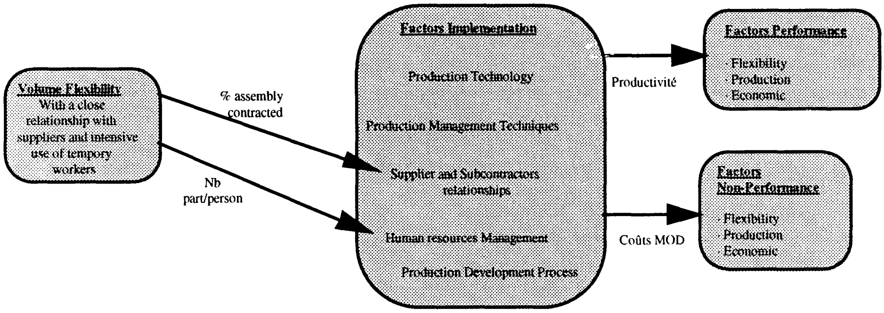

Figure 4. Example of performance and non-performance analysis

To make this example, we used Suarez et al. [11]'s works.

4. Example of the Body Construction Phase in Automotive Manufacturing and Perspectives

For few years, the body construction process of automotive manufacture met a lot of problems due to the increasing frequency of model changes (*product flexibility*), the varying production output (*mix flexibility*) or the increasing number of cars produced (*volume flexibility*). In fact, it refers to series of processes in which the pressed parts are assembled by spot welders, to produce the so-called *White Body* yet to be painted.

In the early days of mass production, welding operations were performed by hand, a few years latter the welding machine replaced human labour which lead to the automation of the welding process. Nowadays, advancements in robotics has enabled automatic welding of different models, something impossible before. Then, automotive manufacturers envisioned manufacturing flexibility as a strategic consideration and tried to replace their dedicated lines by a flexible line. In fact, a flexible assembly system for car bodies allows for model changes and addition of models at anytime with a minimum preparation lead time, a minimum investment and without affecting the operation of the existing line.

A number of concepts has been developed and implemented. The most notable are Toyota and Honda which were based on measures [1]: to improve body accuracy, to ensure flexibility, to enhance efficiency and streamline production management, to simplify the preparation and reduce lead-time.

European Automotive manufacturers like Volvo, have successfully adapted the Toyota concepts at their plants. Others are not at the same stage but they are looking for the best way to achieve it.

The questions that always remain in their mind are:

- Which flexibility does the company need to develop with regards to their manufacturing strategies and requirements ?
- Has flexibility been successfully implemented somewhere ?

That is the reason why we are trying to apply our previous concepts to help automotive manufacturers to focus on the specific kinds of flexibility that they need to develop and to evaluate which methods to implement. Evaluation emphasizes the impact of various kinds of required flexibility on the performance parameters of the system under the effect of different leading strategies and various configurations.

In this way, our working plan is to apply the conceptual model for *required flexibility* to narrow the list of MF configurations. Afterwards, from the decision support framework, we describe the causality graph between the significant parameters of the systems, to evaluate all possible MF alternatives. Then, we will develop a simulation which enables the generation of real data and measures both quantitative and qualitative performance. These data constitute important information on which a decision can be based.

5. Conclusion

It is evident that if market uncertainties continue to intensify over the next few years flexibility responsiveness may become the most significant dimension. Then, only the achievement of flexibility in manufacturing will be a source of competitive advantage for many manufacturing firms. But, despite the popularity of Flexible Manufacturing, managers still use inadequate recipes to efficiently incorporate flexibility into their strategic decisions. Moreover, they are unable to express exactly what are the required of flexibility and also a working plan of implementation.

In this study, we attempt to provide a decision support framework to help managers in these ways:

- To provide a common base of understanding.
- To identify the kinds of *required flexibility* it needs to manage in operations or the extent to which they need managerial attention.
- To formulate an implementation plan to use those flexibility in order to remain competitive.

So, we hope the flexibility framework will act as a tool to aid the development of different strategies by ensuring communication between engineering and other important manufacturing functions, as well as describe the best ways to achieve, to manage or to control it.

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Chapter 2
FEATURE BASED MODELLING

INTEGRATED CAD AND CAPP AROUND FEATURE RECOGNITION TECHNIQUES

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The following paper aims at presenting the results of an original cooperation between a Canadian and a French team, both of them working on the computer implementation of the concurrent engineering concept and on related integration problems. The two fields addressed here are manufacturing preparation and analysis preparation (automatic mesh generation of geometric models for finite element methods) for mechanical parts. The article focuses on the way how a common product model and feature recognition techniques have been successfully used for both mesh generation (Finite Element Methods) and CAPP automation.

1. Introduction

An international marketplace, an aggressive competition, increasingly exacting consumers, products rapidly becoming obsolete, these are today's attributes of manufacturing industry activity . This new challenge has obliged industrial companies to rationalize their practices and to gradually adopt the principles of concurrent engineering. The fundamental concept of concurrent engineering is not a brand new one: the aim is to compress the time to market by realizing the different phases of the product life cycle concurrently (simultaneously). Computer Integrated Design and Manufacturing is the cornerstone of the implementation of the concurrent engineering concept in today's CAD/CAM systems, which requires mutual interaction and cooperation between the different actors in the product elaboration cycle. Still, how to implement interaction while integration has not yet been completely achieved?

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In the concurrent engineering context, the integration of all these tasks in the system has to be made or directed at three different levels [2][4][6]:

- Data level: the main difference between interfacing and integrating applications in the CAD/CAM field concerns the use (in the latter case) of a product model that contains a sufficient quality and quantity of information to be able to handle all of the activities involved in the whole process.

- Procedure level: each of the applications involved in this process features procedural devices (numerical procedures, mathematical background, geometric calculations, visualization procedures, feature recognition, etc.) that are common to several other applications. Thus, it is necessary in a global approach to take this into account in order to avoid redundancy and also to take advantage, for a given application, of all high and low level procedures.

- Intelligence level: adding intelligence to CAD/CAM systems is also made possible through the conjunction between the high level of information and semantics that is or might be present inside the product model and the experts' knowledge and experience of the considered activities. The integration at this level consists in sharing the inference procedures on the one hand and handling the links and interactions between the design and manufacturing knowledge models on the other hand.

The following paper aims at presenting the results of an original cooperation between a Canadian and a French team, both of them working in two different fields, on the computer implementation of the concurrent engineering concept and on related integration problems. These two fields are manufacturing preparation and analysis preparation (automatic mesh generation for finite element methods) for mechanical parts.

2. Data integration in the system

Figures 1 and 2 are used to describe briefly the structure and the features of the product model that has been built around the ACIS™ solid modeling kernel in order to allow the full automation of both computer aided analysis and process planning processes. The data structure that has been implemented to model functional (dimensional and geometric tolerances, surface roughness, etc.) and analysis (materials, behavior laws, boundary conditions, etc.) constraints on the original Brep model is mainly based on the use of ACIS™ attributes. Indeed, a key point in the building of such a general purpose model is the addition of analysis and technologic data (Figure 2) to the topologic and geometric classical Brep structure (Figure 1) in order to obtain a homogeneous, complete and non redundant data structure, suitable for the automatic handling of all the tasks that are part of the concurrent engineering process. For example, Face F1 on Figure 2 is specified, via attributes and cospecification, as a reference datum plane for the perpendicularity tolerance with F3. A pressure distribution on F4 and F5 as well as a displacement boundary condition on F3 are applied in the same way.

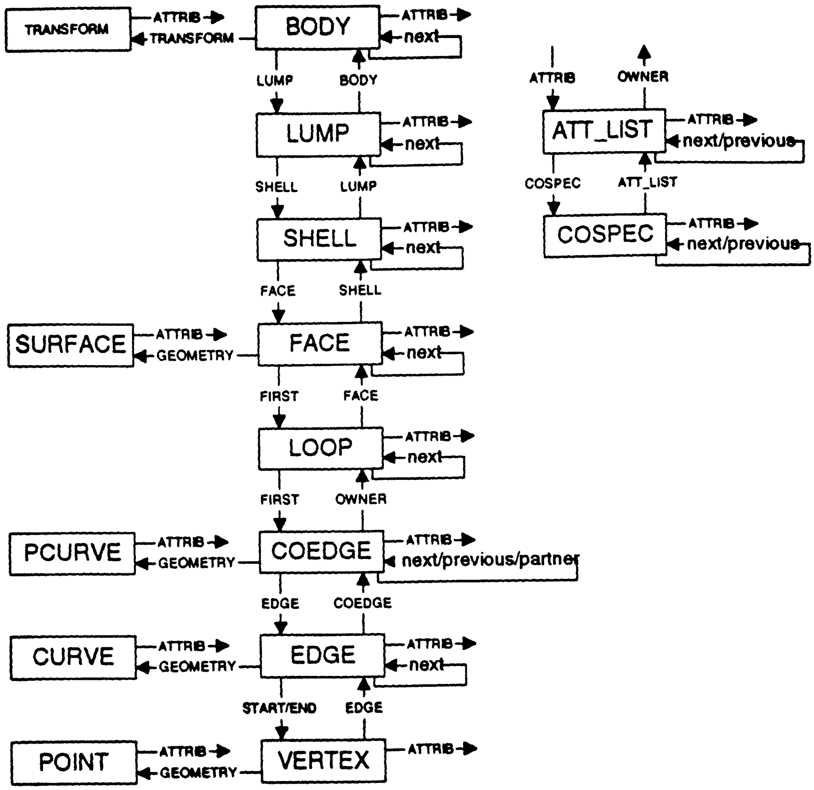

Figure 1: ACIS™ basic BREP structure

These features are given to the product model by the user himself during the conceptual and detail design processes (geometric features, geometric constraints, analysis constraints, etc.). Later, the product model is enriched with four original types of features that are automatically identified from the product model and integrated in its structure in order to uncover a higher degree of semantics before the achievement of the analysis and process planning activities. First, there are the three following types of features (manufacturing): *tool feature*, *setup feature* and *machine feature*; and the fourth feature is used for intelligent mesh generation purposes: *analysis feature* [2][6].

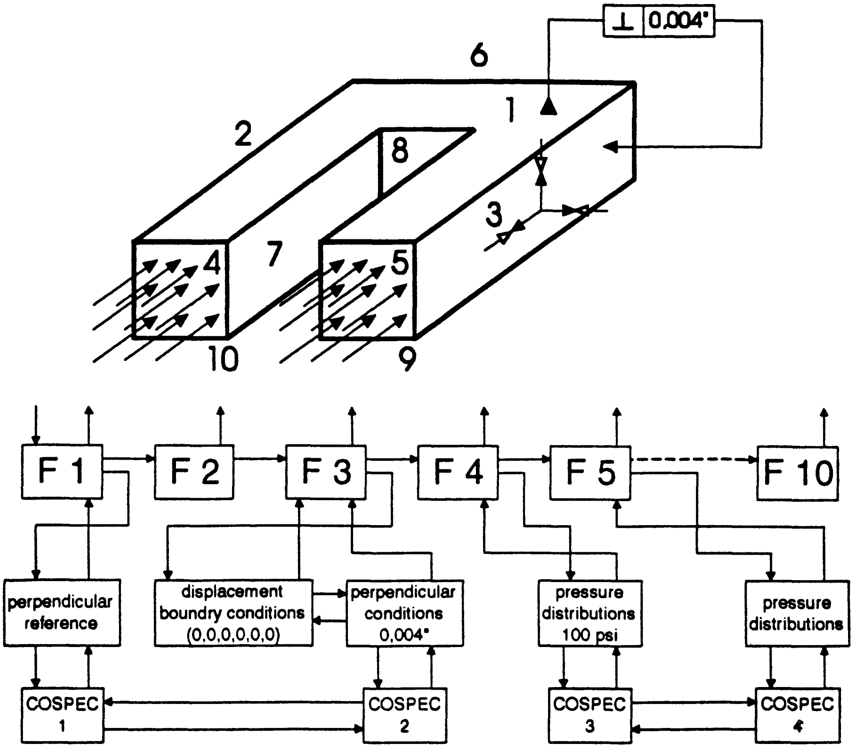

Figure 2: Enrichment of the BREP structure with attributes and cospecifications

A *tool feature* includes portions of the part's boundary that must be machined with the same machine, the same setup and the same tool, either simultaneously or immediately subsequently. The dispersion about the dimensions and positions of the faces involved in a same tool feature is minimal.

A *setup feature* consequently refers to a set of tool features that can be machined (notion of technical equivalence of different possibilities) without modifying the setup (no dismounting of the part from the setup no antagonist dimensions, same machine same combination of feed and cut vectors).

The *machine feature* consequently refers to a set of setup features that can be machined on the same machine tool (no dismounting of the setup from the machine continuous sequence in the precedence graph, compatible combination of feed and cut vectors). The dispersion about the dimensions and positions of the faces involved in a same machine feature is quite maximal.

An *analysis feature* refers to the geometric singularities of the solid model and the type of analysis that is to be applied (we have restricted our work to the study of three-dimensional linear elasticity problems). The identification process of analysis features leads to the automatic and generic construction of a spatial function describing the nodal density variation across the part to be analyzed, that has a high engineering significance. Thus, this process consists in the "a priori" (before any finite element analysis) and automatic identification of geometric singularities that could be at the origin of high stress gradients in the part analysis results and in the use of these singularities to apply a three-dimensional mesh density map more suitable to the part's finite element analysis. This process is definitely original as compared to the classical analysis-error estimation-remeshing scheme as the mesh refinement step takes place before any analysis. This new original approach is called mesh density pre-optimization [2].

Of course, even if in some very simple cases we might have an identity or at least a close relationship between manufacturing features and analysis features, one cannot argue that this could be considered as a general law. Thus, these features will be seen, in this study, as completely distinct. Following the same idea, we can underline that it has never been clearly proved that feature based design would make feature recognition easier when there is no one-to-one mapping of the design or (and) analysis features and manufacturing features, which is generally the case for products requiring more than one manufacturing process.

In fact, these features, whatever their type, are built and rebuilt as long as the concurrent engineering process goes on. That is to say that the features identified in the product model are in constant evolution through the design process. These features are automatically refined by the system and they can be used whenever they are needed during the execution of any of the tasks composing the whole process: they are becoming part of the product model itself.

3. Procedure integration in the system

The main point considered here is the integration of the two following tasks: manufacturing preparation and intelligent analysis preparation, around feature recognition techniques[8][9][10][11]. In fact, even if the two families of features are different, the basic process for generating them remains the same. The only differences between the two feature recognition processes are the searching strategy and the purpose of the identified features. An important aspect of our recognition scheme that has to be outlined is the fact that the process is fully automatic and generic. Indeed, we do not make any assumption about the design process or (and) design philosophy (eventually a design by feature approach or not) that has been applied during the construction of the geometric model.

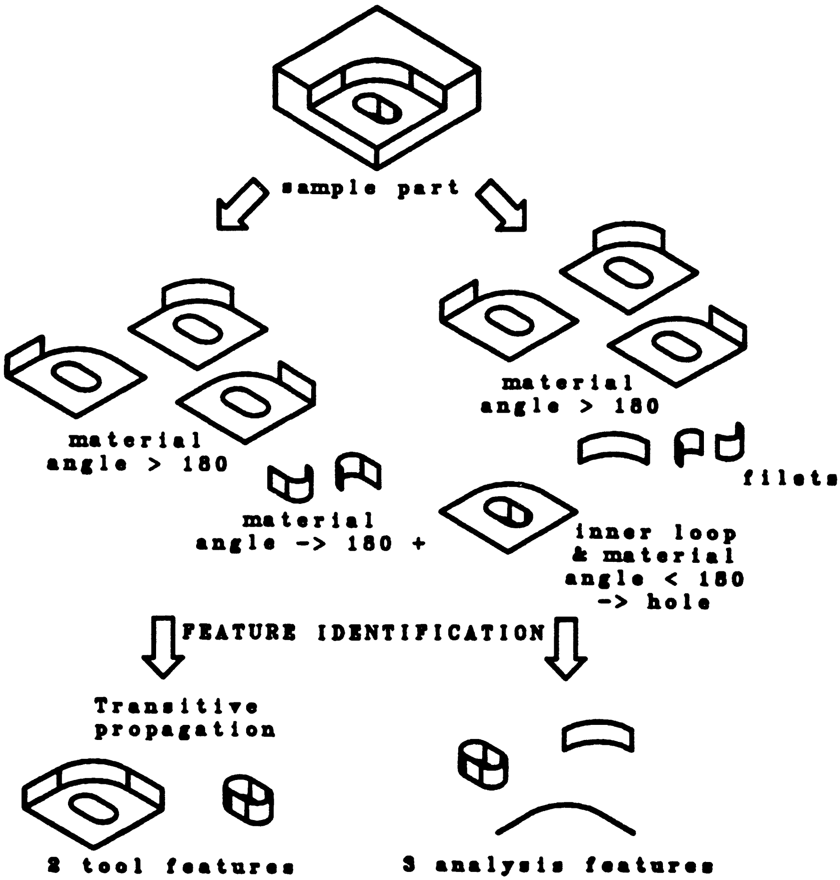

Figure 3: Tool and analysis feature recognition

Basically, the notions of tool feature or (and) analysis feature (Figure 3) can be represented as a graph in which the nodes are topological faces of the part B-Rep model and the arcs are edges between binary sets of nodes. In addition, some analysis features can be represented as isolated faces, edges or vertices. Nevertheless, all these features can be identified using a common strategy mainly based on edge concavity and convexity calculations.

The determination of an edge concavity can be performed by examining what could be called the material angle (portion of a full rotation made by a vector originating from a point lying on an edge, in a plane perpendicular to the edge at that point). If the material angle is comprised between 180° (included) and 360° (excluded), the edge is concave.

The extraction of concave edges is not a revolution in feature recognition and many laboratories even tried to identify form features by recognizing sub-graphs in the part's graph, but the originality of our method concerns the following aspects. The classification of the recognized feature is not addressed.

Actually, the system performs the recognition of all the sets of entities by considering only geometric and topologic information and no assumption is made upon the feature type of the resulting set. Thus, no consideration has to be made about mapping between different types of features. The recognition is fully generative, which is a consequence of the latter remark. The recognition virtually applies identically to any kind of part (sheet metal, rotational, prismatic, etc.) with analytically or mathematically (i.e. Spline or NURBS) expressed edge geometries, since the material angle criterion is sufficiently low and general to be process-independent.

4. From features to CAPP and FEM

On the one hand, analysis features are automatically extended to the construction of an intelligent three-dimensional mesh density map (see Figure 5) by increasing, via influence zones, the nodal density around analysis features [2]. On the other hand, tool features are automatically derived in order to generate a logical precedence graph (considering the functional dimensioning of the geometric model). This graph will be evaluated at last by the system to provide a basis for the subsequent associations between candidate setup features and machine features that will be used to achieve the process planning activity [6].

5. Results

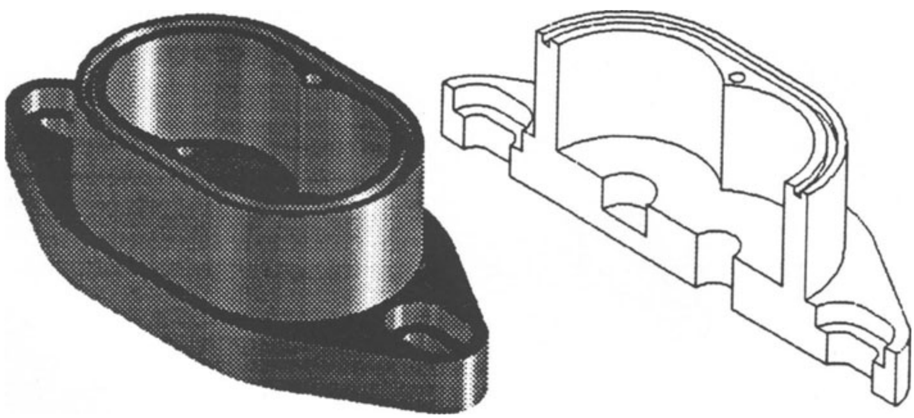

Figure 4: Solid model of the sample part and a full section view

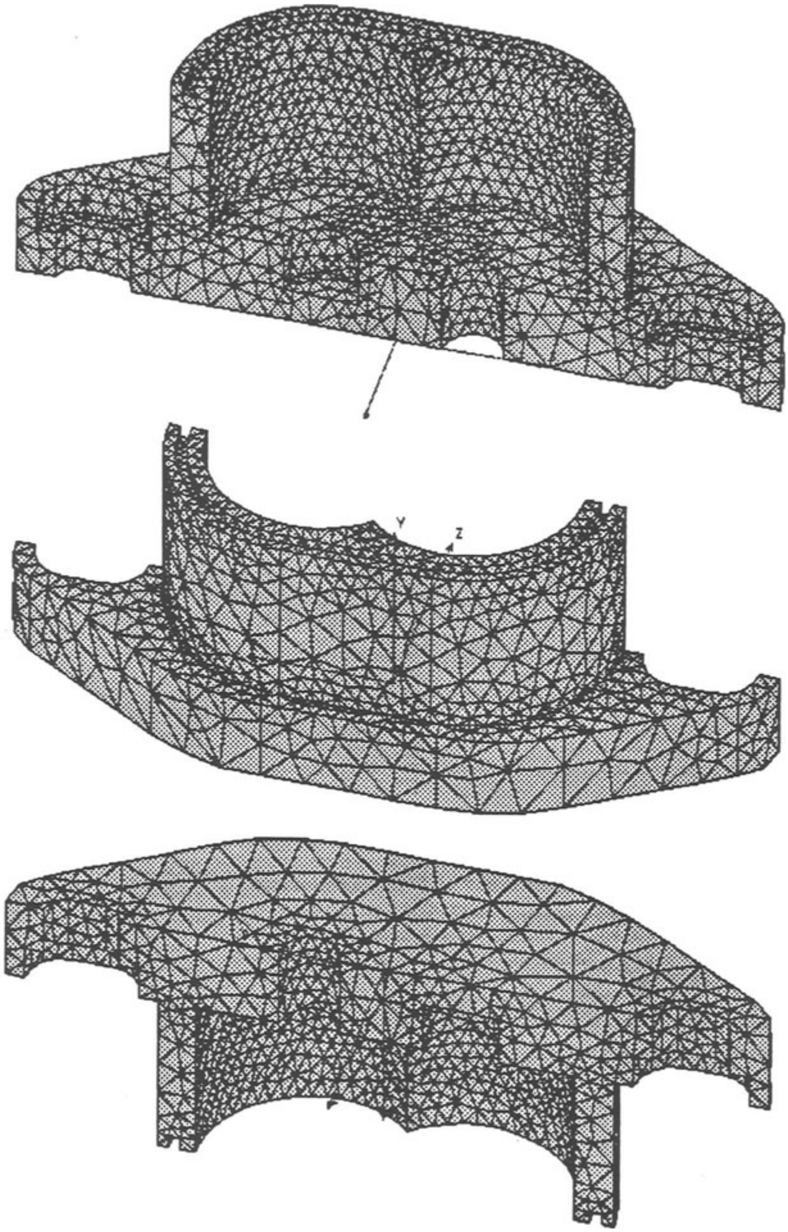

Figure 5: **Results of the intelligent mesh generation on the sample part**

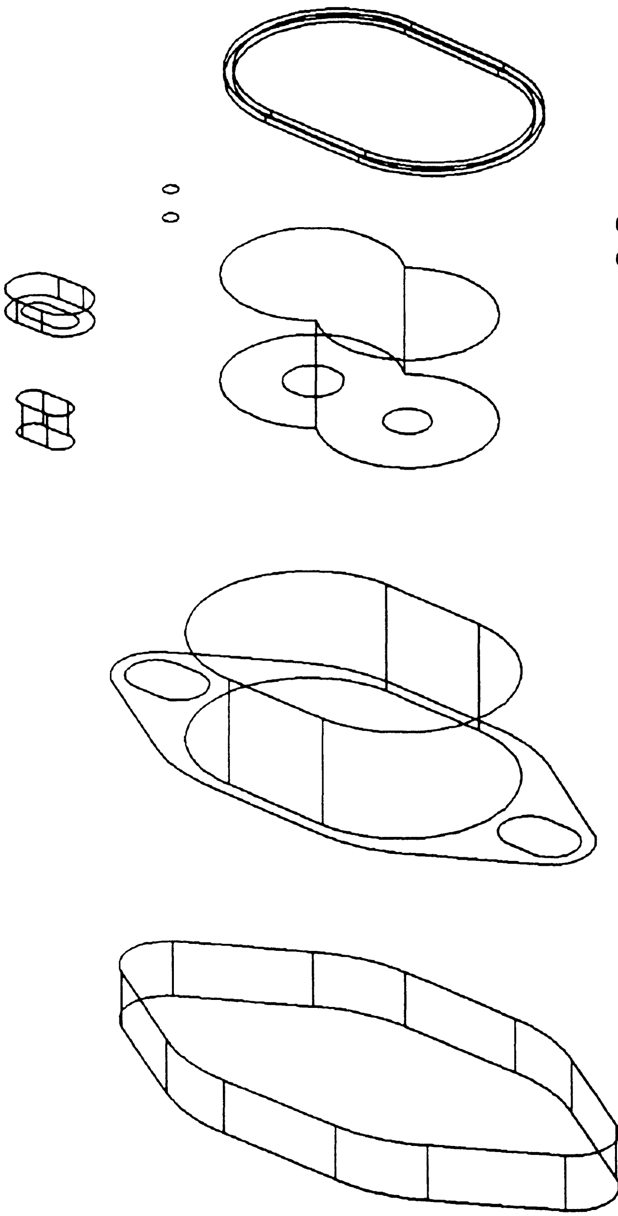

Figure 6: Identified machining features on the sample part

6. Acknowledgments

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FEATURE-STATE APPROACH FOR OPERATION SEQUENCE GENERATION

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Abstract. This paper presents a definition of the machining feature and the machining state used as a concept for CAPP (Computer Aided Process Planning). Several approaches for generating operation sequences (also called machining processes) of features are also presented. In these approaches, the consideration of machining constraints between features, the processing of overlapped features, the limitation of the choice of tools among the ones available and the search for common operations and tools for the machining of different features are pointed out. Finally, a method for recognising machining features based on the concept of manufacturing features is presented.

1. Introduction

1.1. STATE OF THE ART

In the different research works realised in recent years, the integration of design and manufacturing functions is mainly based on the use of the concept of features (Dang et al., 1993). The use of this concept aims to allow the construction of descriptive models and to facilitate the elaboration of exploitation and communication models. The different definitions of the feature concept proposed in research works are of two types : generic (Krause et al., 1991) and specific (Salomons et al., 1993). However, the lack of explicit correspondence between the different types of features makes it difficult to respect the federative concept of design and manufacturing integration.

In this paper, we analyse several aspects of the use of the feature concept applied to Computer Aided Process Planning. Approaches for generating operation sequences of features elaborated at the LURPA are also presented through five subjects of research :

- The GALILEE project, which is a common research work between the LURPA and the DDPI of Polytechnico di Bari answers the problem of form recognition for the

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definition of machining features by introducing a technological expertise.
- The project LURPA-TOUR endeavours to accurately generate the operation sequences of rotational parts realised on a turning centre, according to the tools really available.
- The CAPP system OMEGA, designed in collaboration with PSA, deals with the case of milling using a semi automatic method, set-up by set-up.
- The PAG (Process Ascending Generation) concept mainly tackles complex features using a recursive method which associates cutting tools with their machining properties.
- For the CN3D project, dedicated to the machining of complex shaped parts such as forging dies, the rough machining has to be processed on the totality of the die cavity while finishing requires a specific study to each local shape.

1.2. THE ISSUE

In the scope of Computer Aided Process Planning from a CAD model, the "machining feature" approach has to assist the creation of process planning and not solely express the final process retained. P. Bourdet (1990) gives a generic definition of a machining feature that federates several different approaches developed by researchers of the GAMA[1] group. "A machining feature is both a geometrical shape and a set of specifications for which an operation sequence is known. This operation sequence is quasi-independent from the operation sequences of the other machining features". This generic definition does not provide answers for the following fundamental question : how is it possible to know if an association of surfaces for defining a machining feature is relevant to choose an operation sequence easily ? In fact, from the CAD model, several steps are necessary to create associations of surfaces so as to define machining features that one can consider independently. We therefore propose using the term "machining feature" only for surface associations obtained in the ultimate step of the processing of the geometry of the part. Each machining feature will then be analysed to generate one or several operation sequences. In the last part of this paper, we will introduce the manufacturing feature concept for groups of surfaces created temporarily during the search for machining features.

In this paper, we limit the study to the automatic generation of the operation sequences for a given set-up. First, we assume that all necessary cutting tools are effectively available or can be bought. The opposite hypothesis will be studied in section 4.

2. Machining feature and machining state

2.1. DEFINITIONS

Machining features and machining states are defined as tools for the part decomposition allowing the automatic generation of the operation sequences. We reserve the term "feature" for shapes defined on the finished part and the term "state" for intermediate

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[1]GAMA is the Process Planning work group of the French Society for Information and Systems Sciences and Technology (AFCET)

shapes that appear temporarily on the part during the machining of a feature (figure 1).

"A machining feature is both a geometrical shape extracted from the finished part and a set of specifications for which a method for generating its operation sequences exists. The generation of these operation sequences is quasi-independent from the other machining features." Constraints between features are taken into account by neighbourhood parameters.

Therefore, the admissible machining features are those whose process of operation sequence generation has been formalised. Machining features can therefore be listed in a machining feature library that enriches along with the system. This definition has been specified according to the definition of the GAMA group quoted in 1.2. It insists on the objective of assistance to the generation of operation sequences. To transform the part from a state to another, it is necessary to realise one machining operation, each operation being realised with one single cutting tool. If it concerns a production for a NC machine prepared on a CAM system, the change from a state to another has to correspond to one of the machining operations listed in the CAM system. Therefore, the library of the operations available depends on the CAM system and the characteristics of the machine tool available. This implies that it is possible to restrain the feature library according to the production context. For example, to realise the rough machining of a forging die on a 2D1/2 CAM system, the volume will have to be decomposed by layers so as to use the pocketing function. States will be numerous. With a more powerful 3D system, one will be able to define a single group of surfaces realised with a very complex roughing operation.

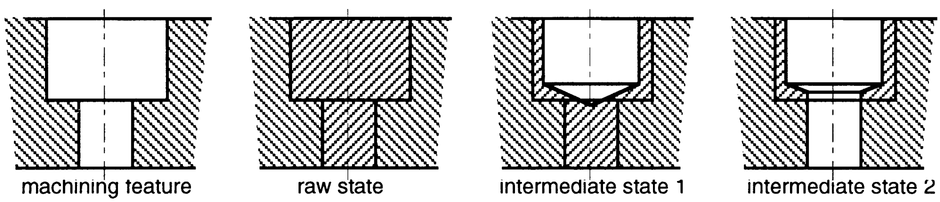

Figure 1. Machining feature and machining states

When a process planning is realised in several set-ups, machining features will be identified on the finished part. Between each set-up, the part will be in an 'intermediate state' characterised by the machining states of the machining features.

The machining feature concept implies a chronology of process planning generation generally expressed according to the four following steps:

- Recognition of the machining features
- Search for one or more operation sequences for each machining feature
- Search for the best combination of operation sequences and cutting tools for all the features. Sharing out the machining operations in different set-ups (by an optimiser)
- Layout of the machining operations

2.2. ABOUT MACHINING FEATURE INDEPENDENCE

The machining feature concept is effective for it allows to separate the part in different groups of surfaces so as to process them independently for the search of operation sequences. All intermediate states of each feature are equally processed apart from the intermediate states of the other features. To guarantee this independence, one has to associate all the required neighbourhood information to the machining feature, so as to be able to generate an adequate operation sequence suited to each specific case. For example, for the machining feature "hole" (Figure 2b), neighbourhood parameters define constraints of cutting tool passage through the upper hole.

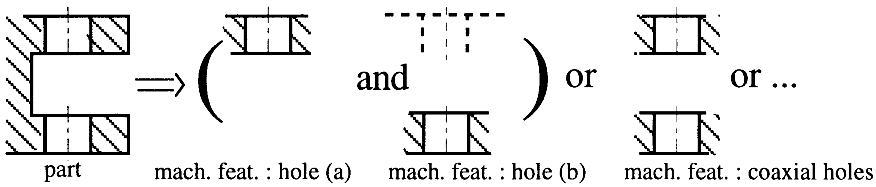

Figure 2. Constraints between machining features

If the aim is to have common cutting tools for several machining operations, there are two machining feature types (Figure 2) :

- The simple machining features (occurrences a and b), which require very rich neighbourhood parameters. They impose to create a lot of suitable operation sequences with, if necessary, precedence constraints to find a posteriori common operations or cutting tools.
- The complex machining features (occurrence c) which include a lot of surfaces and allow to generate specific operation sequences.

For each machining operation, it is possible to define a set of cutting tools, among which defining a range for diameter and length of the cutting tool. Subsequently, the "optimiser" will be able to search for common cutting tools for several operation sequences.

For the first type of machining features, a very large set of operation sequences and an effective "optimiser" are required. The second type of machining feature implies a very large machining feature library.

We believe both types are necessary : to create a new CAD/CAM system, the simple machining features have to be comprehensively listed. The global optimisation of the process planning will depend on the quality of the "optimiser" and the fullness of the neighbourhood parameters taken into account. As soon as the system progresses, the machining features library will increase to integrate more and more complex features.

3. Operation sequence of machining feature

3.1. MONO PROCESS ASSOCIATION

The mono-process association is a simple method which links a given feature to one operation sequence composed of one or more machining operations. This approach has two limits :

- The interweaving of machining features cannot be analysed easily. So, an aggregate

(or complex) feature has to be created. The feature library is quite voluminous so the machining features recognition from CAD models is uneasy.
- The aggregation of machining operations from different features is quite difficult.

This simple method is reserved for simple machining features isolated in the part. The more parameters describe the feature, the more alternative operation sequences the process planner's algorithm has to be able to generate. Then, a choice has to be performed according to the parameters values. To create a lot of parameters to describe machining features is complex, but the feature library is small (Figure 3).

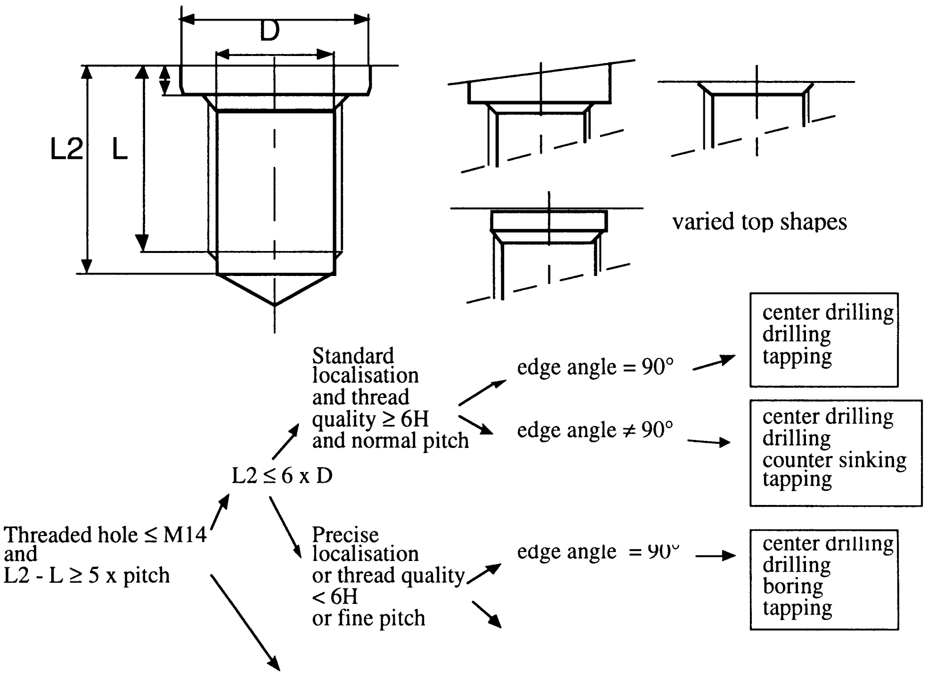

Figure 3. Threaded hole machining feature in "OMEGA" (Sabourin, 1995)

In LURPA-TOUR, this approach is used for grooves, threadings, and features realised with rotating tools.

3.2. MULTI-PROCESS ASSOCIATION

When features are overlapped, there are many precedence constraints between their machining operations, notably to obtain a common roughing machining. The association of several operation sequences to each feature is one of the possible alternatives, for it emphasises the independent character of the processing of the feature by envisaging several solutions. So, the processing of multiple solutions makes the optimisation more complex (figure 4).

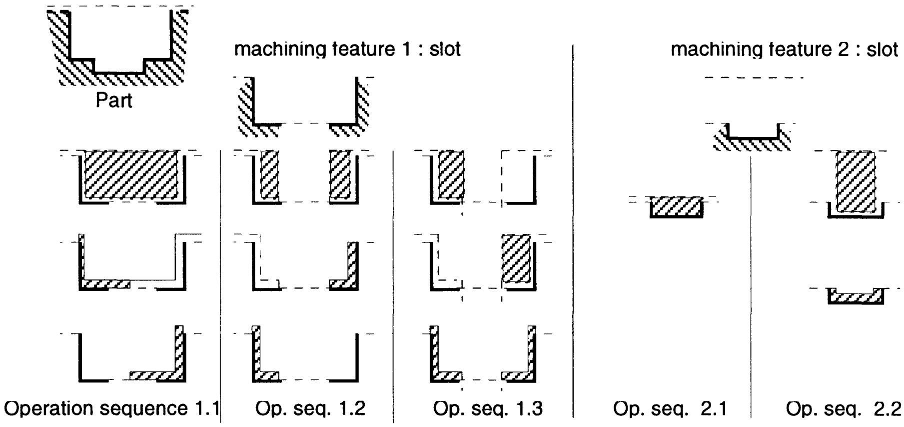

Figure 4: A posteriori search of an adequate operation sequence

The search for the best combination of machining operations on the whole part can be rudimentary, for example by choosing the most economic operation sequence of each feature. The optimisation is more delicate. To find common tools, the gain obtained by limiting the number of adjustments and changes of tools has to be compared with the loss of productivity due to the absence of the optimum tool.

3.3. GENERATION OF OPERATION SEQUENCES FOR COMPLEX FEATURES

3.3.1. Specific operation sequence

To each family of features, one associates a specific operation sequence proposing an orderly list of manufacturing steps. Parallely, a strategy for generating the operation sequence has to be elaborated to define :

- a finishing operation and the state of the feature before finishing (with fuzzy frontiers)
- a global roughing machining method
- a semi finishing method.

OMEGA uses this approach to process the features "hole" made of several coaxial cylinders (Sabourin, 1995). In LURPA-TOUR, this approach named "specific operation sequence with progressive refining" (Anselmetti, 1994) (Chep, 1992) is used for external, internal and frontal features. Due to the combinatory explosion, the best operation sequence of the feature is chosen without taking the other features into account, by specifying the operation sequence step by step thanks to centres of decision.

3.3.2. Process Ascending Generation (PAG)

The concept of Process Ascending Generation (PAG) (Villeneuve, 1990) is to build the detailed description of all the reliable operation sequences producing a given machining feature. The expert knowledge is mainly defined in the Cutting Tool Charts (CTC). A CTC includes a family of cutting tools associated to one or more work cycles. The CTC describes the abilities of its work elements to perform a given state of a machining feature on the one hand and, on the other hand, the necessary values of the attributes of the former state. The advantages of the CTC concept are that the knowledge about the cutting tools is clearly located. Therefore, any cutting tool family can be added or removed without updating the whole set of expert system rules. The PAG determines the operation sequence for a given feature, starting from its finished state and, by successive steps, leading up to its raw state. On each state Ei, we scan all the CTC to determine all the machining operations producing this state. Then, with each selected operation and the attributes of the state Ei, we determine the necessary characteristics of its former state. The ascending generation will stop when the former state is the raw state of the feature.

3.3.3. Process Semi-Ascending Generation (PSAG)

The objective of the PSAG (Mawussi, 1995) is to link the advantages of the ascending and descending concepts, to avoid the multiplication of possible combinations of forms in the raw state. Experimented in the machining of forging dies, the PSAG considers the machining features defined on the finished part, to generate their semi-finished and finished states using an ascending method. For roughing, we consider a descending generation, starting from a raw state of the part and leading down to the semi-finished states. We have to manage semi-limited volumes to generate manufacturable forms compatible with machining operations.

4. Characterisation of resources

4.1. DATA BASES

The knowledge of resources is indispensable to select cutting tools with precision and to compare their performances for a given situation. The cutting parameters have to be calculated taking the limitations of the machines into account. The description of the machines and cutting tools available requires the creation of a large database. For example, in LURPA-TOUR, a machine is characterised by 100 parameters, each material by 100 parameters to allow the calculation of cutting parameters, 30 parameters per tool, 20 parameters per insert. We believe that without a large database, the definition of a tool becomes a laconic description as “End mill, diameter 20” or “copy turning tool”.

4.2. AVAILABILITY OF TOOLS

If the process planning is aimed to prepare a production that has to take place in the medium term, all the necessary cutting tools can be ordered. The database has to describe all the tools available from the different suppliers.

If the process planning is destined to be very rapidly used in production, it is necessary to choose a process that uses only tools effectively available in the workshop, therefore it is necessary to identify them in the database.

The control of the existence and the availability of a tool can lead to a failure. So, for a given machining feature, several operation sequences have to be generated with different machining operations and different families of cutting tools. In this case, it is necessary to select the “best” operation sequence and the best cutting tool. This implies the mastering of the determination of cutting parameters. This control makes the system more efficient, but more complex (this concept is exploited in LURPA-TOUR).

5. Recognition of machining features

5.1. MACHINING FEATURES LIBRARY

We have just shown that there exist different methods to generate operation sequences for machining features and that, depending on the methods available, different types of features can be processed. It means that for each automatic process planning system, a catalogue of machining features exists that can be recognised and for which identification algorithms must exist. This catalogue of features can considerably increase during the life cycle of a software.

As shown in figure 2, a set of surfaces can belong to several different features. It is therefore up to the system to ensure the global consistency of the process planning.

5.2. FEATURE RECOGNITION METHODS

In CAD, parts can be defined according to two approaches:

- Strictly geometrical definition of surface or solid model (B-REP, CSG) possibly with variational models.
- Definition by using the design features of a library generally belonging to the CAD system, possibly enriched by the user or stemmed from a design expert system.

The direct association of a machining feature to each design feature proves difficult and imposes to continuously enrich the catalogue of machining features. Besides the complexity of some features, this approach is unsuitable especially when design features have to be associated to form a machining feature. For example, the "rib" feature used by the designer corresponds to two machining "pocket" features situated on each side of the "rib". Moreover, all the designers claim the liberty to define forms without limiting themselves to a feature library.

The method retained in the scope of the GALILEO project consists in recognising manufacturing features from the CAD model without taking the real production means into account. These manufacture features group surfaces that cannot be dissociated when searching for operation sequence. These surfaces are associated according to four criteria : geometrical, topological, technological or tolerancing. These independent criteria permit to detect surfaces that are linked either by common edges or by technological constraints indicated by normalised symbols or comments.

The methods used for machining feature recognition can thus be applied to each manufacturing feature taken independently.

6. Conclusion

If there is no problem for simple shapes of parts (hole, plane, groove,...), the more complicated shapes impose more complex strategies for the generation of operation sequences which can be implemented thanks to the machining feature approach.

The association of the machining operations realised by the same tool can be carried out either by the association of surfaces in the same machining feature according to geometrical criteria (which implies that a set of surfaces can be incorporated in several features) or by searching for intersections of possible sets of operation sequences for each feature taken separately.

We have thus concluded that for a given process planning system, the possible machining features were in fact defined by all the shapes to process to choose a machining sequence. It is therefore proved impossible to give a general definition of machining features to allow their identification within a part model. Features are therefore simply defined by a library proper to the process planning system.

The complete machining process of the part can be represented with the machining features which have been retained by the process planning system. Characteristics of features can then be enriched : for instance by material removal volume, machining operation, tools,... This new use of the machining feature concept must not be mixed with its main role which is to assist the generation of process plans.

The feature approach presented in this paper is not unique.

The machining feature approach today is an interesting method to update process plannings in case of modifications (re-engineering). The analysis of the modifications can quickly show the features which must be examined, without altering the machining operations related to the other features.

Despite a great number of works carried out in this matter, automatic process planning is not a settled problem. If today there exist several ways to describe the expertise, the generation of the operation sequence for a given machining feature and especially the design of the system used for searching the best combination of operations remain to be clarified. Moreover, the identification of features remains a difficult problem, especially for parts whose surface independence cannot easily be detected.

Research works carried out in the last two decades have indeed allowed to release fundamental concepts. It is still necessary to carry on this effort in order to elaborate a consistent and complete process planning approach, with, in particular, the property of being flexible so that all users can integrate their know-how and their constraints.

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MACHINING FEATURES: INTEGRATION OF THE MACHINING FUNCTION IN THE MODELLING OF PARTS FOR AUTOMATED PROCESS PLANNING

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Abstract

The purpose of this article is to present machining features, their interest and their use in the creation of a process planning system. We show how the analysis of all the parameters of the feature can automatically define the operation sequences of machining features using production rules. The methods developed in this article have been implemented as an expert system named OMEGA.

1. Introduction

The creation of the process plan is the main issue of the dialogue between the designer and the manufacturer. The most important reason for automating these phases is due to the ensuing cost and delay reduction and quality improvement both for part machining and for part designing in the concurrent engineering approach.

In the field of Computer-Aided Process Planning (CAPP), many different approaches, (referred to in several articles [1] [2]) have been explored since the 1970s. The most recently created systems are generative. Two main trends appear among the various generative approaches to process planning. The first consists in analysing a geometric model so as to extract the set of the part's machining features using recognition such as FEXCAPP [3], PART [4], QTC [5]. The second is based on direct part creation from machining features such as PROPEL [6], GAGMAT [7], GENOA [8]. The latter bring out the better features of the concurrent engineering approach.

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We have oriented our study toward the second of these approaches [9]. The process planning generation is derived from a machining feature set that allows us to describe the part from a manufacturing point of view. The machining feature notion provides an element of response to the problem of feature representation [10] [11] since the notion includes some of the potential of the geometric tolerance specification [12] [13].

In this paper, the machining features are first introduced together with the part representation model. We give its definition and we show its use in the CAPP.

2. Part representation model

2.1 THE VARIOUS SOLUTIONS GIVEN FOR PART MODEL REPRESENTATION

For the past fifteen years, CAD/CAM environments have given significant help in design job, especially in the geometric modelling area. The usual CAD software allows us to describe parts by solid, surfaces and wire modelling. Parametric modelling may be used to describe the relationship between the various geometric parameters of a model's features. With regard to variational systems we extend the concepts of parametric geometry and provide tools for solving geometric equation systems and updating the relationships. Nevertheless, these tools are only viable for geometric modelling tasks and do not provide all the necessary functions to really assist in redesigning industrial products and in aiding process planning activities.

Some of the most recent approaches allow us to take into account non-geometric information:

- Object languages linked to traditional CAD systems: they allow developers to use directly a geometrical object structure including a hierarchy of geometric classes defined by sets of manipulation and computed methods. Systems such as ICAD and Concept Modeller operate in this manner.
- The rule-based system linked to traditional CAD systems: in such systems, the developers may describe their knowledge using a set of production rules [14] [15] [16].
- The constraint solver systems used in conjunction with traditional CAD systems: the problem is described by a set of geometric or other relationships which must be satisfied (bi-directional relationships between variables). At this point various on-line calls to the geometric modelling functionalities are made [17] [18].

2.2 THE USER'S POINT OF VIEW

The designer and the manufacturer may consider the same product from different points of view. Each point of view may be in the DEKLARE project [19] which links the available models, both functional and physical.

2.2.1 *The functional model*

The functional model is composed of articles, thinking blocks, concepts, technical solutions and features. The thinking blocks, features and concepts represent the functions of the article (the product). The concepts are associated with the principal functions, which can be divided into sub-functions. The technical solutions correspond to the realisation of concepts. Figure 1 shows the functional model of a cylinder head. The model is composed of thinking blocks and concepts required by the description of the problem. The model thus presents all the different functions to be realized.

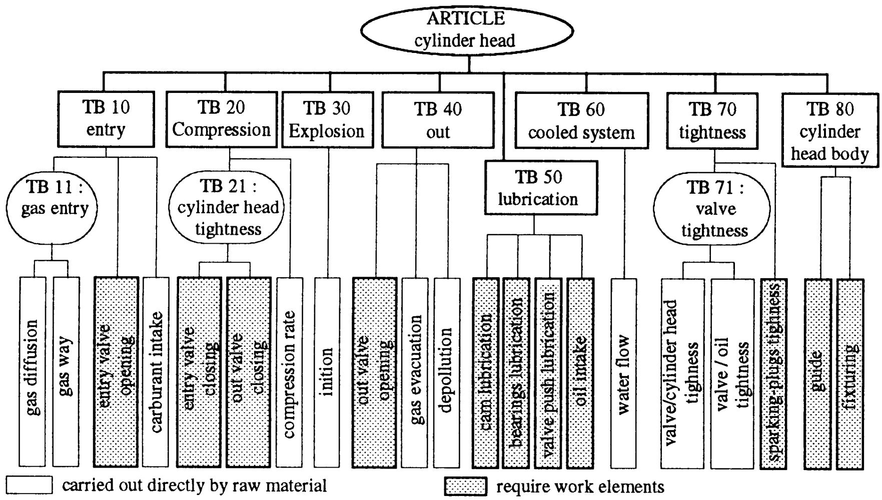


Figure 1. Cylinder head modelling.

2.2.2 *The physical model*

The physical model is composed of articles, assemblies, parts and features. An article is defined by a set of assemblies, and an assembly by a set of parts. A part is made up of one or several features which represent a physical model of the technical solutions. Several parts may have some features in common. The physical model is obtained from specialist documents, drawings and technical documentation.

The area studied concerns the prismatic parts for automobile prototyping activities. In our approach, the physical model is divided into two sub-models (Figure 1.) :

- The first sub-model which represents the inner and outer forms is defined by its means of manufacture: foundry and forging [20]. It allows us to take into account certain functions such as gas or water circulation, etc.
- The second is relative to the set of surfaces which require finishing by work elements. The set of machining features is included in this second sub-model.

The machining features provide those involved in the designing and manufacturing process with a good understanding of the parts. These features may be generated or, alternatively, may be a sub-element of the mechanism. They represent a specific element of the part's function.

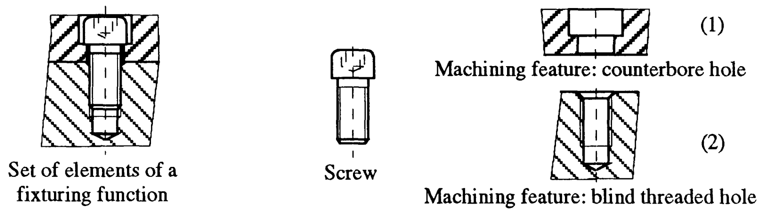


Figure 2. Example of a fixturing function broken down into its machining features

Figure 2 highlights the breaking down of a fixturing function into machining features. The machining feature of the first part (1) is a counterbore hole which provides the positioning and the support of the screw head. For the second part (2), the machining feature is a blind threaded hole.

3. Machining feature: definition and example

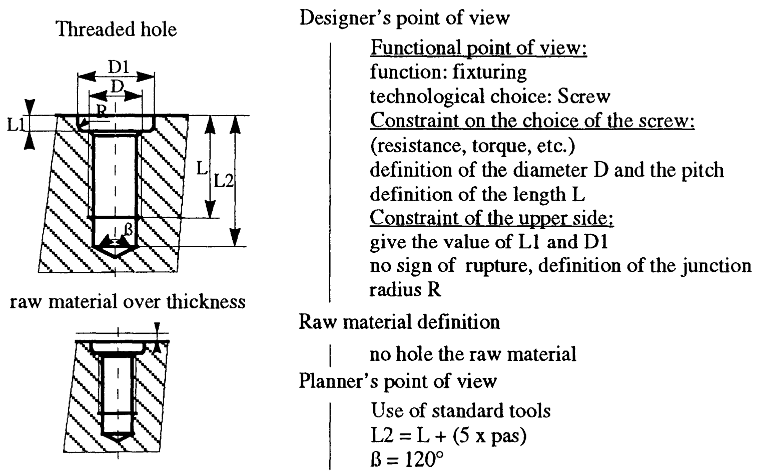
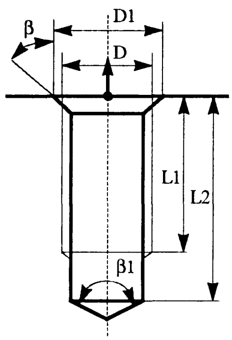


Figure 3. Characteristics of a machining feature

A machining feature represents a set of specifications which are defined by the various jobs to be designed and the product's manufacturing cycle. Then, the constraints linked to the know-how of the designer and the planner's semantic are taken into account (Figure 3.). The use of these features enables a homogenization of the geometric forms connected to a set of functions and thus a standardisation of operation sequences associated to these features.

3.1 DEFINITION OF A MACHINING FEATURE

The definition proposed is close to the machining feature definition of the GAMA working group [21]. Other operations have been added in the operation sequences such as operation control, assembly, head treatment, etc. Thus, the operation sequence is not merely limited to the work element.



Threaded hole machining feature	
D Tapped diameter	8
Thread quality	7H
Pitch	1.0
L1	20
L1 Tolerance	0.5
L2	26
L2 tolerance	0, +0.5
D1 edge chamfer diameter	9
D1 Tolerance	0, +0.5
β Edge chamfer	60°
β1 Edge	120°

Technological semantics			
Localization	Ø	0,2	Datum

Topological semantics	
Starts on	Plane

"Roughing" operation sequence:

Operation sequence	Cutting tool	Tool holder
Center drilling	Center drill	Standard
Drilling	Standard twist drill	Standard
Countersinking	Countersink	Standard
Tapping	Tap	Tap tool holder

"Auto-control" operation sequence:

Operation sequence	Mesuring device
internal diameter threaded hole	gauge
thread	Leitech gauge
L1 thread deep	Leitech gauge
β edge chamfer	visual control

Figure 4. Threaded hole machining feature

The machining feature (Figure 4.) is defined by:

- One form or a set of elementary geometric surfaces which represents an element of the part; this element allows us to carry out an elementary function,
- a set of attributes which characterize these geometric surfaces, such as tolerance information, roughness, etc.
- an operation sequence which is a series of work elements that can be interrupted. It represents the sequencing of the work elements leading to the realization of a machining feature. The operation sequence includes not only the cutting operations but also auto-control, heat treatment, assembly operations.

3.2 SEMANTICS OF THE MACHINING FEATURE

The machining feature is characterized by three semantics (Figure 4.):

- the intrinsic semantic to a feature includes not only all the geometric information (tolerance, roughness),
- the technological semantic collects information about the relationship of the other features such as: parallelism, perpendicularity, localization, coaxiality, etc.
- the topological semantic often implicit in design, defines topological relations between features which are required by the generation of operation sequences and their planning. Four main categories have been defined: starts in, starts on, ends in, ends on. (Figure 5.)

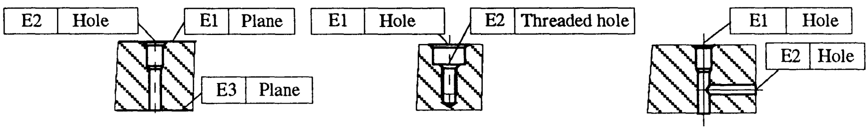


Figure 5. Topological relations

3.3 THE OPERATION SEQUENCE

The GAMA working group has determined its terms in relation to the problem of process planning. This work is founded upon the experience and the varied approaches to the problems of automatic process planning put forward by manufacturers and scientists within the group. The notion of process classes must first be defined before developing these ideas:

- three classes for cutting process : roughing, finishing, super-finishing.
- other process classes : auto-control, heat treatment, assembly.

The operation sequence of a machining feature is a set of several processes that may originate from various classes, and which are necessary for the realization of the part.

3.4 MACHINING FEATURES FOR OUR DEVELOPMENT

We have defined (Figure 6.) five families of machining features for our development: plain round holes, threaded holes, bored holes, face milled flat surfaces, simple pockets without islands. The data set of the machining features and the work element are founded upon an object representation. For each family of machining features, a set of descriptive geometrical parameters defines the elements of this family. Each machining feature is merely a specific case of the more complex machining feature which generates a family.

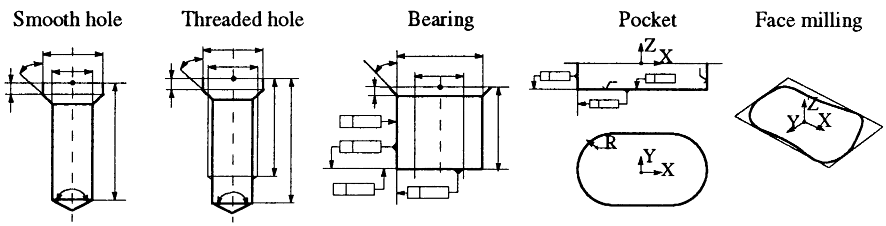


Figure 6. Various families of feature representation

4. Illustration: OMEGA

The expert system called OMEGA is the result of a partnership with Peugeot Société Automobile (PSA). The OMEGA prototype provides us with the validation of a part analysis method for the creation of a CAPP system.

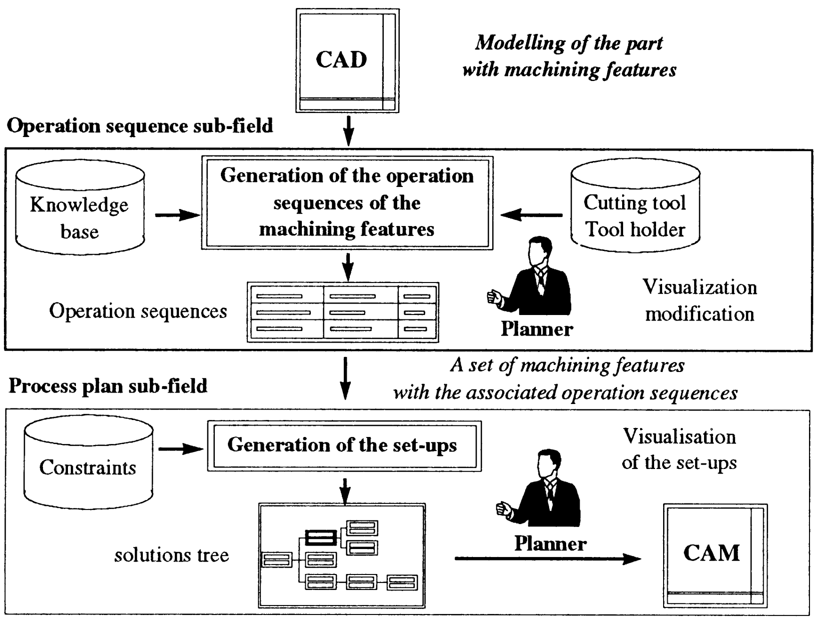


Figure 7. Representation of the OMEGA system

The concepts used are:

- definition of the parts by machining features,
- a generative approach,
- the problem is broken down into sub-problems and this reflects the organization of the planning department. We have thus defined two sub-fields that both possess their own expertise. The first defines the automatic generation of operation sequences carried out according to production rules. The second is relative to the

process plan generation and allows the arrangement of the work elements in sub-phases using a constraint propagation strategy.

4.1 OPERATION SEQUENCE GENERATION

For each machining feature, a knowledge base allows the generation of an associated set of operation sequences. The generation of operation sequences takes into account the specific, technological and topological semantics of the machining feature to provide high level quality in the manufacturing process of the part. Then, the set of operation sequences of the various features can be generated separately from the process planning in set-ups. The start of the process planning generation is founded upon the machining features completed by the operation sequences. This method respects the definition of the GAMA working group relative to the operation sequences: the operation sequences of the machining features are independent of each other.

4.1.1 *Gathering of expertise*

The first step in setting up the knowledge base consists in extracting the expertise connected to the operation sequences. This expertise is therefore gathered with the planning specialists and contains the company's know-how. In order to cover all cases, the more complex machining features have also been defined. For any given family, the other operation sequences are merely particular cases of the most elaborate case sequences. These complex machining features generate different families of machining features. For each family, a catalogue of operation sequences standardized for the scheduling of work elements and tools has been used.

4.1.2 *Structuring of the expertise*

Although the number of operation sequences associated to features is high (more than one hundred operation sequences for each kind of feature), the elementary work elements, common to all the operation sequences, are relatively scarce (fifteen sorts of work elements). We have therefore turned towards an generative approach in order to construct the operation sequences.

The whole of the expertise associated with a machining feature is allotted two domains (Figure 8.). The first domain is related to the characterization of work elements. This expertise structured by “operative” tasks gathering a set of rules, is common to all features. The second domain specific to each feature type, allows the step-by-step creation of the operation sequences by successive addition of work elements. The knowledge base of five families of machining features has been developed on the knowledge base system shell SMECI [22]. This covers approximately one hundred tasks and four hundred rules.

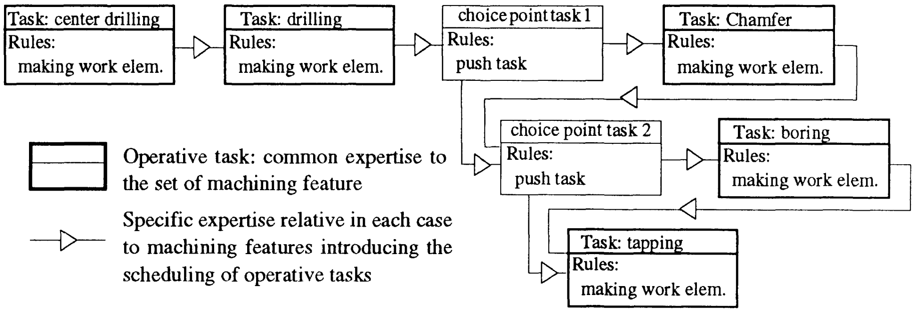


Figure 8. Structure of the task associated with the threaded hole

4.1.3 *Experiment evaluation*

The prototype OMEGA has been focused on parts of the French car manufacturer PSA (gear box, cylinder head, etc.). The tested parts have been allowed to evaluate the potential of the chosen concepts and the consistency of results compared with the planner's results. We note that the CPU time required by our system for the creation of operation sequences of the 16 valves cylinder head is about three minutes on a IBM RS6000. The time required to create the set of all available process plans for different types of machine kinematics is evaluated at between four and ten minutes. The process plan generation, the analysis and the validation by the planner of proposed solutions represent about 20% of the time required by the implementation of the process plan of the same part without an aided system.

5. Conclusion

The work reported highlights the relevance of the use of machining feature concepts in the automatic generation of machining process plans. These features are elementary objects to which the planner is accustomed and have great significance as regards the manufacturing process. They are used as a starting point for the process plan generation. Taking into account the set of each feature semantics allows us to generate automatically the associated operation sequences separately from the set-up generation. The operation sequence describes both the set of work elements providing a high level quality in the manufacturing process and auto-control elements.

Our current research in the field of automatic process planning opens up good prospects for part modelling in concurrent engineering. Currently, this point is giving rise to a good deal of research since its influence on design information modelling is great. In our opinion, the job features, as, for instance, machining features, must be defined first in order to define the design and functional features.

Acknowledgements

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EXPRESSION AND RECOGNITION OF DESIGN INTENTIONS

The contributions of multimodality

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Abstract. Looking for a best adequation between human intuitive design methods and industrial tools of modern engineering, the new CAD systems must try to recognize user's conceptual intentions. The use of a multimodal man - machine interface is one of the techniques that should be implemented to ease the expression of design intentions. A multimodal contextual editor is presented to illustrate these new possibilities. To recognize deep conceptual intentions, we rely on an initial prototype that is elaborated to avoid the manual achievement of the complete functional specifications. In this case, we consider the prototype under construction as a concrete example illustrating the functional specifications. Indeed, the former contains several choices which are not globally relevant but necessary for its realization. To find the true conceptual intentions, it is therefore necessary to extract the hidden abstraction of these choices, and thus, to generalize the example.

1. Introduction

The industrial systems used in design, workflow, monitoring or learning are becoming more and more integrated and collaborative. This dimension of integration has been largely investigated and brought into operation in industrial contexts. We studied it during the CIM-ONE project [1]. This project ended with propositions of data-based integration models and architectural models for integrated systems. Moreover, we started to study how to express and model design process in order to define clearly roles and group dynamics. Such a modeling has been used in IPDES [2] (an ESPRIT project) introducing design contracts. Thanks to a new project on cooperative design, financed by the *Région Rhône-Alpes*, we are able to study design process thoroughly in the field of mechanics. Several models of design process have been proposed from sequential design to concurrent design. Each one expresses the links between each phase of the process specifying parts of design contracts, activities, rights and duties of each participant, and desired results on objects under construction.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 113–120.

For several years, computer science has been trying to become an efficient tool of technical data acquisition, computation and exchange. Today, it is looking for a new way to help people in their design works. In order to propose good helps, computers need to capture and understand the designers' intentions. These intentions can be quite simple (e.g.: implicit choice of parameters), or more complex when they are linked to the interpretation of design process. So, the assistance brought by the expression and recognition of design intentions can be various : implicit choices, automatic validations, regards for constraints, proposals of generic or specific solutions...

In our study, we considered two steps in recognition of design intentions. The first step is the **construction of a prototype.** During this phase, the expression of design intentions can be simplified by a good organization of workspaces, a large amount of reusable information and by the use of a multimodal interface. The second step consists in the recognition of the intentions of the designer(s) using the prototypes which are just concrete examples of a solution. The aim of this approach is to find the real conceptual intentions **generalizing these examples**. It is this generalization operation which extracts information expressing intentions from specific information linked to a particular example. Such mechanisms let users realize more innovative designs.

2. Design intentions during prototype generation

During prototype generation, it is necessary to give designers tools which let them express their ideas very freely. This fact is particularly valid concerning the design of kinematic diagrams. Up to now, builders of kinematic diagrams and analysis tools stand on human-computer interfaces which were very far from the "natural" interface used by designers (pen and paper). Thus, the acquisition of kinematic diagrams usually consists in an iterative hand-typing of the nature of the linkages, their positions and orientations, and the names of the parts that are linked. These approaches are generally due to the fact that they are used by software specialized in the analysis and validation of mechanisms and not in the construction of kinematic diagrams.

For these reasons, we try to build a new software that proposes more natural and intuitive techniques of construction. Whereas another team of our project worked on the recognition of scanned handwritten diagrams [3], we chose to explore a more classical solution: the editor. However, we did our utmost not to fall into CAD editor traps such as the multiplication of menus and dialog boxes.

In this context, we built a first version of an editor named *CinémaTek.* This software proposes viewing windows (in a 3-D projection) in which users can build tri-dimensional diagrams. First of all, the edition of a kinematic diagram is realized by the construction of the skeleton of each part. In our context, a skeleton is a set of nodes and branches. On these skeletons, the user drops linkages using contextual menus which appear under the position of the pointer (Figure 1 & 2).

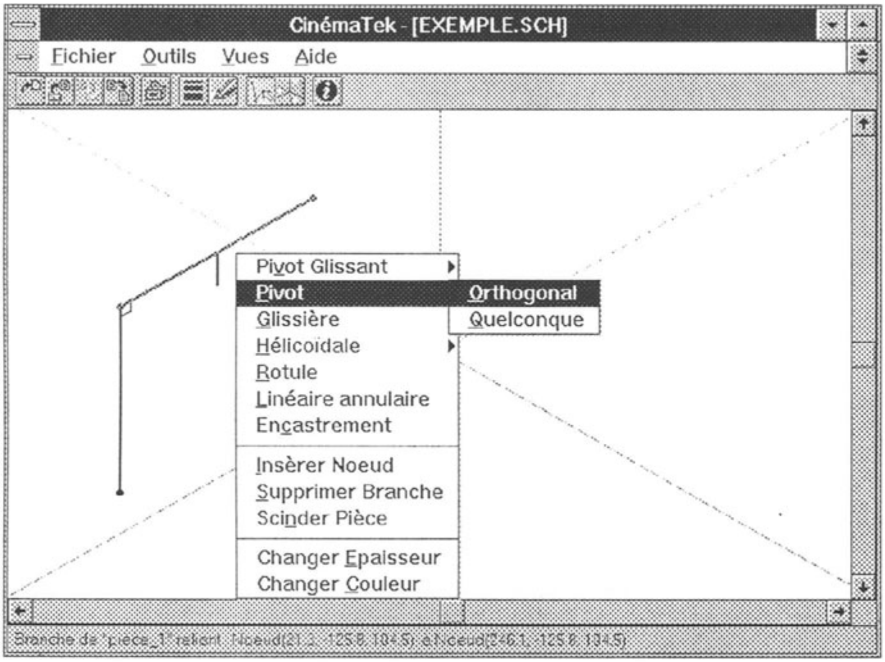


Figure 1. Construction of a linkage on a branch using a contextual menu.

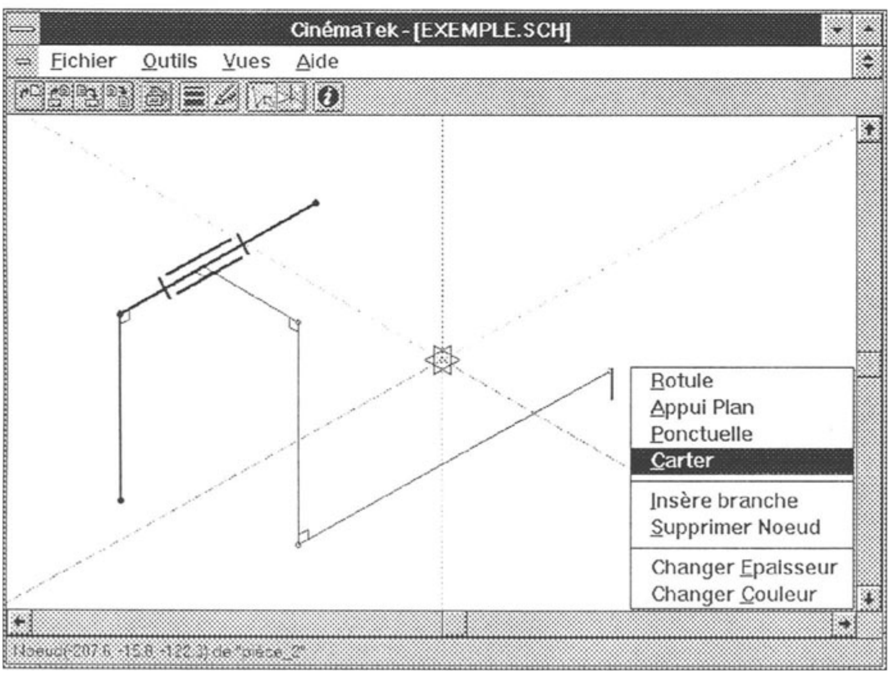


Figure 2. Insertion of a fixed linkage to the body on a node using a contextual menu.

All the edition functions (create, change, move and delete) can be executed on nodes, branches, linkages and whole parts. All the phases of creation, addition or moving are dynamic, i.e. the diagram is transforming itself according to the user's actions on the screen pointer in real-time (WYSIWYG). Finally, it is possible to rename parts or highlight them using different colors or thickness.

The main goal of our editor is to provide a flexible system that lets designers express easily and rapidly their ideas with kinematic diagrams semantically as complete as possible. Moreover, these diagrams should be directly used, i.e. printed or exported to analysis tools such as *MECAmaster* [4]. To ease the manipulation of the pointer in a 3–D space, its movements are analyzed according to the three main directions given by the reference axis. Of course, these directions depend on the position of the observer. This method allows to propose an easier system than the classical ones where three projection windows are used. Thus, the acquisition is really faster in a context where no extreme precision is required in the positioning of the parts. However, to assist designers in their perception of the depth of the scene, we draw projection cubes under each node of the part which is under construction (Figure 3).

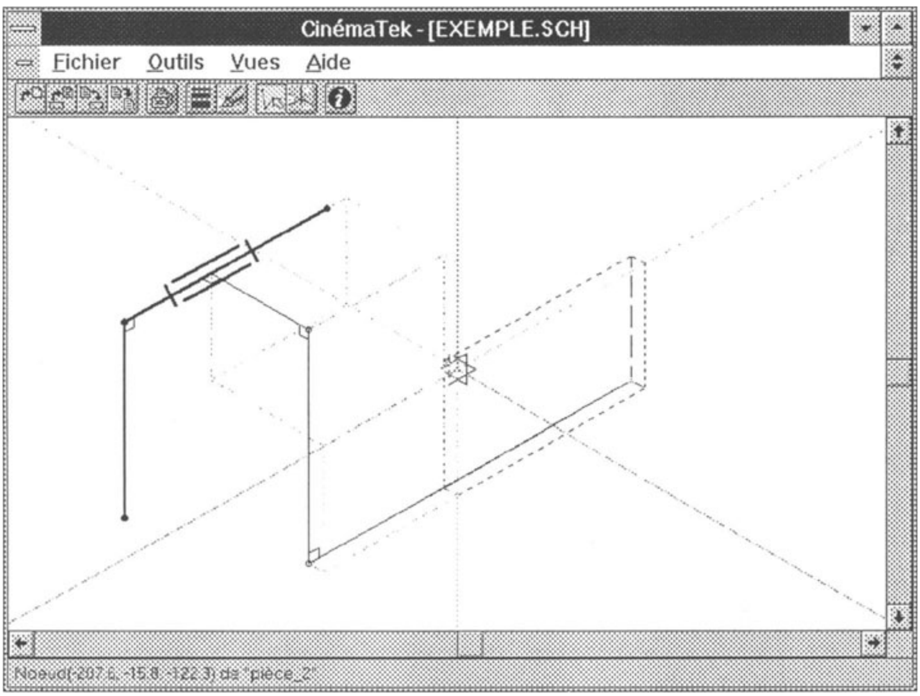


Figure 3. The projection cubes used to perceive the 3-D position of nodes.

Furthermore, it is possible to create other viewing windows to observe a diagram under different points of view. It is also possible to manipulate several diagrams in the same time. Finally, the system automatically detects perpendicularities between branches and represents them with small parallelograms. De facto, *CinémaTek* proposes elementary techniques of expression of simple intentions like perpendicularity or parallelism. At the present time, we study how to take in account these constraints during dynamic transformations.

In this version, *CinémaTek* eases construction of kinematic diagrams. The flexibility of its functionalities lets designers rapidly test various solutions. Thanks to its coupling with *MECAmaster* users can validate immediately their propositions (as well in terms of isostatism as in terms of strength or couple). For the moment, this coupling is manual (exportation and importation), but its automation is in progress. The detection of the main directions and of orthogonalities is a first level of recognition of design intentions. Indeed, a designer does not need to explicitly express the fact that he wants a particular orientation on a main axis or that he wants two branches of a skeleton to be orthogonal.

To continue our works, we studied how multimodality [5] can improve expression and recognition of conceptual intentions. We consider that the identification of designer's intentions can be largely improved when they are expressed with more adapted media.

In order to build an interface as near as possible than a natural one (pen and paper), we tried to improve this metaphor adding to *CinémaTek* a multimodal system developed in our laboratory [6]. This system includes a gesture recognition module. So, we use a graphic pad and a pencil to construct the linkages of a diagram. The choice of one linkage can be made not only thanks to contextual menus, but also by an elementary gesture based on its standard bidimensional representation (Figure 4).

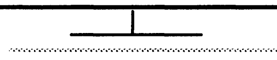
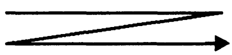
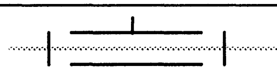
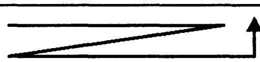
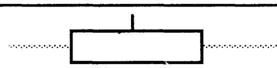
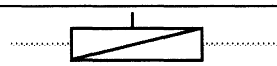
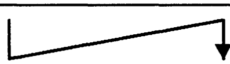
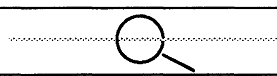
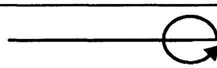
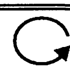
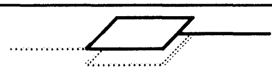
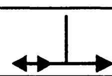
Linkage name	2D standard representation	Gesture in CinémaTek
Sliding Pivot		
Pivot		
Slider		
Helicoidal contact		
Spherical slider		
Ball joint		
Point contact		
Planar contact		

Figure 4. The set of gestures associated to kinematic linkages.

As a matter of fact, the designer can concentrate on its design task using a pen and "drawing" diagrams forgiving the constraints that could impose an editor. The elementary design intentions (orthogonalities, main directions, etc.) are automatically considered by *CinémaTek* because the mode of expression chosen to build diagrams transposes implicitly these intentions.

In the same way, we study the advantages that can offer a speech recognition system, especially in the expression of technical data. For the moment, we use speech recognition to specify the orthogonality parameter of linkages [7]. The skeleton of the under construction part presented on figure 3 has been obtained building an orthogonal pivot linkage from a previous part. The insert command was run drawing the "Pivot Linkage" gesture on the chosen branch and saying simultaneously the keyword "orthogonal". If the orthogonality parameter is not produced by one of the possible medias (speech or contextual menu), this parameter is fixed to the default value "any" (orthogonality is not imposed).

3. Design intentions during prototypes generalization

The construction of prototypes can be done during different phases of design process. Usually, it occurs after the writing of a functional design contract and it is used to put kinematic diagrams and structural diagrams in concrete forms. This approach is exactly the one we presented before (§2).

However, in many cases, writing a strict and complete functional design contract is a very complex and tedious task even when it is done with the help of computers. Indeed, design activity, and especially design of new products, is not well adapted to approaches based on an "abstract" expression of full design contracts.

In this context, we consider that construct a prototype can be used in another way, especially during the phase of elaboration of kinematic chains. Indeed, usually prototypes are built in the aim of fulfilling kinematic functionalities imposed by the design contract. Yet, these operations can be done in a reverse order, that is: build a prototype of kinematic diagram in which several elements of design contract will be found. To reach this objective, it is necessary to eliminate *a posteriori* all the elements concerning the specific solution implicitly expressed by the designer of the prototype. For instance, a kinematic diagram can include technological elements (e.g.: gears) which are not significant if we just consider the functional associated principles. In this case, it is necessary to replace those predefined elements by other more generic elements, that is which express pure functionalities without implicit choices (e.g.: angular transfer).

From another point of view, structural diagram is also a precious tool. First, it makes correspondence between the constraints imposed by the design contract, and the parts of the system. Incidentally, in the context of concurrent design, the tasks decomposition is generally realized considering structural diagrams (cutouts in large sets of parts) and functional design contracts.

An interesting method of computer supported work consists in having an approach similar to the one employed in context of "programming by example". This method can be decomposed in five phases :

1. The client writes a minimal functional design contract.
2. The designer builds a kinematic diagram that seems to fulfill all the kinematic constraints imposed by this contract.
3. The computer identifies the generic functionalities induced from this prototype and automatically build a structural diagram (identification of the number of parts and of the links between these parts).
4. The computer analyses correspondence between induced functionalities and required functionalities. Then, it shows to the designer all the differences that appear (missing functionalities, redundancies, etc.).
5. The designer builds a valid kinematic diagram from the functional, kinematic and structural information given by the computer.

Conclusion

To improve the computer helps in design activities, it is necessary to model the act of design both in multi-user (organization of collaborative activities - concurrent design) and mono-user dimensions. If computers are able to identify conceptual intentions, it is possible to imagine new kinds of helps. For this reason, we study this problem according to two approaches.

The first one relies on the use of a new generation of editors. These software let designers express their conceptual intentions in a more natural way. Multimodality is one of the techniques that should be used. It can increase the adequation between computer tools and the natural media used by designers.

Reasoning upon examples offers new possibilities. Indeed, the tedious writing of a complete functional design contract, followed by the building of a kinematic diagram, supposes a deductive approach which should be broken by an inadequate initial design contract (too much complete or insufficient). The approach that we propose is more inductive. It lets designers express their ideas in a concrete way: using an example. The functional design contract is then automatically determined by generalization of the example and completed by the designers. This approach seems to be very attractive because it can be applied in innovative design and also in evolutive design (reverse engineering). Identify conceptual intentions in reverse designing is a promising research field.

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INTEGRATION OF THE MACHINING POINT OF VIEW IN THE PRODUCT MODELLING: THE FIXTURING FEATURES.

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Abstract. A fixturing feature model of a part is presented in this paper. United with the machining feature model and the corresponding positioning, it allows a process plan to be generated effectively. Geometrical parameters typical of a good locating or a good clamping and indicators typical of the part behaviour during machining are defined. The capacity for a fixturing feature to be an efficient clamping and an accurate locating is considered.

Résumé. Pour pouvoir générer une gamme d'usinage, nous proposons de compléter le modèle entité d'usinage (et les relations de positionnement correspondantes) par un modèle entité de prise de pièce. Nous présentons ce modèle dans cette communication. En plus des paramètres géométriques caractérisant les surfaces de posage et de bridage capables, nous définissons des indices du comportement de la pièce pendant son usinage. Ceci nous permet de caractériser l'aptitude d'une prise de pièce à un bridage efficace et à l'obtention de la qualité demandée pour la pièce.

1. Introduction

Different works dealing with automatic process planning have pointed out that part representation, proposed by designers and present CAD systems, is very poor [9, 4]. The geometry, even if it is accompanied by technological information with a text representation, does not give enough useful information to the process planner. The machining feature concept has been proposed by numerous authors in the literature in order to encapsulate the useful data and the process planning methods. Those machining features have been widely studied [11, 6, 7, 5]. The concept of feature is accepted and employed in the most of the current studies even if a definition is not accepted.
Machining features have been intensely exploited in works dealing with process planning. Particularly, how the form and the intrinsic quality of the feature can be achieved have been widely studied. The required quality of the positioning of the features is important for the process plan elaboration. Only a few authors propose to base their resolution upon them. Hayes [8] and Brissaud [4] provide guidance for the process planner reasoning with those constraints which are transcribed in rough production rules. Boerma [2] translates them into the resolution of other related problems. The quality of the feature positioning, notably the imposed tolerances, must be studied with a quantitative approach to elaborate reliable process plans. The model of the product under

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study has to explicitly integrate those positioning relationships added to machining features.

A badly fixturing of the part is widely highlighted among the causes of the poor quality of machined part. Fixturing of a part is composed of locating and clamping of the part. Basically, this badly fixturing comes from a lack of knowledge about the behaviour of fixtures during the machining process. Therefore, the choices are not controlled by the process planner. This lack of knowledge is pointed out as the principal obstacle for achieving reliable process plans [2, 13, 10]. The fixturing features, which integrate the geometrical definition and the mechanical behaviour of the part fixturing, is proposed by the authors to capture information about fixturing.

Then, the product model is composed of machining features, positioning relationships between features and fixturing features. Therefore information is available for process planner reasoning. Under this form of a feature, information is perfectly formalised and can be easily exploited.

The aim of this communication is to clearly define the fixturing feature advocated by the authors. This notion allows the locating and the clamping of a part to be integrated and the global mechanical behaviour of the part during machining to be estimated. Heavy links between fixturing feature, machining feature and positioning relationship can be expressed. The interest in controlling the choice of a fixture to assure the machining quality is recalled in section 2. The fixturing feature is detailed in section 3: the attributes and the different models are presented. The attributes from the part geometry and the technological attributes which represent the expert know-how are complementary. The set of those attributes allows us to propose an assessment of the fixture ability. In section 4, the extraction of the fixturing features from a CAD environment is quickly presented.

2. The process planning context

During process planning, the machining processes, associated to each machining feature, has to be determined by the process planner or the numerical system. Then the different machining operations can be gathered into set-ups to propose a process plan architecture. This organisation in set-ups is only possible if the machining operations can be realised on the same machine tool and a solution for an efficient fixturing is adapted. At a rough estimate, one may consider that the machining cost of a part decreases with the number of set-ups necessary for the production. Therefore, it is essential for the maximal number of machining features to be gathered onto the same fixturing. So, the estimating of the fixturing quality becomes an important element for an efficient process planning reasoning.

This fixturing research can be essentially performed in two ways:

- The first one consists in designing first the process plan architecture and then studying the fixturing compatible with this architecture. This strategy consists in gathering the machining features into a set of set-ups according to the positioning relationships of the features and the capacities of the available machine tools. Then a fixturing is searched for each set-up. If one of those fixturings does not exist, the process plan architecture is rejected and a new one is searched adding one or several supplementary constraints. An important inconsistency appears with this approach. On one hand, a fixture needs a large space around the part in order to locate the different elements. On the other hand, the aim of gathering the machining features reduces this useful space. Therefore, this approach forces numerous backtracks onto process planning. However, this process is adopted by most of the authors [2, 13, 14].

- The second one consists in controlling the process plan architecture elaboration and the fixturing detailing with parallelism. No backtrack can be necessary. But however, it needs two antagonist tasks to be integrated into process planning: choosing a fixturing and gathering the machining features. This strategy needs first the fixturing knowledge to be formalised and, secondly, the process planning knowledge and strategy to be enriched with this fixturing knowledge [10].

A strong link between the fixturing choice and the process plan architecture design is pointed out by our work at 3S laboratory. The process adopted by the authors allows the process planning and fixturing tasks:

- to be lay down and solve with a global and linked manner,
- to be simultaneously performed (therefore the interactions under consideration are taken into account).

3. The fixturing feature model

A fixturing feature is a geometrical form and a set of requirements for which locating and clamping qualities are accepted. This feature encapsulates geometrical information (locating and clamping places) coupled with technological information extracted from the machining job. Thus the fixturability of the part is assured. An assessment of the fixture ability is calculated by indicators relative to the mechanical behaviour of the part during machining. Fixturing feature attributes and used models are respectively presented in sections 3.1 and 3.2.

3.1 THE FIXTURING FEATURE ATTRIBUTES

The different attributes of a fixturing feature are:

- a locating. The part is put in location in the machine tool system of reference in order to assure that the machined surface are at the "right place".
- a clamping. The static equilibrium of the part in the machine tool system of reference has to be assured during all the machining process.
- a list of the reachable machining features. A machining feature can be reached, for a given fixturing, if first the machining and locating directions are compatible and secondly an available space allows the clamping elements to be located.
- a mechanical behaviour. Indicators represent a fixturing assessment: necessary minimal clamping force, sliding and revolving indicators, minimal quality for locating surfaces.

3.2 THE USED MODELS

3.2.1 The locating model

The locating is modelled by a locating geometry which is a combination of locator surfaces : 3-2-1r principle (plane, orientation, point), 3-2-1c principle (plane, centre, point) or 4-1-1 principle (centre, point, point). A system of reference, locating reaction and a locating quality are the other attributes. The primary locator is called the

dominating locator, the secondary one the orientation locator and the tertiary one the stop.
The different locator types are plane type, rectilinear type, punctual type, sliding pivot type. The locator is characterised by a locator direction, a locator system of reference, a locator kinematical model, a locator reaction, a locator quality and a locator reachability.

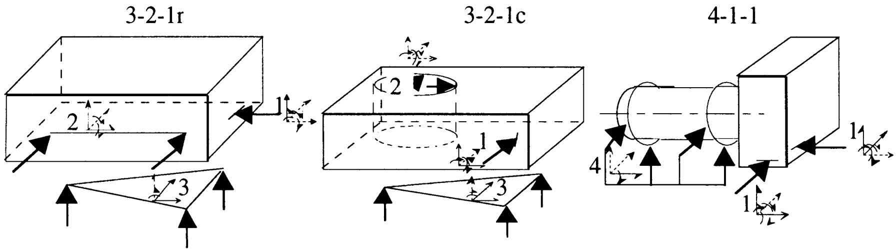

Figure 1 : the locating principles

The locator reaction
When the contacts between the part and the locator are local in places called locator contact points, the locator reaction model is a set of forces located at each locator contact point. Each force is oriented by the locator direction at the locator contact point and is into the friction cone [12] (figure 2). Therefore the locator reaction can be modelled by a force and a moment expressed in the locator system of reference.

The locator quality
The contact between part and fixture is generally not perfectly rigid. The locator surface of each part of a batch takes up a different location in the locator system of reference. The error is essentially dependent upon the contact defaults at a locator contact point. Bourdet represents the locating error at a locator contact point belonging to the part, relative to its theoretical location in the machine tool system of reference, by a short displacement [3]. The locating error at each locator contact point can be modelled by a translatory movement e in the locator direction (figure 3). The set of locating errors at each locator contact point creates a short displacement of the part modelled by a linear and a angular displacements expressed in the locator system of reference. The locating errors at each locator contact point essentially come from the form default of the geometry of the part surface, the mechanical properties of the part material and the possible play between the geometry of the part and the geometry of the fixture.

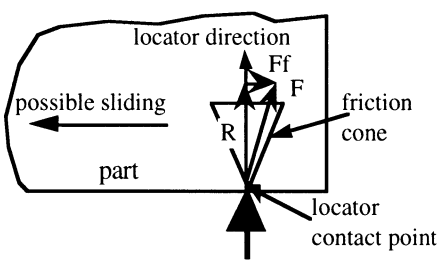

Figure 2: the locator reaction model

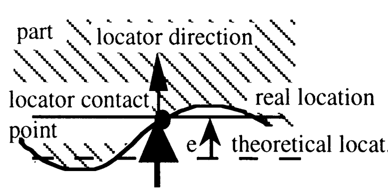

Figure 3: the locating default of the part at the locator contact point

The locator reachability

The locator reachability is defined by two indicators called a_n and a_p (figure 4). The first one a_n indicates if the locator can be able to take the physical elements of the fixture in the locator direction. The second one a_p indicates if the locator can be materialised by elements with greater dimensions than the locator surface has, notably if the part can be directly put onto the table of the machine tool.

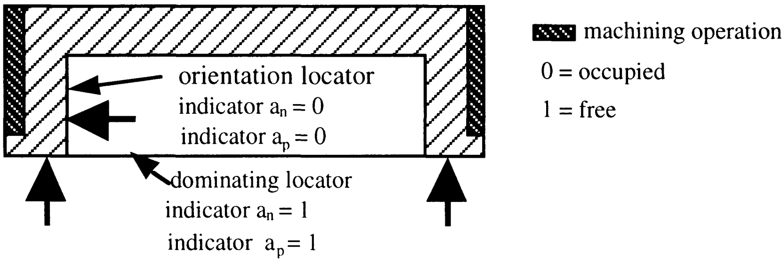

Figure 4 : the reachability indicators a_n and a_p.

3.2.2 *The clamping model*

The clamping is characterised by a clamping mode, a clamping centre and a clamping force and moment at the clamping centre. The mode can be the strap mode where the clamping is opposite to the primary locator, the vice mode where the clamping is opposite to the secondary locator and the chuck mode where the clamping and the locating are onto the same geometrical surface. Combinations of those modes are also used, notably the strap + vice mode where the resulting clamping combines a strap and a vice clamping modes. The clamping centre can be considered at the barycentre of the geometrical part places where a physical clamping can be located.

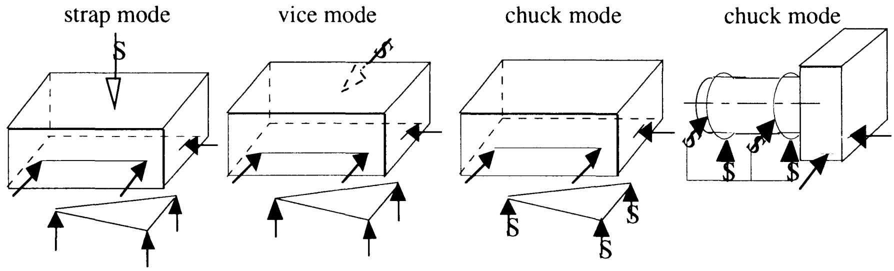

Figure 5: the clamping modes

3.2.3 *The list of the reachable machining features*

The list of the reachable machining features is defined for a given fixturing feature. It is determined in verifying that, for each machining feature,

- the machining direction agrees the locating type. In general, when the locating is a 3-2-1r or a 3-2-1c principle one (figure 1), the cutting tools do not go through the primary locator. Therefore the machining directions are accepted if they belong to the upper half space relative to the primary locator.

- the geometry of the machining feature does not interfere with the geometry of the fixturing feature. Of course, it is impossible for one of the fixturing surfaces to be machined because the elements belonging to the fixture will systematically make a collision with the cutting tools.
- the path of the cutting tools agrees the fixture. The space occupied by the cutting tools must never interfere with the physical elements belonging to the fixture.

3.2.4 The mechanical behaviour model

Determination of the minimal clamping force and the indicators of stability
The fixturing feature model that the authors propose has to be a support for the process planning reasoning. The model of the real behaviour of the part - fixture - cutting tool system has not to be very fine. Therefore a simple model of this behaviour is proposed; it is quite a long way from the real behaviour. The fact that the contact between the part and the fixture is local at the six locator contact points is our work hypothesis.
During the machining process, the part is affected by the cutting forces for which the model is a force Fc and a moment Mc at the point T, the clamping forces for which the model is two forces S_1 and S_2 which are respectively a strap clamping mode at the clamping centre B_1 and a vice clamping mode at the clamping centre B_2, the locating force for which the model is six forces R_1 to R_6 at the locator contact points P_1 to P_6 (figure 6). The gravity and the inertial phenomena are neglected.

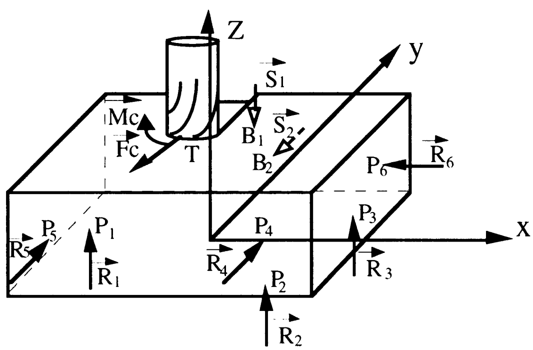

Figure 6 : the model of the mechanical forces which perform the part during the machining process.

The intensity of the clamping forces is calculated to assure the part equilibrium during all the machining process. The stability of the locating is assured if the perturbations, that the cutting tools create when they are working, do not upset the part equilibrium. The intensity of the minimal clamping force gives the locator reactions. The indicators of stability are calculated from, for the first one, the distribution of the locator reaction intensities and, for the second one, the location of the locator reaction into the friction cone. Therefore, they are the translation of the risk for the part to be revolved around the locators or slid on its locators during the machining process.
The forces and the moments of the cutting tools are estimated from the machining feature to be realised and the material volume to be removed. This estimate is reliable for the drilling operations [15]. For the milling ones, a study based upon Altintas' work

[1] has been developed at the 3S laboratory. The estimation of the intensity of the cutting forces and their orientation relative to the cutting tool path can be estimated.

Determination of the minimal locating quality
Three indicators of quality perform the minimal locating quality. They represent the space in which each locator geometry has to be located. Those indicators are evaluated from the short displacement of the part which is considered presently perfectly rigid [2]. This displacement agrees the positioning tolerances. This tolerance, called factor of tolerance, is a intrinsic machining feature data. It is calculated from a distribution of the tolerance of the positioning relationships onto the two concerned features. The tolerance distribution can be performed by an optimisation and an expertise to obtain the highest indicators of quality.

4. Recognition of fixturing features

MIAP (MIse et mAintien en Position) is a numerical module which recognises the fixturing features. It has been developed by the authors. It works from a geometrical description and a feature description of the machined part. A large amount of the reasoning is essentially geometrical. This module has been integrated into CAD-CAM environment Euclid-IS: the very efficient Euclid geometrical functions and handling can be used in this module. The calculus of the mechanical behaviour of the part - fixturing couple is also integrated in the same environment.

4.1 THE USE OF THE MIAP MODULE

The process planner creates the CAD model of the machined part and describes it by machining features with the aid of a predefined library of machining features and positioning relationships. The module working leans on a geometrical analysis and an expertise which is translated under the form of geometrical parameters. However a process planner is needed to build the combination of the three locators which determines a locating. This intervention is necessary because the expertise about the assessment of a fixturing to be a good fixture uses a deeper study before being formalised.
The MIAP module proposes to the process planner the list of the possible fixturing features which agree each machining feature. It visualises the geometry and the non geometrical information within the CAD-CAM environment. Therefore, the process planner has all the important information available for process planning.

4.2 AN EXAMPLE OF A FIXTURING FEATURE RECOGNITION

The figure 7 screen shows a fixturing feature which agrees the machining operations of the sloping hole called trou_1U. The locating, in a Bezier's representation, is composed of a primary locator of plane type on the lower part face, a secondary locator of linear type and a stop. The possible clamping places for a strap mode are represented with cones. The information in the window says that, when the stop direction is X+, the minimal clamping force to assure the part equilibrium is zero. Of course, the cutting forces put the part upon the locators. On the other hand, when the stop direction is X-, the part can slide in the X axis (the sliding indicator is equal to 1 in the X direction).

The minimal clamping force to avoid this sliding is 631 daN. The hole is put in position relative to the sloping plane with a tolerance of 0,08mm. The minimal locating quality is therefore 0,047mm on the primary locator, 0,040mm on the secondary locator and 0,028mm on the stop. The orientation of the machining direction related to the primary locator direction imposes the machining operation to be realised on a four axis machining centre with the fixture on a square.

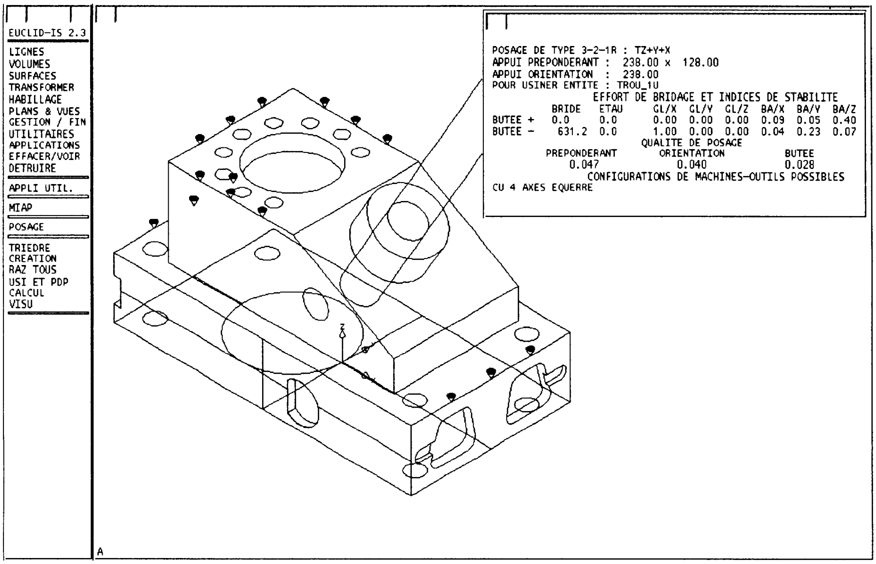

Figure 7 : a fixturing feature agrees the machining feature trou_1U.

5. Conclusion

Our machining fixturing knowledge has increased thanks this study. This knowledge must be organised in fixturing features which, added with machining features and positioning relationships, form a complete part model in a machining point of view. Nowadays, the assessment of a fixturing can be characterised to be an efficient clamping and achieve the part required quality. And this, while the parameters of the machining process are not detailed. The choice for a good part fixturing can be controlled thanks to this assessment all along the process planning; one of the limits for an automatic process planning is going to go back. This study carries on with the parts which can be bent during the machining process.

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FROM DESIGN TO MANUFACTURING OF FORGED PARTS : AUTOMATIC PROCESS PLANNING FOR DIES AND PARTS

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Abstract : in a concurrent engineering process, industrial product manufacturing has to be based on high semantic level models, used by all the actors of the product life-cycle. In this context, the aim of this paper is to present more particularly two automatic process planning generators for machining. The first one allows us to generate data for forge die milling, the second one is related to the process planning (determination of fixturing and machining operations) of parts machined from the forged raw parts.

1. Introduction

The design and manufacturing process of mechanical systems needs a dispartitioning, an efficient control and distribution of information. An integrated approach based on the product and its information system (Bocquet *et al.*, 1990) allows us to insure an efficient communication between the different actors in the development of the product. New data models, which integrate consistently geometry, functions, assembly, technology, ... have to be defined in order to be able to store, manipulate and control all the information (IMPPACT, 1991) (Charles *et al.*, 1991). The ideal approach would be to use an adaptive model which integrates know-how progressively and allows us to control incomplete models. In this way, the first step was the design of a product definition model (Mony, 1992) which allows us to describe the designed and defined product in order to be able to manufacture it. The development of high semantic level applications is possible with this model, consistent with the design process and a large know-how integration, at each stage of the design-production cycle. In this context, it is necessary to be able to design and manufacture raw parts, which are machined in order to obtain the final part. The raw part design is linked on one hand to the process planning of the final part, and on the other hand to the design and manufacture of the dies used for forming raw parts (moulding, forging, ...). So, it is necessary to take into account the mutual constraints between machining and forming processes, during the design and the process planning generation of parts and dies. The intermediate design consists of the definition of the die geometry from the raw part geometry. In general, this step is assumed by the process specialist and depends mainly on his personal know-how

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 131–140.

(Chamouard, 1970). Some studies related to automatic dressing of forged parts have been made for axisymetric parts (Tichkiewitch, 1989) and more recently for three dimensional ones (Boujut, 1993). They represent a first step in an integrated design and manufacturing approach for dies and raw parts. The design of the final product and the layout of raw parts often do not match. There is very little research on interactions between different trades. One of them, process planning and fixturing generation for machining of raw parts (Paris, 1995), is an interesting step to an integrated approach for design and manufacturing of raw and final parts. For all that, it is necessary to build a high level semantic model, valid for raw part design, die design and machining process planning for parts and dies. The goal of this paper is to show how automatic process planning can be applied to die manufacturing (Mawussi, 1995) and to part machining from raw parts obtained with dies (Brissaud, 1992), using an integrated product model (Mony, 1992).

2. A model for product definition

The diversity and the interaction of the components of a mechanical product result in complex structures of a high semantic level (Mony, 1992). It is necessary to be able to store all the information related to the mechanical product, starting from the early design stages, in order to avoid data reinterpretation. So, we have defined a high semantic level model which allows us to store all these information. This model is based on three basic structures (Mony, 1992) :

- features (Mony *et al.*, 1990) (Lenau *et al.*, 1993) : geometry is represented using groups of parametric geometric elements which are specific for each application (functional, machining, raw part making, etc...). Attributes (dimensions, tolerances, quality, etc...) and methods for feature manipulation (creation, instanciation, management, modification, destruction) are associated with these groups

- a functional structure : is a hierarchical graph made up of functions and sub-functions, whose leaves are the functional features ; its root is the main function of the system. Each sub-function is formed with functional features which lead to different parts, and if necessary with industrial components. This functional structure, which is the basic element of the logical structure of the product, allows us to store the designer's intent. It is possible to justify afterwards the choice of a technical solution.

- a physical structure : is a hierarchical graph made up of the physical components of the product (system, sub-system, machined parts, standard components). A machined part is defined as a functional shape (set of functional features located by functional specifications), and a blending shape (set of technological features which are not machined and which define the general topology of the part). Two types of relations have been defined between these two groups, the local topology (goes in, emerges from, lies on) and the reference to raw shapes. The functional and physical structures are linked through two kinds of relations ("a part is dedicated to a few functions" ; "a function is assumed by a few parts").

Let us first explain the definitions of the feature models used in our approach.

2.1. FUNCTIONAL FEATURES

A functional feature is a set of geometrical elements which are linked to technological elements. Each functional feature allows us to assume a specific subfunction of the part. The functional feature model of each part of the product can be built using a functional approach (Dupinet, 1991). Functional sets can be defined for each part in order to model the structure of the technological solutions of the physical model of the mechanical product. Then, the internal specifications and locations are built up using the functional graph concept (Dupinet, 1991).

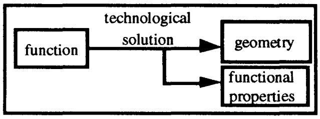


Figure 1. Functional feature model

2.2. MACHINING FEATURES

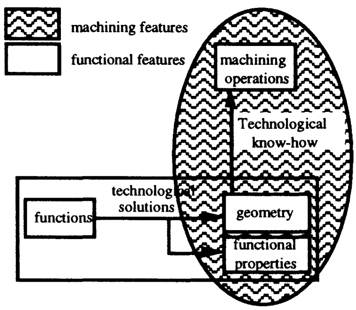


Figure 2. Functional and machining feature models

GAMA research group defined a machining feature as "a geometrical shape, linked with a set of specifications, associated to one or more well known machining processes. The latter are quasi-independant of the processes of the other machining features of the part" (GAMA, 1990). These features are the starting point of the machining process design. The machining feature model is based on the association or the decomposition of functional shapes, which can be machined during the same process. The figure 2 shows the relationship between the functional feature model and the machining feature model. A set of machining features is deduced from a set of functional features.

2.3. FIXTURING FEATURES

A fixturing feature is a geometric shape and a set of specifications. This feature is well-adapted to define the position and the clamping of the part during a machining operation (Paris, 1995). The fixturing feature model is built up from the functional feature model, according to the geometry and the topology of the features defined in the latter. The capability for fixturing features to represent an efficient positioning or clamping element is assessed from the quality and the form of the machined and the raw shapes. The figure 3 shows the relationship between the functional feature model and the fixturing feature model. A set of fixturing features is deduced from a set of functional features.

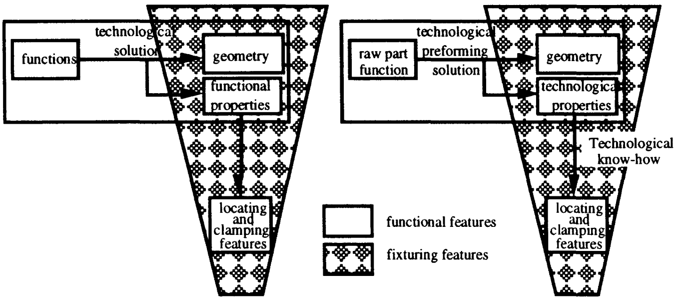


Figure 3. Functional feature and fixturing feature models

2.4. TECHNOLOGICAL FEATURES

A technological feature (Bernard, 1989) is a set of lines and/or surfaces which are the basic elements of caracteristic shapes (morphologies) of the raw parts and the dies. This set of shapes can be associated with the same design rules and the same die machining sequences (Bernard, 1993). The geometry of technological features depends on the choice of the die line, on the rules of dressing of the shapes of the final part, on rounds and draft angle values. Blending features are added to this set of basic features in order to complete the body of the part (rib between two boss shapes), with respect to strength, esthetic, width, mass, etc... (Mawussi, 1995) (Mawussi *et al.*, 1995). Figure 4 shows the links between the functional feature model and the technological feature model for the raw part and its dies. The link with machining features has been demonstrated (Mony *et al.*, 1991) and will be illustrated by the case study (hub of a car wheel).

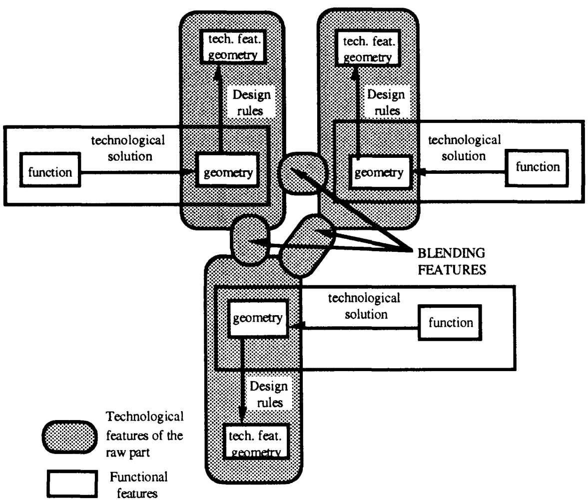


Figure 4. Raw part model based on technological feature model

After the design of raw parts and dies, it is necessary to rapidly generate reliable information related to the manufacturing of the dies and the machining of the parts. In the following, we will present two automatic process planning generators, the first one dedicated to die manufacturing, the second one for the choice of the fixturing systems and the generation of the machining operations of the part.

3. Integration of automatic process planning in die manufacturing using technological features

The main objectives of manufacturing preparation are the processing of the definition data in order to generate the process plan on the one hand and the computation of tools paths and cutting conditions in relation to the definition data and the generated process plan on the other hand. The data associated with the manufacturing resources (machine, cutting-tools, ...) are also taken into account during this preparation phase. The method we propose for generating a machining process groups four tasks which allow us to elaborate a process plan with a specific structure (Mawussi, 1995) based on the definition data and machining knowledge. According to this method, the machining process is split into several machining states generated at the beginning of the processing. Each of the states defines the features linked to the machining sequence. After the characteristics of all the states and machining sequences have been specified, the machining process is created based on the previously obtained data. Thus the process plan results from the planning of machining sequences. In the roughing stage, we aim at the construction of cavities representing pockets which requires either a simple roughing sequence or a combined roughing and semi-finishing sequence. In order to prepare the finishing stage, we define the associations of complex features and determine the characteristics of meta-primitives or complex features (Mawussi *et al.*, 1995) which require a finishing by form machining. In any case, the machining states are liable to the existence and the choice of cutting tools through the specification of machining sequences and states. In a generative CAPP (Computer Aided Process Planning) approach, in opposition to the variant approach (Elmaraghi, 1993), the determination of the intermediary states of a part generally corresponds to a backward generation of states, which consists in defining the intermediary states from initial state (raw form) to final state (design or definition model), or to a forward generation which is obtained by the inverted procedure (Villeneuve, 1990). Our method is a semi-forward approach whose general architecture is given in Figure 5.

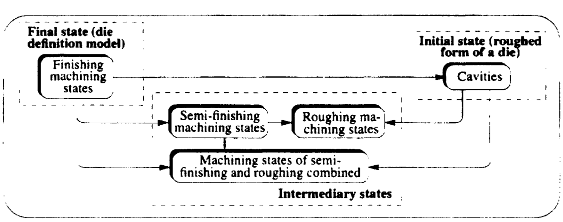


Figure 5. General architecture of the semi-forward generation of machining states

Our semi-forward approach allows us on the one hand to generate the finishing and semi-finishing states from the definition model of the die in a recursive and forward way.

On the other hand, the cavities and their roughing states are defined from the raw form of the die. This approach avoids problems of manifold intersections between complex features and of non-parallel evolution of the geometric shapes, mainly during the roughing stage. The model of the intermediary states is defined by the machining thickness S and the cutting height H. The determination of these two parameters and the specification of the states are also carried out in a recursive way based on the expressions given in Figure 6 where δ_{i+1} is a parameter related to the material, H_Tool_{i+1} represents the real cutting height of the tool, other than the theoretical height given by the manufacturer, and λ_{i+1} is a factor defining the operating conditions of the cutting tool. The values of δ_{i+1}, H_Tool_{i+1} and λ_{i+1} are specific to the machining sequence which switches from the $E_{k,i}$ state of a set of complex features to the $E_{k,i+1}$ state.

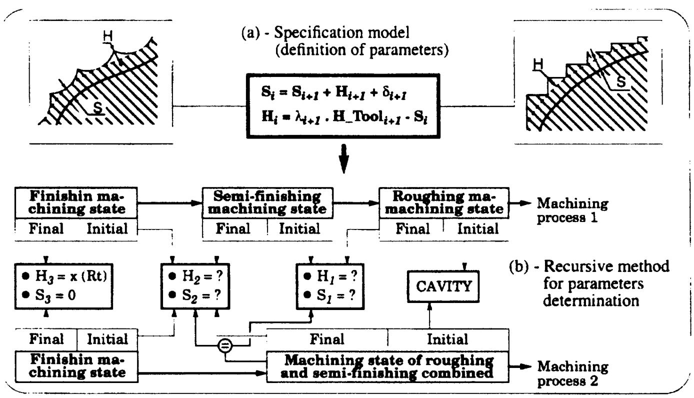


Figure 6. Recursive determination of intermediary machining states.

4. A part process planning solver based upon machining and fixturing features

The process planning problem is a problem of planning : as far as the description of the part and the description of manufacturing facilities is considered, it is a matter of determining a sequence of actions and recommending adapted manufacturing resources (machine-tool, fixturing, tool) for every action in order to achieve a machined part from a raw part. The OCP planning (Opportunist Combining of Plans) (Tsang, 1987) is based on the process plan model and on a description of the part by means of machining features in order to work in two steps : a generation of the association « machining feature - machining process » and a generation of the complete process of the whole part (Brissaud *et al.*, 1989). Before starting the OCP planning, fixturing features of the whole part are determined. The system builds up the set of the fixturing resources available for the machining of the features. In the first step, called the initialisation stage, the part is considered as a set of independent machining features. The system builds a part of the process plan (a machining process) for every feature by using a first knowledge base, the initialisation base. The set of all those parts of the process plan represents the initial process plan of the part : it is an implicit set of all possible process plans of the part. In a second step, the constraint stage, the system modifies the general process plan in order to take into account the interactions between the features (geometrical, topological and tolerancing relations).

The global approach is based on two distinct structures (Figure 7) : a model of the current process plan and a history of the elaborated process plan storing the applied constraints and their consequences. The initialisation step (loop 1 : initialisation of the structure of the process plan) then the constraint step (loop 2 : choice of the constraint to apply and its application) are executed refering to the compromise module if necessary.

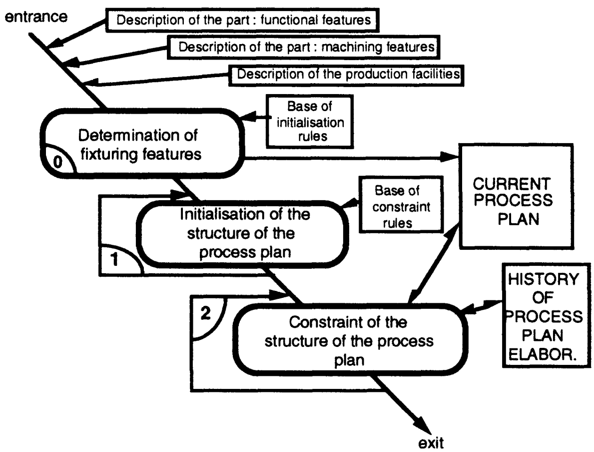


Figure 7. General algorithm for PROPEL working

The determination of the part fixturing features consists in building the set of all the potential fixturing features of the part. A fixturing feature can be created either from the geometry of the raw part or from the geometry of an intermediate geometrical state of the part corresponding to its geometry at the end of a machining setup. Those geometries are extracted from the sets of functional features and machining features. In the case of a forged part, machining features are generally scattered and both the rough geometry and the intermediate geometry are approximatively known with an over-thickness added to the final part geometry.

5. The case study : hub of a car wheel

The case study is related to the manufacturing of a critical part of a car : a hub of a car wheel. This component contributes to different functions :

- centring of the axis of the wheel

- interface between the body of the car and the road through the MacPherson springing system (shock absorber, bottom triangle)

- interface between the wheel and the direction system (steering knuckle)

- interface between the wheel and the brake system (stirrup of disc brake).

The functional features of the hub are defined in order to satisfy the functions through the technological solutions (Figure 8). The results which will be presented are related to part n°1. We will summarize the process planning generation of the die used for the final forging operation, and the process planning and data generation for the machining of the raw parts (fixturing, machining operations, global process planning).

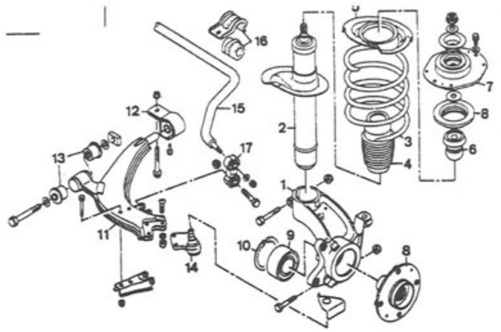
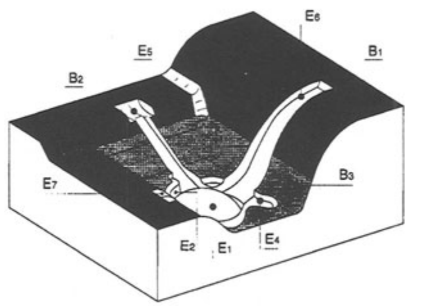


Figure 8. Split view of a shock absorber of a car

5.1. PROCESS PLANNING FOR THE MANUFACTURING OF THE DIE



Die model

E_1, E_2 ---> Rotational surface
E_3, E_4 ---> Twisted surface
E_5, E_6, E_7, B_3 ---> Transition surface
B_1, B_2 ---> Drawable surface
(E_3 does not appear in the figure)

Parting surface ---> B_1, B_2, B_3
Die cavity ---> E_1, E_2, E_3, E_4, E_5, E_6, E_7

Process plan

1.1 B_1, B_2, B_3	1.6 E_6	3.1 B_1, B_2, B_3
1.2 E_4	1.7 E_7	3.2 E_1, E_2, E_4, E_3, E_5
1.3 E_1, E_2	2.1 B_1, B_2, B_3	3.3 E_6
1.4 E_3	2.2 E_1, E_2, E_4	3.4 E_7
1.5 E_5		

1.i ---> Roughing states and sequences
2.i ---> Semi-finishing states and sequences
3.i ---> Finishing states and sequences

Figure 9. Scheduling of operations for die machining

5.2. PROCESS PLANNING FOR THE MANUFACTURING OF THE PARTS

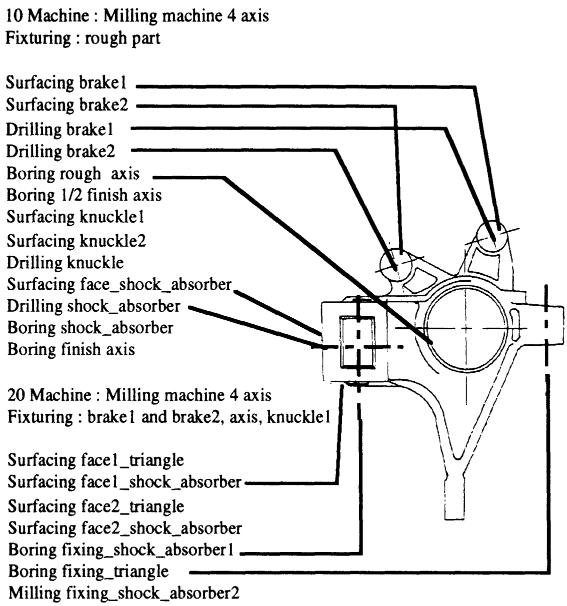


Figure 10. Process planning of the raw part

6. Conclusion

This paper gives, in an integrated product modelling approach, some elements for the concurrent process planning generation of the raw parts and their dies. The software environments used for the experiments are based on a coherent representation of the geometrical, functional and technological data. We think that it will be possible, in a near future, to control the global consistency of the models during the design-production of the new part. This appears to be essential for re-engineering objectives. We are also working on the complete integration of the global design-production process.

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Chapter 3
AUTOMATIC MODELLING WITH FINITE ELEMENTS

TOOLS FOR OPTIMAL OR NEAR-OPTIMAL SENSOR LOCATION

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1. Introduction

A satisfactoring prediction of the dynamic behavior of complex structures such as machine-tools needs representative models. These models, which are often finite element modelings, have to be improved by means of experimental data. The improvement consists in correcting estimated mass, stiffness and damping parameters using the results of dynamical testing. This updating problem is mathematically ill-posed as soon as the modal characteristics are incomplete. Generally, instabilities, i.e. great variations of structural variables, appear for small variations of the observed measures (for example, the measured components of eigenmodes). Then, the key-point is to restore the missing relevant information.

We here examine the optimal positioning of sensors in order to complete the measures at best, for example, the displacements, or to restore the unmeasured information at best (stress fields, strain energy,...). The problem of sensor location is a commonplace problem for control engineers and the typical questions it induces are : How many sensors and actuators to use to implement the control action ? Where to position the sensors ? Here we are interested in the mechanical point of view and the purpose will be to chose optimal locations to obtain an efficient updating.

We consider methods which associate both the objectives fixed by the control engineers with the final purpose expressed by the mechanical engineers and propose common tools, which in our case, can be specialized to treat updating problems. Approaches based on the maximization of the observability degree proposed by the authors in [1] are described and discussed considering other existing methods based on the effective independance proposed by Kammer [2] or based on the minimization of the condition number of the modal reduced matrix proposed by Lallement [3]. The following questions must be answered: What is this pertinent datum? How to reconstruct it? Where to locate sensors?

2. The Effective Independance Approach

2.1. DISPLACEMENT OR KINEMATICAL ENERGY POINT OF VIEW

A common strategy is to remove all coordinates that are of little signifiance with regard to the kinematical energy contribution related to the zones having small

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displacements. This approach is chosen by Kammer [2] who selects a first set of sensors. Afterwards Kammer uses an iterative procedure to select measurement locations which make the mode shapes of interest as linearly independent as possible. The displacement "x" is described with the target modes $x=[\varphi]\ q$. Considering the measures only, the estimate of the target modal coordinates q is found in a least-squares sense $\hat{q} = \left[[\varphi]^T[\varphi]\right]^{-1}[\varphi]^T x$. The, so-called "effective independence", procedure introduces white gaussian noise equally distributed on each sensor, and also obtains a Fisher information matrix proportional to $[A_0]=[\varphi]^T[\varphi]$ where $[\varphi]$ is the reduced modal matrix. The dimension of $[\varphi]$ is (s, k) where k is the number of modes of interest and s is the number of currently selected degrees of freedom. A matrix $[E] = [\varphi]\left[[\varphi]^T[\varphi]\right]^{-1}[\varphi]^T$ is formed, the terms on the diagonal represent the fractional contribution of each measurement location to the rank of E, and hence to the independence of the considered modes. The degree of freedom that contributes least to the independence is associated with the smallest fractional contribution and has to be removed.

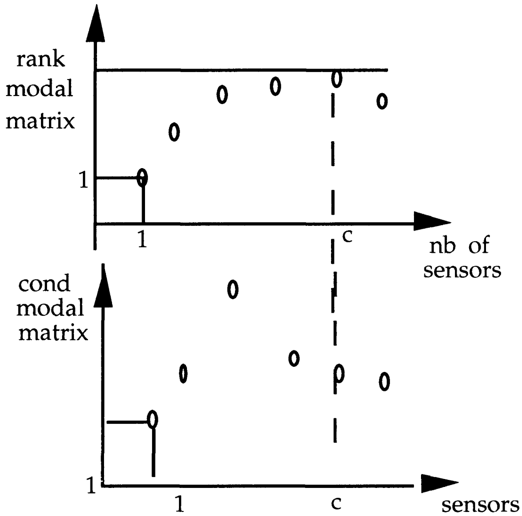
2.2. STRAIN ENERGY POINT OF VIEW

To update a given modeling, stiffness, damping and mass errors have to be "visible"; the stiffnesses of a sub-structure cannot be detected, if this sub-structure is not submitted to any strain energy. Then, it will be more efficient to restore the strain energy distribution. Hemez in [4] proposes to extend Kammer's procedure by defining an "information matrix" $[A_0]=[\varphi]^T[K]\,[\varphi]$ where K is the stiffness matrix associated to the finite element model. The solution procedure is similar to the one proposed by Kammer. Using Cholevski's factorisation of K, $[K] = [L]\,[L]^T$, the matrix $[A_0]$ can be written as $[A_0]=[G]^T[G]$ with $[G]=[L]^T[\varphi]$. The fractional contributions are computed from $[E] = [G][A_0]^{-1}[G]$.

3. Condition number and Rank of the Reduced Modal Matrix

Let $[\varphi]$ be the modal matrix associated with the finite element model where the mode number has been reduced to η: $[\varphi]=\begin{bmatrix} \varphi_{11} & \cdot & \cdot & \cdot & \varphi_{1\eta} \\ \varphi_{21} & \cdot & \cdot & \cdot & \varphi_{2\eta} \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \varphi_{N1} & & & & \varphi_{N\eta} \end{bmatrix}$ N is the number of degrees of freedom.

The problem here is to rebuild the modes. The near-optimum number of sensors comes from the graphs describing the rank and condition number function of the number of selected degrees of freedom; the optimum number of degrees of freedom corresponds to the condition number minimum and the rank maimum.
The initialization procedure computes the norm of the vector associated with each degree of fredom i $\varphi_{i1}\, \varphi_{i2}\, \varphi_{i3}\, \dots\, \varphi_{i\eta}$. All degrees of freedom with a vector norm less than 40% of the computed maximum are removed. In the next step, all the sub-matrices $(2 \times \eta)$ are constructed, the first line is related to the degree of freedom having the maximum norm. The second one belongs to the non-removed degrees of freedom. For each sub-matrix, the condition number and the rank are computed. The second selected sensor will be the one allowing a maximum rank and a minimum condition number.



4. Optimal Locations Based on the Observability Degree

4.1. DISPLACEMENT POINT OF VIEW

The approach is based on the maximization of the observability degree. Several methods [5] have been already proposed based on the notion of observability. The idea given in [6] by De Pieri et al. is to maximise a measure associated to the observability gramian. From this idea, we construct a new approach, first with the norm of displacement $\|x\|^2 = E = \int_0^\infty x(t)^T\, x(t)\, dt$ and then using the strain energy norm

$$\|x\|_K^2 = E_k = \int_0^\infty x(t)^T K\, x(t)\, dt .$$

A finite element model is characterized by $[m]$ the symmetric positive mass matrix, $[k]$ the symmetric positive stiffness matrix, $[c]$ the damping matrix

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=\{f\} \qquad (1)$$

$\{x\}$ is the displacement and, $\{f\}$ is the vector of external forces.

Classically (1) can be rewritten under the state form $\begin{matrix}\{\dot{Z}\}=[A]\{Z\}+[B]\{U\} \\ \{x\}=[C]\{Z\}\end{matrix}$

The frequency range is the low frequency range. We do not discuss here the reduction of the mode number. After the reduction procedure, only η modes are used to describe the response of the structure and A becomes $A=\begin{bmatrix} O & I \\ \psi & \Sigma \end{bmatrix}$. Its dimension is $2\eta \times 2\eta$.

I is the unit matrix, its dimension is ($\eta \times \eta$), O is the Zero matrix, its dimension is ($\eta \times \eta$)

$$\psi = \begin{bmatrix} -\omega_1^2 & & & \\ & -\omega_2^2 & & \\ & & \cdot & \\ & & & -\omega_\eta^2 . \end{bmatrix} \qquad \Sigma = \begin{bmatrix} -2\,\xi\,\omega_1 & & & \\ & -2\,\xi\,\omega_2 & & \\ & & \cdot & \\ & & & .-2\,\xi\,\omega\eta \end{bmatrix}$$

$B=\begin{bmatrix} O \\ [\varphi]^T \end{bmatrix}$ dimension ($2\eta \times N$) and $C=[[\varphi] \quad O]$ dimension ($N \times 2\eta$)

$[\varphi]=[\{\varphi\}_1 \quad \{\varphi\}_2 \quad . \quad . \quad \{\varphi\}_\eta]$ is the modal matrix where $\{\varphi\}_i=[\varphi_{1i} \quad \varphi_{2i} \quad . \quad . \quad \varphi_{Ni}]^T$. $\{U\}=\{f\}$

The matrices (A, B, C) define an observable system if the matrix of the observability gramian

$$W_o=\int_0^\infty e^{A^T t}\, C^T C\, e^{At}\, dt \text{ is positive definite.}$$

The purpose becomes the positioning of the sensors on the domain D(Ω) representing the structure for maximizing a measure related to C : $\begin{cases} \max \sigma\{C(p)\} \\ p \in D(\Omega) \end{cases}$

To each state of the system we associate an observability degree considering the eigenvalues of $W_O(p) = \int_0^\infty e^{A^T t}\, C(p)^T C(p)\, e^{At}\, dt$

Let be $\sigma_{0i} = \lambda_i\{W_o(p)\}$, i=1, 2, ..., 2η $\lambda_i = \lambda min$ characterizes the least observable state. To position the sensors on a finite element model, to each degree of freedomwe associate a variable π_j such that

$\pi_j = 1$ if one sensor is positioned in p_j, and $\pi_j = 0$ if no sensor is positioned. Then each degree of freedom can receive one sensor.

The problem is now rewritten as follows: $\left\{ \begin{matrix} \max \underline{\sigma}(\pi) \\ \pi \in \phi_\pi \end{matrix} \right\}$ where the non-convex domain ϕ_π is defined by : $\phi_\pi = \left\{ \pi \in R^N ; \pi_j \in \{0,1\} ; \sum_{j=1}^{N} \pi_j \le r \right\}$ and r : is the total number of sensors. For a set of locations π, the $W_o(p)$ matrix is given by :

$$W_0(\pi) = \int_0^\infty e^{A^T t} C(\pi)^T C(\pi) e^{At} \, dt .$$

The smallest eigenvalue of $W_o(\pi)$ is related to the least observable state and $\underline{\sigma_0}(\pi) = \lambda_{min}\{W_o(\pi)\}$. The problem is then to position the sensors for maximizing this eigenvalue.

4.2. THE STRAIN ENERGY POINT OF VIEW

Instead of using $E = \int_0^\infty x(t)^T x(t) \, dt$, we now consider the "strain energy" response $E_k = \int_0^\infty x(t)^T K \, x(t) \, dt$. Cholesky's decomposition of the stiffness matrix $[K] = [L] \, [L]^T$ enables us to use an approach similar as the previous one with $W'_O(\pi) = \int_0^\infty e^{A^T t} \, C'(\pi)^T C'(\pi) \, e^{At} \, dt$ where $C' = L^t C$.

The numerical implementation of the optimization problem we have to solve so as to find π_j, uses an approach proposed by Geromel in [7] based on the sub-gradient techniques.

5. Validation of the Approach based on the Observability

A simple supported beam is discretized into 100 finite beam elements (200 degrees of freedom).Its total length is 1 m, Section area = $1m^2$, volumic mass=$1Kg/m^3$, Young's modulus is E =1

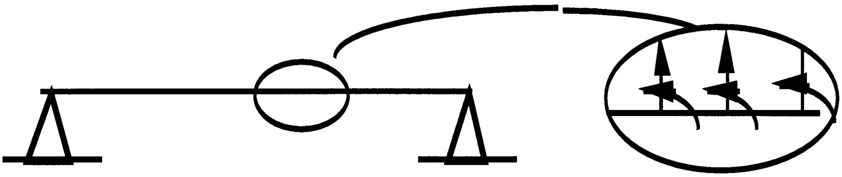


Figure 1 : Simple supported beam discretized into finite beam elements

Respectively, mass and stiffness matrices are given by

$$M^{e} = \frac{m}{420}\begin{bmatrix} 156 & 22\,L & 54 & -13\,L \\ & 4\,L^{2} & 13\,L & -3\,L^{2} \\ sym & & 156 & -22\,L \\ & & & 4\,L^{2} \end{bmatrix} \qquad K^{e} = \frac{EI}{L^{3}}\begin{bmatrix} 12 & 6L & -12 & 6L \\ & 4L^{2} & -6L & 2L^{2} \\ sym & & 12 & -6L \\ & & & 4L^{2} \end{bmatrix}$$

In theory, one sensor is enough to ensure the observability of this system. For a beam with all the parameters equal to 1, the optimal location is known [8] and given by: $P^* = 1 / 2\eta$ or $P^* = 1 - (1 / 2\eta)$ (taking the symmetry property into account)
For three modes, the following table shows the iterative process. Few iterations are needed to obtain the convergence.

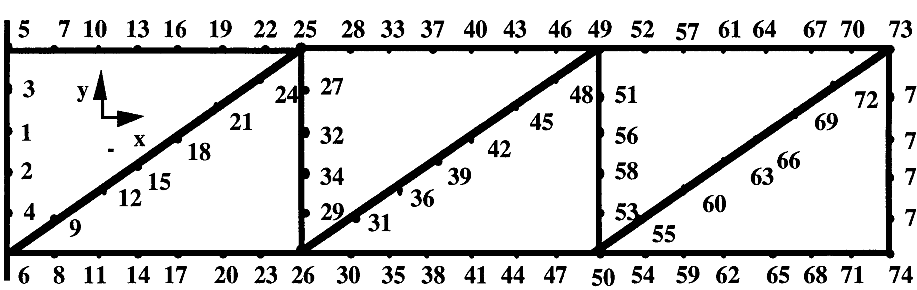
TABLE 1 : optimal location - Modes (1+2+3)

iteration nb	λ_{min}	θ	ddl	position
0	0	1	50.1	0.49
1	7.7636 E-7	1.9691 E-4	76.1	0.75
2	3.8941 E-6	7.7805 E-6	18.1	0.17
3	7.7805 E-6	7.7805 E-6	84.1	0.83
4	7.7805 E-6	7.7805 E-6	84.1	0.83

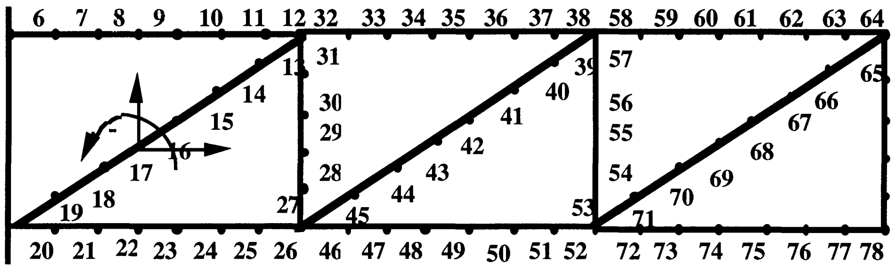
initial position = 0.49, optimal = 0.83. ("50.1" means Node number 50, dof 1)

6. Near-optimal sensor location : Results

All results obtained by the different methods will be described for one given example : the test-structure (figure 2). It is a plane clamped-free truss-system proposed by the Group for Aeronautical Research and Technology in EURope [9] used as benchmark for updating procedures.



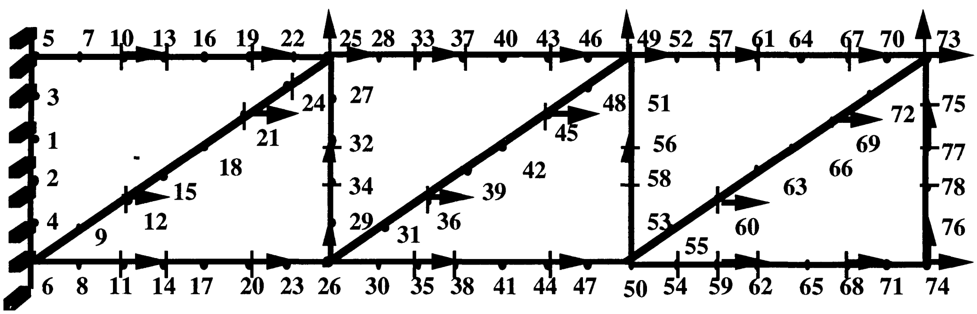
a) node number



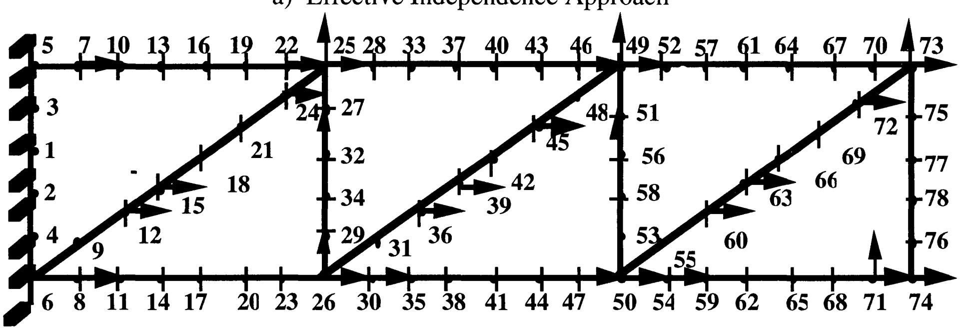
b) element number

Figure 2 : Plane structure discretized into finite beam-bar elements

For example, we here show the result of the method based on the effective independence for 30 target modes. 70 d.o.f. was first selected.

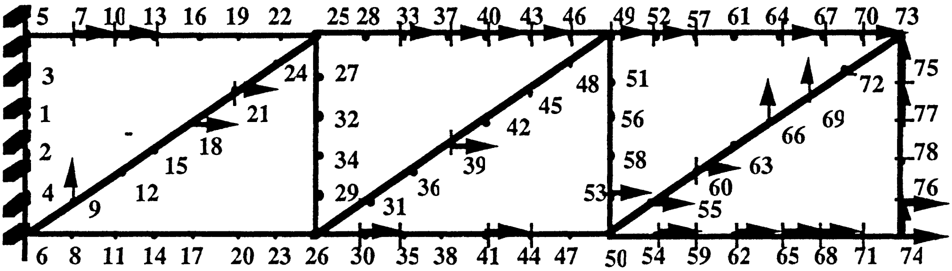


a) Effective Independence Approach



b) Associated Strain Energy Approach

Figure 3: Results of the Location of Sensors (Eff-Ind)



Approach based on the observability gramian

Figure 3: Results of the Location of Sensors (OBS)

7. Sensor Location for Updating Problems

To illustrate the different methods, we finally propose an updating problem. The measured data are simulated by perturbing the geometrical parameters, and the modal parameters are recomputed with a finite element program.

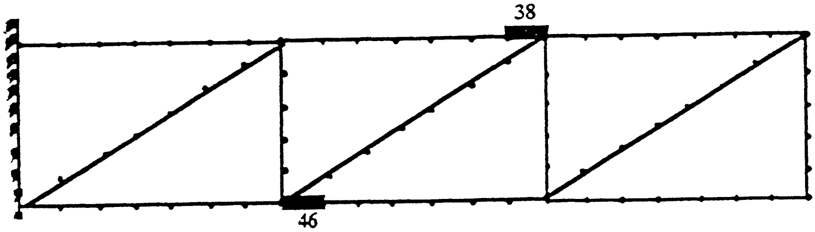
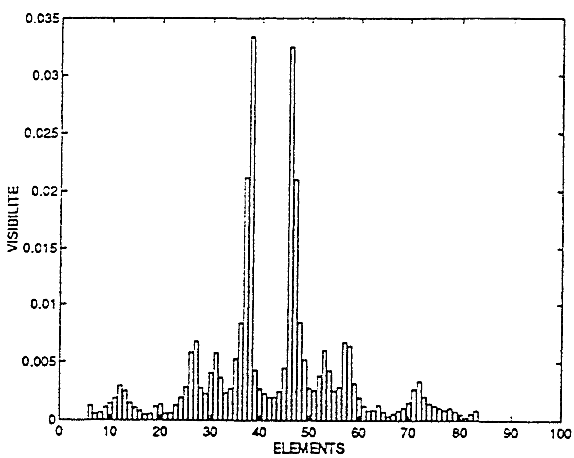
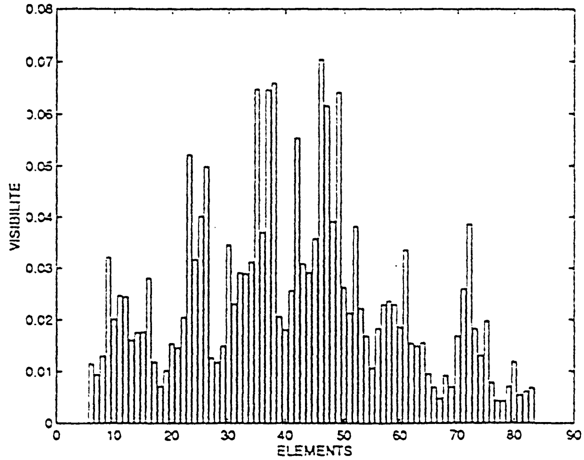


Figure 4 : Simulated Modeling Errors

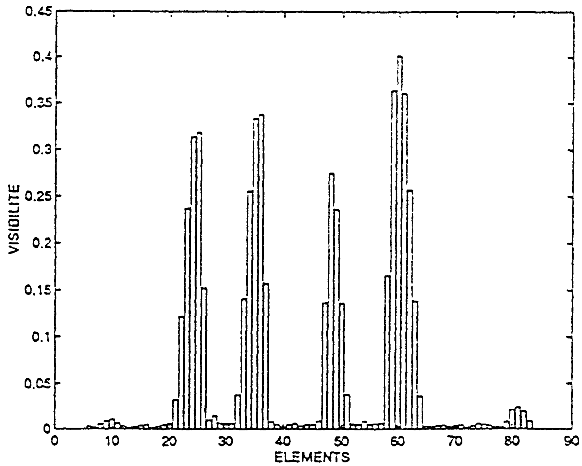
Examples show the different capacities of the described methods to detect or not the modellings errors. The updating procedure here used, is the one proposed by Ladevèze, Reynier [10]. Five modes are assumed to be measured.



a) all degrees of freedom are supposed to be measured- 216 sensors.



b) Effective Independence Approach - 30 sensors



c) Associated Strain Energy Method

Figure 5 : Detection of modeling errors

Conclusion

The described methods allow to obtain a significant reduction of the number of sensors, the location of modeling errors staying satisfactoring. All these approaches constitute efficient tools, because they complete experimental information with an optimum relevant procedure. Considering updating problems, if the modelings errors are well visible, all the previous methods appear to be efficient. If we are interested in the detection of errors having a small vsibility, the methods based on the strain energy appear to be better-suited to our purpose.

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FULLY INTEGRATED FINITE ELEMENT MODELS IN THE DESIGN AND MANUFACTURE OF GLASS PRODUCTS

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Abstract. Finite element models are developed for the design and the manufacture of flat glass products, by pressing and creep forming, and hollow glass products, by press-and-blow and centrifuging. These models take into account Newtonian glass flow, the unsteady glass/tool contact conditions during forming and the unsteady temperature, due to conduction with the tools and convection with the ambient air. Their integration in the classical design and manufacture schemes is enforced by their coupling with Computer Aided design and Metrology.

1. Introduction

The glass processing industry is mainly divided into two distinct parts, the production of hollow glass items carried out by combination of pressing, self-weight deformation and blowing or centrifugal casting (e.g. : bottles, beakers, vases, cups...) and the manufacturing of flat glass products, generally obtained by creep forming or pressing operations (e.g. : products for transport and railway vehicles, building decoration...). In the first case, the actual design evolution is essentially governed by the new customer's needs and the new productions with lower production rate, new geometries being necessary in the face of large competition of the plastic industry. In the second case, the designer today would like to integrate glass elements into his future design whose geometries are becoming increasingly unconventional. In all cases, the manufacturer has to obtain a better control and knowledge of his production means, and his limits to respond quickly to the specifications of the designer. Moreover, to reduce the production costs, it is no longer possible to proceed by trial and error and wait for the results of successive adjustments using a primitive experimental tool.
Research activities on glass forming are concerned with three domains : the first experi-

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mental one is the identification of the mechanical glass properties in the [500°C, 1400°C] ; the glass generally presents a Newtonian flow with a thermodependent viscosity mainly described by Fulcher's model (Fulcher,1925). For thermal aspects, some experiments permitted to measure the heat exchanges which are a function of the glass temperature and the contact surface properties (Fellows *and al*, 1978). For the se-cond numerical domain, finite elements have first been used for thermal computations and then, for the analysis of hollow glass forming by pressing and blowing, using both coupled (Rekhson *and al*, 1992) and un-coupled thermomechanical formulations (Anderson *and al*, 1992). Thirdly, the last domain is interesting in the integration of C.A.D. (Computer Aided Design) (Wallis, 1986) and C.A.M. (Computer Aided Manufacture) (Manchester *and al*, 1987] in glass product manufacture, leading to a reduction in design time in the forming tools and more precise manufacturing. Some solutions involving coupling C.A.D with Finite Element computations have been carried out for the design of moulds for blowing (Hernandez *and al*, 1988), between C.A.M. and Metrology for the design of perfume bottles (Basset, 1987).
In this context, we propose to develop and completly integrate finite element mo-dels in the design and manufacturing schemes of hollow and flat glass products, by cou-pling them to C.A.D. and Metrology and defining adapted strategies to use them. In this paper, reference forming situations are numerically analyzed using our developments, in flat and hollow glass product manufacture.

2. Standard data for the glass forming analyses

2.1. HOLLOW GLASS FORMING PROCESS

Pressing, self-deformation and blowing are the three principal forming processes to produce axisymmetric hollow glass items; for some products, these three processes are successively linked to obtain the final desired glass item. Indeed, during the first step of pressing, the beaker is only preformed: the glass drop is placed in the first mould, and a punch presses it to form a parison with a height of up to 70 % of the final beaker height. During the next step, the parison is introduced to the second mould corresponding to the final beaker form. During the following second forming, the parison becomes longer due to self-weight action until it nearly reaches the base of the mould. Then, at the third blowing step, an internal pressure is applied on the inner beaker side; it ends when the beaker is entirely shaped (i.e., when it has the same shape of the mould). The previous forming processes are the best ones adapted to bottle and other container manufacture. Concerning thin-walled glass items, centrifugal casting is a fast and a minimum energy consuming process with regard to traditional pressing. This original rotating technique is achieved with the mould rotating around its axis, a little after the parison has been dropped on it, to reach the final geometry under its self-weight and centrifugal for-ces. Contrary to traditional pressing, this process requires a maximum level of practical knowledge because manufacturers do not have a direct control on the product thickness and on the shape during the forming. For particular glass item centrifugal manufacture, a distribution finger is used to drive the glass into the desired direction (i.e.

along the mould) in order to obtain the design thickness distribution. At the end of the forming operations, the glass manufacturer is concerned with respecting the geometry constraints according to design specifications and supplying a good glass thickness repartition along the internal mould partition.

2.2. FLAT GLASS FORMING PROCESS

The two basis deformation modes used in the flat glass industry are creep forming and pressing. In the first case, the sheet of glass is placed on a stainless steel skeleton at the furnace exit ; under its own weight, the sheet bends until geometrically deformed as instructed by the designer before toughening. In the second case, the sheet of glass is first placed on the skeleton for horizontal pressing, or held by tongs during the whole process for vertical pressing. Then, it goes out of shape under its own weight for a few seconds before being pressed between skeleton and press covered with abestos and glass fibre. Finally, a second process of creep forming is achieved again before toughening. The success of the processes depends how much the design of the glass sheet geometry is respected, in terms of deformed sheet contour line and slope evolution along this contour line.

2.3. GLASS FLOW NUMERICAL MODELLING

Our studies have been made on NBS 710 soda lime glass (70% silica, 12% calcium and 9% sodium) ; it concerns 90% of the world glass market.
For hollow glass production, the temperature of the glass varies from 1200°C at the beginning of pressing to 700°C at the end of the blowing operation. At this temperature level, experiments showed that the contact remains sticky.
In flat glass production, the sheet is heated in the 600°C - 680°C range in order to obtain a quasi-homogeneous temperature at the furnace exit. This range is ideal for creep forming and press bending because the contact between the glass and tools is sliding, as experimentally observed below 680°C.
The bulk glass behaviour is, in the temperature range [600°C,1000°C], modelled by the Newtonian isochoric viscoplastic law given by

$$\sigma = 3\,\eta(\theta)\,\dot{\varepsilon} \tag{1}$$

σ is the equivalent stress, $\dot{\varepsilon}$ the equivalent strain rate and η the soda lime silica glass viscosity, which is dependent on temperature θ ; NBS 710 is described by the Fulcher model (with η in $N.mm^{-2}$ and θ in celsius).

$$\text{Log}\,\eta(\theta) = -9.3 + \frac{4630}{(\theta - 247)} \tag{2}$$

The other NBS 710 characteristics are density : 2.5 10^{-6} $kg.mm^{-3}$, Young's modulus: 20000 $N.mm^{-2}$, considered constant in this temperature range, and Poisson's ratio :

0.22. For hollow glass, the neglegible elastic part in the total deformation is not considered in the finite element models ; elastic properties are only introduced into the numerical simulations of flat glass forming.

3. Hollow glass items

3.1. MECHANICAL FORMULATIONS

For the mechanical problem, our developments concern the formulation of the total energy function of the deformed glass body with a new three-field mixed approach, leading to a better evaluation of the pressure field and of the stress field in the deformed glass volume (Lochegnies *and al*, 1989) :

$$G(v,e,p) = \int_V W(d)\, dV + \int_V p\,(tr\,D - e)\, dV - \int_{St} t.v\, dS \tag{3}$$

V is the glass deformed volume, Sv the part of the glass surface where the velocities are prescribed, St the part where the load density t is prescribed, W is the Newtonian visco-plastic potential, D is the strain rate tensor with its deviatoric part d, e is the dilatancy, p is the pressure field. For the deformed glass equilibrium, the velocity solution v which minimizes the functional G(3) is found, using the Newton scheme:

$$\left[D_V^2\, G(v,e,p) \right]^{i-1} \Delta v^{i} = -\left[D_V\, G(v,e,p) \right]^{i-1} \tag{4}$$

with Dv and D^2v being the first and second derivatives of G in regard to v.
The unsteady contact non-linearities are treated by penalisation functions for the glass /mould and glass/punch contact conditions ; with specific contact algoirthms, these are automatically reactualized in the iterative Newton-Raphson scheme (Lochegnies *and al*, 1995). Remeshing and interpolation procedures are also called upon if the elements of the mesh become too distorted (Matthieu *and al*, 1990).

3.2. THERMAL ASPECTS

During the forming of axisymmetric glass products, contacts between the glass and the mould are very unsteady and the temperature evolution inside the glass can then affect the workability of the glass ; so, for numerical simulations, the thermal evolution in the glass has to be computed.
During manufacture, the temperature of the glass is influenced by the process time and the thermal boundary conditions: - free convection with the ambient air, which is more sensitive during blowing and self-deformation, - heat-transfer between the glass and the metal surfaces, essentially during pressing and at the blowing end.

In order to reduce the data input and the computation time, our approach is only to compute the thermal evolution in the thickness of the glass ; considering mono-dimensional analytical solutions in convection, the temperature is given as a function of the distance x from the surface, the temperature of the ambient air, the exchange duration t, the initial temperature (corresponding to t=0), the heat-transfer coefficient with the ambient air, the glass density, specific heat and conductivity. For the heat-transfer between the glass and the tools related to conduction and radiation exchanges, the same previous convection solution is considered, now using a heat-transfer coefficient function of time. In our solution, the temperature of one node of the mesh will be computed in an iterative procedure, taking each mesh surface and its thermal boundary condition into account with the previous analytical solution (Noiret *and al*, 1995). The same procedure is used to actualize the mould temperature.
With an un-coupled thermomechanical formulation, the temperature in the deformed glass is computed at each mechanical increment level using our previous iterative procedure, leading to the evolution of the glass mechanical properties for the following increment (2).

3.3. NUMERICAL ANALYSIS OF PRESSING AND BLOWING OF A TALL CHAMPAGNE GLASS

The three main forming operations are given in Figure 1.

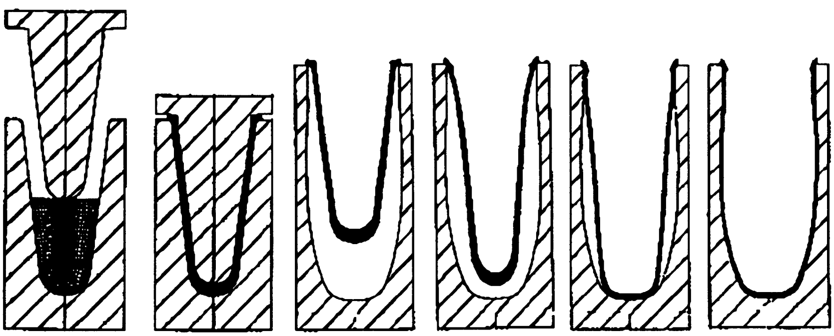

Figure 1 : numerical simulation for the forming of a tall champagne glass

With 352 nodes and 323 elements, the initial glass drop mesh (10^{-3} MPa.s) is deformed by pressing for about 1s. After 5 remeshing steps, the temperature shows significant cooling on the glass surface (from 712°C to 730°C), the heart of the glass remains at 1100°C. During the second step, inside the finishing mould, the 478 node and 362 element mesh does not go out of shape during the first 0.9 s when the temperature becomes homogeneous. When the glass surfaces are hot enough, the parison gets longer under its own weight so that it is at 8mm from the bottom of the mould after 3.5s. Finally, without any remeshing, with 10mbar of inner pressure, the parison reaches the mould after 0.68s and the contact is total after 2s. The temperature varies from 730°C to 950°C on the inner surface, from 580°C on the glass outer surface, a 100°C difference with the mould being noticed.

3.4. NUMERICAL ANALYSIS OF THE CENTRIFUGAL CASTING OF A BOWL

In a first approcah, using the numerical method, we have studied precisely the influence of the process parameters (glass temperature, mould rotation speed, glass/mould contact, forming time) on the forming result, leading to the definition of process design curves (Lochegnies *and al*, 1995). Here, finite element models are used to find the solution to centrifuging: with the initial following parameters (mould rotation : 600 tr/mn, glass temperature: 1080°C, forming duration : 1.74s), the final product (Figure 2) does not meet the design prescriptions (too much glass remains in the bottom of the bowl, the final height is not great important).

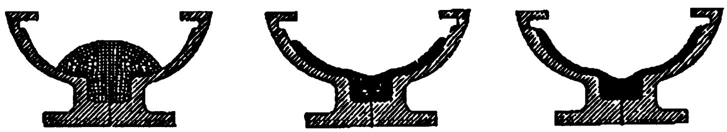

Figure 2 : numerical analysis of the initial centrifugal casting

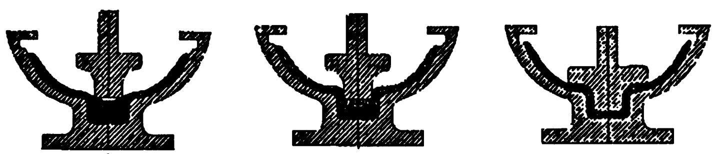

Figure 3 : optimization of the centrifugal casting with numerical method

The optimum solution is numerically found, using a finger distribution acting with a 24mm/s descent speed after 1.45s of centrifuging for 0.55s (Figure 3).

4. Flat glass products

In flat glass production, rather than merely defining finite element models, we have proposed to integrate the numerical simulation tool in the design and manufacture schemes by coupling it with C.A.D. and Metrology.

4.1. BASIC ELEMENTS

The C.A.D. module is based on EUCLID software from MATRA DATAVISION, running on a DEC personal workstation. This module will be used firstly for the generation of the finite element meshes of the sheet and the rigid surfaces of the skeleton, and, secondly, for the analysis of the F.E. (Finite Element) results and experiments with regard to the designer's models. The F.E. models are defined in F.E. module on a Hewlett Packard 700 PA-RISC workstation with ABAQUS software developed by Hibbit, Karlsson and Sorensen, Inc. The 3D Measurements module uses a D.E.A. 3D measuring machine. Experiment data are collected on an IBM PC 486 computer via TUTOR-P software developed by D.E.A. manufacturer.

Two specific interfaces between C.A.D. and F.E. modules and between C.A.D. and 3D M. (3D Metrology) modules are developed for data communications on an Ethernet network.

The C.A.D. - F.E. communication objectives are :

- to transfer mesh and skeleton information resulting from EUCLID into IGES format files in an ABAQUS standard data file.
- conversely, to collect finite element results (node position of deformed mesh of the sheet) from ABAQUS output files and to write them in IGES format files for C.A.D. exploitation via EUCLID software.

For the C.A.D. - 3D M. interface, the objective is merely to collect measurements of the 3D machine with the TUTOR-P software into an IGES format file for exploitation in the C.A.D. module.

Because of C.A.D. and 3D measuring software implementation, C.A.D. - F.E. and C.A.D. - 3D M. interfaces have been developed in C standard language on a Hewlett Packard serie 70 workstation and an IBM PC 486 computer respectively, with the development of the two previous interfaces using standard IGES and C format.

4.2. STRATEGY DESCRIPTION

To succeed in creep forming or pressing, we have developed an original procedure involving the previous inter-connected modules.

The first level of the manufacturer's work is to establish the initial creep forming data base. In the C.A.D. module, using the designer's specifications in Bézier curves, he obtains the initial shape of the sheet by plane projection and skeleton geometry in accordance with the slope evolution along the design contour line. With the EUCLID mesh generation module, he defines the mesh of the sheet with three and four node shell elements and the skeleton with facets built with appropriate nodes of Bézier curves of design C.A.D models. Since the sheet of glass is simply put on the skeleton, no boundary conditions are manually used ; contact is automatically managed by the ABAQUS software routines. The initial creep forming data are finally completed by creep forming parameters (temperature in the sheet at the furnace exit, bulk behaviour of the glass in forming temperature range and forming time).

In order to optimise quickly the manufacturer's choices and thus the creep forming, we develop the second level of analysis strategy based on C.A.D. and F.E. models compared with experimental data. Using previous C.A.D. data on the skeleton geometry and sheet mesh with the C.A.D. - F.E. interface, the finite element analysis is performed under creep forming data (bulk behaviour and forming time). The numerical results are analysed in the C.A.D. module with the help of the C.A.D. - F.E. interface and a comparison with design specifications is obtained. Next, the manufacturer adjusts, via numerical means, the creep forming data base and proceeds to new numerical simulations and C.A.D. comparison to reach the design objectives.

On successful completion, the optimum forming database is used on the production line. Finally, 3D Measurements of the specimen are analysed with the 3D M. - C.A.D. interface and final optimum adjustments are performed on the production line. When finite element analysis has not succeeded in creep forming adjustments, the manufacturer's conclusions are to try another sheet forming process (such as pressing) or to study with the designer possible modifications of the final product (Lochegnies *and al*, 1994).

4.3. OPTIMIZATION OF THE CREEP FORMING OF A REFERENCE REAR-WINDOW

This new strategy has been successfully used for the forming of a reference automobile rear-window, described by the designer through C.A.D. with 14 Bézier' curves (Figure 4).

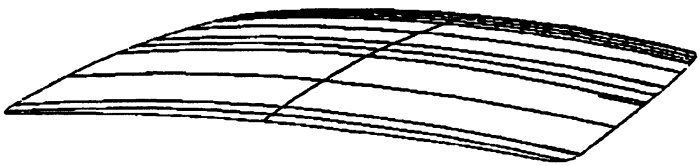

Figure 4 : automobile rear-window in Bézier 'curves.

Our C.A.D.- E.F. - 3D M. strategy has permitted to define the optima values for the creep forming of this sheet, the most significant result being the temperature map at the furnace exit (Figure 5). Taking into account the technological constraints of furnace heating, this map has been determined by different numerical trials and C.A.D. comparisons with the designer's specifications.

The application of the optimized forming databases on the production line has allowed the manufacturer to reach the design objectives : the slope evolution along its contour line is consistent with the design constraints, more than the global geometry of the final product, with less than 5% relative error (Figure 6).

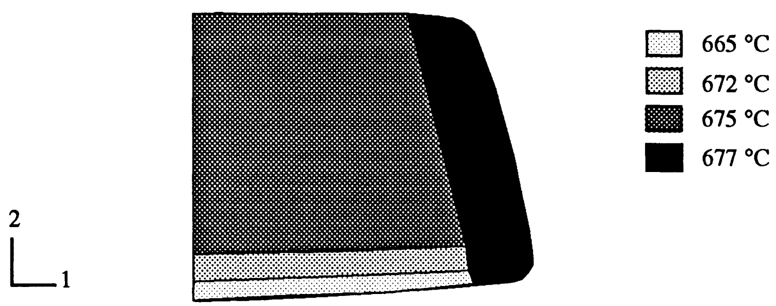

Figure 5 : optimum non-homogeneous temperature distribution in the rear-window.

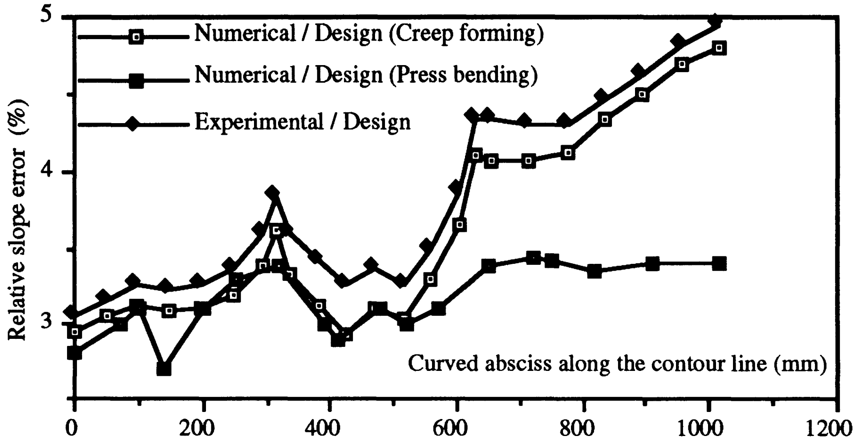

Figure 6 : Relative error on the Computation and Manufacture in regard to the Design specifications.

5. Conclusions

Concerning hollow and flat glass design and manufacture, with

- efficient finite element formulations related to Newtonian glass flow, the glass/tool contact conditions and the conduction and convection heat exchanges between the glass, the tools and the ambient air,
- specific interfaces with C.A.D. and Metrology in IGES standard formats, in order to facilitate the data communications between design, manufacture and quality control,
- and finally adapted strategies to integrate the numerical results into the design and the optimization of the forming processes.

The optimization of the glass production becomes less expensive, with the numerical simulations leading to fewer trials by experiment and a better understanding of current knowledge.

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MAESTRO : A MODULE DEDICATED TO THE INTEGRATION OF STRUCTURAL ANALYSIS WITHIN THE DESIGN PROCESS

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Abstract. The mechanical analysis of parts relies on the use of various solving methods, i. e. : strength of materials, finite elements, etc. and different types of analysis (static, dynamic, thermal, etc.) can be employed during the design process of a single part. An environment, independent of the analysis method used, capable of describing the various types of analysis a part may be submitted to, is described below. The software environment designed aims at allowing a better integration of the structural analysis phase within a product design process. The approach presented here remains compatible with CAD environments of various characteristics as well as different finite element softwares. The developments carried out are based on the use of an object oriented language.

1. Introduction

During the design process of a part, the study of its mechanical behaviour calls for a structural analysis process at various phases. Strength of Materials (SMA) is more often used during the preliminary steps of the product design rather than the Finite Element Method (FEM) which occurs at the stage of the validation of the part dimensions.

In the course of these design phases, the geometric definition of the product may change and does not necessarily coincide with the representation required for manufacturing, assembly or aesthetics.

Currently, there is no available model dedicated to the design of a product within a computer-aided environment, i.e. : an environment that may be used by each actor of the design process. Therefore, the approach proposed here deals with the definition of a module which is dedicated to the implementation of structural analysis and which allows each actor that participates in the dimensioning phases of the product to perform mechanical analyses.

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Through such a module, this work aims at identifying and at structuring the data used during the dimensioning phases of a design process in order to capture their nature and organisation. Effectively, these aspects contribute to a better definition of the architecture of an integrated design system.

The main approaches actually proposed and dedicated to a structural analysis phase may be grouped according to the following categories :

• introduction of attributes and boundary conditions editors for approaches based on finite elements [4], [6],

• development of functions and tools dedicated to an easier transfer of data from a geometric representation of the product to the effective finite elements analysis environments [1], [4], [12],

• introduction of artificial intelligence techniques to represent and manipulate the specific knowledge attached to the mechanical analysis of a structure [2], [12].

Compared to these approaches, the current one which is described here allows the MAESTRO module to :

• provide help to each actor independently of the analysis method (e.g. SMA, FEM, etc.) used to determine the mechanical problem solution,

• organise all the data manipulated in accordance with a structured approach ; during the design process, this one ensures the maintenance of the coherence between information specific to the product and mechanical information which is necessary to the structural analysis of the product,

• organise the specific data and the treatments involved in the idealisation phase of the geometric representation of the product,

• organise all data such that the distinction between the mechanical and the geometric data is preserved. This particular data structure is particularly dedicated to the distributed architecture of the software environment of an integrated design system.

2. Basic Concepts of the MAESTRO Module

After the specification of data that are manipulated during the mechanical analysis phases, mechanical entities are identified and organised to form an " analysis model " [10] that clusters all the analysis data.

The origin of the approach presented here results from the conclusions which state the existence of efficient data structures dedicated to the mechanical analysis phases [11], [9]. These data structures participate directly in the creation of the analysis model which is independent of the solving method employed afterwards. After the specification of such data structures, the concept of a " mechanical analysis module ", called MAESTRO, relying on a mechanical analysis data model which binds those data structures can be introduced.

2.1. GENERIC DATA STRUCTURES

The entities that constitute an analysis model of a product are described below and represented on figure 1 :

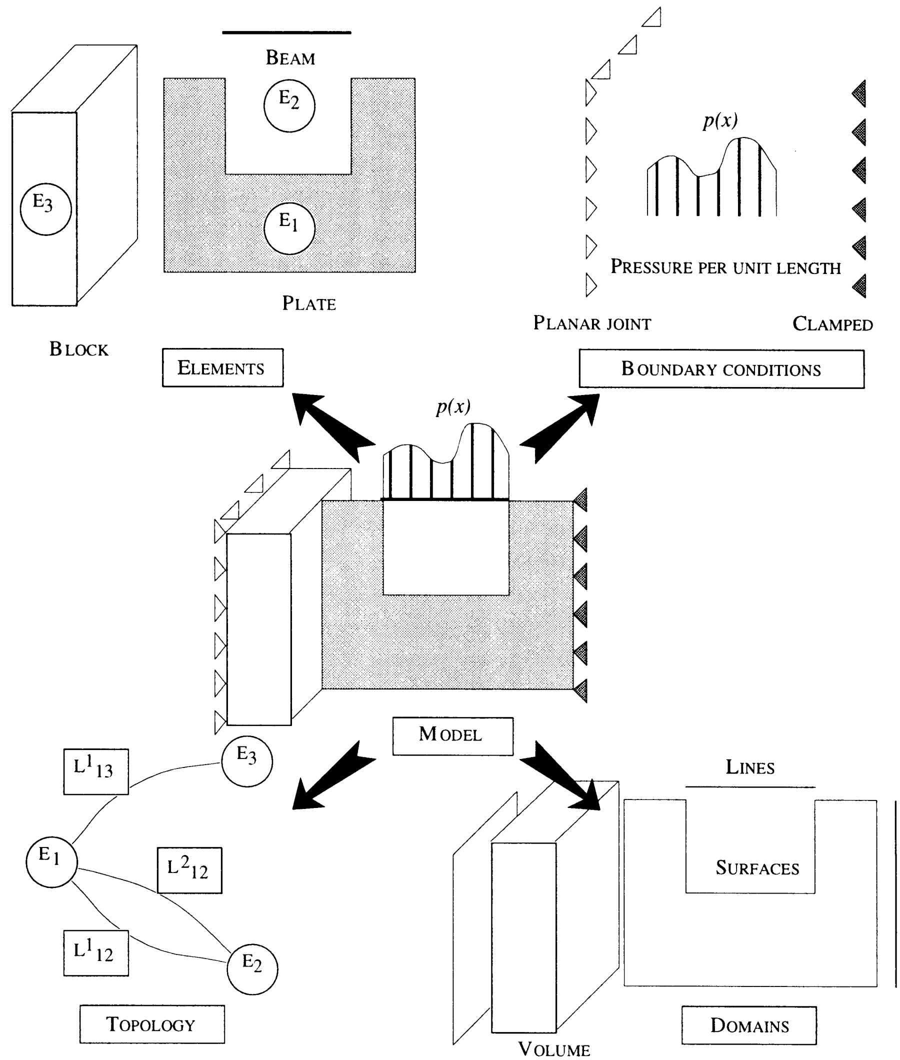

Figure 1. An example of an occurrence of the MODEL entity and its decomposition into the components involved into its definition.

• ELEMENT : it characterises the behaviour of deformable regions of the product. They are governed by behaviours of BEAM, PLATE, SHELL, BLOCK, etc. that represents the specialisation of an ELEMENT behaviour. The ELEMENT concept does not incorporate the notion of discretization because of its independence with respect to the solving method employed afterwards,

• MODELS : they are attached to a same part and characterise the various mechanical analyses that can be carried out with this part. Either the study of the static behaviour, i.e. : stresses, strains and displacements determination, or the study of the dynamic behaviour, i.e. : eigen modes determination, may lead to the use of various MODELS made up from various ELEMENTS located at various places in 3D space,

• BOUNDARY CONDITIONS are associated with a MODEL and characterise the mechanical data that bind the part analysed to its environment,

• TOPOLOGY (of a MODEL) : this entity stores data attached to the relative position of the ELEMENTS that constitute the MODEL. Effectively, the geometric representations currently available do not take into account the mechanical joints between the ELEMENTS of a MODEL. For example, various joints, with different mechanical behaviours, may exist between two ELEMENTS. A geometric representation solely based on a CSG (Constructive Solid Geometry) approach cannot express this type of configuration. Therefore, a specific structure, called here TOPOLOGY, has been introduced to describe such connections. This entity uses a graph structure where the nodes stands for the ELEMENTS and the arcs represent their various links,

• DOMAIN : all the geometric data associated with each mechanical entity references an occurrence of a DOMAIN. Therefore, it represents a geometric model that may be incorporated into BOUNDARY CONDITIONS or ELEMENTS that constitute a MODEL.

Note. The geometric representation of an analysis model must be consistent with the analysis requirements. That means the geometric representation of the part analysed may need to be " adapted " or " idealised " according to its initial geometric representation at the current stage of the design process [15]. Until now, this initial representation is created and managed within geometric modellers.

Thus, the organisation of the data constituting an analysis model results in the definition of an architecture where geometric information is clearly kept separated from the mechanical one. This effectively allows a better partitioning between the data dedicated to the mechanical analysis module MAESTRO and those created and managed by a geometric modeller. This particular distinction aims at specialising the treatments in each module. Therefore, MAESTRO does not " know " the nature of the geometric model involved in the surface description of a SHELL, i.e. : Bézier or NURBS representation, or in the volume definition of a BLOCK. The relative independence thus obtained facilitates the maintenance and the evolution towards a new design environment because it allows a better introduction of new geometric modelling techniques and eventually of new mechanical analysis methods.

2.2. MECHANICAL OPERATORS

The " dynamic behaviour " of the mechanical analysis module MAESTRO is based on the definition of a set of functions dedicated to the creation and manipulation of the data involved into an analysis model. These functions, called here *operators*, are particularly dedicated to the construction of the ELEMENTS belonging to a MODEL and to their assembly, i.e. : their TOPOLOGY. Such operators are briefly described below. As a basic principle, the definition of the mechanical operators of MAESTRO distinguishes the geometric data from the mechanical ones. This organisation aims at making the definition of the operators consistent with the data structures described above.

The operators of ELEMENTS assembling incorporate specific treatments that are applied to analysis models relied on a " non-manifold " geometry. These operators have been established to provide the commutativity and the associativity properties and facilitate the user construction and manipulation of a MODEL. Furthermore, the structure of these operators has allowed to carry out treatments with non geometrically connected parts through the use of mechanical linkages between the ELEMENTS being assembled. An example of such a situation is shown on figure 2.

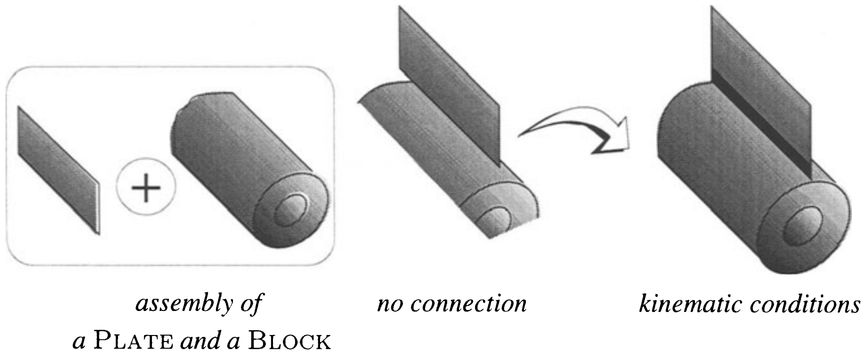

Figure 2. Kinematics conditions between non connected ELEMENTS of a MODEL.

These solutions lead to the extension of the concept of non-manifold geometry as it is used in a geometric context [7], [8]. Moreover, they show that current geometric operators supplied by the actual geometric modellers are no longer useful to be exploited into a mechanical analysis context. Their user interfaces are not adapted enough to create mechanical linkages between ELEMENTS and to modify the TOPOLOGY of a MODEL. Effectively, the result of a geometric Boolean operation do not allow to distinguish the various subsets that serve as geometric supports of distinct mechanical links, as depicted on figure 3.

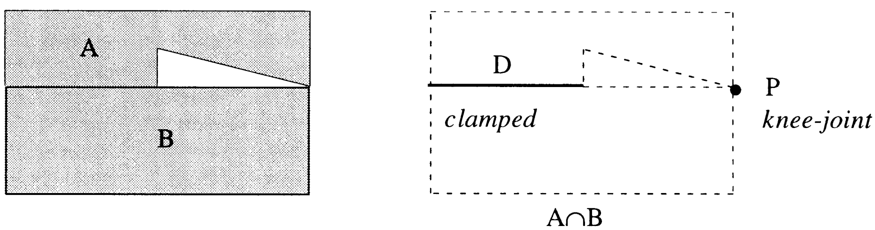

Figure 3. Distinct mechanical links related to a geometric intersection result.

3. MAESTRO within a Finite Element Context

The description of the basic concepts of MAESTRO has shown that the mechanical analysis model of a part is based on sets of geometric and mechanical data which are independent of the solving method employed afterwards. The Finite Element Method is one of the most often used numerical methods in the industry. This justifies the implementation of specific tools dedicated to the transfer of the information attached to an analysis model towards a finite element solver.

The establishment of a " transfer module " (see figure 4) shows that one of the first steps of this task consists in adding a minimal discretization information necessary to the finite element mesh generation. The resulting mesh relies effectively on the geometric representation of the analysis model. Afterwards, complementary information, e.g. : specific to the finite elements nature, is added to the discretization of the model.

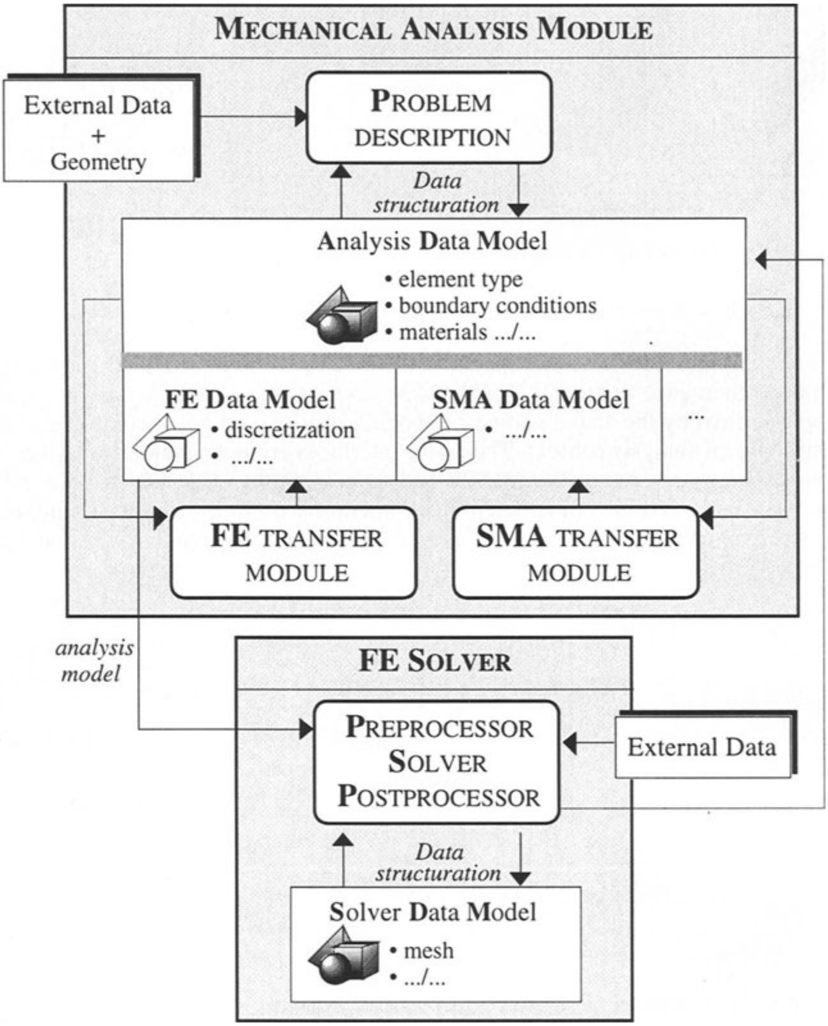

Figure 4. Position of the Mechanical Analysis Module within the analysis process.

In order to keep the independence between the geometric data and the mechanical ones, the creation of a model with a minimum discretisation has allowed the identification of geometric treatments involved in such a transfer of data [9]. Partitioning treatments applied to the analysis model boundaries that rely on elementary decomposition methods (i.e. : domains with no interior lines, two-manifold domains, etc.) are examples of such geometric operations that have to be independent of the treatments applied to mechanical data.

Nevertheless, the maintenance of the coherence between the data related to an analysis model and the data created inside a finite element pre-processor is still an open problem. One solution proposed in [9] consists in keeping the independence of MAESTRO with respect to the solver through the use of a specific process ensuring the data coherence between both modules (see figure 4). This solution guarantees the use of current solvers independently of the mechanical analysis environment MAESTRO and allows analysts to conduct very specific analyses (non-linear analyses, thermal studies or use of particular finite elements, etc.) with their usual computer tools. Such a solution allows to keep the use of an analysis module compatible with the requirements set by an engineering office about a finite elements software.

4. Geometric Adaption and Idealisation of a Part

Though it has been less developed in the current approach, the geometric adaption of a part is very important because it allows the communication between various tools that create models during the design process and the analysis module. As such, it is a necessary path to transfer data from design tools to the mechanical analysis environment.

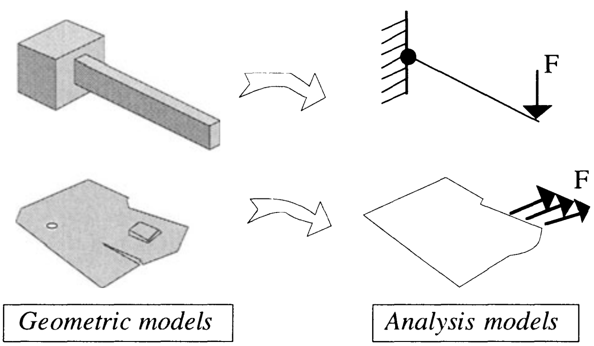

Figure 5. Idealisation and adaptation of geometric models.

The first developments conducted in [9] are dedicated to the idealisation of solid parts into BEAMS. The idealisation process is characterised by the change of the geometric manifold of the part, i.e. : transformation of a volume into a curve (as shown on figure 5). The geometry adaptation process differs from the previous one from a mechanical analysis point of view since it associates an ELEMENT whose mechanical behaviour is compatible with the geometry of the part, i.e. : plate or shell behaviour for a surface, beam behaviour for a line, with its initial geometry. Therefore, this process does not affect the geometric manifold of the part in the sense that it consists in details deletion like small holes, fillets, blending areas with small radii, chamfers, etc. Some of the tools required for these purposes fall into the category of feature recognition techniques [3], [5], [13], [14] and will be incorporated by future works.

The idealisation tools have been implemented inside the EUCLID[1] system. Therefore, these tools have been constrained by such an environment, that's the reason why the geometric treatments used here are based on a CSG approach. The aim consists in extracting medium lines of a solid part required by the BEAM definition.

According to the concepts of the mechanical analysis module introduced above, the idealised representations of parts, or of sub domains of a part, do not require any connection between them to create a coherent analysis model. Therefore, the adequation between the geometric representations before and after idealisation is preserved and may become the basis of the dual way data transfers between the mechanical analysis module and the design environment which occur during the design process.

Nevertheless, the above developments have shown the limits of such approaches according to the constraints of actual geometric modellers and the necessity of a mechanical analysis module. Finally, these two aspects allow a better definition of the nature and of the organisation of the computer tools required for the adaption and idealisation of the geometry of a part.

5. Conclusion

The approach presented here is dedicated to the definition of an environment that allows the integration of mechanical analysis within the design process. It has justified the existence of the mechanical analysis module concept and has defined the position of such a module among the current finite element solvers and CAD tools. Furthermore, the data organisation has allowed the validation of a distributed software architecture which is a key point of the evolution of computer aided engineering software. The object-oriented approach used for the implementation of MAESTRO guarantees the flexibility of the data and operators developed.

The internal data organisation of the mechanical analysis module MAESTRO has brought up to the front end the needs for high-level geometric manipulation functions, particularly their aims and objectives. These results represent a first approach towards the determination of geometric operations that have a polyvalent interface with an integrated design environment.

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THICKNESS OPTIMIZATION OF BEAMS AND SHELLS WITH LARGE DISPLACEMENTS

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Abstract. This work deals with optimum design of isotropic or composite beams and shell structures with geometrical non linearities (large displacements analysis). Suspension parts such as leaf springs are practical applications in the car industry. The thickness distribution is designed to minimize the stresses with a prescribed stiffness for a given load level. An Updated Corotational Lagrangian Formulation is considered for the non linear analysis with large displacements and rotations but small elastic strains. A mathematical programming technique is coupled with the non linear analysis code to design 2D and 3D leaf springs.

1. Introduction

This work has been carried out in collaboration with RENAULT S.A. An optimum sizing problem is studied for isotropic and composite beams and shell structures with large displacement analysis: the design variables are thickness parameters which minimize the Tsai-Hill criteria expressed in plane stresses hypothesis, with constraints on structural flexibility (a displacement component of one or several points is imposed for a given loading).

A Sequential Quadratic Programming (SQP) method is used to solve the optimization problem. The sensitivity analysis is performed numerically by an efficient finite difference scheme taking into account the knowledge of the last known equilibrium solution.

This problem is a classical one in the case of linear behavior ([1] [2] [3]). The originality of our work lies in the consideration of the geometrical non linearities (large displacements and large rotations) for composite beam and shell elements. As the minimization algorithm is iterative, the non linear analysis must be performed by a robust and efficient method. We consider the Updated Corotational Lagrangian Formulation (UCLF) combined with the Newton-Raphson algorithm. Shells are

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discretized with Discrete Kirchhoff triangular elements taking into account membrane and bending effects. Beams are discretized by two nodes elements including transverse shear effects.

2. Optimization problem statement

2.1. OBJECTIVE FUNCTION

The function to minimize is an integral of the Tsai-Hill criterion expressed in terms of the plane stresses components (σ_1, σ_2, σ_{12}) [4]. The objective function is given by:

$$J = \int_V \left[\left(\frac{\sigma_1}{\sigma_{1rup}}\right)^2 + \left(\frac{\sigma_2}{\sigma_{2rup}}\right)^2 - \left(\frac{\sigma_1\sigma_2}{\sigma_{1rup}{}^2}\right) + \left(\frac{\sigma_{12}}{\sigma_{12rup}}\right)^2 \right]^p dV \qquad (1)$$

where the exponent p (p = 2, 4, 6,..) allows to approximate the problem of minimizing the maximum of the Tsai-Hill criteria.

2.2 DESIGN VARIABLES AND THICKNESS PARAMETRIZATION

The choice of thickness approximation h defines the space where optimization is carried out. When the discretization involves a small number of elements, the thickness h_i of each finite element are the natural design variables: h is then a piecewise constant function. As the variables are directly present in the finite element model, this approach is quite easy to implement, but generally this choice would imply too many design variables. Approximation functions are defined, which must be related to the technological constraints. In our applications, the thickness must be at least continuous on the whole domain. Therefore linear or cubic approximations have been used. The design variables are then the thickness values at some given points of the structure (control points).

The thickness distribution around the middle surface is approximated by a piecewise linear or cubic (B-Spline) function [5]. In most of the beam type applications the linear approximation was found to be sufficiently accurate and easier to control, especially concerning the bounds satisfaction. A linear parametrization has been used for general shells. The structure is partitioned in several quadrilateral "super-elements" (Figure 1). The thickness of each triangular finite element is then obtained from the knowledge of its coordinates.

2.3 CONSTRAINTS

One important constraint of the thickness optimization is related to the expected stiffness of the structure after application of a given loading. Some displacement components are imposed at specific nodes such as:

$$W_i = \overline{W}$$

This constraint is added to the optimization problem. It must be noted that the above equality is not a boundary condition for the finite element analysis, but a condition to be satisfied using the Sequential Quadratic Programming algorithm[6].

Finally, bound constraints are introduced to satisfy the manufacturing process.

$$h_{min} \leq h_i \leq h_{max} \qquad i = 1,....,n$$

where n is the total number of design variables.

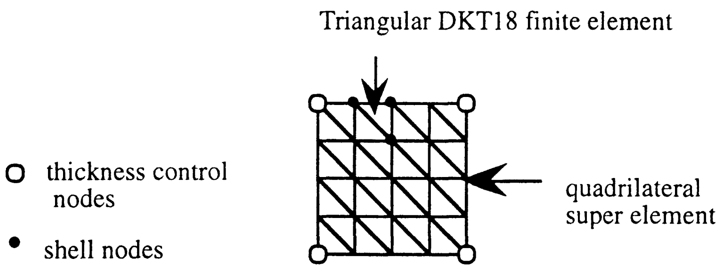


Figure 1. Quadrilateral super element and triangular shell elements

3. Sensitivity analysis

The use of Sequential Quadratic Programming algorithm [6] to solve the optimization problem implies to evaluate the functions (criteria and constraints) derivatives with respect to the design variables. Two approaches are classically used. In the numerical one, each component of the gradient is evaluated by finite difference. In the analytical approach, the derivatives formulas are written out and computed from the finite elements results in the same way as the functions, leading to direct differentiation or adjoint method. It is known that the partial derivative of the functions with respect to the global displacement dJ/dU, where U is the displacement field, are then required. This derivative can be easily evaluated when the function is explicitly written in terms of displacements. In the present study, the criteria is expressed in terms of plane stresses, which are computed by an incremental method.An explicit expression of the criteria is not directly available, therefore the numerical approach has been chosen for the sensitivity analysis.

The finite differences method is very easy to implement. However as it needs n+1 non linear finite elements analysis (n=number of design variables) at each minimization iteration, the required CPU time might be unacceptable for industrial applications. Hence, we propose an accelerated method to solve the non linear analysis corresponding to the n small perturbations of the design variables: in place of performing a complete non linear analysis, we only perform a few iterations for a constant loading taking into account the estimated solution (geometry, strains) associated to the non-perturbated variables. Thus, only one full non-linear analysis (with several load steps) must be performed at every optimization iteration, followed by n additional perturbed analysis. A considerable amount of CPU time can be saved by this method.

4. Finite elements

4.1. BEAM ELEMENT IN UPDATED (COROTATIONAL) LAGRANGIAN FORMULATION

The beam element is a two nodes, three d.o.f. by node (U, W, β) element, with linear approximations of U, W and β (Figure 2). Transverse shear effects are taken into account, and only one integration point is considered to avoid shear locking [7].

The tangent stiffness matrices and internal force vectors are explicit and have a simple form using the UCLF. The stress resultants are evaluated at the center of the element. The non linear equations deriving from the discretization are solved by different algorithms based on the Newton-Raphson method.

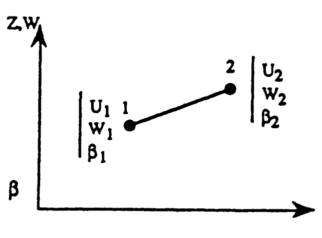


Figure 2 . Beam element

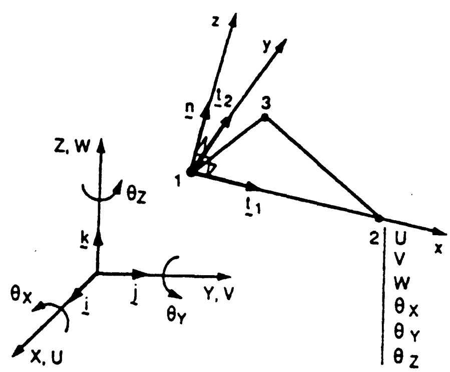


Figure 3. DKT18 shell element

4.2. DKT18 SHELL ELEMENT IN UCLF [8], [9]

We use a triangular facet element with three nodes and six d.o.f. per node ($U,V,W,\theta_X,\theta_Y,\theta_Z$). This element is defined by the superposition of the CST (Constant Strain Triangle) element for the membrane part and the DKT (Discrete Kirchhoff

Triangle) element for the bending part. Small stiffness coefficients are introduced for the rotation around the normal (Figure 2).

The displacements U,V,W are linearly interpolated and the rotations βx and βy in the xz and yz planes are defined by incomplete quadratic approximations [9].

5. Numerical results

5.1. LEAF SPRING

The first example is a leaf spring (Figure 4) with the following properties :

$E_1 = 40000 \text{ N/mm}^2$
$G_{12} = 4500 \text{ N/mm}^2$

This leaf spring is subjected to a vertical loading P = 320 daN. A mesh of 26 beam elements having the same initial thickness (ho = 9.5 mm) is used as a starting solution. The left end of the structure is represented by finite elements with a very high stiffness. The design variables are the finite elements thicknesses; they are bounded by two constant values ($8 \leq hi \leq 30$ mm).

Two cases have been considered concerning the displacement constraints :

Q1 Problem : one displacement constraint at the point C: $\overline{W_C} = 225$ mm.
Q2 Problem : two constraints : $\overline{W_C} = 225$ mm and $\overline{W_A} \geq -70$ mm.

In the first case, the result of optimization leads to a constant thickness between the symmetry axis and the support (Figure 5). In the Q2 problem, the optimization

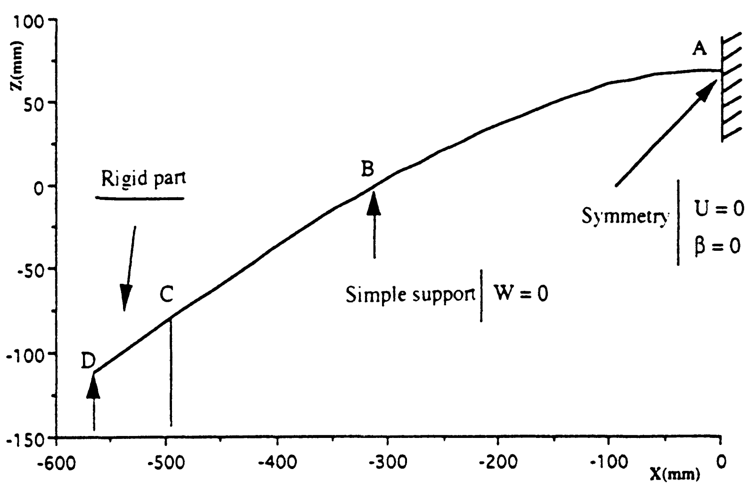
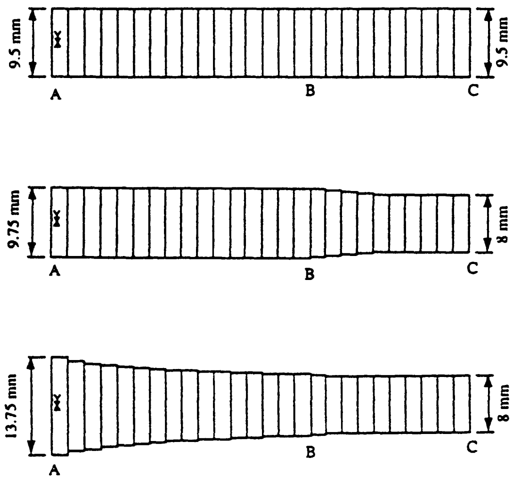


Figure 4 . Leaf spring geometry

process tends to stiffen the central part of the structure in order to satisfy the second displacement constraint. The maximum thickness is then reached near the symmetry plane (13.75mm) and decreases to its lower bound (8mm) near the stiff part.

Figure 6 shows that the second constraint deeply modifies the stress distribution σ_1. It can be noted that σ_1 is increased by 30% compared to the first case.



a) Initial thickness (V^0=687122 mm^3)

b) Problem Q1 (V=666480 mm^3)

c) Problem Q2 (V=684220 mm^3)

Figure 5. Optimum thickness distribution of the leaf spring

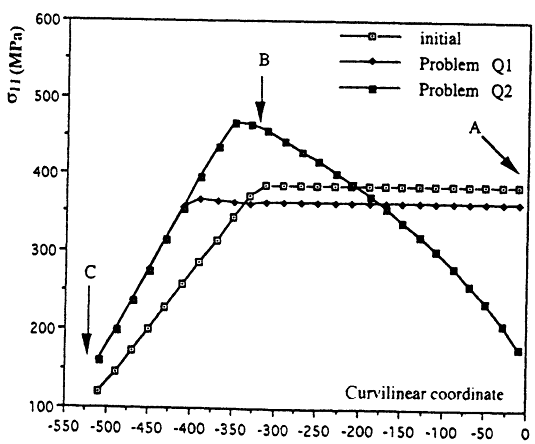


Figure 6 . Stress distribution (σ_1)

5.2. PLATE OF GENERAL SHAPE

The second example is presented on Figure 7. The structure is made of composite material. The plate is clamped along the AI segment, and is subjected to a vertical loading P = 500 daN at the C point. The deformed shape of the structure shows that the non linearity of the problem is important (Figure 8).

The mesh, the number of design variables describing the thickness distribution, and the number of steps for the non linear analysis have to be defined before performing the optimization. After some numerical experiments, a compromise between precision and efficiency of the non linear analysis and of the optimization has been found: 496 elements, 24 control points, 10 loading steps.

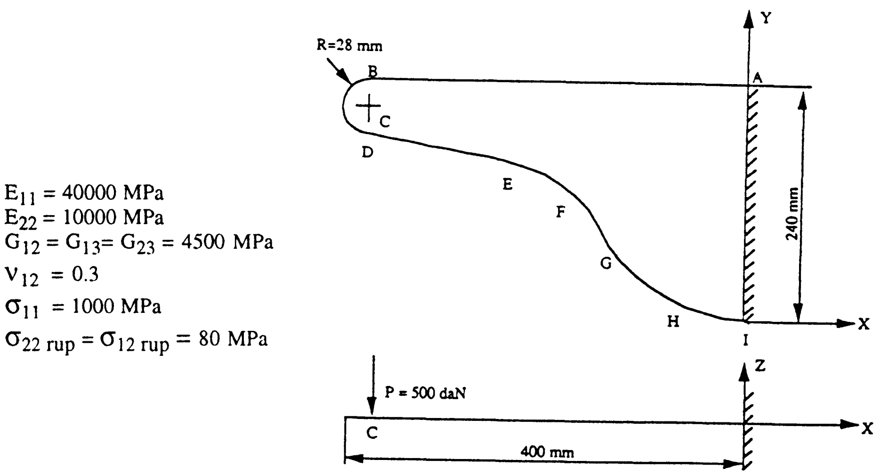


Figure 7. Geometry and characteristics

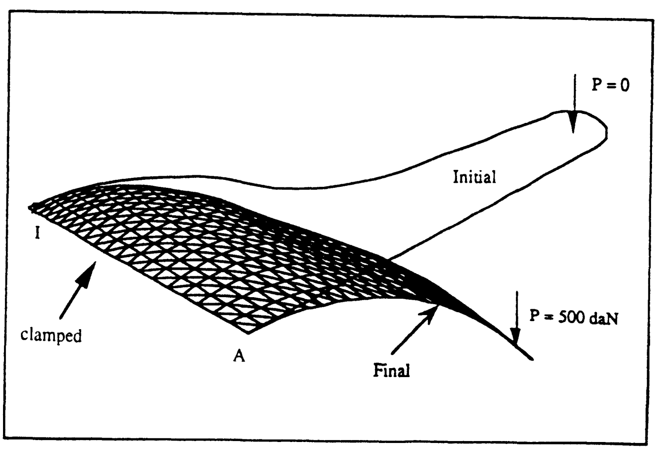
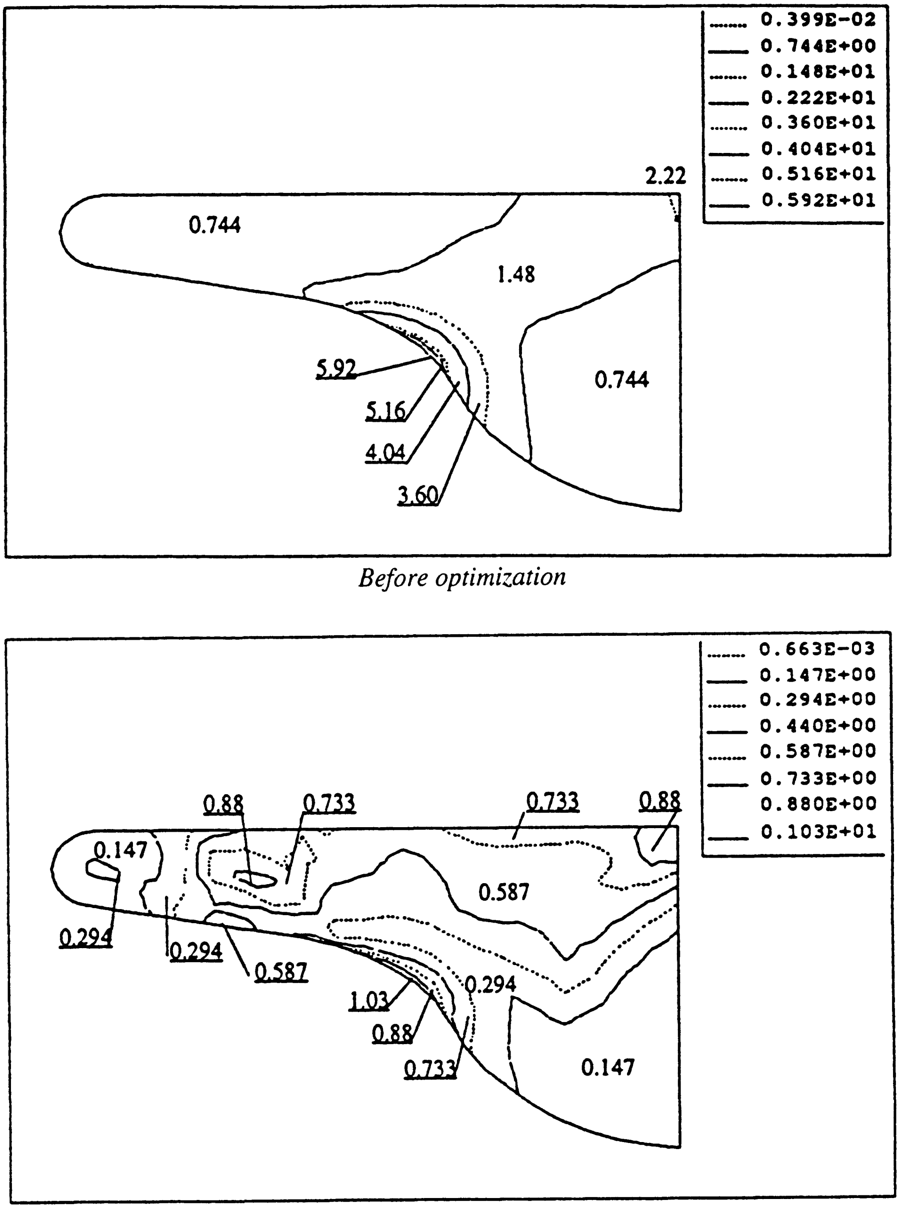


Figure 8. Deformed shape for an isotropic material.(initial thickness)



Before optimization

After optimization.

Figure 9. Tsai-Hill criterion distribution

Convergence is achieved in 35 iterations, after approximately 6 CPU hours (VS4000/90). The value of the objective function has been approximately divided by 15; the σ_{12} max stress decreases from 190 MPa to 78 MPa. The Tsai-Hill criterion distribution before and after optimization are presented in Figure 9. It can also be noted that the volume decrease is rather important (-18% compared to the initial value). The final thickness found by the optimization process is presented on Figure 10.

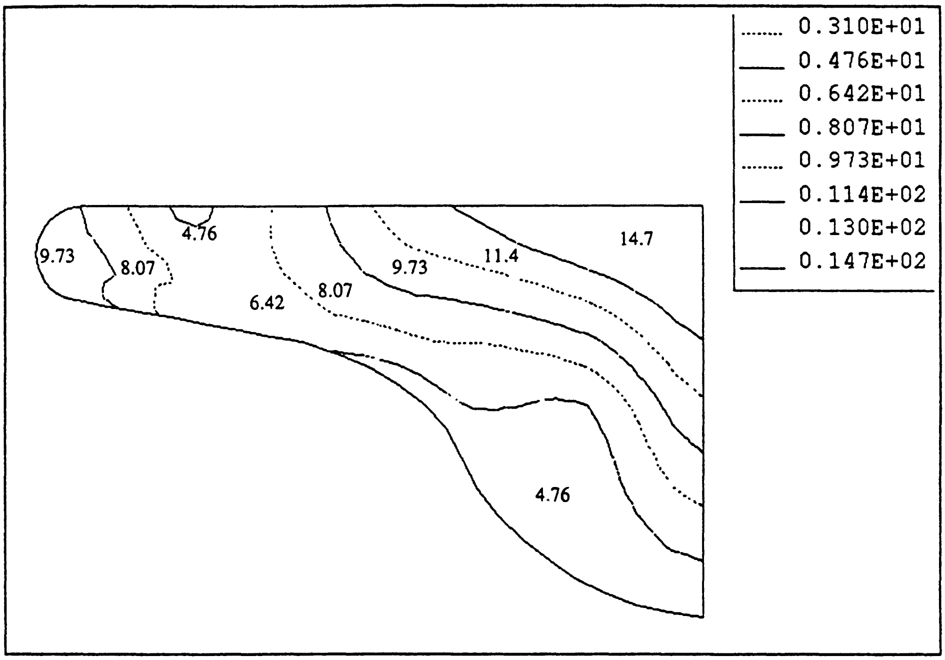


Figure 10. Thickness distribution after optimization

6. Conclusions

Several results have been obtained for academic and industrial problems [10], showing that our global approach of thickness optimization for structure undergoing large displacements is very satisfactory. This approach is based on :

- a finite element discretization using simple beam and shell elements. Isotropic or composite materials can be considered.

- a simple and efficient Updated (Corotational) Lagrangian Formulation valid for small elastic strains and large displacements and large rotations .

- a definition of an objective function in terms of the Tsai-Hill stress criterion (it can be noted that the problem of minimizing the maximum value of the Tsai-Hill criterion can be approximately solved).

- a fast sensitivity analysis method using only "local" non linear analysis in the vicinity of the required solution,

- a Sequential Quadratic Programming algorithm to solve the optimization problem; it is found to be very robust and efficient for this type of problem with highly non linear objective function and constraints.

- a thickness parametrization with piecewise linear functions involving a small number of control variables.

The developed software will be helpfull for the analysis and design of new leaf spring and suspension parts where geometrical non linearities plays an important role.

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QUALITY CONTROL OF FINITE ELEMENT ANALYSES IN SHAPE OPTIMIZATION.

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Abstract. The goal of this paper is to present an automatic optimization procedure which ensures the validity of the final design. The main objective of this work is to find out the best way to combine optimization with finite element error estimation. A numerical example shows the advantages of the procedure.

1. Introduction

Finite element in shape optimization has known a remarkable success these last years due to the great increase in power of computers and work-stations. Quality of finite element analyses is strongly related to the discretization (mesh and polynomial degree of the elements) of the structure. As a consequence, the obtained final design can be faraway from the physical solution if the discretization is not adapted to the studied problem (Duysinx *et al.*, 1994). It is then important to use part of the computing power to find a better finite element solution.

Recent developments in the field of error calculation allow the user to obtain a reliable estimation of the solution precision. An error estimator based on stress smoothing (Zhong *et al.*, 1993) and a mesh adaptation program based on mesh subdivision techniques (Beckers *et al.*, 1994) have been developed at the aerospace laboratory of the University of Liège (L.T.A.S.). This method of mesh adaptation has been successfully tested until now. An automatic procedure of solutions error control during the shape optimization process has then been developed. This work has been performed in the frame of the BRITE EURAM BRE2-CT94-0590-MODSYSS (Multidiscipline Open System for Structural Synthesis) project (Cugnon *et al.*, 1995). A prototype of the program is available for 2-D problems, the extension to 3-D problems is planed for the end of the MODSYSS project.

2. Shape Optimization

The problem of shape optimization can mathematically be stated as follows :

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 183–192.

$$
\begin{array}{ll}
Min\ m(X) & \\
c_j(X) \leq \overline{c}_j & j = 1,M \\
h_k(X) = 0 & k = 1,L \\
\underline{X}_i \leq X_i \leq \overline{X}_i & i = 1,n \\
X^T = [X_1 \ldots X_n] &
\end{array}
\qquad (1)
$$

where X_i are the design variables (parameters of the geometric model), m the objective function (in general the mass of the structure), c_j inequality constraints associated with limitations to structural responses and h_k the equality constraints corresponding to requirements on the geometric continuity of the boundaries of the structure.

The numerical solution uses the following iterative method :

- finite element analysis of the current model;
- determination of the sensitivities of the structural response;
- definition of a linearized sub-problem obtained by convex linearization (Fleury 1989) and it's solution by a classical optimization method;
- check of the solution admissibility and generation of a new geometric model.

The process is stopped when the variation of the objective function is less than a prescribed value and if the constraints are satisfied. Often, in static linear elasticity, the constraint on the maximum stress value is bounding the decrease of the mass. These stress concentrations are localized on the boundaries of the structure. A good evaluation of them is of outstanding importance.

3. Control of Finite Element Error

3.1. ERROR ESTIMATION

Many error estimators are based on the construction of a continuous stress field based on the nodal superconvergence assumption of the finite element stress field. In the present case, the field $\tilde{\sigma}$ is obtained by a method called "interpolation + extrapolation" (Zhong *et al.*, 1993). The $\tilde{\sigma}$ field is obtained by post-processing of finite element results. The a posteriori error estimation is based on the energy norm :

$$\varepsilon_i = \sqrt{\int_{\Omega_i} (\tilde{\sigma}-\sigma_h)^T H^{-1} (\tilde{\sigma}-\sigma_h)\, d\Omega_i} \qquad (2)$$

where H is the Hooke matrix, Ω_i the element volume and σ_h the finite element stress field.

3.2. ESTIMATION OF ERROR CONVERGENCE RATES

If the estimated error level is higher than the prescribed one, mesh refinement is needed. In order to determine the suitable level of subdivision, it is necessary to calculate the error sensitivity with respect to the elements size. At the element level, the theoretical error corresponds to the law :

$$\varepsilon_i = C_i \, h_i^{\beta_i} \tag{3}$$

where C_i is a constant, h_i the element size and β_i the element convergence rate.

If the element size is small enough, β_i is given by formula (4).

$$\beta_i = \frac{1}{2} \min(p, \lambda) \tag{4}$$

where p is the polynomial degree of the element and λ is a coefficient related to the local singularity order of the exact solution.

Usually, β_i is estimated by numerical adjustment of the strain energy density in the neighbourhood of the singular point (Coorevits *et al.*, 1995). This local strain energy density can be written as follows :

$$d(r,\theta) = k r^{2(\beta-1)} + d_0 \tag{5}$$

where k and d_0 are the other two constants to be determined.

3.3. MESH OPTIMIZATION

Knowing the element sizes h_i and the element errors ϵ_i and their sensitivities, it is possible to build a new mesh which minimizes the number of elements and guarantees a prescribed level $\bar{\epsilon}$ of the global error. In a 2-D optimal mesh, element i is subdivided into n_i sub-elements with a size h_i^* :

$$n_i = \left(\frac{h_i}{h_i^*} \right)^2 \tag{6}$$

The problem of mesh optimization can be stated as follows :

$$\begin{cases} \underset{\{n_i\}}{Minimize} \quad I = \sum_i n_i \\ With \quad \sum_i \epsilon_i^2 n_i^{-\beta_i} = \bar{\epsilon}^2 \end{cases} \tag{7}$$

Mesh adaptation is then perform by using subdivision techniques (Beckers *et al.*, 1994).

4. Procedure of Shape Optimization with Error Control

As both procedures of shape optimization and mesh adaptation are iterative, the method requires two overlapped loops :

a) The principal shape optimization loop;
b) an internal mesh adaptation loop.

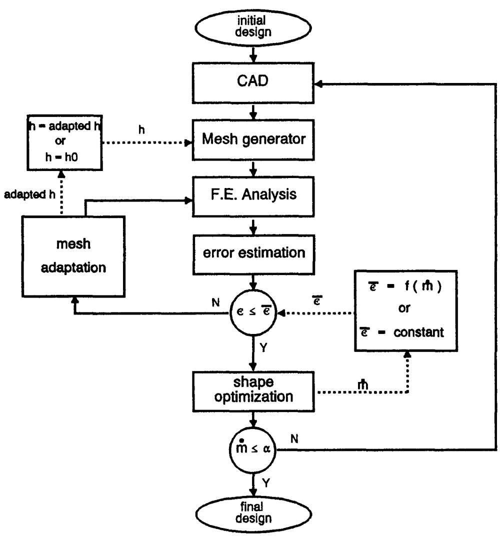

Figure 1. Architecture of the procedure

Remark : full lines indicate the flow of the procedure and dashed lines indicate some information transfers.

Before each shape optimization iteration, a complete mesh adaptation is performed from the initial mesh (h_0).

To limit calculation costs, several improvements have been introduced in the initial method. The main objective is to reduce the number of mesh adaptations without any corruption of the final admissible optimal design. Many solutions have been explored.

a) During the research of a new design at the n^{th} iteration, it is convenient to use the optimal boundary discretization of the $n\text{-}1^{th}$ design (h_{adap}) (Bugeda *et al.*, 1993). Due to an efficient remeshing method, this allows us to obtain a quasi-optimal mesh so that the number of mesh adaptations per optimization is limited.

b) Another solution is to delay the intervention of the error control procedure. The first iterations of the optimization process are done without error control; the initial mesh h_0 is used. This allows us to avoid many mesh adaptations and to perform the first optimizations with a limited number of degrees of freedom. Error control is activated when the variation $\dot{m}$ of the objective function, in general the weight of the structure, is lower than a prescribed value.

c) Progressive control of the quality of the solutions. The prescribed precision used in the mesh adaptation process is now related to the decrease of the objective function. The closer the design is to the optimal, the more severe the error control is. The benefit in computer time is of the same order as for the precedent method.

These improvements have been tested separately. The consequences of the choice of a method, on the violation of the admissible stress, on the value of the objective function and on the CPU time are shown in the numerical example.

5. Numerical Example

Several of the procedures of shape optimization are applied to the connecting-rod described in figure 2. Boundary conditions consist in fixing the interior of the left hole and imposing a load distribution on the interior of the right hole (F_x = 2789 N and F_y = 5066 N). The material has the following properties : Young modulus E = 20.74 10^6 N/cm^2, Poisson coefficient ν = 0.3 and the density ϱ = 7.81 10^{-3} kg/cm^3. The thickness t is 0.3 cm.

The problem is to minimize the mass of the structure constraining the maximum von Mises stress to be lower than σ_{VMmax} = 80000 kg/cm^2. The geometrical constraints on the design variables and their initial values are given in table 1. Finite element analyses are performed with second degree elements.

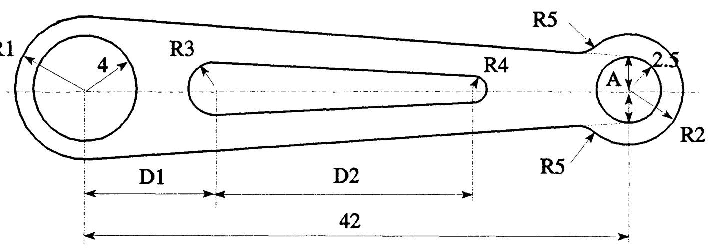

Figure 2. Initial geometric model

TABLE 1. Allowed gaps of the design variables

Design variables	R1	R2	R3	R4	R5	D1	D2	A
maximum	10	10	4	4	10	20	32	R2
minimum	5	3.5	1	0.5	0.5	6	5	0.5
initial	5.42	4.2	1.5	1	2	12	15	3

5.1. OPTIMIZATION WITHOUT ERROR CONTROL

The process is converging ($\dot{m} \leq 0.001$) in 9 iterations. The mass of the structure is then 0.4375 kg which gives a relative decrease of 41.6% (initial mass = 0.7494 kg). The final design and mesh are shown in figure 3.

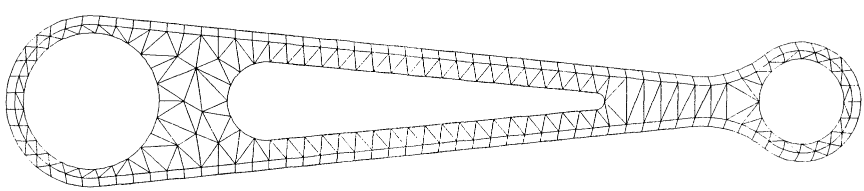

Figure 3. Optimal design without error control -1850 D.O.F.

The analysis of the stress field (figure 4) shows a relative violation of the maximal stress of 4.85% for a finite element solution exhibiting a relative error in energetic norm η = 7.34%. If we refine the mesh (mesh adaptation) we observe a maximum stress even higher (84220) for a better finite element solution with a relative error in energetic norm η = 1.77%. The final design is thus non-admissible.

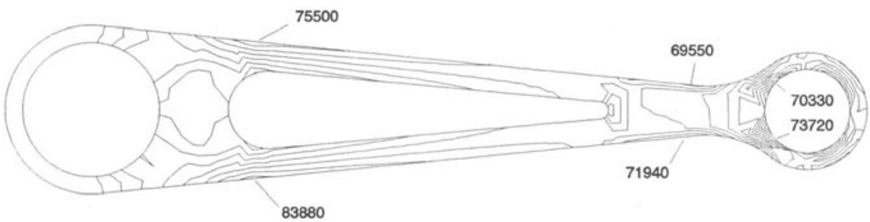

Figure 4. Stress in the optimal structure - η = 7.34%

5.2. OPTIMIZATION WITH FULL ERROR CONTROL

Optimization is performed by using the mesh adaptation procedure to ensure a relative error on the energetic norm less than 3% for every iteration of the optimization process. The procedure is converging in 12 iterations. The refinement of the mesh (figure 5) in the stress concentration areas leads to a better evaluation of the maximal stress (figure 6). The calculation of the sensitivities of the structural response with respect to the design variables is also improved and the admissibility of the final design is then guaranteed. After all, the maximum stress value of 79340 is lower than the maximal allowable value. Moreover, the obtained structure is lighter than the previous obtained without error control.

In spite of the fact that the error control guarantees the admissibility of the design, it is rather expensive. A CPU time of 15348 seconds on a Digital Alpha station 3000 model 500 is necessary to perform optimization with error control and only 1293 seconds without error control.

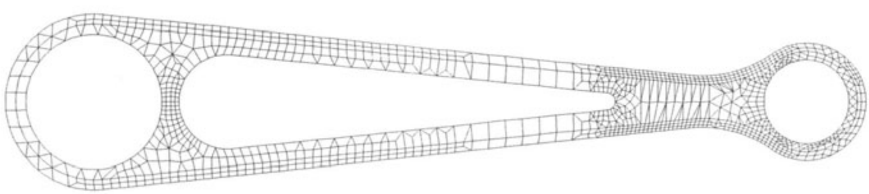

Figure 5. Optimal design with error control - 6592 D.O.F.

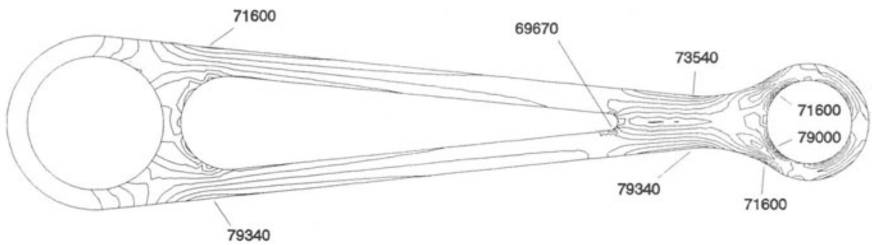

Figure 6. Stress in the optimal structure - η = 1.63%

5.3. OPTIMIZATION WITH DELAYED ERROR CONTROL

To reduce computer time, it seems interesting to delay the activation of the mesh adaptation loop. In the present case, error control begins when the relative variation of the mass $\dot{m}$ is lower than 1%. The objective of this procedure is twofold : reduce the number of mesh adaptations and perform sensitivities calculation with a lower number of degrees of freedom.

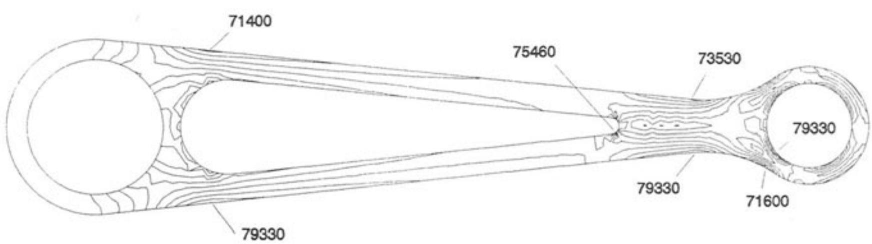

Figure 7. Stress in the optimal structure - delayed error control

The optimum is reached in 15 iterations. This optimal design (figure 7) is almost identical to the second one obtained with full error control (figure 6). The final mass is 0.4103 kg and the design is admissible (σ_{VMmax} = 79330 N/cm^2). Delaying error control do not decrease the quality of the final solution. The procedure is cheeper; the process is now preformed in 11399 CPU seconds, which means a saving of about 25% of the computer time.

5.4. OPTIMIZATION WITH PROGRESSIVE ERROR CONTROL

This procedure impose progressive prescribed precisions on the finite element analyses when the variation of the objective function is decreasing. In the present case, the law of error level involves 3 steps : no error control when $\dot{m}$ is greater than 10%; maximal allowable relative error of 5% when $\dot{m}$ is between 5 and 10 %; and finally, maximal error of 3% when $\dot{m}$ is lower than 1%. Note that the prescribed error is never increasing. The optimization process converge in 13 iterations. The optimal design is the same than with the other procedure including error control (σ_{VMmax} = 79330 N/cm^2, mass = 0.4103 kg). The benefit in computer time with respect to the procedure including delayed error control is very small (10961 CPU seconds).

5.5. CONVERGENCE OF THE PROCEDURE

Evolutions of the objective function for several optimization procedures are shown in figure 8. they lead to the following conclusions:

1) The decrease of the mass occurs mainly during the first iterations.
2) Whatever the error control may be applied, the optimal design is always the same.
3) When the error control is activated, a small increase of the mass due to a better estimation of the stress concentration is occurring.

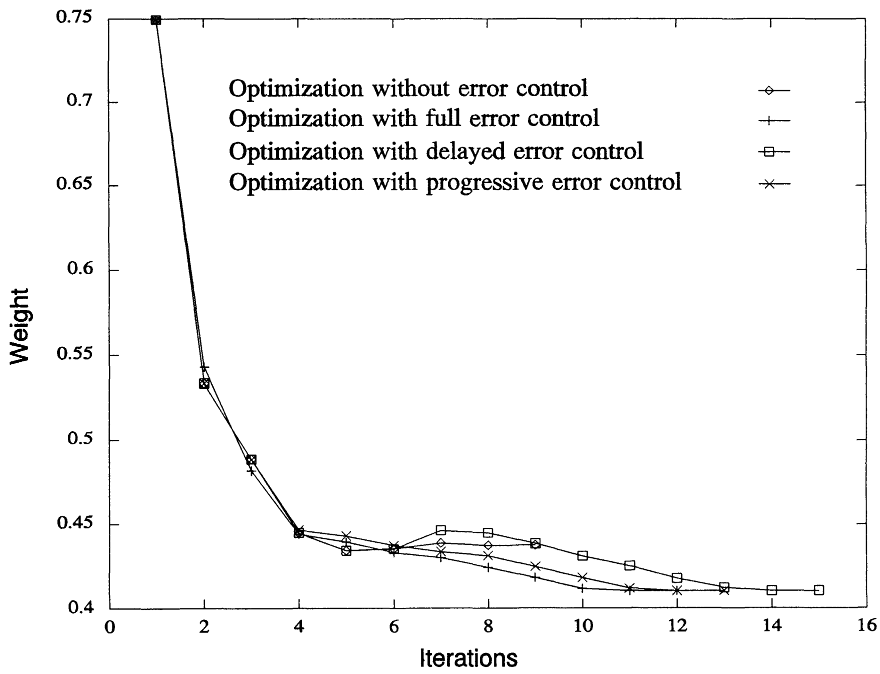

Figure 8. Evolution of the mass during the optimizations

6. Conclusion

Several automatic shape optimization procedures have been tested. Even if the analyses are performed with second degree elements and the constraints are applied to the skin stress, the optimal design obtained without error control leads to a non-admissible solution. To guarantee a good precision level of the finite element analysis it is necessary to refine the mesh in the stress concentration areas.

Error control procedure leads to a significant increase of the number of degrees of freedom. Sensitivity analysis, the most expensive part of the optimization process is strongly related to the number of degrees of freedom. This part of the procedure has to be improved by the implementation of better algorithms and by a better control of the precision of the sensitivities.

Delayed or progressive error control procedures limit the number of degrees of freedom during the first iterations of the optimization; computer times are reduced of about 25%. The way to impose error control has no influence on the final solution; but if it is beginning to early or to late, the cost can strongly increase. The choice of imposing the maximal precision after the variation of the objective function is less than 1% seems to be suitable.

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METHODS AND SOFTWARES FOR THE AUTOMATION OF FINITE ELEMENT ANALYSES IN 3D

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Abstract

During the design phase of a structure, it is often necessary to conduct several studies of the mechanical behavior whose cost in both human and computer time is often very significant. In the context of finite element computations, in order to decrease costs while respecting the user's required level of accuracy, it is essential to control discretization errors and to master calculation parameters. However, in 3D, the development of a correctly-adapted mesh presents a real difficulty. The objective of this paper therefore is to present a method based on several software programs in order to overcome this difficulty.

1. Introduction

Current industrial needs encompass the processing of increasingly complex problems such that economic considerations have become very important: cost in computer time, volume of information to store, cost in human time for preparing calculations and analyzing results. To perform such computations within an industrial setting, it is imperative to master all calculation parameters in order to minimize costs while respecting the user's required level of accuracy. On the other hand, reducing costs in terms of human time requires automating the various steps in the analysis to the greatest extent possible.

Over the past fifteen years, considerable progress has been made in the area of controls of analyses and methods thereby truly the quantification of discretization errors (Ladevèze, 1977), (Ladevèze *et al.*, 1991), (Babuska *et al*, 1995), (Beckers *et al*, 1993). In coupling reliable estimators, robust prediction methods for calculation parameters and automatic meshers, we propose herein procedures that, in elasticity, open the way to a real automation of finite element analyses: the mesh and its development are no longer at the user's expense with respect to defining the problem to process and displaying a value that characterizes the quality sought in the analysis. These procedures are currently operational in 2D elasticity (Coorevits *et al*, 1994), (Coorevits *et al*, 1995).

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The method of error evaluation has also been developed at the LMT for three-dimensional calculations and programmed in the post-processor ESTEREF3D (Gastine *et al*, 1992). From an initial finite element analysis, this method initially allows evaluating and localizing discretization errors, and thereafter defining the element sizes which have to be used in order to respect the prescribed level of accuracy.

The difficulty in obtaining, as in the 2D case, automated analyses is the creation of the optimized mesh since, to our knowledge, no automatic 3D mesher, able to respect a map of sizes, exists (Georges, 1991). The creation of a 3D mesh is based on the definition of the mesh of the skin; it is therefore necessary to obtain an efficient optimization of this surface mesh. The mesher developed in L3S allows, from an initial mesh and a map of prescribed sizes, obtaining this optimization (Noel *et al*, 1994).

The procedure that we have developed associates these two software programs and an automatic 3D mesher. The geometrical description of the studied structure and surface meshes is carried out in the L3S facility in Grenoble, while the finite element analyses, three-dimensional meshes and errors and size calculations are performed in LMT in Cachan. The transmission of the result files is carried out by the computer system.
We will first present the method of controling finite element analyses followed by the principle of the automatic surface mesher. Finally, an initial example on a complex structure serves to demonstrate the efficiency of the procedure used.

2. Control of the Finite Element Analyses

2.1. ERROR ESTIMATOR

To set the framework, we consider herein the problem of the analysis of a structure in elasticity. We suppose that the structure occupies an area Ω. On a part $\partial_1\Omega$ of the edge $\partial\Omega$, it is assumed that the field of displacement is imposed: $U = U_d$. On the complementary part $\partial_2\Omega = \Omega - \partial_1\Omega$, a density of forces F_d is imposed. Moreover, Ω is submitted to a density of body forces f_d, and the elasticity operator of the material (Hooke's tensor) is noted as K. The problem can thus be formulated as follows:

Find a displacement field U and a stress field σ such that:

- U satisfies the kinematic constraints:

$$U = U_d \text{ (+ regularity)} \tag{1a}$$

- σ satisfies the equilibrium equations:

$$\begin{cases} \operatorname{div}\sigma + f_d = 0 & \text{in } \Omega \\ \sigma n = F_d & \text{on } \partial_2\Omega \end{cases} \tag{1b}$$

- σ and the strain $\varepsilon(U)$ satisfy the elastic constitutive relation:

$$\sigma = K\,\varepsilon(U) \tag{1c}$$

To measure the discretization errors, we use the concept of error in constitutive relation (Ladevèze *et al*, 1986). Suppose that $\hat{U}$ is a kinematically-admissible displacement field, i.e. it satisfies (1a) and that $\hat{\sigma}$ is a statically-admissible stress field, i.e. it satisfies (1b). In this case, the quantity: $\hat{e} = \hat{\sigma} - K\varepsilon(\hat{U})$ is called the *error in the constitutive relation* associated to the pair $(\hat{U}, \hat{\sigma})$. If $\hat{e}$ is equal to zero, the pair $(\hat{U}, \hat{\sigma})$ is the solution to problem (1). Otherwise, $\hat{e}$ allows us to estimate the quality of $(\hat{U}, \hat{\sigma})$ as an approximate solution to problem (1). To measure the error $\hat{e}$, we use the standard energy norm over the whole structure:

$$\mathbf{e} = \|\hat{e}\|_\Omega = \left\|\hat{\sigma} - K\varepsilon(\hat{U})\right\|_\Omega \quad \text{with} \quad \|\sigma\|_\Omega = \left[\int_\Omega \sigma^T K^{-1} \sigma \, d\Omega\right]^{1/2} \tag{2}$$

From the absolute error, we define a relative error:

$$\varepsilon = \frac{\left\|\hat{\sigma} - K\varepsilon(\hat{U})\right\|_\Omega}{\left\|\hat{\sigma} + K\varepsilon(\hat{U})\right\|_\Omega} \tag{3}$$

as the contribution to the relative error of an element of the mesh E:

$$\varepsilon_E = \frac{\left\|\hat{\sigma} - K\varepsilon(\hat{U})\right\|_E}{\left\|\hat{\sigma} + K\varepsilon(\hat{U})\right\|_\Omega} \quad \text{with} \quad \|\sigma\|_E = \left[\int_E \sigma^T K^{-1} \sigma \, dE\right]^{1/2} \tag{4}$$

One can find a description of this method for 3D elements in (Gastine *et al*, 1992).

2.2. ADAPTIVE PROCEDURE

The aim of all adaptive procedures is to provide the user with a level of accuracy ε_0 at a minimal computational cost. The present study will be restricted to the h-version which is the most commonly used procedure: one modifies the size and the topology of elements while preserving the same type of shape functions for the various meshes. A mesh $\mathbf{T}^*$ is considered optimal with respect to a measure of the error ε if (Ladevèze *et al*, 1986):

$$\begin{cases} \varepsilon^* = \varepsilon_0 & \text{prescribed accuracy} \\ N^* & \text{minimal (number of elements of } \mathbf{T}^*\text{)} \end{cases} \tag{5}$$

In order to solve problem (5), the following procedure is used:

- an initial analysis is performed on a relatively coarse mesh $\mathbf{T}$,
- the global error ε and the local contributions ε_E are computed for this mesh,
- the characteristics of the optimal mesh $\mathbf{T}^*$ are determined.

The optimized mesh $\mathbf{T}^*$ is built with the help of an automatic mesher and a second finite element analysis is carried out. To construct this mesh $\mathbf{T}^*$, it is necessary to use a mesher which correctly respects a map of prescribed sizes. In 2D, several automatic meshers of this type have been produced (Georges, 1991) and some of these have begun to be marketed. In 3D, the situation is less straightforward; it is currently difficult to produce a mesh which correctly respects a map of sizes.

The geometry is described with a modeller. Then, the mesh of the structure is developed in two steps:

– Mesh of the skin: the optimized mesh is generated by the mesher developed in L3S (Noel *et al*, 1994), (Noel *et al*, 1995a), (Noel *et al*, 1995b),
– Mesh of the volume: the volumic mesh is developed with the mesher GHS3D of the I.N.R.I.A. (Georges, 1991) which is, among the meshers available in industry, one of the most efficient.

In using the entire set of these tools, one can hope to completely automate 3D computations in elasticity. To estimate the quality of mesh procedures, an indicator of size conformance by comparing the real sizes generated by the mesher to those sizes actually being produced by the map of sizes is defined as follows:

$$l_E = \frac{\text{real size}}{\text{prescribed size}} \tag{6}$$

The ideal ratio is equal to 1; however, the conformance of sizes is considered satisfactory if the coefficient is such that: $2/3 \le l_E \le 3/2$. Results are visualized on a histogram that represents a global study of the conformance of sizes.

3. Auto-Adaptive Surface Mesh According to a Distribution of Sizes

3.1. DEFINITION OF THE GEOMETRIC MODEL USED AS A GEOMETRIC REFERENCE

In order to control a surface mesh, a geometric model used as a reference for all the meshing steps must be obtained. This geometric model is created thanks to an industrial geometric modeller. For the application which is described hereafter, the resultant geometric model must be a B-Rep (Boundary representation) one where the boundary of the volume is described as a collection of bi-parametric patches (either Bézier, N.U.R.B.S. or any typical bi-parametric law). A collection of vertices and lines is added to this model of the closed surface of the volume to be meshed. These lines and vertices describe either sharp edges or key points which must be explicitly meshed. Geometric modellers are not able to create any surface because of a unique patch and usually, the resulting patch decomposition does not have any mechanical meaning. Therefore, one important characteristic of the tools presented is their freedom with respect to patch decomposition.

This geometry produced from any C.A.D. software is then transferred to the meshing module by means of an I.G.E.S. file. This step can be accomplished thanks to any standard file commonly used in Computer Aided Design applications like SET, VDA, ..., or STEP. This specification ensures the independence of the process described hereafter from the geometric modeller used at the beginning of the analysis.

3.2. BUILDING AN INITIAL MESH

An initial mesh is built with any industrial surface meshing software. For the described application, the algorithm (Tanabe, 1992), (Sheng *et al*, 1992) used meshes the bi-dimensional parametric space of each patch (Yerry *et al*, 1983), (Lo, 1991), (George *et al*, 1992). The bi-dimensional meshes obtained are projected in the right 3D space thanks to the bi-parametric law defining the corresponding patch. Such an algorithm is patch-dependent, i.e. each boundary of patches is explicitly meshed. Indeed, one can note that any initial mesh for coping with the geometric model could be used (Noel *et al*, 1995a).

3.3. BASIC TOOLS TO ADAPT A SURFACE MESH

Before any adaptation of the mesh, the mesh must be classified on the geometric model used as a geometric reference. This step identifies the node corresponding to each vertex of the geometric model, G, and the subset of nodes and edges corresponding to each line of G. These elements of the mesh are said to be classified on a vertex or on a line of G. The nodes and edges which are not classified on a vertex or on a line of G are classified on the whole surface of G. The concept of classification stores the link between the topology and the geometry of the mesh.

When nodes are classified, optimization of the positions of nodes can be achieved. The classification of each node defines its degrees of freedom. A node classified on a vertex is fixed while one classified on either a line or a surface may slide on this line or surface. The operator used here is patch-independent. This means that nodes are not constrained to stay on their initial patch; then only the mechanical specifications defined by lines and vertices of G and stored by virtue of the classification concept are respected. The boundary of patches is no longer preserved in the mesh.

Displacements of nodes derived from the previous algorithm are not sufficient to adapt meshes to a pre-defined gradient of sizes. Three basic topological tools are thus used:

- *local refinement:* the local refinement procedure uses as an input a subset of edges of the mesh. These edges are to be cut and the faces connected to these edges are subdivided according to pre-defined topological schemes.
- *local coarsing:* the local coarsing procedure deletes a node from the mesh. Any node can be deleted except those which are classified on a vertex. When a node is classified on a line, the algorithm seeks to re-build an edge classified on the line in order to keep the mesh compatible with the geometric model, G.
- *arranging connectivities:* it does occur that some nodes are over-connected. This means that these nodes are connected to a large number of edges and faces; as a result the angles of faces must be degenerate. This problem is solved when swapping some edges which have automatically been selected in order to decrease the number of over-connected nodes.

3.4. MAKING A MESH CORRESPONDING TO A DISTRIBUTION OF SIZES

Now, let's assume that a distribution of sizes is known at each point of the space. The local size which must be obtained at a point is then defined by a law: $\mathrm{LS}(X,Y,Z)$

where X, Y, Z denote the coordinates of the point. The data given by the a posteriori analysis yield a discrete field of sizes (one size for each node of the mesh used for the analysis). The law LS is obtained by an interpolation between points.

The objective then is to apply local refinement or coarsing where it is necessary to render the mesh compatible with the distribution LS. To achieve this goal, every edge of the mesh is scanned and its length, S, is compared to $\mathrm{LS}(X_m, Y_m, Z_m)$ where X_m, Y_m, Z_m are the coordinates of the middle of the edge. A control parameter, $\chi > 0$, is used in order to develop a threshold for the comparison and to define the sharpness for achieving the distribution of sizes. Three cases are available:

- if $S \geq (1+\chi)\mathrm{LS}(X_m, Y_m, Z_m)$: the edge is selected for the refinement procedure,
- else if $S \leq (1-\chi)\mathrm{LS}(X_m, Y_m, Z_m)$: one extremity of the edge between the two available nodes is selected for the coarsing procedure,
- else: the edge is ignored.

After each topological adaptation, an optimization of connectivities and an optimization of the node positions are performed. The process is stopped once all edges have been ignored. Note that the distribution of sizes can be incompatible with the geometry to be meshed. Sometimes, the local size can be larger than the details defined in the geometric model. In such cases, the distribution of sizes can be automatically corrected to match the geometric constraints.

3.5. APPLYING THE BOUNDARY CONDITIONS

To perform a new computation, it is necessary to define boundary conditions on the mesh. When working with an auto-adaptive procedure, the subset of nodes and elements pertaining to a given boundary condition is not a constant set. Then, the boundary conditions must be applied on each mesh. Three possibilities are available:

- apply on each mesh the boundary conditions by hand. This may be a tedious task and one which is not automatic,
- place boundary conditions on an initial mesh and transfer boundary conditions from this mesh to the adapted one. This method must apply techniques from multi-grid data transfer, and then generates some errors,
- apply the boundary conditions on the geometric model G used as a reference and then transfer boundary conditions on a mesh only when necessary.

The third method is used in the present application. The area corresponding with the plane of symmetry, the cantilevered area and the area under pressure are all stored thanks to closed the loops of lines lying on the surface of the geometric model. The elements matching each boundary condition can be extracted in any mesh when a computation becomes necessary. It is thus easy to transfer any boundary condition onto its corresponding extracted elements.

4. Examples

The first example is a simplified structure. Since the surfaces are simple, the procedure of volumic mesh adaptation developed at LMT has been used (Coorevits *et al*, 1995). For reasons of symmetry, only one eighth of the structure is actually meshed. The desired error is 7%. The initial mesh comprises 5,132 10-node tetrahedra and 8,350 nodes; the obtained error is 13.57% (Figure 1). The optimized mesh comprises 5,008 elements and 8,012 nodes; the obtained error is 6.97% (Figure 2). In this example, it can be observed that the optimized mesh comprises fewer elements than does the initial mesh while the error has been cut in half; also the conformance with prescribed sizes is 84.2% (Figure 3).

The second example is the real structure. In this case, surfaces are defined by patches. The L3S mesher has thus been used. The initial mesh comprises 3,574 4-node tetrahedra and 891 nodes; the obtained error is 71.14% (Figure 4). The desired error is 40%. The optimized mesh comprises 7,068 elements and 1,608 nodes; the obtained error is 53.27% (Figure 5). It should be noted that in this example a conformance with prescribed sizes of 93.8% (Figure 6) has been obtained.

In this example, the levels of errors are relatively high; indeed, to limit the cost of computation and data transmission, we have used a coarse initial mesh with respect to the complexity of the structure studied.

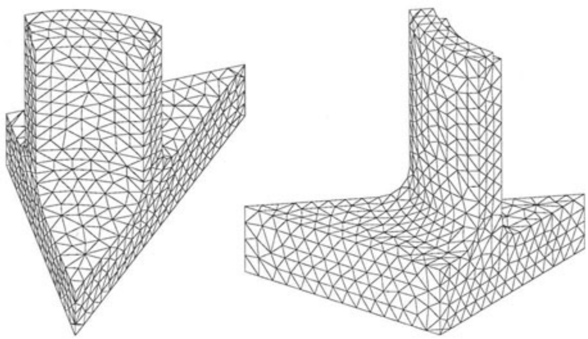

Figure 1. Initial mesh - 5,132 elements - 8,350 nodes - ε = 13.57%.

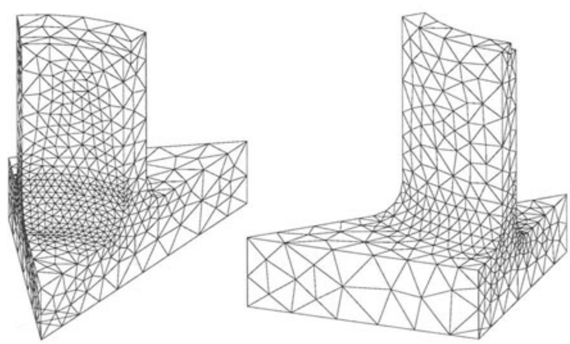

Figure 2. Optimized mesh - 5,008 elements - 8,012 nodes - ε = 6.97%.

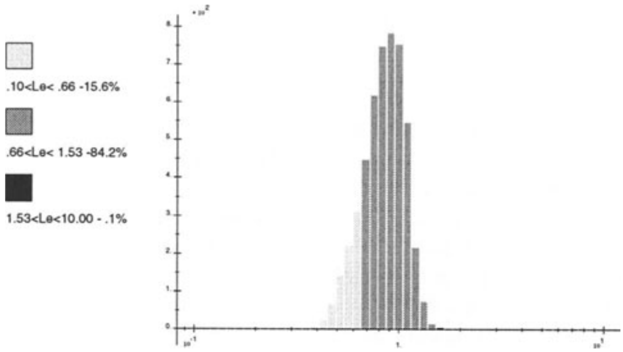

Figure 3. Map of conformance of sizes.

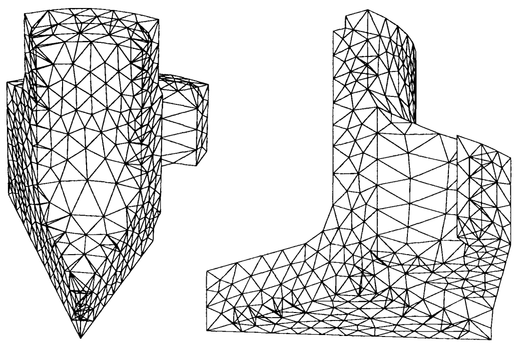

Figure 4. Initial mesh - 3,574 elements - 891 nodes - ε = 71.14%.

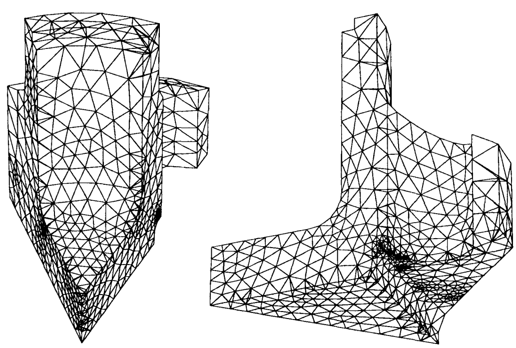

Figure 5. Optimized mesh - 7,068 elements - 1,608 nodes - ε = 53.27%.

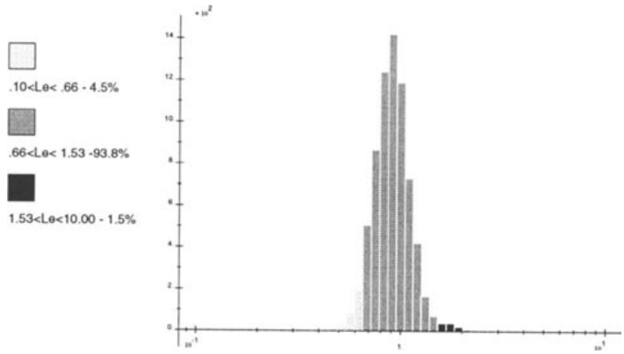

Figure 6. Map of conformance of sizes.

5. Conclusion

We have presented a procedure that allows obtaining adapted meshes in 3D by the use of an automatic surface mesher able to respect a map of sizes, an automatic 3D mesher and a post-processor for the control of finite element analyses. Naturally, several difficulties remain to be overcome, in addition to improving of CAD-computation connection; the transfer of a geometry to an automatic mesher is far from being adequately solved.

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Chapter 4
AUTOMATIC MODELLING OF MECHANISMS

USyCaMs: A SOFTWARE PACKAGE FOR THE INTERACTIVE SYNTHESIS OF CAM MECHANISMS

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1. Introduction

In the last twenty years or so, computer graphics has become a fundamental tool for the study of mechanisms, as made apparent by the software available in this area. We can cite IMP (Integrated Mechanisms Program) as one of the earliest software packages developed for the analysis of arbitrary linkages [7]. A few years later KINSIN III, a package meant for the synthesis of mechanisms, was introduced [6]. The graphical part of these early packages consisted essentially of 2-D lines. Further mechanism software packages, with improvements in their graphics, have been produced, such as LINCAGES [2], MINN-DWELL [5] and SIXPAQ [3].

Given that modern workstations provide a highly integrated environment for computation and interaction, our goal in the development of USyCaMs was that it should be intuitively easy to use and as general as possible. Following these criteria, the user of USyCaMs need not be a CAD expert, although a familiarity with the theory of cam mechanisms is expected, in order to better exploit the capabilities of USyCaMs. Solving complex problems, like undercutting, with visualization aids is reduced to moving the mouse around the appropriate menus.

USyCaMs has many applications. It can be used to give an introduction to cam mechanisms in an undergraduate course, or to solve complex design prob-

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lems involving, e.g., undercutting of spatial cam mechanisms, in a graduate design course. Furthermore, USyCaMs can be regarded as a sophisticated design tool for industrial applications involving dimensioning, balancing, dynamic analysis, simulation and finite-element analysis (FEA) for stress, strain and thermal calculations. Note that USyCaMs provides a database for useful mesh generation in FEA, but is limited to the handling and production of geometric and kinematic information.

2. Kinematics of Cam Mechanisms

The synthesis procedure is based on the minimization of power losses, which is achieved, in turn, by minimizing the magnitude of the sliding velocity along the contact surfaces. To this end, the contact surfaces are designed as ruled surfaces, and motion is transmitted along a common line, the contact generatrix, which gives rise to a higher kinematic pair. Two more kinematic pairs arise, namely, the cam-frame and the follower-frame pairs, which belong to the class of lower kinematic pairs, and can be either revolute or prismatic [1]. USyCaMs thus allows the synthesis of cam mechanisms not only with rotating, but also with translating cams or followers.

One objective of USyCaMs is to synthesize the contact surfaces of all the elements involved for two cases: (a) mechanisms comprising the frame, the cam, and the follower, henceforth termed *three-link mechanisms*; and (b) mechanisms similar to the former, but with an intermediate fourth element, the roller, henceforth termed *four-link mechanisms*. As a matter of fact, we are here following the established terminology in the realm of cam mechanisms, but, properly speaking, the intermediate element between cam and follower is not always a 'roller'. Indeed, when minimizing the magnitude of the sliding velocity between cam and 'roller' and between 'roller' and follower, the 'roller' turns out to be a hyperboloid of revolution that both slides and rotates with respect to the cam and the follower, in the most general case in which the axes of rotation of the cam and the follower are skew. In this case, we have a *spatial mechanism*. If the same axes intersect, we have a *spherical mechanism* and the roller takes the form of a cone of revolution and rotates without slipping about both the cam and the follower. Therefore, in the case of three-link mechanisms, two ruled surfaces are synthesized, while three are synthesized in the case of four-link mechanisms. The shape of the foregoing surfaces is determined so as to produce a given *input-output function* between cam and follower.

3. Software Description

We give an outline of USyCaMs for a *Silicon Graphics Inc. IRIS* workstation. It can run on other *UNIX* workstations with suitable graphics software and hardware, but then, obviously, all device-dependent features must be modified.

At the outset, we divide the window into five *viewports*, VP1, VP2, VP3, VP4 and VP5, as shown in Fig. 1. Each of these viewports serves a specific function:

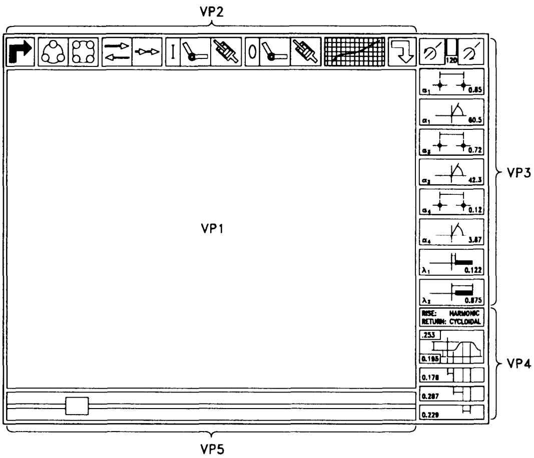


Figure 1. USyCaMs interface window.

VP1: This part of the screen is devoted to the rendering of both the still solid models and the animation of the motion of the mechanism under design.

VP2: This viewport displays the main menu in two modes, namely, passive and active. In passive mode, VP2 tells the user what kind of mechanism is in the process of synthesis; in active mode, the user can interact with the program and choose the type of mechanism desired.

VP3: This viewport shows the design parameters and interacts simultaneously with VP1, so that a change in any of the mechanism parameters is reflected in the solid models of the mechanism.

VP4: As VP3, VP4 interacts with VP1; this viewport shows the parameters pertaining to the input-output function.

VP5: If at least one of the parameters of VP3 or VP4 is active, a sliding bar appears in VP5, so that the user can modify continuously the parameter values by moving the cursor, with the aid of the mouse, along this bar.

3.1 ICONOGRAPHY

The main menu is iconized and displayed in VP2 as shown in Fig. 2; the user can choose the type of mechanism to be synthesized by clicking these icons with the mouse. Thus, VP2 is divided into seven sections called POSi, for $i = 0, 1, 2, \cdots, 6$, as described below:

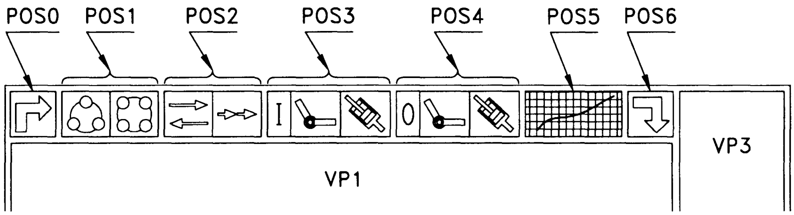


Figure 2. Icons of the main menu.

POS0: When this area is selected, VP2 changes from passive mode to active mode.

POS1: The mechanism can comprise either three links or four links. The option selected is highlighted to let the user know which one is active.

POS2: Similar to POS1, except that, in this case, the user chooses either an oscillating or an indexing mechanism.

POS3: The input kinematic pair can be revolute or prismatic; the user selects the type here.

POS4: Similar to POS3, but, in this case, the kinematic pair is chosen for the output.

POS5: This icon is used to define the input-output function with the aid of a submenu displayed in VP4.

POS6: The user can exit VP2 any time by selecting this icon, VP2 thus switching into passive mode.

In order to identify the type of mechanism under synthesis, we introduce a suitable labelling, namely, `x_xxx_xx`, the meaning of each of the three fields being

- `x`: The number of links of the mechanism, three (`3`) or four (`4`).
- `xxx`: The type of the follower motion, indexing (`ind`) or oscillating (`osc`).
- `xx`: Two characters are reserved for this field, `p` and `r`, which stand for prismatic and revolute, respectively. Thus, if we read from left to right, the first character tells us the input pair, while the second, the output pair.

For example, `4_osc_rr` indicates a four-link mechanism with oscillating follower, revolute input and revolute output.

The two square icons at the top of **VP3** allow the user to animate the motion of the mechanism. Here, the user can choose the sense of the input motion. With the six icons below these two, it is possible to modify the distance and the angle of three pairs of axes, namely,

1. The distance a_1 between the input and output axes;

TABLE 1. Design Parameters of VP3

Type of Mechanism	**VP3**							
	a_1	α_1	a_3	α_3	a_4	α_4	λ_1	λ_2
3_ind_pp								
3_ind_pr	×	×					×	×
3_ind_rp	×	×					×	×
3_ind_rr	×	×					×	×
4_ind_pp and 4_osc_pp		×	×		×		×	×
4_ind_pr and 4_osc_pr	×	×	×		×		×	×
4_ind_rp and 4_osc_rp	×	×	×		×		×	×
4_ind_rr and 4_osc_rr	×	×	×	×	×	×	×	×
3_osc_pp	×				×		×	×
3_osc_pr	×	×			×		×	×
3_osc_rp	×	×			×		×	×
3_osc_rr	×	×			×	×	×	×

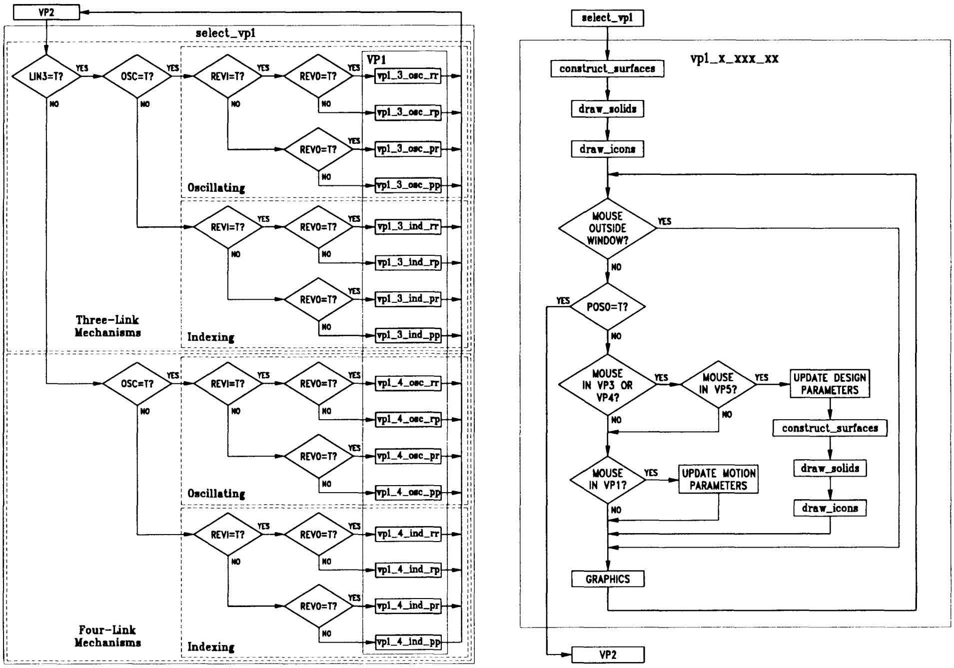
2. the angle α_1 between the above two axes;
3. the distance a_3 between the output and roller axes;
4. the angle α_3 between the above two axes;
5. the distance a_4 between the roller axis and its generatrix; and
6. the angle α_4 between the above two axes.

With the eighth and ninth icons of **VP3**, the user can modify the thickness of the contact surfaces, λ_1, λ_2, which do not affect the kinematics of the mechanism, but have to be specified for manufacturing purposes. The design parameters vary depending on the type of mechanism selected. The parameters pertaining to a given mechanism type are marked with × in Table 1.

3.2 MAIN LOOP

As mentioned above, viewport VP1 is used to display the solid model representation of the mechanism selected in VP2. If we look at Fig. 3*a*, we notice that there are up to sixteen different types of mechanisms with independent *synthesis procedures*, which are identified with the labels shown at the right-hand side of Fig. 3*a*. The flowchart sample of these procedures is shown in Fig. 3*b*. In the synthesis of one of the sixteen mechanisms the user will be working most of the time in its corresponding procedure, which is the reason why we call it the main loop.

All sixteen procedures have similar structures; what changes in each case is only the synthesis algorithm, `construct_surfaces`, the procedures to generate



(a) (b)

Figure 3. Flowchart of a) the `select_vp1` procedure; b) VP1 procedures.

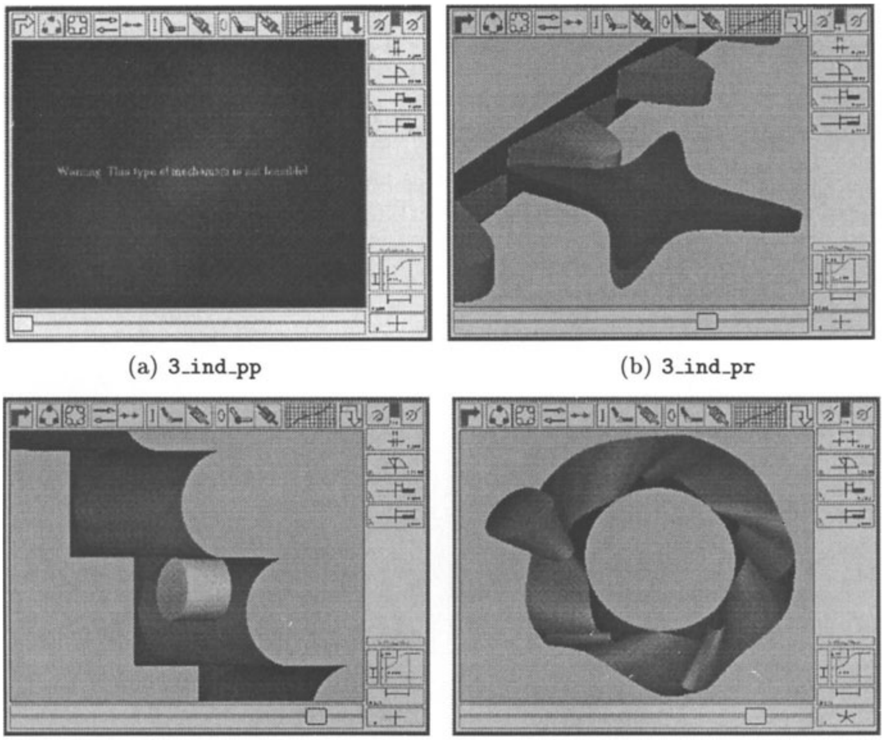
the solid models of cam and follower, `draw_solids`, and the procedures to draw the icons of VP3 and VP4, namely, `draw_icons`. At the main-loop level, USyCaMs performs the algorithm of the flowchart of Fig. 3*b*.

4. Rendered Examples

In this section we display still frames for each one of the cases mentioned above. Thus, in Fig 4 we include the possible solutions of three-link indexing mechanisms, one of them being unfeasible [4].

Three-link oscillating mechanisms with constant pressure angle are shown in Fig. 5. If we set $\alpha_1 = \pi/2$ in the mechanism shown in Fig. 5*c*, the solution is well known as the *cam mechanism with translating flat-face follower.*

Shown in Fig. 6 are the solutions of four-link indexing mechanisms, while, in Fig. 7, the solutions of four-link oscillating mechanisms. If we set $\alpha_1 = \pi/2$ in the mechanism shown in Fig. 7*c*, the resulting mechanism is known as the *cam mechanism with translating roller-follower.* The spherical counterpart of the planar cam mechanism with oscillating roller-follower is shown in Fig. 7*d*. The latter can be obtained by changing the design parameters.



(a) 3_ind_pp (b) 3_ind_pr

(c) 3_ind_rp (d) 3_ind_rr

Figure 4. Three-link indexing cam mechanisms.

5. Conclusions

The first version of USyCaMs has been completed according to the guidelines and objectives outlined in [4]. This version, called USyCaMs 1.0, was coded in C and supported by the graphics library GL.

Thanks to the graphical potential of USyCaMs, it has been possible to design mechanisms never conceptualized before. In this way, we have been able to develop innovative transmission systems; such is the case of PRICAM (Pure Rolling Indexing Cam Mechanism), whose prototypes were fully designed on the monitor, and then, built in two versions, planar and spherical.

6. Acknowledgements

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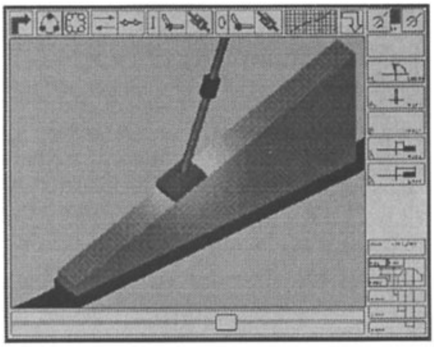

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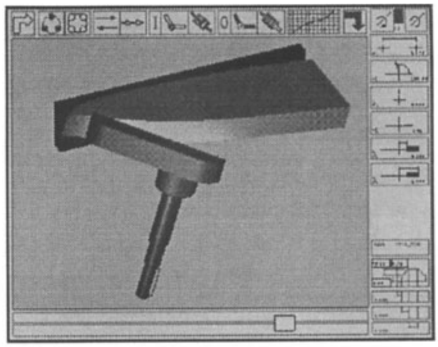

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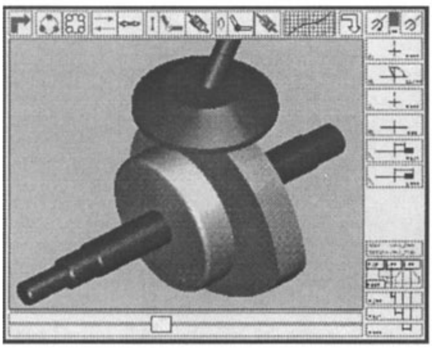

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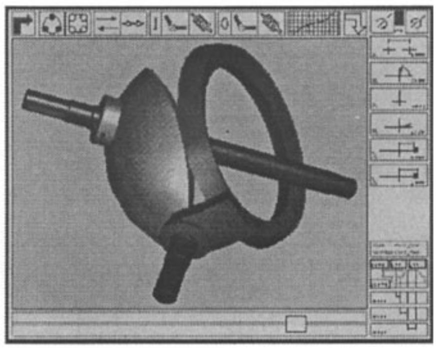

(d) 3_osc_rr

Figure 5. Three-link oscillating cam mechanisms.

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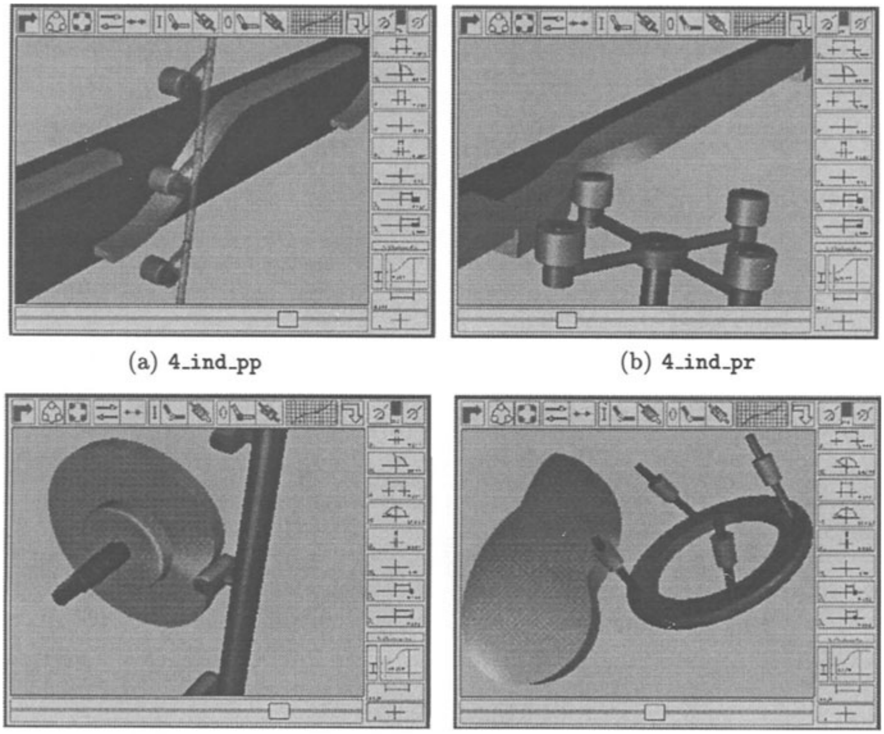

(a) 4_ind_pp (b) 4_ind_pr

(c) 4_ind_rp (d) 4_ind_rr

Figure 6. Four-link indexing cam mechanisms.

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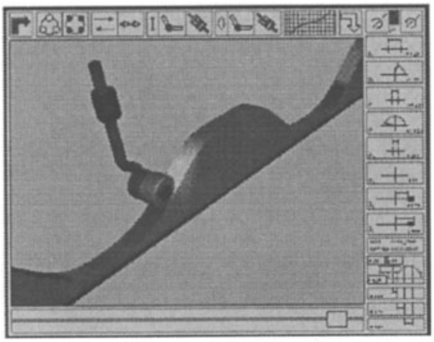

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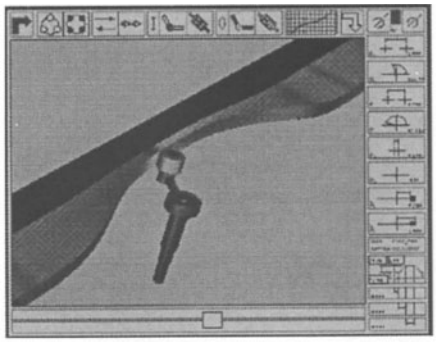

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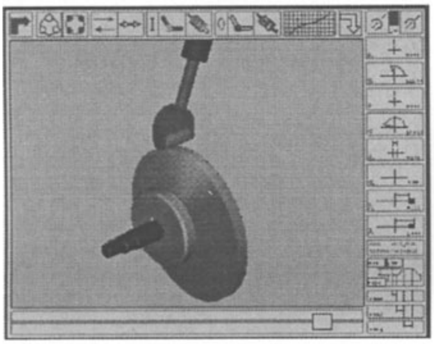

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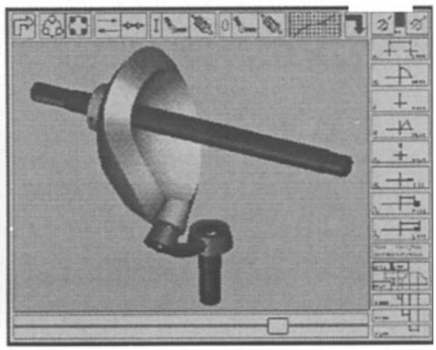

(d) 4_osc_rr

Figure 7. Four-link oscillating cam mechanisms.

WORKSPACE-ORIENTED METHODOLOGY FOR DESIGNING A PARALLEL MANIPULATOR

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Abstract.

One difficulty for designing parallel robots is that their performances are heavily dependent upon the geometry of the robot. We present a method for designing optimal parallel manipulators of the Gough platform type, according to design constraints like a specified workspace, best accuracy over the workspace, minimum articular forces for a given load, etc.... We show how the method has been used to design robots with high accuracy and high nominal load.

1. Introduction

Let us consider a 6 d.o.f. parallel manipulator as represented in figure 1. It consists of a fixed base plate and a mobile plate connected by 6 variable-length links. One of the extremities of each link is articulated with the base plate through an universal joint and the other extremity is articulated with the mobile plate through a ball-and-socket joint. By changing the 6 link lengths (which are measured with linear sensors) we are able to control the position and orientation of the mobile plate. This type of manipulator is well known and the first prototype was proposed by Gough [5], hence its name of Gough platform.

The main features of this type of robots are their high accuracy and high nominal load. Consequently they are very often used in flight simulation system [10] or as high accuracy positioning device.

But this highly unusual architecture is such that finding the "optimal" design i.e. the geometry of the robot which is the best with respect to some criterion, is a difficult task. This is this problem which is addressed in this paper.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 215–224.

2. Notation and design parameters

First we define a reference frame $O(x, y, z)$ and a mobile frame attached to the platform $C(x_r, y_r, z_r)$. A superscript ^{r} will denote a vector written in the mobile frame. The following symbols and variables will be used in this paper:

- A_i,B_i: center of link i passive joint attached to the base and end-effector of the robot.
- R: the rotation matrix between the moving frame and the reference frame (defined by the Euler's angles ψ, θ, ϕ)
- C: a fixed point on the moving platform. The posture of the platform will be defined by the coordinates of C in a reference frame and by the matrix R.
- ρ_i: length of the link i. There are two important parameters related to the link length: the dead length ρ^i_{min} of the link which correspond to the length of the link when the actuator is fully retracted and l_i which is the stroke of the linear actuator.

The geometry of a robot is defined by the 18 coordinates of the A_i in the reference frame, the 18 coordinates of the B_i in the moving frame, the 6 dead lengths ρ^i_{min} and the 6 actuator strokes l_i. Hence the total number of design parameters is 48. But in practical applications some other parameters may play an important role like, for example the overall size of the robot, the accuracy of the sensors measuring the leg lengths, the articular forces and the singular configurations. In the design process we want to determine the design parameters so that the robot fulfills a set of constraints. These constraints may be extremely different but we can mention the workspace requirement, the maximum accuracy over the workspace for a given accuracy of the sensors, the minimum articular forces for a given load, the maximal stiffness of the robot in some direction and the maximum velocities or accelerations for given actuator velocities and accelerations.

Few authors have addressed this problem. Claudinon [1] assumes that the joint centers lie on circles with fixed radii. He then uses a numerical method to determine the angle between two adjacent joint centers such that the resulting robot has a workspace which includes a specified workspace and it has a maximal linear velocity in a given position. Han [6] has proposed some general ideas to determine a parallel robot with a maximal accuracy. Ma and Angeles [7] have determined the side lengths of the base and moving plates for obtaining a minimum of the condition number, and therefore the best accuracy. Masory [8] gives some rules of a thumb for the variation of the workspace volume according to the change of the position of the joint centers and the range of the linear actuators. Gosselin [3] has studied the spherical 3 DOF parallel manipulators for obtaining the maximal workspace while taking into account the singularities [4].

3. Design methodology

In our design methodology we assume that the design specifications include a workspace requirement. In our approach we will proceed in two steps: first determine all the possible robot geometries such that the robot workspace includes the specified workspace, then among all these geometries we perform a numerical search to determine the robot which fulfills the other design specifications (consequently the methodology is *workspace oriented*).

3.1 DETERMINATION OF THE ROBOTS VIA THE WORKSPACE REQUIREMENT

Our purpose is to determine all the robot geometries such that the robot workspace includes a specified workspace. Our design program is based on the algorithm described in [9]. In this method we have reduced the set of design parameters by using the following assumptions:

- for each A_i point we know an unit vector $\mathbf{u_i}$ such that $\mathbf{OA_i} = R_1^i \mathbf{u_i}$, where R_1^i is the distance from O to A_i (i.e. the angle α_i is known, see figure 1).
- for each B_i point we know an unit vector $\mathbf{v_i}$ in the moving frame such that $\mathbf{CB_i^r} = r_1^i \mathbf{v_i}$, where r_1^i is the distance from C to B_i, i.e. the angle β_i is known.
- the dead lengths ρ_{min}^i and the strokes of the actuators are known (although this assumption can be relaxed as we will see in one of the application examples)
- the specified workspace is described by a set of geometrical objects which define the possible locations of C, the orientation of the moving platform being constant for each element of the set (but in the set the same object may be specified with different orientations). The geometrical objects may be segments, polygons or polyhedra.

Under these assumptions the number of design parameters is reduced to 12 (6 R_1^i and 6 r_1^i). But an advantage is that each pair of parameters (R_1^i, r_1^i) is totally independent in the sense that to achieve the desired workspace the possible values for a pair are independent from the values of the other pairs because the leg lengths necessary to reach a given posture are independent. Consequently we have reduced the problem to the determination of the possible values of the 6 pairs of parameters (R_1^i, r_1^i) i.e. we have to determine what are the valid regions in the 6 different planes R_1^i, r_1^i. The flavor of the algorithm may be introduced on a simple example where we

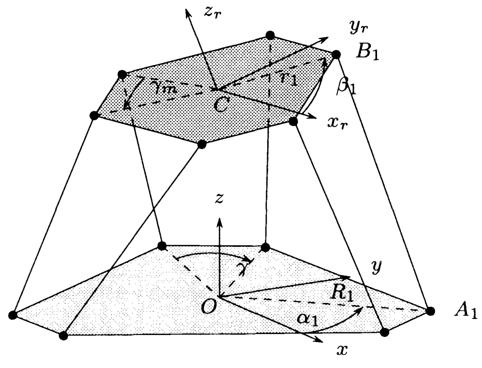

Figure 1. Design parameters

will assume that the desired workspace is specified via a segment describing a needed translation of the platform, with a given orientation over the segment. Assume that you want to determine the possible R_1^i, r_1^i of a link such that the leg length over the segment is always lower than the maximum leg length $\rho^i_{min} + l_i = \rho^i_{max}$.

Let us define the start and goal points of the segment as M_1, M_2. Any position of the end-effector on the trajectory may be defined as:

$$\mathbf{OC} = \mathbf{OM_1} + \lambda \mathbf{M_1M_2} \quad \text{with} \quad \lambda \in [0, 1] \tag{1}$$

The leg length ρ is the norm of the vector $\mathbf{A_iB_i}$:

$$\mathbf{AB} = \mathbf{OA} + \mathbf{OC} + R\mathbf{CB^r} = R_1\mathbf{u} + \mathbf{OM_1} + \lambda \mathbf{M_1M_2} + r_1 R\mathbf{v} \tag{2}$$

where R is the constant rotation matrix between the moving frame and the reference frame and $\mathbf{u}, \mathbf{v}$ are unit vectors defining the direction of the lines on which lie A_i, B_i. Consequently as ρ is the norm of the vector $\mathbf{AB}$ we get:

$$\rho^2 = R_1^2 + r_1^2 + 2R_1 r_1 \mathbf{u}.\mathbf{v^T} + R_1 F(\lambda) + r_1 G(\lambda) + H \tag{3}$$

where F, G, H are only dependent upon λ. Let ρ_{max} denote the maximum leg length and consider the equation $\rho^2 - \rho^2_{max} = 0$. For a given λ this equation defines an ellipse in the R_1, r_1 plane. For any point R_1, r_1 inside the ellipse we have $\rho^2 - \rho^2_{max} < 0$ and consequently any point inside the ellipse defines valid parameters with respect to the maximum leg length for this particular λ. As we want the valid points for the whole trajectory (i.e. for any λ in the range [0,1]) the valid points are obtained as the *intersection* of the set of ellipses. Furthermore it appears that this intersection can be computed as the intersection of the two ellipses calculated for $\lambda = 0$ and $\lambda = 1$.

If we consider now the minimum leg length constraint a similar reasoning enables to state that the forbidden R_1, r_1 points are obtained as the *union* $\mathcal{U}$ of the set of ellipsis defined by $\rho^2 - \rho^2_{min} = 0$, which is parameterized by λ. Although computing this union is a little bit more complex than the previous intersection this operation does not present real difficulty.

In summary we are able to determine the closed region of the R^i_1, r^i_1 plane which define the possible values of the R^i_1, r^i_1 parameters for a segment trajectory as the intersection of 2 ellipses minus the union of a set of ellipses. This closed region will be called the *allowed zone*.

Similar result are obtained if the specified workspace is a polygon or a polyhedra. For a set of such objects we compute the allowed region for each element of the set and then compute the intersections of all the allowed regions. Mechanical limits on the passive joints at A_i, B_i can also be introduced without any difficulty in this algorithm. Links interference can also be considered but with a higher complexity.

3.2DEALING WITH THE OTHER CRITERION

Using the workspace requirement we have deeply reduced the size of the search area for the parameters. We will assume now that we are trying to find the best robot with respect to some criterion. As an example we will consider that the sensors errors are known. The errors $\Delta\rho$ in the sensors measurements induce a positioning error ΔX of the moving platform. These two quantities are related by $\Delta X = J(X)\Delta\rho$ where $J(X)$ is the jacobian matrix of the robot, which is configuration dependent. So we may be interested in the geometry which leads to the smallest value of ΔX over the specified workspace i.e. in some sense the most accurate robot (on the opposite such an approach enables to determine the maximum value of the sensor accuracy for a given positioning accuracy of the platform over the workspace i.e. to look for the cheapest sensor). Unfortunately as there is no known analytical formulation of the jacobian matrix we have to rely on a two level sampling method: first to choose a set of possible robots i.e. a set of R^i_1, r^i_1 in the allowed zones and then to sample the workspace for determining the worst Cartesian positioning accuracy.

But at the same time note that we can also compute the maximal articular forces τ for a given load on the moving platform. Indeed if m denote the mass of the load and x_g, y_g, z_g the coordinate of the center of mass in the moving frame, we have:

$$(\tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6) = J^T(0, 0, -mg, -mgy_g, mgx_g, 0) \qquad (4)$$

and therefore in the second step we can also compute the articular forces. Remark also that we may check if there is a sign change in the articular forces in the workspace, meaning that the leg will be submitted both to traction and compression stress. Usually in view of accuracy it will be better that the legs are submitted only to one type of stress (in general compression) enabling to almost cancel the backlash in the actuators and reduction gears.

Similarly it is possible to compute during the same process the variations of the joint angles, and therefore to determine the best suitable joints.

It is also possible to examine the stiffness of the robot during this part of the process. Indeed if we assume that the longitudinal stiffness of the legs are k_i the stiffness matrix $\mathbf{K}$ of the robot is defined by:

$$\mathbf{K} = J^{-T}\mathbf{k}J^{-1} \tag{5}$$

where $\mathbf{k}$ is a diagonal matrix whose elements are the k_i. Consequently we may compute and record the lowest and highest stiffness of the robot in the desired workspace.

4. Application examples

The methodology proposed in the previous sections was used to design various fine positioning manipulators for the European Synchrotron Radiation Facility (ESRF) located in Grenoble. The purpose of these manipulators is to support various devices dealing with X-rays. For thermal stability the device lie on a granite bench whose dimensions is 1m x 1m x 15cm and the overall mass of the load and the bench vary from 500 kg to 1000 kg and has to be manipulated with an accuracy of the order of 1 to 10 μm. An example [2] is presented in figure 2. The repeatability of this robot under a load of 230 kg was determined using X-ray interferometry: it was estimated to be better than 0.1 μm and therefore in compliance with the accuracy requirements. Ten other prototypes have now been built.

4.1EXAMPLE: THE HFM2 MANIPULATOR

The nominal load for this manipulator is about 850 kg. The desired robot workspace and its accuracy defined in table 1. An additional requirement was that the stiffness of the robot should satisfy the quantitative requirement given in table 2. The stroke of the linear actuator was fixed to 80 mm so that existing actuators can be reused.

It was assumed that all the joint centers were lying on circles (i.e. R_1 and r_1 are identical for all joints). Basically the joint centers are disposed symmetrically along three lines with an angle of 120 degree between them

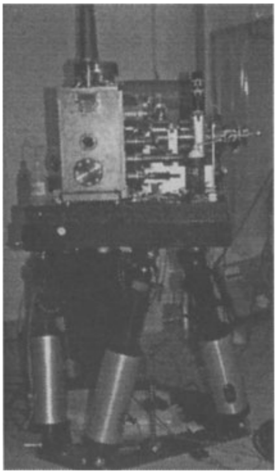

Figure 2. The ESRF-INRIA fine positioning device

x	y	z	θ_x	θ_y	θ_z
±30mm	-	±20mm	±5mrad	±5mrad	0-10 mrad
±0.01mm	-	±0.1mm	±0.1mrad	±0.1mrad	±0.05mrad

TABLE 1. *Workspace and accuracy requirements*

but to avoid interference between the actuators an angle γ of 20 degree was used for adjacent joint centers (figure 1, both on the base and on the moving platform. A set of 19 segment trajectories were specified for defining the desired workspace.

Our first problem was to determine the value of the minimal leg length ρ_{min}. To define this value we have first computed the area of the allowed zone as a function of ρ_{min}(figure 3). Using this graph it was possible to

k_x	k_y	k_z	k_{θ_x}	k_{θ_y}	k_{θ_z}
++	- -	-	-	-	+++

TABLE 2. *Stiffness requirements.*

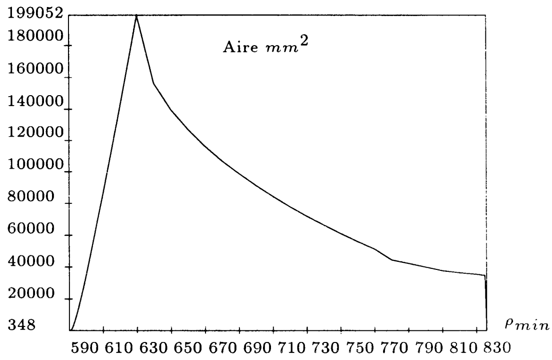

Figure 3. Variation of the area of the allowed zone as a function of ρ_{min}.

to determine that ρ_{min} should lie between 590 and 835. Various trials has enabled to compute that a value of 750 was the most suited for our purpose.

Next we have to determine the geometry leading to the desired accuracy with the maximal possible error for the length sensor together with a resulting satisfactory stiffness. We have decided to consider the robot whose sensor accuracy should be not less than 2 μm and to select the robot whose stiffness for the rotation around the z axis is the best.

The allowed zone was sampled (each point of the zone represent an unique robot) and the sensor accuracy and stiffness was computed for each point. It was found that the robot with the maximum stiffness along the x axis and for the rotation around the z axis has a sensor accuracy of 4μm, leading to the worst case accuracy defined in table 3. It may be seen that

Δ_x	Δ_y	Δ_z	Δ_{θ_x}	Δ_{θ_y}	Δ_{θ_z}
0.010000	0.009549	0.004870	0.009272	0.010488	0.011673

TABLE 3. *Maximal positioning error for a sensor error of 4 μm (mm,mrad)*

these errors lie well within the accuracy requirement. It has also been noted that the maximal sensor error leading to the desired accuracy is extremely variable according to the geometry: a ratio of 120:1 between the best and worst case was observed. The maximum articular force was estimated to be at most 2000 N and it was determined that the ball-and-socked joint should enable a rotation of 6.27 degree.

4.2EXAMPLE: THE HDM1 MANIPULATOR

In this example the robot nominal load is about 850 kg. The requirements on the workspace and accuracy are presented in table 4. The stiffness re-

	x	y	z	θ_x	θ_y	θ_z
Workspace	±5mm	-	±28mm	±5mrad	±5mrad	0-8 mrad
Accuracy	±0.01mm	-	±0.1mm	±0.1mrad	±0.1mrad	±0.05mrad

TABLE 4. *Workspace and accuracy requirements.*

quirements are given in table 2 and the stroke of the actuator was also 80 mm. The difference with the previous example was that the values of R_1, r_1 should not be greater than 360 mm.

It was first assumed that all the joint centers were lying on circles. Basically the joint centers are disposed symmetrically along three lines with an angle of 120 degree between them but to avoid interference between the actuators an angle γ of 20 degree (figure 1) was used for adjacent joint centers, both on the base and on the moving platform.

Our first problem was to determine the value of the minimal leg length ρ_{min}. To define this value we have first computed the area of the allowed zone as a function of ρ_{min}, It was established that the ρ_{min} cannot be lower than 600 but also that there was no robot with $R_1 < 360, r_1 < 360$ if ρ_{min} was greater than 715 mm.

We have decided to consider the robot whose sensor accuracy should be not less than 2 μm and to select the robot whose stiffness for the rotation around the z axis is the best. The investigation has shown that the best stiffness was obtained for a value of ρ_{min} equal to 662 mm.

To improve the stiffness we have investigated what was the influence of the γ, γ_m angles on the stiffness for a rotation around the z axis in the nominal position. It was established that the stiffness was increasing if all the successive articulation points, both on the base and on the mobile plate, were close to each other (i.e. the stiffness was maximum if the base and mobile plate were triangles and the angle $\gamma = \gamma_m = 0$).

Due to the size of the joint and possible interference between the links it is not possible to reduce γ to 0 but a value of 5 degree was considered. The investigation has shown that the best stiffness was obtained for a value of ρ_{min} equal to 670 mm. Two solutions have therefore been proposed to ESRF: one with ρ_{min}=662 mm, a sensor accuracy of 0.002443 mm and a stiffness for a rotation around the z axis at least 800216 N.mm/mrad and another one with ρ_{min}=670 mm, a sensor accuracy of 0.002795 mm and a stiffness for a rotation around the z axis at least 1070747 N.mm/mrad.

5. Conclusion

We have proposed a methodology to design a parallel manipulator of the Gough platform type according to desired requirements. This approach is workspace oriented in the sense that an important reduction of the search domain is obtained by first looking for the possible robot geometries whose workspace includes at least the desired workspace. Then the other requirements are used to determine the "optimal" robot. Successful applications of this methodology have been presented for the design of highly accurate robots was presented. In this application the slowest part of the design process was to determine the maximum sensor error leading to the desired accuracy and the minimal stiffness, as a numerical search over the workspace has to be used (due to the difficulty of obtaining the jacobian matrix of the robot). We intend to pursue our research on this particular topic in order to speed up the design process.
Acknowledgment: the author gratefully acknowledged the support of ESRF for this study.

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DESIGN OF ROBOTIC WORK CELLS : SYNTHESIS AND APPLICATION

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1. Introduction

The problem of designing robotic work cells has become a major field of research. Basically, this involves difficult issues like choosing suitable robots and placing them properly in the environment, as well as planning feasible time-optimal trajectories. Clearly, no global solution to this problem exists. Commercial robotic CAD systems, however more and more efficient, answer partially the questions of the designer.

The purpose of this paper is twofold. First, we make an extensive comparative survey of existing published work in the field of robotic work cells layout design. Research developments as well as industrial applications like robotic CAD softwares are considered.

Second, we point out our approach in this regard. This is a synthesis of the research work carried out in our laboratory during the last ten years. We set the robotic work cell design problem in the context of computer integrated manufacturing, using a unified global approach. We regard it as a general design problem, in which the design parameters, the objectives and the constraints are clearly identified and classified. This approach is illustrated with an industrial case in which the optimal design and placement of a manipulator inside a steam generator is studied.

2. State of the art

2.1. AVAILABLE ROBOTIC CAD SYSTEMS

This section describes the general layout design functionalities of some of the most well-known available industrial Robotic CAD systems : ROBCAD from Tecnomatix,

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 225–234.

CIMSTATION from Silma, IGRIP from Deneb, ACT from Aleph-Technologies, ROBOTICS from Mac Donell Douglas, CATIA-ROBOTIQUE from Dassault Systèmes and EUCLID-ROBOT-CP from Matra-Datavison.

The "Autoplace" functions provided by most of them are intended to help the designer in placing the robot (chosen by the designer itself) in function of given functional points.

The possible computed placements must be checked afterwards by the user since not all constraints are taken into account in the search procedure.

Most current robotic CAD systems include powerful graphic functions, allowing for realistic motion simulations. On the other hand, their approach uses a time consuming check and change loop procedure, in which the change step is to be carried out by the user himself.

The efficiency of robotic CAD systems strongly depends on the complexity of the robotic work cell to be designed.

2.2. RECENT RESEARCH WORK

Recently, and more specifically during the last five years, a lot of research work have been devoted to the problem of designing robotic work cells.

The proposed methods aim at finding out a particular set of design parameters :

-in [1-7], the design parameters are the position of the robot's base in the work cell,

-in [8-10], the design parameters are the link lengths of the robot and/or the position of the tool on the terminal link,

-one paper [11] was found which attempts to estimate the most suitable number of robot joints,

-in [12], the robot placement is searched together with the link lengths

-other authors assume that the robot is definitely defined and located in the cell, while the work points and parts are to be properly situated in the robot's Workspace [13-16]. In [28], the trajectory is prescribed relative to the workpiece, which is manoeuvred by a second robot, while the first robot handles the tool. In this case, the proper location of the work points in the cell is treated by optimizing the co-ordinated motion of the two robots.

-Finally, two papers were found which optimize the link lengths and sections together with the actuator sizes, while, however, the robot's base is assumed to be given [17,18].

Most of the objectives are defined geometrically : reaching the work points in [3-7] and [9-14], while additionally optimizing the cycle time in [28].

Some others are set in terms of dynamic performance : exerting a prescribed force or working with a given compliance or dexterity in [1,2,9,15,16].

The physical constraints are due to collisions with fixed obstacles in [4-6] and [12].

The generality character of the studies is not ensured. For instance, in [6,12], the study is restricted to planar robots with telescoping unlimited joints. In [5], collisions are detected only at the work points. In [4], the collisions are checked for only the first three links of the robot by using a grid in the Cartesian space.

Finally, a lot of work has been devoted to the problem of planning the motion of the robot's end-effector between the work points, while these work points as well as the robot's base are assumed to be fixed in the cell [19-21]. In this last case, the main objective is the non collision during motion while, if possible, minimizing the cycle time.

As a matter of fact, no attention has been paid as to how the robotic work cell design problem can be stated in a more global, coherent way.

3- A unified formulation

We propose in this section a global formulation of the robotic work cell design problem. This formulation was initially set in [30].

First, the design variables, the criteria and the constraints of this problem are classified. They are derived from the schedule of conditions of the robotized application.

The last part of this section is devoted to the presentation of an industrial case for illsutration purposes.

3.1. CLASSIFICATION OF THE ROBOTIC WORK CELL DESIGN PROBLEM

In a robotic work cell, we have to consider the robot(s), the process machines (milling, turning, welding, cutting, ...), and the perirobotic hardware with the transfer and the storage systems. We suppose thereafter that the main components of the work cell have been specified by the global objectives of the application.

The number of robots, machines, etc...and their nature is given.

The design of the robotic work cell needs to define -or to choose- the robot(s), and to describe the layout of the various components.

We propose to consider the following general design variables of the work cell :

dv1/ number of joints of the robot and nature of its structure (open or closed loop),

dv2/ type of joints (revolute or prismatic),

dv3/ relative orientation of the joints, and length of the links (the Denavit and Hartenberg parameters)

dv4/ geometric and physical characteristics of the actuators (size, electric and thermal characteristics), dv5/ geometric and physical characteristics of the links (cross section, material),

dv6/ the scheduling of the tasks,

dv7/ location (position and orientation) of the base of the robot in the work cell,

dv8/ location (position and orientation) of the end effector on the last link of the robot,

dv9/ location (position and orientation) of the peripheric hardware,

dv10/ location of the functional points, trajectories or domains to be reached by the robot.

The first five variables (dv1 up to dv5) are related to the robot design. The other ones are more general and concern the robotic work cell.

The task is described with the following constraints :

co1/ the given functional points, trajectories and domains to be reached and travelled through by the robot for performing the task (for instance spot welding points, or continuous welding trajectories, or assembly zones),

co2/ a given dynamic (forces, velocity, acceleration of the end effector) and a given load on the end effector,

co3/ a given environment with obstacles (static and mobile).

Finally, the work cell should be designed for satisfying the following criteria :

cr1/ a successful completion of the task,

cr2/ the minimum financial cost of the work cell,

cr3/ the minimum time cycle for the execution of the task.

The aforementioned enumeration is not exhaustive, but permits to treat a large number of industrial cases.

The global initial problem of the robotic work cell design can be stated as follows :

Find out the design variables :	dv1, dv2, dv3, dv4, dv5, dv6, dv7, dv8, dv9, dv10
With the constraints :	co1, co2, co3
Satisfying the criteria :	cr1, cr2, cr3

3.2. DESIGN OF A ROBOTIC CELL FOR THE INSPECTION OF A STEAM GENERATOR

3.2.1. Problem formulation

The application described in this section was realized in the frame of a research contract with EDF-DER (Electricité de France, Département Etudes et Recherche) [22].

The frame of this study is the robotization of inspection tasks inside a steam generator. The inspection tasks can be defined by the following requirements :

- reach and follow continuously the inner surface of a full half-sphere,
- enable tool changes : the end-effector should be able to go out the half-sphere through a circular opening (see figure 1).

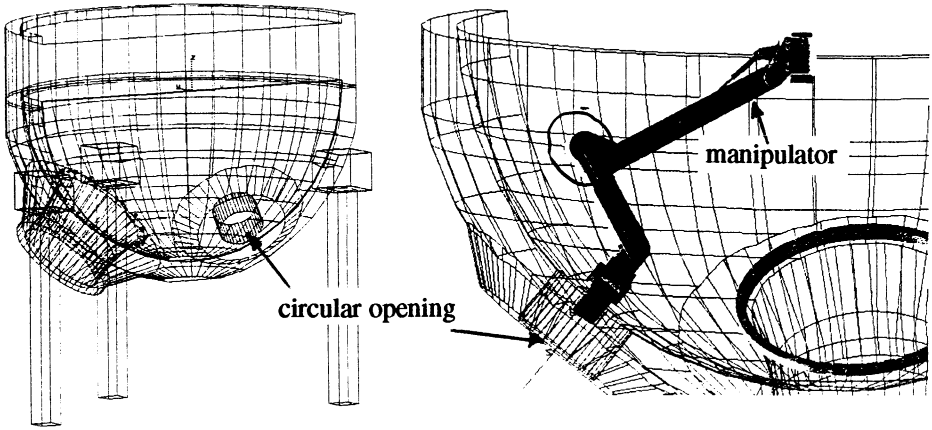

Figure 1 : Description of the environment

A first attempt for the placement of a TITAN-II manipulator (figure 2) had been carried out by EDF, using a commercial robotic CAD software (ROBCAD). However, no placement could be found for this manipulator [23]. In effect, the link lengths of the manipulator were clearly ill-conditioned to the problem.

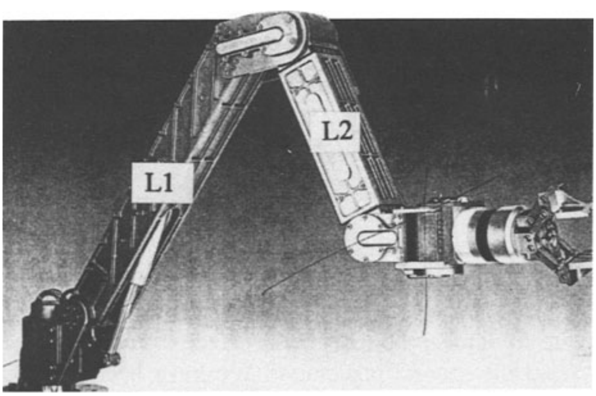

Figure 2 : Manipulator Sshilling TITAN II

The problem to solve now is the following : starting from the kinematic architecture of the TITAN-II manipulator, find :

- the two main link lengths L1 and L2 (dv6),
- and the robot placement (dv8)

which are best suited to the task,

under the following constraints :

- follow continuously the inner surface of the half-sphere (co1),
- without collision (co3).

The criteria to be considered are :

- success of the task (cr1), which can be ensured by verifying that the inner surface of the half-sphere is recovered by a t-connected[1] region of the manipulator workspace ;
- minimization of the cycle time (cr3), which can be performed in this case by minimizing the number of re-positioning of the manipulator base.

3.2.2. Solution to the problem

We have used a software package, POSOPT [24], which has been developed in our laboratory on the basis of the unified formulation of the robotic site design problem stated above. POSOPT had been successfully used for robot placement and design in car industry applications [25]. Today, POSOPT can optimize any set of design variables chosen in (dv3) to (dv11), under the constraints (co1) to (co3), with the criteria (cr1) and/or (cr2).

The optimal link lengths found by POSOPT for the problem at hand are L1=0.530m and L2=0.740m and , instead of 0.482m and 0.843m, the respective initial link lengths of the TITAN-II manipulator (see figure 3). We observe that the optimal link lenghts are closer to each other than the initial ones

The task can be successfully performed with only two distinct placements of the manipulator base : only one repositioning of the manipulator base is required. These results have been validated with the commercial robotic-CAD software CIMSTATION. Figure 4 (resp. figure 5) depicts the reachable surface of the half-sphere from the first placement (resp. from the second placement. We have been able to devise feasible continuous trajectories for each corresponding reachable surface.

[1] A t-connected region is a region of the manipulator workspace where any path can be continuously followed by the end-effector with no collision and no change of posture [29]

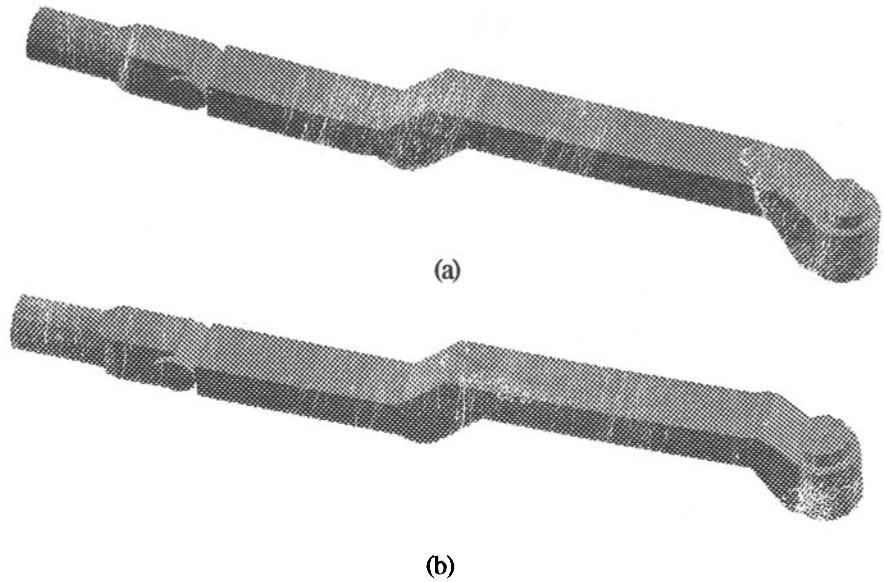

Figure 3 : Initial (a) and final (b) link lengths

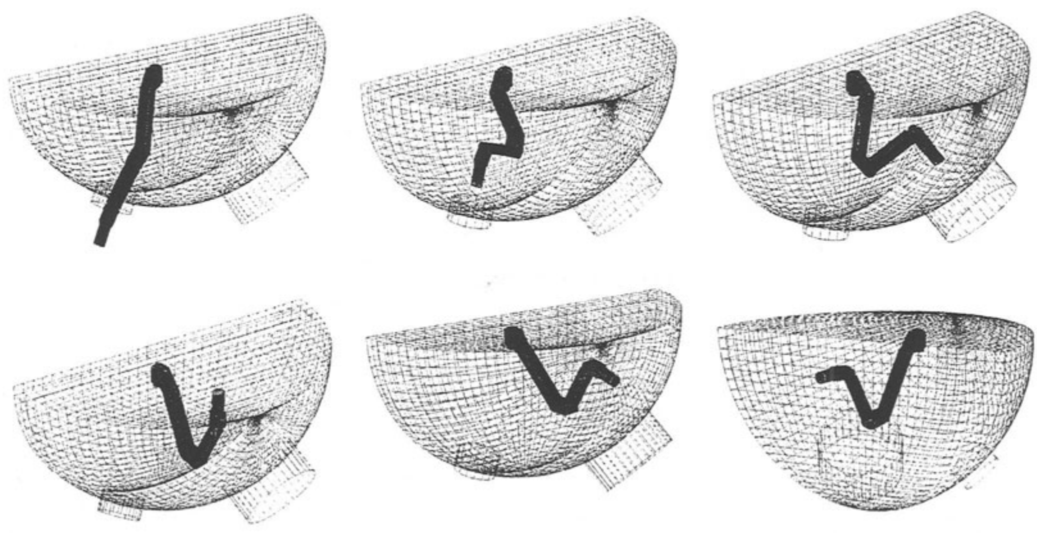

Figure 4 : Reachability from the first placement

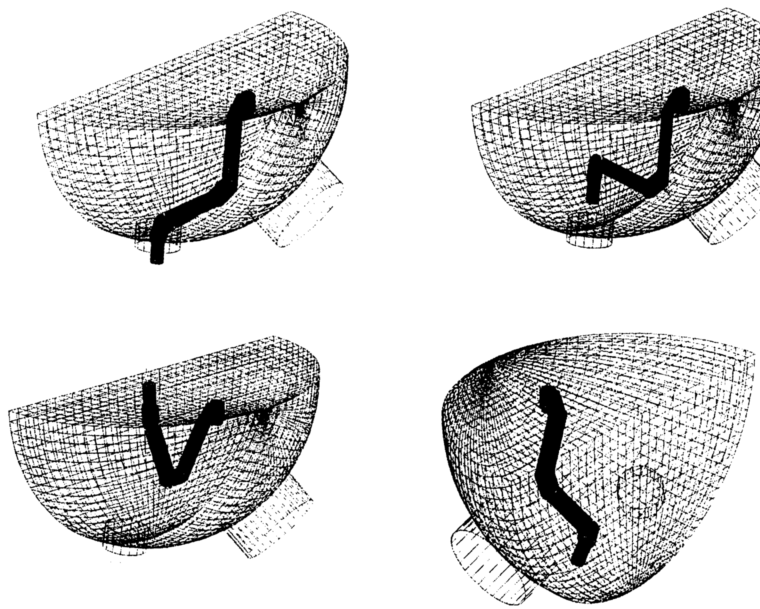

Figure 5 : Reachability from the second placement

4- Conclusions

In this article, the general problem of designing a robotic work cell has been stated using a unified formulation. The design variables, constraints and criteria involved in this issue have been classified. An industrial problem has been described, which illustrates an application of the concepts. This problem has been solved using POSOPT, a software developed in our laboratory for the design of robotic work cells. Other similar industrial applications have been treated with POSOPT (see for instance [26]). Clearly, it turns out that two difficult issues still remain unsolved : 1. finding the appropriate number of joints -design variable : dv1-, and 2. choosing the best suited types of joints -design variable : dv2-. This problem is the subject of current research work in our laboratory, using genetic algorithms [27].

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A TOOL FOR ROBOT DESIGN : FEASIBLE TRAJECTORY FROM A SINGULARITY

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Abstract. At a singularity, the Cartesian velocity along a particular direction (called singular direction) is zero for any joint velocity. In this paper, the feasibility of an acceleration along the singular direction is studied. The expression of the acceleration along the singular direction as function of joint velocity is analysed to define all the feasible trajectories starting at the singularity with a non zero initial acceleration. The study includes redundant or non redundant robots

I. Introduction

During the robot design stage, it is necessary to describe which task the robot will be able to execute. Often the task consist of successive motions. The first description of the robot capability is given by the workspace or the "t-connected regions" of the workspace when the feasibility of continuous trajectories in the output space is studied (Wenger 1992). The t-connected regions do not contain singularity. In this paper we describe for a given robot, all the trajectory in the output space that can be achieved from a singularity.

When the manipulator is at a singularity, it cannot perform a velocity along some special direction in the task space, referred to as *singular direction* (Kieffer 1994). A velocity in the output space can be produced only in the image of the jacobian matrix **J**. Such results could suggest that to be perfectly tracked, a trajectory should not lie outside the image of **J**, and should be orthogonal to the singular direction. However, this is misleading, as shown by L. Nielsen, C. Canudas de Wit and P. Hagander (1990). In some cases, a trajectory that is tangent to the singular direction can be tracked with finite joint rates, if the time parametrization of the trajectory is properly chosen. The conditions on feasible trajectories are often raised through controllability studies (Nielsen et al 1990, Tuhmed and Alford 1988, Pohl and Lipkin 1991). However it is important to study feasibility regardless of the definition of a control law, because a non feasible trajectory is non feasible whatever the control law. But some control laws like

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the use of pseudo inverse of weighted pseudo inverse of $\mathbf{J}$ reduce the number of trajectories which can be followed (Nakamura 1986, Maciejewsky 88).

Kieffer has paid particular attention to the study of singularities at path following problems (1991,1994). In (Kieffer 1994), the path tracking problem is analysed through the geometric investigation of curves in the space (x0, x1,..., xn), where x0 is the arc-length parameter of the prescribed path, xi ($1 \le i \le n$) are the manipulator joint variables. These curves are obtained by computing a local model using a Taylor series expansion of the matrix equation of closure. If the path can not be precisely tracked with arbitrary time parametrization, the suitable velocities, accelerations and jerk solutions can be derived on each position along the path. The approach proposed in (Kieffer 1994) cannot be extended to redundant robots.

This paper investigates the feasible trajectories for a robot manipulator starting at a singularity. By trajectory, we mean a path defined in the task space, together with a time parametrization: $\mathbf{X}(t)$, $0 \le t < T$. The robot is assumed to be at a singular configuration $\mathbf{q}(0)$ at $\mathbf{X}(0)$. A trajectory is said to be feasible if there exists finite joint velocities that produce a motion of the end-effector along this trajectory. The feasibility is defined, first, geometrically by the initial tangent and the curvature of the path, and then, in terms of time parametrization by the initial velocity, acceleration and jerk. It is worth noting that the main objectives of this work differ from the ones in (Kieffer 91, 94). The path is not assumed to be given, but, the set of all feasible trajectories is computed for a given robot and a given singularity. In addition, the proposed algorithms for the feasibility analysis can also be applied for redundant robot. The study uses a symbolic differentiation computations of the jacobian matrix $\mathbf{J}$, and can be simply implemented on dedicated softwares like Mathematica or MapleV.

This paper is organised as follows. Section 2 is devoted to some preliminaries. Since the velocity along the singular direction is zero at the singularity, the possible existence of a non zero acceleration along the singular direction is studied in section 3. Different cases of singularity are analysed in section 4. The results for an example are given in section 5

2. Preliminaries

We assume that the robot starts from an initial singular configuration where the jacobian rank deficiency is 1.

In this work, the particular case where the robot remains singular all along the trajectory (the end-effector follows a boundary surface of the workspace for example) is not studied, since in this case the trajectory can be executed with arbitrary time parametrization (Spanos, Kholi 1985). The trajectories of interest are such that, at $t = 0$, the robot configuration is singular, and for any $t \neq 0$, the configuration is non singular. The feasibility analysis needs to be carried out only at $t = 0$ since any trajectory is feasible as soon as $t > 0$ (the robot has left the singularity).

The vector of velocities in task space denoted $\dot{\mathbf{X}}$ ($\dim(\dot{\mathbf{X}})=m$) is related to the vector of joint velocities $\dot{\mathbf{q}}$ ($\dim(\dot{\mathbf{q}})=n$ with $n \ge m$) through the following relation:

$$\dot{\mathbf{X}} = \mathbf{J(q)}\,\dot{\mathbf{q}} \tag{1}$$

The rank of the jacobian matrix **J** is m-1, the jacobian matrix can be written (after rows and columns permutation if necessary and a corresponding reorganisation of $\dot{\mathbf{X}}$ and $\dot{\mathbf{q}}$)

$$\mathbf{J} = \begin{bmatrix} \mathbf{J_p} & \mathbf{J_s} \\ \mathbf{J_q} & \mathbf{J_r} \end{bmatrix} \tag{2}$$

where $\mathbf{J_p}$ is a (m-1 x m-1) invertible matrix.

As **J** is not full rank there exists a linear combination of the rows of **J** which is zero.

The unity vector $\mathbf{u_m}$ defined on the singularity by (at t=0) :

$$\mathbf{u_m(0)^t} = \sqrt{\frac{\mathbf{1}}{\mathbf{1+\ (J_q\ J_p^{-1})^t\ (J_q\ J_p^{-1})}}}\ \mathbf{[\ -J_q\ J_p^{-1}\quad 1\ ]} \tag{3}$$

describes the singular direction at the singularity because for any vector $\dot{q}$:

$$\dot{\mathbf{d}} = \mathbf{u_m(0)^t}\,\dot{\mathbf{X}} = \mathbf{u_m(0)^t\ J(q)}\,\dot{\mathbf{q}} = \mathbf{0}$$

the velocity along this direction is zero.

As $\mathbf{J_p}$ is invertible, the first m-1 components $\dot{\mathbf{X}}$ are independent and allow us to describe the velocity along the non singular direction. These components will be denoted $\dot{\mathbf{Y}}$. Any $\dot{\mathbf{Y}}$ can be created with finite joint velocities. $\dot{d}$ is the velocity along the fixed direction $\mathbf{u_m}(0)$. At t=0, $\dot{d}$ is zero as **L(q)** defined by $\mathbf{L(q)} = \mathbf{u_m}(0)^{\mathbf{t}}\,\mathbf{J(q)}$ is zero at the singularity. In the next section we will study the derivative of $\dot{d}$.

$$\begin{bmatrix} \dot{\mathbf{Y}} \\ \dot{d} \end{bmatrix} = \begin{bmatrix} [\mathbf{J_p}\quad \mathbf{J_s}]\,\dot{\mathbf{q}} \\ \mathbf{L(q)}\,\dot{\mathbf{q}} \end{bmatrix} \qquad \begin{matrix} (4) \\ (5) \end{matrix}$$

A necessary condition for a motion to exist along the singular direction, is that the joint velocities appear explicitly in the expression of one of the higher derivatives of $\dot{d}$ at t = 0. This condition is not sufficient because the joint velocities are related to the effector velocity along the non singular directions as well as via equation (4).

3. Acceleration feasibility along the singular direction

The acceleration along the singular direction $\mathbf{u_m}$ is denoted $\ddot{d}$. For a trajectory, defined by $\dot{\mathbf{Y}}$ and $\dot{d}$, to be feasible, the joint velocities have to satisfy equation (4) and to produce the acceleration $\ddot{d}$.

The m-1 equations of system (4) are regarded as constraints that reduce the choices for $\dot{\mathbf{q}}$. The problem of searching for a n-component vector $\dot{\mathbf{q}}$ with m-1 constraints will be treated as looking for a n-m+1 vector

$$\dot{\mathbf{Y}} = \mathbf{J_p}\,\dot{\mathbf{q}}_\mathbf{p} + \mathbf{J_s}\dot{\mathbf{q}}_\mathbf{s} \tag{6}$$

and the joint velocities $\dot{\mathbf{q}}$, solution to equation (6) are :

$$\dot{\mathbf{q}} = \mathbf{M}\,\dot{\mathbf{Y}} + \mathbf{N}\,\dot{\mathbf{q}}_\mathbf{s} \tag{7}$$

$$\text{where}\quad \mathbf{M} = \begin{bmatrix} \mathbf{J_p^{-1}} \\ \mathbf{0_{n-m+1,m-1}} \end{bmatrix},\ \mathbf{N} = \begin{bmatrix} \mathbf{-J_p^{-1}\,J_s} \\ \mathbf{I_{n-m-1}} \end{bmatrix}$$

The vector $\dot{\mathbf{q}}_\mathbf{s}$ is an arbitrary (n-m+1) vector describing the set of solutions $\dot{\mathbf{q}}$, The matrix $\mathbf{N}$ is composed by a basis of the kernel of $\mathbf{K}$. Thus, the choice of $\dot{\mathbf{q}}_\mathbf{s}$ has no influence on $\dot{\mathbf{Y}}$. On the other hand, $\ddot{d}$ may depend on $\dot{\mathbf{q}}_\mathbf{s}$ as we will see. By differentiating equation (9), and since $\mathbf{L} = \mathbf{0}$ at the singularity, the acceleration along the singular direction is, at t = 0:

$$\ddot{\mathbf{d}} = \dot{\mathbf{q}}^\mathbf{T}\ \nabla\mathbf{L}\ \dot{\mathbf{q}} \tag{8}$$

with $\nabla\mathbf{L} \in \Re^{nxn}$, the gradient of $\mathbf{L}$ with respect to $\mathbf{q}$.
Using equations (7) et (8), the acceleration $\ddot{d}$ can be expressed as function of $\dot{\mathbf{q}}_\mathbf{s}$:

$$\ddot{d} = \dot{\mathbf{q}}_\mathbf{s}^\mathbf{T}\ \mathbf{A}\,\dot{\mathbf{q}}_\mathbf{s} + \mathbf{B}\,\dot{\mathbf{q}}_\mathbf{s} + \mathrm{C} \tag{9}$$

where : $\mathbf{A(q(0))= N^T\ \nabla L\ N,\ B(q(0),\ \dot{Y}(0)\ )= \dot{Y}^T\ M^T\ (\nabla L^T{+}\nabla L)\ \ N,}$

$\mathbf{C(q(0),\dot{Y}(0)\ )= \dot{Y}^T\ M^T\ \nabla L\ \dot{Y}}$

All calculations are done at the singularity, at t=0. The question is whether a vector $\dot{\mathbf{q}}_\mathbf{s}$ exists which produces the acceleration $\ddot{d}$. From equation (9), it is clear that $\ddot{d}$ depends explicitly on $\dot{\mathbf{q}}_\mathbf{s}$ if $\mathbf{A}\big(\mathbf{q}(0)\big) \neq \mathbf{0}$ or if $\mathbf{B}\big(\mathbf{q}(0),\dot{\mathbf{Y}}(0)\ \big) \neq \mathbf{0}$.

4. The different classes of singularity

The matrix $\mathbf{A}$ can be written as the sum of a symmetric matrix $\mathbf{A_S}$ and of an anti symmetric matrix, which does not affect $\ddot{d}$. Thus, equation (9) can be rewritten as:

$$\ddot{\mathbf{d}} = \dot{\mathbf{q}}_\mathbf{s}^\mathbf{T}\ \ \mathbf{A_S}\,\dot{\mathbf{q}}_\mathbf{s} + \mathbf{B}\,\dot{\mathbf{q}}_\mathbf{s} + \mathrm{C} \tag{10}$$

This equation depends explicitly on $\dot{\mathbf{q}}_s$ if $\mathbf{A}_s(\mathbf{q}(0)) \neq \mathbf{0}$ or if $\mathbf{B}(\mathbf{q}(0),\dot{\mathbf{Y}}(0)) \neq \mathbf{0}$. The singularities will be classified into class 1 or 2 depending on whether $\mathbf{A}_s$ is zero or not.

The feasible trajectories are characterised by $\ddot{d}(0)$ which may depend on $\dot{\mathbf{Y}}(0)$ through the coefficients **B** and C in equation (10).

The initial tangent to the trajectory is defined by the vector $[\dot{\mathbf{Y}}(0)^t \;\; 0]^t$ if $\dot{\mathbf{Y}}(0) \neq 0$, and $[\ddot{\mathbf{Y}}(0)^t \;\; \ddot{d}\,]^t$ if $\dot{\mathbf{Y}}(0) = \mathbf{0}$. The case $\dot{\mathbf{Y}}(0) = \mathbf{0}$ is especially interesting as it describes a large class of trajectories, this case implies **B=0** et C=0.

<u>Class 1</u>: $\mathbf{A}_S(\mathbf{q}(0)) \neq \mathbf{0}$

Here, equation (10) is a second order equation in $\dot{\mathbf{q}}_s$ for which a solution may or may not exist according to the value of $\ddot{d}$. Consider the special interesting case $\dot{\mathbf{Y}} = \mathbf{0}$:

$$\ddot{\mathbf{d}} = \mathbf{A}_s(\mathbf{q}(0))\; \dot{\mathbf{q}}_s^{\;2} \qquad (11)$$

The matrix $\mathbf{A}_s(\mathbf{q}(0))$ is real and diagonal in the basis of its eigenvector. Let $\dot{\mathbf{q}}_b$ denote the expression of $\dot{\mathbf{q}}_s$ in the aforementioned basis. We have:

$$\ddot{\mathbf{d}} = \sum_{i=1}^{n-m+1} \lambda_i\, (\dot{q}_{bi})^2 \qquad (12)$$

where λ_i is the i^{th} eigenvalue of $\mathbf{A}_s(\mathbf{q}(0))$.

Case 1.1.: If the eigenvalues have different signs, it can be easily shown that all trajectories starting at the singularity are feasible (even if $\dot{\mathbf{Y}} \neq \mathbf{0}$).

Case 1.2.: If the eigenvalues of $\mathbf{A}_s(\mathbf{q}(0))$ have the same sign, then $\ddot{d}$ keeps the same sign for any $\dot{\mathbf{q}}_b$. Thus in this case, the trajectory can be tracked in one sense only. For a non redundant robot, only the case 1.2 exists. Physically, this means that the end-effector starts from a boundary between two regions of different degrees of accessibility in the workspace. The end-effector can move only in one sense, namely, toward the region of higher accessibility.

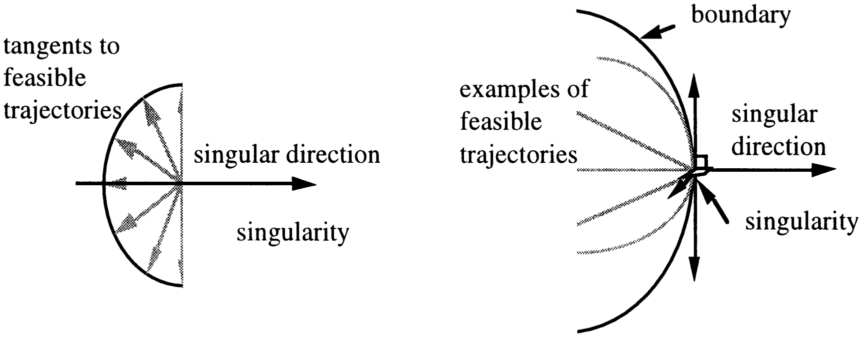

Figure 1.: Typical feasible trajectories for $\mathbf{A}_S \neq \mathbf{0}$

In summary, for class 1 case 1.2, the feasible trajectories have the following characteristics (figure 1.):

- their initial tangents lie in a half space.
- the feasible trajectories that start orthogonally to the singular direction ($\dot{\mathbf{Y}} \neq \mathbf{0}$) are such that their initial curvature is constrained.

<u>**Class 2**</u>: $\mathbf{A_S}(\mathbf{q}(0))=\mathbf{0}$

For any trajectory such that $\dot{\mathbf{Y}}(0) = \mathbf{0}$ (thus $\mathbf{B} = \mathbf{0}$ and $C = 0$), equation (10) implies that the acceleration along the singular direction is necessarily zero. Then, such trajectories are non feasible with a non zero initial acceleration.

On the other hand, the trajectories that start orthogonally to the singular direction ($\dot{\mathbf{Y}} \neq \mathbf{0}$), but such that $\mathbf{B}(\mathbf{q}(0),\dot{\mathbf{Y}}(0)) \neq \mathbf{0}$ are feasible with non constrained curvature (since when $\mathbf{A_S} = \mathbf{0}$ and $\mathbf{B} \neq \mathbf{0}$, equation (10) admits one solution for any $\ddot{d}$).

Finally, the trajectories that start orthogonally to the singular direction and such that $B(\mathbf{q}(0),\dot{\mathbf{Y}}(0)) = 0$ are feasible if and only if their curvature in the plane defined by the singular direction and their initial tangent satisfies $\ddot{d} = C$ (see equation (10) when $A = 0$ and $B = 0$). Typical feasible trajectories when $\mathbf{A_S=0}$ are depicted in Figure 2.

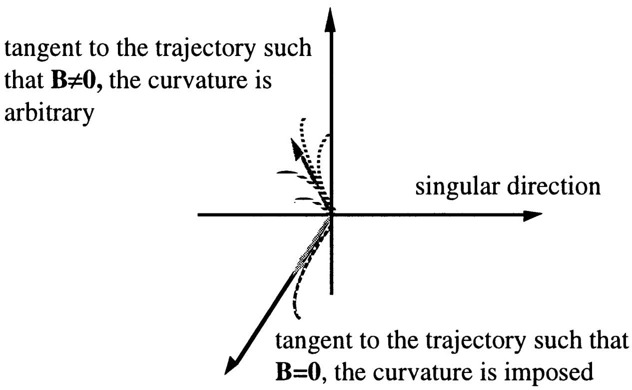

Figure 2.: Typical feasible trajectories for $\mathbf{A_S = 0}$

5. Examples

For a two degree of freedom planar robot, if the length of the two links are different, all singularities are class 1-singularities. As this robot is non redundant: $\mathbf{A_S}$, $\mathbf{B}$ and C are scalar, the only singularities corresponds to external boundary of the workspace. If the two link lengths are identical, the internal singularity (full folded back arm singularity) is a class 2 singularity. An acceleration can not be produced along the singular direction neither in one way or in the other way (Chevallereau 96). If a degree of freedom is added in order to transform the robot into a three-degree-of-freedom planar robot, the singularities are modified. In the next section we will study this example.

5.1. THE PLANAR 3-DEGREE-OF-FREEDOM REDUNDANT ROBOT

We study here the planar 3-degree-of-freedom redundant robot with link lengths: l_1, l_2 and l_3, respectively. The singular configurations of this robot are $q_2 = k_2\pi$ and $q_3 = k_3\pi$, where k_2 and k_3 are integers.

The velocity model is:

$$\begin{cases} \dot{x} = -(l_1S1+l_2S12+l_3S123)\,\dot{q}_1 - (l_2S12+l_3S123)\,\dot{q}_2 - l_3S123\,\dot{q}_3 \\ \dot{y} = (l_1C1+l_2C12+l_3C123)\,\dot{q}_1 + (l_2C12+l_3C123)\,\dot{q}_2 + l_3C123\,\dot{q}_3 \end{cases}$$

Sijk and Cijk stand for $\mathrm{Sin}(q_i+q_j+q_k)$ and $\mathrm{Cos}(q_i+q_j+q_k)$, respectively.

At the singularity the rank of $\mathbf{J}$ is one :

$$\begin{cases} \dot{x} = -S1(l_1+\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_1 - S1(\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_2 - S1\varepsilon_3l_3\,\dot{q}_3 \\ \dot{y} = C1(l_1+\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_1 + C1(\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_2 + C1\varepsilon_3l_3\,\dot{q}_3 \end{cases}$$

where $\varepsilon_2 = \mathrm{Cos}(q2)$ and $\varepsilon_2 = \mathrm{Cos}(q2+q3)$

The value of q1 at the singularity is denoted $q1=q1_0$. We assume that $S1_0 = \mathrm{Sin}(q1_0)$ is not zero (a similar study can be done with $C1_0 = \mathrm{Cos}(q1_0)\neq 0$).The chosen invertible sub matrix is : $\mathbf{J_p} = [\,-S1(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3)\,]$.

The singular direction is defined by:

$$\mathbf{u_m}(0)^t = \frac{1}{\sqrt{\left(\frac{C1_0}{S1_0}\right)^2+1}}\begin{bmatrix} \frac{C1_0}{S1_0} & 1 \end{bmatrix} = [\,C1_0 \quad S1_0\,]$$

The velocity along the non singular direction can be defined by:

$$\dot{x} = -S1(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3)\,\dot{q}_1 - S1(\varepsilon_2 l_2+\varepsilon_3 l_3)\,\dot{q}_2 - S1\varepsilon_3 l_3\,\dot{q}_3$$

For $l_3 \neq 0$ and $S1\neq 0$:

$$\dot{q}_3 = \frac{\frac{\dot{x}}{S1} - (l_1+\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_1 - (\varepsilon_2l_2+\varepsilon_3l_3)\,\dot{q}_2}{\varepsilon_3l_3}$$

This equation can be written as equation (7) with:

$$\dot{\mathbf{q}} = \mathbf{M}\,\dot{x} + \mathbf{N}\begin{bmatrix}\dot{q}_1\\ \dot{q}_2\end{bmatrix}, \text{ where } \mathbf{N} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ -\frac{(l_1+\varepsilon_2l_2+\varepsilon_3l_3)}{\varepsilon_3l_3} & -\frac{(\varepsilon_2l_2+\varepsilon_3l_3)}{\varepsilon_3l_3} \end{bmatrix}$$

The expression of **L(q)** is given by $\mathbf{L(q)}=\mathbf{u_m}(0)^t\,\mathbf{J(q)}$, we have:

$$\mathbf{L} = [-(l_1\ S10+l_2\ S120+l_3\ S1230)\quad -(l_2\ S120+l_3\ S1230)\quad -L_3\ S1230]$$

where $Sijk0=\mathrm{Sin}(qi+qj+qk-q1_0)$

The gradient $\nabla\mathbf{L}$ is first computed using Mathematica, and then evaluated at the singularity:

$$\nabla\mathbf{L} = \begin{bmatrix} -(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3) & -(\varepsilon_2 l_2+\varepsilon_3 l_3) & -\varepsilon_3 l_3 \\ -(\varepsilon_2 l_2+\varepsilon_3 l_3) & -(\varepsilon_2 l_2+\varepsilon_3 l_3) & -\varepsilon_3 l_3 \\ -\varepsilon_3 l_3 & -\varepsilon_3 l_3 & -\varepsilon_3 l_3 \end{bmatrix}$$

The matrix **A** is defined by : $\mathbf{A}=\mathbf{N}^t\ \nabla\mathbf{L}\ \mathbf{N}$

$$\mathbf{A} = \begin{bmatrix} \dfrac{-(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3)(l_1+\varepsilon_2 l_2)}{\varepsilon_3 l_3} & \dfrac{-(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3)(\varepsilon_2 l_2)}{\varepsilon_3 l_3} \\ \dfrac{-(l_1+\varepsilon_2 l_2+\varepsilon_3 l_3)(\varepsilon_2 l_2)}{\varepsilon_3 l_3} & \dfrac{-(\varepsilon_2 l_2+\varepsilon_3 l_3)(\varepsilon_2 l_2)}{+\varepsilon_3 l_3} \end{bmatrix}$$

A is symmetric and non zero since the link lengths are assumed to be non zero. Thus, the singularities are of class 1.

5.1.1 Planar 3-DOF redundant robot : full extended arm singularity.

We study the case where $l_1 = l_2 = l_3 = 1$.

The singularity analysed here is $\varepsilon_2 = \varepsilon_3 = 1$. In this case, **A** can be computed as:

$$\mathbf{A} = \begin{bmatrix} -6 & -3 \\ -3 & -2 \end{bmatrix}$$

The eigenvalues of **A** are -7.6 and -0.39. Since they have the same sign, the motion along the singular direction is feasible in one sense only. The singularity studied here is the external boundary of the workspace, this means that the end-effector cannot move outside the workspace. These results are illustrated in figure 3.

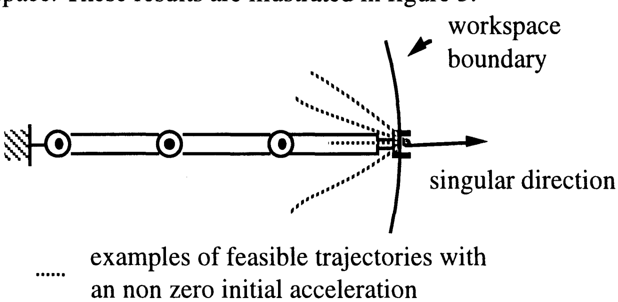

Figure 3.: The 3.D.O.F. Planar Robot: Full extended arm configuration

5.1.2 Planar 3-DOF redundant robot : link 2 outstretched and link 3 folded back.

This type of singularity is defined by $\varepsilon_2 = 1$ and $\varepsilon_3 = -1$. **A** can be computed as :

$$\mathbf{A} = \begin{bmatrix} -2 & -1 \\ -1 & 0 \end{bmatrix}$$

The eigenvalues of **A** are -2.41 and +0.41. Since their signs are different, the motion along the singular direction is feasible in both senses. Physically, the end-effector, starting from an internal singularity, will remain in its workspace for both ways of motion. These results are illustrated in figure 4.

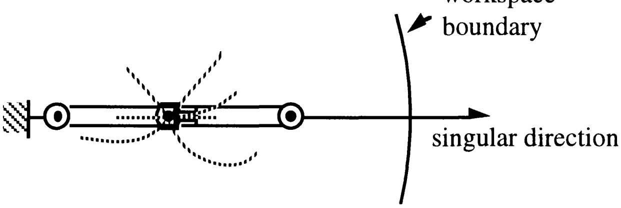

Figure 4.: The 3.D.O.F. Planar Robot: link 2 outstretched and link 3 folded back.

The eigenvalues of **A** instruct on the difficulty for the robot to move in one way. Smaller is the value, higher must be the joint velocity to produce a given acceleration. But due to the quadratic expression of the acceleration along the singular direction, if the eigenvalue is divided by 100 the joint velocity must be multiplied by 10 to have a given acceleration.

5.2 REMARK ON FEASIBLE TRAJECTORIES WITH INITIAL NON ZERO JERK

The search for feasible trajectories was performed for initial non zero accelerations. However, a path that is non feasible with a non zero initial acceleration may become feasible with a zero initial acceleration and a non zero initial jerk. The method proposed in section 3 and 4 can be extended as shown in (Chevallereau 96) for non redundant robots.

For a 2 degrees of freedom planar robot with equal link lengths, the feasible paths are unchanged by considering time parametrization such that initial acceleration is zero and initial jerk is not zero. But for other robots some path non feasible with non zero initial acceleration may become feasible with non zero jerk only (Chevallereau 1996) as for the robot described in (Wenger 1992). For this robot, the studied singularity is a singularity with three equal inverse kinematic solutions. There is a relation between the behaviour of a robot at a singularity and the number of equal roots of its inverse kinematic model as shown be Lloyd (1996).

6. Conclusions

This work has been devoted to the feasibility analysis of trajectories starting at a singularity with rank deficiency of 1. The tools proposed here can be used for any robot and singularity and allows to characterise easily all the feasible trajectories with zero initial velocity and non zero acceleration. Both redundant and non redundant robots were considered. It turns out that the set of feasible trajectories with non zero initial acceleration depends on the type of singularity encountered, and these information about the capability of motions of the robot must be taken into account during the robot design.

In the feasibility analysis proposed in this paper, the control inputs are the joint velocities. To prevent infinite joint accelerations, a more tedious but similar study can be completed using joint acceleration as control inputs. In this case, the feasible trajectories depend on the initial joint velocities (Ait Mohamed 95).

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SENSITIVITY ANALYSIS FOR OPTIMISATION OF FLEXIBLE MULTI-BODY SYSTEMS

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Abstract. A method for the sensitivity analysis of the dynamic transient response of flexible multi-body systems is presented. The main objectives in developing the method are: 1) to reduce cost and achieve accuracy of the sensitivity analysis, 2) to develop a performant tool for the sensitivity analysis and the optimisation of flexible multi-body systems. Practical applications are located in the automotive industry, with the optimisation of the driving behaviour of vehicles and in the aerospace industry. The method consists in solving simultaneously the dynamic and the sensitivity problem. Two simple examples are presented to demonstrate the method, one for a dynamic response problem, and the second one for a kinematic problem.

1. INTRODUCTION

Flexible multi-body systems are an assembly of structural members linked by kinematic joints. For the last ten years, research has focused on the analysis problem, resulting in an abundant literature on the topic (Geradin, 1994).

Another problem concerns the structural optimisation of such systems. That is to say, modifying the design definition, in order to improve the response. Optimisation methods consist in formulating the design problem as a mathematic programming one, in which a structural characteristic is made minimised or maximised under constraints (Braibant, 1985; Haftka *et al.*, 1993). One main difficulty in structural optimisation is the high computational cost resulting from sensitivity analysis.

Indeed, as the initial problem is both nonlinear and nonexplicit, the usual strategy is to replace the optimisation problem with a sequence of approximated sub-problems, obtained by a linearization process. These approximations require sensitivity analysis which can be achieved by finite differences. Several methods are presented in the

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literature to reduce the cost of the sensitivity analysis. The direct method proposed here was previously used for static and dynamic linear analysis. We develop here this method in the case of the dynamic transient or kinematic analysis of flexible multi-body systems.

This paper is organised as follows : the first part concerns the theoretical formulations of the structural and the sensitivity analysis problems. Two illustrative examples are given in the second part. A damper-spring-mass system illustrates the dynamic behaviour and the deployment of a landing gear illustrates the kinematic case.

2. THEORETICAL FORMULATION OF THE SENSITIVITY ANALYSIS

The formulation of the optimisation problem makes reference to the set of design variables, the optimisation constraints related to the structural behaviour and the objective function : the structural response to be improved. The usual strategy in structural optimisation consists in replacing the exact problem by a convergent sequence of approximated sub-problems, in which the design objective function and the constraints are obtained through a linearization process (Braibant, 1985). The latter requires the knowledge of the derivatives of the functions describing the problem with respect to the design variables. These derivatives can be approximated by finite differences. It is however expensive and accuracy and even differentiability are not guaranteed. In the sequel, the derivatives are computed using a semi-analytical method (direct method). Equations of motion and their numerical solution are presented in section 2.1. Section 2.2 gives the sensitivity analysis theory.

2.1. Equations of motion of flexible multi-body systems

The computer methods used to simulate and solve the dynamic response of flexible multi-body systems must give an appropriate representation of motion. As a result, they must take into account the frame flexibility, the geometrical nonlinearities, and the algebraic constraints representing the kinematic joints. We present in this section the solution developed by Cardona and Geradin (Geradin, 1994; Cardona, 1989), which is implemented in the MECANO software (Manuel Mecano, 1995).

The motion is represented in terms of absolute coordinates and finite rotations, which allows an easy expression of the kinematic joints. The problems are geometrically nonlinear, and they can present nonlinear material behaviour.

The temporal integration is implemented using the implicit method of Newmark, for two main reasons :

1) the implicit integration entails the use of Newton Raphson method and makes it possible to satisfy the constraints imposed on the system precisely,
2) in the nonlinear case, the implicit integration of Newmark leads to an unconditional stability in all the spectrum frequencies. Consequently, this method is well suited for flexible multi-body systems, for which high frequencies can be generated by the vibration of some elements. These vibrations induce numerical instability for most integration methods.

The general form of the dynamic equilibrium equations for constrained systems is the following :

$$\begin{cases} \mathbf{M}\ddot{q} + g^{INT}(\lambda, \dot{q}, q, t) = g^{EXT} \\ \phi(q,t) = 0 \end{cases} \tag{1}$$

where : **M** is the mass matrix,

$g^{INT}(\lambda, \dot{q}, q, t)$ is the sum of internal inertial loads ($\mathbf{C}\dot{q}$ or $\mathbf{K}q$) and the contribution being the result of kinematic constraints ($\mathbf{B}^T\ \lambda$),

g^{ext} is the sum of external inertial loads,

q is the vector of generalised coordinates,

λ is the vector of Lagrangian multipliers,

$\phi\ (q,t) = 0$ represents kinematic constraints at joints.

Upper points indicate time derivatives.

The first step of Newmark's method is the Taylor development of displacements and velocities limited to the second order :

$$\begin{cases} q_{n+1} = q_n + h\,\dot{q}_n + (\tfrac{1}{2} - \beta)h^2\ddot{q}_n + \beta h^2\ddot{q}_{n+1} \\ \dot{q}_{n+1} = \dot{q}_n + (1-\gamma)h\,\ddot{q}_n + \gamma h\,\ddot{q}_{n+1} \end{cases} \tag{2}$$

where h is the time step size and (β,γ) are free parameters.

Next the constrained nonlinear problem (1) is solved at time t_{n+1}, with the iterative method of Newton-Raphson which leads to inverse the linear system :

$$\begin{bmatrix} \mathbf{S}' & \mathbf{B}^T \\ \mathbf{B} & 0 \end{bmatrix} \begin{bmatrix} \Delta q \\ \Delta\lambda \end{bmatrix} = \begin{bmatrix} r(\bar{\lambda}_{n+1}, \bar{q}_{n+1}, \dot{\bar{q}}_{n+1}, t_{n+1}) \\ -\phi(q_{n+1}, t_{n+1}) \end{bmatrix} \tag{3}$$

where : $r(\lambda, q, \dot{q}, t) = g^{EXT} - g^{INT}(\lambda, q, \dot{q}, t) - \mathbf{M}\,\ddot{q}$ is the residual vector,

$\mathbf{S}' = \dfrac{1}{\beta h^2}\mathbf{M} + \dfrac{\gamma}{\beta h}\mathbf{C}' + \mathbf{K}'$ is the iteration matrix of the linearized system,

$\mathbf{K}' = \dfrac{\partial g^{INT}}{\partial q}$ is the tangent stiffness matrix,

$\mathbf{C}' = \dfrac{\partial g^{INT}}{\partial \dot{q}}$ is the tangent damping matrix,

$\mathbf{B} = \dfrac{\partial g^{INT}}{\partial \lambda} = \dfrac{\partial \phi}{\partial q}$ is the matrix of constraint gradients.

2.2. The direct method for sensitivity analysis

The method consists in differentiating the equations (1) with respect to a design variable x. We obtain thus the sensitivity problem, equations (4) :

$$\begin{cases} \mathbf{M}\,\ddot{Q} + G^{INT}\left(\Lambda, Q, \dot{Q}, t\right) = G^{EXT} \\ \Phi\,(Q,t) = 0 \end{cases} \tag{4}$$

where $G^{INT}\left(\Lambda, Q, \dot{Q}, t\right) = \mathbf{K}^t(q)\,Q + \mathbf{C}^t(q)\,\dot{Q} + \mathbf{B}^T\Lambda$,

$$\Phi\,(Q,t) = \mathbf{B}\,Q + \frac{\partial\phi}{\partial x},$$

$$G^{EXT} = \frac{\mathrm{d}\,g^{EXT}}{\mathrm{d}\,x} - \frac{\partial g^{INT}}{\partial x} - \frac{\partial \mathbf{M}}{\partial x}\ddot{q}\,,$$

and capital letters indicate derivatives of displacements, velocities and accelerations. The mass matrix $\mathbf{M}$ is assumed to be independent of q and $\dot{q}$. Initial conditions and matrix derivatives are obtained either analytically or numerically by finite differences.

We point out that as for equations (1), equations (4) can be solved with the Newmark's method. Furthermore a similarity exists between the two linearized problems. For the sensitivity problem, we have a similar expression to the linearized equations (3), with a new tangent matrix and a new residual vector:

$$\begin{bmatrix} \tilde{\mathbf{S}}^t & \tilde{\mathbf{B}}^T \\ \tilde{\mathbf{B}} & 0 \end{bmatrix} \begin{bmatrix} \Delta Q \\ \Delta\Lambda \end{bmatrix} = \begin{bmatrix} R(\overline{\Lambda}_{n+1}, \overline{Q}_{n+1}, \dot{\overline{Q}}_{n+1}, t_{n+1}) \\ -\Phi(Q_{n+1}, t_{n+1}) \end{bmatrix} \tag{5}$$

However we point out that the expression of G^{int} leads to the equality of tangent matrix for both problems :

$$\tilde{\mathbf{K}}^t = \frac{\partial G^{INT}}{\partial Q} = \mathbf{K}^t,\ \tilde{\mathbf{C}}^t = \frac{\partial G^{INT}}{\partial \dot{Q}} = \mathbf{C}^t,\ \tilde{\mathbf{B}} = \frac{\partial G^{INT}}{\partial \Lambda} = \mathbf{B} \tag{6}$$

So, at each time step, the strategy is to solve successively the dynamic and the sensitivity problems. This method is very attractive, because at the cost of one time integration, we obtain simultaneously the dynamic and the sensitivity solutions, and the cost of sensitivity analysis is extremely low.

3. SIMPLE PROBLEMS

To evaluate effectiveness of the method presented above, two numerical examples are provided. The optimisation problem can next be solved using a classical programming method like the convex linearization method or the recursive quadratic programming method or the generalised method of moving asymptotes.

3.1. A one DOF nonlinear impact absorber

The nonlinear one DOF system of *figure 1* consists of a fixed mass m and two design variables (c ,k) which represent respectively damping and spring coefficients.

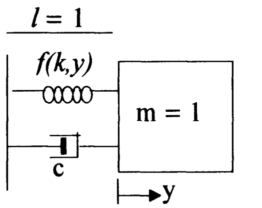

Figure 1. A one DOF nonlinear impact absorber.

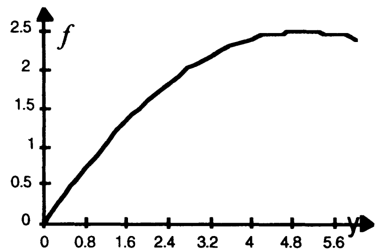

Figure 2. The law between load and elongation of the nonlinear spring.

The law between load f and elongation y of the nonlinear spring is :

$$f(k,y) = ky + y^2/10$$
$$\text{avec } k = 1$$

The system impacts a fixed barrier at time $t = 0$ with initial velocity $\dot{y}(0) = 5m/s$, where $y(0) = 0$. The equations of motion are :

$$\begin{cases} m\ddot{y} + c\dot{y} + f(k,y) = 0 \\ y(0) = 0 \\ \dot{y}(0) = 5 \end{cases} \tag{7}$$

Figure 3 shows the results obtained for the dynamics response of the mass.

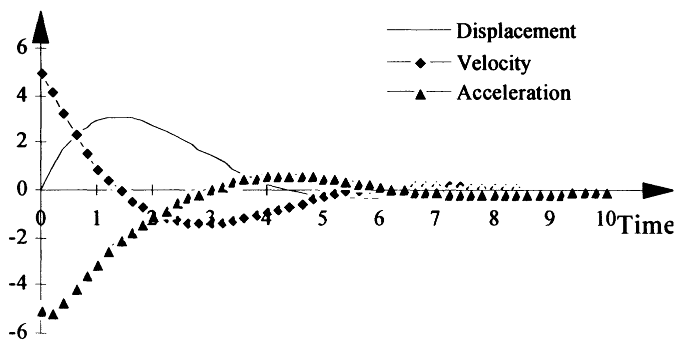

Figure 3. Dynamic response of the mass.

The direct method for sensitivity analysis leads to the general form of the sensitivity problem as :

$$\begin{cases} m\ddot{Y} + G^{\text{int}} = G^{\text{ext}} \\ + \text{ initial conditions} \end{cases} \tag{8}$$

where $Y = \dfrac{dy}{dx}$, $G^{\text{ext}} = -\dfrac{\partial g^{\text{int}}}{\partial x}$, $G^{\text{int}} = c\,\dot{Y} + \dfrac{\partial f}{\partial y}Y$, with $\dfrac{\partial f}{\partial y} = k + 2k\,y/10.$

x is the design variable k or c, so that we obtain for the two sensitivity analysis problems the following expressions :

Sensitivity analysis problem with respect to the design variable k :

$$\begin{cases} m\ddot{Y} + c\dot{Y} + \dfrac{\partial f}{\partial y} Y = -y \\ Y(0) = 0 \\ \dot{Y}(0) = 0 \end{cases} \tag{9}$$

Sensitivity analysis problem with respect to the design variable c.

$$\begin{cases} m\ddot{Y} + c\dot{Y} + kY + \dfrac{\partial f}{\partial y} Y = -\dot{y} \\ Y(0) = 0 \\ \dot{Y}(0) = 0 \end{cases} \tag{10}$$

The *figures (4 et 5)* present the results obtained by the direct method. No difference is found with the results obtained with finite differencies.

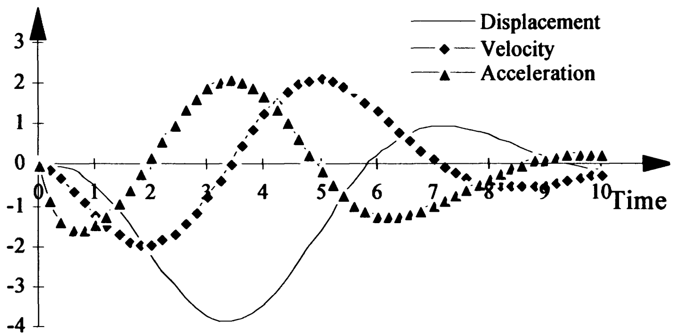

Figure 4. Sensitivity of the mass with respect to the parameter *k*

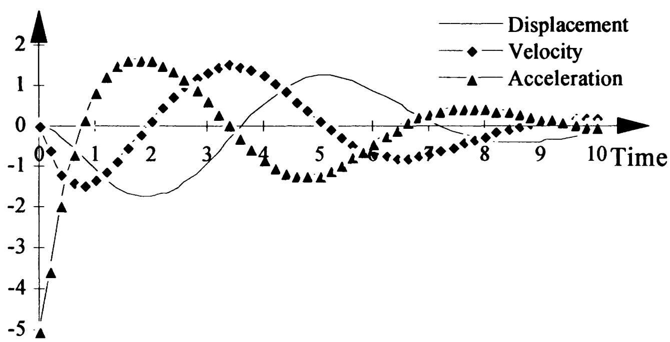

Figure 5. Sensitivity of the mass with respect to the parameter *c*

3.2. Deployment of a landing gear

This application was initially proposed at the Delft Technologic University. The simple model of the landing gear of *Figure 9* consists of two rigid bars and a rigid triangular part. The point P where the wheel is fixed at the triangular part is initially in position C_1 , and it must be moved to the unfold position corresponding to the location C_2 of the point P, by a fixed rotation of 70° of the first member.
β is the angle which drives the opening of the mechanism.

The objective is to minimise at the final position (β = 70°), the difference between the position of point P and the position C_2. Design variables are the location of points 1 and 4, and the length of the bars. The solution of the optimisation problem requires to compute the sensitivity of the final position of P with respect to the different design variables, explicitly the coordinates of the four nodes.
Nodes displacements are constrained by the built structure.

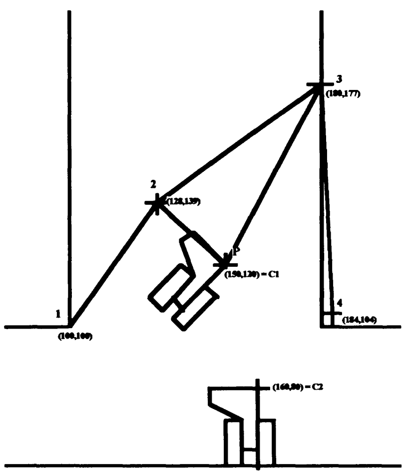

Figure 6. Simple model of a landing gear

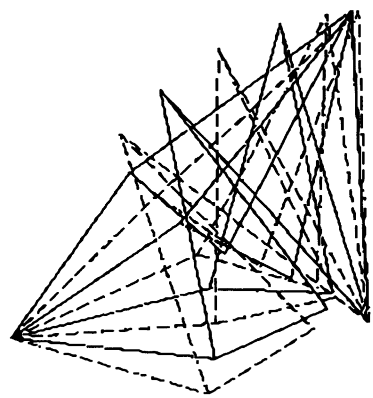

Figure 7. Deployment of the landing gear, one visualization of mechanism per 10° of rotation of the first member.

Generalised coordinates are chosen as for each member i as the coordinates of the centre of gravity and the angle formed between the member and the horizontal axis x of spatial coordinates: $q^T = [xg_1, yg_1, \theta_1, xg_2, yg_2, \theta_2, xg_3, yg_3, \theta_3]$. The rotation of the first member prescribe the movement.

We present the results obtained for the sensitivity analysis with respect to the first coordinate of point 1. Equations (11) give the form of the sensitivity problem, where the initial conditions, and the derivatives of the g^{int}, ϕ and **M** matrix respect to the x_1^0 variable are calculated analytically, so as to determine G^{ext}.

$$\begin{cases} \mathbf{M}\,\ddot{Q} + G^{INT}\left(\Lambda, Q, \dot{Q}, t\right) = G^{EXT} \\ \Phi\,(Q,t) = 0 \end{cases} \tag{11}$$

+ initial conditions

The results of this problem are obtained by solving simultaneously the dynamic and the sensitivity problems. *Figure 8* shows evolution of position of the point P, *Figure 9* provides the comparison between results obtained by this method and the finite differences method.

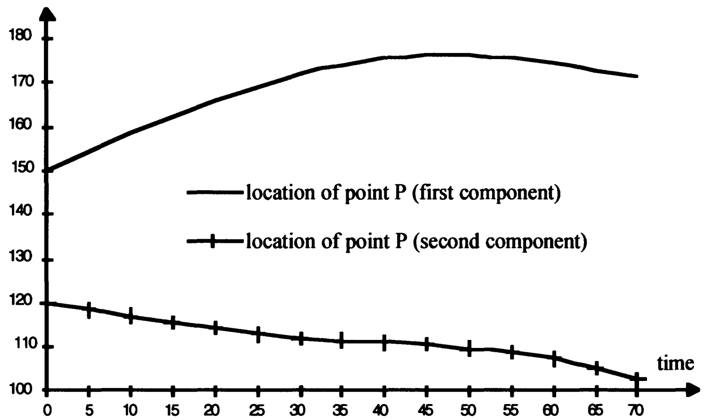

Figure 8. Evolution of position of the point P

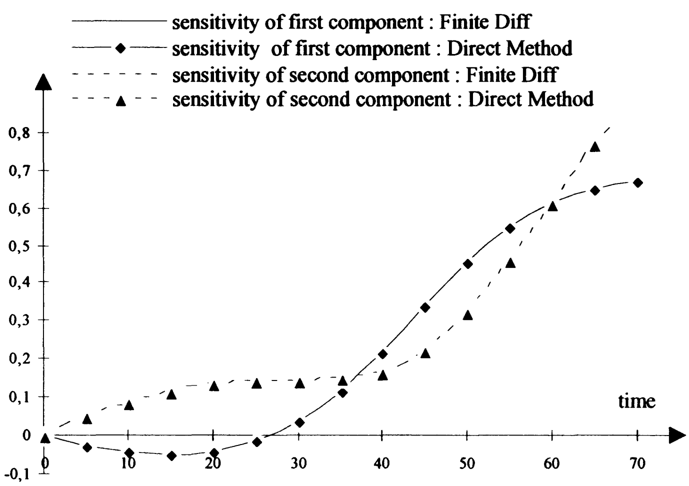

Figure 9. Sensitivity of location of point P with respect to the x_1^0 design variable

The results are as conclusives as for the first example, and similar results are obtain for all the design variables.

The next step is to optimise the behaviour of the system. For that we have modified an existing procedure early developed by V. Braibant. This routine realises the different tasks necessary to resolve the optimisation problem. The optimisation methods proposed are quadratic recursive programming (RQP) and convex linearization (CONLIN). The procedure proposes the management of the finite elements analysis necessary to approximate the sensitivities by finite differences. We have replaced this functionality to directly provide the sensitivities resulting from a routine which provides simultaneously the calculation of the dynamic response and the sensitivity analysis response (with direct method).

In this particular case, for the optimisation problem defined above, the CONLIN method fails. However the RQP method was particularly well adapted to this problem (quadratic objective function and linear constraints), and the results obtained after three iteration are satisfying. Indeed, the new configuration obtained for the landing gear (*Figure 10*) leads, after rotation of 70° of the first member, to a final position of the point *P* where the distance between *P* and C_2 is (9.28), in initial configuration this distance is (25.52).

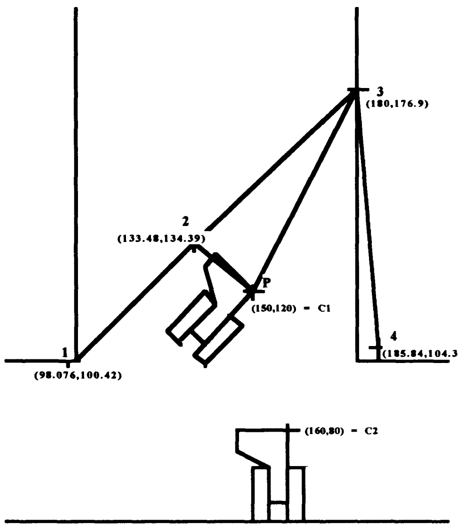

Figure 10. New model of a landing gear

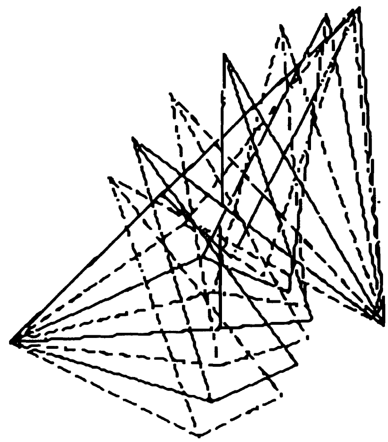

Figure 11. Deployment of the landing gear, one visualization of mechanism per 10° of rotation of the first member.

4. CONCLUSION

A semi-analytical sensitivity analysis method for the dynamic transient response or the kinematic response of flexible multi-body systems was presented. This method requires only one finite element analysis to obtain the dynamic response and the sensitivities with respect to all design variables. So this method allows to reduce significativelly the

computation. Accuracy is automatically achieved as the analysis problem and the sensitivity problem, which are simultaneously solved.
The next step is to integrate and validate this semi-analytical method in the BOSS optimisation architecture developed by the SAMTECH company (Manuel Boss/Quattro, 1995), so as to solve industrial optimisation problem.

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Dynamic modelling of mechanisms.
Qualifying of three integration schemes.

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Abstract.

In this article we present a comparative study of six first order single step integration schemes used in dynamics of rigid bodies. This study was performed in order to qualify three algorithms developed in our laboratory and to compare their performance with three well known algorithms.

1. Introduction

There has been a lot of development in the dynamic simulation of mechanisms during the last twenty years. The reader may find a complete historical account in [Erd92] or [RoS88].

In this paper, we will consider only first order single step algorithms in order to study, in the future, the modelling of contact and clearance in mechanisms. We choose to use here local coordinates but our algorithms can easily be generalised to global coordinates. Our process can be described as follows : Dynamic equations are established for tree structures with a classical Newton-Euler algorithm. In order to treat closed systems, Lagrange multipliers are introduced. The assembly of dynamic equations and velocity constraint equations leads to a mixed system of differential-algebraic equations in which the principal unknowns are relative velocities and Lagrange multipliers.

2. Dynamic formulation.

We consider here a mechanism, whose position and orientation are set in relative coordinates in order to have a minimal number of parameters. We will first establish

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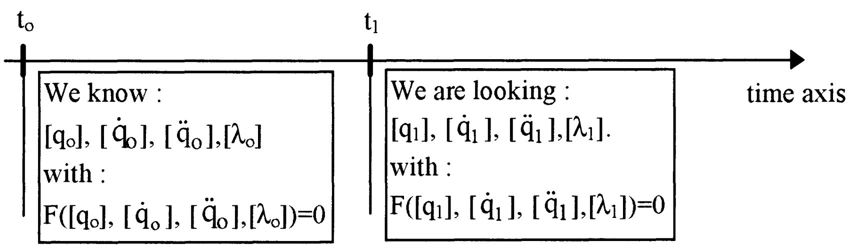
the dynamic equations for tree structures, then we will consider the problem of closed loop systems.
We denote t_o and t_1 the beginning and the end of the time step. Let $[q_o]$ be the generalised position vector at time t_o and $[\dot{q}_o]$, $[\ddot{q}_o]$ the associated velocity and acceleration. We will denote $[\lambda_o]$ the Lagrange multipliers at time t_o associated to the constraints imposed by the loops.
The problem is : given $[q_o]$, $[\dot{q}_o]$, $[\ddot{q}_o]$, $[\lambda_o]$, we want to find all the parameters at time t_1. Hence we are looking for $[\dot{q}_1]$ and $[\lambda_1]$, the parameters $[q_1]$ and $[\ddot{q}_1]$ will then be estimated via the integration scheme.
In classical methods, the dynamic and constraint equations (denoted by F) are often written at the end of the time step. The problem can be described as follows :



We present here another philosophy.

2.1. DYNAMIC FORMULATION - OPEN SYSTEMS.

We write the equilibrium of each solid S_i with regard to an absolute reference R_o, expressed in the body reference R_i tied to S_i :

$$\frac{d\{P_{io}\}}{dt} = \Sigma \left\{F_{ij}\right\} + \left\{F_{ei}\right\} \tag{1}$$

where : P_{io} is the impulsive torsor.
F_{ij} is the force torsor of solid S_j acting on solid the S_i.
F_{ei} is the exterior force torsor.

The virtual power principle gives us :

$$\left\langle \frac{d\{P_{io}\}}{dt}, \left\{V_{io}^*\right\} \right\rangle = \left\langle \Sigma \left\{F_{ij}\right\}, \left\{V_{io}^*\right\} \right\rangle + \left\langle \left\{F_{ei}\right\}, \left\{V_{io}^*\right\} \right\rangle \quad \forall V_{io}^* \tag{2}$$

where V_{io}^* is a virtual velocity torsor and < . , . > denote the scalar product of torsors.
By integrating the equation above on the time step, we obtain the virtual work principle :

$$\int_{to}^{t1} \left\langle \frac{d\{P_{io}\}}{dt}, \{V_{io}^*\} \right\rangle dt = \int_{to}^{t1} \left\langle \Sigma \ \{F_{ij}\}, \{V_{io}^*\} \right\rangle dt + \int_{to}^{t1} \left\langle \{F_{ei}\}, \{V_{io}^*\} \right\rangle dt \qquad (3)$$

Depending on the choice of V_{io}*, the equilibrium will be considered in a different way.

if $\{V_{io}^*\}=\{V_i^*\}_{ti}\,\delta_{ti}$ - local equilibrium.

Where $t_i \in [t_o, t_1]$ and $\{V_i^*\}=1$, with this hypothesis the equilibrium will be located at time t_i. In order to eliminate the constraint efforts, the dynamic equations are projected onto the free mode vectors of the joints. To realise this operation, we can use for example a Newton-Euler algorithm [Walker 82] [Craig 89]. We then obtain n equations on a state space form :

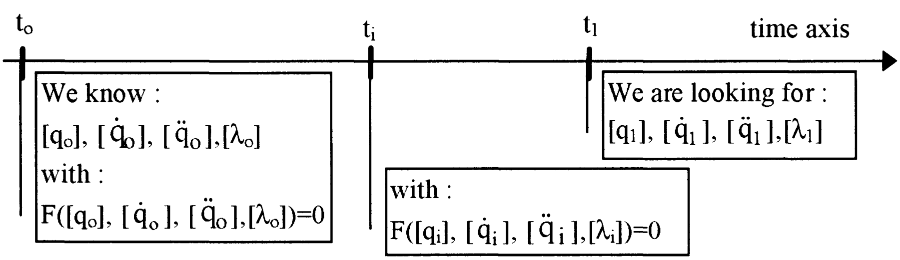
$$[H(q_i)][\ddot{q}_i] + [C(q_i, \dot{q}_i)] = [\tau] \qquad (4)$$

where H is the n*n mass matrix.

C is a n*1 vector of centrifugal and Coriolis terms, including the effects of the gravity and the external efforts.

τ is a n*1 vector of efforts onto the free modes.

The efforts in the joints are then calculated by an inverse dynamic process. We have the following problem :



if $\{V_{io}^*\}=\{V_i^*\}_{ti}.a$ - global equilibrium.

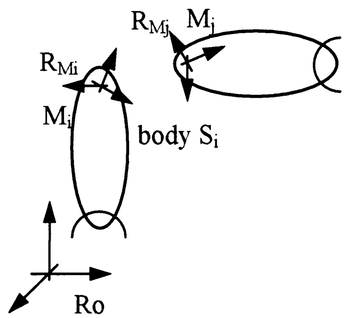
Where a=1 and {Vi*}=1 on the interval (t_o, t_1) and a=0 elsewhere, we find the conservation of the linear momentum principle. We then obtain a problem as a linear function of velocity, all the non-linearities of equations are transfered on geometric parameters. In this article we will only study the local equilibrium formulation, we will limit ourselves to results of the global equilibrium algorithm. The reader may find more informations about this subject in [Boa95].

2.B. LOCAL EQUILIBRIUM - CLOSED LOOP SYSTEMS.

The efforts set by each closed loop are taken into account by mean of Lagrangian multipliers.

If we assume that we have p Lagrangian multipliers, we have to set p additional closed loop equations. Consider that the closure of a loop is made between the solid S_i and the solid S_j, at points M_i and M_j. Let R_{Mi} and R_{Mj} be the local axes associated respectively with M_i and M_j.
The p velocity constraint equations may be written in torsor form :

$$\left[v_{j/i}\right]_{RMi} = 0 \qquad (5)$$



where $\left[v\right] = \begin{bmatrix} \vec{\omega} \\ \vec{v} \end{bmatrix}$ is the velocity torsor.

If we write these equations in generalised coordinates and with matrix notation, we obtain :

$$\left[v_{j/i}\right]_{Ri} = \left[J_{ji}(q)\right]\left[\dot{q}\right] \qquad (6)$$

where $[J_{ji}]$ is a p*n matrix
The velocity constraint equations are then written :

$$\left[J_{ji}(q)\right]\left[\dot{q}\right] = 0 \qquad (7)$$

2.C. ASSEMBLY OF DYNAMIC AND VELOCITY CONSTRAINT EQUATIONS.

We have to solve a system of n+p equations of n+p unknowns, with n differential equations and p algebraic equations as follows :

$$\begin{cases} [H(q_i)][\ddot{q}_i] + [C(q_i, \dot{q}_i)] + \left[J_{ji}(q_i)\right]^T [\lambda] = [\tau] \\ \left[J_{ji}(q_i)\right][\dot{q}_i] = 0 \end{cases} \quad \text{pour } t_i \in [t_o, t_1] \qquad (8)$$

We chose as principal unknowns the n velocity parameters $[\,\dot{q}_1\,]$ and the p Lagrangian multipliers $[\lambda]$.
It is a wellknown fact that if we verify only the velocity constraint equations, we will then obtain a violation of the goemtric constraint equations. We can note that numeral techniques to solve this problem exist [Sch94][RoS88][KaH84], but few are easily implementable and effective (except the Global Coordinate Partionning developed by [Hau89]).
Nevertheless, in this article we are going to treat the problem on its algrebraic-differential form. We will study the geometric drift given by three of our algorithms compared with other wellknown algorithms. The effects of the Baugmarte's stabilisation method are also studied on the velocity level. We can note that the choice of velocity, instead of acceleration, as principal unknown minimizes the geometric drift.

3. Numerical algorithm.

3.1. TIME DISCRETIZATION.

We consider the equilibrium at a time $t_i \in [t_o, t_1]$ with $[\dot{q}]_{t1}$ and $[\lambda]$ as principal unknown. We have to express the parameters $[q]_{ti}$, $[\dot{q}]_{ti}$, $[\ddot{q}]_{ti}$ as a function of the datum $[q]_{to}$, $[\dot{q}]_{to}$ and of the unknown $[\dot{q}]_{t1}$. To solve this problem, we use a linear interpolation of the velocity under time [Boa95] :

$$[\dot{q}_i] = (1 - \frac{(t_i - t_o)}{h})[\dot{q}_o] + \frac{(t_i - t_o)}{h}[\dot{q}_1] \quad \text{avec } t_i \in [t_o, t_1] \text{ et } h = t_1 - t_o \tag{9}$$

If we derive this expression with respect to time, we obtain the acceleration $[\ddot{q}]_{ti}$. We can notice that this acceleration is constant on the time step :

$$[\ddot{q}_i] = [\ddot{q}_1] = \frac{[\dot{q}_1] - [\dot{q}_o]}{h} \tag{10}$$

If we integrate the same expression between t_o and t_i, we find $[q_i]$. We then replace $[q_i]$, $[\dot{q}_i]$, $[\ddot{q}_i]$ by their expression in the equations (8). Once this system is solved, we then obtain $[q_1]$ and $[\ddot{q}_1]$ via the integration scheme.

3.2. INTEGRATION SCHEMES.

We consider here six different integration schemes. In all the case presented in this article the acceleration is constant upon the time step.
We have two types of velocity non-linearities in our equations :

- non-linearities which come from the use of an implicit integration scheme for the goemetry.
- non-linearities due to the centrifugal and Coriolis efforts.

In order to solve those problems, we will use a fixed point algorithm with an iterative approximation of the geometry.

- Small Perturbation hypothesis.

Equilibrium is written at time t_1, but the geometry parameters are evaluated at time t_o. This hypothesisis correct in the case of small displacements.
We have :

$$t_i = t_1 \begin{cases} [q_i] = [q_o] \\ [\dot{q}_i] = [\dot{q}_1] \end{cases} \Rightarrow \langle equations(8) \rangle \Rightarrow [q_1] = [q_o] + h[\dot{q}_o] \tag{11}$$

- Explicit method.

Equilibrium is written at time t_1 with an explicit approximation of the geometry at the end of the time step. This approach is often used in the case of large deformation problems.

$$t_i = t_1 \begin{cases} [q_i] = [q_o] + h[\dot{q}_o] \\ [\dot{q}_i] = [\dot{q}_1] \end{cases} \Rightarrow \langle \mathit{equations}(8) \rangle \Rightarrow [q_1] = [q_i] \tag{12}$$

- Implicit method.

We have here an iterative procedure. Equilibrium is written at time t_1.We set at the k^{th} iterative step an implicit approximation of the geometry as a function of the velocity calculated at the $k\text{-}1^{th}$ iteration.

$$t_i = t_1 \begin{cases} [q_i] = [q_o] + h[\dot{q}_1^{k-1}] \\ [\dot{q}_i] = [\dot{q}^k{}_1] \end{cases} \Rightarrow \langle \mathit{equations}(8) \rangle \Rightarrow [q_1] = [q_o] + h[\dot{q}_1] \tag{13}$$

- Equilibrium at the middle of the step.

We have also an iterative procedure with an implicit valuation of the geometry.

$$t_i = t_o + \frac{h}{2} \begin{cases} [q_i] = [q_o] + 3\frac{h}{8}[\dot{q}_o] + \frac{h}{8}[\dot{q}_1^{k-1}] \\ [\dot{q}_i] = \dfrac{[\dot{q}^k{}_1] + [\dot{q}_o]}{2} \end{cases} \Rightarrow \langle (8) \rangle \Rightarrow [q_1] = [q_o] + \frac{h}{2}([\dot{q}_o] + [\dot{q}_1]) \tag{14}$$

- Hybrid algorithm.

We write the equilibrium at the middle of the time step with an explicit valuation of the geometry.

$$ti = t_o + \frac{h}{2} \begin{cases} [q_i] = [q_o] + \frac{h}{2}[\dot{q}_o] \\ [\dot{q}_i] = \dfrac{[\dot{q}_1] + [\dot{q}_o]}{2} \end{cases} \Rightarrow \langle (8) \rangle \Rightarrow [q_1] = [q_o] + \frac{h}{2}([\dot{q}_o] + [\dot{q}_1]) \tag{15}$$

- Global equilibrium.

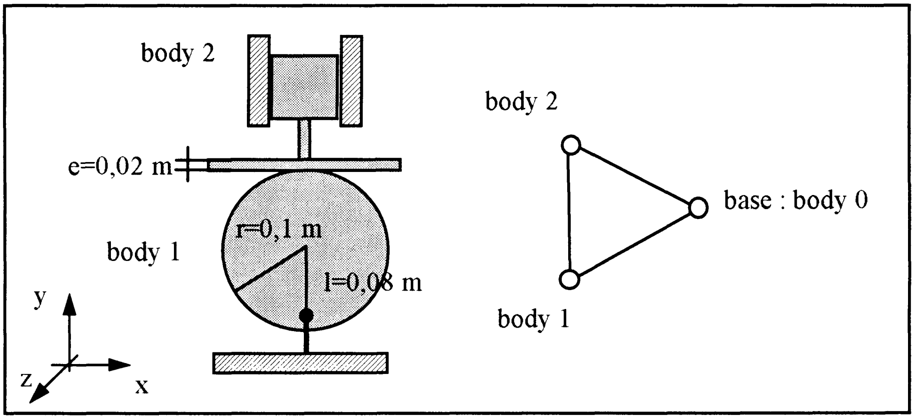
We have here once again an iterative approximation of the geometry. The principal difficulty of this method lies in the expression of the impulsive efforts P as a function of the efforts F. In order to solve this problem, we make the following assumption :

$$P = \int_{t_o}^{t_1} F(t)dt \approx hF(t_o + h/2) \tag{16}$$

4. Application

In order to qualify our algorithms, we have chosen a simple example. We consider a piston-eccentric transformation motion system. This mechanism presents interesting perspectives such as unilateral piston-eccentric joint or clearance and friction in joints. We denote by F the effort set by the eccentric onto the piston and U the torque applied on the eccentric.

The system and its functionnal graph may be pictured as follows :



We consider here that the torque U is constant, we then estimate the rotationnal velocity dq_1 of the eccentric, the translationnal velocity dq_2 of the piston and the joint effort F.

In this particular example, under the assumption made above, the algorithms « equilibrium at the middle of the step » and « global equilibrium » give the same results (because the mass matrix is constant). Consequently we will only present results of the « equilibrium at the middle of the step » algorithm.

We propose here a study of the algorithm responses with a fixed time step h. All the results will be compared with the « theorical solution » estimated with a Runge-Kutta of order 5 algorithm (the continuity of the movement allow us to make this hypothesis). We choose h=0.01s and a simulation of 6s.

If the equations are written in the form of (8), we observe an excessive geometric violation of the constraints for the three first algorithms. In order to minimize this problem, we are going to use some modified constraint equations a little as the Baugmarte's method suggests to. We set :

$$[J_{ji}(q)][\dot{q}] = -b[f(q)] \qquad (17)$$

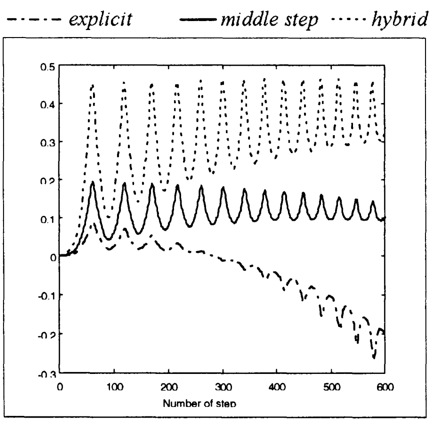
where [f(q)] is the geometric constraint vector and b an arbitrary parameter.

We are going to study the geometric error in the piston-eccentric joint and the error with respect to the theorical solution in the eccentric joint. Results are presented in the following array :

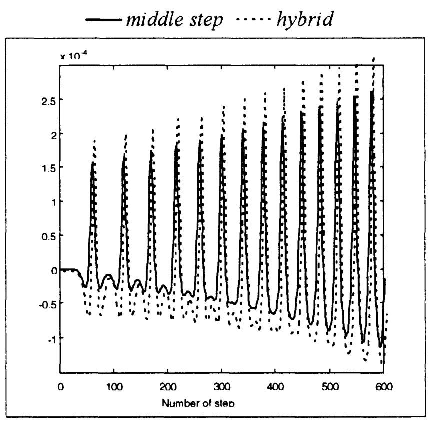
	algo. 1 HPP	algo. 2 explicit	algo.3 implicit	algo. 4 middle step	algo. 5 hybrid
geometric violation	4.10^{-2} m	$1.5\ 10^{-3}$ m	8.10^{-3} m	$2.5\ 10^{-4}$ m	$3\ 10^{-4}$ m
theorical error	3.5 rad	-0.3 rad	no rotation	0.2 rad	0.45 rad
stabilisation b	5	200	10	none	none
time cpu	10 s	10 s	29 s	26 s	11 s

Algorithm 1 leads to an exagerate geometric violation despite the stabilisation method implemented. Algorithm 3 exhibits the same behaviour, with in addition an energy dissipation so important that the eccentric can't perform a complete cycle.

Algorithm 2 presents a good behaviour with respect to our treatment. Algorithms 4 and 5 give better results. The theorical error is stable (figure 1), furthermore the piston-eccentric joint error is smaller than the one given by the algorithm 2 (figure 2).



<u>figure 1</u>
Theorical error in the eccentric joint.



<u>figure 2</u>
Geometric constraint violation.

We have to notice that the choice of the paramter b is extremly tactful. As a function of this parameter the response of the system is very different. In fact, most of the time,

the « theorical solution » is unknown, the choice of b then become very complicated. Algorithms 4 and 5 allow us to avoid this problem.
Furthermore, it is very important tonotice that the algorithms 4 and 5 give physically acceptable results wathever h we choose. We can study the responses given by algorithms 4 and 5 at the stability limit (h=0.03 for 4, h=0.02 for 4).

—— middle step ····· hybrid

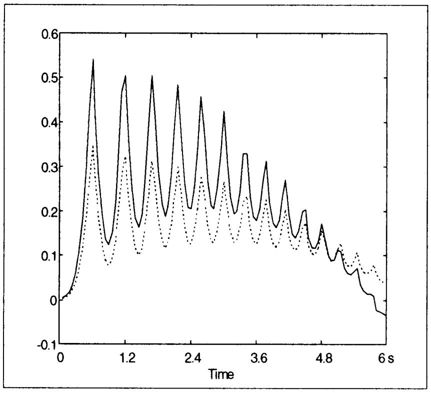


figure 3
Theorical error in the eccentric joint.

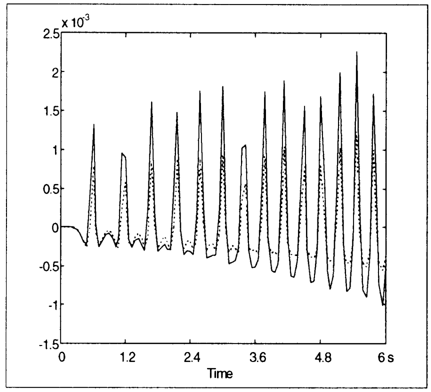


figure 4
Geometric constraint violation.

We can see clearly that our algorithms give consistent results even at the stability limit.

5. Conclusion.

The precision and stability of our algorithms have been highlighted on a simple example. This study confirms results which have been established by [Boa96]. Upon the three methods presented, the hybrid algorithm presents the better ratio precision-computation time, it is a robust algorithm easy to implement which avoids the calculation of H and J at each iteration step.
The algorithms presented here constitute the beginning of our study whose aim is to effectively simulate mechanisms subject to real conditions such as clearance and friction.

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Chapter 5
MODELLING OF PROCESSES

THERMAL ANALYSIS OF ORTHOGONAL CUTTING
Simulation and Experiments

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Abstract. In order to determine temperatures in orthogonal cutting, a technique based on the use of infrared-CCD camera has been developed. This method makes it possible to obtain the complete distribution of temperatures at the cutting edge of the tool. To conduct this experimental analysis, a finite element method is used to calculate the temperatures in orthogonal cutting under steady state conditions. The comparison of simulation and experiments allows us to study the thermal flux distribution and to understand the influence of various parameters such as cutting speed, feed rate or material properties.

1. Introduction

A thorough understanding of metal cutting which allows optimisation of machining parameters requires a good understanding of physical, thermal and mechanical mechanisms involved.

The thermal aspects constitute a fundamental part of the problem, and heat generation occurring during metal cutting is an important factor which affects the properties of the machined material as well as tool life. The heating of the cutting zone actually due to high plastic deformation, tool/chip and tool/piece friction, weaken locally tool resistance and promote some diffusion of chemical elements in it [1], which lead to an embrittlement phenomenon.

Moreover, the assessment of the thermal field permits the analysis of power consumed during cutting. We have developed a method relying on experimental observation and thermal simulation of orthogonal cutting, which will give in the short term a better understanding of tool wear mechanisms and provides in the long term enhancement of understanding and eventually the mastering of machining processes.

2. Main Thermal Results Obtained In Machining

The thermal analysis of metal cutting achieved until now shows that there is a maximum temperature level at the tool/chip interface, above the edge of the tool on the cutting face [2][3][4]. The temperature can reach 800 °C and above at this point and increases further with cutting speed. When the depth of cut is raised, the maximum temperature

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moves away from the edge of the tool [4]. Within the workpiece, the temperature level reached is much less high. Matsumoto [5] finds that the workpiece surface temperature never exceeds 100 °C.

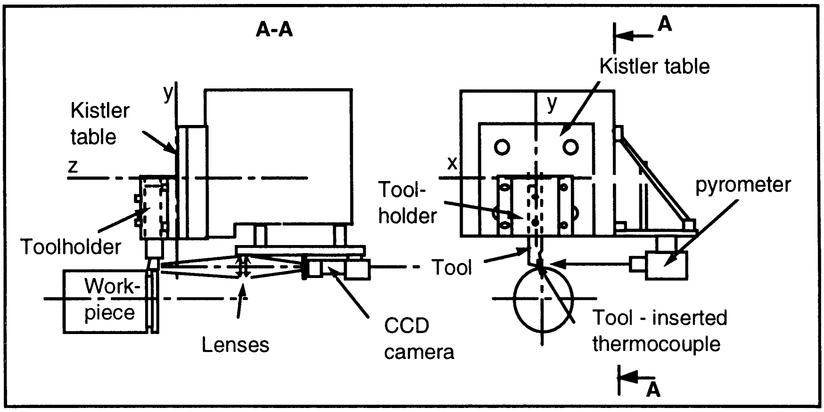

Figure 1. Cutting temperature measurement experimental device.

3. Experimentation

Our experimental analysis of the thermal field relies on the use of a CCD-Infrared camera which enables us to obtain the complete temperature distribution at the edge of the tool. In addition to the camera, thermocouples are inserted in the lateral face of the tool and a pyrometer (figure 1) is used in order to determine the temperature of the side cutting face (during the fall of the chip).

The cutting tests are carried out, without lubrication, on a low alloyed chromium and molybdenum steel with different hardness values. The cutting tool is a bulk CERMET with a cutting angle of 10° and a clearance angle of 5°. All the devices and experimental results are described elsewhere [6].

4. Numerical Thermal Simulation of Cutting Implementation of the Model

In addition to the experimental recordings, a numerical thermal simulation is carried out using a finite element program, Systus of FRAMASOFT+CSI. It consists in the resolution of the heat transfer equation by the finite element method applied to orthogonal cutting under steady state conditions :

$$\sum_{i=1}^{3} \lambda(T).\frac{\partial^2 T}{\partial x_i^2} - \rho.c.\sum_{i=1}^{3} V_{x_i}.\frac{\partial T}{\partial x_i} - \frac{dQ_{sint}}{dt} = 0 \qquad (1)$$

Qsint is the quantity of heat due to internal sources. The *xi* are the axis components, λ the conductivity component is assumed to be isotropic and *T* is the temperature. *V* is the speed (constant with time) at each point, ρ the density and c the specific heat of the material.

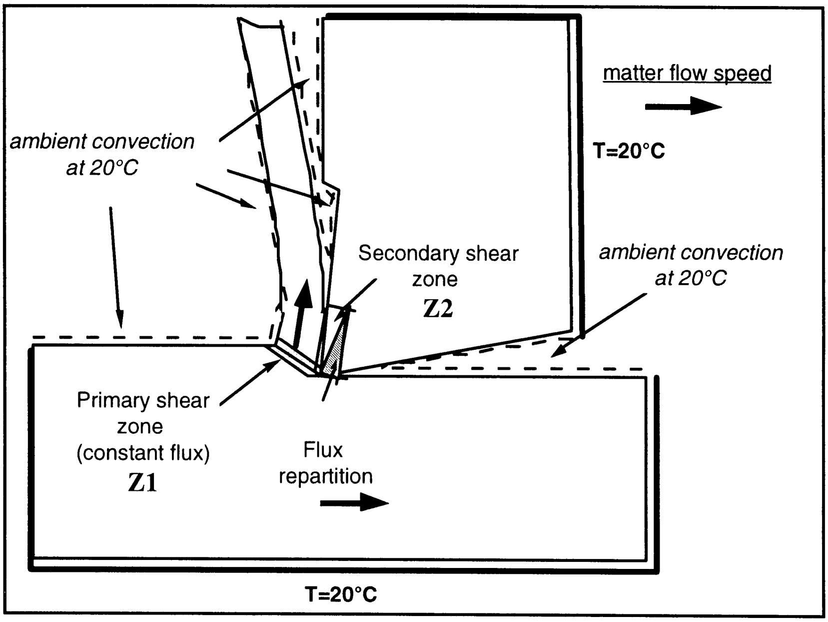

Figure 2 . Thermal loading and boundary conditions of the finite element model.

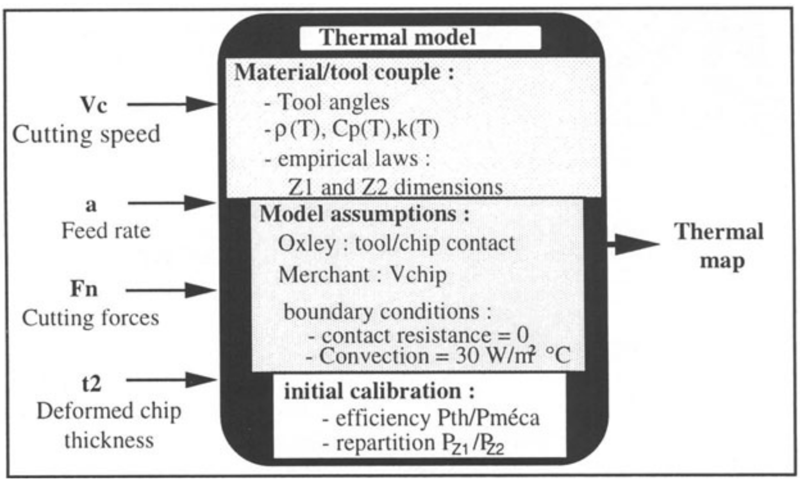

Figure 3 . Using principle of the model.

The thermo-physical properties of the material/tool couple have been experimentally determined for a wide range of temperatures. The definition of the problem requires, in addition to the analytical relations of Merchant [7] and Oxley [8][9], an assessment of the cutting zone geometry which can be deduced from a microstructural analysis of the chip. The cutting forces measured are used to estimate the amount of energy consumed during cutting. The structure of the model and the boundary conditions are shown in figure 2. In order to be able to modify the parameters used in the simulation, the mesh has been parametered and specific software allows an automatic calculation of the structure and thermal loading from the cutting parameters (feed rate, cutting speed, tool angles), the cutting and feed forces and the deformed chip thickness.

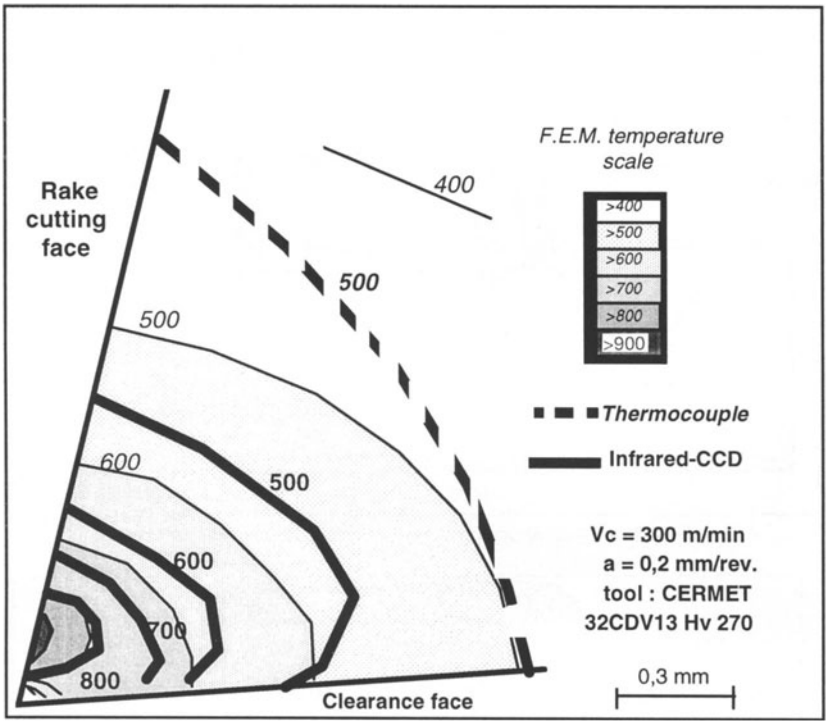

Figure 4 . Comparison between the simulated and experimental thermal map.

4.1. CALIBRATION OF THE MODEL AND ESTABLISHMENT OF THE ENERGY BALANCE

Our model includes two variables :
- the efficiency between the mechanical power consumed during cutting (assessed from the forces and the cutting speed) and the dissipated thermal power.
- the distribution of this thermal power between the two shear zones.

For each material/tool couple, these two parameters have to be frozen by comparing simulation and experimental results obtained on a working point.

When machining 32CDV13 (Hv 270) with the CERMET tool, we have shown that 90 to 100 % of the dissipated mechanical power was transformed into heat and 80 % of this heat was dissipated in the primary shear zone. The remaining thermal power is dissipated in the secondary shear zone. Concerning the working point, after this initial calibration is completed, the simulation requires the definition of only four parameters : cutting speed, feed, feed force and deformed chip thickness (see figure 3).

4.2. NUMERICAL RESULTS AND COMPARISONS WITH THE EXPERIMENTAL RESULTS

In our case, the initial calibration is carried out for a cutting speed of 300 m/min and a feed rate of 0.2 mm/rev.

Figure 4 shows calculated isotherms in grey levels, isotherms derived from CCD-IR thermal analysis, represented by continuous bold lines, and interpolated isotherms from thermocouple measurements are represented by bold dotted lines. The comparison between simulation and experimental measurements shows a very good agreement between CCD-IR and calculation for temperatures above 700°C, a shift for the low isotherms of the camera, and a difference lower than 50°C in a radius of 3 mm around tool edge, between the thermocouple data and the simulation. Despite slight differences observed, the simulated and measured thermal maps are quite similar. This point constitutes a validation for the initial calibration and also for the hypothesis proposed in the calculation.

5. Analysis of the model. Influence of different parameters on temperature distribution

The initial calibration being validated, the model can be used in order to analyse the influence of cutting parameters.

5.1. INFLUENCE OF FEED VARIATION

From the mean working point used for calibration (Vc=300 m/min, a=0.2 mm/rev, tool : CERMET, steel 32CDV13 Hv 270), the feed rate is allowed to vary between 0.1 to 0.25 mm/rev. Figures 5.a and 5.b represent the results of the simulations.

It can be seen that the hot point moves towards the top of the tool. The temperature of this point increases slightly, from 900°C at 0.1 mm/rev to 1000°C, at 0.25 mm/rev. These results can also be observed through experimental measurements [6].

In order to have understand better the effect of feed variation effect on temperature, the three following parameters are followed : the temperature of the chip free surface, the maximum reached in the tool/chip friction zone and the maximum temperature reached at the workpiece surface. Figure 6 shows the evolution of these three temperatures with feed variation.

The evolution of the maximum temperature is not very regular with the feed. An increase of one hundred degrees (10%) for a variation from 0.1 to 0.25 mm/rev is however noted. The temperature of the chip free surface decreases slightly (change lower than 50°C, ~ 10%), as well as the temperature of the workpiece surface (10%). Experimentally, it is seen that the forces i.e. the dissipated power, strongly increase with feed. The increase in power is compensated by an increase in the section of the chip in the primary deformation zone. However, in the secondary zone, an increase in the temperature of the hot point is detected. It can be assumed that, considering the primary zone, the increase in power consumed is compensated by an increase in the volume of material to be heated. On the other hand, in the secondary zone, the contact length being higher, the heating time of the friction surface increases as do maximum temperatures.

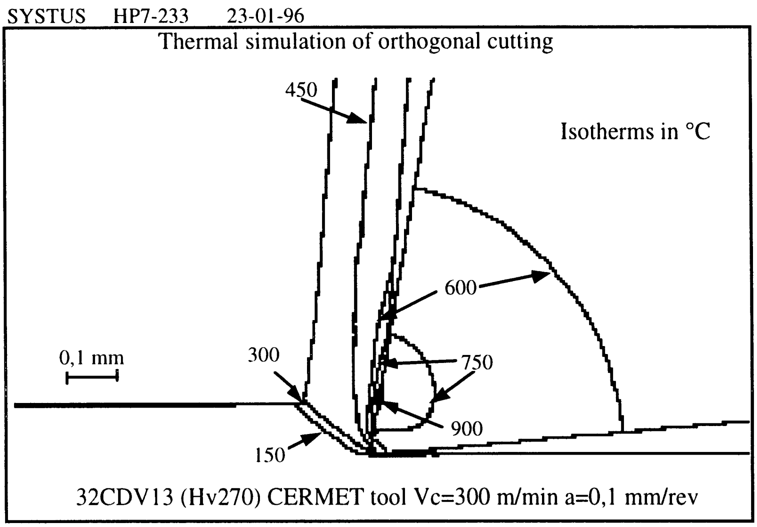

Figure 5.a . Feed variation,a=0.1 mm/rev.

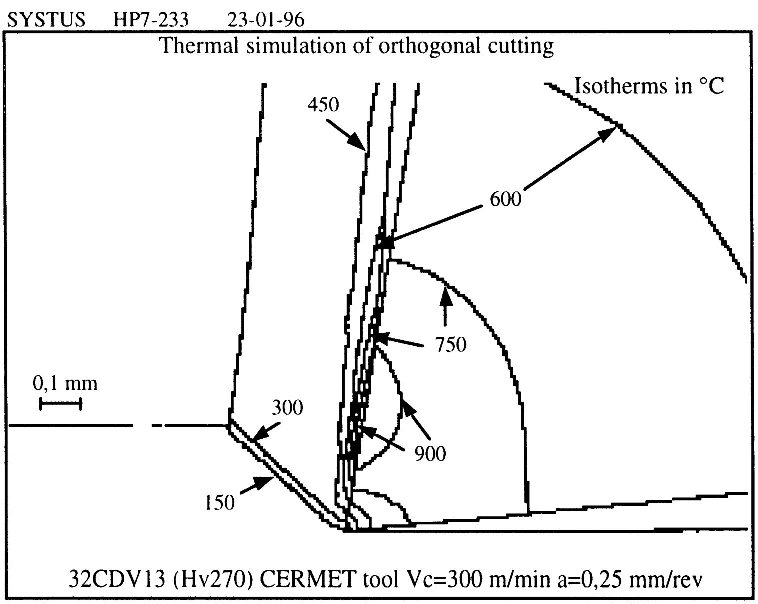

Figure 5.b . Feed variation,a=0.25 mm/rev.

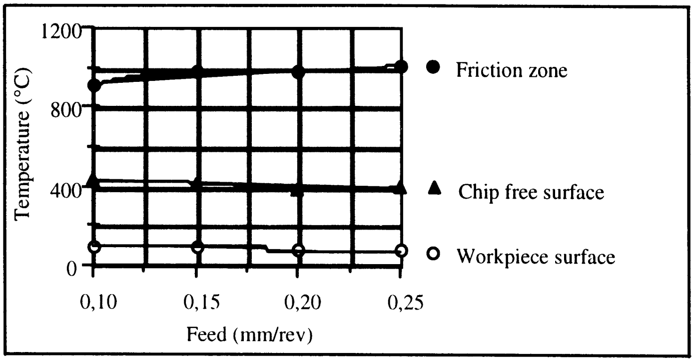

Figure 6 . Influence of feed variation on temperature.

5.2. VARIATION OF THE CUTTING SPEED

From the mean working point used for the calibration (Vc=300 m/min, a=0.2 mm/rev, tool : CERMET, steel 32CDV13 Hv 270), the cutting speed varies between 100 to 400 m/min. Figures 7.a to 7.b represent the results of the simulations.

The thermal map does not change significantly with cutting speed, except the narrowing of isotherms in the primary shear zone. On the other hand, the maximum temperature point (contact tool/chip) highly increases in temperature : from 800°C at 100 m/min to 1050°C at 400 m/min. These results are in good agreement with experimental observations [6].

Figure 8 shows the evolution of the maximum temperature reached in the friction zone, the temperature of the chip free surface and the maximum workpiece surface temperature with cutting speed.

A clear increase in the temperature of the hot point with cutting speed of 300°C (30%) for an increase of 300 m/min of cutting speed can be observed. The temperatures of chip and workpiece surface are either stable or slightly decreasing. Experimentally, it is noted that the width of the primary shear zone decreases with cutting speed. In spite of an increase in dissipated power, the high temperature region being less wide and the cutting speed higher, the primary zone does not heat more the matter when speed is increased. But as the geometry of the secondary zone is more stable (experimental observation), power increase is sufficient to compensate the decrease in the heating time due to the rising speed and thus to increase the temperature of the hot point.
The analysis of the evolution of the temperature with time of the points located on the free or friction surfaces of the chip or on the workpiece surface makes it possible to underline the very high speed of thermal loading : about 10^6 °C/s on the workpiece, and 10^7 °C/s on the chip.

Moreover, the metallurgical state of the initial machined material can vary so as to show that the thermal isotherms map calculated remains on the whole stable but that the temperature of the characteristic points increases with hardness [6]. Concerning tool thermal properties, it has been shown that the temperature of the chip does not vary with the conductivity of the tool. On the other hand, the temperature of the workpiece slightly increases with conductivity whereas the temperature of the friction zone of the tool/chip interface decreases.

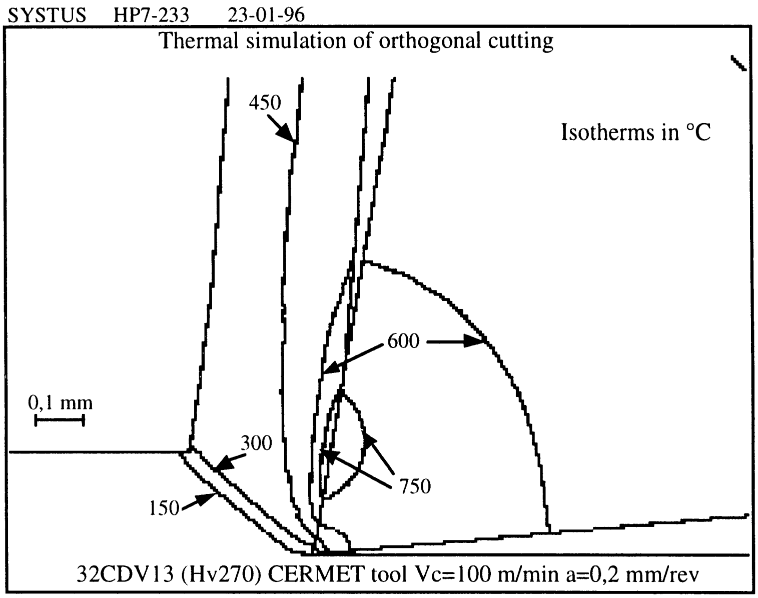

Figure 7.a . Cutting speed variation, Vc=100 m/min.

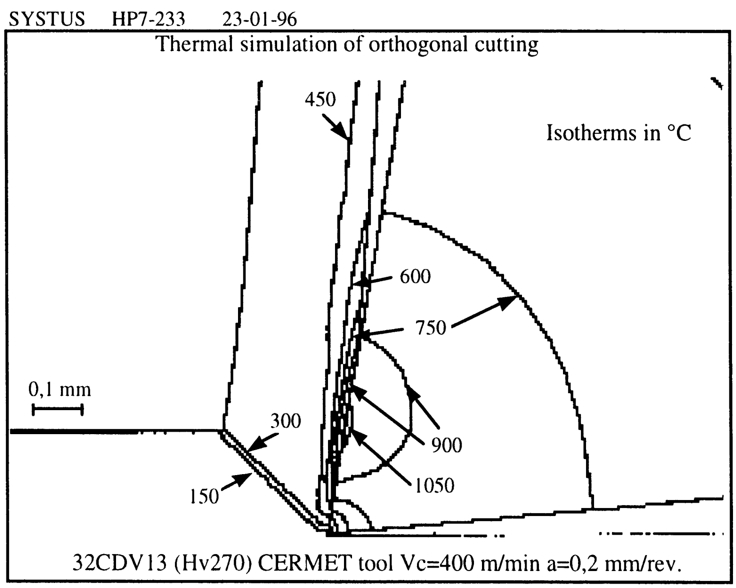

Figure 7.b .Cutting speed variation, Vc=400 m/min.

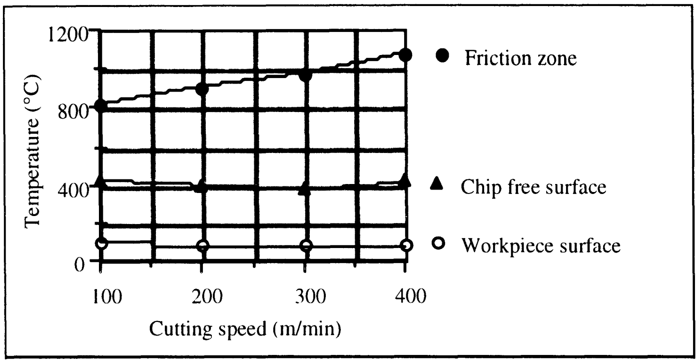

Figure 8 . Influence of cutting speed variation on temperature.

6. Conclusion

A simple finite element model used to simulate the thermal aspects of orthogonal cutting under steady state conditions, from experimental data and analytical relations has been presented here. This model enabled us to follow the distribution of the dissipated power from the initial mechanical power to the final temperature field.

The increase in feed leads to a slight rise in the temperature in the secondary zone and a decrease in the temperatures of chip and workpiece. The increase in cutting speed leads to a high increase in temperature in the secondary shear zone with no changes in chip and workpiece temperatures. The influence of metallurgical properties of the material and the thermal properties of the tool on the distribution of temperatures in tool, chip and workpiece has also been investigated.

The combination of our experimental and numerical tools allows us to master the problem of thermal analysis of metal cutting. It remains to use the equipment in order to have a better understanding of the physical mechanisms involved in metal cutting, and in particular tool wear.

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A SYSTEMATIC APPROACH TO THE SURFACE MODELLING OF FORGED PARTS

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Abstract. The approach presented here is centred on a systematic construction technique of surface models of forged parts. After having presented a construction scheme, some coherence checking routines for the generated forms are presented. Effectively, any defect related to the construction process leads to disasters at the machining stage or during other treatments, i.e. : modification of the part geometry, simulation of the forging process, part dimensioning, etc. The developments introduced here are related to the set up of a systematic process of surface creation, to the identification of the entities used during this process and of the operators involved. An approach guaranteeing the compatibility of the construction parameters of the surface is also presented.

1. Introduction

Today's situation where industrial companies must cope with a strong concurrence environment leads to a large scale reduction of time to market and therefore to the duration of the design process. Numerous works of economists have already demonstrated such a necessity [Cla91]. Most of the solutions proposed focus on deep modifications of the organisation of industrial companies.

In the context of forged parts, computer tools have been introduced in order to increase the efficiency of actors involved in the forging process. COPEST [Bou93], a design software, ForgeRond [Mar95], a software for fast simulation, softwares for rapid assessment of preforms [Vem86] and tools for parts modelling that are dedicated to the machining of forging dies [Maw94] are among the examples of computer tools related to this context. These tools form a wide range that covers in a large extent the activity of the forging technicians. However, these developments strictly focus on the forging process except for the work of Mawussi and Bernard [Maw94] which is centred on the machining phase and COPEST which deals with the design phase. Most of the forging professionals are members of companies acting as sub-contractors. Their activities cover also tasks related to the forging process. As an example, one can find tasks like cost estimation or part modelling from data provided by a client. Currently, these models are mainly numerical ones. Among the important activities of the forging office is the construction of CAD surface models, most often from blueprints. Though this

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highlights an obvious organization problem, this task is long and tedious and therefore risky and costly since model checking is essentially visual. CAD tools allow the generation of correct NC paths only when the surface models are coherent. The current development aims at reducing significantly the amount of time required to model the forging dies at the forging office of sub-contractors or of large companies as well. Typically, the modelling of the steering mechanism of an automotive vehicle currently amounts to 500 hours as stated by an automotive company.

The approach presented here is centred on a systematic construction technique of surface models of forged parts. A second and important aspect, already mentioned above, focuses on the coherence checking of the forms created. Effectively, any defect related to the construction process leads to disasters at the machining stage or during other numerical treatments, i.e. : modification of the part geometry, simulation of the forging process, part dimensioning, etc. The developments introduced here are related to the set up of a systematic process of surface creation, to the identification of the entities used and the operators involved during this process. An approach guaranteeing the compatibility of the construction parameters of the surface is also presented.

2. Presentation of the initial data

2.1 DESCRIPTION OF THE MINIMUM DATA REQUIRED

According to the hypothesis stating that the initial data are contained in a 2D drawing which can lie on a paper medium or can be described numerically, the forging engineer must interpret the data embedded inside such a document. This interpretation phase occurs for a majority of forged parts. Sometimes, the engineer may have to interpret a blueprint because of a lack of specification or, locally, he or she may go beyond some specifications when a construction becomes impossible.

A second hypothesis states that the data are contained in the sections issued from a dressing process (COPEST) where the dressing parameters are calculated. Therefore, the engineer has to make some choices depending on the capability of the production hardware of the forging dies in order to ensure the overall coherence of the part. These choices are no longer a matter of interpretation, of decoding a drawing but the goal is to coordinate the values of various parameters such as tooling allowances, blending radii, flash, web, etc.

The problems treated here are independent of these two hypotheses. However, the work presented here has been developed within the scope of the first hypothesis : the most frequently encountered.

2.2 THE “SURFACE” ENTITIES

Within the scope of the current approach, entities incorporating characteristics that are specific to the forging process and that serve as basis for the construction process have been identified. They enumerate (see figure 1) :

- the flash lines. This line determines the flash surface associated with the matrices, it greatly influences the forging forces and the flow of metal,
- the bottom/top die surfaces. They are, most often, planes located at various altitudes and are set up in a somewhat parallel position to the « flash plane »,

- the lines of support. They delineate the bottom/top die surfaces and serve as support of draft surfaces,

- the draft surfaces. Slanted of the value of the draft angle, they rely on the support lines associated with various bottom/top surfaces of the die,

- the blending surfaces located at the bottom/top of dies and of drafts. Most often, they are straightforwardly manufactured by the radius of the milling tool in order to simplify the machining of the matrices. In the context of the forging process, they strongly determine the closing force required during this process,

- the blending surfaces between areas (see figure 6). Generally, they are generated during a contouring phase and can admit more easily varying radii. These radii are highly constrained by the flow of metal, something which justifies their large values compared to the other radii of the part,

- the pre-set surfaces. Frequently defined from sections and represented with free-form surfaces, their geometry directly comes from the function of the part (aerodynamics, link with another complementary part, etc.).

2.3 VARIOUS CATEGORIES OF PROBLEMS

Though the objective of systematic modelling considered in the whole seems a priori complex, it can be divided into two main families of problems. These families differ one from the other by the construction technique guided by the shape of the object. The characteristics of each family can be stated as follows :

1 - the object shape contains areas embedding free form surfaces defined from sections. This type of problem leads to interpolation processes between the sections and the extremities that rely on criteria which are not specified on the « blueprint »,

2 - the object shape contains areas which do not involve free forms apart from the blending surfaces. These areas are defined from « classical » dimensioned blueprints.

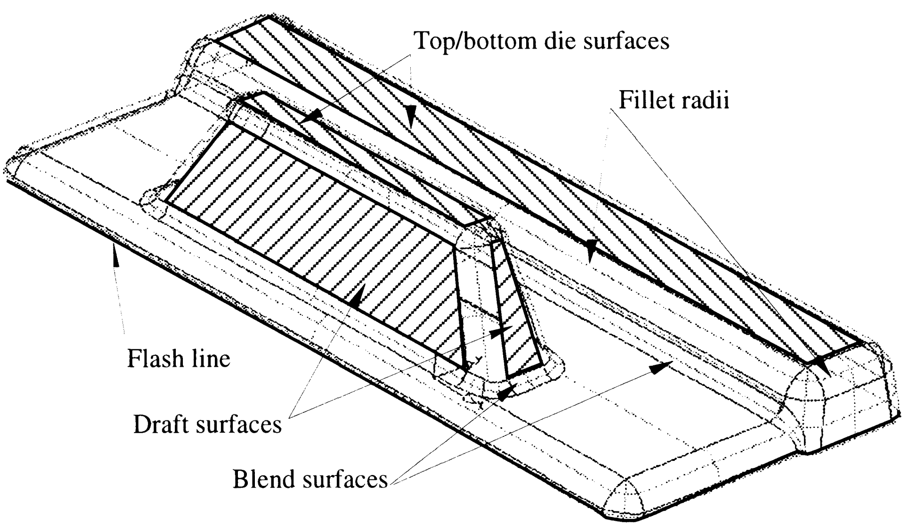

Figure 1 : Different forging features.

3. Construction process

3.1 METHOD

The method presented here can cope with both situations described above. However, the figure 1 above is an illustration of the second family of construction techniques. The principle of this method can be summarized by the following steps :

- construction of pieces of a surface based on a generation process from sections (if the part involves such elements),
- set up of the flash line and of the support lines (see figure 3),
- set up of the flash plane and of the bottom/top surfaces of the dies (see figure 3),
- extension of the support lines (see figure 2),
- set up of the draft surfaces and trim these surfaces to keep their useful part (see figure 5),
- blending of the draft surfaces (see figure 6),
- intersection with the bottom/top surfaces of the dies (see figure 6). In case of multiple areas of blending, a rule of priority has been set up.

However, it should be mentioned that splitting down the object into the different areas is not always obvious but the examples treated show that a solution can be found even though the object seemed complex a priori. Reaching a decomposition of the object into a set of entities belonging to the list above determine into a large extent the efficiency of the last phase, namely the blending between the various areas.

At the end of the previous step of construction of elementary areas of the part, their blending takes place (see figure 7). The blending order starts from the bottom/top surfaces of the die that are the farthest from the flash surface and propagates, step by step, towards that surface. This process illustrates the principle that allows to construct the whole surface of the part.

The blending operation is critical point with respect to the quality of the surface obtained. Effectively, it is during this operation that may appear the major part of the surface folding and incoherence problems when there is not simply a lack of solution. This last configuration is less problematic because it indicates explicitly the incompatibility between the parameters used during the construction process. At the opposite, in the first case, the software environment produces a result without informing the user when it is not coherent, something unacceptable when the automatization of the construction process is the goal pursued. For this reason, several analyses have been conducted and are briefly described in the following section.

Figure 8 shows an example of a part that fits into the second family of construction methods. The resulting geometry has been obtained with the use of the above procedure. Figure 9 represents a shaded view of the same part.

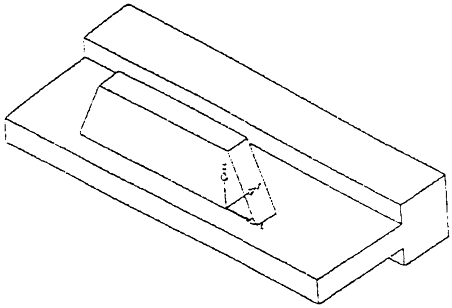

Figure 2 : 3D volume of the machined part.

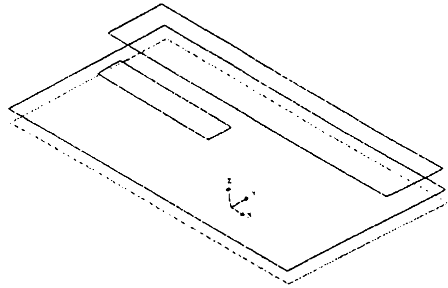

Figure 3 : Flash line and top/bottom surfaces

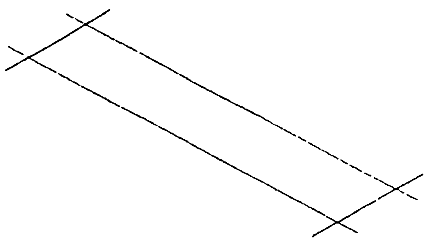

Figure 4 : Supporting lines of draft surfaces

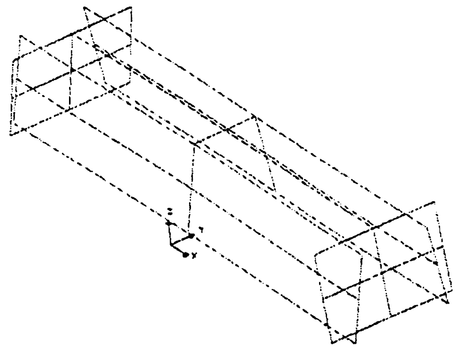

Figure 5 : Draft surfaces.

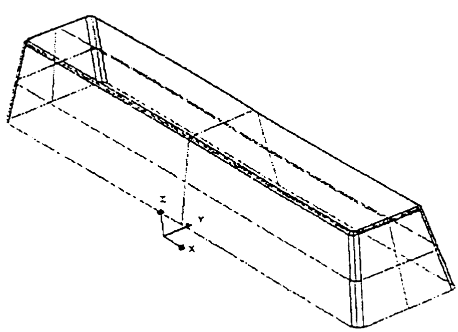

Figure 6 : Blending radii.

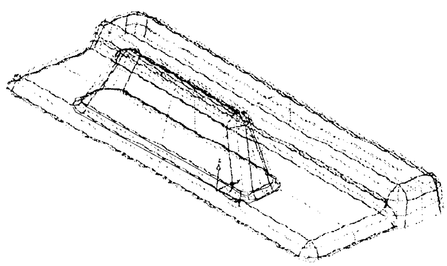

Figure 7 : Connection between the various areas.

3.2 GENERIC ASPECT OF THE METHOD

The generic aspect of the method characterizes its ability to be adapted to various CAD environments from the point of view of the geometric models used for surface modelling as well as from the point of view of the construction operations that they provide. Effectively, the experimental phase of the present work has been carried out within the software environment of Euclid-IS. However, the geometric modelling operations have been selected on the basis of their compatibility with the construction process described above and on the basis of their generic principles. This last criterion takes into account their ease of implementation within CAD environments of various types, i.e. : environments having a different surface model, a different management of geometric entities, etc. The result of this approach allows to obtain the widest portability possible of the construction method set up.

4. Geometric coherence checking: examples of simple cases

Coherence checking is a critical step of the approach proposed since the next step is dedicated to the automatization of the construction process and as such, it can be effectively achieved only if the user gets some guarantee about the correctness of the result provided by the software environment.

This environment should also provide tools allowing the user to modify dimensions in order to obtain a satisfying result. In fact, two sensitive questions can be raised by the user when he or she constructs a surface model.

Firstly, is the surface just generated by the designer acceptable from the standpoint of the manufacturing of the dies ? Currently, only a visual check allows to provide an answer to this question.

Secondly, when the designer identifies an incompatibility between dimensions of the part (see figures 10 and 11), which parameter value must be specified by the designer to get rid of it ? Currently, his or her know-how is the only tool available.

The answer to these two questions seems to be fundamental in the scope of the development a tool aiding at the design of dies. The firsts developments required for that goal are described thereunder.

4.1 COHERENCE OF DRAFT SURFACES

As a first approach, the coherence of draft surfaces has been studied through a series of three simple cases frequently encountered in the geometry of parts designed for forging :

- the plane support line is parallel to the flash plane and the flash surface is plane,
- the plane support line is slanted with an angle α and the flash surface is plane,
- the support line is a free-form line and the flash surface is plane.

Simple analytic equations that describe the evolution of the curvature radii of the surface with respect to the draft angle and to the height of the surface have been set up. Thus, explicit criteria for the determination of the maximum radii of curvature of the support line into a specific context (draft angle, height of the surface) have been obtained.

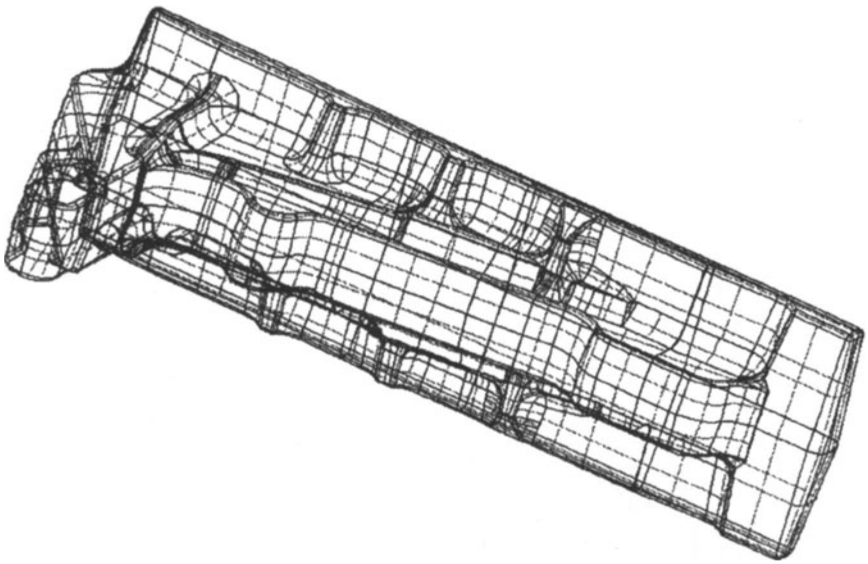

Figure 8 : Surface model of a part after the construction process.

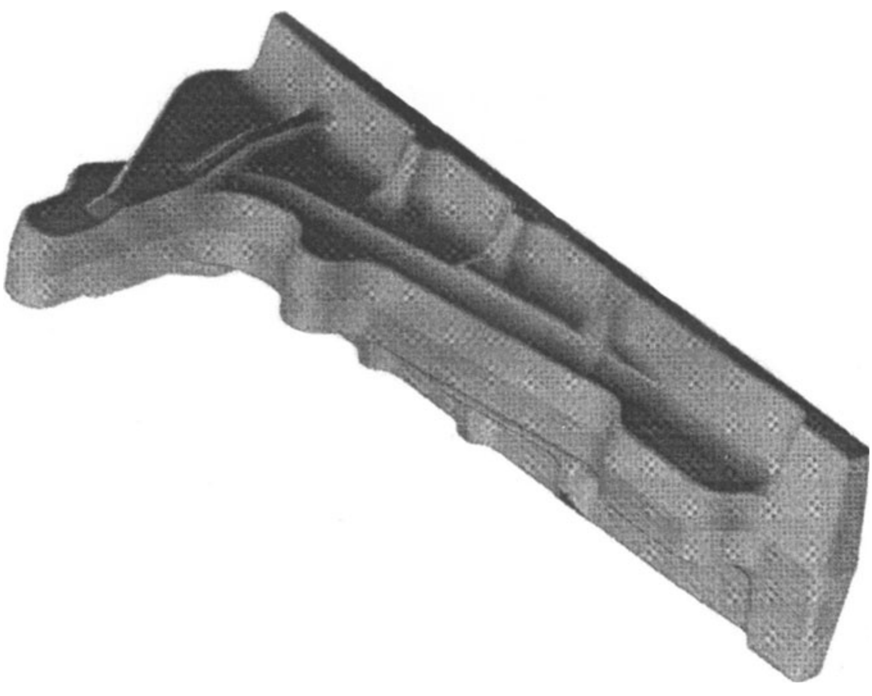

Figure 9 : Shaded view of the above part.

4.2 COHERENCE OF THE BLENDING SURFACES

Once the draft surfaces have been positioned, there may subsist potential incompatibilities of the blending radii between the various areas of the surface. Checking their compatibility is therefore important. As previously stated, hypotheses have been set up to reduce the problem complexity though it characterizes configurations frequently encountered. They enumerate :

- the plane support line is parallel to the flash surface and the flash surface is plane,
- the blending surface connects the flash surface to a draft surface,
- the draft angle is strictly greater than zero,

to allow a first analysis of the coherence conditions.

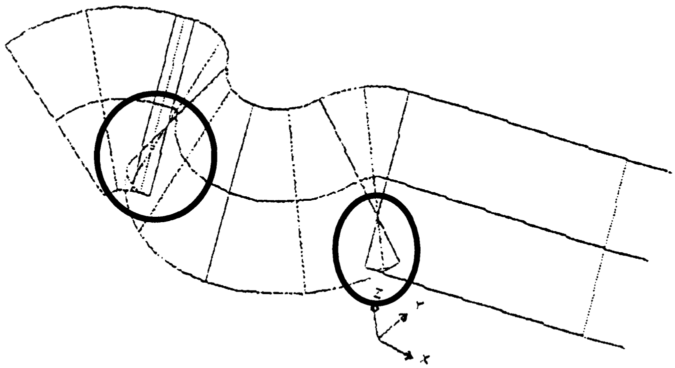

Figure 10 : Folded surface.

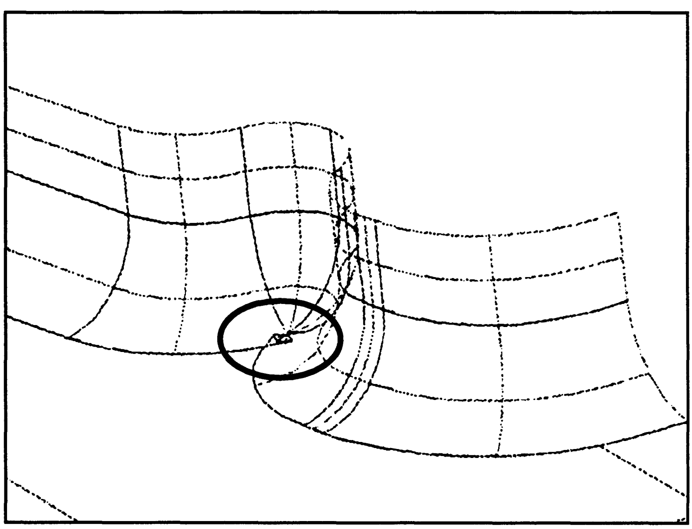

Figure 11 : Folded surface.

The equations thus obtained allow to determine the incompatibilities between blending radii and radii of curvature of the draft surface intersecting the flash surface to submit a minimum value of radius that is compatible with the configuration given. Thus, incompatibilities have been highlighted between the dimensions of the part depicted in figures 10 and 11 as they were specified on its blueprint and the three dimensional surface geometry of the same part.

5 Conclusion

The results obtained have demonstrated the conformity of the construction process described with respect to its systematic generation. Thus, the work presented is a first step towards the automatization of the construction process of a surface model of forged parts. The industrial impact of this approach is significant since the time spent for the surface modelling of forged parts should be reduced in a large extent. Moreover, such an approach is a step forward for computer tools helping to analyse and to propose local improvements of the part geometry while taking into account constraints related to the manufacturing phase.

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SIMPLIFIED STAMPING SIMULATION: AN AID FOR COMPONENT DESIGN

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Abstract. In order to facilitate the design of stamped parts, to improve their quality and to reduce the design cost and time, it is necessary to take into account during all the conception phase, the feasibility constraints. We are introducing a simplified computing method which provides the evaluation of the stamping problems as soon as the product design stage and which may help the tools design office for the definition of the stamping process. The interest of this method and the speed of execution are illustrated by two industrial examples, using the *Isopunch* software developed by **SOLLAC** to help for design of optimised steel parts.

1. Introduction

Faced with increasingly stiff competition, ever more restrictive environment and safety regulations, more severe quality requirements and the need to renew their products more rapidly, manufacturers, and in particular car manufacturers, have vastly modified their design methods.

In order to satisfy ever more precise and complex specifications (stiffness, lightness, sound proofing, impact resistance, etc.), the designer is required to find the best balance between geometry, thickness and grade of steel to achieve an optimum design. It becomes difficult to call these choices into question when the stamping sequence is in the process of being finalised.

In order to reduce the amount of toing and froing between the design office and the stamping engineering, to avoid later verification and reduce design cost and time, it is thus necessary to take feasibility considerations into account from the very start of the design process and throughout its duration : the design must be "stampable".

Design methods have thus been reviewed using simultaneous engineering, partnerships with major suppliers and finally scientific computer applications allowing virtual models representing the different solutions envisaged to be quickly built and so limit costly try-out to proven solutions.

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2. Why a simplified approach ?

While there are now many programs available for predicting the behaviour of components in service (mechanical resistance, fatigue, crash, etc.), few allow the difficulties of stamping to be predicted at the product design stage (see [3]). The digital simulation stamping codes which have appeared over the last few years (ABAQUS Explicit, DYNA-3D, OPTRIS, PAMSTAMP, etc.) are intended to be used by the process design department to help in defining and validating the stamping, and require all of the parameters of the stamping sequence to be fully defined.

In the design office, informations such as the stamping direction, the blank holder surface, the complete shape of the punch or the blank holder pressure will not yet have been defined. At this stage, it is not a matter of determining whether or not the part can be made, but of highlighting any areas which will cause problems during stamping and allow decisions concerning any modifications which may be required, to be made as early as possible in the design process. What is required at this stage of the design process is therefore a geometrical analysis of the shape of the component, from which the strains necessary to achieve the required shape can be estimated, rather than an accurate simulation of the stamping process. This analysis is carried out in parallel with calculations of the performance in service and facilitates communication between the product design office and the stamping engineering.

Moreover, despite rapid increases in computing power, the time required to enter the data and run these stamping simulation programs remains very long, and thus does not allow the methods department to carry out final checks and validations before making the dies. An analysis based on a simplified approach allows a quick choice of some parameters of the stamping sequence, such as the stamping direction (part tipping), the binding surfaces or the shape of the blank holder surface by comparing a greater number of different solutions and thus possibly reduce the number of test dies required. For those parts which are difficult to form by stamping, it can also rapidly show when it is necessary to use intermediate stages in order to obtain the final shape.

3. The inverse approach

The aim of the inverse approach is therefore not to simulate the stamping process as realistically as possible, but to quickly evaluate the strains of the stamped parts. Based on a mechanical formulation of large transformations (see [1] and [2]), this approach only takes account of the two extreme configurations of the component :

- the original steel sheet, for which the thickness and the bearing surface are known, but not the outline.

- the final part, for which the geometry is known but not the stress and strain conditions.

The behaviour law is assumed to apply throughout and the path of strain is assumed to be radial between these two geometrical states.

Working from a description of the part to be stamped (punch or product shape), the strain distribution on the part, and the shape of the original blank (flat or based on a given geometry) are calculated. These results are obtained by balancing the external forces, assumed to be normal to the surface, and the membrane stresses associated with the strains according to an incompressible stress-strain law. The lack of intermediate configurations (historical phenomena such as contact, etc. are not taken into account) makes this more of a geometrical method. However, the range of strains obtained is sufficiently significant to highlight the difficulties of stamping and allow different geometries to be compared in order to select the most suitable.

The use of the final geometry as input data makes this a method that is well suited to the product design office. Indeed, at this stage of the design, it is the only geometry known.

4. Isopunch : the inverse approach developed by SOLLAC

In order to assist our customers to optimise the design of their steel components, the Research and Development Centre of **SOLLAC** has developed *Isopunch*, a finite element based program which uses the inverse approach.

This program is very complete and includes a mesh generator, a pre-processor and a post-processor in addition to resolution modules. Its user-friendly graphic interface makes it easy to use for the designer or the press operator and not reserved for digital computing specialists. It only requires a few parameters to be entered and default values are always proposed to the user.

The description of the geometry to be analysed is obtained directly from the CAD files via standard interface formats such as UNISURF, IGES, SET or VDA. The file type is automatically detected. Using a trans-patches method, TRANSK, the mesh generator of *Isopunch* allows a meshing to be obtained, independently of the surface modelling and respecting the geometrical characteristics of the part (contours and sharp edges). The mesh generation operation is automatic and tolerates inaccurate CAD models (overlapping and disjointed surfaces, etc.)

After having checked, or possibly changed the mesh obtained, the user runs the finite element resolution program using a dialog box. Three computing models for estimating stamping difficulties are available :

- FLPLAN which allows to start from a flat initial blank

- FNPLAN which uses blank holder surface meshing
- CONFORME which allows the operation of "conformation" to be simulated between an intermediate shape and the final shape without any flow of metal under the blank holders.

Beside the meshing and part geometry, these resolution modules require no other parameters than the thickness of the initial blank.

The results are then analysed by means of the post-processor which, with its user-friendly interface, allows the different results obtained to be displayed:

- initial blank shape
- range of thicknesses, variations in thickness and strains
- principal strains direction.

Isopunch requires no particular computing skills and can be used directly by the designer or the press-operator. It is very fast and easy to use, and allows numerous alternative solutions to be tested for a given part in a few hours. It thus allows changes to be made very early on in the design process by facilitating communication between the product design office and the stamping engineering.

5. Example of application in the product design office.

The component studied is a car dashboard (figure 1), which is located between the engine compartment and the passenger cell. It is currently mass produced from 0.75mm XES steel. Stamping remains difficult.

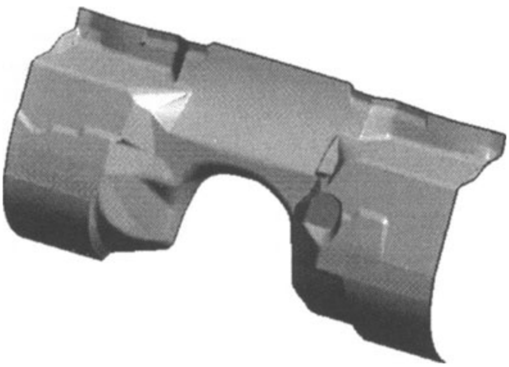

figure 1: dashboard

The aim is to stamp this component using a higher yield strength steel 0.4 mm thick. Despite using the elastoforming process developed by **SOLLAC** for the drawing of extra thin sheets, it is necessary to adapt the geometry, as the defects noted will become more important due to the thinner sheet steel used.

A Silicon Graphics Indigo2 workstation was used.

The component, composed of 806 Bezier patches, was recovered using a UNISURF file (figure 2). Given the size of the component, the minimum element size is set at 10 mm. The default values were used for the other parameters. The meshing obtained consists of 11,821 elements. The total time required to recover the geometry, retrieve the contour of the model and generate the mesh is of the order of 5 minutes.

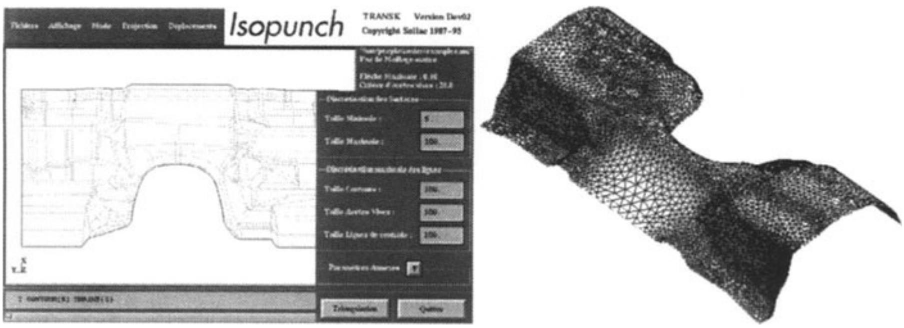

figure 2: retrieval of geometry and running of mesh generator

The program is run very simply by means of a dialog box. The FLPLAN (flat blank holder surface) module was used. 4 minutes were required to complete the calculation.

The results of the calculation (blank holder contour and thickness variation at all points) are then displayed by means of the post-processor (figure 3). At this stage of the analysis, the strain values are indicative only and are not those which would be obtained experimentally by stamping a real sheet. They are however sufficiently significant to highlight those areas which will cause problems during stamping:

- very significant and localised reductions in thickness which could lead to necking
- large areas in compression, which will lead to buckling.

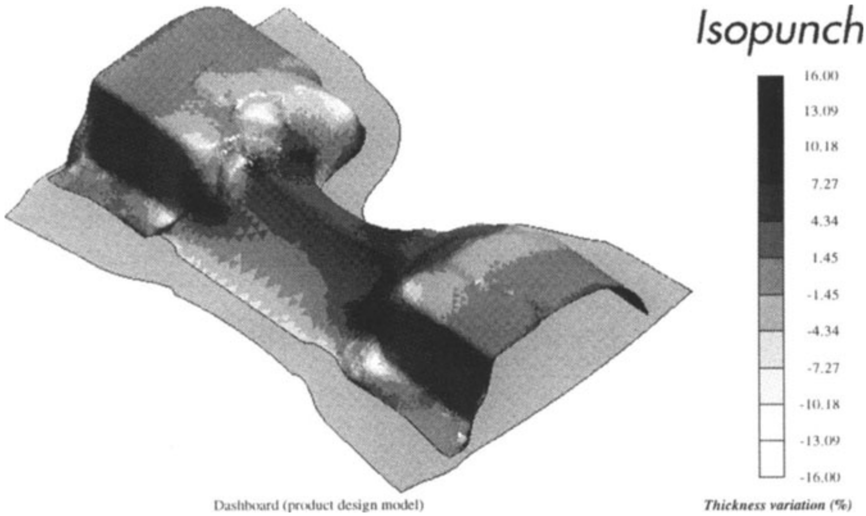

figure 3: display of variations in thickness and of initial blank

Because of the thinness of the sheet and the grade of steel used, the geometry was modified in an attempt to achieve a greater homogeneity (removal of non functional details, smooth of some radii) and a new analysis carried out. Comparing the variations in thickness achieved with the modified geometry to those of the initial geometry (figure 4), it can be seen that the modifications go some way towards improving the stampability.

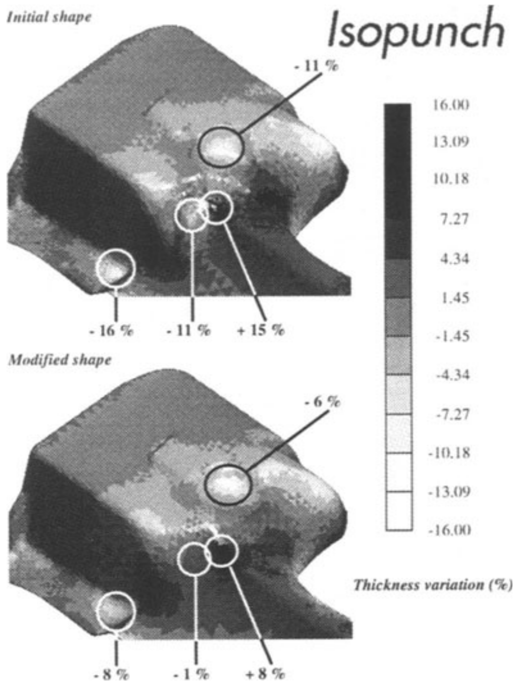

figure 4: comparison of initial and modified geometries

6. Example of application in the stamping engineering

The component studied is a wheel housing - left- and right-hand components - (figure 5). The aim of this study is to define the stamping sequence of the two wheel housings so as to be able to produce these parts using 0.7mm thick electro-galvanized SOLCONFORT sandwich panels.

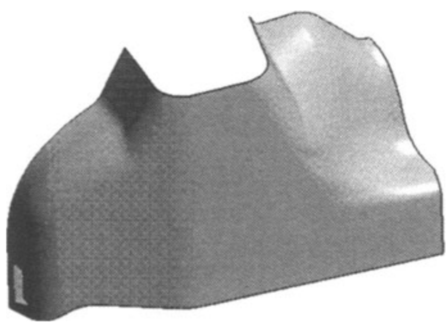

figure 5: right-hand wheel housing

The left-hand and right-hand components shall be stamped together. Three versions of tipping, position, binding surfaces and associated blank holder surface have been tested (figure 6). The final shape of the blank is not considered at this stage of the study.

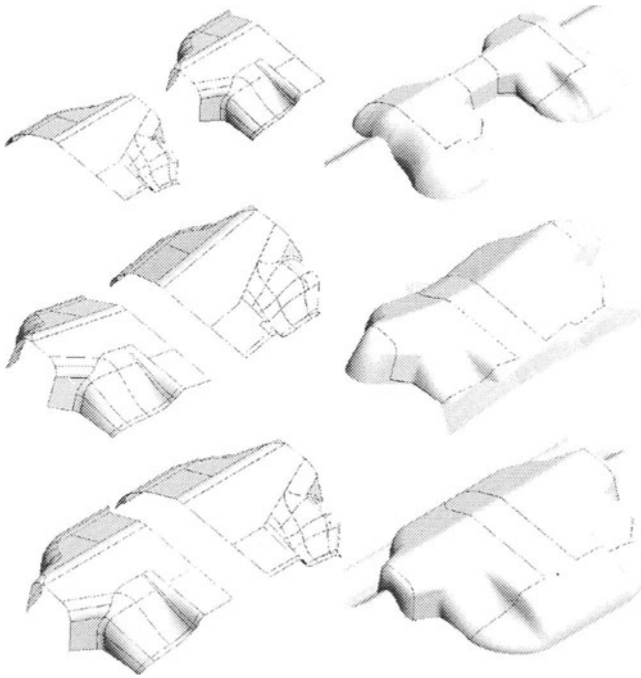

figure 6: three versions of position, tipping and binding surfaces

The study was carried out on a Silicon Graphics Indigo2 workstation.

The CAD models (between 150 and 300 Bezier patches) were recovered using the UNISURF format. The default values were used to generate the meshing, requiring 5 to 7 minutes for each configuration. The three meshes obtained contain 12,228, 19,953 and 13,842 elements respectively.

Because the three blank holder surfaces can be developed, the FLPLAN calculation module (working from a plane blank) was used. Computing times varied between 4 and 13 minutes for the three configurations.

Comparing the variations in thickness (figure 7) allows us to eliminate the first solution which presents areas of greatly reduced thickness and areas of compression close together within the centre section of the component.

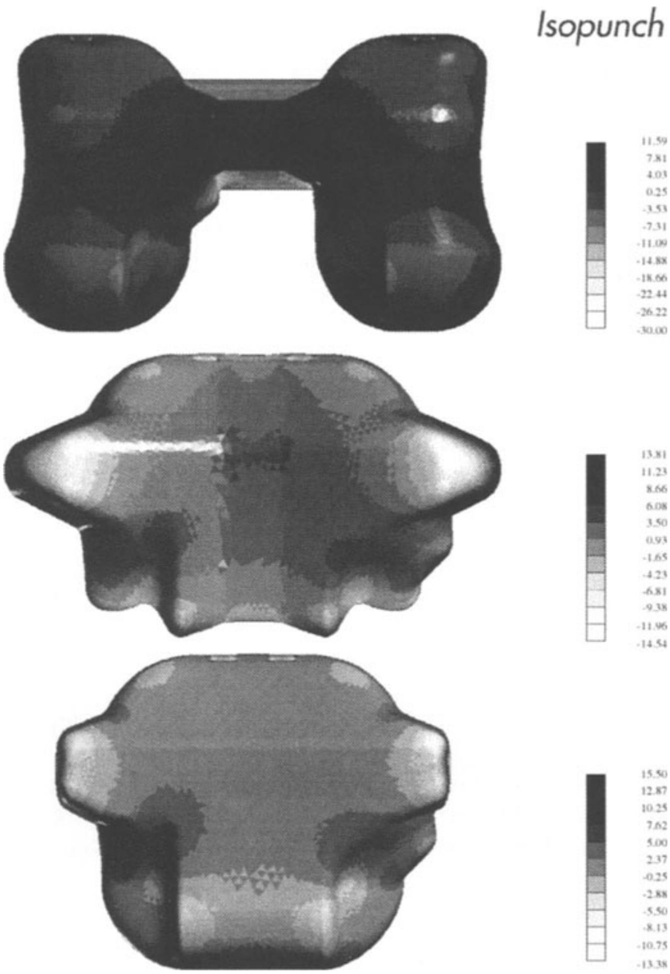

figure 7: variation of thickness over the three stamping sequences

While the reduction in thickness of the second solution is of the same order of magnitude as that of the first, it highlights areas of compression in the centre of the component which may cause undulations within an area of close contact, on account of the material used, and areas of high stress at the attachment of the cup onto a tapered section. The last solution has therefore been chosen, as it is the more homogeneous, despite the fact that it still results in areas of compression where buckles were observed on the stamped prototype panels.

The total time required to carry out this comparison (including CAD, mesh generation, calculation and analysis) was approximately 3 days.

7. Conclusion

Taking examples of the application of the *Isopunch* program developed by **SOLLAC** to industrial situations, we have shown the advantage of a simplified method of calculation to assist the designers and the press operators to design optimised steel components.

Isopunch makes it possible to quickly detect problem areas at the product design stage, without having to define the complete stamping process. Used in parallel with mechanical resistance programs to ensure compliance with the specifications, it allows modifications in geometry to be made at an early stage improve the formability.

In the process design office, *Isopunch* facilitates the definition of the best stamping sequence, by helping to choose the stamping direction, the binding surfaces and the blank holder surface from among a number of solutions. The semi-quantitative values of strain highlight problem areas which will become apparent during development (buckling, necking, etc.).

Moreover, in the event of a problem being detected in the press-shop during the press adjustment stage, *Isopunch* can be used, after having first adjusted the simulation to take account of the measured values, to search among different die modifications, that which is most likely to rectify the defective geometry.

A simplified approach such as this allows ranges of strains to be obtained which are sufficiently representative to highlight the geometric problems associated with the shape to be stamped and compare the feasibility of different geometries. By facilitating communication between the product designer and the process designer, it helps in the choice of an optimum solution from a very early stage in the design process.

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MECHANICAL SIMULATION OF MACHINING

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Abstract We have developed a new mechanical simulation for machining with precision cutting tools in order to predict vibratory behaviour, but more importantly, resulting final surface. For this simulation a new machining model has been developed. The various mechanical aspects of the problem, including vibratory motion of flexible machine parts, cutting law and the interaction between tool and workpiece, have been taken into account within the same experimental software.

1. Introduction

High precision machining is our concern. We set out to keep the model at a macroscopic level using a new computational approach [Dek95] to obtain a mechanical simulation for machining, taking into account workpiece deformation. This new computational approach provides for better understanding of the behaviour of the Workpiece-Tool-Machine system (WTM) as well as the modelling of the WTM system.

This research is a step towards exploring higher cutting speeds, new materials and deformable workpieces. The objective is to predict what occurs while machining and the consequences on the resulting surfaces; more precisely:

1) vibratory behaviour during the machining process (i.e. chatter and deformations in WTM)

2) final resulting surface: roughness and undulations along selected sections.

Deformable workpieces do neither figure in the computer code nor in the simulations ; nevertheless, the design of the method has been completed. These workpieces have been included in the software structure since the outset of the research.

An efficient tool for making simulations must be able to take into account and predict the above objectives in a wide range of practical situations. We intend here to propose such a tool. As it is impossible to obtain analytical results in such a complicated context, numerical computation must be performed. Two experimental software programs have been developed to carry out these calculations. The first validates principles, and can be used in simple situations such as end or peripheral milling. It is based on a 2.5D geometric modelling. The second one is entirely 3D. It

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was designed for face milling results, but with the intention of extending it to practically any other cutting situation. We believe that the attempt to couple existing CAD and FEM software is inefficient due to the interpenetration between FEM solving and intersection computations required at the deepest level of programing: the common data structure and communications between both parts have to be optimised. Recent, papers going in the same direction as ours are not entirely clear on this point ([ScB93], [SpA94], [WeA94], [TCK95]).

2. Microscopic and Macroscopic approaches

Our macroscopic approach contrasts sharply with the microscopic one.

2.1 MICROSCOPIC APPROACH

This approach deals with refined modelling of the cutting area in the tool vicinity and now figures as a means of predicting chip flow and the detailed descriptions of temperature, stress and strain states in tool and workpiece. [Mer45] and [PaO59] are examples of first attempts made on this scale. Recent work, (e.g. [MaO95], [RJT93], [SeC93]) have been based on two or three dimensional finite element simulations including viscoplasticity, friction, thermomechanical coupling, damage and fracture mechanisms. At the present time, this kind of microscopic approach is not well suited for the kind of results we desire, as it requires an enormous amount of computer time for only local results in rather simple situations.

2.2 MACROSCOPIC APPROACH

Material removal is modelled very schematically in this approach towards a better understanding of chatter, vibrational behaviour and final surface (cf. [TlM75], [DKZ80], [KDS82], [MoA91], [ScB93], [EhH94], [BuA96]). In fact, the mechanical details governing material are left untreated.

Here, in our work, the main assumption underlies the concept of an erasing tool. Only the macroscopic physical phenomena (i.e. material removal and related forces) are modelled. The tool is considered as a material eraser – wherever the tool passes, corresponding workpiece parts disappear. Although this could be considered a rough idealisation, there is literature to substantiate this assumption. Moreover our test results demonstrate that it gives satisfactory results for the above mentioned aims. Assuming the piece is perfectly rigid and at rest in the inertial frame, the erasing assumption leads to:

$$ {}^{t}\Omega_P = {}^{0}\Omega_P - \bigcup_{\tau \in [0,\, t]} {}^{\tau}\partial\Omega_c \qquad (1) $$

where ${}^{t}\partial\Omega_P$ and ${}^{t}\partial\Omega_T$ are the boundaries of ${}^{t}\Omega_P$ and ${}^{t}\Omega_T$, the workpiece and tool domains at time t, and ${}^{t}\partial\Omega_c = {}^{t}\partial\Omega_P \cap {}^{t}\partial\Omega_T$ their area of contact.

3. WTM modelling fundamental aspects

Four different models are required in our approach. They are described below.

Two geometric models: adopted geometric models (denoted GM) give a surfacic description of the domains solely based on their boundaries. Depending on spindle rotation, feed and vibrations, one moving geometric model is associated to each elementary tool. The geometric model of the Tool (denoted TGM) is their union and describes ${}^t\partial\Omega_T$. The central point is the vibrating and evolutionary geometric model of the piece (denoted PGM) which is used to follow all the geometric changes of the workpiece, including material removal, following (1). The final state of the geometric model of the piece gives the final surface ${}^f\partial\Omega_P$. We can then predict in detail, geometric imperfections and their occurrence in the machining process.

A model for the cutting law: The tool is considered as a material eraser. The interaction between piece, chip and tool is taken into account by a model for the cutting law. This hypothesis is commonly adopted for orthogonal cutting and end milling. DeVor *et al.* [EDK93] introduce a mechanistic model, we employ a similar model in our approach. In face milling [FDK94] they also propose an approach, but the situation is more complex because 3D cutting conditions are encountered. We adopted here a very simplified approach to generalise the 2D model. Let S^* be the potential area of contact between the tool boundary and the workpiece: ${}^t\partial\Omega_c \subset S^*$. Note that S^* is a part of the tool boundary. The cutting edges are divided into segments l_e. We associate a part S_e^* of S^* and a point P_e to each segment l_e. Let $S_e = {}^t\partial\Omega_c \cap S_e^*$. An associated formula is then adopted to give the force components ϕ_{ie} that we apply at P_e as a function of the ratio S_e/S_e^*. This allows us to generalise 2D orthogonal cutting laws, using the ratio S_e/S_e^* where h/h_0 would be used (with h depth of cut and h_0 an arbitrary reference length). For instance a power law for each component ϕ_{ie} is adopted:

$$\phi_{ie} = \begin{cases} \kappa_{ie}\,(S_e/S_e^*)^{\alpha_{ie}} & \textbf{if } {}^t\partial\Omega_c \neq \varnothing \textbf{ and } \mathbf{V}_r.\mathbf{n} > 0 \\ 0 \ \textbf{if } {}^t\partial\Omega_c = \varnothing & \textbf{or } \mathbf{V}_r.\mathbf{n} \leq 0 \end{cases} \tag{2}$$

where $\mathbf{V}_r$ is the actual relative velocity (as computed from the numerical integration of equation (4) thereafter) between tool and workpiece at point P_e belonging to the tool boundary ${}^t\partial\Omega_T$, $\mathbf{n}$ the unit external normal of ${}^t\partial\Omega_T$. κ_{ie} and α_{ie} are physical coefficients identified from experiments.

A mechanical dynamic model for the WTM: if we exclude the rotating part (either the piece in turning or the cutter in milling) which we normally take into account in a rotating frame, small deformations are assumed. Therefore, a linear model from classical continuum mechanics can be used, leading to the classical virtual work approach where:

$$\forall\, t,\ \forall\, \delta\mathbf{U},\ \int_{{}^t\Omega} \delta\mathbf{U}\bullet\rho.{}^t\ddot{\mathbf{U}}\ {}^t d\Omega + \int_{{}^t\Omega} \mathbf{tr}(\delta\varepsilon\bullet{}^t\sigma)\ {}^t d\Omega = \int_{{}^t\partial\Omega_c} \langle\langle\delta\mathbf{U}\rangle\rangle\bullet\mathbf{p}_{cut}\ {}^t d\Gamma \tag{3}$$

the left exponent t denotes the time. ${}^t\Omega$ is the WTM domain. ρ is the mass density. $\mathbf{U}$, $\delta\mathbf{U}$ and ε, $\delta\varepsilon$ denotes the actual and virtual displacement and strain. ${}^t\sigma = \mathbb{D}:\varepsilon + \mathbb{D}':\dot{\varepsilon}$

is the stress tensor assuming viscoelastic constitutive relations ($\mathbb{D}$ and $\mathbb{D}'$) for all parts. $\langle\langle \delta \mathbf{U} \rangle\rangle$ is the jump of $\delta \mathbf{U}$ on ${}^{t}\partial\Omega_{C}$. Finally $\mathbf{p}_{cut}$ is the cutting force coming from the cutting law.

The forcing term in the equation of motion (3) comes from the imposed relative movement of the tool and workpiece which gives rise, between them, to internal forces in the system, when cutting occurs. Within the framework of the cutting law, these forces vary depending on local relative velocities, local depth, width of cut, etc. In our approach, we only need an estimation of resultants ϕ_e for each l_e once the problem has been discretized.

4. WTM modelling practical aspects

We assume that changes in stiffness and mass resulting from material removal and feed can be neglected in considered applications. Thus, matrices which are needed to complete the simulation are supposed to be constants and can be obtained through the use of external tools such as classic finite element solvers.

Discretization using a Finite Element Model leads, from (3), to the classic relation (4). From left to right in (4) appear, the mass, coriolis+damping (ω is the angular velocity of a rotating part) and stiffness matrices. $\mathbf{q}$ includes all unknown dof. $\mathbf{Q}_{cut}$, coming from the right hand side of (3), is the non-linear part of the equation.

$$\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{C}(\omega)\,\dot{\mathbf{q}} + \mathbf{K}\,\mathbf{q} = \mathbf{Q}_{cut}(\mathbf{q}, \dot{\mathbf{q}}, t) \tag{4}$$

As stated above, geometric models are necessary for the essential result, which is the final boundary ${}^{f}\partial\Omega_{P}$ of the workpiece. They are also needed to follow at each time t, the evolution of ${}^{t}\partial\Omega_{C}$, which has to be known to calculate the right hand sides in (3) and (4) and, thus, resolve the equation. In situations such as peripheral milling, a 2.5D model can be adopted. The 2.5D model only needs a 2 dimensional approach in a set of planes perpendicular to the rotating axis. In each plane, the topology is given by a set of segments connected to a set of points. Point coordinates complete the description. In 3D, such as face milling, in order to be able to face any cutting process, a full 3D approach is adopted. This is based on a topological representation with a set of plane triangular facets connected to segments. These segments are connected to points. Both geometric models allow nearly any complexity in the piece geometry, including complicated initial defects, or holes and internal cavities.

4.1 SOLVING THE DISCRETIZED PROBLEM

The computational process is based on a step by step integration of the discretized mechanical equations of motion (4). The Newmark method ([Bat82]) is used for this purpose and leads to (5). As the problem is non linear, iterations (exponent k hereafter) are needed for each time increment. Modelling of material removal due to machining is simulated via an algorithm searching out and managing intersections, under the assumption of an erasing tool. This intersection operator also provides required information to define the input for the cutting laws and get applied internal forces ϕ_e

from its output allowing the current evaluation of $\mathbf{Q}_{cut}$.

Starting at t=0 from the initial conditions, the algorithm is the following:

Do For each time step t in the interval of interest $[0,t_f]$: [
 $t := t+\Delta t$; $k:=1$; Update TGM; $\hat{\mathbf{q}}^{(0)} \overset{d}{=} {}^{t+\Delta t}\mathbf{q}^{0)} := {}^{t}\mathbf{q}$; Compute ${}^{t}\bar{\bar{\mathbf{Q}}}$;
 While the norm of left hand side of (5) ≥ a prescribed tolerance [
  Let $\mathbf{x}^T \overset{d}{=} ({}^{t+\Delta t}\mathbf{q}^{(k-1)T}, {}^{t+\Delta t}\dot{\mathbf{q}}^{(k-1)T})$ (known quantity at iteration k) ;
  Get estimation of ${}^{t+\Delta t}\partial\Omega_c^{(k-1)}$, from $\mathbf{x}$, through the intersection operator ;
  Get estimation ${}^{t+\Delta t}\mathbf{Q}_{cut}^{(k-1)}$ using $\mathbf{x}$ and ${}^{t+\Delta t}\partial\Omega_c^{(k-1)}$ and the cutting law;
  Solve (5) for the increment of estimated displacement $\mathbf{u}^{(k)}$;
  Update current estimation of $\hat{\mathbf{q}}^{(k)} := \mathbf{u}^{(k)} + \hat{\mathbf{q}}^{(k-1)}$] **EndWhile**;
 Update PGM (convergence occurred): ${}^{t+\Delta t}\partial\Omega_p := {}^{t+\Delta t}\partial\Omega_p^{(k)}$] **EndDoFor**;

$$\hat{\mathbf{K}}\,\mathbf{u}^{(k)} - \mathbf{Q}_{cut}(\hat{\mathbf{q}}^{(k-1)}, \hat{\dot{\mathbf{q}}}^{(k-1)}, t+\Delta t) - {}^{t}\bar{\bar{\mathbf{Q}}} + \hat{\mathbf{K}}\,\hat{\mathbf{q}}^{(k-1)} = 0 \tag{5}$$

where $\alpha=1/4$, $\beta=1/2$, $\hat{\mathbf{q}} \overset{d}{=} {}^{t+\Delta t}\mathbf{q}$ and $\hat{\mathbf{K}} \overset{d}{=} \mathbf{K} + a_0\mathbf{M} + a_1\mathbf{C}$,

$${}^{t}\bar{\bar{\mathbf{Q}}} \overset{d}{=} \mathbf{M}\,(a_3\,{}^{t}\ddot{\mathbf{q}} + a_2\,{}^{t}\dot{\mathbf{q}} + a_0\,{}^{t}\mathbf{q}) + \mathbf{C}\,(a_5\,{}^{t}\ddot{\mathbf{q}} + a_4\,{}^{t}\dot{\mathbf{q}} + a_1\,{}^{t}\mathbf{q})$$

$$a_0=\frac{1}{\alpha\Delta t^2},\ a_1=\frac{\delta}{\alpha\Delta t},\ a_2=\frac{1}{\alpha\Delta t},\ a_3=(\frac{1}{2\alpha}-1)\Delta t,\ a_4=\frac{\delta}{\alpha}-1,\ a_5=(\frac{\delta}{2\alpha}-1)\Delta t$$

4.2 THE WORKPIECE DEFORMATION

Despite the macroscopic aspect we adopt here, the workpiece deformation can be taken into account without any fundamental change in the computer code. This is under development at present. The main difficulty arises from required mapping between a workpiece rest frame reference domain ${}^{r}\Omega_p(t)$ and its deformed configuration ${}^{t}\Omega_p$. This implies an additional iterative process to bring back the new facets (and related segments and points) describing ${}^{t}\partial\Omega_p$ to the rest frame to obtain ${}^{r}\Omega_p(t)$ from its boundary description. ${}^{t}\partial\Omega_p$ comes from the intersection operator. This necessitates the use of two meshes to render the operation efficient.

The first mesh, which we call mesh-1 is the standard *a priori* unstructured one (to fit 3D curved boundaries, cavities, etc.) used in FEM calculations with selected elements and associated dof $\mathbf{q}_1$. The second one, called mesh-2, is a regular structured one, built up from a set of equal rectangle parallelepipeds in 3D. $\mathbf{q}_2$ is the associated dof vector. The virtual domain Ω_v associated to mesh-2 fully includes the domain Ω_P associated to mesh-1. A preliminary phase, which only needs to be performed once prior to starting computations, builds the application from mesh-1 to mesh-2, such that small constant matrices may be constructed, allowing a rapid computation of $\mathbf{q}_2$ from $\mathbf{q}_1$.

Rapidity is required here since each passage from $\mathbf{q_1}$ to $\mathbf{q_2}$ must occur at each iteration k of each time step. From the integer part of normalised coordinates of a point belonging to Ω_V a very simple and fast algorithm gives the element of mesh-2 to which the point belongs. Without this intermediate mesh, the initial and very time consuming phase should be repeated for each iteration.

Mesh-1 is a part of the WTM FEM model and $\mathbf{q_1}$ can be a part of $\mathbf{q}$, the solution vector. However, in order to reduce the size of $\mathbf{q}$, and due to the fact that we only want to observe relatively long wave deformations, the solution under development involves Guyan's reduction so that only $\mathbf{q_m}$ a part of $\mathbf{q_1}$, is contained in $\mathbf{q}$. $\mathbf{q_1} = \mathbf{G}\,\mathbf{q_m}$. $\mathbf{G}$ is a constant matrix which will be computed only once before the beginning of increments from static condensation on the chosen master dof $\mathbf{q_m}$.

5. Examples

Examples here are only given to demonstrate the ability of the proposed method for dynamic results, such as forces and displacements versus time, and characterisation of the final surface. In the examples, cutters used in end and face milling only have one tooth. Numerical values used for these results are not given. Simulations shown usually need several thousand time increments (Δt less than 0.0001 seconds).

5.1 EXAMPLE IN 2.5 D: END MILLING

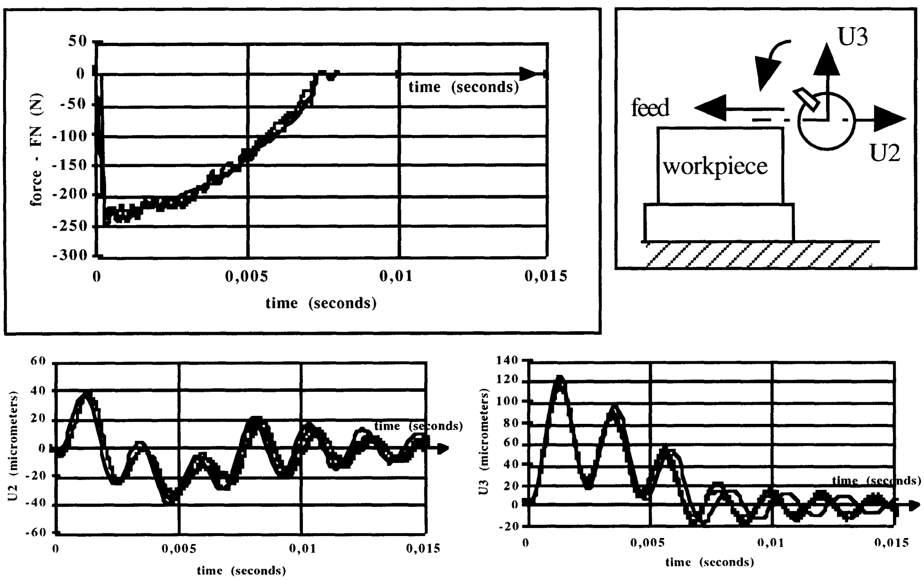

Figure 1. End milling using a 2.5D modelling: Comparison between experiments (thin lines) and computations (thick line).

Figure 1 shows the experimental set-up (top right) and the comparison between experimental results for 3 half revolutions (the 3 thin lines) and a current computed one (the thick line). The tool is special and the WTM model uses only 2 dof, one in each direction. The workpiece is a thin plate and only one plane is used to idealise the surface by a set of segments. Displacements U2 and U3 are shown (bottom left and right), and the perpendicular force to the rake face FN (top left). They prove that a rather good agreement can be achieved between simulation and experiments.

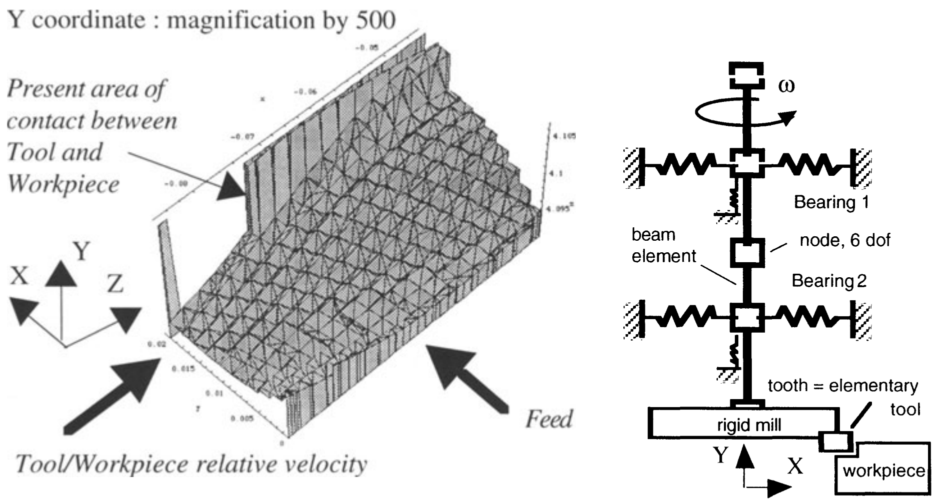

Figure 2 Face milling using a 3D modelling. Mechanical model and some geometric available results: geometric model of the detailed surface (zoom and Y magnification).

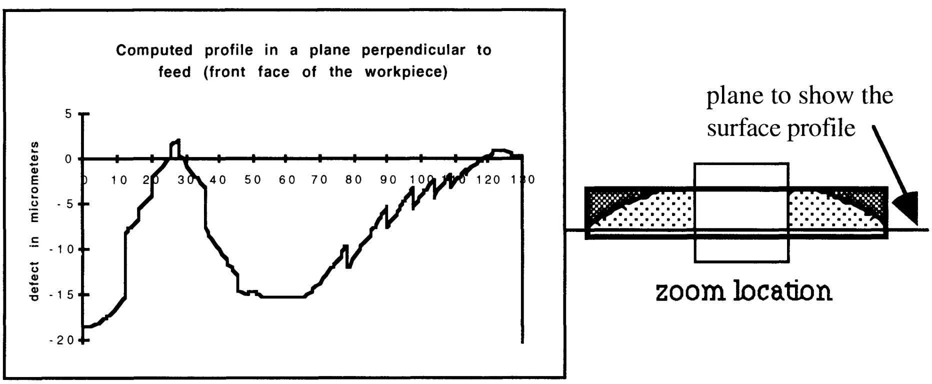

Figure 3 Face milling using a 3D modelling.
Zoom location and surface profile in the (Y, Z) plane .

5.2 EXAMPLE IN 3D: FACE MILLING

The example, shown by Figures 2 and 3, uses a simplified 29 dof model (Figure 2, right) for the WTM system, mainly considering the dynamic behaviour of the spindle and its bearings. Numerous experiments have been run by the automobile constructor Renault, but no detailed comparisons have been made yet between experiments and computations. A rather large feed rate was used here to show the principle of the GM used for the surface.

A zoom (Figure 2, left) of an obtained surface in the plane (X-Z) is given with a magnification factor of 500 in the Y direction in order to be able to show the simulated resulting defects coming from the coupled vibrational problem that was solved, as in the 2.5D example. The region for the zoom is in the centre of the workpiece (shown Figure 3, right). The feed is in the X direction and the cutter axis is the Y axis. Undulations can be seen on this figure; they are the result of the theoretically imposed relative movement to which, vibrations induced by the cutting process are added. A cross section in a plane parallel to the (Y-Z) plane gives the resulting profile of the surface (Figure 3, left). Defects of this nature have been observed in our experiments.

6. Present limits of our approach

The obtained results closely depend on the accuracy of two models: the macroscopic cutting law and the dynamic model of the WTM system in the vicinity of a working point. The WTM model and the cutting law are difficult to obtain in an *a priori* way. Comparison between experiments and numerical results can be used to improve them. Once a model is postulated, an identification of the related parameters can be achieved.

That is what we are working on at present. Significant work still has to be done in this direction, as the influent dynamics, when looking to high precision, must be able to simulate the relative movement between tool and workpiece, taking into account stiffness and damping, including those due to numerical command control loops. Moreover, in the case of thin deformable workpieces, the material removal has a significant influence on stiffness and mass of the workpiece. This will have to be taken into account in the future.

7. Complex experiments and use of this kind of approach

The proposed approach and the simulator which have been presented can also be used for a more fundamental purpose, as they allow us to refine our present knowledge in machine and cutting law modelling. Due to a lack of simulation capabilities and despite the fact that numerous experiments and models have been, and are still under study (cf. [EDK93], [KiE93], [FDK94], [YMO94], [BeL96]), we believe that there remains an impelling need to define rational cutting laws. Usually, macroscopic laws such as the one we need, are derived from stationary tests or from near stationary tests. In this case, the use of a simple theoretical approach will not allow an objective definition of the cutting law in a frame linked to the active edges of the tool. This gives rise to corrections in the empirical laws, and these corrections do not appear very physical to us. Macroscopic laws must be updated and tuned with each WTM set. Our approach will define simplified laws in frames linked to the tool. It seems that such an approach could avoid the use of artificial damping terms in empirical laws, as in some cases these terms seem to be the result of the relative rotation of the frames linked respectively to the cutting edge and the workpiece. Moreover, a rational use of different models in conjunction with experiments could allow the separation of the relative influence of the cutting process itself from vibrations of different parts. As a matter of fact, dynamic behaviours are very often more difficult to understand intuitively than static ones and it is very easy, without modelling, to include a non identified modal behaviour in a pseudo empirical cutting law.

8. Conclusion

We have described here a new approach coupling mechanical models and refined geometrical models to simulate machining. Specially designed experimental software programs were built, and examples of some available results shown.

Many practical difficulties have been overcome. We have made large advances towards obtaining the kernel of an operational industrial tool, including workpiece deformation. Many simulations and experiments still have to be done in order to fully validate the approach, but many references show that the main assumptions are reliable, mainly those associated with the concept of an erasing tool.

Acknowledgements

We wish to thank François Lapujoulade from LPTPM ENSAM for his collaboration and for his work with Renault. He is still working with us on both the refined experimental part, which he has completely developed, and the related simulations for identifying cutting laws and machine dynamics. This work is now partly funded by French MESR (*action spécifique* DPST8).

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THERMAL MODAL ANALYSIS AND MODELLING OF MACHINE-TOOLS

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Abstract. Thermal errors due to thermal deformations are one of the most important problems one comes accross when dealing with machine-tool accuracy improvement. Analytical approaches are making progress, but they must be complemented with experimental methods. Thermal modal analysis, parallel to dynamic modal analysis of machine structures, is presented in this paper. Applications of this experimental method are presented.

1. Introduction

Thermal deformations, due to different heat sources, are one of the main causes of lack of accuracy in machine tools.

When a machine tool is working, there are many heat sources. Some of them are internal sources such as the heat originated from different elements of the machine, by motors, spindles, gears, rolling elements, ball screws, guideways, etc. Other heat sources come from the machining process itself, such as the heating that tools, workpieces, chips undergo, or the heat (or cooling) provided by lubrication and cooling systems. There are also external heat sources such as variations in ambient temperature, radiation, air streams, etc. Some of these sources are more or less well known and controllable, but others are difficult to control.

Another difficulty is that during the machining process, the thermal state is transient in normal operations, because the time constants involved in the thermal problem are of the order of hours, longer than most machining operations, and therefore a steady-state situation is not reached.

Although analytical approaches are making progress, they must be complemented with experimental methods. Thermal modal analysis, parallel to dynamic modal analysis of machine structures, is presented in this paper as a modelling method of machines in order to:

- analyse thermal modes in a rational form,
- predict the thermal behaviour, and

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- control deformations.

In the last years a lot of work has been developed at Universities and Research Centres, especially on compensation techniques.

In 1990, A. Balsamo, using 100 sensors, corrected up to 85% of the thermal deformation in a CMM [1]. In 1992, K.C. Fan utilised multiple variable nonlinear regression techniques to compensate for the thermal deformations in a machining centre with 19 thermocouples [2]. In 1992, J.S. Chen improved the accuracy of a machining centre by a factor of ten using two different methods: multiple regression analysis and artificial neuronal networks [3]. In 1993, Y. Hatamura reduced the angular thermal deformation in a machining centre using thermal actuators on the column and neural network approaches [4].

J. Bryan [5], G. Spur [6] and M. Weck [7] have carried out very good summaries on the state of the art in thermal deformations.

2. Numerical Calculation of Thermal Deformations

Spatial integration of transient heat flow equations along the structure and elements of the machine, with the appropriate boundary conditions, can be performed by the FEM (finite element method).

Matrix equations of the following type are obtained:

$$[\rho c]\{\dot{T}\}+[K]\{T\}=\{q\} \tag{1}$$

where:

$[\rho c]$ band or diagonal matrix, "thermal capacity matrix",

$[K]$ symmetrical matrix, containing conductivities K and film coefficients h, "heat transfer matrix",

$\{q\}$ applied heat flows vector, which can take into account changes in ambient temperature,

$\{\dot{T}\}$ time derivates of temperatures vector,

$\{T\}$ temperatures vector.

Deformations are the result of temperature field, geometry, heat expansion coefficients and elastic constants of the materials.

The relationship between displacements δ and temperatures T can be represented by means of the matrix equation:

$$\{\delta\}=[\alpha]\{T\} \tag{2}$$

The use of analytical methods for modelling the thermal behaviour of machine tools is progressing and is leading to more and more accurate solutions [8], but errors are always present in both transient and steady-state problems.

In general terms, there is not sufficient knowledge on heat sources. In some cases the deformations themselves modify heat generation conditions, for example, by changing preloads in some roller bearing systems. Thermal and elastic problems are coupled [9].

Some heat transfer coefficients are not well known, especially the film coefficient, which can change greatly from natural to forced convection due to air streams produced sometimes by the movement of machine components. Another problem is the heat transfer between joins, which depends on preload and it is difficult to be evaluated. Here we are also faced with a thermo-elastic coupled problem.

The complex modelling of machines contributes to the lack of accuracy resulting from theoretical calculations.

As a consequence of this it is proposed that analytical methods are completed through machine modelling from experimental results, as it happens in dynamic problems.

3. Thermal Modal Analysis

Instead of using a step by step procedure for time integration of equation (1), it can be integrated by searching for particular solutions of the form $\{T\}=\{C\}e^{rt}$.

The general solution is:

$$\boxed{\{T\} = [\lambda]\left\{C\,e^{rt}\right\} + \left\{T_{\infty}\right\}} \qquad (3)$$

where $[\lambda]$ is the matrix of "thermal modal vectors" corresponding to each of the values of r or "eigenvalue" of the characteristic equation.

Temperature at each point is the sum of some exponentials [10] affected by coefficients which are proportional to the values of the thermal modal vectors [11].

Experimental determination of the values of the exponents r, eigenvalues o characteristic values, (or $\tau=-1/r$, characteristic "time constants") and of the thermal modal vectors constitutes **"thermal modal analysis"**.

Displacements are related to temperatures through matrix $[\alpha]$, and each thermal displacement mode corresponds to one temperature mode. Displacement at each point can be obtained by a linear combination of the exponential functions with the same time constants used for temperature determination.

Experimental determination of temperature modes and of displacement modes corresponding to the points of interest (δx, δy, δz) between tool and work-piece, can be carried out using the heat sources of the machine itself, activating them one after the other, and measuring temperatures and relative displacements of the machine. After that, exponential functions must be fitted to the heating or cooling curves, the exponents providing the time constants and the coefficients, temperature and displacement modes.

Understanding how machines respond to heat flow has important applications, many of them not yet explored: applications parallel to those that can be obtained from modal analysis of vibrations in machine tools.

This parallelism between dynamic and thermal modal analysis can be seen in figure 1.

The most important modes are those with high time constants, and the relative importance of subsequent modes with lower time constants is reduced accordingly.

Modal shapes can be used to predict thermal behaviour when any heat source is applied. The importance of some modes can be reduced by locating heat sources on nodal lines, and the relative influence of different modes on some displacements can be analysed. They are useful to analyse in a rational form the zones of location and laws of heating or cooling systems for compensation. The number, position and compensation formulae for deformations as a function of temperatures measured at different points of the machine can be rationally defined, etc.

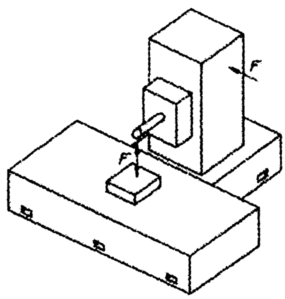
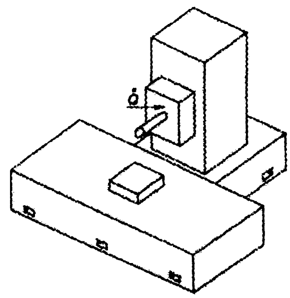
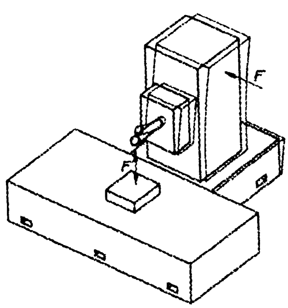
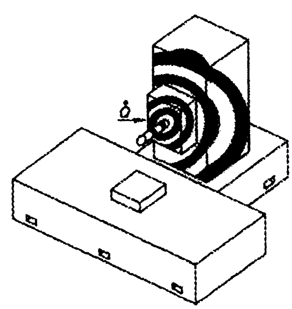
	Dynamic analysis	*Thermal analysis*
EXCITATION		
TRANSFER FUNCTION	$G_{ij}(s)=\sum_{k=1}^{n}\frac{U_{ijk}+jV_{ijk}}{s-(\delta_k+j\upsilon_k)}+$ $+\frac{U_{ijk}-jV_{ijk}}{s-(\delta_k-j\upsilon_k)}$	$G_{ij}(s)=\sum_{k=1}^{n}\frac{C_{ijk}}{s+r_k}$
MODAL PARAMETERS	$U\pm jV$ = complex amplitude ν = natural frequency δ = loss factor	C = amplitude $\tau=1/r$ = time constant
RESPONSE		

Figure 1. Parallelism between dynamic and thermal modal analysis.

However there is a difference when the zone of influence of vibration is compared to the zone of influence of heat sources. Vibrations propagates from the source to the whole structure of the machine, due to low damping. Temperature fields surrounding heat sources decay quickly as the distance from the source increases. For example the characteristic distance for a thin wall surface is $x_0 = \sqrt{ek/h}$, which for normal values of conductivity of ferrous materials can be approximated by $x_0 = 230\sqrt{e/h}$, (x_0 and e in mm, h in w/mm^2°C). At a distance of $3x_0$ from the source the influence is negligible. However, displacements must be considered in the whole machine.

4. Examples

4.1. EXAMPLE 1. PARAMETER DETERMINATION. CALCULATION OF DISPLACEMENTS AS A FUNCTION OF TEMPERATURES

During the heating period temperature at 13 points of the machine was measured by means of a contact thermocouple. At the same time relative displacements δx, δy, δz, between a point of the headstock and the workpiece were also measured. Chart 1 gives mathematically fitted expressions for some of these temperatures and displacements.

$$T_1 = -3.75\ (1 - e^{-t/2.02}) + 14.01\ (1 - e^{-t/1.36}) + 0.04\ (1 - e^{-t/0.30})$$

$$T_3 = 17.72\ (1 - e^{-t/2.02}) - 3.21\ (1 - e^{-t/1.36}) - 0.44\ (1 - e^{-t/0.30})$$

$$T_{13} = 23.20\ (1 - e^{-t/2.02}) - 8.04\ (1 - e^{-t/1.36}) + 2.01\ (1 - e^{-t/0.30})$$

$$\delta z = -164.19\ (1 - e^{-t/2.02}) + 250.24\ (1 - e^{-t/1.36}) - 5.75\ (1 - e^{-t/0.30})$$

t in hours, δ in μm, T_n in °C

Chart 1.

Fitting of displacement δz is represented in figure 2.

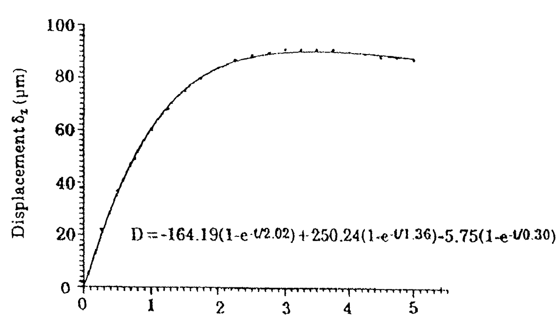


Figure 2. Displacement δ_T versus time.

For the 13 temperature and 3 displacement points an overall fitting of exponents and coefficient has been made. The exponents or non linear part of the fitting are determined by a repetitive approximation procedure by the "least-squares" method minimising the error between measured and analytically approximated functions. The coefficients are calculated by solving a series of linear equations.

As temperatures and displacements are approximated by means of only three modes, it is possible to reproduce, for example, displacement as a function of the temperature of three points, as a linear combination of these temperatures.

Thus, for example:

$$\delta z = -73.242\, T_4 + 77.597\, T_6 + 18.292\, T_{13} \qquad (4)$$

or

$$\delta z = 18.014\, T_1 + 11.563\, T_2 - 14.466\, T_3 \qquad (5)$$

The application of one of the two formulae (to use in compensation) can lead to very different results when measurement errors are taken into account.

So, in figures 3 and 4 the results of applying formulae (4) and (5) can be seen, with fitted values (exact result) and with measured values. The results provided by formula (5) are very much better than those provided by formula (4).

The measured points of temperatures used to compensate for displacements must be located at points with significative and different values for the modal coefficients. Errors, in general are minimised when the coefficients of the compensation formulae have the minimum absolute values.

If $\delta = \{\alpha\}^T \{T\}$, Minimising criterion is: $\Sigma|\alpha|$ = minimum

A programme to provide the optimum combination was developed.

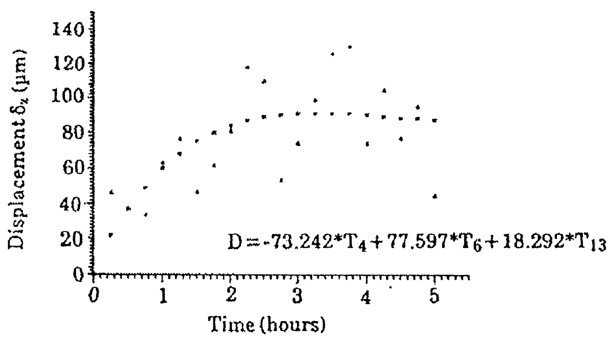


Figure 3. Results of applying formula (4).

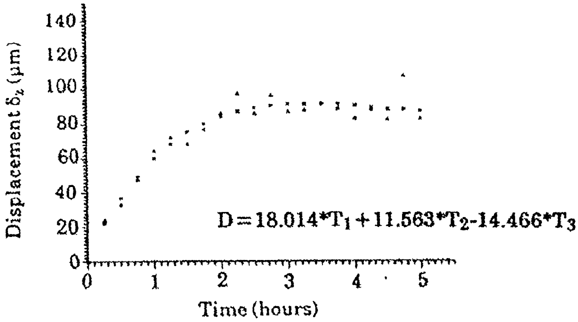


Figure 4. Results of applying formula (5).

4.2. EXAMPLE 2. MODAL ANALYSIS OF THE HEADSTOCK OF A MILLING MACHINE

Thermographic images of the headstock and of a part of the milling slide of a NC milling machine were taken, during its heating period, at a spindle speed of 2000 r.p.m., and during its cooling period with the spindle stopped.

During the heating phase, the temperature versus time curve undergoes some variations which can be explained by some relaxation of the heat generation produced by changes in the bearing preload.

It is easier to fit exponents to the curves obtained during cooling, although the system characteristics, and therefore the modal parameters can be somewhat different when the characteristics of the movement of the air surrounding the machine, due the spindle movement, vary.

From thermographic images temperature distribution was calculated.

In figures 5, 6 and 7, the three main thermal modes of temperature distribution on the analysed surface are represented.

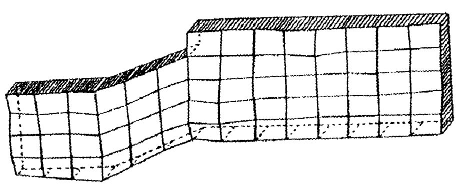


Figure 5. Mode 1 τ = 3.07 hours.

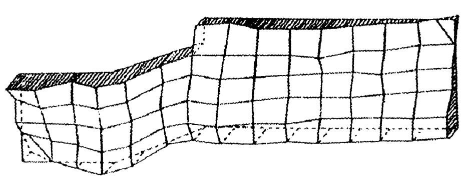


Figure 6. Mode 2 τ = 2.18 hours.

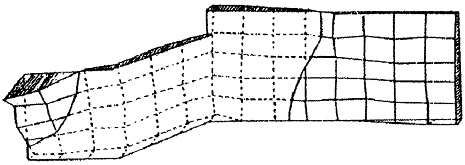


Figure 7. Mode 3 $\tau = 0.37$ hours.

In the first mode, temperature distribution is approximately constant, and in modes two and three two node lines can be appreciated.

5. Conclusions

1. During machining processes, non steady situations predominate, steady state temperatures not being reached.
2. The knowledge of laws governing thermal behaviour facilitates a rational application of methods for reduction or compensation for thermal deformations.
3. Machine modelling by thermal modal analysis can be a first lineal approach to the problem of thermal deformations and plays a role analogous to the role played by vibration modal analysis in vibratory problems.
4. Thermal modal modelling of the machines allows for the reduction of deformations and for their control by numerical control compensation.
5. Thermal modal modelling of the machines aids to solve the problem of optimisation of the number of points for temperature measurement.
6. There are many ways of applying and improving modal thermal analysis techniques, most of them not yet explored. Some first applications of these techniques are presented here.
7. This method is complementary to analytical modelling and also to models based in others techniques like neural networks.

6. References

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FIXTURE DESIGN PROCESS MODELING

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Abstract

Modeling the tool design process is a particularly difficult activity because several types of knowledge are involved: design, process planning and manufacturing. Therefore we present a model of the fixture designers' knowledge. The design process is analyzed with the support of a knowledge modeling methodology. The modeling of the part and the fixture are explained. The implementation of the design process model is carried out using an expert system.

1. Introduction

Modeling a design process is always difficult to achieve. The difficulty is even greater for tools design. Not only does tool design depend strongly on the part data but must also take into account production constraints.

The fixture is the necessary link between the part to be machined and the machine-tool. Its design and implementation must be done efficiently in order to reduce the lead time to market the product. The fixture is particularly important because it is generally the deciding factor for the lead time and the quality of the operations.

We propose a model for the fixture design process. Our presentation is organized in three parts.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 317–325.

First, we introduce the methodological principles for extracting, structuring and validating the technological knowledge for design.

Then, we present a model for the fixture design process. Two connected areas are developed in the model: the product representation and its characteristics (including its dimensioning) and the development of fixture solutions (particularly for the evaluation of partial solutions).

Finally, we provide the results of the implementation of the design process as obtained with an expert system.

2. Knowledge Modeling

2.1 KNOWLEDGE EXTRACTION

It is generally difficult to extract technological knowledge from any professional field. In fact, this knowledge is a non-explicit knowledge: it corresponds to the expert know-how based on cumulative experience rather than defined procedures.

The expert must apply this know-how to solve problems but he can not easily explain his mode of reasoning.

Several processes such as ACQUINAS, MACAO, KADS, etc. could be used to extract knowledge in these situations (Aussenac, 1989).

The overall principle of these methods is applied to the development of our own methodology of knowledge modeling.

Our approach is based on the following points.

- The necessary dissociation of the technological knowledge from those of the area in which it acts.
- The efficiency of the process of collecting the knowledge. This requires a pre-analysis and representation of the area and a modeling of the reasoning process. The type of model must facilitate communication in order to favour the gathering of information as extensive as possible and a first ratification.
- Our study has shown that the most effective method to obtain the necessary data is for the researcher to be "immersed" in the firm so as to meet the people who have the know-how and these who need to use it.

2.2 KNOWLEDGE REPRESENTATION

We propose a procedure to express the various steps in the reasoning process.

The problem to be tackled -*design process analysis*- brings another dimension to the expertise: the progressive refinement of functions. We can map it by using several levels of abstraction for each function. Thus, the process design leads to a refinement of each function, allowing a progression from one function to the next.

We have defined three levels of abstraction: functional, technological and physical, on which any product design process can be structured. Similarly, we have introduced the notions of virtual product and physical product to bypass the problem that the expert (designer) only expresses the end solution (i.e. "physical solution") and not the steps leading to the end solution.

Technological knowledge is often vague and incomplete. So, the mode of representation has to allow for some important modifications and additions to be made.

The associated supports need to be adapted to analyse the accuracy and level of completeness of the acquired knowledge.

According to this situation and prefacing the validation step, we recommend the use of an expert system to model this technological knowledge.

The first result is the use of this model which constitutes an aid for the designer to complete his tasks. Another consequence is the change of the informational environment of the designer's work which results in an improvement of the design efficiency. This change is detailed in sections 3 and 4.

2.3 KNOWLEDGE VALIDATION

The acquired knowledge has to be validated in relation to both the design process (according to steps and sequence logic) and the obtained results (applying the identified rules).

We propose sequences involving tests and meeting with the expert's knowledge. Examples are taken from several areas (of the whole studied set) and are regarded as representative of these areas. These examples validate each area.

The figure 1 summarises the whole knowledge handling process.

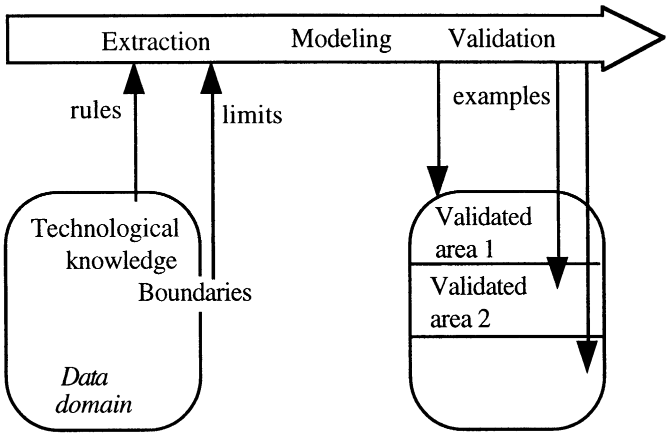

Figure 1. Knowledge handling process

3. Modeling of the Fixture Design Process

3.1. MODELING OF THE PART

Several papers deal with the product modeling in order to make the definition of the production process easier (Brun, 1994). Numerous models of the part based on features have been developed (see the survey (Salomons *et al.*, 1993)).

In our work, we kept this principle of breaking the part down into features.

We have modeled the part into faces. Each face has a type and particular characteristics on which the decisions for fixture design will be made.

Our choice for this representation has been guided by the remark that the process planners use this point of view to define the production process and also to design the tools.

The break down of the part into faces allows the relevant face(s) for each function of the fixture to be selected. Each function is supported by one or several faces.

The characteristics of the faces allow the accurate definition of the functions of the fixture.

We establish a model of fixture which develops with the design process. The model of the part is linked to the model of the fixture with rules that have been identified. An illustration of this type of link is presented in figure 2.

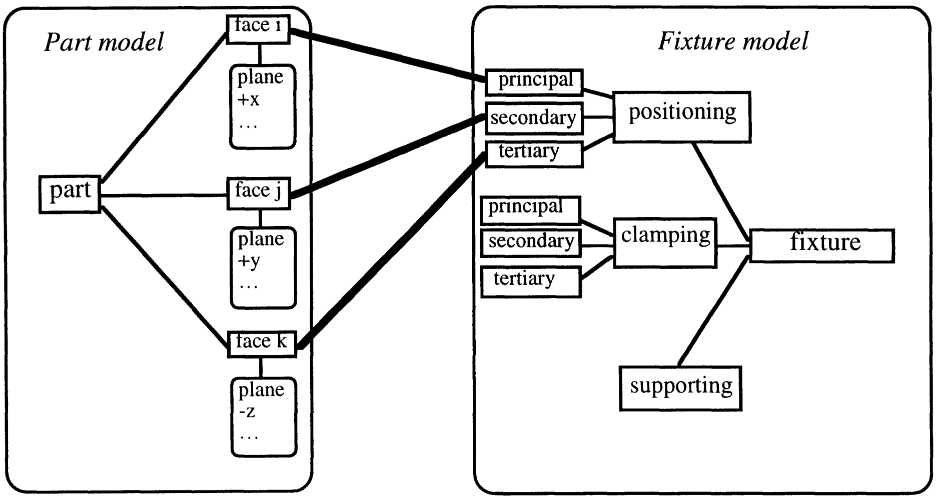

Figure 2. Links between the model of the part and the model of the fixture for positioning

3.2. STRUCTURING OF THE DESIGN PROCESS

The functions and main characteristics of the fixtures are not presented here but can be found in (Boyes, 1989), (Dietrich *et al.*, 1981), (Pazot, 1989).

The first stage in structuring is to present in an organized way the different steps followed by the experts in fixture design. Twelve steps have been identified and validated with the logic plan of their organization. The diagram of the fixture design process is presented in figure 3 (see (Caillaud *et al., 1993*) for more information).

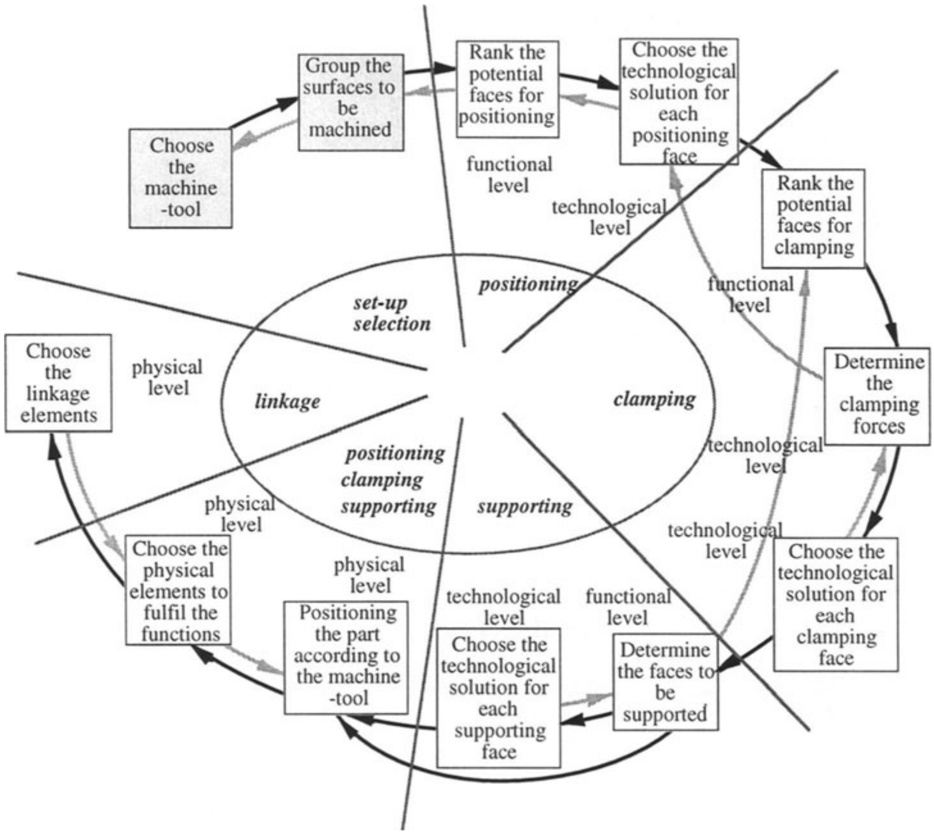

Figure 3. Fixture design procedure.

The following development focuses on the expert rules involved in each of these steps.

The particularities of the problem *-modeling a design process-* led us to define several types of rules and data to which the rules are applied.

We distinguish the rough data as can be obtained from CAD or CAM software (data type D I) from the elaborated data which are more advanced (closer to their use for design), established intuitively by the designer based on the rough data (data type D II).

The types of rules depend directly on their particularities of use: expression of the elaborated data (rules type R I), definition of possible solutions (rules type R II).

The basic data related to the part (data D I) are converted with the rules of the R II type into characteristics of the faces. The dimensioning of the part is transformed into "accuracy" of the face according to the faces to be machined in the specific set-up (based on Boerma et *al.* works (1988).

For example, the "accuracy" of a plane is defined as the diagonal of the face divided by the tolerance to the machined face (A = D / T).

Moreover, we associate some qualitative characteristics to the faces in order to tackle the unknown cutting conditions (at this stage of design) e.g.: tool trajectories, cutting parameters which influence the cutting forces and consequently the tool design.

The partial organization of the rule bases Ri and the data type Dj is shown in the data flow diagram figure 4.

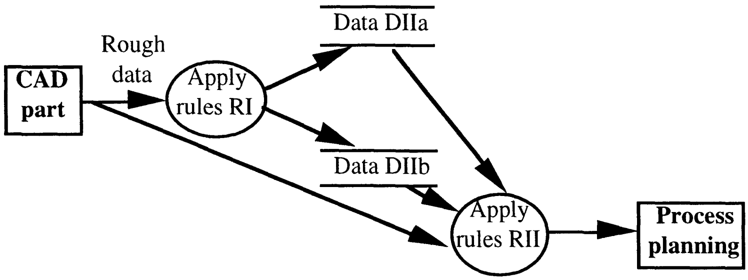

Figure 4. Partial typology of the rules.

4. Application: an Assistant Tool for Fixture Design

The whole know-how that has been extracted about the fixture design has been laid out, modeled and then put into an Expert Assistance System fixture design called SEACMU (Système Expert d'Aide à la Conception de Montages d'Usinage).

SEACMU is based on the NEXPERT™ expert system shell. Our choice for this solution has been guided by the concern to facilitate the progressive enrichment of knowledge and its validation (some literature develops the principles and the characteristics of expert system(Barr *et al.*, 1981), (Farreny *et al.*, 1987),...).

SEACMU is based on a product modeling dedicated to fixture design. This model can be defined with CAD/CAM system data of the part using RI rules (about 35 rules).

The use of a decision support system modifies the environment of decision making as well as the nature of the decisions to be made (Le Moigne, 1974).

According to our previous comments (cf. section 2), the use of SEACMU in the context of simultaneous engineering does not escape this principle. SEACMU modifies and improves the environment of the work of the fixture designer (Caillaud *et al.*, 1995).

For example, the expert can develop several competing solutions, evaluate them and then choose the best solution using multiple criteria.

The decisions to be made by the expert are more complex (but also more efficient) and require all his experience. The expert is not "threatened" by this decision support system but is assisted so as to be able to use it to its fullest.

This induces other types of rules : the evaluation of solutions and the selection among the acceptable ones (rules of type RIII and type RIV).

Finally, the fixture design process is based on four types of rules and two types of data as shown in figure 5.

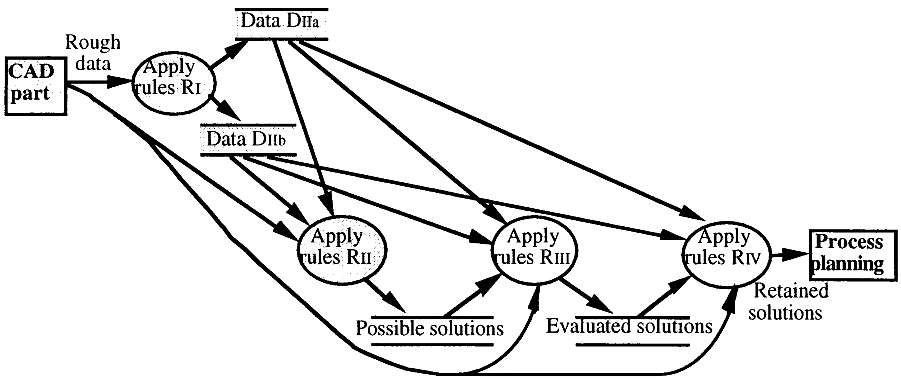

Figure 5. Typology of the rules.

We have structured these rules into independent rule bases managed by a control base summarizing the sequence of the steps.

Figure 6 illustrates the general organization. About two hundred rules have been introduced into SEACMU (rules of RII, RIII and RIV types).

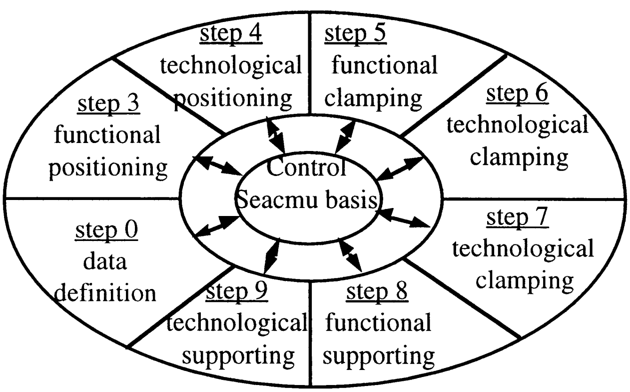

Figure 6. Knowledge bases organization

5. Conclusion

We have proposed a model of the fixture design process.

The main characteristics of the design process have been made explicit: modeling of the product and structuring of the knowledge into different types of rules and data. This modeling has been used to develop a Design Support System for Fixture Design (SEACMU).

The formalism imposed by SEACMU and the proposed ways of evaluation bring support to the designer. This formalism provides the basis of the expression of the knowledge into rules.

Mastering the tool design process is the basis for concurrent engineering allowing the integration of the constraints of tool design to be made at the level of product design.

Acknowledgements

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Chapter 6
MODELLING FOR CONTROL AND MEASURING

INTEGRATING DESIGN AND MANUFACTURING BY TOLERANCE CHART ANALYSIS

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1. Introduction

The manufacturing of complex parts like sheet metal welded assemblies requires a validation of the process plan to meet the part requirements. These requirements can be the dimensional control of the part, the true position of a hole, the reduction of costs, the manufacturing constraints or any combination of these. In any case, the manufacturing engineer must first evaluate and make strategic choices in order to define a process plan that best suits the requirements within the known limitations of the available process capabilities.

To perform a systematic analysis of the process plan, manufacturing engineers use a proven tool known as the tolerance chart [1]. A tolerance chart is a graphic representation of the accumulation of dispersions of a process to meet the dimensional requirements of the part called a part dimension. The resulting manufacturing dispersions are obtained by adding up the dispersions associated with each operation of the sequence. The result then has to fall within the tolerances of the corresponding part dimension as discussed in previous papers by Bourdet et al. [2] and Rivest et al. [10].

A tolerance chart is usually generated from a nearly-defined process plan. The manufacturing engineer then establishes the capabilities of each process with reference to the known capabilities of the selected machine to perform the operation and the type of fixturing used. Most of the time, this evaluation is based on experience or the similarity of equivalent parts. Tolerance charts have been used profitably for many years in industry as they offer a number of advantages:

- easy retrieval of the accumulation dispersions for a given dimension.
- traceability of the process capabilities.
- charts can be used to benchmark different process alternatives or suppliers.
- when updated, it is a reliable source of information.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 329–338.

However, tolerance charts still possess certain weaknesses:

- they can only analyse a process in an axial or radial direction.
- their generation is tedious and error prone.
- manual updates, reflecting manufacturing or design changes, are long and tedious.
- geometric tolerances and the behaviour of some processes are not easily considered.

The objectives of the current research project are therefore:

1. To develop a CAD software technology to accelerate the generation of a tolerance chart from a product definition and a process skeleton.
2. To integrate geometric and dimensioning tolerances inherent in most manufacturing processes like welding and machining.
3. To provide the manufacturing engineer with the possibility of alters the process plans and optimizes operation specifications.

2. State of the Art

A review of the literature shows that many research projects have been carried out to automate the generation of the optimal process plan using tolerance charts [3], [12], [7], [11]. The methods used are efficient to solve an axial tolerance chart by generating sets of linear equations. Any of the developed algorithms must find the dimensional chains of a process. In order to reduce the complexity of the searching algorithm, the information is organised so as to easily find a dimensional chain. Therefore, the authors adapted their data structure to suit the needs of the searching algorithms which backtrace the information in an easy-to-read and easy-to-compute form. Tang et al. [11] use a list approach to specify dimensional chains from a sub-list : sub-list being either a list of operations using a given surface as datum or a list of operations affecting the given surface. Ngoi et al. [8] have developed an approach which take advantage of smart data organisation using decimal points to represent the existing link between 2 surfaces : the datum face and the worked face. Irani et al. [3] and Ji [4] have also introduced an objective function of cost so as to minimise the cost of making a part based on a list of unit costs for each process type to achieve a given tolerance. The technical interest is unquestionable and needs to be supported by reliable cost functions.

The efficiency of such algorithms is very high but requires an effort by the user to interpret and establish the correlation between different sets of alphanumeric values denoting surfaces #id and operation #id. This interpretation becomes heavier as the complexity of the part increases. Furthermore, the efficiency of the algorithm using specific data organisations narrows the 3-D computation possibilities, which needs to be more generic. Moreover, the effect of the welding process has not been included in any of the above research projects.

This effect must to be considered with regards to the accumulation of dispersions, particularly weld distortion, weld shrinkage and weld offset depending on the type of welding process.

Based on an axisymmetric part, it is true that an axial tolerance chart will allow the resolution of 80% of the part dimensions on a drawing, leaving 20% still to be verified and re-checked. Ngoi et al. [9] demonstrated an algorithm for a radial tolerance chart and Nee et al. [6] developed an agorithm which is able to consider angular cuts. The work required to apply the above algorithms to generate a 3-D tolerance chart appears to be quite significant and generally employs a case by case approach. Martinsen [5] has used the application of vectorial tolerance analysis to interpret 3-D dispersions and stack-ups.

Unfortunately, although the developed algorithms require a minimal amount of information to obtain the stack-up of dispersions, they are not directly geometrically linked to a CAD system. Parametric modelling now offers this possibility.

3. 3-D Tolerance Chart Information Flow

In order to meet these objectives, a generic approach to the computation of 3-D tolerance charts was developed. The proposed approach was divided into different tasks, each associated with a software module, and all linked to an object-oriented database and a CAD system. These tasks can be summarized as follows:

- a dimensioning and geometric tolerancing input module,
- a process plan input module,
- a resolution of the dispersions and tolerance chart output module,
- a simulation of alternative process plans module.

By definition, an assembly is composed of many details all linked together. This implies that each detail must be defined dimensionally and geometrically before the assembly itself is defined.

Due to the variety of acceptable dimensioning methods and primarily in order to minimise the quantity of information, an adapted method of dimensioning and tolerancing the part geometry is proposed here. All of the relevant information and relationships between faces and features are thus defined to correctly parameterize the part to be produced. This task generates a tree-like graph comprising all of the pertinent dimensions, geometric tolerances and reference frames of the final product.

To input the skeleton process plan, a series of specific panels for each major process type was developed. The process is entered sequentially through an interactive selection, of the set-up references and surfaces to be processed, for each operation.

The process capabilities are also specified but some information can be left blank at this time and computed or derived later. A sequence of operations for the sheet metal welded assembly as presented in Figure 1 is described in section 5.

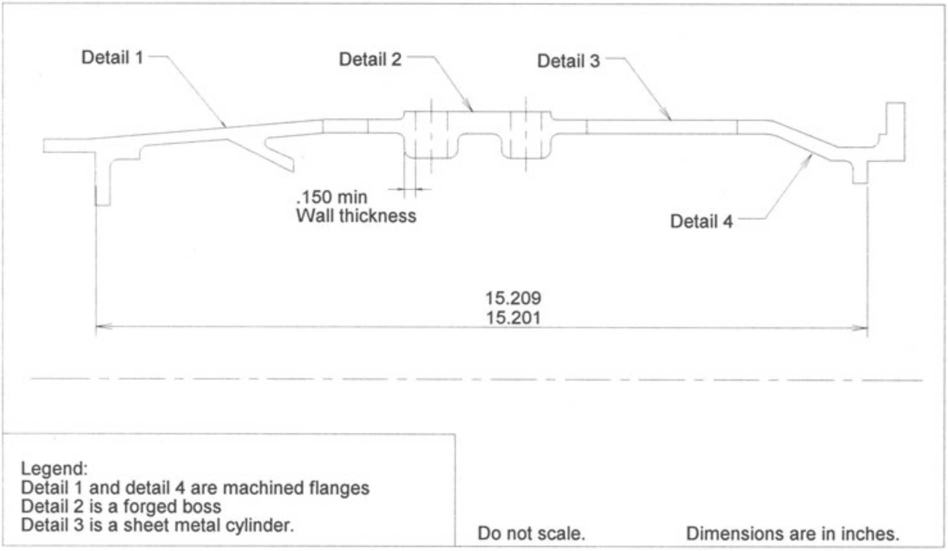

Figure 1. Sheet metal welded assembly

Once the required information has been captured, sets of linear equations are then formulated. The user must then specify any constraints and can then make the computation. If further analysis is required, further simulations may still be performed.

4. Analysis of Process Dispersions

Upon reviewed the different cases of dispersion accumulations found on a representative tolerance chart, two main categories of dispersions were identified :

1- the distance between flanges ; and
2- the minimum wall dimensions.

Many of the algorithms already discussed in section 2, will readily solve the first identified case. However, most dispersions falling in the second category will be positioned in 3-D and therefore have a 3-D incidence on the process dispersion stack-up. For example, a minimum wall requirement must be maintained around a hole with respect to the outside diameter of a boss as shown in Figure 1. In this example, the combination of the axial and angular dispersions must be considered.

5. 3-D Tolerance Chart Modelling

The computation of a tolerance chart appears as a two-part problem: first extracting the relevant information from the object oriented database of the part ; and secondly, establishing the sets of equations needed to resolve the dispersions stack-up of parts dimensions.

A resolution tree was written to solve the first problem in a recursive manner, based on the fact that a part dimension requirement links two surfaces or features of the final product. When all dimensions are identified, they are being stacked. From the stack, a goal is extracted and the algorithm backtracks to the operation involved in the generation of one of the two surfaces or features of the part dimension requirement that creates a new node in the tree. For all types of operation (turning, welding, coating, drilling), an object oriented approach is used to identify the pertinent stack-up information between the related surfaces or features and their specific states (finished, semi-finished or rough). The algorithm then uses the new pair of surfaces or features as a new goal, identifing recursively all the product or process information in order to construct a screw model of each tolerance or dispersion. A screw is a pair of momentum and resultant vectors. The algorithm stops when a known dimension between two surfaces is found.

The second portion of the resolution is then activated and all the previously identified screws are linked together according to each operation's behaviour to establish 3-D dimensional chains and 3-D dispersions stack-ups, to solve a part dimension requirement. The 3-D dimensional chain equation will be used to compute the nominal dimension. Referring to the example described in Figure 3, the principle of the 3-D dispersion calculations is explained below.

5.1. PRINCIPLES OF THE 3-D DISPERSION CALCULATIONS.

In Figure 3, a 3-axis reference frame is positioned at the insertion point of a new manufactured feature. The translation errors following each of the 3 axes and the angular errors around those 3 axes generated by to manufacture of each single surface or feature of the product need to be considered with respect to the datum faces. These possible movements are called the six degrees of freedom or 6 dof. A common way to represent those 6 dof is at an origin point O, like the screw expression presented in Figure 2.

$$\begin{Bmatrix} x & a \\ y & b \\ z & c \end{Bmatrix}_O$$

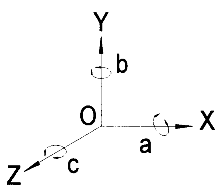

Figure 2. Degrees of freedom in 3-D and screw expression.

Each component represents a numerical boundary of dispersions preceded by the symbol ± ; *x, y* and *z* are units of length; *a, b* and *c* denote small angle dispersions following such constraint as *tangent (a) ≈ a.*

Assembling a component consists of locating each detail origin in the assembly ; this mean that, for each manufacturing operation, there is theoretically a dispersion associated to each of the 6 dof. It may be necessary to formulate constraints limiting dispersions combinations as described in the following process based upon Figure 3.

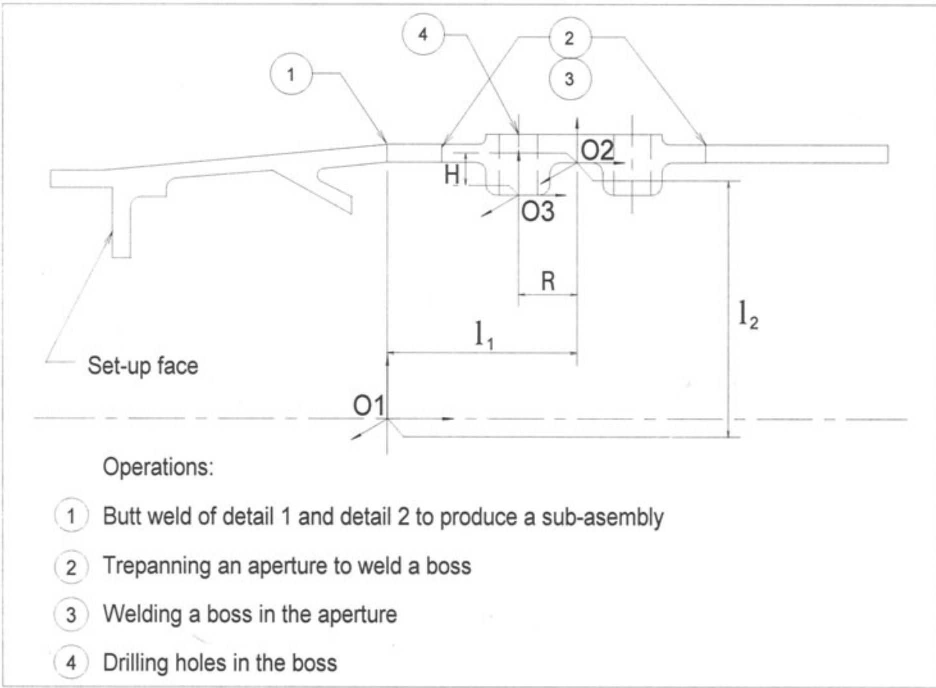

Figure 3. Reference frame positioning for a process plan analysis

5.1.1 Butt Weld Operation

The dispersion screw is: $\begin{Bmatrix} x_1 & a_1 \\ y_1 & b_1 \\ z_1 & c_1 \end{Bmatrix}_{O_1}$

Where: x_1 = weld shrinkage dispersion;
y_1 = weld offset dispersion;
z_1 = weld offset dispersion;
a_1 = relative angular positioning of the 2 welded details;
b_1 = parallelism and conicity dispersion;

c_1 = parallelism and conicity dispersion.

An applicable constraint would be:

$y_1^2 + z_1^2 \leq$ *(25% of the material thickness)*^{2} (permissible weld offset).

5.1.2 Trepanning an Aperture

The dispersion screw is: $\begin{Bmatrix} x_2 & 0 \\ 0 & 0 \\ z_2 & 0 \end{Bmatrix}_{O_2}$

Where: x_2 = trepanning axial dispersion;
y_2 = trepanning radial dispersion, $y_2 = 0$;
z_2 = angular dispersion;
a_2 = roll of trepanning, negligible;
b_2 = yaw of trepanning, negligible;
c_2 = pitch of trepanning, negligible;

Constraint: $x_2^2 + z_2^2 \leq 0{,}015^2$ (true position capability of trepanning process).

The cumulative dispersion screw in O_2 is the sum of every dispersion screws of the process so far, evaluated in O_2. Here, it is required to compute the dispersion of operation #1 in O_2 frame by applying the following vectorial product:

$$\begin{Bmatrix} x_2 & 0 \\ 0 & 0 \\ z_2 & 0 \end{Bmatrix}_{O_2} + \begin{Bmatrix} x_1 + \begin{vmatrix} a_1 \\ b_1 \\ c_1 \end{vmatrix} \wedge \begin{vmatrix} l_1 \\ l_2 \\ 0 \end{vmatrix} & a_1 \\ y_1 + & b_1 \\ z_1 & c_1 \end{Bmatrix}_{O_2} = \begin{Bmatrix} \varepsilon_x x_1 + x_2 - l_2 c_1 & a_1 \\ \varepsilon_y y_1 + l_1 c_1 & b_1 \\ \varepsilon_z z_1 + z_2 + l_2 a_1 - l_1 b_1 & c_1 \end{Bmatrix}_{O_2} \quad (1)$$

The butt weld and the trepanning operations use the same reference surface on their respective set-up: x_1 and z_1 are then respectively independent of x_2 and z_2. Coefficients of x_1 and z_1 would thus be equal to zero while coefficient of y_1 would be one. x_1 and z_1 will disappear from the resultant dispersion screw in O_2. Only the dispersions resulting from the last set-up have to be considered because no dispersion stack-up is propagated through the set-up for face or feature that have dimensions with that set-up.

5.1.3 Welding a Boss

The dispersion screw is: $\begin{Bmatrix} x_3 & a_3 \\ y_3 & b_3 \\ z_3 & c_3 \end{Bmatrix}_{O_2}$

Where: x_3 = axial dispersion + weld distortion + minimum fit gap (x_{3g});
y_3 = radial dispersion due to weld offset;
z_3 = angular dispersion + weld distortion + minimum fit gap (z_{3g});
a_3 = roll effect of welding a boss;
b_3 = yaw effect of welding a boss;
c_3 = pitch effect of welding a boss.

Constraint on a .001 minimum fit gap: $x_{3g}^2 + z_{3g}^2 \le 0.001^2$.

In this operation, it is required to locate the point on the boss where the minimal thickness is most likely to be affected by dispersions which have the largest moment arm. In this example, the point $(-R,-H,0)$ with respect to O_2, would be the point to choose as O_3 origin.

The sum of cumulative dispersion screws in O_2, of operations 1, 2 and 3 is obtained by adding the dispersion screw (1) and the dispersion screw of operation #3. The cumulative dispersion matrix in O_3 is thus the sum of the preceding result and of the following vectorial products:

$$\left\{\begin{array}{ll} x_3 + \left|\begin{array}{l} a_3 \\ b_3 \\ c_3 \end{array}\right. \wedge \left|\begin{array}{l} -R \\ -H \\ 0 \end{array}\right. & \begin{array}{l} a_3 \\ b_3 \\ c_3 \end{array} \\ y_3 & \\ z_3 & \end{array}\right\}_{O_3} + \left\{\begin{array}{ll} x_2 - l_2 c_1 & a_1 \\ y_1 + l_1 c_1 & b_1 \\ z_2 + l_2 a_1 - l_1 b_1 & c_1 \end{array} + \left|\begin{array}{l} a_1 \\ b_1 \\ c_1 \end{array}\right. \wedge \left|\begin{array}{l} -R \\ -H \\ 0 \end{array}\right. \right\}_{O_3} =$$

$$\left\{\begin{array}{ll} x_3 + x_2 - l_2 c_1 + Hc_1 + Hc_3 & a_1 + a_3 \\ y_3 + y_1 + l_1 c_1 - Rc_1 - Rc_3 & b_1 + b_3 \\ z_3 + z_2 + l_2 a_1 - l_1 b_1 - Ha_1 - Ha_3 + Rb_1 + Rb_3 & c_1 + c_3 \end{array}\right\}_{O_3} \qquad (2)$$

5.1.4 Drilling Holes through the Boss

The associated dispersion screw is: $\left\{\begin{array}{ll} x_4 & 0 \\ 0 & 0 \\ z_4 & 0 \end{array}\right\}_{O3}$

Where: x_4 = drilling axial dispersion;
y_4 = radial dispersion following axis of drill, $y_4 = 0$;
z_4 = angular dispersion of drilling;
a_4 = angular dispersion with respect to O_3, negligible;
b_4 = drill rotation, $b_4 = 0$;
c_4 = angular dispersion with respect to O_3, negligible.

Constraint: $x_4^2 + z_4^2 \leq 0{,}010^2$ (true position capability of drilling operation).

The cumulative dispersion screw in O_3 will then be obtained by adding the cumulative dispersion screw (2) to the drilling dispersion screw:

$$\left\{\begin{array}{cc} x_4 + x_3 + x_2 - l_2 c_1 + H(c_1 + c_3) & a_1 + a_3 \\ y_3 + y_1 + l_1 c_1 - R(c_1 + c_3) & b_1 + b_3 \\ z_4 + z_3 + z_2 + l_2 a_1 - l_1 b_1 - H(a_1 + a_3) + R(b_1 + b_3) & c_1 + c_3 \end{array}\right\}_{O_3} \quad (3)$$

5.2 RESULTS ANALYSIS

The interesting components of the dispersion screw (3) appear in the left hand column. The first component gives the axial dispersion X of the hole in the boss :

$$X = x_4 + x_3 + x_2 - l_2 c_1 + H(c_1 + c_3) \quad (4)$$

We could show that this equation contains the same elements as those used to compute manually the dispersions of the location of a hole in an axial tolerance chart. However the formulation found is more precise because it considers the influence of the angular distortions around the z-axis. The second component yields the boss radial dispersion :

$$Y = y_3 + y_1 + l_1 c_1 - R(c_1 + c_3) \quad (5)$$

The third component gives the angular dispersion Z of the hole at the critical point on the boss :

$$Z = z_4 + z_3 + z_2 + l_2 a_1 - l_1 b_1 - H(a_1 + a_3) + R(b_1 + b_3) \quad (6)$$

The X, Y and Z components individually could be used to build unidimensional tolerance charts as axial, radial and angular tolerance charts. But they offer much more for a tridimensional analysis. For instance, the minimum thickness of material around a hole can be simplified to a true positioning tolerance which can be verified in 3-D under the following constraint:

$$X^2 + Z^2 \leq 0{,}053^2$$

The value 0,053 would represent the permitted true position of the functional dimensioning of the assembled parts. Hence, the formulated constraints will serve to validate the given informations from the drawings. They will also be used to simulate alternative process plans.

When this algorithm is applied to every part dimension of a component, it generates two sets of non-linear equations and quadratic constraints. The resolution of this optimisation problem can then be carried out using mathematical algorithms.

As described, the algorithm appears to be simple. In fact, the ability of the algorithm resides in the possibility to consider the physical three dimensions of a part using vector algebra and screw theory that approximates small displacements.

6. Conclusion

The results of the tolerance chart are then presented in an appropriate easy-to-read form. As usual, the manufacturing engineer can analyze the results of the chart corresponding to its process. The software also provides him with the opportunity to simulate changes to the accumulated dispersions by introducing changes in the product definition and process capabilities.

The entire application has been developed to suit known industrial needs and has proven the efficiency of the tolerance chart analysis as a powerful tool for the integration of design and manufacturing as encountered in current concurrent engineering practice.

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The TTRE : Micro tolerancing Model for CAD-CAM Modelers

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In CAD-CAM fields datum numerisation leads to a gap between the geometry desired by the designer and the geometry realized by the computer. These gaps or deviations entail topological violations. One solution to this problem consists in defining a micro tolerancing model for CAD-CAM modelers.

1. Introduction

Technical data exchange between CAD-CAM systems is of great importance for the industrial firms. To achieve this aim, various exchange standards (PDES, SET, etc.) have been defined. Among these, the STandard for Exchange Product model data, commonly called STEP, is under development. STEP seeks to define a data model capable of representing the totality of the information defining the products throughout their life cycle. STEP gathers *Part Resources*, which concerns tools and generic as well as the *Application Protocols* or AP, which define the rules of use. AP 203, [7], regroups the elements necessary for the management of product configuration data, related to the geometric representation of the product design in varied form : wireframe or surface design, with or without topology, as well as the exact Boundary Representation. AP 203 has reached an experimental stage, notably in the American aeronautical industry's AEROSTEP project.

However, these standards has not provided a solution for fail-safe data exchange : during tests numerous problems arose. One of those problems resulted from the use of the algorithms based on the floating point arithmetic; these algorithms may generate topologic and geometric conflicts. The current solutions are based on the definition of a tolerancing attribute for each geometric entity. Henceforward, we will speak about **micro tolerancing** in order to differentiate it from the mechanical part tolerancing.

Mark SEGAL, [2], has proposed an initial micro tolerancing model without any reference system, for adjusting the accuracy errors. His theory draws its inspiration from the tolerancing with tolerance zones; this tolerancing is attached to the entity.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 339–348.

Two main points of his theory are the *merging* and the *backtracking*. Merging is applied in the case of topologic violation, that is, in cases of non coincidence while aligning, intersecting and including entities defined in actual and geometric ways. This algorithmic method allows the recalculation equations linked to those entities, so that they can enter the tolerance zone, which is theoretically defined, in order to converge on a coincidence. Backtracking consists in relaunching the algorithm until the coincidence is obtained.

This model lacks a datum system in order to specify the tolerance. No distinction was made between the different types of geometric defects, arising from either translations or rotations. Moreover, these transformations are not amenable to the mathematical operation of composition.

At present, there exists no structured model for micro tolerancing. Our goal is to transpose the model for mechanical part tolerancing, developed within our laboratory and more widely known as the TTRS model (Technologically and Topologically Related Surfaces) [4], to the entities created by CAD-CAM modelers, in order to define a micro tolerancing model.

2. The Problematic

2.1 5 TYPES OF GEOMETRIC PROBLEM

Table 1 shows a list of topologic entities which have an associated geometry and which, as a consequence, may potentially be implied in **toleranced relations**.

TABLE 1. Correspondence between topologic and geometric entities

Topologic Entities	Geometric Entities
vertex	*cartesian_point*
edge_curve	*curve*
face_surface	*surface*

The cursive terms correspond to the vocabulary defined in the standard [6], which describes topology and geometry.

In the topologic space, the entities are linked using the relation **R1 : ″limits″**. For instance, a vertex ″ limits ″ an edge_curve, as well as, an edge_curve ″ limits ″ a face_surface.

In the geometric space, the entities are linked using the relation **R2 : ″ belongs to ″**. For instance, a cartesian_point ″ belongs to ″ a circle, as well as, a parabola ″belongs to″ a b_spline_surface.

The relation between an topologic entity and its geometric homologue is **R3 : ″ lies on ″**. For instance, a vertex ″ lies on ″ a cartesian_point, as well as, an edge_curve ″ lies on ″ a curve.

These relations are displayed on figure 1 :

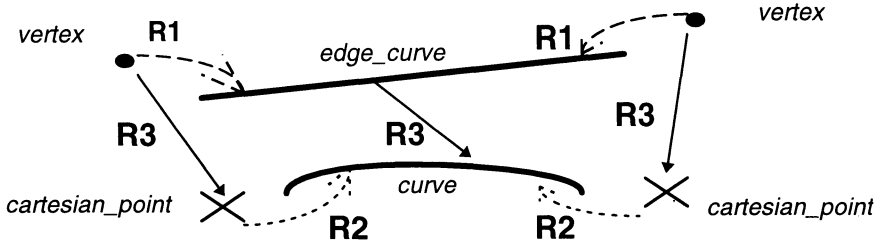


Figure 1. Display of the 3 relations R1, R2, R3

Relation R1 is both used between an edge_curve and its vertices and between a face_surface and its edge_curves. That leads us to the two corresponding relations R2, first the toleranced relation between the geometry of the edge_curves and the geometry of the vertices, and second the toleranced relation between the geometry of the face_surfaces and the geometry of the edge_curves.

The geometric-topological tests concern the relation **R2 : « belongs to »** and generally ask the question of whether a coincidence exists between two entities. Five test types occur, namely the coincidence between :

- a cartesian_point and another cartesian_point,
- a cartesian_point and a curve,
- a cartesian_point and a surface,
- a curve another curve,
- a curve and a surface.

2.2 OBJECTIVES

We want to determine whether the position discrepancy between two geometric entities en in the course of R2-type tests results from the uncertainties which accumulate while creating each entity or not.

2.3 NECESSITY OF A PHYSICAL MODEL

To decide whether such is the case, we need a physical model, [3], [8], which describes a given entity's position uncertainty. This physical model is itself based on a mathematical tool, the uncertainty tensor of position.

The uncertainty arising during the entity's creation stem from algorithms based on floating point arithmetic and of the limited resolution of the computation.

2.4 PRESENTATION

In this section, we present an example in order to illustrate a problem of topological inconsistency.

Regardless the modeler internal tolerance value, ε_0, it will always be possible to compute an angle α, such that :

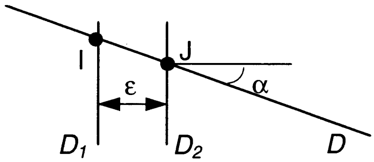
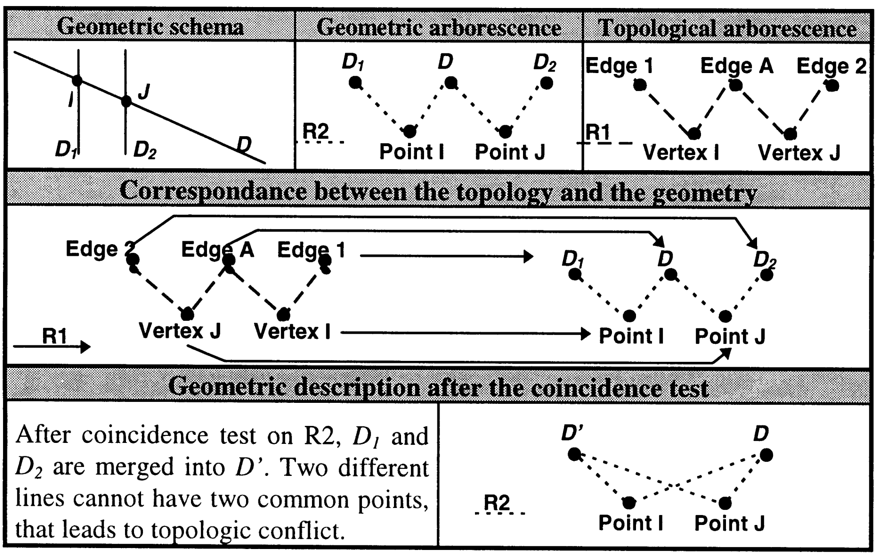


Figure 2. The three lines, almost concurrent

- d(D_1, D_2)< ε_0, implies D_1 and D_2 are coincident (test on R2) and
- d(I, J)> ε_0, implies I and J are none coincident.

Thus the two straight lines are coincident while the points I et J are not. This fact may induce a topologic conflict. Using table 2, we describe the situation in figure 2 with respect to a geometric space and afterwards to a topologic space.

TABLE 2. Topologic and geometric description



3. Modelisation of the micro tolerancing

3.1 FROM THE TTRS MODEL TO THE TTRE MODEL

We shall here provide a further example of the relative positioning as it applies to two entities between two entities in the TTRS model. The goal is to relatively position two TTRS, [9]. Each TTRE has an MRGS (Minimum Reference Geometric Set). It is also possible to declare the construction of derived MRGS such as the point A, shown on figure 3.

The prismatic surface is oriented position using the positioning constraints :

- the point O_2 belongs to the line D_2 (which corresponds, in table 3, to the relative positioning constraint *C4* : point-line coincidence),
- the line D_2 has to be parallel to the line D_1 (which corresponds, in table 3, to the relative positioning constraint C12 : line-line-parallel distance) and
- the plane P_2 is inclined with regards to the plane P_1 (which corresponds, in table 3, to the relative positioning constraint C7 : plane-plane angle).

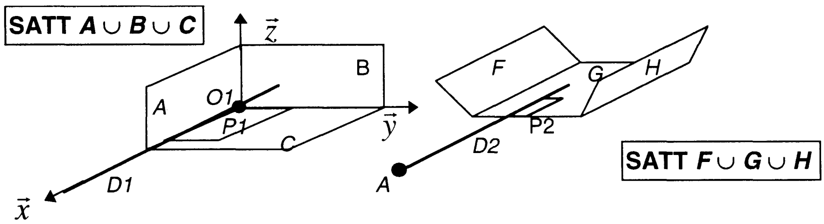


Figure 3. Orientation of a prismatic surface with regards to a complete datum

The positioning of any entity is achieved using the list of the 13 relative positioning constraints, as follows :

TABLE 3. Relative positioning constraint list

C1 : point-point coincidence	C2 : point-point distance
C3 : point-plane distance	C4 : point-line coincidence
C5 : point-line distance	C6 : plane-plane-parallel distance
C7 : plane-plane angle	C8 : plane-line perpendicularity
C9 : plane-line-parallel distance	C10 : plane-line angle
C11 : line-line coincidence	C13 : line-line distance and angle
C12 : line-line-parallel distance	

Bear in mind that each positioning constraint applies to the definition of the relative position of two elementary MRGS. Because the TTRS model solely concerns the association of surface designed entities and because we wish extend that model to the set of geometric entities used in the CAD-CAM modelers, we will henceforth speak of **TTRE** (**T**echnologically and **T**opologically **R**elated **E**ntities) and we will develop one micro tolerancing model for these TTRE.

3.2 POSITIONING UNDER CONSTRAINT, CINEMATIC MODELISATION

First we shall deal with the case of a line or a cylindrical surface with regards to a complete datum.

The following cinematic schema represents that positioning :

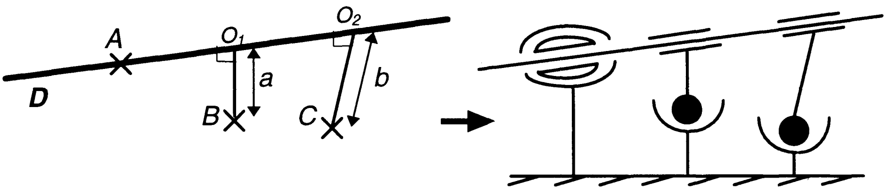
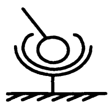
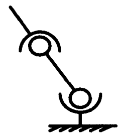
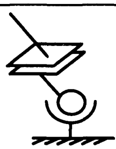
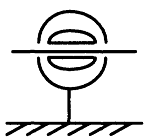
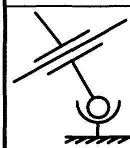
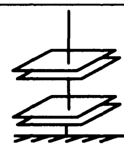
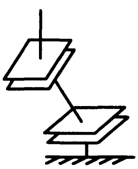
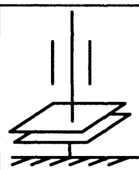
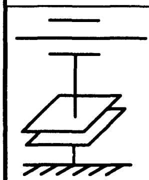
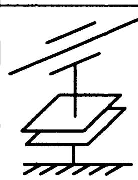
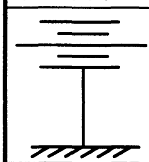
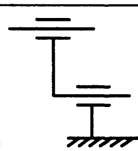
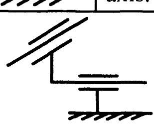


Figure 4. Line *D* oriented under constraints

We position the line *D* under constraint; it has to pass through the point *A* and to be located at fixed distances from the points *B* and *C*.

All positioning constraint was represented by the association of two elementary joints in series (see table 4).

TABLE 4. Relative positioning constraint modelization

	**Constraint C1** A point-point coincidence is modelised by two spherical displacements, overlapped.		**Constraint C2** A point-point distance is modelised by two spherical displacements, distant.
	**Constraint C3** A point-plane distance is modelised by one spherical and one planar displacements.		**Constraint C4** A point-line coincidence is modelised by one spherical and one planar displacements, overlapped.
	**Constraint C5** A point-line distance is modelised by one spherical and one actuator displacements.		**Constraint C6** A plane-plane-parallel distance is modelised by two planar displacements, parallel.
	**Constraint C7** A plane-plane angle is modelised by two planar displacements, inclined.		**Constraint C8** A plane-line-parallel perpendicularity is mo-delised by one planar one actuator displacements, with perpendicular axis.
	**Constraint C9** A plane - line - parallel distance is modelised by one planar and one actuator displacements, with parallel axes.		**Constraint C10** A plane-line angle is modelised by one planar and one actuator displacements, with non parallel axes.
	**Constraint C11** A line-line coincidence is modelised by two actuator displacements of the same axis.		**Constraint C12** A line - line - parallel distance is modelised by two actuator displacements with parallel axes.
	**Constraint C13** A line-line distance and angle is modelised by two actuator displacements, with inclined axes.		

3.3 TORSOR RELATED TO A CONSTRAINT

A torsor can be associated to each constraint of the list of the 13 constraints.

The present study is here limited to the expression of the cinematic torsor associated with the positioning constraint *C5 : point-line distance* :

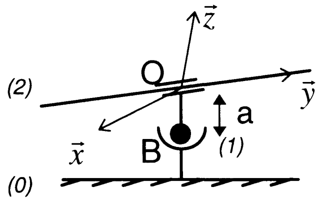


Figure 5. Cinematic modeling of a point-line distance

The cinematic torsor related to the spherical displacement at point B, is : $\mathbf{C}_{B,1/0} = \begin{Bmatrix} \alpha_{1/0} & 0 \\ \beta_{1/0} & 0 \\ \gamma_{1/0} & 0 \end{Bmatrix}$ and has for expression at point O, $\mathbf{C}_{O,1/0} = \begin{Bmatrix} \alpha_{1/0} & a\beta_{1/0} \\ \beta_{1/0} & -a\alpha_{1/0} \\ \gamma_{1/0} & 0 \end{Bmatrix}$. The cinematic torsor related to the actuator displacement at point O, is : $\mathbf{C}_{2/1} = \begin{Bmatrix} 0 & 0 \\ \beta_{2/1} & V_{2/1} \\ 0 & 0 \end{Bmatrix}$.

By addition, the cinematic torsor associated to the positioning constraint *C5 : point-line distance* is obtained : $\mathbf{C}_{O,2/0} = \begin{Bmatrix} \alpha_{1/0} & a\beta_{1/0} \\ \beta_{1/0}+\beta_{2/1} & -a\alpha_{1/0}+V_{2/1} \\ \gamma_{1/0} & 0 \end{Bmatrix}$. By complementarity, we obtain the tolerancing torsor [5] relative to the positioning constraint C5 : $T_{O,2/0} = \begin{Bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & W_{2/0} \end{Bmatrix}$. If the distance *a* equals to *0*, then we obtain the tolerancing torsor related to the positioning constraint *C4 : point-line coincidence*, $\mathbf{T}_{A,2/0} = \begin{Bmatrix} 0 & U_{2/0} \\ 0 & 0 \\ 0 & W_{2/0} \end{Bmatrix}$.

3.4 POSITION UNCERTAINTY OF AN ENTITY

The position uncertainty of an entity containing the point M is defined by the variance $Var(M)_n$, whose expression is : $Var(M)_n = E([\overrightarrow{D_M} \bullet \overrightarrow{n}]^2)$, [1].

The scalar product, $\overrightarrow{D_M} \bullet \overrightarrow{n}$, represents the projection of the vector representing a series of small displacements at point M following any normal or direction $\vec{n}$. The direction of the uncertainties is seen on figure 6.

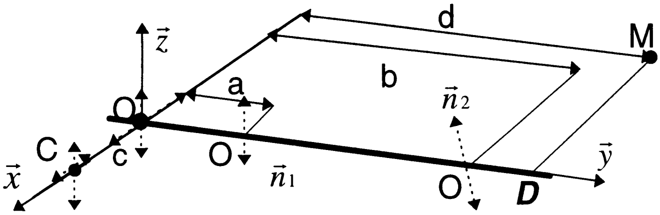


Figure 6. Uncertainties on line *D*

The objective is to show how to model the position uncertainty on the line *D*, having uncertainties at points *O1* and *O2*, and also at point *O* in a given direction.

4. The position uncertainty tensor

The following calculations refer to figure 7, [8].

4.1 APPLICATION TO A LINE

The uncertainty of line *D* is determined using the following data :

Points		*O*	*O*	O_1	O_2	*C*	*C*
Uncertainty		10^{-10}	10^{-10}	10^{-10}	10^{-10}	0	0
Direction of the uncertainty	$\vec{x}$	1	0	1	1	0	0
	$\vec{y}$	0	0	0	0	0	1
	$\vec{z}$	0	1	0	1	1	0
Coordinates of the point	$\vec{x}$	0	0	0	0	-0,01	-0,01
	$\vec{y}$	0	0	0,01	0,02	0	0
	$\vec{z}$	0	0	0	0	0	0

Be a point M(0, y, 0) belonging to the line *D* :

$$Var(M)_n = n^T * T * n,$$

where n is such as :

$$n^T = (a\ b\ c).$$

n represents the coordinates of the unitary vector in the direction under consideration.

The matrix **T** represents the uncertainty tensor of order 3, [8], and in this case, for a point M on the line *D*, is equal to :

$$T = \begin{pmatrix} 2y(100y-10)*10^{-8}+10^{-10} & -2y*10^{-8}+10^{-10} & -y(175y-0,5)*10^{-8} \\ -2y*10^{-8}+10^{-10} & 2*10^{-10} & 1,5y*10^{-8} \\ -y(175y-0,5)*10^{-8} & 1,5y*10^{-8} & y(175y-1)*10^{-8}+10^{-10} \end{pmatrix}$$

4.2 APPLICATION TO THE INTERSECTION OF TWO LINES

The position uncertainty at point I (x_I, y_I, z_I), intersection of the lines *D1* and *D*, is represented by the uncertainty tensor, which is the sum of the uncertainty tensors $\mathbf{T_{D1}}$ and $\mathbf{T_D}$.

4.3 APPLICATION TO DEVIATION UNCERTAINTY CALCULATION

In what follows, the calculations refer to figure 2. The solution proceeds as follows :

❶ The line D_1 passes through two points. Since the uncertainty position of each point is known, the position uncertainty of the line may thereby be ascertained by using the deviation tensor.

❷ **The process is iterated in order to determine the position uncertainty of the lines D_2 and D_3.**

❸ We are interested in the point *I*, where the lines D_1 and D_2 intersect and the related position uncertainty is obtained, by addition of the two uncertainty tensors.

❹ We proceed likewise with point *J*.

❺ The deviation between the point *I* and the point *J* is identified.

❻ We identify if there is intersection of the uncertainty zones of the points *I* and *J*, following the direction $\overrightarrow{IJ}$. The probability that the points be coincident is evaluated.

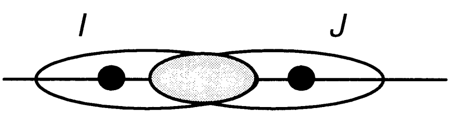


Figure 7 : Intersection of the uncertainty zones

5. Conclusion

The discontinuous nature of data numerisation leads, in CAD-CAM, to a discrepancy between the **geometry desired** by the designer and the **geometry generated** by the modeler.

These discrepancies may either induce topological conflicts within the modeler itself or data exchange conflicts between two modelers.

A solution to these problems consists in defining a structured model for micro tolerancing.

The TTRE, by its use of the position uncertainty tensor for each geometric entity, constitutes an initial response to that industrial need.

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MODELS FOR TOLERANCING PROCESS BY CONSIDERING MECHANISM FLEXIBILITY.

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Abstract: We propose to take the elastic displacements into account in the tolerancing process. In this paper, four models are analysed an order of increasing complexity. First of all, a « perfect mechanism » which allows a static or a kinematik analysis is described. The second model deals with a « rigid mechanism with clearances » which permits a preliminary tolerancing approach. The third model is a « perfect elastic mechanism without clearance». The displacement analysis relative to the loads can be done. The strain can then be considered in the last model by mixing the second and the third models.

1. Introduction

The classical approach of a designer in front of a geometrical mechanism tolerancing consists in making the assumption that the parts to assemble are not perfect in reference to the nominal geometry which defines them and these parts are infinitesimally rigid. The literature gives many tolerancing models : the geometrical tolerancing ones, the SATT model with the small displacements model, etc. But few or no models take into account the mechanism elastic displacements.

The assumption of inelastic solids leads us, either to investigate an isostatic solution or to increase the clearance relatively to the geometrical defects (the clearance makes up for the defects). Which is not satisfactory from manufacturing cost viewpoint.

A number of hyperstatic mechanisms are studied and realised by taking into account, case by case, part flexibility as well as the local crush of the surfaces in contact. Parts are more and more optimised: their thickness decreases, thus their flexibility increases. Moreover the use of plastic material (to build flexible parts), in mechanisms, spreads because of the low cost of their manufacturing. Generally it is not possible to say if the local elastic displacement at the joint surfaces is higher (or lower) than the elastic displacements within parts. Therefore, it seems important to define more general models which integrate these two points of view.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 349–356.

Thus, the integration of these problems into the design approach, and more particularly into the tolerancing must be considered. Two kinds of elastic displacements then appears :

- the **local** elastic displacements which are linked to the contact pressure on the joint surfaces between parts.
- the **global** elastic displacements of parts under external loads which are applied to joints between parts.

We propose an approach which takes these two complementary aspects into account. The local elastic displacements can be studied for example with models like Hertz's law. The global elastic displacements are studied in a conventional way either from an analytic model of elasticity, or with the finite element method. Many parts are designed by CAD. Their behaviour is studied by frame computations. It is thus not necessary to define one particular calculation but it is better to use results which are given by these studies.

Four general models are presented below in increasing order of complexity.

2. Description of the model :

2.1 1ST MODEL : MODEL WITHOUT CLEARANCE AND DISTORTION:

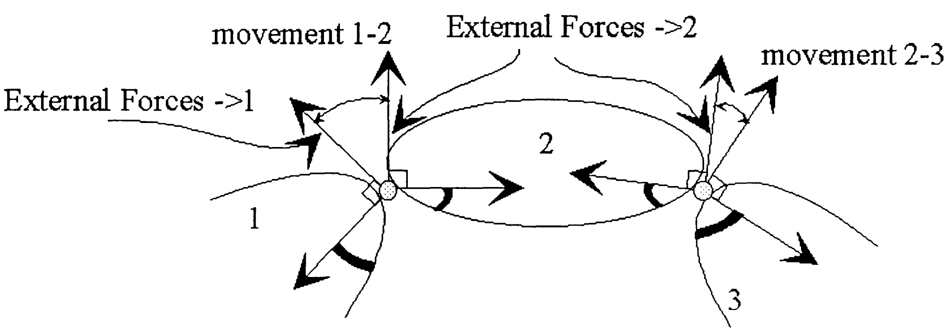


Figure 1

Here, the assembled parts and the joints are perfect from a geometrical point of view. This model is used for the kinematic and dynamic studies of the mechanism.

Kinematic aspect: It allows the study of the mechanism mobility and of the relative motions.

Static aspect: It allows to the determination of hyperstaticities and the calculation of some joint forces.

Dynamic aspect: It allows the calculation of some joint loads i.e. if the kinematic aspect for each independent loop of the mechanism is considered([Aub92]), then a relation between joint kinematic screw operators (motion composition) is :

$$\{C_{1/2}\} + \{C_{2/3}\} + \ldots \{C_{n/1}\} = \{0\} \qquad (1)$$

2.2 2[ND] MODEL: CLEARANCE AND DISTORTION MODELS:

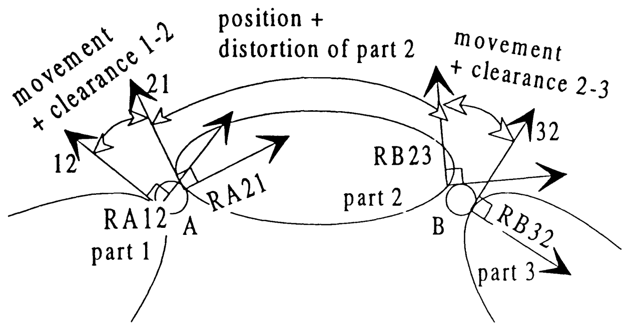


Figure 2

This is the model which is used by some authors to tolerance the mechanisms. The assembled parts have not got a perfect geometry but they are rigid.

Distortions between the real surfaces and the nominal ones at the part level and clearances between real surfaces at the joint level, are both taken into account.
In most models ([CDR91], [GAU94], [WIR93]), the real surfaces are supposed to be perfect from their shape point of view. Only their position deviates from the nominal position.
The kinematic loop relation of the first model will be changed into small displacement loops on the one hand. On the other hand, we will input into each loop, the clearance screw operators at the joint level and the deviation screw operators at the part level (Fig. 2):

$$\{D_{12/21}\}+\{D_{21/23}\}+\{D_{23/32}\}+\ldots+\{D_{n1/1n}\}+\{D_{1n/12}\}=\{0\} \qquad (2)$$

with
$$\{D_{ij/ji}\} = \{D^{P}_{ij/ji}\} + \{D^{J}_{ij/ji}\} \qquad (3)$$

where $\{D^{P}_{ij/ji}\}$ represents the small displacement screw operator which is compatible with the **ij** joint.

$\{D^{J}_{ij/ji}\}$ represents the small displacement screw operator of the clearance in the **ij** joint.

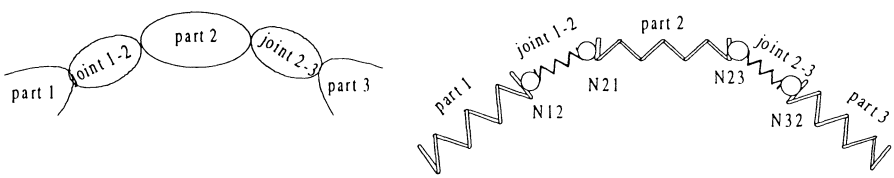
and $\{D_{ij/jk}\}$ represents the deviation screw operator on the j part of the **ij** joint surface with respect to the **jk** joint surface

In spite of the numerous studies ([GiD93], [Bal95]) which have been realised on this kind of models, their development is not completely achieved, mainly because of the difficulties involved in determining clearance screw operators. Indeed, the contact conditions of the surfaces at the joint level show admissible limits for these clearance screw operators, but they do not allow to determinethese operators. Only the dynamic (or static) considerations will give the configuration (relative position of parts) in terms of loads.

2.3 3RD AND 4TH MODEL : TAKING INTO ACCOUNT THE ELASTIC DISPLACEMENTS :

The relative displacements of the mechanism parts under external loads, are not negligible in reference to the geometrical clearance and deviation. We have to taken into account in order to do an appropriate tolerancing.
This model also allows to define the loads which are required for the hyperstatic mechanism assembly (the clearance and deviation are supposed to be known). It is interesting to notice that these loads involve a prestressing which allows the mechanism design.
However, in order to define clearly the problems, it will be first supposed that the joints are without clearance and that the parts are perfect. Then the displacements which are linked to the flexibility of the joints and parts will be taken into account. This model will be called the 3rd model.

2.4 3RD MODEL: WITHOUT CLEARANCE OR DEVIATION BY TAKING THE ELASTIC DISPLACEMENT INTO ACCOUNT:



« elastic » graph *FEA type model*

Figure 3. elastic model

The mechanism is modelised as an assembly of "part elements" which are linked one an other by "joint element" see fig 3. The process is like the finite element one, the nodes represent the "link points" between parts and joints. We introduce a link element with nought dimensions in order to take into account the external elastic displacement of the links in the analysis. The different nodes of "joint elements" are then merged into a representative point of the link. The "stiffness" of these elements remains to be defined .

The static study allows to determine known node displacements (fixed DOF) and external forces necessary for calculus in on the other hand.

2.4.1 "Part element" stiffness:

This "part element" allows the study of global displacements. In order to calculate the stiffness matrix of such a "part element", we have to build a nodal displacement vector and external forces (which is are given by the rigid mechanism study). We can determine all terms of this matrix by manymethods. For example:

① an analytic method which is based on the elasticity study.

② a FEA method (easier today, linked with CAD systems).

③ an experimental method.

We make the assumption that the behaviour is linear elastic. Only joint forces are taken into account.

2.4.2 Joint element stiffness:

We can use here a similar method with parts. There are several kinds of joints (which build a non-homogeneous set). A joint can be a mechanism (a bearing for example) or a surface (spot, cylinder, plane, ...). However, the contact study often gives a non linear behaviour. In order to deal with this problem, it is possible to linearize it (or to use a polynomial interpolation).

2.4.3 Outline of the 3^rd^ model:

Let a pin joint be study outlined as follow:

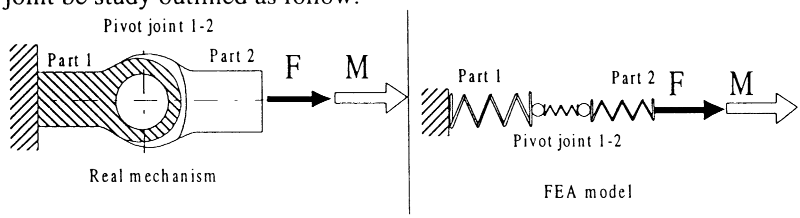


Figure 4. Elastic modelization

A load screw operator is applied at the end of part 2 which is linked with part 1 with a pin. Each part and each joint is modelized by an elastic element (as FEA). Thus a classical elastic analysis can be developed as:

$$\{F\}=[K]\{\delta\} \Leftrightarrow \begin{Bmatrix} F_c \\ F_i \end{Bmatrix} = \begin{pmatrix} k_{ci} & k_{cc} \\ k_{ii} & k_{ic} \end{pmatrix} \begin{Bmatrix} \delta_i \\ \delta_c \end{Bmatrix} \qquad (4)$$

where

F_k = known nodal forces,
F_u = unknown nodal forces,
δ_u = unknown nodal displacements
δ_k = known nodal displacements

} compatible with joints

We can then determine the nodal forces as well as the nodal displacements. Both depend on boundary conditions. It is now possible to build the elastic displacements screw operators (from δ). They are defined for every couple of "contact" surfaces in every joint and every part.

2.5 4TH MODEL: GLOBAL MODEL

A synthesis of the previous models is realized in order to make the tolerancing of the (eventually hyperstatic) mechanism under external loads.
The elastic displacements of the 3rd model are "added" to the displacements of the 2nd model (clearance and distortion). It means that elastic displacements screw operators of parts and joints are integrated to clearance and distortion screw operators.
Locking loops equations (2) remain the same but clearance and distortion screw operators are split as below:

$$\{D^{J}_{ij/ji}\}=\{D^{J0}_{ij/ji}\} + \{D^{Jd}_{ij/ji}\} \qquad (5)$$
$$\{D^{e}_{ji/jk}\}=\{D^{e0}_{ji/jk}\} + \{D^{ed}_{ji/jk}\}$$

where

$\{D^{J0}_{ij/ji}\}$ is the total screw operator of small displacements **without deformation** in the **ij joint**.

$\{D^{Jd}_{ij/ji}\}$ is the screw operator of **elastic** (small) displacements in the **ij joint**.

$\{D^{e0}_{ji/jk}\}$ is the screw operator of distortions (displacements of the ji surface from the jk surface) in the **rigid j part**.

$\{D^{ed}_{ji/jk}\}$ is the screw operator of **elastic** displacements of **part j** between ji and ij joint surfaces.

Displacements in the joints depend both on the mechanism configuration and the clearances between the parts. This requires the calculation of the joint stiffness matrix in terms of the relative position parameters of the parts linked by the studied joint. In the case of some elementary joints, it is possible to configurations to various kinds of loads.

For example, as shown in fig. 4, if we only apply a tensile load, the contact configuration gives two linear contacts. On an other hand, if we input a torque along the horizontal axis the contact configuration is completely different.

3. Application example:

Let the mechanism be illustrated in figure 5. It is hyperstatic if we consider the left joint between parts 1 and 2 to be a ring joint and the right one to be a sliding pin joint.

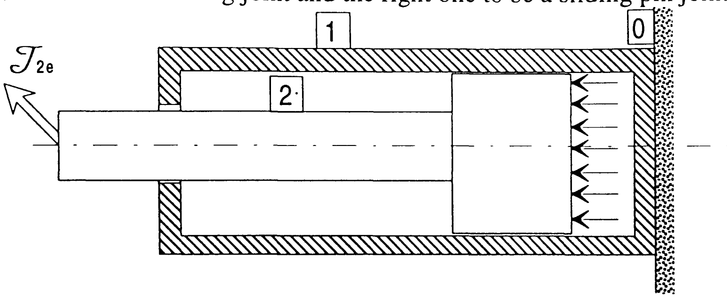


Figure 5

We propose the following models

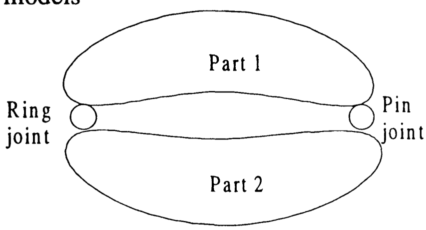


Figure 6. kinematic model

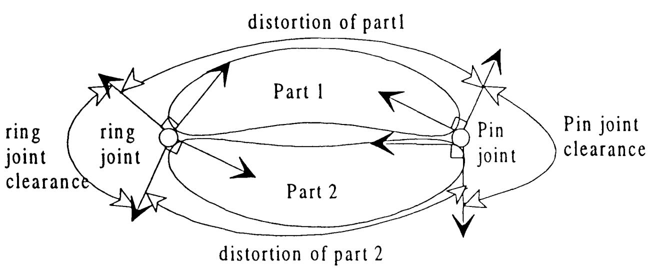


Figure 7. clearance and distortion rigid model

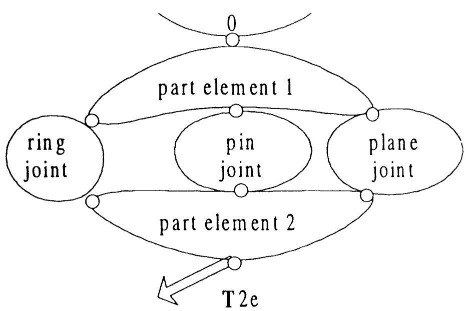


Figure 8. elastic model without clearance and distortion

Fig. 8 represents the elastic study model (according to the 3^{rd} model). In order to take into account the loads between parts 1 and 2 we have input a plane joint. Two nodes for each joint and one node to link parts 1 and 0 are introduced. One node to apply the external loads on part 2 is also added.

4. Conclusion

The classical model of rigid bodies with perfect joints allows a kinematic study and the load solving in the isostatic case. The elastic solid model with perfect geometry allows to solve hyperstatic problems with external forces. These models are in current use by the designers and they are well known models.

The next model is closer to reality and must take clearances, distortions and global and local elastic displacements (which are on the same nature) into account. This problem is complicated and the approach with the four models above enables to split this complexity.

The presented model allows a new way of studing the tolerancing approach if it concerns mechanisms loaded by external forces or/and internal forces which are generated by hyperstaticity. Computers should be useful for the design process, particularly in the concurrent engineering environment , where the interactions between the structural analysis aspects and the tolerancing aspects will be considered.

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PROBE DEFINITION FOR INSPECTION OF MECHANICAL PARTS BY C.M.M.

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Abstract

Accessibility of measured points to touch probes is crucial in planning dimensional inspection of mechanical parts by Co-ordinate Measuring Machines (CMM). This paper presents a new method to define the kind of touch probe needed to measure the various points of a mechanical part. The limits of the notion of visibility as it is usually defined for machining purposes are shown. We propose a new definition of visibility, dedicated to measurement. A method allowing the determination of the probe's characteristics (maximum length of the stylus, sufficient number of styli) is described.

1. Introduction

1.1. AIM

The measurement of mechanical parts with a Co-ordinate Measuring Machine (C.M.M.) involves many tasks. As noticed by Spyridi and Requicha (1990), we must perform the :

- selection of workpiece orientations,
- selection and placement of fixtures and clamping devices,
- probe selection,
- determination of the stylus orientation versus the surface normal,
- generation of the probe's trajectory.

The techniques used to achieved these tasks are often manual, laborious and error prone. Our research deals with the automatic inspection of mechanical parts and focuses on definition of probes. In this paper we limit our investigation to the problems related to the accessibility of measured points to touch probes and the design of dedicated probes. A full study whose aim will be the complete optimization of the measurement of mechanical parts on C.M.M. will take into account the whole phenomena.

In order to reduce the time of the measurement procedure -in the case of mass production parts -, we want to have access to the points that are to be measured in a minimum number of workpiece positioning on the C.M.M. table and for that purpose dedicated probes are often used to reduce the number of assembly-dismantling of the mechanical part. The dedicated probe is defined thanks to the part's geometry and the

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C.M.M. used, and moreover the design of such probes usually requires user expertise.

We propose a formalization of the problem of the definition of the probe based on the part's geometry (CAD model). The method we present makes it possible to obtain automatically the number and orientation of the styli. The position and orientation of the part on the machine's table can be deduced from our method, but we shall not present it in this paper.

The first section describes the methodology used for measurement with the help of a C.M.M.. Then, we describe the basic tools linked to the notion of visibility as it is usually defined for applications such as manufacturing (machining of surfaces - continuous sets of points). We suggest an application of that concept to the measurement of a discrete set of points. Finally, a methodology is proposed, which allows the determination of the number and orientations of the styli constituting the probe.

1.2. HYPOTHESES

There are two possible ways of viewing the measurement of mechanical parts defined by simple geometrical forms (planes, spheres, cones) :

- either directly on the C.M.M. : the definition of the measurement cycle is performed by hand on the first mechanical part positioning on the machine's table, and repeated automatically for the following parts. The main drawback of this method lies in that it implies the machine's immobilization so it is expensive. Moreover this method is slow and tedious.
- or with the help of a software : the definition of the measurement cycle is performed off-line.

As far as the choice of the probe and the orientation of the part are concerned, both methods depend on the user's experience. In fact all of the informations allowing their a priori determination is contained in the mechanical part's CAD model. Those various pieces of information make it possible to determine automatically the choice of the styli to be used (number and orientation) in order to measure all the points.

The method presented in this paper is based on the existence of a CAD model of the mechanical part, and on the existence of the data concerning the set of points that are to be measured on this part.

It leads to :

- the definition of a probe dedicated to the measurement of a given set of points when such a solution is possible. When it is not, we propose the use of an articulated-probe, with precisions concerning the sufficient orientations it is to use (e.g. type PH9 - Renishaw- heads)
- the proposition of the optimal orientation of the part on the machine's table : minimisation of the number of assembly-dismantling of the part.

Moreover, we suppose that the machine does not have a turntable.

2. Visibility : some definitions

In this part, we define the general notions linked to visibility.

2.1. VISIBILITY DOMAIN OF A POINT

In our research, it appears that the study of visibility is linked to the nature of the task we want to achieve the mechanical part : - machining (milling, turning,...) - dimensional inspection -...

In the case of milling or turning, visibility is associated to the notion of continuity of the tool's trajectory (surface to be milled) and we have to perform its determination for the whole surface of the mechanical part.

The visibility of an elementary surface is the one which is used to determine the workpieces' orientations on a machine tool. In this case, the aim is to allow the machining of the surface divided in elementary surfaces. A lot of papers deal with this domain of research. Particularly we can cite (Chen et Woo, 1992), (Woo et Von Turkovich, 1990), (Woo, 1994), (Haghpassand et Oliver, 1995), (Hascoët et al., 1996).

The visibility domain of an elementary surface is then defined as the set of points belonging to half-line (infinite length) which the point P_i is visible. The set of solutions gives a conical volume centered on P_i : collection of half lines with a common end point P_i (Figure 1).

In the case of inspection on C.M.M., we take into account only a finite number of points and we do not have the constraint of continuity of the probe's trajectory on the surface of the mechanical part : the notion of visibility in case of C.M.M. machine is less restrictive than in machining case. Spyridi et al. (1990) has applied the notion of visibility to the measurement on C.M.M. without making this distinction. In (Spyridi and Requicha, 1994) the authors present a planner that generates automatically an inspection plan for a mechanical part. The set of solutions they propose is linked to the surface features. In order to perform the accessibility analysis they use the visibility notion defined for machining.

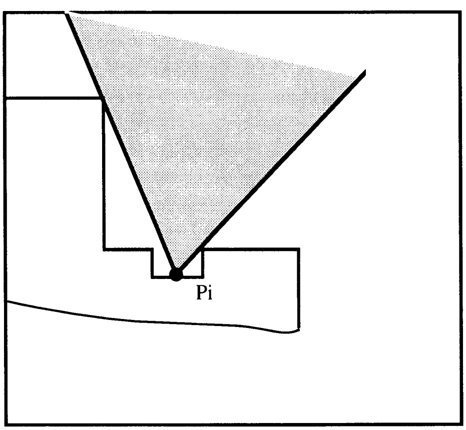

Figure 1. Visibility domain - case of machinng

We propose a new definition for the visibility in the case of inspection on C.M.M.

Definition :

The visibility domain of a point is the set of points from which the point P_i is visible.

$$\mathcal{V}_i = \{ M, M \in \mathcal{E} \;/\; [M\,P_i] \cap \mathcal{S} = \emptyset \} \qquad (1)$$

where :
$\mathcal{V}_i$ is the visibility domain of P_i belonging to the surface of the part $\mathcal{S}$,
$[M\,P_i]$ is the segment of line whose extremities are M and P_i,
$\mathcal{E}$ is the three dimensional space.

This domain is the half-line bundle stemming from P_i and whose intersection with the part is the empty set as shown in Figure 2.

We can notice that the segments $[MP_i]$, whatever their length, can represent the position and orientation of the stylus during the measurement.

Now two choices can be made :
- first : the length of the styli is given. We continue the study with a limited visibility domain,
- second : we search the best stylus - in the whole domain- which allows us to make the best measurement.

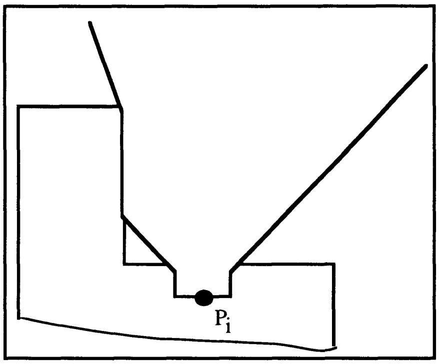

Figure 2. Visibility domain - Case of the C.M.M. -

2.2. VISIBILITY DOMAIN

In the case of machining, thanks to the study of visibility we can find the best position and orientation of the mechanical part on the machine tool. This determination is done via the use of the visibility sphere associated to a point P_i. The visibility is represented as a surface on the sphere : surface defined as the intersection between the visibility domains and a sphere centered on P_i and of radius 1 (Woo et Von Turkovich, 1992), (Woo, 1994).

If we consider a set of points, the visibility sphere is obtained by taking into account the set of conical volumes related to the center of the sphere : the extremities of the

conical volumes and the sphere's center are into one another (Figure 3).
This sphere is designed as the V-map sphere.

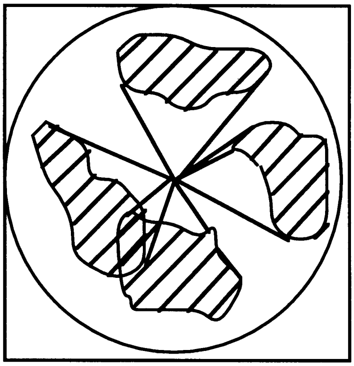

Figure 3. Visibility sphere in the case of a set of points

Remark : One of the properties of this approach is that the representation is independent from the radius of the sphere.

The definition we have given in the case of dimensional inspection with a C.M.M. makes it impossible to use the V-map sphere : the visibility domains are not conical volumes and therefore their intersection with the sphere are dependent on the radius chosen for the sphere. This specificity is linked to the fact that we can use a bent probe to measure a point.

Figure 4 shows the difference between the notion of visibility linked to machining (VUs) and the notion of visibility linked to the C.M.M. (VMm). In this last case, we make the following assumption : the maximal length of a stylus is l.

3. Determination of a dedicated probe

In this part we tackle the problems directly linked to measurement with C.M.M. and particularly the need to design (for a given mechanical part and a set of points to be measured) a dedicated probe in order to measure, in a minimum time and a minimum of assembly-dismantling, the set of points.

The probe will have to be composed of a minimal number of styli of length and orientation to be defined.

3.1. HYPOTHESIS

We consider a mechanical part and a set of points to be measured on this part :

- For each individual point, a configuration of the machine and of the part exists which allows the point to be seen by at least one stylus and without collision.

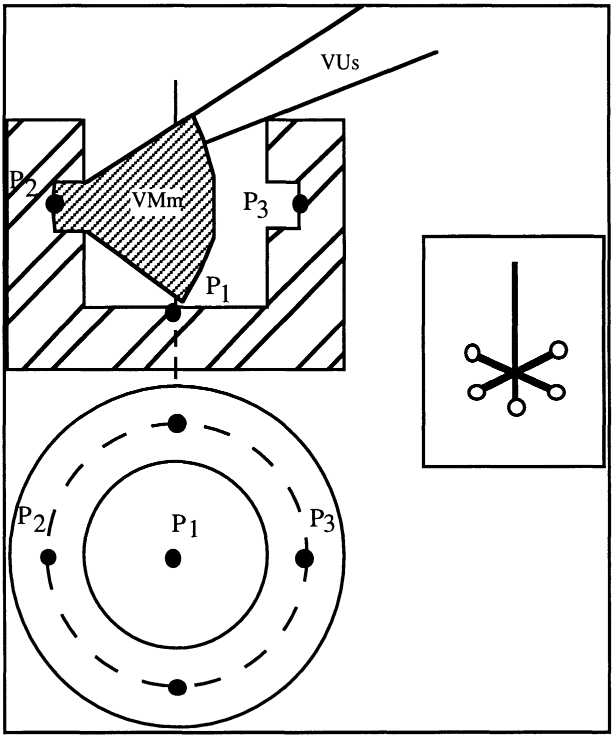

Figure 4. Mechanical part and a probe

In our study we suppose that the C.M.M. and the probe are in a configuration near the point to be measured : we do not take into account the generation of probe trajectories between two points and no solution for the collision problem is given (the collisions which can occur are of three types : stylus / mechanical part and fixtures, probe / mechanical part and fixtures, C.M.M. / mechanical part and fixtures).

3.2. CHOICE OF THE STYLI

If we do not take into account the possibility to use bent styli, the solution consists in studying the surface deduced from the intersections between the conical volumes and the V-map sphere (Hascoët et al., 1996).

In the general case, the solution is obtained by studying the intersections of the visibility domain connected to a given point (intersections of volumes).

The construction of the intersection is performed as it is mentioned in rule 1.

Rule 1 : the intersection's construction is performed step by step :

At step k we consider the intersection between V_i and V_j : V_{ij}

if the intersection is the empty set ($V_{ij} = \emptyset$) we perform the study of the

intersection of V_i with the following domains
otherwise we consider V_{ij} to continue the analysis (the initial domains V_i and V_j are ignored for the following)

From the intersection (set of generated domains), we propose some rules which allow the determination of the probe : number of styli, orientation and length of the styli, …

Rule 2 : The intersection of the set of visibility domains exists and is limited to a single and infinite volume : a probe with a single and straight stylus allows the measurement of the whole set of points. See the example of Figure 5 (6 faces polyhedral and 5 points to be measured).

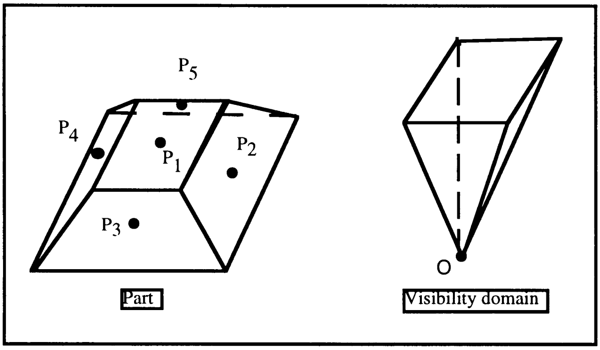

Figure 5. Example of infinite volume.

Rule 3 : The intersection of the set of visibility domains exists and is limited to a single and closed volume : it is possible to measure the set of points with a probe composed of a single stylus but the stylus is necessarily bent. See the example presented in Figure 6.

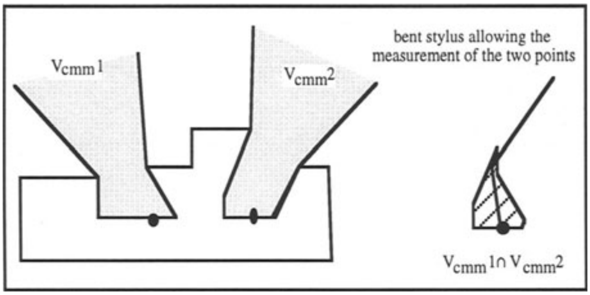

Figure 6. Example of closed volume

Rule 4 : The intersection of the set of visibility domains exists and is not limited to a single volume, the measurement of the set of points require the use of several styli- which can be bent or not - (cf. rules 1 and 2).

A sufficient number of styli is equal to the number of volumes defining the intersection.

Rule 5 : The orientation of the styli must be in the intersection of the visibility domains.

3.3. EXAMPLE

We consider the mechanical part described in Figure 4.

The visibility domains of three of the five points to be measured are represented in Figure 7, the others two have their axis of symmetry orthogonal to the figure's plane. The intersection of these domains is reduced to four volumes : three of the four are the initial volumes, the fourth is the intersection between domain N°1 and domain N°2 as shown in Figure 8.

For the proposed mechanical part, the number of stylus is at least 2. For instance, we can propose :

- one stylus whose orientation belongs to the intersection of domains 3 and 5,
- one stylus whose orientation belongs to he intersection of domains 1, 2 and 4.

With this example we have shown the possibilities of the method. The solution we have obtained in this case is not the best one - the obvious solution is a probe with five styli (as shown on figure 4). This is due to the fact that we have not integrated conditions dealing with the stylus' orientation compared to the surface normal.

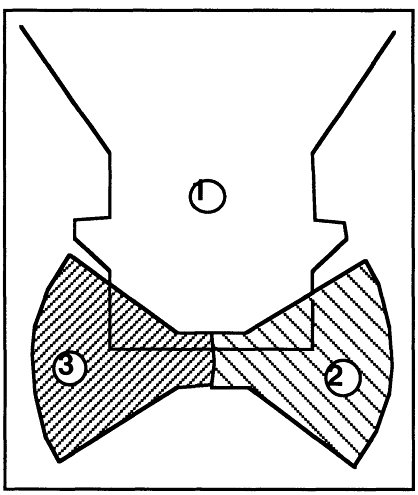

Figure 7. Visibility domains

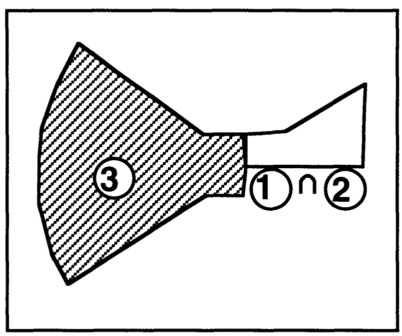

Figure 8. Domains' intersection

4. Conclusion

The definition of visibility used in the case of machine tools is too restrictive to be used for C.M.M. applications. We have proposed a new definition which is adapted to this case. We obtain a visibility domain which includes the domain obtained in the case of machine tools.

Some rules which allow the automatic definition of the number of styli and their orientation for a mechanical part's set of points are given.

Further developments deal with :

- taking into account the probe's orientation
- automatic calculation of the visibility domains' intersection
- automatic determination of the bent stylus (length and angle)
- position and orientation of the workpiece on the CMM table.

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INTEGRATED DESIGN AND MANUFACTURING FOR PRECISION MECHANICAL COMPONENTS

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Abstract

Four levels of integration observed in the design to fabrication cycle of precision mechanical components are presented. Burr formation is described as a process metric to illustrate the interactions between design and manufacturing decisions on the shape and size of the burrs formed. The types of interactions observed are utilized for a discussion about the levels of integration between design and manufacturing, and for the development of integrated design software. The architecture for the core burr software is presented and lowest level of integration is illustrated through the enhancement of the core software for sensor-based robotic deburring process planning.

1. Introduction

Current manufacturing favors high quality components, small batch sizes and short lead times. This calls for agility and the integration of all manufacturing concerns during design and planning (Dornfeld and Wright, 1995). In the early stages of part specification, an integrated CAD/CAM environment is the key to rapid off-line simulation and verification of new part designs. However, the traditional CAD/CAM approach has been the development of process planning systems which support one particular concern, such as design for manufacture, design for assembly, or design for environmentally conscious production. In the literature, the term DFX is used for these individual design modules. While there is great potential in the DFX approach, each of these concerns have invariably been considered in isolation in the past. This has led to stand alone DFX systems with no regard to integration.

This paper describes a proposal for integrating the design and manufacturing functions and the levels of integration appropriate for the design and manufacture of precision mechanical components. The methodology for integration is illustrated by application to the design, manufacture and process planning of mechanical components

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with the objective of minimizing the requirements for edge finishing and deburring processes. Burr formation is described as a process metric which is used to illustrate the interactions between design and manufacturing decisions on the shape and size of the burrs formed. The types of interactions observed are further utilized as a basis for a discussion about the various levels of integration between design and manufacturing, and for the development of integrated design software to assess burr formation.

2. Burr Formation as a Process Metric

Burr formation is gaining attention as a process metric which can be controlled and influenced by changes in design and manufacturing plans. To identify burr formation mechanisms which serve as the basis for burr control strategies, the burr formation process must be examined in ever-increasing levels of detail - starting with the part design and the process plan for a particular process, and culminating with an investigation of the tool/workpiece geometry interaction (Figure 1). Investigation of the detailed interactions between each design and manufacturing parameter will result in the identification of a variety of burr formation mechanisms. One goal of controlling burr formation is to facilitate the choice of an effective deburring process. In order to

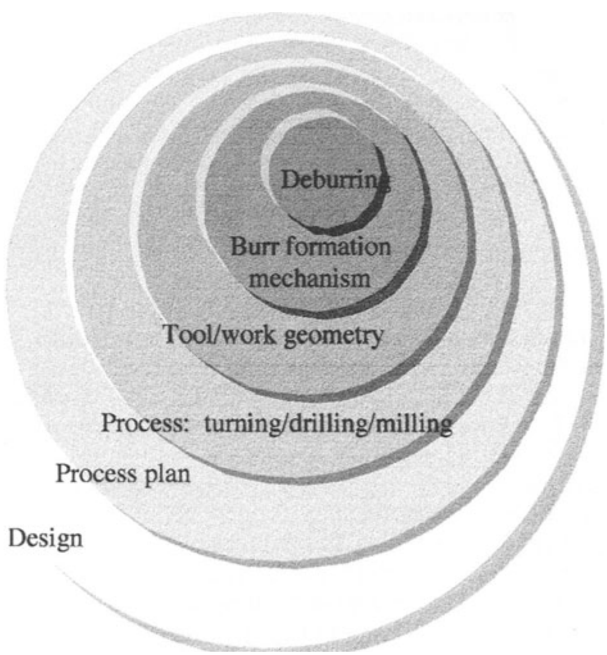

Figure 1. Factors which influence burr control and deburring

optimize the performance of most deburring processes, and minimize the chances of damaging the part during deburring, the deburring process should be selected to match the characteristics and size of the burrs on the part. To achieve this matching of the deburring process to the burr, the burr size and shape should be predictable and controllable. Therefore, burr formation mechanisms must be identified.

The drilling burrs shown in Figure 2 illustrate the inter-relationships between part design and manufacture, tool/work geometry, and tool/work material. Each of these three holes was drilled using a 0.91 mm (0.036") diameter drill with a 118° point angle and a regular helix angle. The petal burr in aluminum and the uniform burr in 304L stainless steel resulted from drilling into workpieces with planar exit surface geometry. The workpiece edge angle does not vary from 90° for this geometry. The burr in aluminum was ragged and rolled back with many fragments compared to the stainless steel burr which was quite continuous, smooth and uniform with an intact drill cap which was easily removed. The uneven crown burr in 304L stainless steel resulted from drilling off-axis intersecting holes, in which the 0.91 mm drill intersected a 3.2 mm (0.25") cross hole at an offset of 0.8 mm from the major diameter of the cross hole. The difference in the exit geometries of the two workpieces, specifically the variation in the workpiece exit angles observed in the intersecting holes (Stein, 1995), resulted in the differing shapes of the two stainless steel burrs shown below.

Petal burr in aluminum | Uniform burr in 304L stainless steel | Uneven crown burr in 304L stainless steel

Figure 2. Burr shapes from same drill for different work materials and edge geometries

The influence of the tool/work geometry and the work material is also observed in the face-milling process. For instance, the in-plane exit angle, which describes the angle at which the cutting edge exits the part, has been shown to influence the burr size significantly (Narayanaswami and Dornfeld, 1995) and the existence of chamfers on a part (parameterized as the “out of plane exit angle”) can effectively reduce or prevent burr formation (Gillespie, 1981).

3. Levels of Integration of the Design to Fabrication Cycle

Design, process planning and manufacturing integration occurs at several levels depending upon the objective of the exercise and the degree of "flexibility" (that is to say the degree to which the design or process are fixed). The level of integration attainable between design, manufacturing, and finishing is dependent upon several factors:

1) the nature of the design, manufacturing or finishing task;
2) the environment in which the task is performed;
3) the tools available to assist the designer with the task.

Four distinct levels of integration between the tasks of design, manufacturing and finishing have been identified in present day and futuristic production environments. Levels of integration can be described in terms of the ability at each level to predict, influence and optimize part production objectives at various stages of the total part production process. The objectives encompass a variety of process metrics which influence the goals of maintaining tolerance of shape, tolerance of form, and desired surface characteristics. These four levels of integration are illustrated in Table 1 below, using burr formation as a process metric.

Integration Level	Burr Software Expert and Agent Tasks	Degree of freedom for adjustment
Level I	Burr prediction, control, optimization, and relocation in an iterative design and process planning environment	Design: High Manufacturing: High Finishing: High
Level II	Burr prediction, control, and optimization through the selection of a manufacturing plan in an "over-the-wall" design-to-manufacturing environment	Design: Low Manufacturing: High Finishing: High -> low
Level III	Burr prediction and control through limited adjustments to a pre-established manufacturing process	Design: Low Manufacturing: Limited Finishing: High -> low
Level IV	Burr prediction for finishing process planning, robotic deburring trajectories and sensor-feedback strategies	Design: Low Manufacturing: Low Finishing: High

Table 1. Four levels of integration in the design to fabrication cycle

At Level I, the highest level of integration, the designer is contemplating the design and any feedback on the impact of the design on the process plan and manufacturing should be utilized to improve the overall "manufacturability" of the component. For instance, by simulating the manufacturing process using a knowledge driven CAD tool, the designer can identify critical features of the part design which may cause problems in the manufacturing process. At this highest level of integration, these features (and the workpiece material) may be modified before any commitment to a design has been established. Simulation at this level is especially important to identify features which are not critical to the functionality of the part yet create difficulty during the manufacturing process. In the case of burr formation, locations of features with respect to other features may be altered at this level to influence part edge angles.

At a slightly lower level of integration, Level II, the design is usually fixed and there is no flexibility for adjustment. However, the high level of flexibility in developing the manufacturing process plan and manufacturing configuration should allow the process planner to insure that the part specifications are met. For instance, at this level, tool trajectories are freely chosen and can be optimized with respect to the part features. For the case of burr formation, the tool trajectory around critical features of the part can be chosen to either minimize burr formation in this area or to relocate the burr formed to an area of the part where burrs are less critical. Proper feature sequencing is also possible at this level of integration. The process planner can choose, for example, whether to 1) drill first and mill second or 2) mill first and drill second when encountering a drilled hole in a part face. The burr formed will be different in each case and the process planner can determine the feature sequence which best satisfies the part specifications and the deburring capabilities before the manufacturing configuration has been finalized.

At a still lower level, Level III, the design and process plan, as well as the machinery for manufacture, may be fixed with no flexibility for adjustment or change. Even at this level, however, it is still possible and useful to consider optimization and fine-tuning of the manufacturing process to accommodate unexpected problems through changes in tool geometry or localized tool paths. For instance, an example of a problem which can occur, and must be addressed at this level, is a change in workpiece material which occurs after a part design and the manufacturing configuration have been finalized. Since workpiece material properties influence burr formation, a manufacturing configuration and process plan which did not cause burr problems for one alloy of a particular aluminum might cause very significant problems for another alloy of aluminum. When tremendous resources have been devoted to a part design and manufacturing configuration, the only remedy to this type of significant burr problem is to locally alter segments of individual machining paths, change tool geometries for individual operations and alter process parameters such as feeds and cutting speeds.

Finally, at Level IV, the lowest level of integration, it may be of interest only to assist in insuring that subsequent manufacturing processes, such as finishing, for example, are efficiently and accurately carried out. Knowledge generated by simulating the manufacturing process outcome can be fed forward to assist in the planning of finishing operations. For instance, predicted burr size for a chosen process plan and part design can be used to choose and plan an appropriate deburring process.

As the level of integration between design, manufacturing and finishing increases from Level IV to Level I, the ability of the software tools (and the designer) to influence and optimize the process metric of burr formation increases. The result of allowing the designer to work within the highest level of integration is to increase the sensitivity of design decisions for one process metric, such as burr formation, and to enable the designer to optimize and balance opposing process metrics through analysis, simulation and decision evaluation.

4. A Burr Agent for Integrated, Intelligent Manufacturing

Each level of integration may require different elements of an integrated design and manufacturing system. The system proposed here is an agent-based system where-in the expert strategies for process optimization and process modeling are encapsulated as agents which communicate with other agents, the design system, and the designer on a real time basis (Dornfeld, 1995), (Wright and Dornfeld, 1995). Recently, agent-based architectures have been shown to be ideally suited for the integrated design applications (Kwok and Norrie, 1993), (Mayrand *et al.*, 1993) and concurrent engineering systems (Cutkosky *et al.*, 1993), (McGuire *et al.,* 1993). The internal structure of each agent is irrelevant to other agents and to the rest of the design system. The message-passing capability of the agent satisfies all communication requirements of the integrated system because all agents observe an identical message passing protocol. The protocol for this communication must allow the transmission of data on the part, processing conditions, sequence and any other information necessary.

As a typical example of an agent, a burr agent is examined, first by looking at the roles it can play, which can be listed as:

1. visual feedback on burr type and size (VF)
2. process parameters selection (PP)
3. feature sequence suggestions (FS)
4. part design improvements (PD)
5. deburring feedback (DF)

Thus, a burr agent can offer advice at several levels consistent with the levels of integration described above. To provide visual feedback (VF), the burr agent calls upon internal expert functions which utilize the machining feature sequence, feature definitions and the machining operations. VF can be provided by color coding (on the CAD screen) of part edges to reflect burr type/size, for example. Optimal process parameter (PP) selection is performed for individual features. To perform this function, the agent requires the feature definition, the machining operation and edge tolerances. The output could be a list of optimal cutting conditions, the tool geometry and the cutter approach direction. Part design (PD) improvements could consist of part feature geometry changes, as well as workpiece material changes. The objective of part design improvements might be burr avoidance on a particular edge, for instance. Deburring feedback might take the form of a data set of burr dimensions and properties along the edges of the workpiece based on process plan inputs.

The proposed strategies for integration of the advice of the burr agent into a CAD system depend upon the burr expert software which serves as the flexible core of the burr agent described above. This burr expert software, the BurrEXPERT, and the burr database which drives the expert, BurrDATA, has been developed at the University of California at Berkeley in partnership with industry and national laboratories in the United States. A conceptual architecture of the core module of the BurrEXPERT for face-milling is shown in Figure 3. The performance metrics output from the BurrEXPERT may encompass a variety of metrics such as burr size (height, thickness, volume), burr shape, total burr length, or burr variability. Examples of value-added modules include deburring cost assessment, burr-related part acceptance/failure probabilities, and pre-processors or set-up modules for finite-element modeling of burr formation.

Depending upon the level of integration in which this core module is utilized, the part drawing and process plan may be input to the BurrEXPERT in various ways. For a level III or level IV application, the part drawing and the process plan are predetermined and are not basically modifiable. These files may be input in a standard file format, such as IGES or DXF, to the CAD package housing the BurrEXPERT. In a level II application, the part drawing is basically non-modifiable, but the process plan will be generated and/or modified by the BurrEXPERT, via the BurrAGENT, in consultation with other agents such as a process planning agent or a fixturing agent. In a level I application, both the part design and the process plan will be reviewed and/or modified by the BurrEXPERT, via the BurrAGENT, in consultation with other agents as for level II.

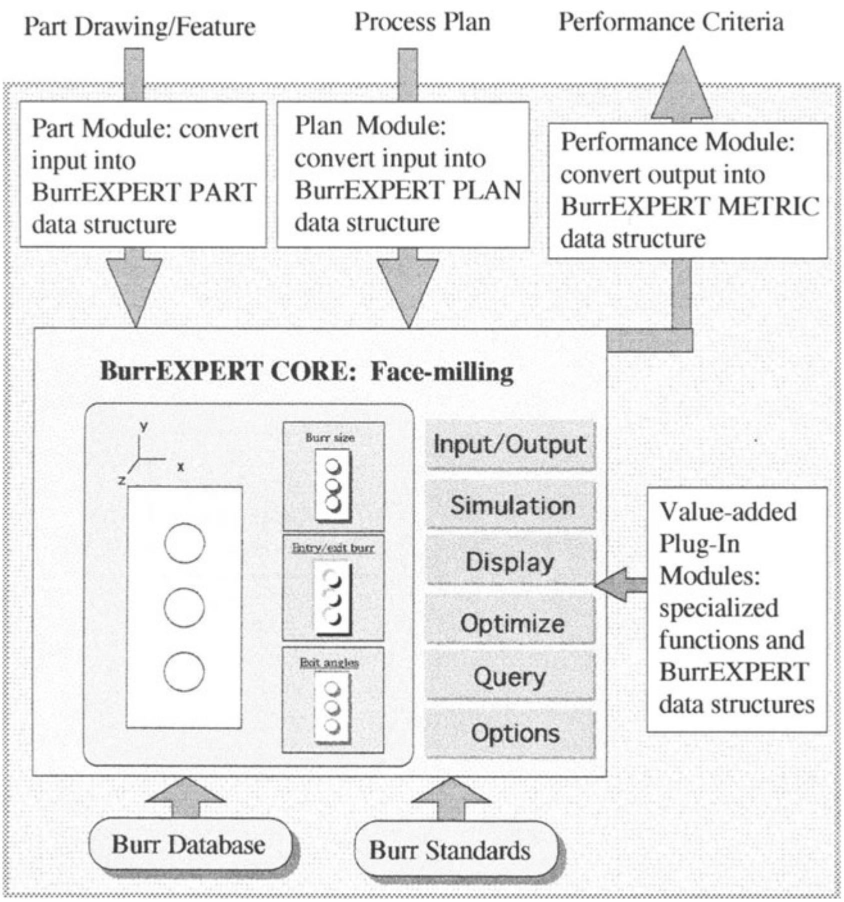

Figure 3. Core functionality of the face-milling BurrEXPERT

5. Level IV BurrEXPERT for Process Planning of Robotic Deburring

A more detailed example of a system integrated at level IV is given here, in which the BurrEXPERT face-milling core software is integrated with the CAD package Pro/ENGINEER to provide burr formation size and location information to a sensor-based robotic deburring process planning module. This project is a joint effort between the University of California and Sandia National Laboratory. The architecture for this system is shown in Figure 4. A nominal deburring trajectory for a particular part,

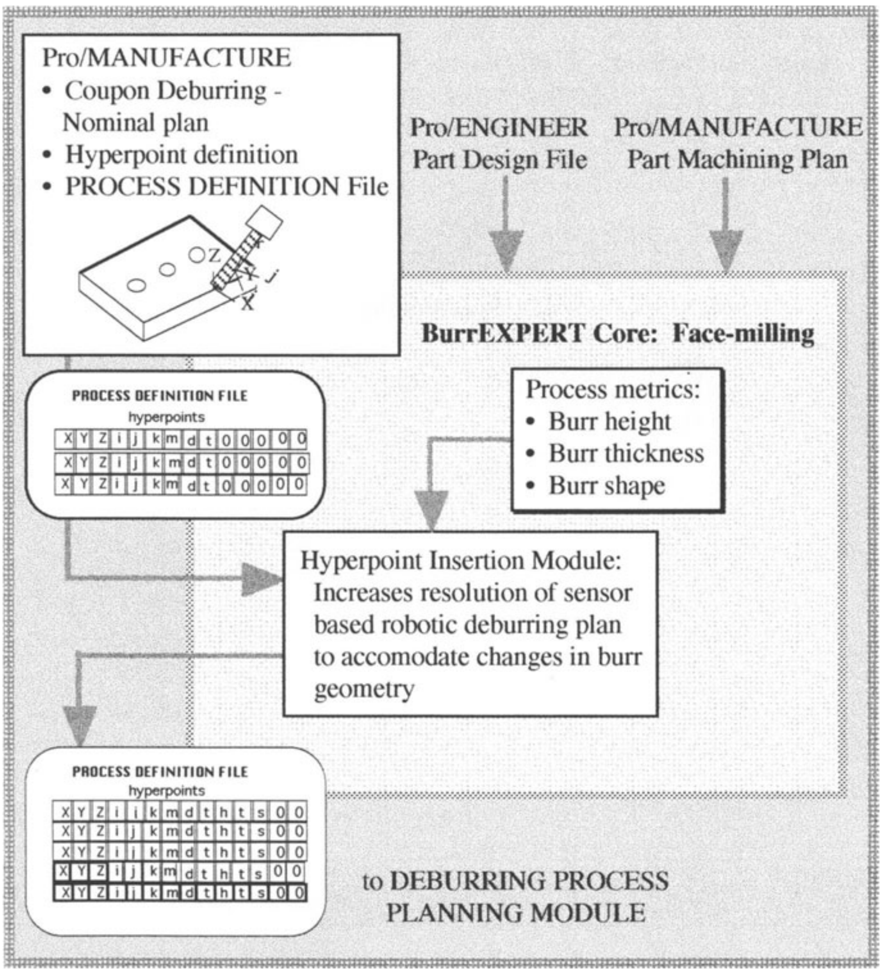

Figure 4. Architecture for level IV integration of the BurrEXPERT with Pro/ENGINEER

communicated in the form of a system file, is input to the BurrEXPERT. The BurrEXPERT also receives the part design file and the part machining plan. From these two files, the burr size and shape information is predicted along the part edges. When a change in burr properties occurs which is significant enough to require an alteration of the deburring process sensor feedback parameters to maintain a target chamfer depth, the BurrEXPERT updates the deburring system file with burr information and increases the resolution of the deburring trajectory, indicating locations along the part edge at which the deburring feedback should be adjusted. The system relies upon a database of burr measurements and characteristics for the face-milling process and on a systematic classification strategy for the burrs observed.

6. Conclusion

A methodology for classifying four levels of integration which have been observed to occur between design, manufacturing, and finishing processes has been proposed. Based upon this classification strategy, architectures for development of flexible, modular agent-based intelligent software are being developed to provide direction for future development of integrated CAD tools with links to specialized software advisors. One such advisory system, the BurrEXPERT, is presented. The core architecture of the BurrEXPERT illustrates the potential for seamless integration with CAD packages at all levels of integration, as evidenced by the level IV integration that has been accomplished and is presented here.

7. Acknowledgments

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Chapter 7
CAM AND OFF-LINE PROGRAMMING

CHOICE OF MACHINE TOOL CONFIGURATION

Determination of real visibility

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Abstract. Within the context of mechanical parts machining, it is useful to reduce the number of manufacturing sequences required for a workpiece. In the case of milling, we must choose milling machine configuration and a workpiece setup. The collisions between the tool and the finished part are an essential stage to be taken in account; this study is based on the notion of visibility. By comparing those visibilities with the milling machine abilities, it is possible to known if the piece can be machined in only one phase.

1. Introduction

A workpiece is manufactured in numerous sequences, if necessary on several machines. However, the machine is not productive during the setup. Each setup also leads to a positioning uncertainty. An expensive machine-tool can be interesting, if it allows the piece to be manufactured in a reduced number of sequences. The problem is then to choose how to manufacture a given piece. Today's CAM (Computer Aided Machining) systems work with simulations. On the basis of its know-how, the user chooses a machine-tool, the situation of the workpiece on the machine, the tool, the cutting conditions, the toolpath, etc. The software checks if the operation is feasible. Finding a solution for a complex part may require several attempts; it is not sure that this solution is optimal in terms of sequence number.

Those questions are valid for any manufacturing process. In the context of **machining optimization**, we are interested in **milling**. For a given workpiece, we search for the type of milling machine (3-, 4- or 5-axis) and the orientation of the workpiece on the machine.

2. A tool: the visibility

We will study the setup of a workpiece on a milling machine. This problem can be divided into three subproblems. The workpiece is machined by the milling-cutter and the cutter moves regard to the machine-tool table; visibility is a tool for describing

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those two interactions. The orientation of the workpiece on the machine table is directly related to our problem of piece setup.

2.1. VISIBILITY OF A WORKPIECE

We have a number of surfaces S_i to mill on a workpiece. Some tool directions cannot be used for the milling of a surface S_i. For each surface S_i, we link the set noted V_i, of tool directions allowing the milling of this surface. For machining a point of a workpiece surface, we must use a tool direction so that there is no collision with another surface of the workpiece. We consider only collision between the tool and the finished part. We use a tool with a spherical tip. This tool is represented by an infinite halfline; the ray of the tool is taken in account by using offset surfaces [1] [2] [3].

For a free-form surface, the computing of V_i is reduced to a visibility calculation. When the milling-cutter collides a portion of the workpiece, this obstruction blocks the visibility from the surface. Additionally, for machining a feature like a drilled hole, some technological constraints can further restrict the set of allowed tool directions. For example, for drilling a hole, the tool direction must be the same as the hole axis. Consequently, we name *visibility* of a surface S_i the set of tool directions allowing the milling, considering the risks of collision between the tool and the finished part, as well as technological constraints linked to a particular feature. A visibility is a cone bounded by the extreme tool directions. With this formulation, visibility is a powerful tool for describing how the workpiece could be machined. Without loss of generality, we choose to intersect a visibility cone with a sphere of unit ray, centered at the apex. A visibility is then represented as a surface on this unit sphere. From now on we will use this representation. The unit sphere is called the Gauss sphere and noted S^2.

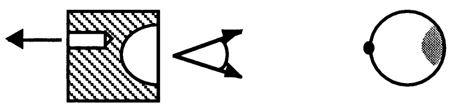

Figure 1. Visibilities of a hole and a pocket, and their representations on the sphere

2.2. VISIBILITY OF A MILLING MACHINE

Notice that the preceding calculation does not take into account the kinematic of the milling machine. However, it is not always possible to use just any tool direction; joints placement and stops limit our choice. We define the *visibility* of a milling machine as the set of tool directions allowed by the machine kinematics. This set is noted V_F. This approach was proposed by Woo & al. [4] [5] for milling machine. On a 3-axis milling machine, the tool direction is fixed and cannot be changed during the machining. The visibility is a single point on the sphere. A 4-axis NC machine is a 3-axis machine with a rotating table (figure 2). This degree of rotation freedom allows the tool to rotate all around the workpiece during machining. The spindle can be tilted manually; after this setting, the angle between the spindle and the plate axis has a fixed value α. Of course, this manual setting must be done before the machining sequence. The visibility of this machine is a small circle on the sphere S^2. On a 5-axis milling machine, the spindle can move during the machining between two stops α_1 and α_2; the machine visibility is a spherical band on the sphere S^2.

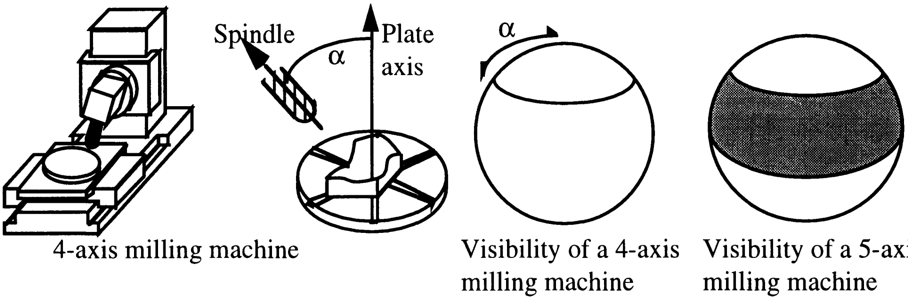

Figure 2. A milling machine visibility

2.3 RESOLUTION OF THE PROBLEM

For milling all surfaces in a single sequence, the visibility V_F of the machine tool must be in contact with all visibilities V_i of the surfaces S_i to be machined. This is expressed as : $\forall i \in \{1...n\},\ V_F \cap V_i \neq \emptyset$. Then, there is always a tool direction allowed by the machine kinematics that can be used for milling a surface S_i; different tool directions can be used for the machining of different surfaces. The problem of finding a workpiece orientation, so that all surfaces S_i are machinable in a single sequence, can now be reformulated as follows : *Find an orientation of the machine visibility* V_F *on the sphere* S^2*, so that* V_F *is in contact with all surfaces visibilities* V_i $(i=1 \rightarrow n)$. However, under this formulation, solving this problem is fairly complex. The existence of a solution is not always sure.

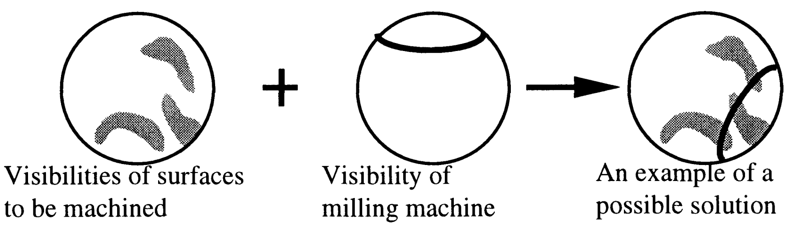

Figure 3. How to search a solution

Woo [4] and Haghpassand [7] give a solution for 3-axis milling. The relative orientation between the tool and the workpiece is fixed and V_F is reduced to a single point on the Gauss sphere S^2; we must find a tool direction which is in contact with all surfaces visibilities V_i. The workpiece must be set up so that the spindle axis is parallel to a tool direction in the intersection of all surface visibilities. If this intersection is empty, it is not possible to machine the surfaces in only one setup. Woo [4] studies the case where numerous setups are necessary in 3-axis milling; the visibilities are clustered into groups, each cluster being machinable in a single setup.

In 4- and 5- axis milling, searching for a solution is more complicated. We must find a circle or a spherical band (the milling machine visibility V_F) which is in contact with numerous surfaces (the visibilities V_i of the surfaces to be machined). show some algorithms for searching such a solution in 4-axis milling, with some restrictive hypothesis. The spindle must be perpendicular to the plate axis (α=90°).

A simplified definition of the surfaces visibilities V_i is also used in [4], [8] and [9]. A milling tool with a spherical tip can machine a point P on a workpiece surface, if the angle between the tool direction $\vec{d}$ and the normal $\vec{n}p$ is less than 90°. The *tool accessibility hemisphere* is the corresponding hemisphere on the Gauss sphere (figure 4a). This approximation greatly simplifies all subsequent calculations by introducing some convexity properties [9]. However, tool accessibility hemisphere does take in account only collision with the local environment of the point to be machined. But the milling tool can also collide another part of the workpiece. The real visibilities of a point P is often much smaller than the accessibility hemisphere (figure 4b).

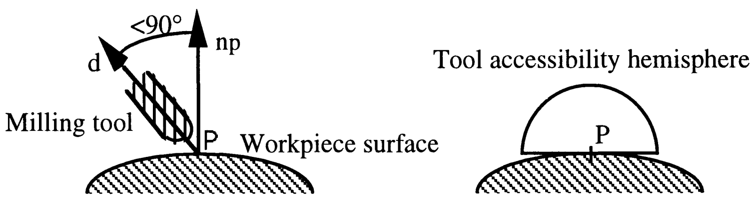

Figure 4a. Tool accessibility hemisphere

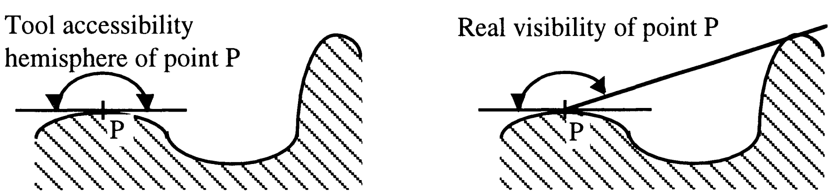

Figure 4b. Accessibility hemisphere and real visibility of a point P.

The visibility of a surface is obtained by intersecting the tool accessibility hemispheres for all point of the surface. However, we notice that the final result of the algorithms depends heavily on how the workpiece has been divided into surfaces. By definition, the visibilities V_i of a surface S_i is the set of tool directions allowing the milling of the whole surface. It means that any *single* tool direction chosen in this set allows the milling of the whole surface. But the specificity of 4- and 5- axis milling is that it is possible to modify the tool direction during machining. In a constrained situation, different points on a complex surface can be machined with different tool directions. Consequently the visibility of a surface is not a well adapted tool for finding a solution in 4- and 5- axis milling. In order to have more reliable result, we can use a great number of small surfaces, which amounts to use points visibilities.

3. Calculation of the real visibility of a point

3.1 INTRODUCTION

We have seen that the use of tool accessibility hemisphere leads to a problem: since we neglect the collisions between the tool and the workpiece other than those in the direct nearing of the point to be machined. We propose a calculation method of the real visibility of a point. For describing the potential obstacles, we use a surfacic meshing of the workpiece with Nm triangular meshes. As usually, the normal to a surface (or of a mesh) is directed outwards from the workpiece volume.

Contrary to the accessibility hemisphere, the point visibility has no particular properties which could facilitate its calculation and use. It can be non convex, cut into several pieces and even reduced to a point or an empty set. We can only say that the point visibility is a subset of the accessibility hemisphere of this point.

3.2 AN APPROACH BY DISCRETISATION OR BY PROJECTION ?

We want to calculate the visibility of a point P belonging to the workpiece. The naïv approach consists in discretizing the Gauss sphere S^2 into a set E_d with N_d tool directions regularly dispersed on S^2. The calculation of the visibility of a point P is reduced to see if the halfline $(P,\vec{d})$ is in collision or not, for each direction $\vec{d}$ belonging to E_d. The calculation time is excessive, since the value N_d is to high as soon as we try to obtain some precision. Our second approach is to center the Gauss sphere S^2 on the point P. Then we project any potential obstacle surfaces on S^2. The visibility is the part of the sphere that is not covered by any projected surfaces (figure 5).

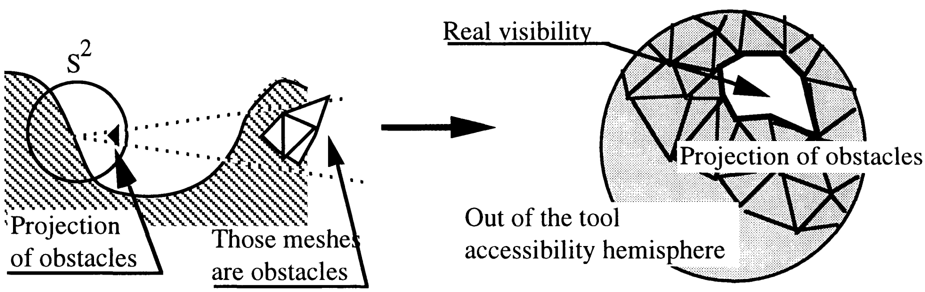

Figure 5. Calculation of a point visibility by projection .

3.3 PROJECTION IN NUMERAL ORDER

In order to project all triangular meshes, the basic solution is to treat them in numeral order. This approach is disappointing since the relations between adjacent triangles are forgotten. After some mesh projections, we have on S^2 several distinct polygons, build up by a few triangles in contact. A newly projected triangle can be in contact with any polygon; numerous situations appear. We must treat an important and variable number of polygons, and proceed to multiple transformations, sometimes fairly complex.

3.4 PROJECTING GROUPS OF CONTIGUOUS TRIANGLES

The meshing of the workpiece is constituted of contiguous triangles. Two adjacent triangles stay adjacent after projection on S^2. This property is the basis of our method. We search polygons made from contiguous triangles. After some trials, we see that even for complex part, with hundreds of triangular meshes, it is exceptional to obtain more than ten polygons. Their union is then fairly easy. We begin from any projected triangle and we search for the adjacent one to each border segment. We can easily pick out two types of surfaces for which projection is unuseful for calculation. Figure 6 shows the two concepts used on a 2D example. We try to calculate the visibility of the point P.

1) The visibility of P is a subset of the tool accessibility hemisphere. The calculation of this hemisphere is very simple. Any triangle which is projected outside of this hemisphere can intercept only tool directions already rejected; we can easily detect those surfaces and discard them.

2) Two adjacent triangles can be respectively visible and not visible from the point P. To illustrate this, we can say that their common segment is a part of the crest separating visible and invisible sides of a hill. The projection of both sides on S^2 is redundant; we choose to project only visible surfaces.

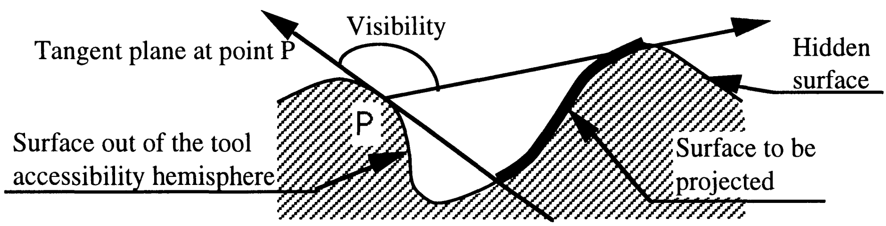

Figure 6. Surface to be projected and surfaces rejected.

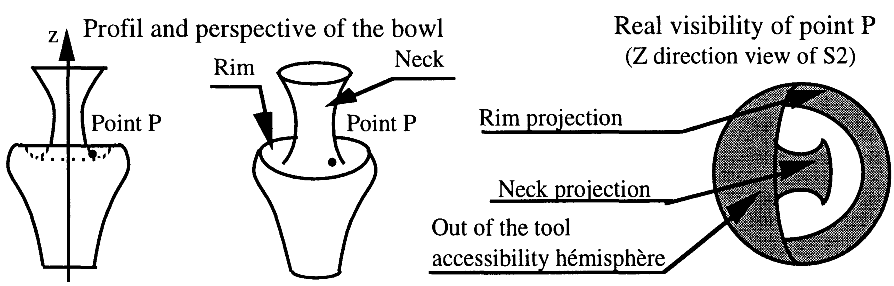

Figure 7. Example of a real point visibility.

Figure 7 shows the method on a 3D piecebowl shaped workpiece. We want to calculate the visibility of a point P at the neck base. We clearly distinguish on the projection on S^2 the unallowed zones of the visibility on S^2, due to the neck as well as to the rim and the tool accessibility hemisphere.

3.5 INTERFERENCE PROBLEMS

It is easy to distinguish the border of a polygon, using the second note in §3.4. We could say that in order to obtain a polygon to project, it is sufficient to find a border and follow it. However, there are some unexpected difficulties.

We will study the case in figure 8 as an example. After eliminating invisible parts of the surface, we follow the outline AB...H. This border is projected on S^2 as A'B'...H'. This projected outline intersects itself and cannot be used immediately ! In fact, there are some tool directions intercepted two times (or more) by the surface. Then the projected surface on S^2 covers itself at least partially. We must eliminate unuseful parts of the outline A'B'...H'. Several attempts in this direction appear not to be really reliable, due to the number and diversity of the encountered situations.

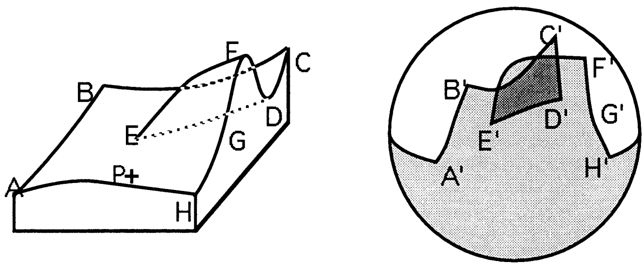

Figure 8. A surface projected on itself

There is also another problem when we have to treat a surface with a hole. This surface is limited by two borders at least (internal and external). It is possible to search separately all possible borders for all polygons; however, it is definitely not easy to link two of them for describing a surface with a hole. By assembling iteratively contiguous triangles, these two problems never appear.

4. Choice of machine-tool configuration

We try now to answer the following problem: for a given part and a given milling-machine configuration, does our machine allow the milling of the whole part in only one sequence ? If the answer is positive, how should we setup the part on the milling machine ?

First, we study the case of the 3-axis milling. These 3-axis machines are relatively cheap and have widespread use. The solution is obtained by using the real visibility intersection of the surfaces to be machined. The setup of the part must be done so that the spindle axis is parallel to a tool direction belonging to this set. If the intersection is empty, the part cannot be milled in only one sequence in 3-axis milling.

The figure 9 gives an example. We assume that the spindle axis is vertical. The workpiece is a cube with two pockets to be milled on two perpendicular faces. The trivial solution consists in setting up the part on a plane face and in milling the opposite pocket; this approach requires two sequences (one for each pocket). By applying our method, we automatically notice that it is possible to mill the two pockets in a single sequence by tilting the part on the table of the 3-axis milling machine.

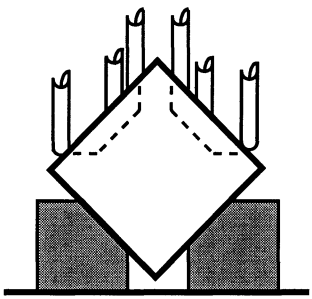

Figure 9. Example in 3-axis milling.

Now, we search a solution in 4-axis milling. We suppose that the fourth axis is a 360° turning plate and that the tilting angle between the tool and the plate axis is fixed. From an industrial point of view, choosing the tilting angle is not always easy ; this problem can be bypassed by undertaking the research for a number of different tilting angles between 0° and 90°.

By transforming a visibility V_i, we obtain a set O_i containing the orientations of the workpiece on the machine, allowing the milling of the surface S_i. As in the case of 3-axis milling, we compute the intersection of all O_i sets to find the solutions. Then we know if the workpiece can be milled in only one sequence on 4-axis milling-machine. We also obtain the possible setups of the workpiece.

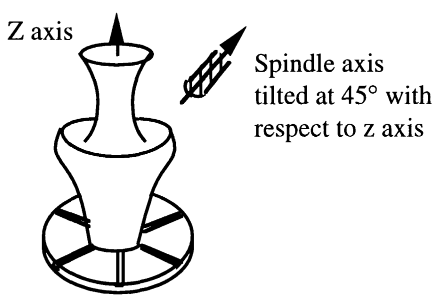

Figure 10. Example in 4-axis milling.

We illustrate this on the figure 10. The part to be milled is the bowl already illustrated on figure 7. The intersection of visibilities V_i is empty (in order to verify this, it is sufficient to study the visibilities of three points around the neck base). So, the part cannot be milled in a single sequence with a 3-axis milling machine. Therefore, we try 4-axis milling. A solution consists in setting up the workpiece with his Z-axis aligned with the rotating table axis, the spindle being tilted to 45°.

5. Conclusion

We search for the setup of a part on a milling-machine, in order to allow the whole part to be milled in only one sequence. This problem is solved for 3- and 4-axis milling. Collisions between the tool and the finished part are taken in account by using real visibilities from the points to be milled. We propose a method to calculate these visibilities.

Finally, we obtain the configurations of usable milling machines (3-, 4- and 5-axis). Moreover, the set of the possible setups of the workpiece is also computed. This set will be reduced to take in account various technological parameters, such as joint limits of prismatic axis of the milling-machine, the heel angle of the tool, the fixturing easiness. The toolpaths generation is then easier. We are currently improving our method for 4-axis milling (notably by taking in account joint limits on the rotating axis). A similar solution for 5-axis milling is in development. We are also working on an algorithm which could give us directly the spindle tilting angle (in 4-axis milling) or the fifth axis limits.

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FLANK MILLING OF RULED SURFACE WITH ADDITIONALLY-FIVE-AXIS CNC MACHINE

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Abstract: Flank milling is the crucial feature that the five-axis NC machine offers. Compared with bottom-edge based machining, the machinability can be greatly enhanced by the flank milling in that the side cutting edge is mainly used. In this paper, we present the flank milling method for NC machining of ruled surface with the three-axis CNC machine interfaced two-axis controlled tilt/rotary table. In particular, the main thrust has been: a) hardware setup and synchronization of the two CNC control units, b) motion characteristic and machinability of the ruled surfaces, c) tool path planning and execution methods, and d) verification of the proposed method via real experiments.

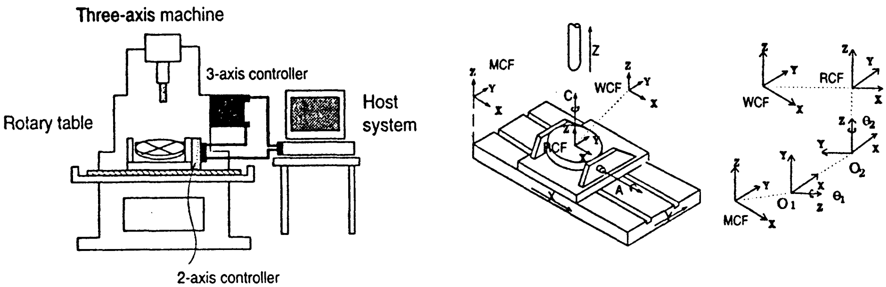
1 Introduction

Since ruled surfaces are represented by one-parameter family of straight ruling lines(e.g. a conic surface), they are particularly well suited for five-axis machining by the flank milling method. Compared with ball-end milling on three-axis machine, flank milling of ruled surface enables a tremendous increase in productivity as well as improvement of the surface finish. In spite of the strong potentials, the flank-milling method has not been widely used in practice due to the large investment for the five-axis CNC machine (capable of controlling the five axes simultaneously). This paper is concerned with investigation of a versatile CAM system together with hardware interface method such that the ruled surface machining can be effectively carried out with additionally-five-axis (AFA) CNC system composed of two controllers: one for three-axis CNC machine, the other for two-axis tilt/rotary table.

2 Additionally-Five-Axis (AFA) machine

AFA machine is a three-axis CNC machine equipped with a two-axis rotary table. Based on the type of CNC machine and rotary table, there exist a variety of configurations. In this research, we take the system shown in Figure 1(a), consisting of a vertical three-axis CNC machine, a tilt-rotary type table, and a host control system coordinating the machine and the rotary table controllers. With reference

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 389–398.



(a) Structure *(b) Kinematics*

Figure 1: AFA machine.

to the typical structure of the five-axis CNC machine, the presented AFA machine has two rotary axes, A and C, on the machine bed.

2.1 Kinematic structure

The detailed kinematic structure of the above configuration is illustrated in Figure 1(b), composed of three main coordinate frames and two auxiliary coordinate frames: WCF(for workpiece), RCF(for rotary table), MCF(for machine), and O_1 and O_2.

Note that the part surface model and its CL data are defined in WCF, while the cutter motion during machining in MCF. The transformation between WCF and MCF can be represented through RCF, which is determined by tilting (θ_1) and rotating (θ_2) angles of the rotary table. The tool axis in WCF can be aligned with the Z axis of MCF, the cutter axis of 3-axis machine, by tilt and/or rotation table. By 4 × 4 homogeneous transformation matrix, the coordinate transform from WCF to MCF via RCF, O_2, O_1 can be expressed as follows [1]:

$$\begin{aligned} T_{WCF}^{MCF} &= T_{O_1}^{MCF}\; T_{O_2}^{O_1}(\theta_1)\; T_{RCF}^{O_2}(\theta_2)\; T_{WCF}^{RCF} \\ &= T_{RCF}^{MCF}(\theta_1,\ \theta_2)\; T_{WCF}^{RCF}. \end{aligned} \tag{1}$$

2.2 Feasible tool orientations

Depending on the number of simultaneous controls for rotary table, the AFA system can be classified into three: a) three-axis control, b) four-axis control, and c) five-axis control. Three-axis control means that the rotary table is an indexing table, four-axis means that only one of the two axes can simultaneously controlled, and five-axis control means that both axes can be simultaneously controlled. For the first case, where the rotary table is not controlled during the motion, we previously developed AFA system for free surface machining [2]. In this paper, we are concerned with the rotary table having controllability of four-axis control or five-axis control.

Defining the tool orientation as the direction vector on the unit sphere, the feasible tool orientation for the three modes can be represented as shown in Figure 2. As shown in the figure, the feasible tool motion is a set of discrete points, planar arcs, and spherical surface, respectively for three-, four-, and five-axis mode. Furthermore, the machinability of part surface could be investigated from the figure. For example, if cutter orientations for machining a part surface exist on a planar arc, the surface would be machinable on four-axis mode. This fact is useful to define the machinability of ruled surface. The details of ruled surface are discussed in Section 3.

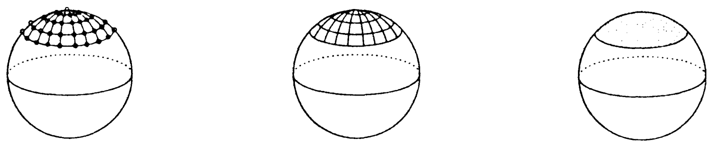


Figure 2: Feasible tool orientation in various modes.

2.3 Control scheme of rotary axes

Depending on how the rotary axes are interfaced with the main (three-axis) CNC controller, the control of the rotary axes can be classified into three modes: a) ***directly*** synchronized (DS) where the rotary axes are directly controlled by the main CNC controller, b) ***indirectly*** synchronized (IS), where the motion of the rotary axes and machine table are controlled independently by two control units, and c) ***sequential***, where the motion of the rotary axes is sequentially executed after the Cartesian motion is performed. For NC machining of ruled surface, the tool orientation should be synchronized with the tool interpolation, indicating the sequential mode is not appropriate. For genuine DS mode, the main controller should be (originally) designed such that it can control all the five axes. Thus, additional axes method dealt with in this paper seeks for the method of synchronization via IS.

In this method, synchronization of the two control units(one for three-axis linear interpolation, the other for the two-axis tool orientation) is the key to the successful implementation of the AFA retrofitting scheme, which has been one of the main thrusts of this paper. Our method is to decompose one block of the five-axis G-code into two parts (one for linear motion, the other for rotary motion), followed by executing them independently. The two parts of the CL-data are synchronized by M-code by the host control, so that the translational and rotational motion of the tool can be synchronized. The details on our implementation will be given in Section 5.

3 Process planning for ruled surface machining

3.1 Ruled surfaces

A ruled surface is generated by a ruling line guided by a base curve called directrix [3]. Let $p(u)$ be the base curve and $a(u)$ a unit vector. The ruled surface $s(u, v)$ can be defined by

$$s(u,v) = p(u) + v\, a(u),\ u,v \in [0,1], \tag{2}$$

where u and v are the parameters of the surface. The ruled surface can be also defined as a surface of linear blending of two boundary curves($p(u)$ and $q(u)$)

$$s(u,v) = p(u) + v\,(q(u) - p(u)),\ u,v \in [0,1]. \tag{3}$$

Normalizing the second term of Eq.(3), Eq.(2) can be represented by

$$s(u,v) = p(u) + v\,|l(u)|\, a(u),\ u,v \in [0,1], \tag{4}$$

where $l(u) = (p(u) - q(u))$ and $a(u) = \frac{l(u)}{|l(u)|}$.

3.2 Machinability of the ruled surface

Ruled surfaces are particularly well suited for five-axis machining by the flank milling method. The basic idea of this type of machining is moving the cutter edge along the straight ruling lines of the ruled surface. This indicates the ruling vector can be a good information in determining the cutter orientations. For instance, if $a(u)$ is a constant, $s(u,v)$ is a cylindrical surface which can be machined by the three-axis machine.

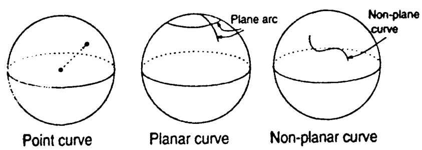


Figure 3: Three types of ruling curves on sphere.

In general, projecting $a(u)$ onto the unit spherical map, the curve of $a(u)$ can be classified into three: a) a point, b) a planar curve, and c) a non-planar curve, as shown in Figure 3. The point(curve) means that $a(u)$ is a constant unit vector meaning $s(u,v)$ is a cylindrical surface. The cylindrical surface is machinable on the 3-axis machine by taking the orientation of the cutter parallel to $a(u)$ (after positioning the workpiece appropriately on this machine to align $a(u)$ with the Z-axis of the machine). Thus, the cylindrical surface can be machined on the three-axis control mode of the additional-axis machine mentioned above. If the spherical curve of $a(u)$ is the planar curve, $s(u,v)$ is machinable by the four-axis control mode as the feasible tool orientation is a plane arc in this case (see Figure 2). If $a(u)$ is non-planar curve, the five-axis control mode should be taken.

Let $\tau(u)$ and $\kappa(u)$ denote the torsion and the curvature of $a(u)$, respectively. Then, the following can be used as a classification rule:

If $a'(u) = 0$, then $a(u)$ is a point curve,
else if $\tau(u) = 0$ or $\kappa'(u) = 0$, then $a(u)$ is a planar curve,
else then $a(u)$ is a non-planar curve (where $a'(u) = \frac{\partial a(u)}{\partial u}$).

3.3 Setup determination

Suppose part surface model is given in the workpiece (or design) coordinate (WCF) and the machine coordinate frame (MCF) is set at the origin of machining. Let FTO^k be the feasible tool orientation of k-axis control mode, FTO^k, $k = 3,4,5$, are respectively a set of points, a set of plane arcs, and a solid area on the unit sphere (see Figure 2). Further, since FTO^k and $a(u)$ are defined in MCF and WCF, the problem of part setup is to move $a(u)$ into the region of FTO^k. In other words, the problem of determining the part setup orientation is finding the relationship between MCF and WCF such that $a(u)$ is a subset of FTO^k;

$$R\ a(u)\ \subset\ FTO^k,\ \forall\ u, \tag{5}$$

where R is $(3\ \times\ 3)$ rotation matrix of WCF.

Figure 4 shows an example setup process for a conic surface. Before setup, $a(u)$ of the conic surface is not included in FTO^4. To make $a(u)$ be a subset of FTO^4, WCF is rotated about the X axis of MCF, until $a(u)$ is included in FTO^4. Since the geometric property and the region of FTO^k are changed with the types of ruled surface and control mode, the setup orientation algorithm should be solved for every combination of the two factors.

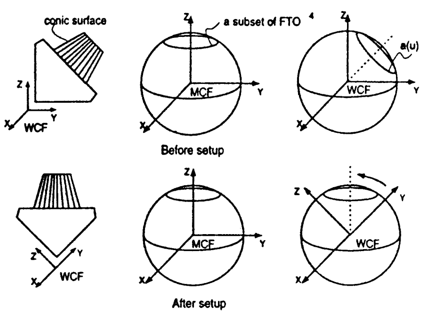


Figure 4: The setup process of a conic surface.

4 Tool path planning and execution

4.1 Tool path planning

For NC machining of the ruled surface, it is necessary to generate the five-axis CL-data including the tool-tip positions and the tool orientations such that the machining error is within the given tolerance. The CL-data can be generated in three steps.

1. Generation of CC (Cutter Contact) point via sampling the surface points.
2. Tool-tip point computation.
3. Tool-axis determination.

Since the above steps are well known, we do not give the details (See [4] for the details). In Step 3, it is worth mentioning that the tool orientation vector (o_i) should be kept identical to the ruling vector (a_i) in ruled surface machining. Without loss of generality, we assume that the CL-path for a CC-path is composed of N points; $P_i = (t_i, o_i)$, $i \in [1 : N]$.

4.2 Tool path execution

For the given CL-data, a G-code file can be readily generated by transforming the CL-data into joint axis data by using the kinematic relationship given in Eq. (1). Each block of G-code file is composed of five coordinates together with feedrate information. Now, the problem is to execute the G-code file with AFA, where the three positional components are executed by the machine controller and the two rotational ones by the rotary table controller.

Suppose the following NC blocks are to be executed

$$\text{G01 X } x_i \text{ Y } y_i \text{ Z } z_i \text{ A } a_i \text{ C } c_i \text{ F } f_i,\ i \in [1 : N].$$

Decomposing the block into two parts

$$\text{G01 X } x_i \text{ Y } y_i \text{ Z } z_i \text{ F } f_i^l; \qquad \text{G01 A } a_i \text{ C } c_i \text{ F } f_i^r,$$

the problem is to determine f_i^l and f_i^m such that the two execution times are the same as the one indicated by f_i.

The motion time for the block can be computed as

$$\lambda_i = \frac{|P_i - P_{i-1}|}{f_i} \tag{6}$$

where $|\cdot|$ means the Euclidean distance between two positions. (Note that P is 5×1 vector representing the position (t) and orientation (o) of the tool. Also, in the case that f means feedrate of the tool position (t), such as in Reference [5], P in Eq. (6) should be replaced by t.) Then, feedrates for the machine and rotary table can be determined as follows:

$$f_i^l = \frac{|\,t_i - t_{i-1}\,|}{\lambda_i}, \qquad f_i^r = \frac{|o_i - o_{i-1}\,|}{\lambda_i}. \tag{7}$$

It is worth noting that the feedrate in general is not an integer, and hence will not be effectively accommodated for the controller allowing only integers. For such a case the inverse time function (G93) can be used, where feedrate is specified by FRN (Feed Rate Number) defined as follows:

$$FRN = \frac{l}{T} = \frac{fd}{60}, \tag{8}$$

where T is motion time , and f and d are respectively the feedrate and moving distance.

Finally, in some cases, the NC block may contain motion for only one controller. To distinguish such a case, it is necessary to tell the host controller via flag called binary selection list (BSL). This is for the sake of efficiency and computing amount when executing G-codes for two controllers. Table 1 illustrates G-code decomposition and BSL.

Table 1: G-code decomposition and BSL.

Five-axis M/C	Three-axis M/C	Rotary table	BSL	
G01 Xx1 Yy1 Zz1 Aa1 Cc1 Ff1	G01 Xx1 Yy1 Zz1 Ffm1 M00	G01 Aa1 Cc1 Ffr1 M12	1	1
G01 Xx2 Zz2 Cc2 Ff2	G01 Xx2 Zz2 Ffm2 M00	G01 Cc2 Ffr2 M12	1	1
G01 Xx3 Yy3 Zz3 Ff3	G01 Xx3 Yy3 Zz3 Ff3 M00		1	0
G01 Aa4 Cc4 Ff4		G01 Aa4 Cc4 Ff4 M12	0	1
G01 Yy5 Zz5 Aa5 Ff5	G01 Yy5 Zz5 Ffm5 M00	G01 Aa5 Ffr5 M12	1	1

5 Implementation, calibration and experiment

5.1 Implementation

The presented AFA scheme was implemented for Bridgeport 3-axis CNC milling machine run on the three-axis controller (Heidenhain TNC 151 model). A rotary/tilt table (manufactured by Troyke Manufacturing Co.) was interfaced with a two-axis controller (DSP board). The two controllers were coordinated via a host controller PC-486. Figure 5 shows the AFA composed of machine tools, three-axis controller, rotary/tilt table, a host computer where DSP board is installed together with V-CAM system.

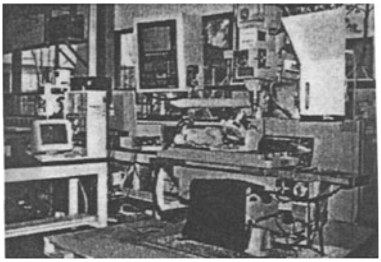


Figure 5: The implemented AFA machine

Execution of two sets of NC programs is made through indirect control (IS), where the two motions are executed independently. To ensure synchronization, communication protocol between the three controllers is designed as follows. To initiate execution of each block, the host controller sends SOB (Start Of Block) signals to both controllers. Upon receiving the SOB signal, each controller starts the motion and send EOB (End Of Block) signal (M00 and M12 by the machine tool controller and rotary table controller, respectively) upon completion. After receiving the EOB signals from both of the controllers, the host controller sends SOB signals for the execution of the next block. The synchronization scheme including overall internal structure is shown in Figure 6.

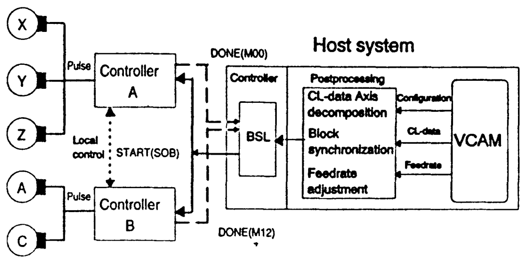
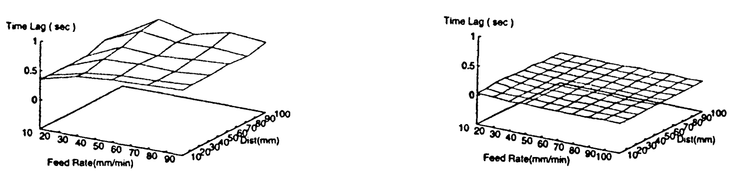


Figure 6: IS control scheme of AFA.

5.2 Calibration of the controllers

The practical validity of the above synchronization method is determined based on the difference of the execution time. Let $T_{i,m}$ and $T_{i,r}$ be the execution time of block i by the two controllers. Then, ideal case is $T_{i.m} = T_{i,r}, \quad \forall\ i\ [1 : N]$. However, there exists difference in almost all the cases, even if the computed time was the same. This is due to difference in control logic of the two controllers. Also, it was found that the time difference is dependent on the values of feedrate and moving distance as shown in Figure 7(a) (called characteristic map or CM), showing time difference under various feedrates and distances. In this case, the rotational controller in general finished the motion earlier than the machine tool controller by 550 ms (equivalent to 0.916 mm in position under feedrate of 100 mm/min) which is not acceptable at all.

This can be solved in two ways: software based and hardware based methods. The software based method is to accommodate the time difference data of characteristic map as a database in computing the feedrate for each of the controllers. The hardware based method is to adjust the motion parameters for each controller (such as acceleration, transient response, and gains of the position and velocity) until consistent results are obtained (See Reference [6] as an example). Taking the second approach, we obtained characteristic map shown in Figure 7(b) indicating the maximum of 30 ms throughout the entire range of the moving distance and feedrate. In practice, 30 ms is allowable for most of the precision. Further, as



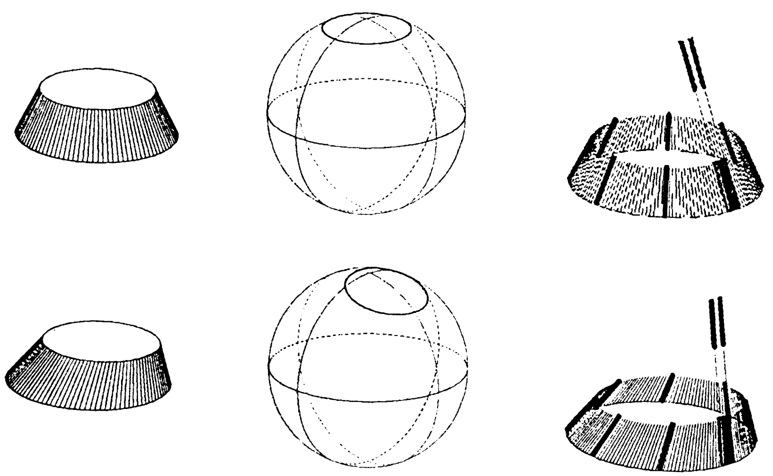
(a) *before calibration* (b) *after calibration*

Figure 7: Characteristic map.

the time difference is constant over the entire range, its effect can be virtually eliminated by compensating the time lag in postprocessing procedure.

5.3 Cutting experiment

Two examples shown in Figure 8(a) are ruled surface with the circle diameter of 60 mm and 80 mm for the upper and lower base curves. Note that in the upper surface, center of one circle coincides with the other along Z axis, but not in the circle second surface. As the spherical curve of the upper (resp. lower) surface is a planar circle (spherical ellipse), the upper (lower) surface is machinable by the four-(five-) axis control. The CL-paths including tool approach and departure are shown in Figure 8(c). The actual cut was made only for the first surface due to lack of inverse time function in both of the controllers. Note that there is a method working with integer feedrate but only works for the four-axis ruled surface. Thus, in our experiment, the actual cut was made for the four-axis ruled surface.



(a) (b) (c)

Figure 8: Two cone ruled surfaces.

As the spherical curve of the four-axis surface was included in FTO[4], the part was set up so that WCF and RCF are coincident. Applying the procedures of tool path planning followed by path execution, the two parts of G-codes were obtained. By executing the G-codes for the two controllers, parts shown in Figure 9(c) was obtained. Note that Figure 9 also includes the results of rough cut (a) and semifinish cut (b). The finished part showed dimensional accuracy and good surface finish.

(a) (b) (c)

Figure 9: Cutting experiment.

6 Conclusion

In this paper, we presented a software based retrofitting method for five-axis CNC machining method, where flank milling is chosen as a representative for five-axis tool motions. The method is powerful strategy to deal with the cost problem in equipping five-axis machine while utilizing the existing machine. To support the proposed method, we presented algorithms and practical issues required for the implementation and utilization in practice.

Through the actual experiments, the effectiveness of the method has been verified. Although the experiments were rather primitive, the results convinced us that the presented method can be used as a means for dealing with the cost problem for five-axis machine. Although the details for the interface and implementation may vary depending on the situations, the method in general can be applied. In our case, inclusion of inverse time function is left for the near future. Further, precise and detailed comparison (surface roughness, dimensional accuracy, machining time, etc.) with parts machined by the full five-axis is required. Theories and algorithms for the implementation of a versatile CAM system supporting NC machining of a variety of part shapes under various additional-axis environments are under investigation.

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SYNTHESIS OF RECONFIGURABLE-FIXTURE SUPPORT CONFIGURATIONS FOR THIN-WALLED OBJECTS

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Abstract. This paper proposes a methodology for the synthesis of fixture-support configurations for thin-walled objects, whose surfaces are defined in parametric-polynomial form within CAD systems and which are subject to deformations due to external forces during manufacturing. The specific problem addressed is the optimal placement of discretized 3D support walls underneath a given object, minimizing deformations measured at selected points on the surface.

Résumé. Cet article propose une méthodologie de synthèse de la configuration de support pour des pièces de faible épaisseur, décrites par des surfaces polynomiales paramétriques dans les systèmes de CFAO, et se déformant lors de l'application d'efforts d'usinage. Utilisant la minimisation des déformations en certains points sélectionnés de la surface, le problème de conception consiste à déterminer la position de supports de type courbes 3D utilisant un certain degré de discrétisation.

1. Introduction

In many industrial robotic applications, objects must be precisely fixtured at known positions and orientations. This objective can be achieved using fixtures and jigs. These fixtures constrain all the degrees of freedom (dof) of the objects and, thus, do not allow any motion. In certain cases, they can also be utilized to limit deformations due to applied forces. However, one must note that, in the majority of past cases, these fixtures have been either object or/and task specific. This necessitates re-fixturing of complete production lines when new products are introduced, at a tremendous productivity expense. Use of reconfigurable fixtures is one of the solutions proposed by many in the manufacturing-research community for increased flexibility in robotic production lines.

A survey of flexible fixtures can be found in [1], presenting the fundamental principles of reconfigurability in modular fixtures. These are utilized herein for the development of a synthesis environment for reconfigurable fixtures dedicated to thin-walled deformable objects. More specifically, the synthesis process targets the minimization of object deformations under stress. A notable example in this area is the

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 399–406.

work presented in [2], where the authors concentrated on the optimization of fixture configurations for planar and prismatic objects.

2. Overall Description of the Synthesis Environment

Recent research interest in the fixturing of non-planar, thin-walled flexible objects is justified by the lack of pertinent significant progress, except in the area of mainly-planar and/or rigid object fixturing. Also, the primary concern of researchers has been simply the constraint of the dof of the objects. The synthesis and analysis procedures developed may, therefore, not be suitable for semi-rigid objects, which can deform under applied forces. Such objects are commonly encountered in the automotive and aeronautics industries. Use of reconfigurable fixtures is a necessity in such environments, where such devices can adapt to different object shapes. Our objective is therefore, the development of a synthesis environment for determining optimal support configurations for fixtures targeted to thin-walled, flexible objects.

The proposed support structure comprises 3D, curved, vertical walls placed underneath the object. The support walls are discretized via the utilization of a set of height-adjustable locators. The corresponding reconfiguration methodology is an iterative two-phase procedure: synthesis and analysis. The analysis phase allows us to estimate the "goodness" of a potential support configuration. An elastic-deformation-based objective function, calculated using a Finite-Element Method (FEM), describes this goodness. The synthesis phase provides the analysis phase with different support candidates, which are determined using a non-linear search through the variables domain.

3. Geometric Modeling of the Object and the Support Configuration

Objects, considered in this paper, can be modeled using a CAD system, where their thin walls lend themselves to surface representation. These surfaces are modeled herein in a parametric polynomial form $S(u,v)$:

$$S(u,v) = \sum_{iu=0}^{mu} \sum_{iv=0}^{mv} P_{iu,iv} \; u^{iu} \, v^{iv} \text{ with } (u,v) \in [0,1]^2 \text{ and } P_{iu,iv} \in R^3 \qquad (1)$$

The above representation provides us with several important advantages, for the definition and manipulation of support curves, $C_c(w)$, in 2D parametric space, including:

- Discretization of the curves, and allowing individual locators to be in contact with the object's surface; and,
- Representation of these curves in parametric Bézier polynomial form, by utilizing the Bernstein, $B_{k,mw_c}(w)$, polynomials as the basis function, [3]:

$$C_c(w) = \sum_{k=0}^{mw_c} Q_{c,k} \, B_{k,mw_c}(w); \;\; B_{k,mw_c}(w) = \frac{mw_c!}{(mw_c - k)! \, k!} \, w^k \, (1 - w)^{mw_c - k} \qquad (2)$$

where $w \in [0,1]$ and $Q_{c,k} \in R^2$ is the k'th control point of the mw_c-order support curve.

The discretization of the support curve is uniform with respect to the parameter w, it depends on the discretization W_c, and is represented by w_d:

$$w_d = \frac{(d-1)}{(W_c-1)} \quad \text{where } d = \{1, \ldots, W_c\} \tag{3}$$

The real position of the support points in 3D space can be obtained by the following transformation, where the d'th point of support, $PS_{c,d}$, shown in Figure 1, is given by:

$$QS_{c,d} = \begin{bmatrix} us_{c,d} \\ vs_{c,d} \end{bmatrix} = \sum_{k=0}^{mw_c} Q_{c,k}\, B_{k,mw_c}(w_d) \quad \text{where } d = \{1, \ldots, W_c\},\ Q_{c,k} = \begin{bmatrix} uq_{c,k} \\ vq_{c,k} \end{bmatrix} \tag{4}$$

$$PS_{c,d} = \begin{bmatrix} xs_{c,d} \\ ys_{c,d} \\ zs_{c,d} \end{bmatrix} = S(us_{c,d}, vs_{c,d}) = \sum_{iu=0}^{mu} \sum_{iv=0}^{mv} P_{iu,iv}\, (us_{c,d})^{iu}\, (vs_{c,d})^{iv} \tag{5}$$

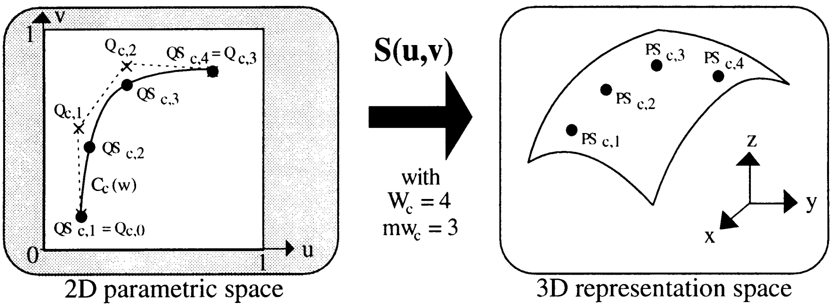

Figure 1. 3D transformation of support points.

The variables of the synthesis problem, as described above, are the coordinates of the control points, $(uq_{c,k}, vq_{c,k})$, of $Q_{c,k}$. The definition implies a complete independence between the number of variables of the optimization problem and the order of the 3D support curve. If *NC* denotes the number of curves, the set of independent variables is defined below by the n'th order vector, $x \in R^n$:

$$x = [uq_{1,0}, vq_{1,0}, uq_{1,1}, \ldots, vq_{1,mw_1}, uq_{2,0}, \ldots, vq_{NC,mw_{NC}}]^T \tag{6}$$

$$n = 2 \sum_{c=1}^{NC} (mw_c + 1) \tag{7}$$

4. Analysis Module

The role of this module is to analyze the goodness of a support configuration in terms of linear, elastic deformation of the object. Due to the generic nature of the object's surface a FEM must be utilized.

4.1. FORMULATION OF THE OBJECTIVE FUNCTION

The objective function, $f(x)$, is defined herein as the sum of displacements measured at selected points on the object:

$$f(x) = \sum_{ne=1}^{NE} \sqrt{D_{ne}{}^{T} D_{ne}} \tag{8}$$

where NE is the number of evaluation nodes and D_{ne} is the displacement vector.

The same set of points is utilized for the evaluation of all different potential support curves. The choice of their number and relative locations are user-chosen parameters. Under certain loading circumstances, one may increase/decrease their resolution at some sections of the object.

4.2. MESHING

The meshing process, carried out automatically, is based on the classical Delaunay triangulation method [4]. The resultant triangulation is unique for a given set of points and the triangles are as equilateral as one can achieve.

Four different types of nodes are considered: (i) Objective-function evaluation nodes; (ii) Functional nodes, where external forces are applied; (iii) Support nodes, which represent contacts between the locators and the object; and, (iv) Auxiliary nodes, which are non-functional and used for meshing purposes.

Once a reference mesh is attained for the object under consideration, re-meshing only involves changing the location of the support nodes. This process solely causes local changes.

5. Synthesis Module

The objective of the synthesis module is to determine the optimal support configuration, which minimizes the objective function defined in Equation (8).

5.1. A NON-LINEAR SEARCH TECHNIQUE

The "flexible tolerance method" [5] chosen in our work, is a non-linear constrained search method. It does not require the calculation of gradients, and thus overcomes a serious difficulty with FEM-based procedures. This strategy is associated with the "flexible polyhedron search" [6], where the polyhedron adapts itself to the landscape of the search domain using operations such as: reflection, expansion, and contraction. In addition, this method deals with equality/inequality constraints by tightening the feasible zone as the search progresses.

5.2. GEOMETRIC CONSTRAINTS

Constraint regions are necessary in order to solve practical problems. They may include, but not limited to, the following [7]:

- All support points must be within the underneath surface limits of the object,
- Support nodes should not coincide with functional nodes, and
- Support nodes are separated by a minimal distance due to physical shapes of the locators.

Each support curve, $C_c(w)$, is associated with a corresponding constraint region, RCG_c. The latter is defined, in the parametric domain, by a set of inequalities, $r=\{1,\ldots,R_c\}$, Figure 2:

$$G_{c,r}(u,v) \geq 0 \quad where \quad r = \{1, \ldots, R_c\} \tag{9}$$

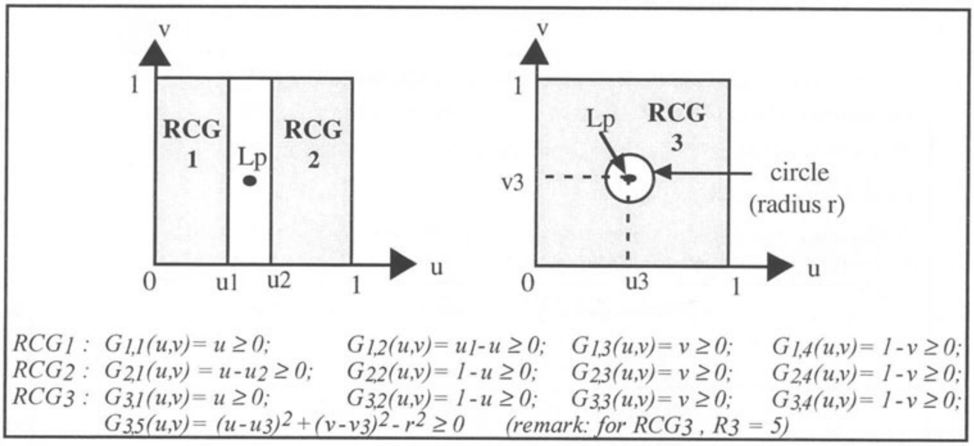

Figure 2. Some exemplary geometric-constraint regions.

The above formulation can also be written in terms of support coordinates as follows:

$$G_{c,r}(us_{c,d}, vs_{c,d}) \geq 0 \quad where \quad r = \{1, \ldots, R_c\} \tag{10}$$

6. A Simulation Example

We illustrate our methodology via a simulated example run on an IBM RISC 6000 workstation, utilizing the CATIA CAD software. User interfaces were achieved using the CATGEO module of CATIA.

For the example at hand, the object's Young modulus was set as E=210 GPa and the Poisson coefficient was set as μ=0,3. The object's thickness was set as 1 mm. The evaluation nodes were uniformly distributed, Figure 3. The parameters of the simulated example are given in Table 1. The number of search variables for the optimization problem was 8.

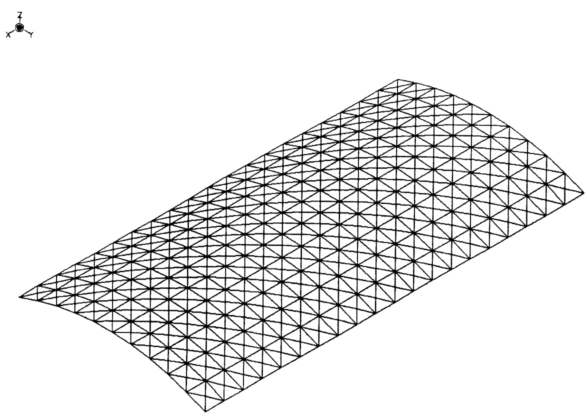

Figure 3. Surface shape (reference mesh).

TABLE 1. Parameters of the simulated example.

<u>Parameters of the surface and of the reference mesh:</u>
431 nodes including 233 evaluation nodes, 800 triangles
Dimensions of the bounding box in mm (x, y, z): 2000 x 1000 x 100
u and v degrees of the surface: mu = 1; mv = 2
Coefficients $P_{iu,iv}$ of the surface: $P_{0,0} = [0, 0, 0]^T$; $P_{0,1} = [0, 1000, 400]^T$; $P_{0,2} = [0, 0, -400]^T$; $P_{1,0} = [2000, 0, 0]^T$; $P_{1,1} = [0, 0, 0]^T$; $P_{1,2} = [0, 0, 0]^T$
<u>Parameters of the fixture support configuration:</u>
Number of support curves: NC = 1; degree of a support curve: $mw_1 = 3$; degree of the discretization: $W_1 = 7$
<u>Functional node position $[x, y, z]^T$:</u>
5 clamping nodes: $[1000, 0, 0]^T$; $[1000, 1000, 0]^T$; $[0, 500, 100]^T$; $[2000, 0, 0]^T$; $[2000, 1000, 0]^T$
<u>Applied forces: module in Newton, direction $[x, y, z]^T$, application point $[x, y, z]^T$</u>
1st effort : module 2000 N, direction $[0, 0, -1]^T$, application point $[200, 500, 100]^T$
2nd effort : module 1300 N, direction $[0, 0.2696, 0.9630]^T$, application point $[1750, 150, 51]^T$
3rd effort : module 1000 N, direction $[0, 0.1961, 0.9806]^T$, application point $[1750, 750, 75]^T$
<u>Geometrical constraints:</u>
Constraint region RCG_1: $G_{1,1}(u,v) = u - 0.125 \geq 0$; $G_{1,2}(u,v) = 0.85 - u \geq 0$; $G_{1,3}(u,v) = v - 0.05 \geq 0$ $G_{1,4}(u,v) = 0.95 - v \geq 0$
Minimum distance between 2 support points: $d_{min} = 1$ mm

Figure 4 illustrates the initially-guessed as well as the optimal (final) fixture support configurations. One must note that, certain support points lose contact with the object once the external forces are applied.

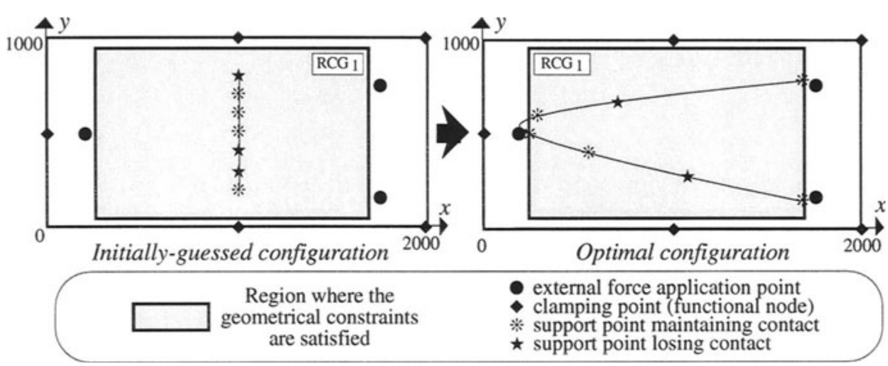

Figure 4. X-Y locations of the support points.

Table 2 gives the initial and final data for the simulation. Figures 5 and 6 give an exaggerated visualization of the object deformations, respectively for the initially-guessed and the optimal support configurations.

TABLE 2. Data for the initially-guessed and optimal support configurations.

Initally-guessed solution	
Variables:	$x^{(0)} = [0.5, 0.2, 0.5, 0.4, 0.5, 0.6, 0.5, 0.8]^T$
Support point locations:	$PS_{1,1} = [1000, 200, 64]^T$ $PS_{1,5} = [1000, 600, 96]^T$ $PS_{1,2} = [1000, 300, 84]^T$ $PS_{1,6} = [1000, 700, 84]^T$ $PS_{1,3} = [1000, 400, 96]^T$ $PS_{1,7} = [1000, 800, 64]^T$ $PS_{1,4} = [1000, 500, 100]^T$
Deformation:	$f(x^{(0)}) = 3564.5856$ Maximum deformation: 72.44 mm (node $[0, 1000, 0]^T$)
Optimal solution	
Variables:	$x^* = [0.85, 0.141, 0.215, 0.462, -0.448, 0.537, 0.85, 0.773]^T$
Support point locations:	$PS_{1,1} = [1700, 141.4, 48.6]^T$ $PS_{1,5} = [263.7, 575.8, 97.7]^T$ $PS_{1,2} = [1078.7, 283.3, 81.2]^T$ $PS_{1,6} = [710.2, 666.6, 88.9]^T$ $PS_{1,3} = [558.5, 395.4, 95.6]^T$ $PS_{1,7} = [1700, 772.9, 70.2]^T$ $PS_{1,4} = [250, 489.2, 99.9]^T$
Deformation:	$f(x^*) = 237.4676$ Maximum deformation: 6.82 mm (node $[200, 500, 100]^T$)

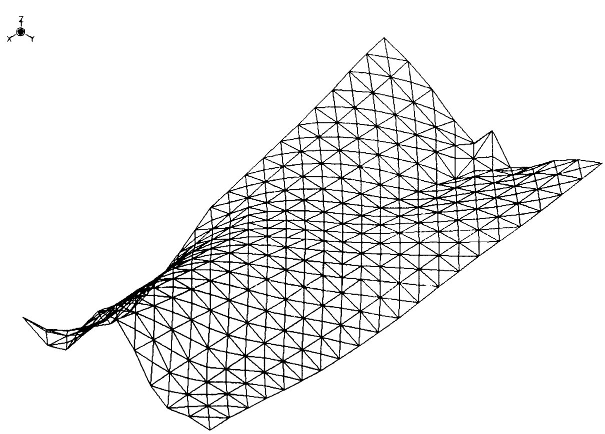

Figure 5. Visualization of the object deformation for the initially-guessed support configuration.

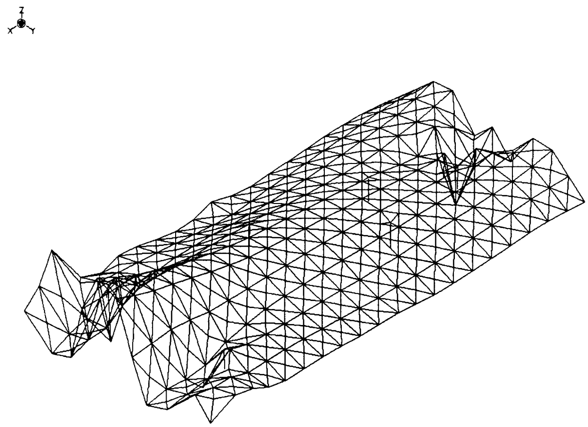

Figure 6. Visualization of the object deformation for the optimal support configurations.

The optimization has converged in 260 steps, requiring a total of 446 objective-function evaluations. The maximum deformation noted for the optimal solution was 6.82 mm.

7. Conclusion

In this paper, a synthesis methodology was presented for the reconfiguration of modular fixtures dedicated to thin-walled flexible objects. The optimization process assumes the utilization of 3D, discretized, vertical support walls.

The primary advantage of our method is the independence of the search order from the order of the discretization. The solution is also globally optimal due to the effective search technique utilized herein.

8. References

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COMPUTER AIDED PROCESS PLANNING IN TURNING : ASCENDANT DESIGN BY FEATURES

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Abstract. This paper presents a method of automatic process planning in turning. One difficulty to generate automatically process plans is to create new intermediate shapes. These shapes are intermediate states between the finished part and the raw form. Each shape defines a phase. Our method is based on the feature concept. An intermediaite shape is obtained by associating some internal form features and external form features.

1. Introduction

Difficulties met to generate automatically process plans essentially concerne the following points[Elm 93][Hou 90][Ans 94]:
- formalisation of the knowledge of the expert in process plans (knowledge based on scientific calculations but also on the experience),
- judicious use of this knowledge within an expert system,
- description and construction of the different phases of the process plans studied.

This article develops this third point.

2. Description of process plans

Our method of process plan generation is based on a graph of the different possible solutions[Mog94a][Mog94b]. Each summit of this graph corresponds to a phase defined by the clamping of the workpiece, the different parts to manufacture and the final form to obtain at the end of the phase. The graph is built up from the finished workpiece to the raw workpiece. The precedence between summits is given by the fact that the final form obtained from a phase is the initial form of the next phase.
The finished workpiece is analyzed by evaluation criteria. The purpose of this study is to classify the different possibilities of clamping. For each of these clamping surfaces, the analysis continues by the evaluation and the construction of the different shapes so as to determine the different possible phases. At this stage, we obtain the totality of the last possible phases to obtain the finished workpiece. Then, by iteration, each shape

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thus built is studied until an acceptable raw workpiece is obtained (figure 1).

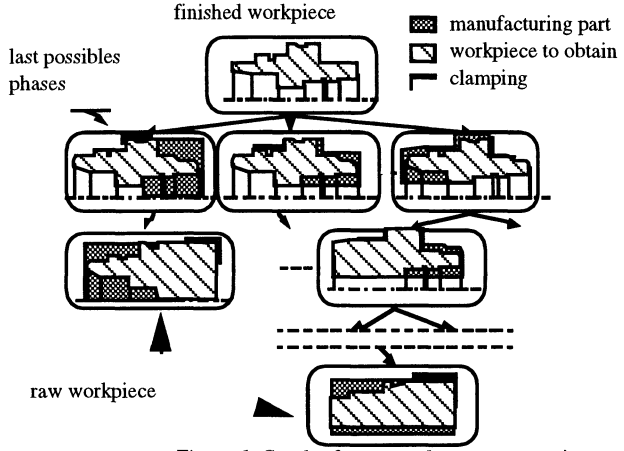

Figure 1. Graph of process plans representation

To each steady path on the graph corresponds a process plan. The construction of this graph is therefore made by iteration. For each summit, the various possibilities of manufacturing until the obtaining of a raw workpiece are study. The different process plans obtained are classified with the help of criteria. The process plans retained are then proposed to the expert that undertakes the final choice.

3. Construction of process plans

3.1. STUDY OF CLAMPING POSSIBILITIES

Studies of potential clamping possibilities and manufactured parts are linked. Our choice has been to select many criteria, the different possible clampings on the workpiece (sufficiently long support,...). The criteria used allow to formalize the knowledge and to verify the respect of rules of the art for manufacturing [Mog95]. These criteria aim to eliminate all non viable solutions or those that do not respect a level of quality.

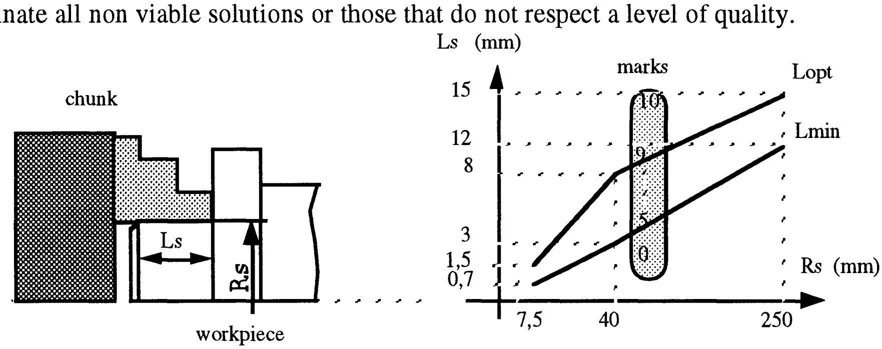

Figure 2. Evaluation criterion

A criterion is associated to a condition to fill. It depends on one, two or three parameters. This evaluation consists in associating a function of evaluation delivering a mark of 0 to 10 to each constraint of production.

The mark 0 translates a technical impossibility or a danger, the solution is then

eliminated. The mark 10 shows that the condition is perfectly validated.
An intermediate mark allows to evaluate risks (in the general senses) of the solution studied. This criterion evaluates, for example, the quality of a clamping with a chunk in turning (function of the radius and the length of clamping) (figure 2).
Finally, a solution will be retained if all criteria validate it satisfactorily. This validation is obtained by making an average of the marks obtained. This technique of study allows to evaluate the different solutions very precisely (a criterion is associated to a very precise problem) and to compare them more globally (thanks to the average).

3.2. STUDY OF THE POSSIBLE MANUFACTURING SOLUTIONS

3.2.1 Principle

For a given clamping solution, there therefore remains to study the possible manufacturing solutions for each of these clamping.
It is seldom possible to entirely manufacture a workpiece all at once. It is going therefore to be necessary to *cover* the finished workpiece to obtain an intermediate shape between the raw and the finished workpiece. The raw workpieces envisaged are cylindrical.
The next step therefore consists in covering the finished workpiece in several states to obtain an acceptable raw workpiece. We add material (volume to manufacture) to obtain an acceptable raw workpiece. To realize this covering, we have imagined the most generic case in constituting a clamping at the end of the workpiece. The accessible volume to tools is decomposed in zones to manufacture (figure 3).

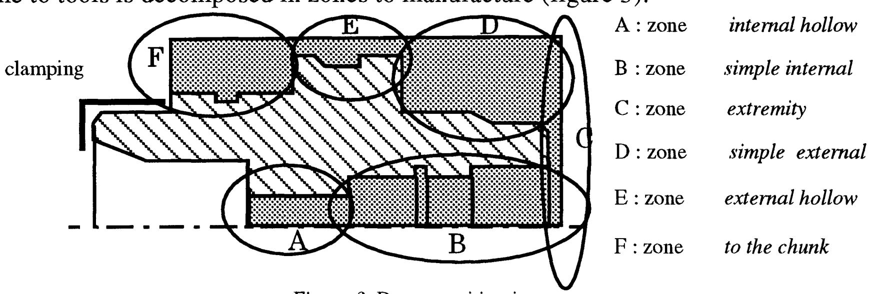

Figure 3. Decomposition in zones

The maximal theoretical manufacturing possibilities are defined as shown in figure 3. This step can entirely be used for forging or moulding parts.
When the clamping position is on part E for example, volumes E and F are not considered.
This theoretical volume has been decomposed in to several zones that represent well specified difficulties of manufacturing (interior manufacturing, exterior manufacturing,..). For each zone, material is added according to the strategies of manufacturing types that we call features. We have defined four great feature types that correspond to strategies of manufacturing classically used. Thus, these features go from the *finishing* feature to the *roughing* + *half finishing* + *finishing* feature that allow the complete manufacturing (figure 4).

for example for the zone simple internal (B) :

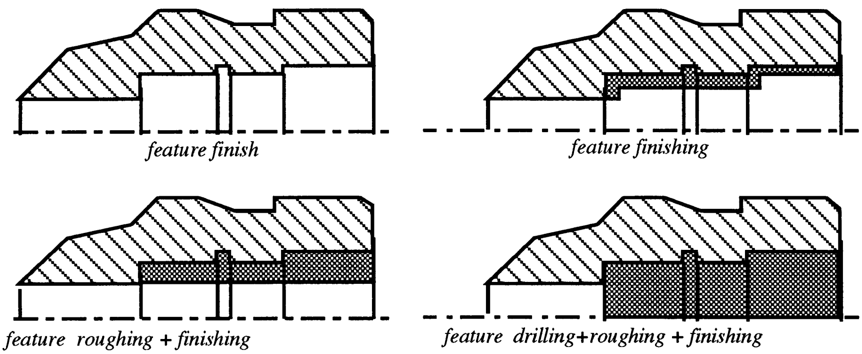

Figure 4. Example of features

This observation has allowed us to obtain a non exhaustive catalogue of 43 features that distribute as follows :

-twelve features *internal hollow,*
-four features *simple internal,*
-six features *extremity,*
-five features *simple external,*
-twelve features *external hollow,*
-four features *"to the chunk".*

The defined features correspond to methods of machining included in the CAM System used.

In function of workpiece constraints, this strategy allows to select one or several features for each zone (for example, a workpiece that risks being deformed by hard machining will have only finishing features). Each feature can be studied separately by specific criteria (tool accessibility, precision of the desired surface,..).

Features are then combined to create several shapes, that are all acceptable as they are realized with selected features.

Example of the building of a shape with features :

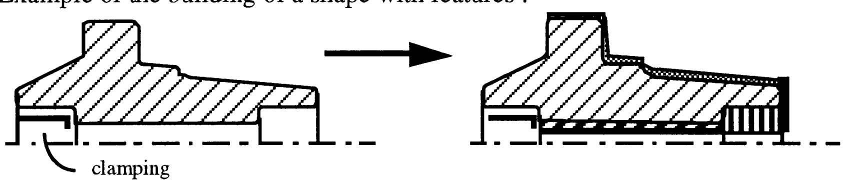

Figure 5. Building of a shape

Features are thus evaluated by criteria (that are of the same type as those seen previously). A threshold of acceptability (based on the average of mark obtained with the criteria) allows to retain only features that answer the problem. Then, the combination of the different features retained give the different possible shapes.

Our method of part decomposition in zones then in features allows to create an important number of shapes (about 70,000 possibilities) with a small number of features without having to evaluate all these possibilities. So, most rotational parts can be realized.

When this prior study is not satisfactory, specific features are required in particular to facilitate the clamping of workpieces.

3.2.2. Feature for clamping of workpiece

This feature is used when there are only spherical or conical surfaces on the workpiece. The length of the fixture surface is calculated for a clamping in a chunk .

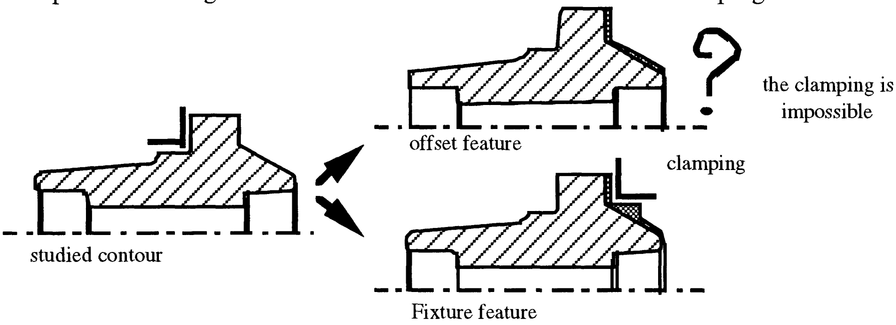

Figure 6. Feature for clamping of workpiece

3.2.3. Overlength feature

The overlength feature allows the fixture of the workpiece outside manufacturing surfaces in a chunk with or without a tailstock.

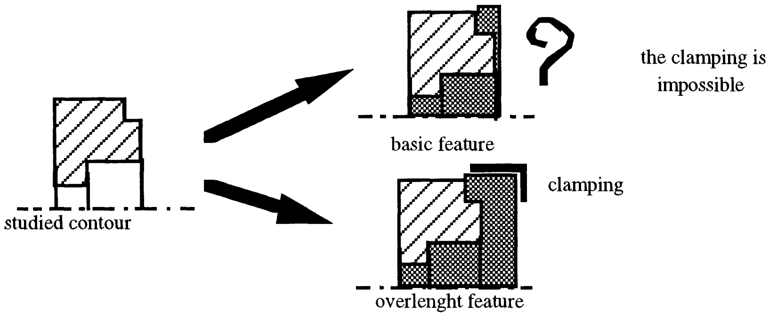

Figure 7. Overlength feature

3.2.4. Feature tailstock

These specific features are set on the ends of the part to allow a fixture between centers or a facing with a tailstock. It is also possible to drill a center without damaging the finished face of the part. The drilling of the center can then be realized on a specific machine.

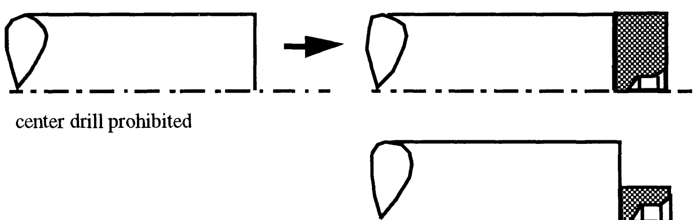

Figure 8. Feature Tailstock

All these specific features are not used systematically but they are examined when the dimensions and the shapes of the workpiece answer some geometrical criteria.These features are studied for each iteration of the graph and can be called for every level of this graph.

3.3. COMBINATION OF THE DIFFERENT FEATURES

All the features can be combined to give an intermediate shape. The offset for the finishing operation is currently arbitrarily fixed at 1.5 mm by default because the definitive value can only be refined when the finish tool is identified.

The combination of features is made from the interior to the exterior. The intermediate contour has to be built with the limits of each zone (figure 9). We think that this method of decomposition generates a sufficient number of possible intermediate contours to allow the machining of practically all rotating parts. It is very general and does not limit the process plan to some solutions established in advance.

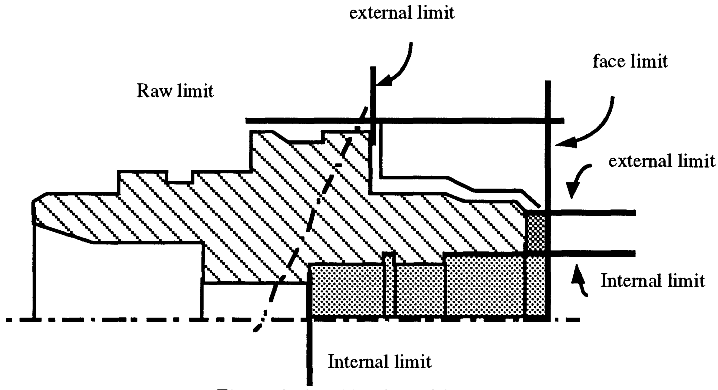

Figure 9. Combination of features

New features can also easily be added. In this case, the current criteria of evaluation will be applied on the new features, but new criteria can be added.

4. Results

This method has been validated whit a model integrated in the software LURPA-TOUR (Anselmetti 1994).

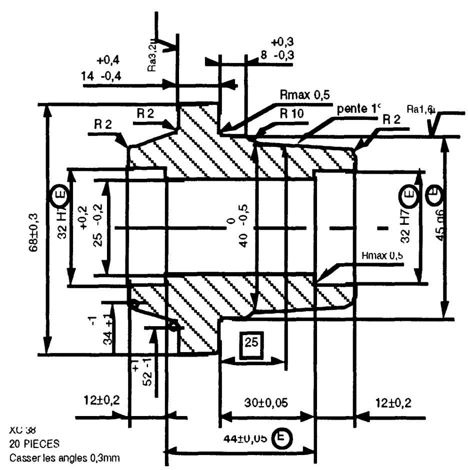

Figure 10. Definition drawing of part

The workpiece is described by a definition drawing (paper or CAD model)
The operator gives some general information :

TABLE 1. General information

Part name : PALIER
Machine tool : NC Lathe ERNAULT HES 44
Gripper : chunk GAMET 220
Raw material : XC 48
Hardness : 180 HB
Number of parts : 200
Raw diameter : 70 mm

The geometry is described with the help of a specific modeler, or extracted from a model CATIA.

Solutions are described under the following form :

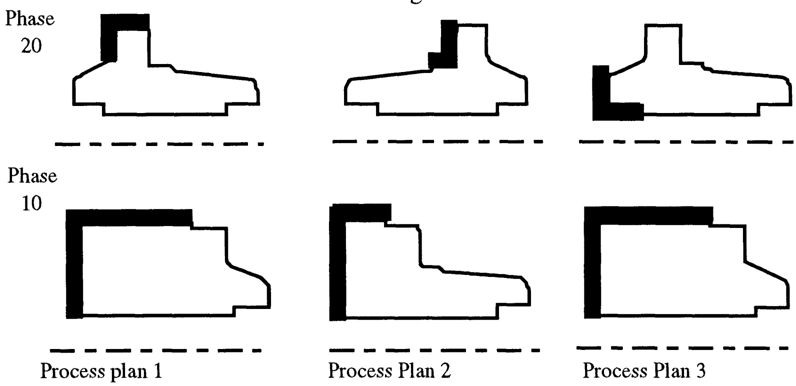

Figure 11. Process plans

Operators can make their choice among the best solutions.

The process plan generator automatically generates two files for phases 10 and 20 that correspond to process plan 1. These files are analyzed by the generator of phases that defines a completely detailed manufacturing process.

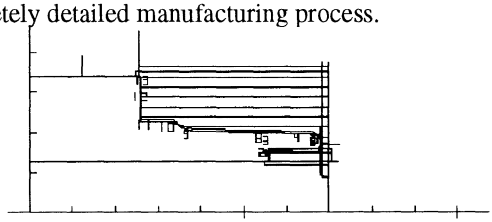

Figure 12. Tool paths

The NC Program is automatically generated with the LURPA-TOUR :

```
%10.1
N10 (29 MAR 94 14h26 PALIER - PH20)
N20 E30050 =20 (CHUNK PRESSURE)
N30 E30037=3 M136 (MONITEUR ON)
N40 E30037=12 E30036=78 M136 (RAPID SPEED)
N50 E30037=12E30036=20 M136 (COLLISION)
N60 G0 G52 X0 Z-98.77
N70 G92 S4000
N80 T3 M6 (EXTERNAL ROUGHING PCLNR2525M12)
N90 G97 M41 M3 S1085
N100 X74.8 Z68.6 M8 D3
```

Figure 13. NC Program

So, NC data can be automatically created and worked on a NC lathe with no modification.

5. Conclusions

This step has been validated on turning-workpieces of the industry. The method potentially allows to obtain a great number of shapes to manufacture (in the order of 70,000) while studying only 46 features precisely. Currently, this study has shown its interest on workpieces whose raw material are cylindrical shapes. Our research now concentrates on the application of this method to forging or moulding raw parts.

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Chapter 8
INTEGRATED DESIGN AND CAD-CAM SYSTEMS

PROPOSALS FOR A PRODUCT MODEL

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Abstract. We emphasise three important aspects in product modelling : problems that appear because of the use of features during the design step, mapping of the design model into application models and adding new generic features in the generic features library. We study these three stages in order to propose the specifications of a product model. We particularly insist on the library extension.

1. Introduction

Concurrent engineering consists in ratifying design by submitting it to the applications, through a collaboration of all the design and manufacturing process actors (manufacturability analysis, heat or impact resistance ...).

Product modelling consists in storing all data (not only the shape) that could be useful at any stage of the life cycle of a product. All this information should allow to automatically compute application models from the design model and, thus, to validate (or not) the design stage. Hence product modelling appears as an important support for concurrent engineering.

This product information is called features. It is classified in six categories. Our study turns essentially on form features, which describe the shape's local aspects and their semantics (hole, slot ...). In a wider sense, every part's component is often considered as a form feature (box, cylinder, cone ...). The five other categories are precision features (tolerances, surface quality), material features, technological features (texture, threading, knurling), assembly features and administrative features. However, the trend is to consider all constrained objects as a feature.

We have studied (Gardan *et al.*, 1996) a number of reference papers on product modelling : Chen *et al.* (1991), Duan *et al.* (1993), Laakko *et al.* (1993), De Martino *et al.* (1994), Roy *et al.* (1988), Salomons *et al.* (1994), Shah *et al.* (1988), Sheu *et al.* (1993). We have first stated that they all use, at different levels, the multi-model notion. On one hand, there is a design model and several application models and on the other

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hand, in the design model itself, several models are managed simultaneously. We have also listed a number of unsolved or badly resolved problems. We have classified them into three categories : use of features in the design step, automatic computation of application models (mapping) and extension by the end user of the features library.

2. Use of features

During the design stage, the user describes his/her design model using the features provided by the software. These features are supposed to be stored in a generic features library (described in section 4).

The use of features generates four kinds of difficulties : problems related to the **instanciation** of a feature, the **modification or destruction** of instanced features, their **consultation** and their **management** in an environment that also offers traditional operations. We develop these points in the following paragraphs.

The *instanciation* has to :

- allow the user to choose a feature, to set the dimensions, position and orientation parameters or, on the contrary, to abstain from it : some choices are so put off. Parameters can be explicit values (keyboard, mouse, default values ...) or linked to other quantities by constraints. The constraints are given by the user (e.g. the diameter of the hole to be created equals twice the width of a given slot) or enforced at the generic level (e.g. the hole's diameter is always greater than a given proportion of the depth).

We have distinguished two kinds of constraints : declarative constraints and procedural constraints. The *first* ones are equations involving some object's parameters (diameter, height ...) or quantities depending on this parameters (volume, flow, distance ...). They are solved by a solver. However, for more efficiency, predefined functions can be used to solve some particular constraints combinations. In a dialogue phase, their acquisition is made by the way of grapho-numerical expressions, which mix numeric operators, parameters and graphical objects (this radius equals twice that object's width) as described in Gardan *et al.* (1995). *Procedural* constraints are algorithms translating statements such as : the boring height (supposed to be orthogonal to the starting face) is the distance between the starting face and the first plane face parallel to it and on which the hole comes entirely out, see Gardan *et al.* (1996) ;

- run the functions, among those which constitute the feature's behaviour, that check the feature's validity. For instance, a slot is not valid if its width is superior to the width of the object. In that case, the width must be corrected or the slot changed into another feature, for example a step. So rules must be associated to the slot : they determine the new width in the first case and give the derived feature with its dimensions, position and orientation, in the second case (those of the step in our example) ;

- record the intanciated feature in an appropriate structure, so that it remains accessible. It will then be possible to modify it or to use it in order to support new objects. The structure must also store constraints which link the feature with other entities ; the repercussions of a value modification can so be managed. This management can be parametric or variational.

The feature's *modification / destruction* and its *consultation* raise the same problems as the instanciation so the solutions are the same (solver, constraints manager). The two main difficulties are, on one hand, the temporary or definitive unavailability of reference data and on the other hand, the presence of procedural constraints. We study the possibility of transforming procedural constraints into declarative constraints, during their process by a variational constraints manager.

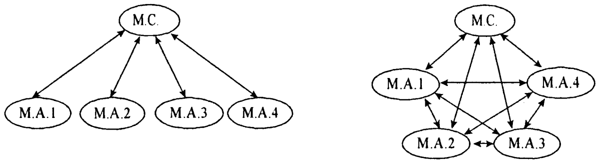
As features interfere with a *traditional CAD environment*, a third category of complications appears. Some of them are listed below :

- apparition of a feature without any explicit instanciation. This can happen if a rib is placed on a box : an implicit step appears, which is not known from the system. Many algorithms have been published for the so-called features extraction but none of them is completely reliable ;
- features behaviour in boolean operations (is it possible to foresee the features that will appear if features of the combined objects are known ?) ;
- incoherence of semantics and geometry of a feature (a through hole which is partially filled up by another part, remains a through hole) (Gardan *et al.*, 1996).

3. Mapping of the design model into application models

The design model is the virtual model provided by the design stage. In addition to *instanciated* features (that is the structure quoted in the previous section), it contains a complete chronological design history and, more generally, all constraints which link the final part components. We recall that the automatic computation of application models from the design model (for instance the machining manufacturing model, with raw stock calculus, operations scheduling, necessary tools, cuts number, access and work trajectories) is a way to check the design validity and a useful tool for concurrent engineering. Nevertheless, these transformations can't be permanently performed because they are costly and not completely solved. Moreover, at some stages of the design, the part might not be valid and, so, not "mappable". Thus, mapping should happen only on the designer's request or at some key moments determined by predefined rules.

When an application model is modified, an analogue update must be performed on all other models, to keep them consistent. A hierarchical structure of the models, with the design model at the root, seems suitable for this purpose because all the applications can communicate through the design model ; Only communication protocols between the design model and application models are necessary. A network arrangement is not fully adapted because it increases the number of interfaces and their management (figure 1).



Interfaces number (IN) = 2 * application models number (AMN)

too many interfaces
IN = AMN (AMN - 1)

Figure 1 : Interfaces between different models.

The explicit knowledge of features that are instanced in the part is an advantage for the mapping of the design model into application models. Let us consider, for instance, a material removal manufacturing process : form features directly suggest part of the machining process (motion, speeds and scheduling planning), tolerance and material features make the choice of tools and cuts number easier. Another example is given by analysis, where it is very important to simplify the object to be meshed : the knowledge of features and their dimensions gives a way to know whether these features are large or small with respect to the part and consequently if they must be neglected or if the mesh is to be refined near them. In this context, semantics of features can also be used in another purpose : for instance, a rib makes the part more rigid.

4. New generic features creation

The CAD/CAM system can't be expected to provide the designer with all the features of his speciality. Hence, it should be able to integrate new ones the designer could use as often as necessary.

If you expect the user generic features to be as usable as the predefined generic features, they should have the same structure (data and behaviour) ; instanciation procedures (feature choice, dimensions/orientation/position parameters valuation), consultation and modification procedures will then be the same for all features. This also generates the major following problem : a non computer scientist operator should be able to achieve a software development without programming knowledge, which is theoretically the job of a computer scientist as the behaviour must be described by algorithms (shape generation, validity checking ...).

You are then faced to two types of problems : description of the feature (parameters - names, nature, default values ... - and behaviour algorithms) and its integration in the software.

4.1. DESCRIPTION OF THE NEW GENERIC FEATURE

We have underlined that user defined-features should have the same structure as predefined ones. A normalization of the six features categories formats is then essential because the user can be precisely guided in the stages of the description of a new feature : the skeleton of the feature can be automatically generated and the user just have to complete it.

The user should also be able to reuse parts of predefined features ; a hierarchical organization of the library, combined with an object oriented approach, is then particularly useful. When the created feature is a particularization of another feature, as the dovetail is for the classical slot, it seems obvious that inheritance and overloading mechanisms make things easier : the inheritance mechanism automatically gives the dovetail the slot's behaviour ; the overloading mechanism offers the possibility to adapt part of this behaviour. This confirms the interest of an object oriented approach in the library structuration.

Any non computer scientist should be able to access the language used for the behaviour description. We consider it as a superset of the CAD/CAM system development language because it provides the end-user with the same tools but it integrates them in a more adaptable environment. For instance, it could give access to algorithmic tools to review all faces of an object or all edges of a face. Nevertheless, hoping to give a non computer scientist the means to describe whatever process it may be, seems to be very ambitious. A computer scientist intervention remains undoubtedly necessary, except for the shape description of a *form* feature. In this case, the CAD environment interactivity can be exploited and takes the place of the development language (see paragraph 4.3).

4.2. INTEGRATION OF A NEW GENERIC FEATURE IN THE LIBRARY

We have supposed that there exists a library of generic features which can be instanciated on designer's request. Its existence needn't be justified : these features have to be stored in one way or another. The discussion rather turns on the way to do it. Two trends can be considered : the library is either a set of functions compiled and linked with the code (it's a part of the program) or an extern data base.

In the first case, the feature's instanciation involves some functions calls that check the validity of the feature or compute its exact shape, etc. If the library is an extern database, the instanciation requires the execution of non compiled functions, leading to the necessity of an interpreter. From a performance viewpoint, the first approach is better.

The new feature integration doesn't cause any particular problem if the library is a database : one just has to add an element. On the contrary, if the library is integrated in the software as a list of compiled objects, the integration implies the following stages : behaviour translation in a programming language (for example C++), compiling (insignificant because of separate compiling) and linking (insignificant because of incremental linking). Because of the first stage, the user has to wait a moment ; so this looks as an argument for the database organisation. In reality, the translation time shouldn't be taken into account because it happens in the database organisation too, as rules have to be interpreted at the instanciation time : the wait is just displaced at another moment. So finally, this argument doesn't plead on a database behalf, it even upholds the first approach as we have to wait at each instanciation of the feature, with the interpreted structure. For these reasons, we choose the first of the two proposed organisations.

4.3. SHAPE DESCRIPTION OF A FORM FEATURE

Form features are shape modifications on the boundary of an object. At the generic level, they are parametrized with their dimensions, position and orientation. There are several ways to model the shape of a generic feature. We shall illustrate this with the slot.

One method is to store a volume corresponding *exactly* to the amount of material to be added or removed : for a slot, the volume is a box, whose parameters are length, width and depth. This technique has several drawbacks. First, it is not easy for the user to compute the values of the parameters as they are not always available. For instance, the bottom face of the slot might be defined with respect to a face that is not the face that carries the slot : thus, the height can't be easily deduced (figure 2.a). The parameters also have constant values ; this forbids a tilted slot, whose height varies (figure 2.b).

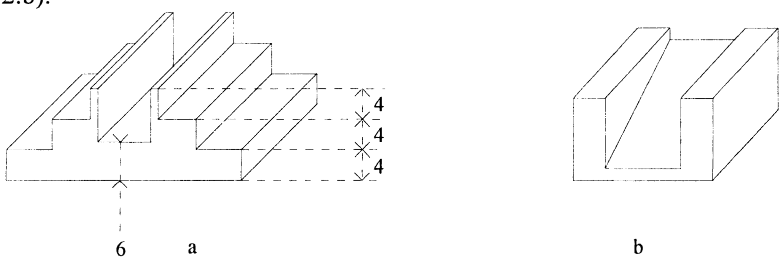


Figure 2 : Drawbacks of exact feature's shape representation.

More generally, it seems difficult to have a shape whose geometry and topology are general enough to represent any kind of slot. For example, the shape of a three faces slot cannot be described precisely in all cases, because its faces highly depend on the object carrying it, as shown in figure 3.

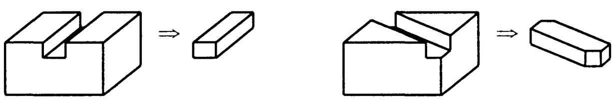


Figure 3 : The feature's shape depends on the main object.

Another solution to model the shape of generic form features is to initialize non significant parameters to "exaggerated" values, to notify that they must just be large enough to "reach" the material or the outside. This is the case of the length and the height of the slot. In fact, it seems even more adapted not to parametrize these quantities, as their values are not really useful.

So, we finally choose to model generic form features as half-spaces which will generate, after dimensioning and boolean operation, the instanciated feature. For instance, a blind cylindrical boring is represented with a cylindrical surface, limited on one side by a disc (representing the hole's bottom) and infinite on the other side. Whatever the aspect and orientation of the volume to be bored may be, this technique allows to realise the instanciation by a boolean operation. It also has an interesting behaviour : the feature automatically extends up to the faces where it is supposed to end (if it adds or subtracts material).

Thus, the description of a generic feature shape by a surface instead of an overdimensionned volume has another advantage : it reduces the number of parameters. This seems logical since, on an overdimensionned volume, some regions with no active roles must be specified and then parametrized. For the slot, only one dimension parameter, the width, remains necessary.

The method we propose to define new generic form features, takes these remarks into account and consists in three steps :

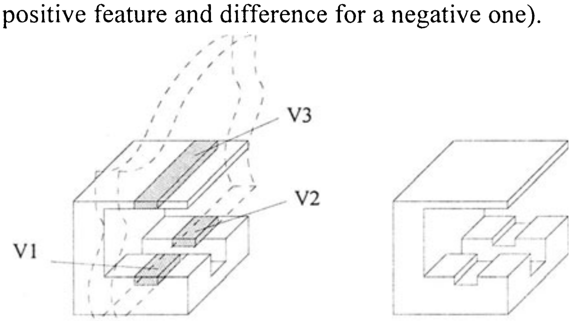
- definition, at the generic level, of the surface which carries the feature's skin : the surface will be called the feature generating surface ; it extends infinitely in some directions (see figure 4). A number of description methods will be detailed in the following ;

pocket: infinite surface in one direction slot : infinite in two directions

Figure 4 : Generating surfaces of a pocket and a slot.

- at the instanciation stage, as the generating surface extends infinitely in several directions, it might happen that it interferes many times with the object, whereas only some of these interferences correspond to the instance. A first boolean operation is then performed, between the half-space limited by the surface and the main volume. The operation is an intersection in the case of a negative feature (half-space $\cap$ main object) and a difference in the case of a positive one (half-space – main object). Many volumes could result from this boolean operation ; the choice of the volumes that correspond to the instance may be directed by the user or automatic, if some rules are written for that (see Chen and Hoffmann, 1995, for proposals in that field). Note that there might be more than one *useful volume* : if a slot crosses another deeper slot, then there will be two useful volumes (figure 5.a) ;

- second boolean operation : once the feature's useful volumes are known, one only has to make a boolean operation between these useful volumes and the main object to perform the instanciation (figure 5.b) ; the operation's nature depends on the feature type (union for a positive feature and difference for a negative one).



a b

Figure 5 : The two main stages of the instanciation

We state now the methods chosen for the interactive description of the generating surface.

The first one applies to features which could be represented by sweeping : the generating surface is then described as a sweeping of an opened or closed 2D section, along a finite or infinite trajectory. This method is similar to the one described by Duan *et al*. (1993) and has the advantage to apply to many usual features (U-slot, T-slot, V-slot, dovetail, hole, step, pocket, round, fillet, chamfer ...).

Tools for volumes manipulation are often easier to use than those dedicated to surfaces. That is why we emphasize a second method, which consists in using volumes instead of surfaces to describe the generating surface. We think that this technique is more intuitive than any other one when the shape of the surface can not be easily described by a sweeping operation. The principle is to construct a volume corresponding to the feature's shape and to remove some of its faces. When a face is removed, its adjacent faces are extended as much as possible along the surfaces that carry them, until they cross another face or infinitely if this doesn't happen. For example, let us assume that we want to define the shape of a pocket with a rectangular section. The corresponding volume is a parallelepiped, but to extend the pocket upwards (where it comes out the support), the top face is deleted. We then obtain the first half-space of figure 4. To get the second one, we just have to remove two other opposite faces.

Both proposed methods suggest a B-Rep modelling of the generating surface. A CSG tree is however not excluded because it is possible to integrate a volume obtained by an outline sweeping in a CSG tree (Minich, 1991) (method 1) and to express a convex or concave volume as a half-spaces combination (method 2).

5. Implementation

We want the feature based modeller that was partly specified above (the whole specification is given in Gardan, Minich and Poinsignon, 1996) to become a real server for our laboratory's project (REGAIN). Before starting the integration of the different functionalities in REGAIN, we have developed a first software (Gardan *et al*., 1995) to validate some ideas. This software is a CAD system for the design of 3D objects with features. The functionalities are :

- creation of a 2D outline with automatic detection of geometric constraints (parallelism, perpendicularity, tangency, intersection ...) ;
- constraints adding and their variational management. The added constraints are grapho-numerical expressions but might be of any kind ;
- outline sweeping ;
- user-friendly insertion of form features on the swept object (round, fillet, slot, rib, step, cylindrical hole, boss, parallelepipedic hole and protrusion).

The instanciation methods include the parameters acquisition (for positioning and dimensioning) in a user-friendly manner due to the use of rubber banding behaviour.

This first software is operational and confirms the validity of the concepts which it implements. We are now developing the full modeller.

6. Conclusion

We have proposed in this paper solutions to several problems which appear to be essential to reach real product models. This approach was validated by the development of a software that implements some of the ideas given in the previous sections. However, the development of a complete modeller requires very important programming efforts. It is in progress in the frame of the laboratory's project (REGAIN).

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TOWARDS DECLARATIVE GEOMETRIC MODELLING IN MECHANICS

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Abstract. Present day modelling systems constrain the designer to describe the studied object by means of lists of coordinates, values or geometric primitives which are often complex and tedious to create. Declarative modelling allows us to create shapes by only providing a set a geometric, topological or physical properties. The computer explores the universe of potential shapes, selecting those corresponding to the given definition. Using suitable tools, the designer chooses one or several shapes. An example of curve modelling using declarative mechanisms is detailed.

1. Introduction

Current application packages frequently make extensive use of geometric modellers and image synthesis techniques. There exist powerful algorithms for visualising highly realistic scenes. All available geometric modellers make it possible to construct complex shapes. Nevertheless, these modellers constrain the designer to describe the studied object by means of lists of coordinates, values or geometric primitives, which are often complex and tedious to create. Their role is limited to converting the data defining the already designed object into an internal numerical model. We call this way of working *imperative modelling*.

In our opinion, research must now focus on the development of modellers allowing us to describe objects using more abstract notions, based on properties and constraints. This is why we have introduced the concept of *declarative modelling* ([LMM90], [Luc91]. The goal is to permit the creation of objects by only providing a set of abstract specifications, generally based on geometric, topological or physical properties. The role of the computer is to explore the universe of potential shapes to select those corresponding to the given definition. Using suitable tools, the designer chooses one or several shapes meeting his/her requirements.

The general notions exposed above have been tested through numerous studies which have led to an improved analysis of the mechanisms and the underlying difficulties of such an approach [Des95]. Promising results have been obtained.

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essentially in the field of polyhedra, imaginary landscapes or architecture ([MaM93], [CMM94]). We should note that programming under constraints and parameterisation ([HoP95, BFH95, WeV95]) are approaches partly pertaining to the declarative modelling process and that their associated techniques must be included in a declarative modeller.

Our objective is now to apply the knowledge we gained in other fields to the field of mechanics. Designing a component in mechanics is a complex task. Numerous professions must be taken into account, leading to the notions of integrated or concurrent design. So, at least for the time being, we intend to restrict ourselves to declarative geometric modelling in mechanics. In the next paragraph, we present the steps of a declarative design process. A preliminary attempt at B-splines curve modelling (detailed in [Dan95]) is proposed in paragraph 3.

2. Principles of declarative modelling

Geometric declarative modelling consists in expressing the desired properties of the object. The modeller is in charge of computing all the numerical values leading to the definition of the object, for example the control points for curves and surfaces. The properties to be satisfied for an object are geometric or correspond to functional constraints. In order to describe, construct, and study the objects pertaining to the universes of shapes, one must have available the tools for description, generation and understanding. An overview of declarative modellers and its associated bibliography is proposed in the report [Des95].

2.1 DESCRIPTION TOOLS

The basic idea consists in using a set of necessary and sufficient conditions to describe a set of objects completely. The main difficulty is to determine whether a precise vocabulary is associated with a given field. Specific vocabularies are shared by different applications (absolute or relative location (object, observer), division of space (in 2 or 3 dimensions), ...). Descriptions can be entered in literal form (with key-words, sentences in pseudo-natural language), drawings or graphical inputs.

We can point out that stating properties does not exclude the need for very accurate modifications. Moving points directly, and thus their coordinates seems unavoidable. Experience tells us that it may be more difficult to apply an accurate modification by giving a set of properties than operate directly on point coordinates (using a more or less automatic process). Declarative modelling must then be considered as a *powerful tool for rough draft realization,* obtained from the given properties. These drafts can evidently be the inputs of classical modellers which then appear as complementary to declarative modellers, the user getting rid of the most tedious part of the design.

2.2 GENERATION TECHNIQUES

A problem solved through a declarative approach can have no solution, one solution, several or even an infinite number of solutions. The main problem is to transform the formal model into the geometric model. Algorithms specific to the given object, random sampling (which requires a parameterisation of the objects) or methods allowing an accurate control on the produced solutions can be applied. There exist two different approaches: a generation in **exploration mode** which consists in computing all the solutions or a set of them, and a generation in **sampling mode** which provides one solution which can be modified by the designer. The latter can call for another one. For finite universes, exploration trees are constructed. A structure is thus given to the universe to be explored. Defining a cutting mechanism makes it possible for a partial discovery of the universe by cutting uninteresting branches. For infinite universes, a total tree is not available. Construction trees (or deduction trees) can be introduced. The modelling of abstract properties means defining constructive or destructive rules. An inference engine producing new facts from initial ones and from the rule base makes it possible to scan the objects of the universe.

It seems that most of the problems encountered in the field of mechanics can be better studied with the sampling mode. This does not mean that several solutions cannot be obtained, which is necessary for a creative design. The declarative modeller must propose, on request, new solutions taking into account initial properties and additional constraints that may be added by the designer.

2.3 UNDERSTANDING TOOLS

Declarative modelling requires mechanisms for a quick understanding of created objects. This leads us to develop visualisation techniques making the most of the known properties of the system. Different visualisations must be available (wire frame, removal of hidden parts, transparencies). All the object components, a part of them, or even a skeleton, will be shown. These different modes can simultaneously appear on the same image.

The possiblity of exploring a large number of potential solutions visually guarantees the success of systems in the exploration of universes. Mechanisms for browsing through sets of solutions are absolutely necessary. This is the reason why we studied and implemented a manager of multiple views which allows the user to define pages made of sets of rectangular views. The layout, the binding with modules and the display ordering are controled in a declarative way. This is achieved by means of a vocabulary for describing absolute or relative locations (for page layout) and order of appearance of information for each group of views (to browse through the set of solutions). A manager of multiple views allows us to create pages, to modify them, and to store them for future uses. What is also particularly valuable is the creation of an interface in all applications that enable the user to consult sets of documents, with a view to compare and select them.

What is more, techniques to select a good view point automatically have also been studied. The underlying idea is that algorithms taking into account given and deduced properties would allow the modeller to automatically select a view point emphasizing such and such a property. Selecting a good view point is based on the notion of observation zones, themselves linked to the property tobe emphasized.

2.4 CONTRIBUTIONS OF DECLARATIVE MODELLING

There are numerous avantages to be derived from the declarative approach. First, of all, it frees the designer from a mathematical technique for modelling by having him describe the results he/her wishes to obtain in a "simple" vocabulary. The description is more or less complete, the software finds automatically the missing information by using default values or exploring the set of solutions. The vocabulary for description can be specific to a given field which provides the opportunity of using the system even to a non-specialist of geometric modelling. Numerous tests can also be easily carried out. Moreover, unexpected but original and interesting solutions can also be computed. The designer's pencil strokes can be translated into properties and modelled with our approach.

The advantages of declarative modelling are not to be found only at the stage of the initial creation of the objet but can also be felt during all the design process. As a matter of fact, it is possible to benefit from the modeller retaining all the knowledge about object properties. We have already introduced the notion of good view point. The automatic lighting of surfaces in order to detect drawbacks could be another application: we can imagine that all the techniques based on light rays automatically choose view points according to the properties and thus the geometry of the object being studied.

3. An example: the declarative modelling of curves

3.1 SEARCH FOR VOCABULARY

The study of vocabulary can be summarized as follows: how to describe a curve without giving a list of coordinates? Various past experiences proved that was possible. This does not mean that a set of words and/or an associated syntax can be easily deduced. The relevant vocabulary can be divided into three categories:

* mathematical vocabulary which is universal and undisputable. Shades of meaning cannot be introduced. *Concave, convex, inflexion, curvature, cups*, ... belong to this category.
* qualitative vocabulary which allows shades of meaning, but is subjective and sometimes differently understood. Words such as *flat, round, slender,* ... belong to this category. The set of words best interpreted by a maximum number of persons must be defined.
* Quantifiers such as as *too much, little, much, more, less very,* ... enrich the

description and allow modifications to occur.

On the other hand, a set of terms allows us to describe the functional constraints to be respected (*reaching, beginning in, ending in, with such a length, surrounding such an area*, ...). The study of vocabulary must be improved, but the principles of declarative modelling can be applied using a minimum vocabulary. Managing a dictionary of synonyms and antonyms is necessary in order to allow each designer to use his own words. Moreover, simply juxtaposing words seems insufficient to describe a curve. Building sentences according to grammar rules must be considered.

3.2 MODELLING TECHNIQUE - PARAMETERS

We chose to study the most frequently encountered curves: the B-splines (described for example in [Far88]). Uniform B-splines of order 4 (cubics) have been selected. The knot vector satisfies the classical multiplicities of extreme knots. It is thus completlely defined when the number of control points (and the order) is chosen. The relationships between a curve and the location of its control points are well mastered for cubics ([StD89], [KaS93]). These curves have many practical advantages (local control, computing time, ...). For creating a curve, we finally have to define the number of control points and their coordinates.

Note. In what follows, we assume that a frame (O,x,y) is associated with our workspace so that it is possible to consider a curve segment (defined by an equation like $y=f(x)$) convex or concave.

3.3 CREATION TECHNIQUES

3.3.1 Bounding box

The first step is to specify the variation domain of control point coordinates. This is defined by a box bounding all the points. The techniques associated with the different cases cannot be described here. We only suggest a general sketch. The box is split into 9 regions TL, T, TR, L,C, R, BL, B, BR (see figure 1). The two extreme points of the curve are put in these regions depending on the required properties. Their coordinates are implicitely provided if conditions are requested (*beginning in, ending in*, ...). If necessary, default values are chosen. The box dimensions follow from the extreme point coordinates and their location in the box.

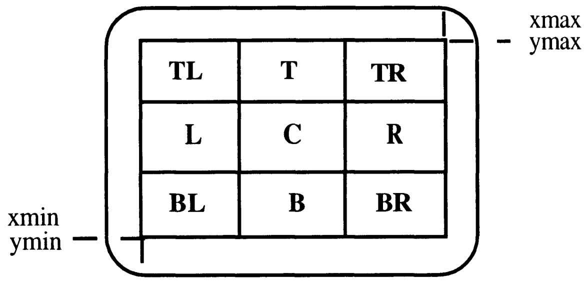


Figure 1. Dividing the bounding box into 9 regions

3.3.2 Number of control points

The higher the number of control points, the more simple the local control of a curve is. Four points are requested to specify a cubic segment. The convexity of the associated control polygon implies the convexity (or concavity) of the corresponding B-spline curve segment. We choose to search within the curve description the number of segments whose curvature sign does not change. We call these segments: simple segments. Each of these segments will be associated to a group of 4 control points. The location of these points depends on the convexity or concavity. Picture 2 illustrates this process for a curve which *at first is concave then convex.* Nothing is said at the moment about the connection of these two segments. If *nc* is the inflexion number, we obtain *(nc+1)* simple segments and *4(nc+1)* points.

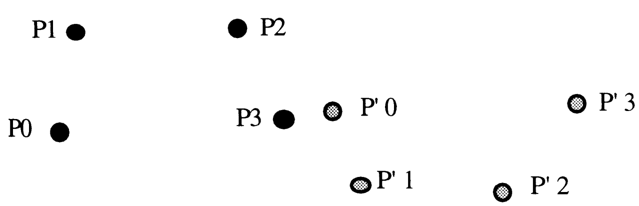
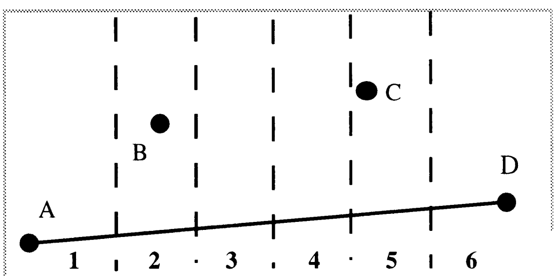


Figure 2. Two groups of control points.

The control polygon of the B-spline is obtained by considering the set of previous points and by merging the extreme points of the simple segments. The chosen number of control points is *(4+ 3nc)*. This construction does not correspond to the definition of *(nc+1)* elementary cubic segments, but to that of *(3nc+1)* elementary cubic segments. It can be demonstrated that the number nc of inflexions is *automatically* respected. Therefore, the creation technique relies on the manipulation and the positioning of groups of four points, two of them being called extreme ones flanking two others called middle ones. These points are not passing points. They only control indirectly the intermediate segments. However, the convex hull property and the local modelling of the B-splines allows us to master the global position of the curve by manipulating these points. This solution needs many points to be defined. If necessary, data reduction could be considered.

3.3.3 Location of control points

The proposed technique deals separately with the abscissa and the ordinates of the points. The abscissa of the extreme control points of simple segments are equally distributed between the two extreme abscissa. The variation of abscissa is therefore monotonic along the curve, this excluding shapes like loops. Then, for each simple segment, we concentrate on the abscissa of the two middle control points B and C located between two extreme points A and D which are already fixed. The interval of abscissa between A and D is divided into 6 areas of equal width. Point B can be located in one of the three areas closest to point A, point C being located in one of the three areas closest to D. The arguments given above are valid for a Bézier cubic and its four control points. It remains valid, although an approximate one, for our process. The relative positions of the abscissa of points A and B on the one hand and C and D on the other hand influence the more or less tight look of the curve segment tips. Therefore, the containing area of the abscissa of points B and C is chosen with respect to the desired properties concerning tensions at extremities, as shown on picture 3. The abscissa of each point is randomly computed within the interval defining each area.



1 loose at the beginning
2 normal at the beginning
3 tight at the beginning
4 loose at the end
5 normal at the end
6 tight at the end

Figure 3. Areas for abscissa location.

The proposed technique for computing the ordinates considers the horizontal line passing through the known point A. The ordinates of points B and C are computed as previously, with respect to the desired convexity. Location of point D is then computed from the ordinate of point C and from the more or less bulging look of the next segment, by reproducing a division process into 6 areas between the horizontal line passing through point C and the limit of the bounding box (see picture 4).

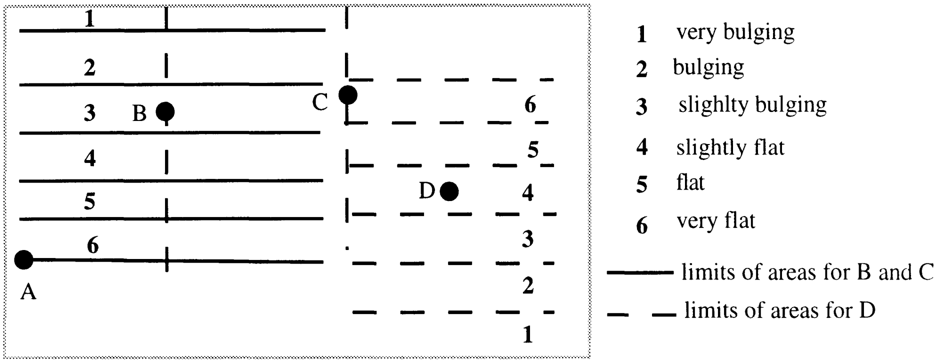


Figure 4. Technique for ordinate location.

3.4 MODIFICATION

Modifications must be possible but, the solutions do not necessarily correspond to the user's wishes. Modifications associated to simple segments or over the whole curve have been implemented. For a simple segment, it is possible to modify the more or less tight look at each end and/or the more or less bulging look. In the first case, quantifiers *more* or *less* allow us to increment or to decrement by one unit the number of the sampling area of the abscissa. In the second case, the location areas of the ordinates are modified, and expressions such as *more and more* and *less and less* allow us to make a 2 area change of the ordinates. For each allowed modification, new values are randomly computed. Modifying the tension of the curve (strain energy) is provided. A curve can be too *tight* or too *loose*, globally or locally. Therefore, one must decrease or increase the strain energy. This is possible a*t the beginning*, *at the end*, *in the middle* or *all along* the curve. We used an optimising process, with proximity constraints, in order to keep the look of the curve.

3.5. RESULTS

We should recall that default values are used when the desired properties do not permit us to obtain a complete definition. Pictures 5.a, 5.b and 5.c illustrate a solution to *a curve*, *a very flat curve* and *a very bulging curve.* Picture 6.a is an example of *a loose curve at the beginning and at the end,* when the example of picture 6.b corresponds to *a tight curve at the beginning and at the end*. Pictures 7.a is a solution to the description: *concave very flat then convex very bulging*. The properties *less flat at the beginning and less bulging at the end* leads to picture 7.b.

In conlusion, one could say that the associated software program can only be considered as a first attempt, making it possible to demonstrate that feasibility is obtainable, but also pointing at the inherent difficulties. One of the main difficulties is to be able to define a set of words and a syntax, allowing the designer to describe a curve. The interface permits the user to obtain easily the properties of the different curve segments, as well as the desired modifications. He/she can control a very partial exploration of the solutions through a new series of random samplings.

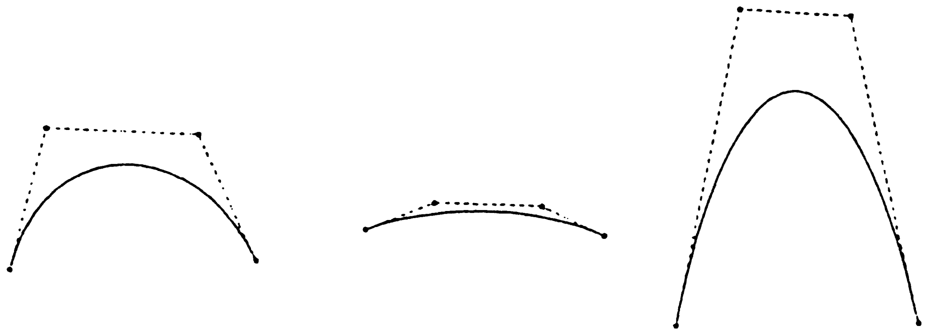
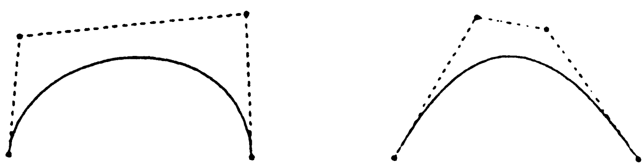
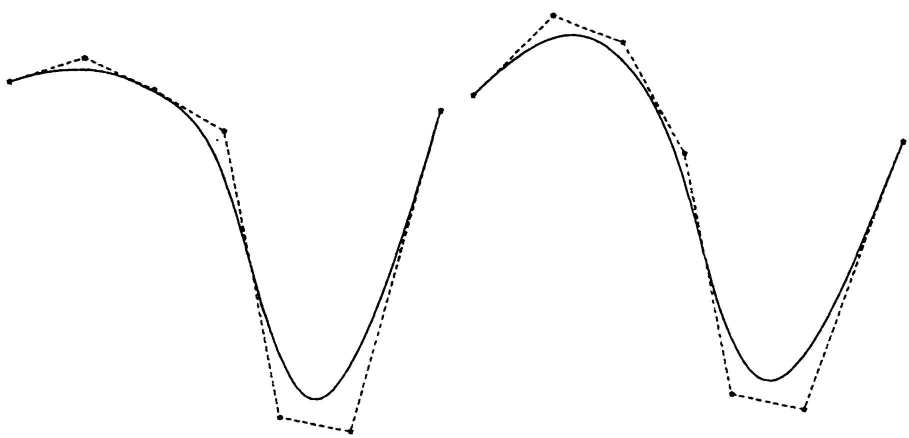


Figure 5. a) a curve b) a very flat curve c) a very bulging curve



a) loose at the beginning and at the end b) tight at the beginning and at the end

Figure 6. Tension effect on a curve



a) initial curve b) less flat at the beginning and less bulging at the end

Figure 7. Modification of a curve

4. Conclusion

The aim of this paper is to draw attention on this new approach in geometric modelling and on the advantages it offers. Numerous modellers, dealing with very different universes of shapes are under development in Nantes (France), within the ExploFormes project. The notion of automatic learning is also being studied. We are considering the domain of geometric modelling in mechanics, which obviously includes modelling of curves and surfaces, enveloppes of numerous objects. We have initiated this work by studying planar curves, and what we offer here is only a first solution which proves the feasibility of the process. However, we realize this is a big challenge, and we hope the present paper gave an insight into what the next generation of geometric modellers could look like.

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MODELING PRODUCT INFORMATION IN CONCURRENT ENGINEERING ENVIRONMENTS

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Abstract

This paper deals with the problem of object description in Concurrent Engineering design of mechanical parts. A model for supporting consistency between different application dependent feature-based representations of an object is presented.

1. Introduction

Markets for consumer goods are characterised nowadays by increasing variety, while the product life-cycle is decreasing at the same time. In facing competition, it is important to optimise performance in delivery and quality (Marcotte et alt. 1992).
The main goal of concurrent engineering (CE) is to reduce product development costs obtained by considering design, installation, organisation and control of the production processes as a whole. In this way all decisions to be taken can be evaluated in consistency with each other during the design phase.
This new paradigm is based on an ideal environment, where engineers from different disciplines work simultaneously on product design. After an initial conceptual model has been defined, several engineers should be able to work at the same time on product definition, altering or adding details to the design and also running application programs (e.g. stress analysis, cost analysis, process planning).
To create such environment, two key points should be recognized:

- the problem of data sharing between the experts involved: all the knowledge related to product development must be stored and made available, but each user should only have access rights to information that is meaningful for his/her specific application. Moreover, data modifications should be handled in a consistent way from the various viewpoints;
- concurrent process management: processes that contribute to product specification and have access to the product database, must be synchronised; modifications should be

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proposed to each of the experts who may be interested in, and then, if accepted, they should be propagated to all the contexts.

The first point is a serious problem, since it involves the definition and modelling of all the knowledge related to the product life cycle, from information strictly related to the object, such as shape and final behaviour, to information more closely related to the enterprise in charge of construction like, for instance, manufacturing processes and tools, materials and other available resources. All these data should be modelled and encoded in a way that renders them usable by the experts involved. This means that each expert should have access to a description of the object in terms of elements that are meaningful for his/her own specific context.

The second point is related to the problem of synchronising access to part description so that analysis can be performed and modificans inserted, since the different actions may influence each other. Good co-ordination is necessary to bring about high-quality product specification in the shortest turnaround. Particular attention should be paid to part model access: it is important to prioritise expert and to define tools for negotiating the modifications to make. This means that the evolving design must be visible globally and its ramifications for any interested team member must be highlighted (Reddy et alt. 1993, Pena and Logcher 1992).

As a consequence, what seems crucial in a concurrent engineering design is complete, high-level definition of the part model and a mechanism supporting inter-process communication.

2. The Product Model

Recently, comprehensive models called *product models* have been widely investigated for representing and supporting all information about the product life-cycle. In this way all the activities involved receive the information they require, redundancy is avoided and post-modification consistency is maintained. Traditional CAD modelers are unsuitable for these ends: the automation of analysis and production processes cannot be directly performed using the geometric description of the parts, since this involves low level entities completely unrelated either to the function the object serves or production operations.

To overcome this limit, the engineering community has adopted *features,* elements that provide a convenient language for describing product parts by associating functional meaning to geometric description. It is now commonly accepted that a product model suitable for running application analysis and simulations should be based on features (Mäntyla 1989, Bronswoort and Jansen 1993, Wilson and Pratt 1988).

The main problem in the definition of features concerns with their dependency on the considered application context, since sets of entities which are meaningful in a certain context may not be so in another one. Thus, the most common definition is the following: a feature is a set of topological entities (faces, edge and vertices) with functional meaning in a certain context (Cugini et alt. 1988), e.g. in the case of machining, features correspond to subsets of the object boundary that can be directly associated to specific machining operation(s) (CAM-I 1986). In general, these context-dependent feature sets are not completely independent, in the sense that features of interest in a specific domain may be partially or fully mappable to features in other domains (Shah 1988). Moreover, the same part may be related to more than one feature. For example, the object depicted in Figure 1 is described in terms of partially overlapping features like slot1 or slot2, which are meaningful in the machining context (figure 1.c) and have some common boundary entities with the T-rib feature, which in turn is meaningful in the assembly context (figure 1.b).

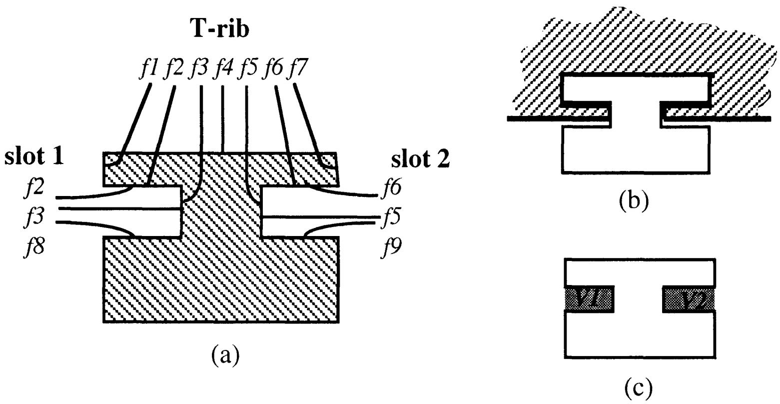
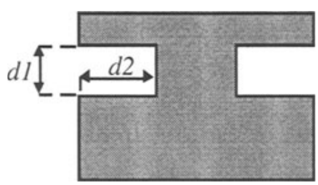


Figure 1. An object and the classification of feature boundary entities (a) according to features meaningful for assembling (b) and for machining operations (c)

The problem with concurrent engineering design is that all the features of interest should be represented at the same time in order to allow each expert to contribute at the right moment to product design, thus requiring all modifications suggested by an expert are immediately transferred to all the others (Le Blanc and Fadel 1993, Prasad et alt. 1993).
As an example, let us consider some modifications that can be performed on the object depicted in Figure 1. Let us suppose that, for economic reasons, the expert in charge of machinability evaluation proposes to modify the dimensions of the two slot features, (Figures 2.b and 2.c). In both cases, the proposed modifications affect the T-rib feature, so they should be validated in the other interested contexts before being accepted. As a matter of fact, assembly analysis would accept only the first solution (2.c), since the other does not fully satisfy functional requirements of assembly.



(a)

Figure 2(a). Parametric description of the slot feature in Fig. 1
-continue-

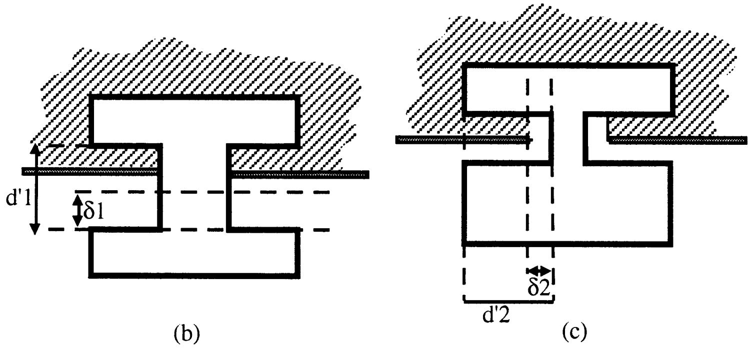


Figure 2 (b). Examples of feature modifications.

3. Feature-based Modeling

In the literature, two main approaches have been considered for creating feature-based representations: *design by features* and *feature recognition.*

The first is a top-down approach: the object is designed directly using featuresso that functional knowledge related to a specific context and strictly associated to the features used can be inserted in the model in design stage. The disadvantage of this approach is that the feature-based description is meaningful only for the context for which it has been created. This means that if a different context is considered, it may be necessary to redesign the object from scratch, using an appropriate set of features (Dixon and Librardi 1990, Ovtcharova and Hassinger 1991). The second approach is bottom-up: all the features are extracted from the geometry, thus permitting consideration ofdifferent viewpoints by changing the recognition rules (Kyprianou 1980, Henderson 1984, De Martino et alt. 1994, Requicha and Vandenbrande 1989, van Houten 1991, Kim and Gossard 1989). Unfortunately, feature recognition is awkward and it is not easy to find an algorithm that can identify all the features of interest.

In a CE design environment, the ideal CAD system should integrate these two approaches for feature-based modelling in order to take advantage of both. The experts should be able to use features in the design phase, while a recognition process should be available in order to support the propagation of modifications from one context to another, this would ensure that all the feature-based representations are updated and consistent (see fig. 3).

In this light, it is important to distinguish between two levels of data representation in collaborative design: the local level and the global level. At local level, all the information related to the specific point of view is represented using the application-dependent language and primitives, including features, parameters and product performance characteristics. In this way, it is possible to simulate and perform the various processes and analyses required by each application involved in the part production directly in the definition phase.

On the other hand, all the data that are common to all the processes and intrinsically related to the object, such as its geometry and constraints, must be available at all times, thus avoiding redundancy and duplication of information. Therefore, it is important to have a data structure that is general enough to be shared between applications, but by the same token is expressive and suitable for maintaining consistency between local models. To these ends we propose a model called Feature Kernel Model (FKM), which structures the common data in a feature-oriented way, thus acting as an effective communication link between context-dependent representations (see Fig.4).

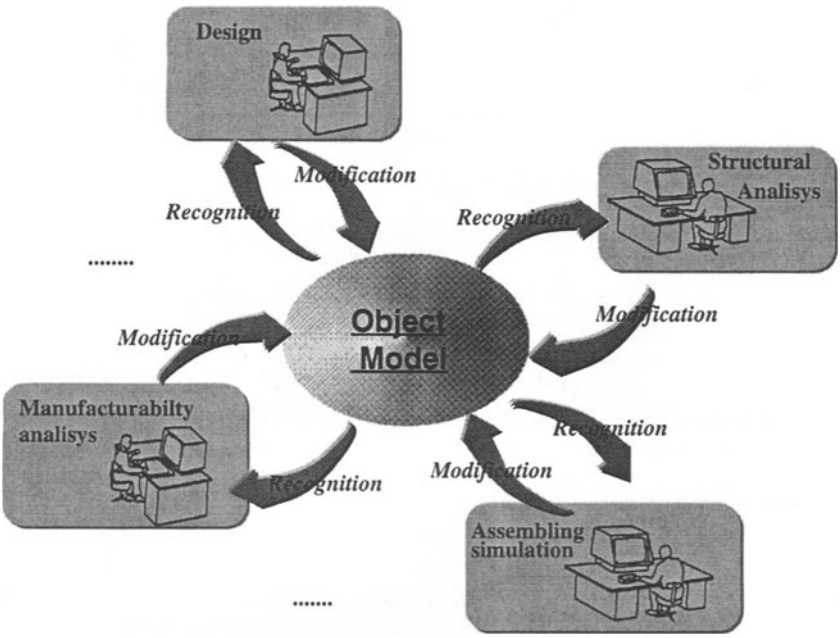


Figure 3. The concurrent engineering design perspective

4. The Feature Kernel Model

The structure of this model is an adjacency graph, where each node corresponds to a set of boundary entities belonging to the same feature. In particular, the entities that correspond to overlapping parts of different features are represented in a separate node. Each arc connecting two nodes represents the adjacency relationship between the corresponding object parts.

All the components in the graph are then labelled, indicating the features, and consequently the applications, where these are meaningful. In this way, each application can derive its specific local model from this neutral and global structure by collecting sets of components. Moreover, when a part needs to be modified in a particular context, all the applications interested in that part can be automatically informed in order to evaluate the proposed variation; if accepted, this can be then propagated in the corresponding local models. The FKM is able to represent features of non-homogeneous dimensions, particularly volume and surface features, but also open face sets (De Martino 1994a).

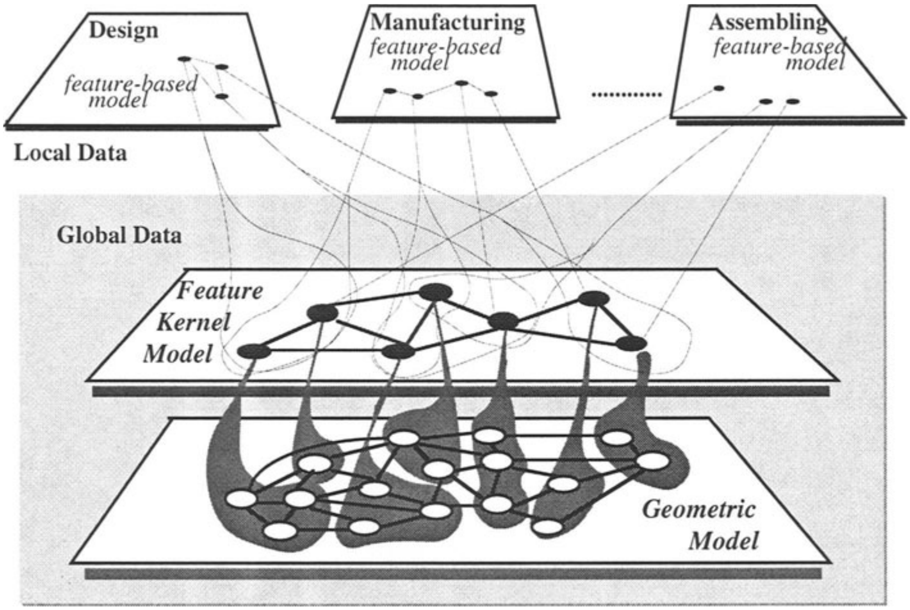


Figure 4. Different levels of data representation: the FKM as the communication link between context-dependent representations.

The main advantage of the model is its dynamic structure, which can be updated by operators that insert or delete a feature. At the same time, they maintain the consistency of model isolating the regions of interest from more than one viewpoint, where conflict exists between different functional interpretations. Moreover, while each application domain maintains visibility of the global model, it only has access rights only to the features that derive from that domain.

5. Implementation

Implementation of the model is currently in progress in C++ language on the top of the non-manifold boundary model provided by ACIS™ geometric modeler toolkit (ACIS 1994). At present the model can be used through two interfaces, as shown in Figure 5. The low-level interface supports operations such as creation, deletion and modification of the model entities, i.e. nodes and links. The high-level interface provides tools to calculate boundary intersections and link directions. Thus, an application can update the model in two ways: using the add feature operation, which calculates all FKM entities necessary for its representation and its connection to all the other adjacent features already present in the model; or by calculating all the necessary information by itself. Since this model has been developed with the aim to be extensible by applications, an attribute handling mechanism is available, which allows each application to define its own set of attributes and attach them to the FKM entities.

The FKM will be integrated in a system that combines different feature modelling techniques (i.e. design by features and automatic feature recognition) that share the same product database (De Martino 1994b).

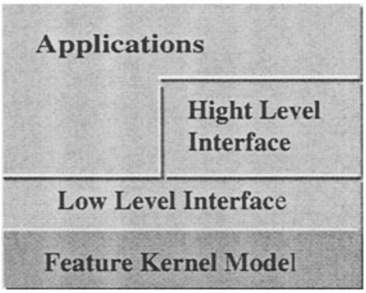


Figure 5. Interfaces provided for communication between an application and the FKM model

6. Conclusions

In this paper the problem of information feedback between different feature-based representations in CE design environment has been outlined.

This is currently handled by using delta files in which the modifications performed in one context are contained, i.e. in a static way. This approach assumes that the different working sessions are performed sequentially: when experts reason about an object they use their own 'instance' of the object representation (including both local and global data). Thus, if the systems allows two users to work simultaneously on the object, two 'instances' of data are activated and two different delta files are obtained. These may contain conflicting modifications that have to be merged and considered, a problem which, as far as we know, has not yet been solved.

The solution proposed in this paper provides a means for dynamic communication between simultaneous activities. It defines an intermediate model layer located between local models and geometric data. It contains built-in associative links between related entities in the various models and contexts, and allows automatic modification in one model to maintain consistency with changes in all the other models. This approach is especially suitable for situations with a shared database, where all the software modules are provided by the same supplier. However, it may also be applied to heterogeneous environments.

Acknowledgements

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INTEGRATION OF DESIGN AND MANUFACTURING DATA MODELS USING STEP

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Abstract

The ISO 10303 (STEP) standard is an international standard that provides a representation and an exchange mechanism for computer-interpretable product information throughout the life cycle of product. STEP has generated much interest from both industrial and academic communities. This paper describes in detail the development of STEP product data models. Firstly, we present the current research works on STEP and, then we describe the STEP product data models and STEP description methods and finally we give examples of using STEP concepts in different mechanical applications.

1. Introduction

During the whole product life cycle, starting with the development and design of the product, process planning, manufacturing and maintenance and support until the product's disposal, "product data" are being processed by various computer systems. The key technology which supports this product data exchange is the use of interfaces. The standard interfaces are classified into the classical interfaces and new generation interfaces. The classical interfaces (IGES, SET, VDA-FS) are the national interfaces. IGES is the norm of ANSI (USA), SET is the norm of AFNOR (FRANCE) and VDA-FS is the norm of DIN (GERMANY). The IGES and SET fulfill the requirements concerning an interface for the exchange of macro-geometric and annotation information. The VDA-FS considers only the surface models. All these classical interfaces can not exchange complete description of a product's shape. Experience accumulated with these interfaces have provided the basis for a new generation of CAD interfaces (IGES version 4, 5.1, CAD*I, PDDI, PDES, STEP). The interface PDDI was the first specification which reflects also the manufacturing technology aspects of a product description. Separate models for the definition of tolerances, form features and organizational data are defined in the PDDI specification.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 445–454.

All actual international developments lead to the interface specification STEP which will reflect all areas of a product's life cycle by defining a number of partial models. The TC184/SC4 of ISO is coordinating the efforts of different institutions and companies from several nations to arrive at one single standard for exchange of product data models called STEP. STEP has used the experiences of all national standards and it has provided the complete model. At the moment some parts of STEP are registered by the ISO (International Standard Organization) as a IS (International Standard). STEP is still under development. The available documents are continuously under review for modification. The STEP documentation is organized into groups, on integrated resources, application protocols, implementation methods and conformance testing. The EXPRESS language is used to describe the integrated resources and application protocols.

1.1 STEP BASED TOOLS

Currently many efforts are under way toward implementing STEP based tools. Urban, Shah *et al.* (1994) have presented an architecture for engineering data management that uses the heterogeneous and active database research and current works on product standards, especially STEP and provides additional extensions to support the modelling of the design process. Blinakov, Shah, et. al., (1995) works on a Design Information System that should support semantic knowledge about the design process and associated product data. P Gu and Kam Chan (1995) have developed a system called GPM based on STEP integrated resources and consists of a generic product model, a product model database, a GPM/AutoSolid interface, a GPM/AutoCAD interface, and a user interface. The models considered in this system are specific and the system seems to be complex to use. We (Ghodous and Vandorpe, 1995) have developed a prototype of a system called SMGS (STEP model Generator System) which provides the experts of applications an interface, to develop their product data models and the corresponding STEP model. The user interface of this system uses the World Wide Web and the Hypertext facilities which provide a better communication with the other models and STEP models. Currently we have added to our system the generic methods for design process (Ghodous and Vandorpe, 1996). Wilson (1994) has provided the complete reference of the tools on the processing of EXPRESS information models and the exchange of STEP physical files.

2. STEP Description Methods

The two most important STEP description methods are EXPRESS language and its graphical subsets EXPRESS-G. The information models in STEP, both in the integrated resources and the Application Protocols are described by EXPRESS (ISO part 11, 1996) (Schenck and Wilson, 1994). This « object flavored » information model is based on the entity-attribute-relationship model with generalization and constraint-specification constructs. It supports a schema concept that is the base of partitioning of each part or section of a part of the STEP standard. Within each schema, the primary focus is on entities which contain attributes for data and behavior. EXPRESS has a graphical form, EXPRESS-G and an instance form, EXPRESS-I. EXPRESS-G supports the notion of schema and at a lower level of abstraction, entity, type, relationship and cardinality concepts. The EXPRESS-G basic notation used in the figures includes: entities (rectangles); supertype/subtype relationships (thick solid lines);

required attributes (normal lines); relationship for optional attributes (dashed lines). Additionally, the direction of an attribute is symbolized by an open circle, where the circle represents the 'many' side of a 'one to many' relationship.

3. STEP Data Models

The architecture of STEP data models is based on three levels of DBMS report of ANSI/SPARC. These three levels are Application Protocols, Integrated Resources and Implementation Methods. The integrated resources level is all the information that is generic and context independent of any applications. The Application Protocol level provides all the information that is relevant to a specific application. The Implementation Methods level enables the implementation of Application Protocols independently of the structure of physical files, data bases, knowledge bases or other implementation methods. This separation enables multiple application views and implementation views to be defined.

The examples of integrated resources data models are geometry, product structure and representation, kinematics, materials and so on. There exist a large number of application protocols under development. The examples are explicit draughting, associative draughting, mechanical design using B-REP, etc. Some of these models are described in the following sections.

3.1 STEP INTEGRATED RESOURCE FOR PRODUCT DATA MODEL

The definition of a product in the STEP product data model is any physical object which is produced by either natural or manufacturing processes. Any part or assembly that contributes to a product is also considered to be a product. A car is a product while its wheels and engine assemblies are considered as other products. Furthermore, each of these products can be further decomposed into smaller components or products. Figure 1 shows a view of STEP product data model. The product model should be able to describe the product during its life-cycle, hence, each version or history of the product can be described and is traceable in the model. The instance of product version entity is used to describe the products at different times. To support the connections between a product and its related information, for example on assembly, tolerance and shape representations, the entities of product definition and product definition relationship are defined. The product relationship can be used to define assembly relationships where the relating product represents the assembly and the related product represents an element of the assembly. Products can also be designated as belonging to specific product categories.

The configuration of relationships between different products (product's structure) does not adequately function as a complete product information. The geometric representation of product is essential for engineering analysis. Figure 2 also shows the relationship between product structure and product shape representations. This view has been extracted from part 41 (product description and support), part 43 (Representation structures) and part 42 (Geometrical and topological representation) of STEP documents. In shape_definition_representation, the relationship between the product and its shape representations is provided. Product_definition_shape is used to identify any instance of product_definition. The representation entity reference, a geometric representation item, which may be a geometric shape model (which includes several types of CAD models). Shape representations can also be organized into relationships with other shapes using the representation relationship. For example, a shaft and a bearing can be geometrically related.

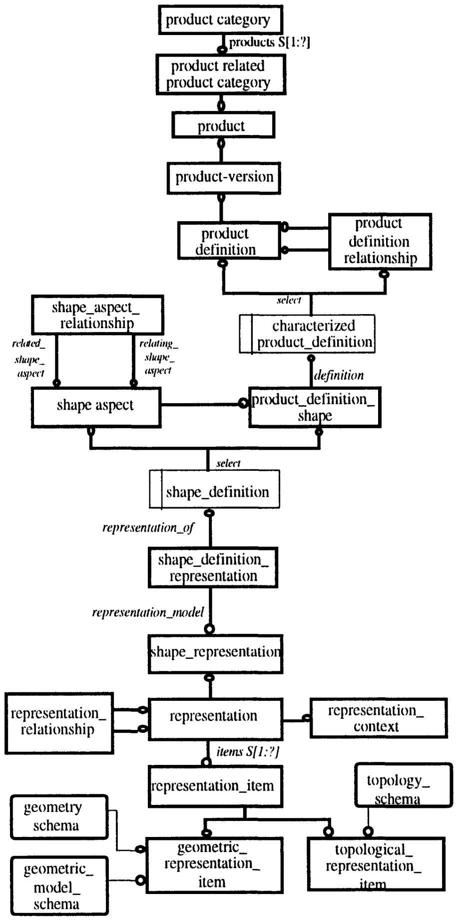

Figure 1. STEP product model

3.2 STEP INTEGRATED RESOURCE FOR GEOMETRY DATA MODEL

To geometrically support the shape representation of a product, the geometry data model is created. This model are classified to geometry, topology and geometric shape models. The geometry model contains the definition of points, vectors, parametric curves and parametric surfaces. The topology model is the definition of the fundamental topological entities such as vertex, edge and face. Each of these entities has a specialized subtype which enables it to be associated with geometry of a point, curve or surface respectively.

There is also ability to collect the basic entities to form more complex topological structures of path, loop and shell and the definition of constraints to ensure the integrity of these structures. For geometric shape models, the CSG, the creation of solid models by sweeping operations, B-rep models, surface models, wireframe models and geometric sets are considered. Figure 2 shows the relations between geometry, topology, geometric model and product structure and representation models.

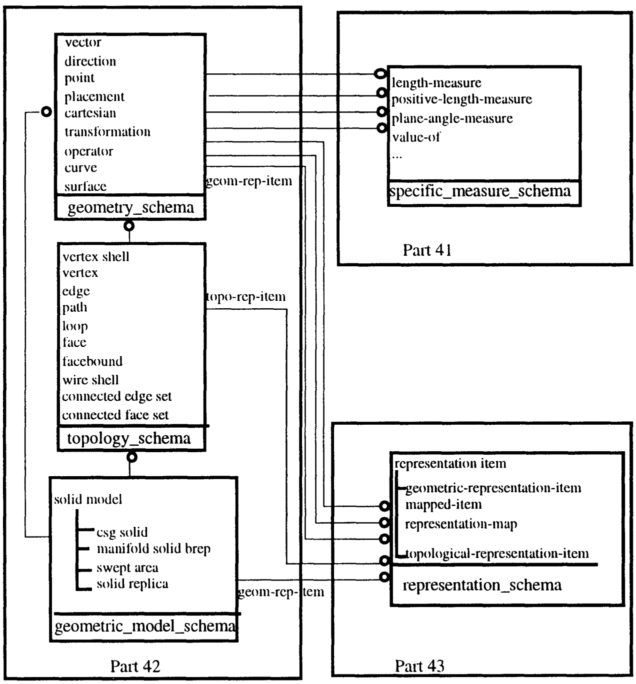

Figure 2. The STEP geometry model and its relations with other STEP parts

There exist other integrated resources model like materials, tolerances, kinematics and so on. Description of all of these integrated resources is not possible in this paper. The interested readers may see the references at the end of this paper.

4. Applications

In this section we describe how we can define our standard product data models using STEP. For this there exist two solutions. The first one is that the standard product data model of our application had defined before as an application protocol. We can just use the application protocol data models and instanciate these models. This is the best solution so it prevents the system vendors to be free to implement non-standardized subsets of the integrated resources, repeating the problems of existing standards (such as IGES). They also provide the comprehensive requirements for implementations, by defining the application domain (or context).

The other solution is in the case that the application protocol of our product has not developed and we want to define a standard data model for our product. For this reason, we use the methodology of application protocol development. This methodology is composed of defining the scope of our application, defining the activity model of our application, defining the data model of our application and then specializing the integrated resources for each construct of the data model.

In the terminology of STEP application protocol development, the activity data model called AAM and it can be formalized with the use of IDEF0 diagrams. The data model of the application called ARM and it can be formalized with NIAM, IDEF1X, EXPRESS-G or EXPRESS representations.

The result of specialization or reusing the integrated resources includes the development of mapping table between the application objects of the ARM and the Integrated Resources, and creation of AIM EXPRESS schema. This process of mapping between the ARM objects and Integrated Resources, is not yet standardized in STEP however, there exist some rules for specialization that you can see in (Huah, 1994), (Grabowski *et al.*, 1994) and (Kramer *et al.*, 1992).

To test and verify the correctness of Application Protocol development, a series of the conformance requirements and test purposes, are derived from the Application Reference Model and Application Interpreted Model. Each implementation of an Application Protocol shall satisfy the conformance criteria.

The AP methodology and the procedures for developing APs are still evolving (Mckay *et al.*, 1994). Currently there exist 19 Application Protocols with an allocated Part number and 20 proposed Application Protocols (Owen, 1993). Before the further expansion of AP methodology and its use for more complex applications, or any new AP projects' initiation, it is necessary to complete and justify the fundamental methods for the APs' development and testing. To be able to properly standardize APs in more complex information domains by the STEP community, stable sets of integrated resource models and adapted framework for planning and implementing the development of APs are indispensable.

4-1 INTEGRATED MODEL FOR FORGED AND MACHINED PARTS

Now, we want to define a standard global view of data model that is not only consider the forged part but also the machined part. This global view is especially interesting for the manufacturers. Normally the manufucturers need to communicate their models and for this reason they want a model which integrates their different point of views. Firstly, we search in the current application protocols related to our application to prevent the redefining the existing models.

Currently there exist a proposal of Application Protocol for Exchange of Design and manufacturing product information for forged parts (Orogo and Radack, 1995). This work is still under development. The first version of application activity data model (AAM) has been developed. The scope of this application protocol includes:

- the characterization of products which are input or output of forging operations, for example the primary stock, preform, near net or net shape part and finished part,

- the characteristics of the distinct products like geometry, tolerances, surface finish, functional requirements, material and inspection and testing results,
- characterization of the forging operations like forging process category, forging sequence, lubrification and forging process parameters,
- tooling and equipment used in forging like die characteristics, including shape, tolerances, and materials and equipment specification.

The application reference model of this application protocol has not finished yet. The first classification of the data models of this application protocol includes:

- the process measurement result
- the process parameter
- the equipment specification
- the tooling description
- the simulation result
- the forging processes,
- the product description
- the finished part description,
- the part inspection specification
- part measurement result
- the forging part and forging process description and
- the customer specification.

Figure 3 shows the partial EXPRESS-G diagram of product description that is defined by (Orogo and Radack, 1995). We have not shown the relationships between other diagrams to product description diagram.This application protocol has not yet developed the AAM model.

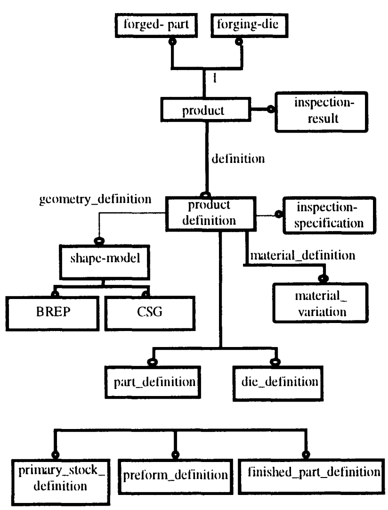

Figure 3. Work draft of ARM diagram of forged product description [Orr95].

We have used the Application Protocol methodology and we have defined the global view of product description of machined parts and forged parts. Since the application protocol of forged parts has not yet developed the STEP standard data model (AAM) we have used our specialization methods for mapping our global views of forged part and machined part to STEP integrated resources. This means that we may access and select the Integrated Resources, introduce the constraints, remove a choice, omit a subtype or supertype of resource entities, define a new subtype of an integrated resource with specific application attributes and drop the optional attributes. The ARM entities from the EXPRESS schema are mapped into AIM entities progressing from the root entities downwards. If any ARM entity does not have an equivalent STEP resource entity, the attributes of the ARM entity should be mapped instead. This process is continued until a complete mapping of the ARM model is achieved. Thus all parts of the ARM model are eventually mapped into STEP resource entities or base type entities. This works has done with help of the STEP Model Generator System (SMGS) that we had developed before for defining the standard product data model of POTAIN industry crane (Ghodous and Vandorpe, 1995). Figure 4 shows the result of this specialization for forged and machined product data model.

The geometry model of parts and tools is based on solid modelling (CSG) and BREP. The CSG model of the forged and machined part is shown in Figure 5.

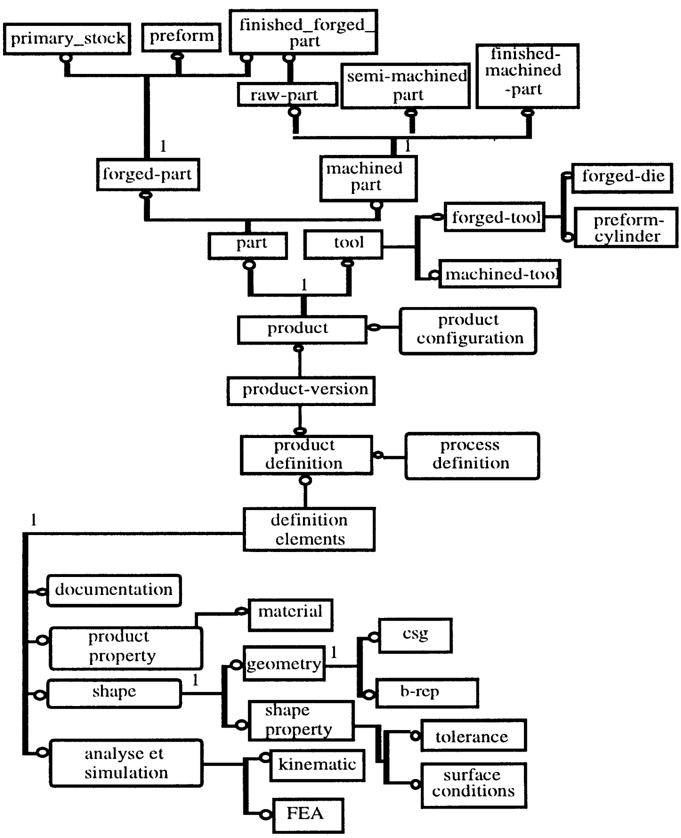

Figure 4. A part of product data model of forged and machined part in EXPRESS-G

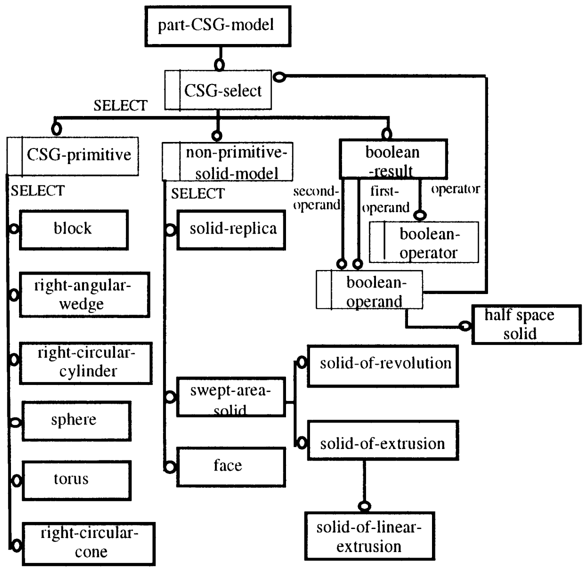

Figure 5. The forged and machined CSG model described in EXPRESS-G

5. Conclusion

In this paper, the state of art of current works in the field of standards has been described. The examples of using STEP have been explained in detail. STEP is the first international standard for representation and exchange of product data models. Therefore using STEP, for defining our standard product data model seems to be necessary. However, the result of modelling using STEP, normally contains an important amount of information and is fairly complex. We can say that the complexity seems to be reduced as familiarity to STEP vocabularies and STEP methodology increases. At this stage, the standard can provide a complete product description. As more parts of the standard become available, the complexity issue will again become a problem. In addition, as the development of product data modelling and analysis advances, it will impose the new requirements and to include new information in the standard. Therefore, the way to manage new parts in the standard, to resolve the interoperability problem and to prevent the redundancy are the important concepts that should not be ignored. The future research must address the inadequacies of the current representations and create models that are able to represent almost all of the different types of provisions in any given standard.

Currently we have tried to define the standard processes on the STEP product data models [Ghodous and Vandorpe, 1996]. We believe that the future standard for product models should not only consider the product data models but also should consider the processes which work on these data models.

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TEMPLATE ARCHITECTURE AND SERVICES FOR INTEGRATING CADCAM AND MACHINING IN SMALL COMPANIES

Architecture réceptacle et services pour l'intégration CFAO-Usinage dans les petites entreprises.

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Abstract : An experimental facility, dedicated to CADCAM, CNC machining and inspection of prototypes and tools has been developed and validated. It calls for communicating workstations and controllers. In order to offer a sound foundation for further productivity inducing services, a global object-oriented approach is developed. It ranges from the machining station level services to the communication services and will result in a complete technical information system.
Keywords : CADCAM, integrated manufacturing, quality control, distributed objects, communication protocols.

Résumé : Une plate-forme expérimentale dédiée à la CFAO, à l'usinage et au contrôle de pièces prototypes et d'outillages a été développée et validée. Elle est basée sur des postes de travail inter-communicants. Pour assurer une base solide au développement ou à l'installation ultérieure d'outils de productivité, une approche "objet" globale est adoptée. Celle-ci concerne aussi bien les services localisés que le service de communication et doit aboutir à un système d'information technique complet.
Mots clés : CFAO, production intégrée, contrôle qualité, objets répartis, protocoles de communication.

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1. Subcontracting precision machining and the new industrial deal

The CIM concept usually suggests large workshops where the essential problems concern automated systems synchronisation and optimised production management. The present work addresses the little automated but strategic activities pertaining to the production of *prototypes* or *manufacturing tools* such as moulds or stamping templates. These are produced in single units or small batches. The shapes to be machined are complex, in that tool trajectories do not restrict to the usual piece wise linear or circular ones. Increasing use of powerful 3D-CADCAM tools has recently caused traditional copying techniques - based on master models - to give way to digital modelling (CADCAM) and to machining on computer controlled machines (CNC), either conventional or using *rapid prototyping* technologies, as described by Bernard (1995).

These activities require high skill and are often subcontracted to small specialised companies. Large companies (automotive and aerospace) urge their subcontracting partners to use compatible CADCAM tools and to work on totally digitised files transmitted through electronic means or DDE [Cha92]). Besides, these powerful clients of SMEs become more and more demanding as regards response times and respect of quality standards.

What is at stake for small companies is to preserve or improve their know-how while keeping up with technological innovation. Browne (1994) and Mory (1995) have given particularly stimulating overviews of the innovation related issues in small and medium enterprises (SMEs). The latter must adapt to a rapidly changing market, where survival may imply offering high quality service to possibly more and more distant clients. In this context, it is crucial for those SMEs who want to go ahead, to know to what extent their existing organisation and equipment (CADCAM and CNC) can be adapted to answer the new requirements, and at what cost.

The need for performance, external opening and reactivity is unanimously recognised. Different answers have been given in various studies, according to different scenarios : complete workshop re-design, down to the detail of machines as implemented at EPFL Lausanne (Decottignie, 1995), or distribution of standardised components in an homogeneous network of design and prototyping sites (Wright, 1994).

The present work is less ambitious and compelling. It proposes moderate cost solutions, appropriate to the case of small companies. The idea is to propose a simple and generic architecture in which functions and services may incrementally be added, so as to bring more performance and process coherence. The relative simplicity of means does not exclude taking into account ideas pertaining to concurrent engineering, to manufacturing oriented design (Gosset 1994) and to the availability of the CIM-OSA's task description standards (AMICE-CIMOSA, 1993), (Foulard, 1994).

In this paper, the main activities to be performed in a CNC manufacturing company will be recalled and the experimental integrated platform will be described. In order to go beyond the early feasibility demonstrations, a methodological approach is being developped . It calls for a common object-oriented approach of all functional elements in the plant (Fofana, 1996), and a high level, multi-interface communication architecture.

2. Needs analysis

Figure 1 is a SADT-like representation showing the interconnection of the main technical functions to be performed in a typical subcontracting company using NC machining.

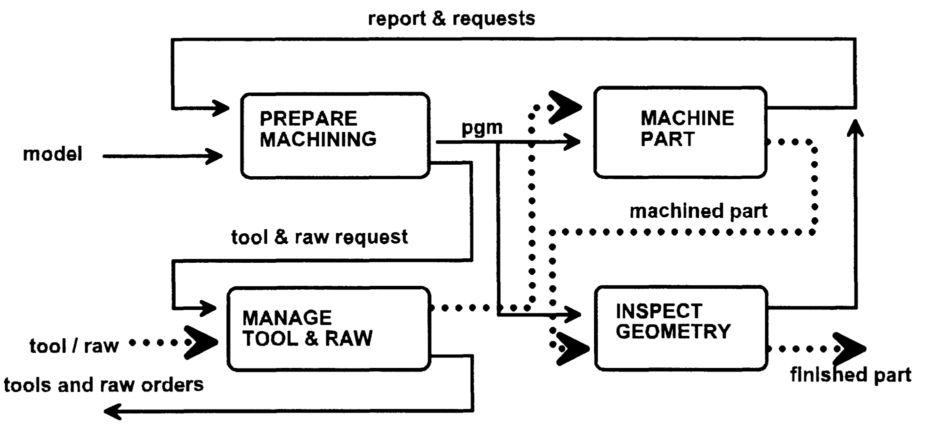


Figure 1. Main technical functions in a CNC plant.

Machining preparation uses CADCAM software packages. Moreover it calls for technical *know-how* and awareness about the available resources. It consists in :

- receiving the project file : transfer, decompression, back-up,
- preliminary analysis of the received CAD data and requirements : choice of material, overall machining parameters, tools and machine-tool,
- geometric analysis, generation of cutter tool paths and machining simulation in order to detect errors,
- post-processing of machining instruction to generate machine-tool programs,
- selection of points and surface patches to be controlled, and generation of sensing sequences,
- possible sequence amendment in case of unsatisfactory inspection results.

Machining data are structured into a process plan, according to accepted standards such as those proposed by the GAMA group (Gama 1990).

Part machining consists in the operator checking in the process plan (or *part machining file*) which comprises one or more G-code programs to be chained, and technical indications about the raw part, its fixtures, the set of cutting tools and various other requirements and advice. The machine-tool operator must then check for the presence and allocation of all required elements. Trajectories, made up of many short interpolation lines, may generate very voluminous (several megabytes) and time consuming (several hours) programs. This justifies studies on high level on line monitoring [Hab95]. Many numerical controllers, not of the latest generation, may fail to reach the required feed-rate due to their limited interpolating power. They may also have insufficient memory capacity and communication opening, even though the machine-tool kinematics may be highly performing [Hyu95].

Geometry inspection of parts ensures the conformance of the finished product. The *co-ordinate measuring* workplace receives an *inspection process plan* or *part inspection file,* comparable to a machining file. According to the requirements, automatic sensing sequences may be started, their results may be locally pre-processed and then up-loaded to the CADCAM workstation for a closer analysis, including visual examination and a possible corrective *feedback* on the machining process.

The raw material and tool management functions must be invoked from the start by the project leader to reserve the necessary resources and arrange for them to be available at the right time. The *cutting tool data base* is updated by the tool operator in the course of his tool management activity. Tool management is non trivial because tools are compound objects, the characteristics of which change with time, due to wear, re-sharpening or re-assembly. Besides, their location may be either in the workshop central store, or in any machine-tool local store, or again in a transient state.

The interconnections in the SADT diagram, clearly show the needs for information exchanges between the workshop components as well as with the external world. Digital data exchange in the considered area is particularly needed, as the parts CAD models and machining programs are very voluminous and stored on very heterogeneous equipment.

3. Communicating workshop implementation

The above mentioned ideas were applied to a demonstration platform at GRPI laboratory and very close to the generic scheme shown on figure 2. CADCAM is performed on IBM-RS6000 workstations, using the Dassault Systemes CATIA package. Connection to the outside world is through a telephone or (preferably) an ISDN line. Access to videotex services, commonly available in France, has proven an effective means of reaching yellow pages, technical databases (like CETIM's, the technical resource centre of the mechanical industries) or commercial ones (like SOUTRAITEL's, a subcontracting market place). However the Internet, as discussed in the last paragraph, offers a more universal and high throughput tool for accessing databases, transferring files and giving one's company a world-wide capability for information diffusion and order taking.

Up to now, effective results obtained at GRPI have essentially concerned the CADCAM-Machining and CADCAM-Inspection links. The small size and simplicity of the plant dispense with performing a pyramidal CIM decomposition, and allow the use of a standard ISO (Ethernet or Token Ring) network for local interconnection. The presence of UNIX based workstations naturally suggested the use of the TCP-IP protocol and services for data exchanges.

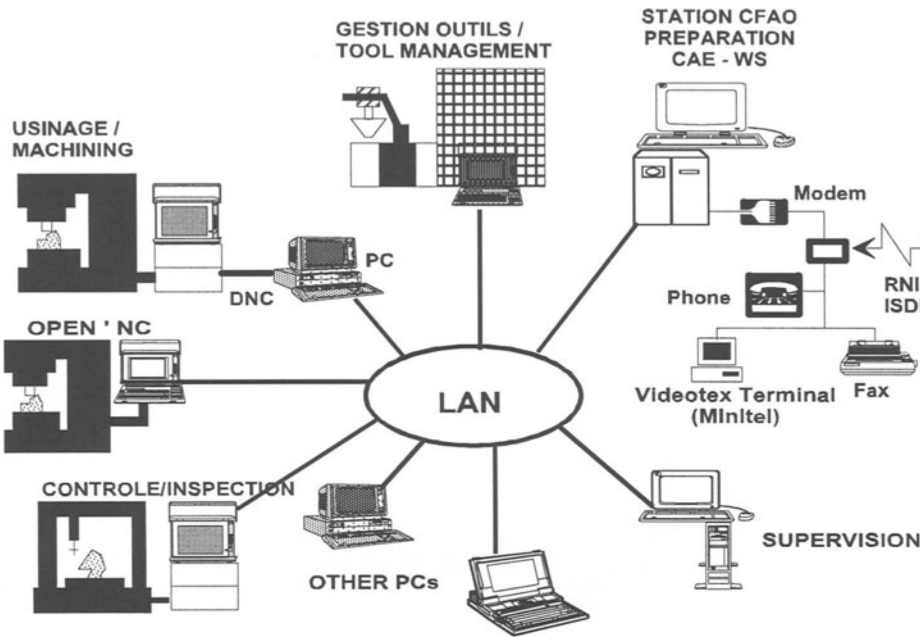


Figure 2. Infrastructure of CNC integrated platform.

For machine-tools having a Direct Numerical Control capability (DNC), a machining cell direct control software was developed (Razafindramary, 1991) ; it comprises all useful functions for performing very voluminous machining programs. For machine-tools with no communication capabilities, an *Open Numerical Control* (Open'NC) concept was specified and implemented (Raddadi, 1992). It is based on an industrial PC computer using standard components : a network adapter for workshop communication, a digital signal processor based unit for rapid multi-axis control, and a remote I/O control card for machine-tool auxiliary functions. This was originally developed through a co-operation with the IBM-France Company. It was presented at Salon de la Productique (Paris, November 1994) and validated by the machining of complex parts.

4. Towards an object-oriented multi-service architecture

While process automation is of little concern in the present context, it is of utmost importance to provide the operators with services and information which will constitute a *Technical Monitoring System* (Fofana, 1995). To this end a global object-oriented approach was decided, thus ensuring a modular, coherent and durable information system.

The technical monitoring system is based on *modules*, as autonomous as possible, which may communicate through appropriate interfaces. Access is thus allowed, at any time, to any information required for taking a decision or performing a particular task. Every module is expected to provide technical assistance to every physical subsystem which constitutes the platform, as indicated in figure 3.

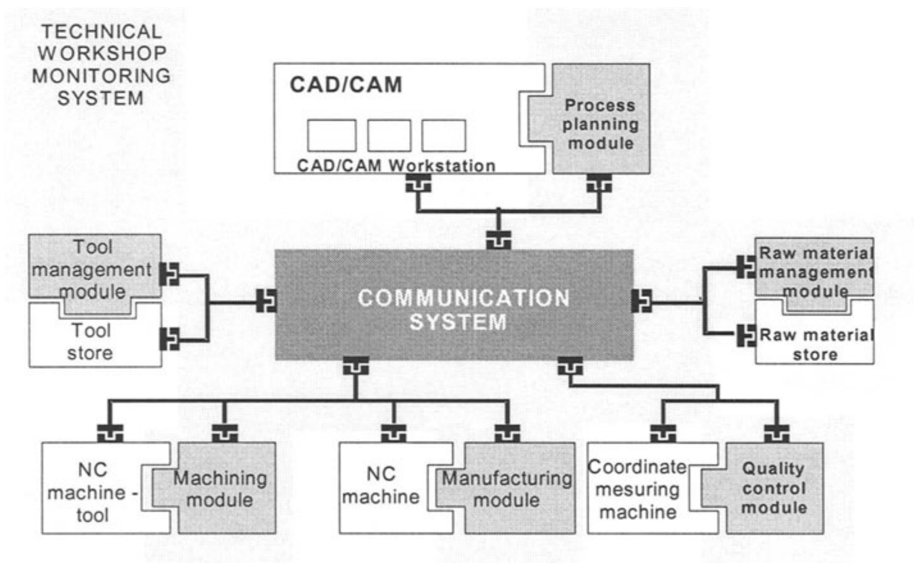
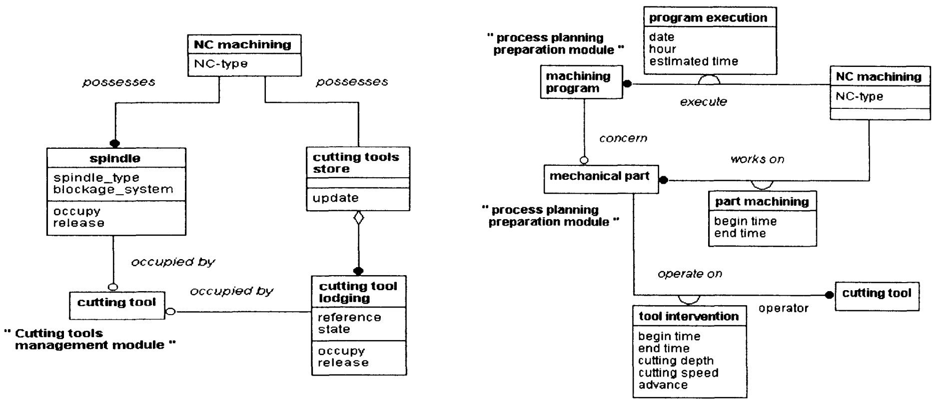


Figure 3. Subsystems and modules of the technical monitoring system.

The object formalism and associated tools were chosen having in mind a rigorous and complete specification, and an easy transition to design and coding. The Object Modelling Technique (OMT) was selected. This method offers a comprehensive set of static, functional and dynamic description levels (Rumbaugh, 1991). Associated software engineering tools are numerous. Among those OMTool (distributed by Verilog), ISF/AD-OMT, designed at Université de Nantes (André, 1995) and BetterState (trade mark of R'Active) were evaluated in the course of this project.

An idea of the formalism for class and link description will be given through two short examples. Figure 4-a displays the links of class *cutter-tool* with the constitutive classes of *NC-machine*. In figure 4-b, information pertaining to the present activity of a tool are grouped in a *tool-operation* class which is attached to the link between the *mechanical-part* class and the *cutter-tool* class. Furthermore, the OMT method allows attaching a state diagram (a statechart, to be more precise) to one class, thus allowing a description of the object response to events. This dynamic aspect is particularly important for modelling such systems as NC controllers, which are characterised by a sophisticated behavioural hierarchy (Raddadi, 1995), (Fofana, 1995, 1996).



(a) (b)

Figure 4. Elements of object-oriented model.

5. Towards a unified communication architecture

The above remarks underline the need of a unifying approach for application communication support. The underlying communication architecture should ease the interoperability of hardware and software heterogeneous components, access to interconnection networks and integration of applications.

At the bottom layer of the CIM hierarchy, the Manufacturing Automation Protocol (MAP) standard protocol stack has been proposed to allow interoperability between heterogeneous programmable industrial devices like machine-tool or robot numerical controllers. MAP essentially relies on a connection oriented ISO profile. The most significant feature in MAP is the Manufacturing Message Specification (MMS) application protocol (Valenzano *et al.*, 1992). MMS is designed to support the interactions between heterogeneous industrial devices. It allows standard definition of abstract virtual manufacturing devices (VMD) in terms of data and services. Remote calls to device services are performed through an encoding/transfer/decoding scheme that uses a unified transfer syntax. From a practical point of view, this leads to an open architecture, independent of the implementation of services in the devices. From a more methodological point of view, MMS is a first step to the object-oriented design of distributed control systems. The promotion of MAP and MMS has lead to important investments both in the USA and Europe. Despite its technical advantages, MMS has not been completely successful. The main objections to the MAP solution are the complexity, poor performances and high cost of ISO protocol stacks. MMS was indeed designed to rely on an ISO protocol stack, however the OSI layering allows to consider MMS by itself, independently of its standard profile.

New market products and emerging requirements from users, providers and integrators assert our previous TCP/IP (Stevens, 1994) based approach. Internet protocols are now widely recognised as the main de facto network standard. Many computers are already sold with TCP/IP included in their standard delivery configuration. Also the world-wide experiment of these protocols in all computer application fields guarantees the durability and efficiency of this network communication protocol. The Internet environment brings interesting tools to CIM applications. Network File System can simplify the downloading/uploading of domains, event recording and file management. File Transfer Protocol or Trivial File Transfer Protocol provide efficient file transfers. Simple Network Management Protocol can help to detect network failures. It is supported by many network device suppliers. The World Wide Web offers a powerful man-machine interface to build simple Intranet tools for supervision and exchange of technical or business information.

As Internet protocols are widespread de facto standards, trying to implement MMS over a TCP/IP stack is a practical and important issue. Three models can be proposed to implement MMS over TCP/IP (Gressier 1996) : MMS ISO over RFC1006 (A), MMS over RPC with ASN1-BER encoding (Lefebvre, 1995) (B), MMS adapted to a distributed object oriented environment. Model (C) extends model (B) : RPCs recall method invocations. The challenge is to develop an original approach that tries to use the best features of the TCP/IP environment and the functional advantages of the MMS standard.

Manufacturing applications use the client/server model. They can be considered as distributed. Distributed Object-Oriented Environments could provide new means to develop co-operation facilities within shop-floor applications. Also, Object-Oriented Technology is suited to the design of industrial applications. It gives a uniform approach to solve the integration of heterogeneous user applications. Future trends in the industrial messaging field will handle the object-oriented approach, thus justifying our modelling choices. The CCE-CNMA Esprit Project (CCE-CNMA 1994) tackled this problem. Solutions that fully preserve the ISO profile need to add an object based interface on top of the MMS layer (Weis, 1996). Alternate TCP/IP based solutions that respect model (C) need to adapt the MMS standard toward an object-oriented structuring. It has been stated that this task is not easy to perform (Clatchey, 1995). Hardware and software heterogeneity are key features of industrial applications. Then, conformance to the OMG/CORBA standard (Siegel, 1996) is mandatory. Preliminary work on a subset of the MMS standard improved our approach with a promising CORBA based prototype (Guyonnet, 1997).

Distributed Object-Oriented middleware environments provide convenient support to hide real resources implementation, the location of production means, and the correspondence between resources and production means. Production objects can be distributed on a software bus and can be handled through supervisory tools. Production objects are reusable. An object oriented software bus approach offers low cost implementations to manage and to control a manufacturing process. It eases the reordering of components to adapt the production mean to changing market demands. Figure 5 gives a general overview of an object oriented TCP/IP based manufacturing process control platform.

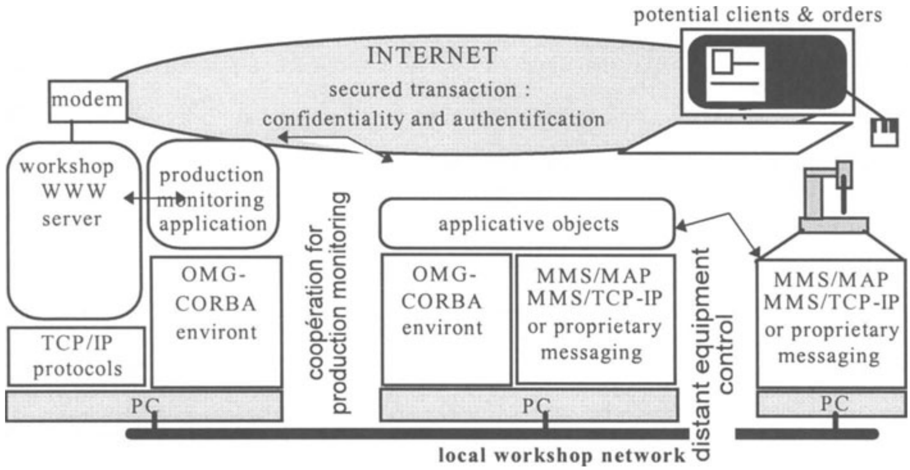


Figure 5. Variants of TCP-IP based communication architecture

6. Conclusion

The platform presented in this paper allows full scale testing of the equipments and services to be implemented, so as to efficiently integrate CADCAM, machining and inspection in the manufacturing parts, particularly those with a complex geometry. A communication architecture based on the widespread TCP-IP protocol and open NC controllers has been developed. A light solution for workshop computer integration is proposed, it consists of a variety of services which will ultimately build a decentralised technical monitoring system. The implementation uses inter-communicating objects. Such an architecture appears as a template allowing well tried solutions to take place, provided they interface with the MMS or OMG/CORBA standards. A homogeneous operator view of the overall system could use a WWW server as a simple and powerful tool. This could also manage outside exchanges and open new frontiers to the concerned SMEs.

The undergoing work has brought together manufacturing and computer specialists. Its aim is to provide small subcontracting companies with tools sufficiently simple and efficient so as to allow them to make the best possible use of their job skills. It is clear however that these companies, faced with the rapid and not always mastered development of computerised exchanges, will have to do efforts and be guided in order to keep up with this new culture.

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MANUFACTURING CAPABILITY MODELLING FOR CONCURRENT PRODUCT DEVELOPMENT

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Abstract

The implementation of Concurrent Engineering (CE) requires a large number of advanced and fully integrated computer aided design and manufacturing tools. Commercially available CAD/CAM systems are mainly designed to solve problems in specific domains and have failed to act as parts of an interacting, dynamic Computer Integrated Manufacturing (CIM) system. Recent research has been focused on design for manufacturing (DEM), design for assembly (DFA), or design for X, where X represents product life cycle activities. In contrast, less effort has been made on the reverse procedure, i.e. manufacturing capability modelling for design (MFD), which is increasingly important to industry. This paper reports the authors' recent work in knowledge based process planning, manufacturing capability modelling and feature based solid modelling. The authors' current research programme is also briefly introduced.

1. Introduction

Concurrent Engineering (CE) has been recognised as the key engineering philosophy of the nineties for lead time compression and manufacturing cost reduction. It requires a large number of advanced computer tools to assist the design and manufacture process [1]. British Aerospace has taken a leading role in exploring the implementation of Concurrent Engineering both as a Human Resources training and organisation issue, and as a technical issue involving a re-evaluation of the Computer Aided Design (CAD) strategy, the Computer Aided Engineering (CAE) strategy and the Computer Integrated Manufacturing (CIM) strategy that are being followed within the manufacturing industry. Cranfield University is one of the company's main academic partners working in this area.

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2. The Limitations to Concurrent Engineering Caused by 2D Drawings

For many years two dimensional engineering drawings have been used to convey geometric information and supporting tolerance, process and material data. This once represented the 'state-of-the-art' in representing three dimensional objects in a two dimensional medium and has been the basis for engineering design and manufacture during that period.

The problems that continued use of this method can bring to a modern engineering operation are far greater than would be immediately apparent. The logistical problems faced by large companies and/or projects have been previously defined [2] and it has been proposed that the radical application of Concurrent Engineering and three dimensional product modelling illustrated in Fig.1 can help to overcome them. There is a common misconception that overlapping the processes described in the diagram by say 10% is concurrent engineering. It is the authors' view than an overlap of something more like 80%-90% is required and that anything less than 30% doesn't deserve to be described as CE at all! The necessity of replacing this outdated approach to engineering has been detailed previously [3] along with the technical issues and the data management implications of undertaking a large product modelling exercise.

3. 3D Geometric Modelling Fails to Integrate Design and Manufacture

The integration of computerised design and manufacturing planning tools is a very significant factor in achieving concurrent engineering but often the commercially available CAD/CAM tools have failed to address the full scope of the integration required by industry as it tries to automate more and more of the engineering activities associated with product introduction [4].

Solid modelling is regarded as the only unambiguous way to represent 3D mechanical parts and assemblies for design, analysis and manufacturing. However, its application has until recently been highly limited for the following reasons [5]:

i) It was highly mathematical in nature and its cumbersome user interface required users to possess an aptitude and complete knowledge of geometric data definition.

ii) Its inflexibility was a major obstacle to its application in an iterative design process.

iii) It did not represent features and technological information such as tolerances, surface finish and engineering characteristics which are essential for design analysis and manufacturing.

iv) Design changes could not be automatically propagated throughout all of the design and manufacturing activities within an organisation without a great deal of manual re-entry and translation of complex data.

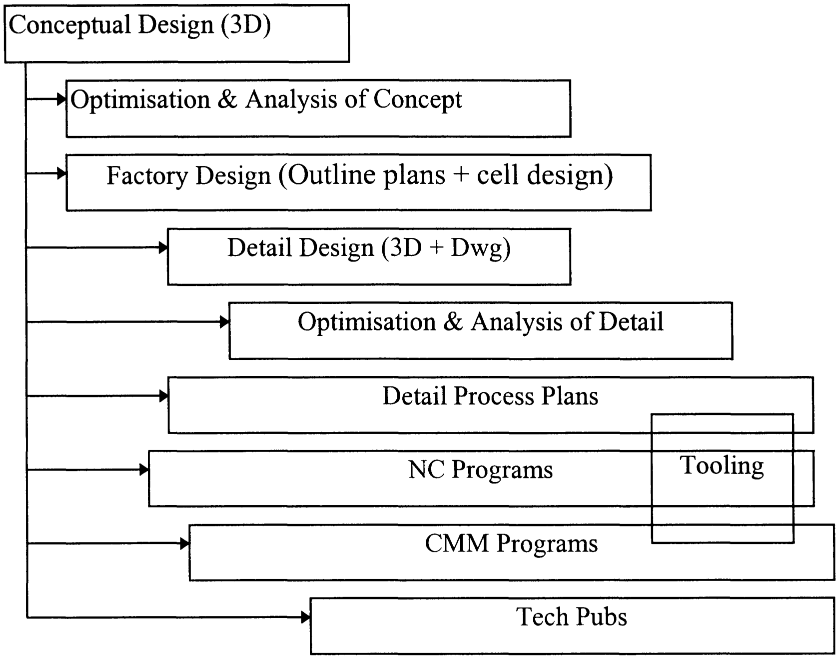

Figure 1 Concurrent Engineering as Applied at British Aerospace

4. Recent Advances in Solid Modelling

In the early 1990's a breakthrough occurred whereby a completely new approach to solid modelling was introduced based on intuitive engineering features and parametric modelling techniques. All the features and dimensions of a part and assembly can be associated. This allows design intent to be encoded to a degree within the model, making modification much easier and efficient. It also raises the possibility of creating relationships between the design and the manufacturing models and therefore making the propagation of design change, throughout the whole enterprise, feasible. Obviously the design change can only be propagated to activities that are driven directly from the product model. In order to achieve a real benefit from the leap forward achieved by the CAD/CAM/CAE tools it is necessary to postulate a model of the product introduction process in which the design model is the master and the other business processes are driven from it. Such a model was first proposed internally within British Aerospace at the end of 1992 and has been further developed through collaborative research to the model illustrated in Fig.2. More strategic development of this model will be required and will continue to define new areas for collaborative research that will be required to allow the application of the product model and associated manufacturing models to other engineering functions not yet served by the model.

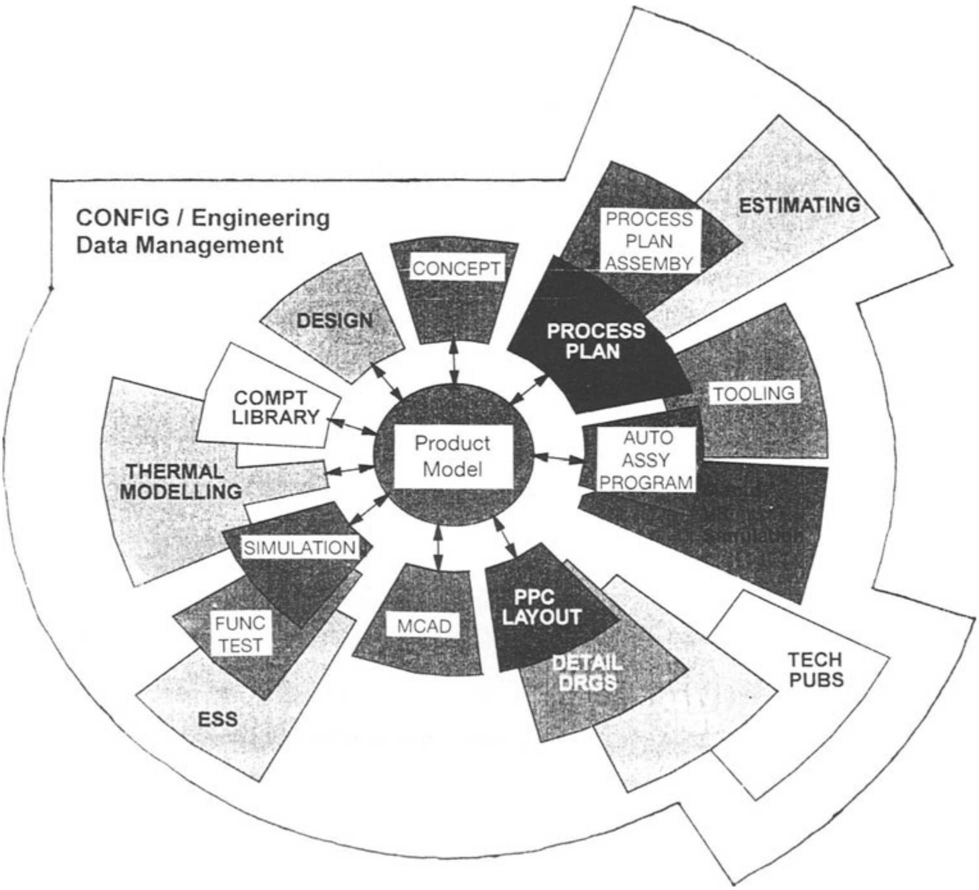

Figure 2 Manufacturing Capability Modelling for Mechanical Parts and Assemblies

5. Business Context for Manufacturing Capability Modelling

It is essential that the implementation of a strategic initiative like Manufacturing Capability Modelling should be driven from the Business Strategy of the organisation and should support the strategic goals of the organisation or it will simply become an expensive exercise in technical innovation but won't yield tangible cash benefits to the company. Figure 3 illustrates the way in which the Business Strategy should drive the systems integration strategy which should in turn determine the CAE policy. Similarly the business goals should drive the technical goals which then determine the requirements for the computer aided design (CAD) system which is then implemented to facilitate Manufacturing Capability Modelling.

The key business drivers that have led to the growth of Manufacturing Capability Modelling have been the need to drive down product introduction lead times, the need to drive down costs to remain globally competitive and the need to achieve a 'Right First Time' environment where quality is engineered into the product rather than inspected in. All of this has led to be achieved with a much smaller and more flexible work force than was previously the case in order to maintain competitiveness in the global marketplace.

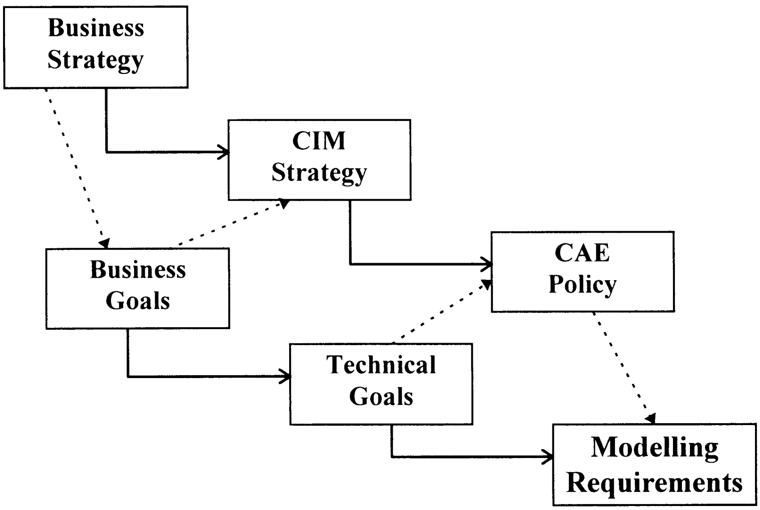

Figure 3 Relationship between Business-Strategy and Manufacturing Modelling Requirements

6. Re-engineering the Product Development Cycle

Re-engineering has been defined by Hammer & Champy [6] as "The fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical contemporary measures of performance, such as cost, quality, service and speed. R.D.Caldwell et al [3] defined a five phase produce development cycle composed of (1) marketing, (2) product design, (3) prototype hardware and testing, (4) pilot production and testing, (5) full production. They proposed that for 'World Class Manufacture' this cycle should be reduced to a four phase cycle consisting of (1) marketing, (2) product design, (3) prototype production hardware and testing and (4) full production.

For many years leading edge engineering organisations have combined the prototype hardware and pilot production phases by producing prototype hardware using full production facilities rather than laboratory facilities. This avoided repeating the method development process and allows design related production issues to be raised early in the product development process as a first step towards concurrent engineering. More recently the goal of a three phase product development cycles has been adopted consisting of (1) Marketing, (2) Product Design, Manufacturing Capability Modelling & Manufacturing Development and (3) Full Production.

7. Manufacturing Capbility Modelling

Manufacturing Capability Modelling takes place at both the macro level and the micro level of manufacturing engineering. The key manufacturing engineering activities impacted by the introduction of Manufacturing Capability Modelling are:

i) Process and Assembly Planning and Estimating.
ii) Factory and Cell Design and Simulation.
iii) NC Programming and NC Simuulation/Validation.
iv) CMM Programming and Simulation/Validation.
v) Tool Design and Manufacture.
vi) Ergonomics Assessment.

If we now take each of these activities in turn we can begin to see the changes that are taking place in modern industrial practise and the directions that this practise and hence supporting collaborative research may need to take.

7.1. PROCESS AND ASSEMBLY PLANNING AND ESTIMATING

The new context for process and assembly planning is one where the source data that is now available to drive these activities includes a full feature based parametric definition of the product to be manufactured in 3D. This has opened the door to the possibility of generating the process and assembly automatically from the features and geometric data held in the design model. The approach taken by the research team to date has been to focus on the manufacturing capabilities and knowledge of the production facilities and staff and to capture this into an explicit rules base appropriate to the processes and activities actually taking place or planned to take place at the target facility. This has allowed the scope of the research activity to be greatly reduced allowing tangible results to be achieved within the tight time scales required for industrial survival. It has also made it easier to validate the logic and to have confidence in the repeatability and reliability of the generated output. The task of capturing and codifying the knowledge into logic can be an onerous one and involves attempting to achieve a consensus amongst the manufacturing design (production engineering) personnel as to the 'Best Practise' for each major process. In order to facilitate this a technique was developed that involved appointing a team of experienced engineers in the discipline and going through a process of 'Logic Brainstorming' followed by analysis of the brainstorm results and synthesis of a proposed logic flowchart which was later documented and reviewed before coding into the system. The average time allocated to each 'Logic Brainstorm' was one hour after which the meeting was dismissed and the engineers were freed to support the ongoing production activities. Within this time the key factors affecting a particular process, would have been identified a first draft logic flowchart generated. It was found that this process in its self was very valuable in helping to identify and communicate engineering 'Best Practise' even before the results were codified in the logic rules base. The area of assembly planning is the subject of future collaborative research that is taking place within the joint research team the results of which will be published in due course. The estimating activity can be driven from the process planning logic where such logic exists.

7.2. NC PROGRAMMING AND NC SIMULATION/VALIDATION

With an accurate 3D design model it is possible to choose an appropriate stock model and define the stages of manufacture in 3D (see Fig.4). These 3D definitions can then be used to create the cutter path for each stage. Furthermore if a 3D solid design is created for the fixture then it is possible to perform a full kinematic simulation of the machining process and fully validate the NC program prior to cutting metal. This opens the door to *'right first time'* manufacturing and to facilitating feedback by Manufacturing Capability Information to the design department.

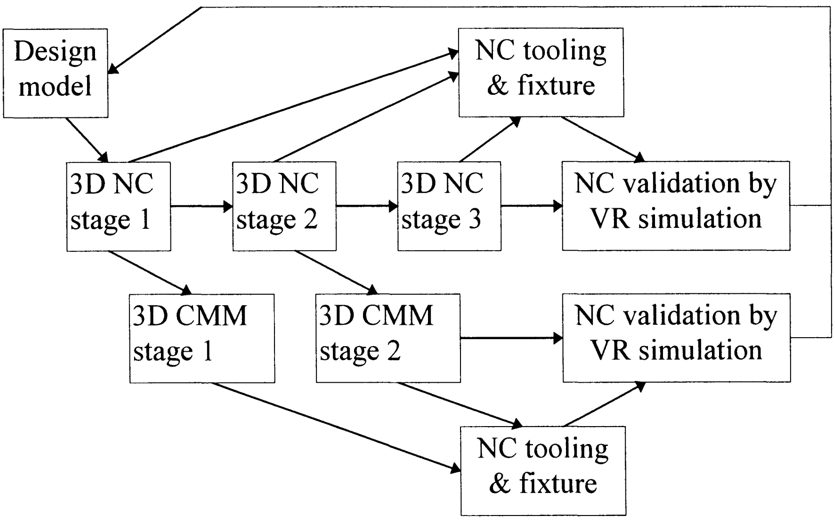

Figure 4 Modelling NC and CMM Capability Closes the Loop with Design

7.3. CMM PROGRAMMING AND SIMULATION/VALIDATION

These 3D staged definitions can also be used to help define the CMM inspection program and if a 3D solid design is created for the fixture then it is possible to perform a full kinematic simulation of the inspection process and fully validate the CMM program prior to inspection. This facilitates the further feedback of Manufacturing Capability Information and statistics to the design department. It should be noted that the original design model cannot be directly in the CMM programming activity because the inspection is to a stage of manufacture prior to the final (design model) stage.

7.4. TOOL DESIGN AND MANUFACTURE

In order to facilitate 3D NC and CMM programming and validation it is essential to have a 3D tool and fixture models. These models can then also be used as the basis for manufacturing the fixtures and tools.

7.5 FACTORY AND CELL DESIGN AND SIMULATION

Whereas in the past the factory design was predetermined and it was the process planning activity that attempted to optimise the production cost and lead time. It is now the case that a new design will need to be planned to achieve a target UPC (Unit Production Cost) and that this will probably involve designing and implementing a new production cell optimised to reduce 'walk times' Factory and Cell design therefore becomes the optimising activity with process planning being taken as a static event. The key tool used in support of this activity has been Factory Simulation. This has allowed the possibility of achieving a macro level model of Manufacturing Capability with a high degree of accuracy. The integration of this macro level model with the micro (process) level model of manufacturing that exists in the process planning system is an activity which will require further research.

7.6 ERGONOMICS ASSESSMENT

The 3D model of the product is also used to perform ergonomic assessment of the design using a 3D ergonomic model to check for visibility, reach, strength required and access. This also represents a relevant Manufacturing Capability assessment activity as long as humans and not robots are being used for assembly and as the ultimate customers of the product.

8. **The CAD System Facilities Required to Support Manufacturing Capability Modelling**

The key to the integration of the large scale engineering enterprise lies in the concept of Manufacturing Capability Modelling and of the Product Model as illustrated in Fig.2 "Manufacturing Capability Modelling System for Mechanical Parts and Assemblies".

V Allada and S Anand [7] proposed three alternative approaches for incorporating features into the product model:

- Human assisted feature definition.
- Automatic feature recognition.
- Design by features.

Of these approaches only the third can allow the design intent of the original designer to be unambiguously determined downstream or by other designers wishing to update the design. For this reason the approach adopted was the design by features approach.

The concept designer creates a 3D CAD model which is fully representative of the product and contains enough information to drive the downstream processes. The model should be surface accurate and not a filleted approximation and should be created to the mean dimensions whilst also holding tolerance information and allowing interference checking. If there is an intention to automate the process planning activity then the model also needs to contain feature information that can later be interrogated by the process planning system as part of the process of generating the process plans.

9. Conclusions

The Manufacturing Capability Modelling activity has facilitated a radical concurrent engineering activity which has brought down the cost and lead times for product introduction and allowed right first time manufacture. It has brought forward the manufacturing engineering process early into the concept design phase and has begun to allow the implications of the capabilities of the manufacturing facility to be fed back into the prime design. Further work remains to be done to further exploit the concept of Manufacturing Capability Modelling and to develop its use further as a business integration tool.

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PERFORMANCE IMPROVEMENT OF A SURFACE-SURFACE INTERSECTION METHOD

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Abstract. We have implemented a surface-surface intersection method. A fine analysis of the required computing time for each step of this method has also been carried out. We have focused on the slower parts and checked different improvements. After a short recall of our method, the introduced modifications are described and the gains of performance are detailed.

1. Introduction

Most geometric modelers are based on Bézier or B-splines parametric curves or surfaces (possibly rational NURBS). Determining the intersection between two such surfaces is still a topical problem. An intersection usually consists of open or closed curves; one particular case (or degenerate case) leads to finding pieces of surface. The limit between these types of intersection corresponds to the case of tangency between the two surfaces which is processed as a piece of surface ([DaN94]). Isolated points can also be found. We must notice that singularities on intersection curves (cups, branches, ...) can be encountered.

Existing methods do not necessary fulfill the three criteria of robustness, accuracy and rapidity which are essential for a CAD software program.

Among the first to appear were recursive subdivision methods based on a "divide to conquer" scheme ([LaR80]). Surface flatness which requires a subdivision process to be reached, is necessary to compute the segments approximating the intersection curves. These methods are slow and numerical problems can occur if too many subdivisions are made.

Marching methods allow us to compute an entire curve if one of its point is first determined ([BFJ87] for example). These are faster than subdivision methods and do not require any special process for connecting the different elementary curve segments in order to define an intersection curve. The fundamental problem is to find one and only one point per curve to initiate the marching step.

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Hybrid methods can help us to overcome this problem ([BaK90], [DaN94], [Nic95]). A detection step leads to splitting the intersection curves into elements, computable with a robust marching technique. Hybrid methods include recursive subdivisions, marching, and eventually other techniques. This allows us to benefit from the advantages of both previous methods: robustness, rapidity and accuracy. The degenerate cases (partially identical surfaces, tangencies, ...) can be detected and treated.

We have implemented a program for computing the intersection between two surfaces by using a hybrid technique. We have analyzed many examples and shown in which stages significant improvements of the performance can be obtained. The general method is explained in paragraph 2. We then describe the improvements we have made in paragraph 3 and finally give the numerical gains in paragraph 4.

2. Description of the initial method

This is a short description of our method (for more details see [DaN94] and [Nic95]) witch is suitable for B-splines surfaces. Nevertheless, all the properties applied in the initial method and in the improvements are available for rational B-splines surfaces (NURBS).

The first process of our mehod is to localize the potential intersection. Our location stage in an original one since it does not require any recursive subdivision ([DaN94]). It is based on local modeling of B-splines surfaces. It first considers the control points of surface 1 and the min-max box of surface 2. The respective position of these control points and the three pairs of parallel slabs of the bounding box indicates which elementary patches defined over elementary parametric rectangles potentially intersect the box. All these critical rectangles of surface 1 are combined into free form parametric areas according to a 4-connex relationship. Each area is disjoined from all others. We now consider these areas and their minmax boxes (computed from the associated control points). We study the potential intersection between each box and surface 2, as described above for surface 1. We obtain on both surfaces a set of corresponding areas where potential intersections can be found. These areas can be reduced by iterating this clipping process. The convergence is quickly obtained.

The detection stage checks if no colinear normal vectors exists on both surfaces. We can then make sure no closed curve or degenerate intersection have to be found. Determining the intersection between the two surfaces amount to finding the open or semi-open curves (an open curve is a curve having two ends on each parametric plane which reach the boundaries; a semi-open curve is a curve for which this property is valid for only one parametric plane). On the other hand, when there are potentially two colinear normals (one on each surface), closed curves or degenerate cases cannot be excluded. It is then necessary to split the two surfaces until the closed curves are decomposed into open curves.

In order to ensure robustness for this stage, we need to define envelopes containing all the normals to a B-spline surface. Several techniques are described in [Dan96]. Using the convex hull property, we can build, for each surface, envelopes containing all the partial derivatives (computed with the first hodographs). Then, we compute the “cross product" of these two envelopes leading to an envelope bounding all the surface normals.

There are two stages for determining open or semi-open curves. We must first compute initial points on each curve. Then we can march along the curve. Initial points pertaining to the boundaries of the pieces of surfaces, they can be found with robust curve-surface intersection algorithms.

A marching process requires two stages. The first one is called prediction. It provides an approximation of a next point on the intersection curve. This prediction must be quickly achieved to preserve the performance of the method, but accuracy is also required so that the next stage (correction) can run under good conditions. Several solutions exist for estimating a next point. We can decide to work in the Euclidean space or in the parametric planes. We can consider the tangency of the intersection curve ([BFJ87]) or its curvature ([ChO88]). We apply simple extensions ([Dan89]). They are computed on each surface, i.e. on each parametric plane. These extensions are rectilinear, or a function of a rough estimate of the curvature if the correction stage proved a failure.

The goal of the second stage, the correction stage, is to converge towards the real intersection point starting from its estimation(s). In the initial method we have developed, the correction is based on heuristic minimization algorithm. Its principle consists in building two sequences of crosses (one in each parametric plane) whose centers converge towards an intersection point. This method is explained in [Mal96]. We have selected this type of algorithm because such a cross can always be defined on a surface. Moreover, we can always find a minimal distance between two points (one on each cross). With this method, we can treat C^0 surfaces with broken lines or peaks.

In order to obtain the global intersection we are looking for, a connection between all the computed curve segments must be provided.

3. Optimization of detection and correction stages

The method we have previously described has been tested on several samples with different types of intersection. The analysis of the results indicates the importance of the detection stage for the complete method. When the detection test of closed curves is valid, each surface is split into four patches which introduce 16 new cases implying an important increase in the number of operations. We have modified this stage in order to improve its performance as described in what follows. After having included these modifications, a second analysis shows us that the most important part of computing time is due to the marching process. Our attempt has been therefore to reduce as much as possible this amount of time.

We present in the following the different improvements that we have carried out for these two stages but we report the gains obtained in paragraph 4.

3.1 DETECTION STAGE

The detection stage requires the definition of a bounding volume containing all the normal vectors of each surface. As indicated above, this bounding volume is constructed with the first hodographs of the considered surface. The first bounding volume we used in our method was a vectorial cone. Defining a cone containing all the partial derivatives in one parametrical direction is an iterative process described in [SeM88]. The cone of normal vectors is obtained by computing the cross-product of the two cones of the partial derivatives through a direct formula. This bounding volume ensures the robustness of the detection stage since all the normal vectors to the surface are included in the envelope. Nevertheless, robustness can be retained considering more accurate bounding volumes.

The second implemented bounding volume was a rectangular pyramid (pyramid with a rectangular planar base [KrP91]). Two steps are necessary: to determine the pyramid principal planes and to calculate the derivative angles with respect to these principal planes.

The last studied bounding volume was a convex pyramid (a pyramid with a convex polygonal planar base [Dan93]). To build such a pyramid, the problem is mapped onto a plan for defining the base. The first step consists in finding the mapping plane (its normal vector being the axis of the pyramid). The calculation of the pyramid then amounts to the problem of determining a convex polygon bounding a set of points in a plane.

This last bounding volume is by definition more accurate than the other two (see figure 1). The tighter the bounding volume, the more the number of surface subdivisions is potentially reduced. We must however remember that dividing surfaces usually corresponds to the subdivision of both surfaces which is particularly expensive in terms of number of operations.

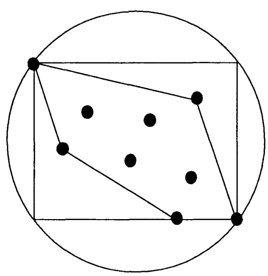

Figure 1: Comparison between a cone, a rectangular pyramid and a convex pyramid.

For all three proposed bounding volumes, we have implemented algorithms checking for the overlap of two such envelopes as described in paragraph 2.

We also have implemented Hohmeyer's detection test ([Hoh92]) with convex pyramids ([Dan96]). The aim of this test is also to decompose closed curves into open curves but it does not search for colinear normal vectors between both surfaces. It is based on the determination of two vectors defining two planes which separates the bounding volumes of normal vectors. This approach also allows us to control the direction of the tangencies approximately along each intersection curve.

3.2 CORRECTION STAGE

As noted in paragraph 2, robustness and rapidity of the marching process mainly depends on the correction stage. We must remenber that the prediction method we have chosen provides us with two approximate points (one on each surface). We have to minimize the distance between these two points in order to find an intersection point. Due to these initial conditions, the developped algorithms for correction work on surface parametric domains, laying on both surfaces. We can find in [Mal96] a detailed and quantitative study of the several methods exposed in this paper.

3.2.1 Heuristic methods

The first algorithm we have implemented consists in defining at each prediction point a cross (with four or height branches). Then, we choose among all the couples of points the couple which minimizes the distance between the two surfaces. We receive two new prediction points and repeat the same process. If one point does not change after the selection of the new couple, the size of the corresponding cross is divided by 2 and the selection is repeated. This algorithm stops when the distance between the two points is lower than a given tolerance. In this case the correction method succeeds. The algorithm may stop if the sizes of both crosses become too small: we must come back to the prediction stage for obtaining two new initial points.

The algorithm of Hookes and Jeeves ([Céa71]) was also tested. It is rather similar to the algorithm we have just spoken about. So, the idea is also to build crosses but the choice of the next centers is different: they are pushed into the direction of convergence. This modification allows a quicker convergence to be obtained. In fact, this method seems to be unsuitable for our intersection problem. We can account for it by the fact that the prediction gives us two points too close to the solution. The acceleration has no time to be correctly executed.

These methods do not require local properties of surfaces. For this purpose, we test some more classical algorithms.

3.2.2 "Classical" methods

One of the first available algorithms is based on descent methods. Exact results exist if we consider only the approximate quadratic forms of the surfaces. Otherwise, initial surfaces are kept and simple minimization algorithms are introduced to compute the different parameters. In the first case, we apply the conjugate gradients method. In the second case, we implement the Fletcher-Reeves method which implies the search of a parameter λ. This is a new and easier minimization problem. It can be solved with simple algorithms like the golden section method or with the so called "economical" methods such as Goldstein or Wolf-Powell's. These algorithms are explained in [Min89].

Newton's method is well-known for its fast convergence. The problem to be solved corresponds to a three by four matrix entailing two possible approaches. The first one introduces pseudo-inverse matrices also called Moore-Penrose matrices ([AlG90]). The second consists in adding to the system an equation of constraint ([Alt91]). In that case we obtain a square matrix. For numerical considerations, inverse matrices are never computed. We prefer to transform the different matrices by introducing a QR decomposition algorithm.

The problem can be considered as a minimization of a distance or a square of distance. There exists special methods for minimizing a sum of squares. Their principles are similar to Newton or descent methods. Nevertheless, they can overcome some unexpected problems (like singular matrix) which constrains the computations to stop. We implemented the improved Marquardt method ([Nas90]).

For each studied method, several criteria have to be determined. For all the methods, the user must choose a tolerance ε_{point}. It is with this tolerance that we can determine whether two points are equal or not.

Ending the marching requires to determine whether we are near a surface boundary or not. In that case, we must have another tolerance $\varepsilon_{boundary}$. If the distance between the point already computed and a boundary is less than $\varepsilon_{boundary}$, we search in the set of initial intersection points computed on the boundaries if one can be the next point on the intersection curve. Such a point is necessarily the last one of the intersection curve segment. Otherwise, we need to march again keeping in mind that we are near a boundary.

One of the initial intersection points is the end point of a curve, if its distance to the last computed intersection point is less thant ε_{step}. This new tolerance corresponds to the step we consider for finding a new prediction point during marching. We should note that this step does not necessarily remain constant during all the marching process. Depending on the methods and the local properties of the intersection curve, this step can be adapted. So, in order to control this value, we introduce two new tolerances ε_{min_step} and ε_{max_step} .

Other parameters can be introduced. As advised in [BFJ87], we can control if the line segment connecting two consecutive points is a good approximation of the corresponding curve segment. If this condition is not met, the approximation is not correct and one or more points have to be computed between the two studied points. We then obtain a better approximation of the intersection curve segment. This tolerance ε_{arc} has not be introduced in our tests. We just checked if, for all the tested methods, we approximately obtain the same number of intersection points with a similar distribution.

We have compared the above methods for the same tolerance ε_{point}. The first criterion is the number of elementary operations on real numbers for each method. This criterion is valid only if each algorithm ensures that all the intersection points are found respecting the tolerance ε_{point}. A gain in number of operations must never alter the robustness of the global method. Independance with respect to the user's parameters is also very important for determining a “ good ” method. In order to compare the different methods, we must find approximately the same number of approximate points for each method which is the case in our tests. Both versions of Newton algorithm give us close numbers of elementary operations. However, the use of a four by four matrix may imply numerical problems due to the numerical singularity of the matrix. So, we prefer to use pseudo-inverse matrices. An analysis of the results shows us that several methods for marching are necessary in regards of their respective avantages.

4. Evaluations of proposed improvements through several examples

We first studied the different possibilities for the detection stage. The separated evaluation of the proposed approaches is not sufficient. In fact, the longer the determination time of a bounding volume, the more accurate this envelope and so the more efficient. We decided to compare the global performance of our intersection method with different versions of the detection tests. This allowed us to evaluate the consequences of volume reductions by taking into account the number of operations necessary to determine each volume. Some examples have been chosen with regards to their relevance. For example, the surfaces proposed in figure 2 have been studied (among those having several intersection curves and important variations of curvature). When several curves exist, an average of the computing times between the different examples is proposed. One running time has been taken as unit time. The other values have to be compared with this unit time. All the results are summarized in table 1.

By reading this table horizontally, we can compare the running times between the different intersection problems. Reading the table vertically gives information on the performance using the different detection tests. The first example is the fastest: the number of calls to the detection test is very low because there is only one nearly rectilinear open curve which allows a particularly efficient localization stage. Using this table, we can conclude that for our intersection program, the use of convex pyramid leads to improving the performance (in a factor up to 19 for the tested examples) in respect with the vectorial cone we first implemented. For extreme examples, more important factors would have been found. The implementation of the Hohmeyer's test does not imply better results. So we decided to keep our implementation with convex pyramids.

At the same time, we studied on several intersection curves the differences of performance between the marching methods described in paragraph 3.2. As they provide similar results, they can be direclty compared. One running time has been taken as unit time. The other values have to be compared with this unit time. All the results are proposed in table 2. For having understanding results, the global times have been replaced by the average times to compute only one intersection point (i.e. for one problem: time to determine all the curves divided by the number of computed points).

Figure 2 : Intersection of two surfaces with important variations of curvature.

TABLE 1: Improvements in computing time of the global intersection method.

	One open curve	Several open curves	One closed curve	Several closed curves
Vectorial cone	1	11	124	400
Rectangular pyramid	0.6	3.4	13	28
Convex pyramid	0.6	2.8	11	21
Hohmeyer's test	1.1	2.9	10.7	22.3

By reading table 2 horizontally, we can compare the running times for different shapes of intersection curves. Vertically, we have the performance of one method with respect to the others. The first example is the fastest because the intersection curves are close to straight lines and the prediction stage proposes a very good approximation (in each parametric plane) of the next intersection point. In the last example, we have important variations of curvature which does not mean that the curvatures are high. So it is not so surprising to have for some methods (conjugate gradients, Newton (3x4), improved Marquardt) better results that for the second example. Nevertheless, we can note that these important curvature variations lead to the problems of convergence for Newton method (4x4).

TABLE 2: Improvements in computing time of different correction techniques.

Intersection / Methods	near straight lines 2 curves 210 points	important curvatures 3 curves 240 points	important variations of curvature 11 curves 2690 points
Crosses	1,000	4,976	8,578
Hookes & Jeeves	1,185	only 1 curve found	only 1 curve found
Conjugate gradients	0,307	1,134	0,674
Newton (4×4)	0,150	0,261	10 curves found
Newton (3×4)	0,177	0,313	0,228
Improved Marquardt	0,148	0,255	0,187

All the results summarized in table 2 illustrate that the improved Marquardt method or the Newton method (3x4) speed up the marching stage in a ratio from 7 to 46. We should note that for some particular cases, either method may fail. To overcome this problem, we can implement both methods and if one algorithm fails the program switches to the other one (we can also use the cross method as an ultimate solution). Combining these methods ensure the robustness.

The definitive choice between the improved Marquard method or the Newton method (3x4) will probably depend on the forthcoming study concerning several prediction methods and their consequences on the correction step.

5. Conclusion

We analyzed the performance of our surface-surface intersection method we have developped. This study led us to consider some modifications. They deal with the detection stage which suppresses the closed intersection curves and the marching stage which computes the different intersection curves. The analysis of several examples prove us that these modifications produce very significant improvements.

Other improvements can still be made. We must study the sensitivity of the accuracy of the prediction stage on the marching stage. We have also to improve techniques to detect and process degenerate cases (tangency, partially identical surfaces and branches) taking into account our actual results and the knowledge we gain on marching techniques.

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Chapter 9
APPLICATIONS OF INTEGRATED DESIGN AND MANUFACTURING

INTEGRATED DESIGN OF ELECTROMAGNETIC MOTORS

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Abstract. The use of constitutive elements at the limit of their capacities is needed for the design of electric motors used in very high speed machining. The study of electromagnetic and mechanical materials properties according to the manufacturing processes used during their elaboration allows, in an integrated design context, to reduce the uncertainty on the computations. So it is possible to decrease the specified tolerances in order to optimise the expected performances.

1. Introduction

For few years in the mechanical domain, productivity and reactivity have compelled design methodologies to have a high change from linear design models to integrated models by concurrent engineering [1].

The integration of manufacturing concepts during design avoids the useless backward stages and allows a global optimisation of the structure. Manufacturing experts can design the surfaces which are not functional, mainly rough surfaces. These surfaces are not chosen just by designers, but have to be designed in order to facilitate the manufacturing process and its characteristics.

Electrotechnics is a domain where manufacturing influences the performance of the product [2], [3]. Material electromagnetic properties depend on the plastic deformations due to manufacturing. This paper presents the profit of an integrated design methodology for electromagnetic motor design [4].

2. Usual design of electromagnetic motors

Figure 1 shows the development of electromagnetic motor design as seen by one of the authors and applied to a switched reluctance motor. This motor is noticed MRV2S here after.

The fast validation of the specifications repulse the physically unfeasible solutions. The design begins by choosing some parameters. Then others can be

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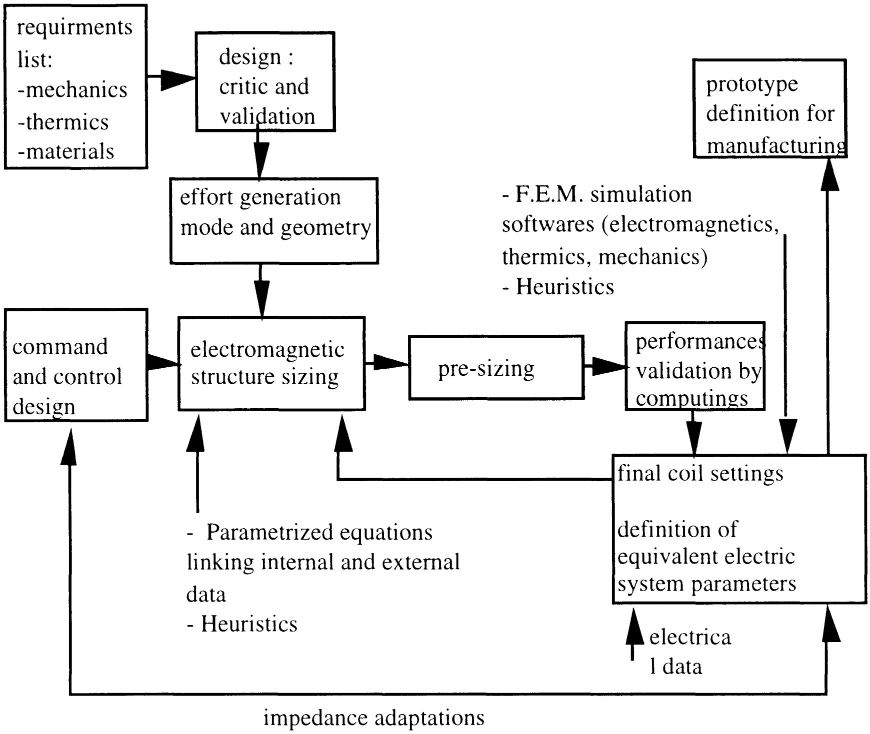

Figure 1 : initial design synoptic of electromagnetic motors (by Vives-Fos)

computed with equations or relations relative to the electrotechnical domain. However, some of them cannot be obtained because of a lack of information. Simulations of motor reaction in use allow the step by step optimisation of these parameters, but never a global optimisation.

In such a design methodology, incomes are only from the electrotechnical domain and the mechanical and thermal properties are simulated later. Material properties are chosen in a data base since the design begins

Figure 2 shows the dependencies between parameters of a MRV2S as described in [4]. The bold ones in squares are the initial parameters chosen by the electrotechnical engineer, the others in circles are the final parameters computed by equations or relations. Some problems like loops are represented. For example, the knowledge of 37th parameter needs the value of the 36th which needs the 35th, which also needs itself the 37th. The same problem exists between 35, 15, 101, 45, 35.

In this study, parameters are associated with a specific job. Electrotechnics of course, but also mechanics, thermics, materials and manufacturing processes are present, as it is shown on Figure 3.

This new graph presents the evolution of the design as a consequence of the parameter evaluation. It marks the interest in integration of the knowledge of several experts for the best design of such a motor.

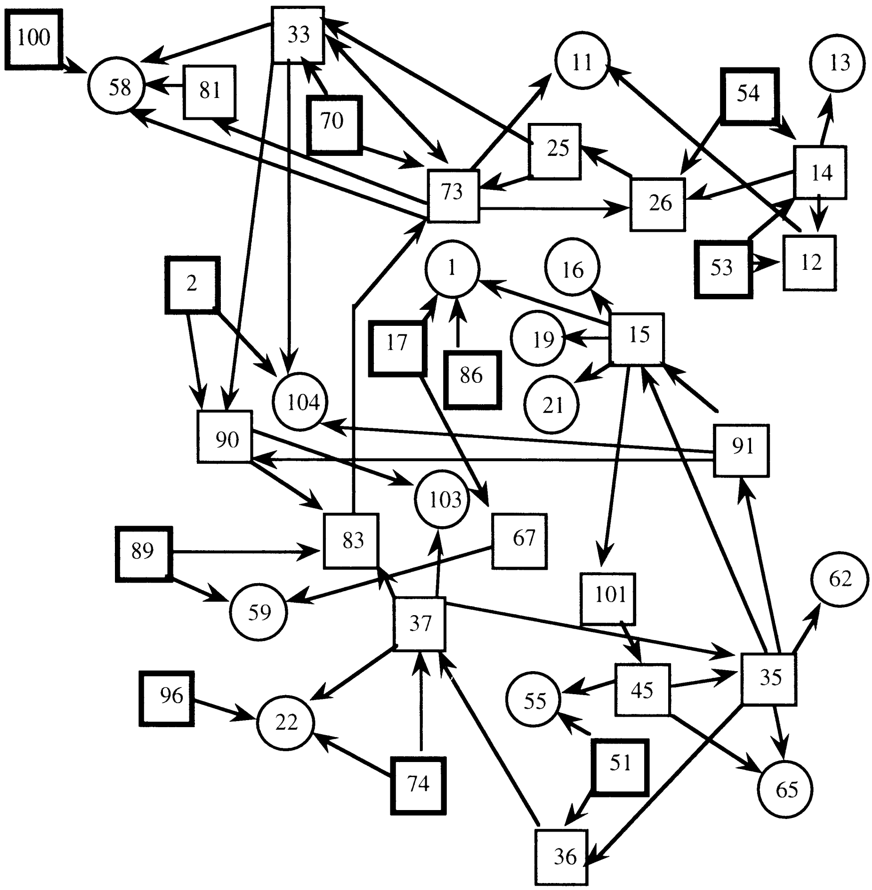

Figure 2 : Interdependence parameters graph of the MRV2S motor

3. Influence of the manufacturing processes on the electromagnetic properties in sheet metal forming

One of the aim of the design is to choose the material used for sheet metal in order to obtain the rotor and stator as defined on Figure 4.

Here, the electromagnetic characteristics depend on the manufacturing processes used to elaborate the material and to cut the sheet metal. The relations between the cost and the quality requirements for the sheet metal are also studied in accordance to the operational tolerances obtained with each available process.

3.1. ELABORATION OF MATERIAL

Two different types of material can be used for the sheets in electromagnetic motors, the crystal alloy and the amorphous alloy.

The crystal alloy is transformed in cold laminated sheets in order to obtain a 0.2 mm thickness. The sheets are grain oriented (GO) or no grain oriented (NO). In a rotational magnetic field motor, like MRV2S, the magnetic isotropy is needed, therefore only NO sheets are used. Either the sheets are "fully process" (the customer has no operation to do and the designer choices these ones for their technical characteristics) or the sheets are "half-process" (the customer has to make an annealing treatment on the sheets but the price is lower). These last sheets are often chosen for their economical characteristics.

The amorphous alloy is elaborated with a fast hardening of a ribbon, followed with an annealing treatment [5]. The thickness of the sheet is between 15 and 30 µm and its width from 10 to 20 mm.

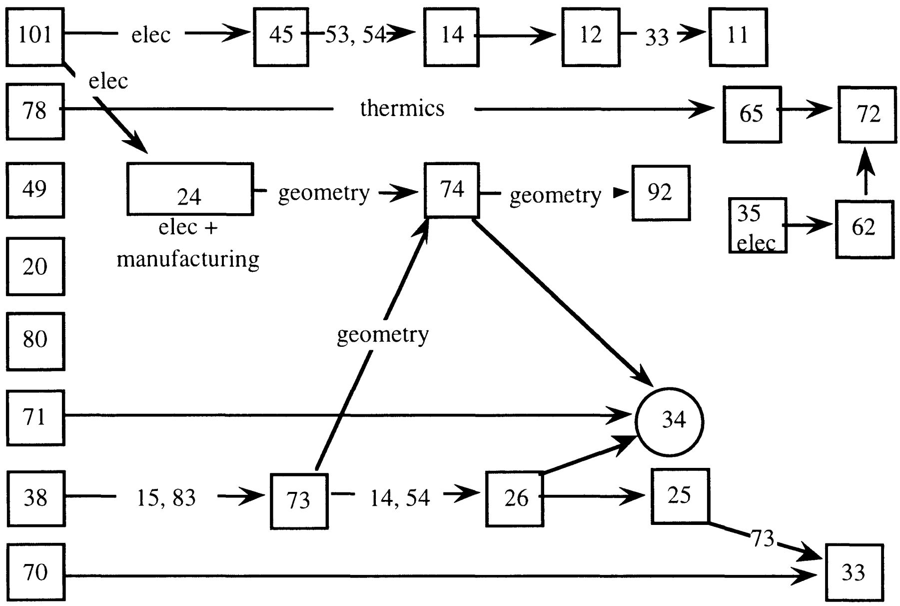

Figure 3 : Association of the parameters and trades used to define them

3.2. SHEET METAL CUTTING AND HEAT TREATMENTS

In the literature, three kinds of cutting processes appear : sawing, shearing and laser cutting. In order to make a choice, the respective technical properties of processed materials (Bs, µr) and the economical characteristics (the material price and the manufacturing price) are compared.

3.2.1. The technical properties of a sheet metal after cutting process

Hug has shown in [6] the influence of the permanent deformations (Ep) on the magnetic properties of a sheet metal. These deformations come from the cutting [7] or the coil stocking [8] and increase the hysteresis losses.

Thereby, the laser cutting may be advantageous because it does not cause any deformation. However, if the deformation does not exceed 1%, an annealing treatment refreshes the initial characteristics of material.

Obviously, the annealing treatment depends on the materials. For example, the magnetic characteristics of the Fe1%Si are restored with an heat treatment at 700°C in dry hydrogen and during 1 hour [9]. During the laser cutting, the process parameters may also influence the magnetic properties. Bs increases with the cutting speed for example. The main problem of laser is the level of temperature which creates oxides as it is done during heat treatments [7].

3.2.2. Economical characteristics

Cutting price is linked to the cost evaluation of the process and to the time used for cutting. Shearing is faster than sawing or laser because in those cases, the total periphery of part has to be run.

Machine cost is cheaper for shearing than sawing and even more than laser cutting. However it depends of the machine tools and the quality required (see 3.2.3).

The falls are equal for the three processes but these falls can be optimised with the ribbon sheet width. So it is useful to know the products we can found on the market in order to make a choice.

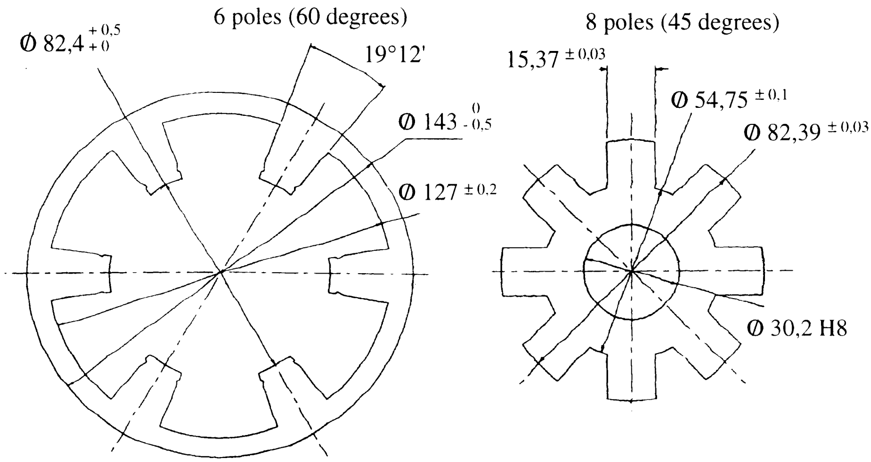

Figure 4 : MRV2S stator and rotor sheet metal geometry

3.2.3. The limits of the processes (accuracy, Ra...)

All the tools could not realise all the requirements on the sheet metal like the curve radius, the sheet metal thickness, the operational tolerances or roughness. It depends on the tool material and the geometry. For example, Figure 4 requires tolerances lower than 9 on a quality scale for the stator radius and the rotor radius. That is why it could not be realised by shearing. We can found in [10] and [11] margins for usual processes.

3.3. MANUFACTURING INFLUENCE ON PERFORMANCES

According to the literature, a specific structure of sheet metal used in our application has been studied in order to increase the magnetic properties. Silicon and aluminium rate must be maximum for increase the magnetic isotropy, Bs and μr. However, Silicon rate must not exceed 3,3% in order to prevent cricks during cold lamination. Likewise, Aluminium rate must be lower than 0,8% in order to prevent aluminium oxidation during the heat treatments. Other oxidation also may be prevented by decreasing sulphur, oxygen, nitrogen or carbon percentages. Crystallography has also its

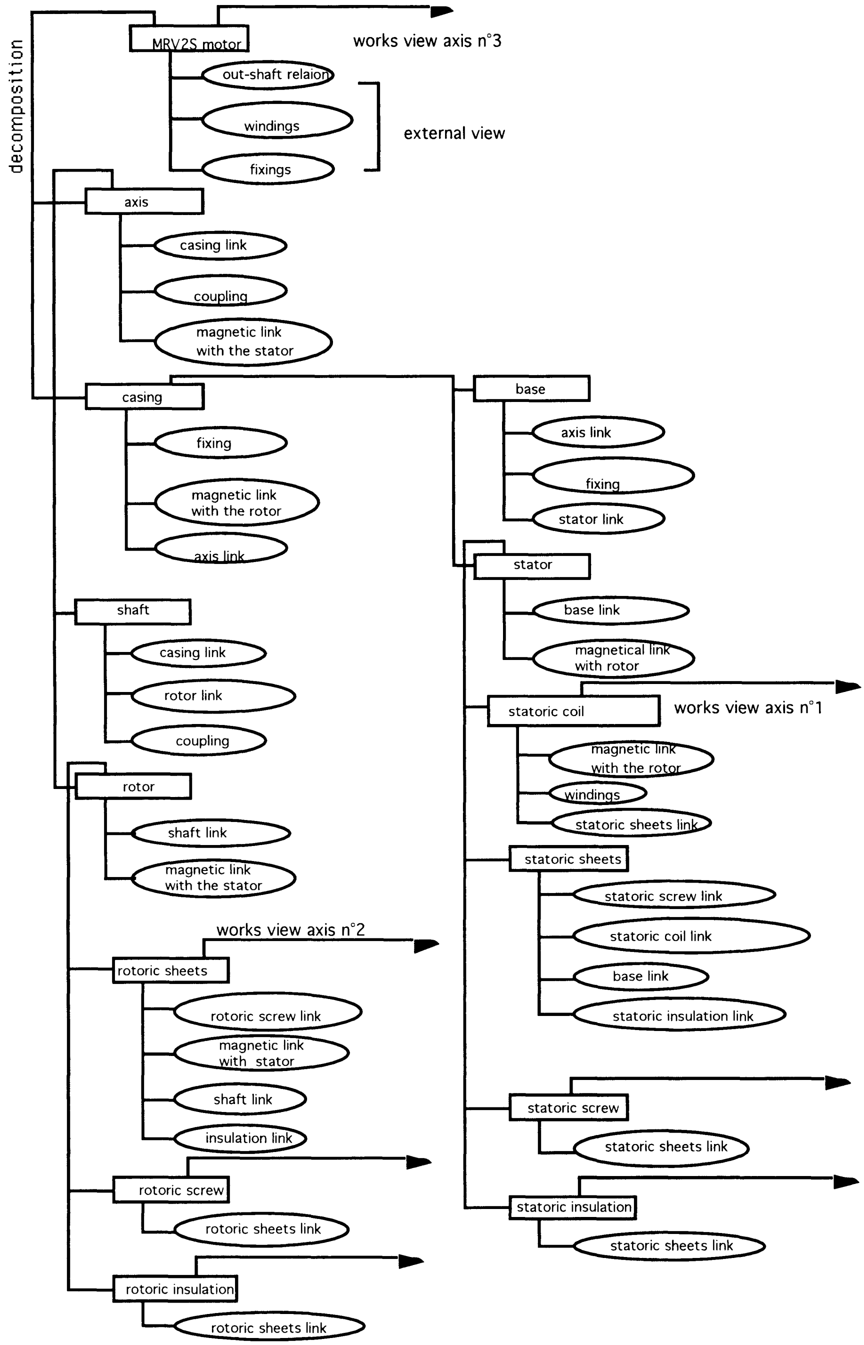

Figure 5 : Structural decomposition of the MRV2S motor

importance and the best orientation is {100} <0vw>.

Core losses have been studied by [12] and [6]. They model, with mathematical relations or experimental curves, the influence of some parameters on such losses. For example, the sheet metal thickness, the grain diameter, the silicon rate and also the roughness. But the roughness depends also on manufacture process...

Those examples show the importance to choose the material and the manufacturing process together. Data bases can improve and accelerate our choice, giving a method of productivity index or the weighted variables.

4. Multi-view product model for electromagnetic motor

In order to take into account the different knowledge of the participants during the design, it is necessary to stock the data produced by these participants and the relations imposed to these data in an appropriate data structure. In this way, the multi-view product model, developed in our Integrated Design Team of the 3S Laboratory at Grenoble [13] is used. This model is based on components, links and relations.

A component describes a material set, may be a set of parts, an unique part or a portion of part view by a specific trade. It is represented by a rectangle. A link is a characteristic of a specified component which allows an external consideration on the component. A link is represented by an oval. The consideration on the component is made by a relation which is pointing on two or more links of the same component or of different components.

One component can be seen as a feature. For example, an electromagnetic motor can be viewed by a user like its out-shaft, its feeders and its case. Those three elements allow to represent the motor at an higher level with a receptor, a plug and a fixing part.

Every components can be viewed at different level with the decomposition operator. Like that, the axis can be decomposed in a shaft and a rotor, the case in a base and a stator, as shown in Figure 5.

The different participants look a component with their specific view (i.e. vocabulary and context), so the component decomposition is not unique. That is why a multi-view support is joined to each component. This support describes the component under specified trade's views. The same trade can exist on several multi-view support. The possibility to link features of different trades is the best advantage of our model. This product model is nowadays on studies in our laboratory to allow the modelisation of an integrated design methodology

In Figure 6, we found the multi-view support of a stator coil.

5. Conclusion

This paper presents the twofold advantages with the use of an integrated design methodology to design an electromagnetic motor. On the first hand, a classic profit is in the fact that it allows the communication between participants who appear during the life cycle of the product, earliest as possible. On the other hand, a specific profit is due to the relation between materials and manufacturing processes which allows to optimise the motor performances.

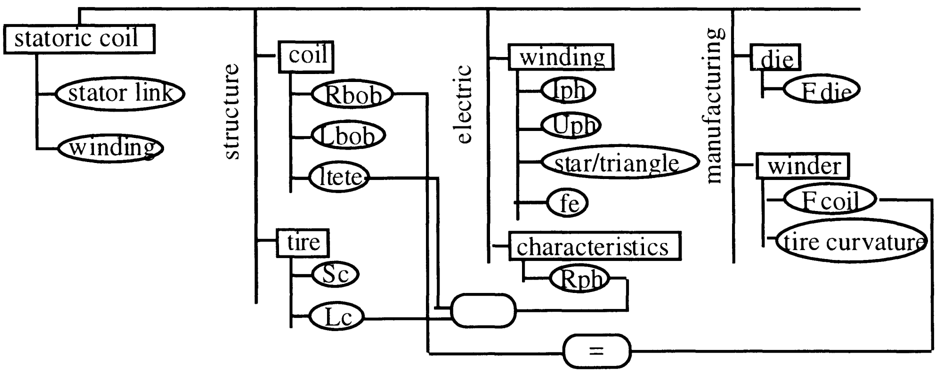

figure 6 : multi-view of stator coil component

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OPTIMISATION OF A STRUCTURE FOR BIAXIAL MECHANICAL TESTS

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Abstract: The subject of this study concerns the design of a specimen for biaxial mechanical tests. After defining needs and examining the existing solutions, the specimen design is achieved by a systematic testing program guided by the results of numerical simulations. The optimisation of the specimen is then accomplished by adjusting the geometric parameters coupled with the analysis of successive results.

1. Presentation of the problem

The aim of this study, conducted jointly with the Gaz de France company, is the experimental validation of the fatigue crack initiation criterion proposed by Dang Van [1]. It concerns more particularly the decision of removal or repair of damaged tubes. This validation must be performed for states of stresses representative of real loadings of gas transportation pipes. The material is subjected to high cycle fatigue and is placed under hydrostatic pressures on the order of 200 MPa [4]. The difficulty herein is two-fold: the local stress is at a level of multiaxiality that is inaccessible in laboratories with classical tension-torsion tests; and tests have to be carried out on samples of material taken from tubes of gas transportation in order to characterize the material in its state of utilization.

2. Biaxial test specimen

To explore the behavior of materials under real loadings, the LMT has purchased a machine for performing multiaxial tests. Named "Astrée", this prototype machine (Fig.1) developed by Schenck is characterized by three perpendicular directions of loading; in each direction, there are two coupled servohydraulic actuators, and the control

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system is such that the center point of the specimen is motionless, thereby avoiding the coupling between the different axes. This specificity has in fact made Astrée a unique machine that allows the exploration of stresses and loading histories, which, until now, had remained inaccessible.

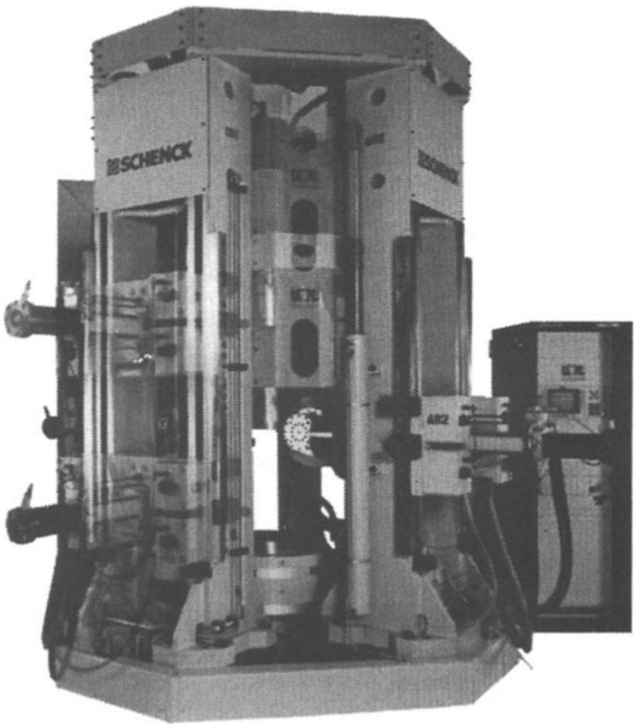

Figure 1: The Astrée testing machine.

The Dang Van criterion [1] chosen by the Gaz de France company stipulates that there is endurance if, over the loading cycle time [0,T], at any point M of a structure Ω, the microscopic local shear stress τ remains less than a threshold value which is a linear function of the hydrostatic pressure.

there is endurance $\Leftrightarrow \forall\, M \in \Omega,\ t \in [0,T],\ \max\,[\,|\tau_{local} - \tau_{average}| + a.p(t)] < b$
where a and b are material parameters.

This stress criterion is developed within the context of Continuum Mechanics and is based on the notion of a "volume element". During testing, quantities of measurement, especially strains, cannot be evaluated accurately on volumes as small as that of the volume element. The idea is to load a volume whose size is sufficiently large to allow the use of several strain gauges. This volume must be connected to the loading actuators; thus, the design of a specimen can be performed by decomposing the structure into three areas:

-The gauge zone, generally called the central zone, in which the stress field must be uniform and correspond to the requested state. At each instant, the level of loading of this part has to bc measured precisely. Its level must also be higher than in the rest of the structure.

-The fixing zone, which insures the connection with the ends of the loading actuators.

-The connecting zone between the two previous parts, whose main function is to avoid the mechanical coupling of the external loadings which are applied in two orthogonal directions. The design of this intermediate zone is difficult. To obtain a uniform stress field in the central zone, it is necessary to filter the undesirable effects due to the setting and to allow the deformation of the structure with no additional stresses.

The specimens have to be extracted from gas transportation tubes whose diameters are on the order of one meter for a thickness of five centimeters. To best satisfy the specifications, the geometry of the specimen has to be plane, and biaxial loadings compatible with Astrée's characteristics will be prescribed. The loadings have to faithfully reproduce real conditions and are applied in two perpendicular directions. Each direction consists of two actuators each of whose range is ±100 kN. This constraint has naturally led to choosing a cruciform geometry.

3. Design of the specimen

The first step consists of seeking geometries compatible with our specifications.

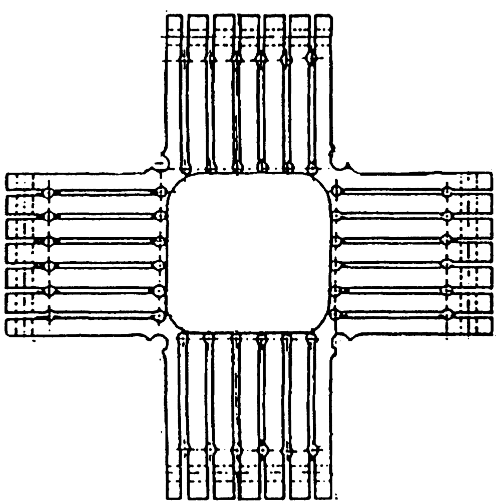

Figure 2: Specimen proposed by Brown and Morisson.

The bibliographical research converged very rapidly on the solution proposed by Brown and Morisson [6]. This entails a specimen with a cross shape whose central zone is a square with round corners and with a connecting part like a comb (connecting arms see Fig.2).

An analysis of the results obtained by various authors along with the experience acquired during the design of specimens for uniaxial tests in our laboratory has led to three modifications of the initial geometry proposed by Brown and Morisson (Fig.3):

-A reduction in the thickness of the gauge zone of the specimen.

This reduction modifies the ratio of the thicknesses between the gauge zone and the connecting part. It is obviously compatible with the performance of Astrée and the desired levels of stresses.

-The modification of the geometry near the right angle of the cross at the separation of the connecting arms (Fig.4).

This modification will play an important role during the optimization; it induces a reduction in stiffness over a stressed zone of the structure and allows reducing the level of stress in the highly-stressed parts of the connecting arms.

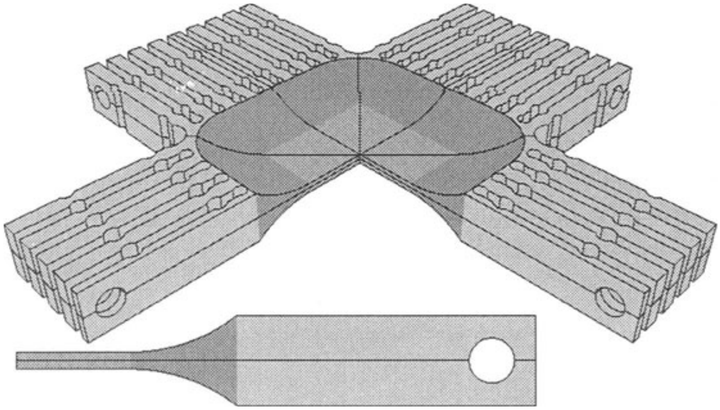

Figure 3: Initial geometry of the specimen .

-The creation of a flexible parallelogram by boring a series of holes into the connecting arms (Fig.4).

The design of the part connecting the gauge zone to the actuator ends is also of great importance. It enables reducing the coupling effects of the two perpendicular loading directions. If one considers the arm located at the end of a connecting part, it undergoes a displacement in the direction perpendicular to the comb close to the central part of the specimen (Fig.4). This displacement is related to the transverse tension being prescribed by the second set of actuators. The elastic connections, obtained by the holes, allow a decrease in the flexural stiffness of the arms, thereby limiting the parasitic effects close to the central part.

In a subsequent step, this initial geometry has been meshed and the stress field determined by the finite element code CASTEM 2000 [7]. For this first calculation, a 2D elastic model of the specimen has been considered. In this model, the underlying hypothesis has been to make a calculation under a plane stress condition that takes into account the variation of thickness through the use of an equivalent Young's modulus. This type of calculation allows an inexpensive study of the sensitivity of various parameters. The result for a 3D calculation is given below in Figure 5.

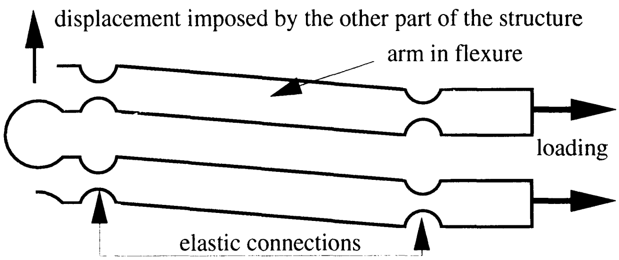

Figure 4: Presentation of the behavior of the connecting arms.

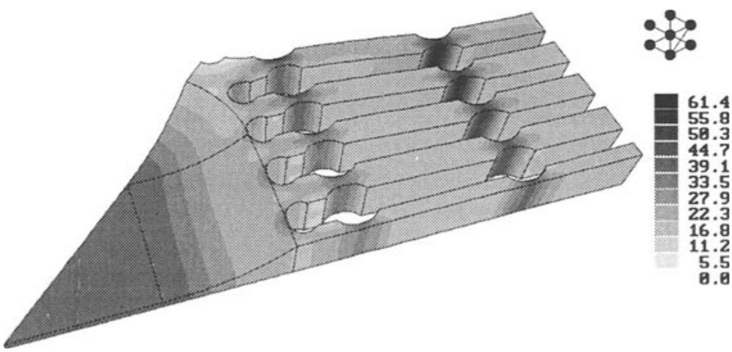

Figure 5: Initial geometry (1/16th)- Von Mises equivalent stress.

Despite the high thickness ratio, the most heavily-stressed zone is not the central one, but rather the hollow one close to the connecting arms (Fig.5). These numerical results have been validated by experimental tests conducted on Astrée.

4. Shape optimization

There are two main optimization criteria: the stress field has to be uniform in the central zone; and this zone must be the most heavily-stressed part of the specimen.

4.1. INITIAL PARAMETERS

The most delicate aspect is the geometrical definition of the central zone and its connection with the linking system while ensuring respect of the specifications. The initial numerical study has enabled listing the geometrical parameters that affect the state of stresses in the specimen. Twelve parameters have been selected (Fig.6).

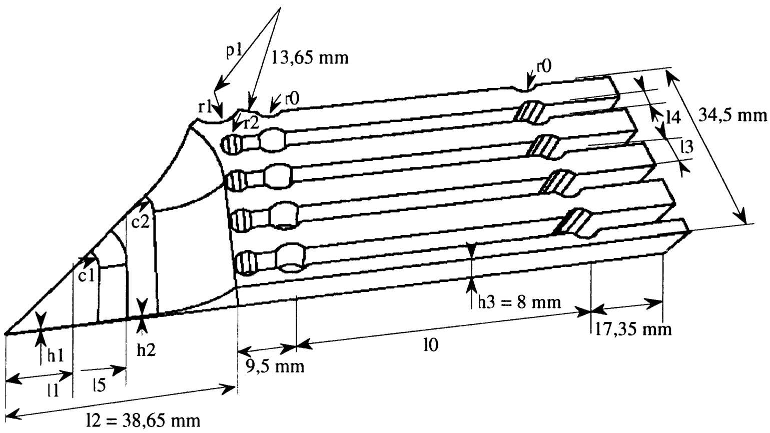

Figure 6: Final geometry (1/ 16th)- chosen parameters.

4.2. SENSITIVITY STUDY

A sensitivity analysis using CASTEM 2000 has allowed us to evaluate the influence of each parameter. The analysis of the results from successive 3D calculations has enabled us to propose the different bounds for each parameter and to define the conditions for the next calculation.

This study (Fig.6) has shown the need to increase the parameters l0 (length of the connecting arms) and r0 (geometry of the elastic connections). It also highlighted the influence of the parameter p1 (geometry of the connection between the arms).

4.3. MODIFICATION OF THE GEOMETRY

The stress field determined by a 3D calculation shows that the maximum shear stress occurs at the corners of the central zone. Moreover, the stress level is similar in magnitude to that in the most heavily-stressed part of the arms. A modification in the radius of the spherical part of the transition zone has demonstrated the relevance of this solution. This verification has led to several modifications in the geometry, thus ensuring a homogeneous and maximal stress state in the central zone. This solution is based on a double reduction of the thickness and on the geometry of the transition zone to minimize stress concentrations. Various possibilities have been studied (Figs. 6 and 7). A circular form for the thickness reduction yields the best results. Each choice has been validated by taking into account the machining constraints of the specimen.

5. Results

5.1. OPTIMIZED SPECIMEN

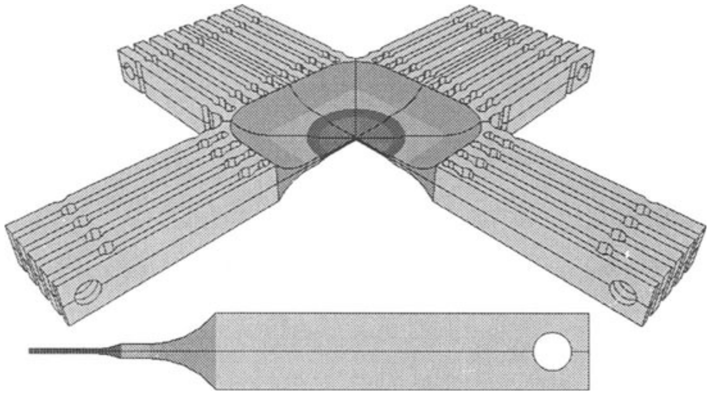

Figure 7: Optimized specimen geometry.

The geometry of the optimized specimen is given in Figure 7. One can note (Fig.6):

- an increase in the length of the connecting arms (parameter l0) without a reduction in the elastic connection,
- a stiffness reduction in the connection between the series of arms (parameters p1 and r1), and
- a significant reduction in the thickness of the central part with a circular form (parameters h1 and h2).

5.2. SYMMETRICAL LOADING

A numerical simulation of the stress field in the final geometry (Fig.7) shows the stress level contours. The stress is uniform throughout the central zone of the specimen. The level of stress in this zone is higher than in many other parts of the specimen (Fig.8). Verifications have been carried out for a finer mesh with more than 340, 000 degrees of freedom [3].

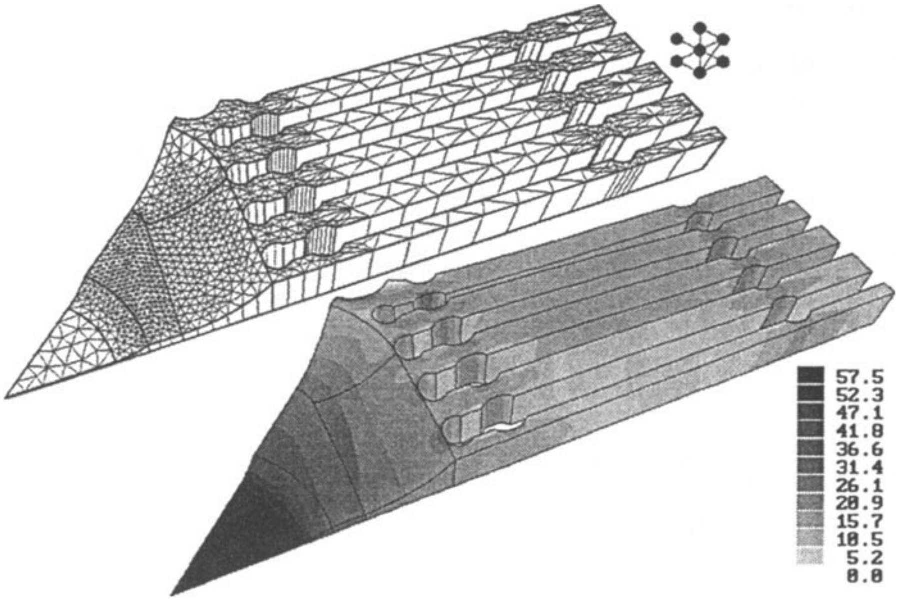

Figure 8: 1/16th of the final geometry- Mesh & Von Mises equivalent stress.

5.3. NON-SYMMETRICAL LOADING

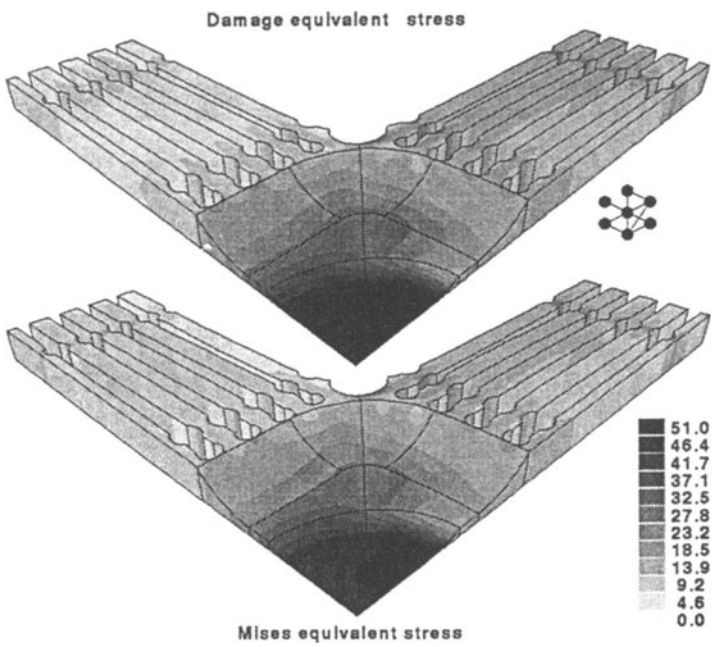

Figure 9: Non-symmetrical loading results.

The previous results have been obtained by applying the same load in both directions. It was important to check the behavior of the proposed optimized specimen in the case of a more realistic loading, i.e. different load levels on each of the two branches of the cross. This validation has been performed, and the results are given in Figure 9 both in damage equivalent stress [5] and in Von Mises equivalent stress. The results have proved satisfactory.

In linear elasticity, this simulation of 1/8th of the specimen is obtained at a low numerical cost from two calculations of 1/16th of the specimen and by applying the properties of symmetry and anti-symmetry.

5.4. EXPERIMENTAL RESULTS

The validation of the Dang Van criterion has been performed by a series of tests [2]. High-cycle fatigue experiments have been carried out using Astrée. The main results are given in Figure 10 in a diagram of shear stress as a function of the hydrostatic pressure, and the initiation limit has been plotted for 10^7 cycles.

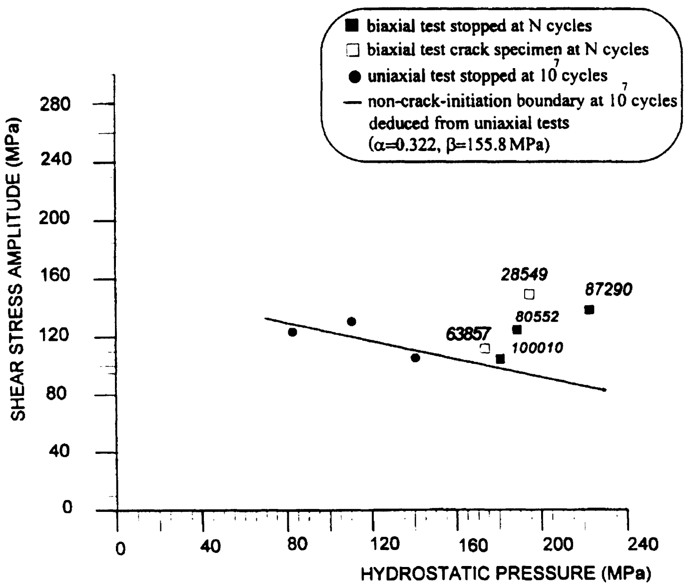

Figure 10: Experimental results and Dang Van criterion.

6. Conclusion

The design of a specimen for biaxial loading is the result of fine-scale numerical studies and appropriate mechanical tests. It has relied on the analysis of an existing solution and has continuously been upgraded by expert knowledge. The result is satisfactory. However, this study confirms the need in the numerical simulation of properly modeling the boundary conditions (Fig.7). Therefore, this study should be extended by integrating the unilateral contact conditions between the specimen and the ends of the loading actuators of the Astrée testing machine.

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HULL DESIGN METHODOLOGY FOR CROSS-COUNTRY VEHICLES

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Summary

Combat vehicles are subjected to widely varying conditions of use. On the road, they incur stresses with a broad frequency spectrum but low in amplitude, whereas during cross-country driving, large stresses are applied to the hull, causing high amplitude overall movements (pitching, roll, etc.) at low frequency.

This paper concerns only the second point. It describes a purely numerical approach used to establish static finite-element computation cases based on definition of reference terrains and vehicle architecture. This allows design offices to proceed to detailed design more rapidly and at lower cost. The method involves a wide variety of tools, such as implicit and explicit finite-element codes and dynamic analysis of articulated systems. It uses a linked sequence of loading cases to solve multilinear systems of equations.

1. Introduction

During their life, cross-country vehicles are confronted with two main types of environments: roads and relatively flat ground which generate low amplitude loading and mainly cause fatigue stressing of the hull, and rough terrain which causes large loads on the suspension and high amplitude overall inertial movements.

Whereas the first type of environment has been extensively studied for both military and civil vehicles, the cross-country environment, generally at the origin of the highest instantaneous stresses, is often approached empirically. This is especially true for vehicles with a large number of axles, which is generally the case for military vehicles.

What can be done at the preliminary design stage to specify and validate the hull design of such vehicles?

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 505–513.

Structural designing can be performed using a number of finite-element dynamic computation codes, discussed below. Unfortunately, the use of such codes is precluded in the design office because of their complexity and cost.

Below we describe an intellectual approach which considerably reduces design costs and lead times for armoured vehicle hulls without jeopardising their structural integrity. This approach also reduces the design optimisation steps during final development of the structure.

2. Context and History

The complete armoured vehicle design process, from specification of the need to building of the first production unit, covers a period of some ten years. Even though the actual designing of a vehicle lasts around five years, the vehicle designs of two consecutive generations of the same class have a completely different configuration: weight, function (troop transport or weapon transport, etc.) which considerably modifies the architecture and profile of use of the vehicle. During the fifteen years that separate one generation from the next, the technology has progressed to such an extent that the performance level has considerably affected the vehicle's capability as regards mobility (increase in specific powers, peak cross-country speed, etc.). Under such conditions, it is practically impossible to extrapolate from former designs.

At the same time, the integration of armour plating is extremely demanding on the supporting structures, which are required to be capable of withstanding higher stresses while supporting increasingly heavy armour plating. Methods are therefore urgently needed for specifying and evaluating the structural integrity of these vehicles.

3. Dynamic Hull Design Approach

3.1. INTRODUCTION

Specifications for driving on roads and level ground are developed using a frequency approach to calculate the fatigue strength. For cross-country driving specifications, the method described below evaluates the stresses arising as the vehicle moves over rough terrain. It can be extrapolated to any time-variable dynamic specification concerning short periods.

3.2. SPECIFYING THE LOADS APPLIED TO THE HULL

Earlier attempts to define stresses induced in the hull by driving a light vehicle cross country (i.e. four wheels with a load of less than one tonne on each wheel) have shown how difficult it was to identify the problem experimentally. Such attempts to quantify the loads transmitted to the hull have failed for three reasons:

* The cost of instrumenting the wheel proved prohibitive because of the level of the loads to be recorded and the particularly rough movements
* When only the wheel train components were instrumented, the measurements were insufficiently accurate for the application considered
* Finally, it is difficult to extrapolate the results obtained, because of the high variability in mobility between vehicles under test and those in design.

The experimental approach was therefore dropped in favour of a sequence of models.

Based on the profile of use of the vehicle (digitised terrains, identified unit obstacles, reference concrete tracks) and its mobility characteristics (engine, suspension, inertia, etc.), the first step consists of defining a mobility map. This is done using the NATO NRMM (Nato Reference Mobility Model) software. The map below shows the speed of movement of the vehicle over each parcel of a given terrain (one colour per maximum possible speed range). The maximum calculated speed is consistent with both the mechanical capabilities of the vehicle (engine rating, suspension movement, etc.) and ergonomic criteria (capability of the driver to withstand the shocks and vibrations).

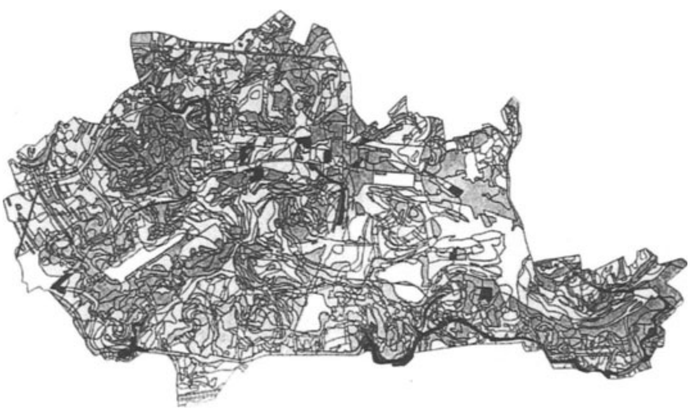


Figure 1. Mobility map of an 8 x 8 vehicle on a digitised military terrain..

Based on the vehicle architecture (suspension location), the ADAMS (Automatic Dynamic Analysis of Mechanical System) software calculates the time-variable dynamic behaviour of the vehicle and determines the loads induced in each anchor point of the hull, assuming the hull to be infinitely rigid.

Figure 2: Examples of ADAMS output for an 8 x 8 vehicle. ADAMS vue at given time.

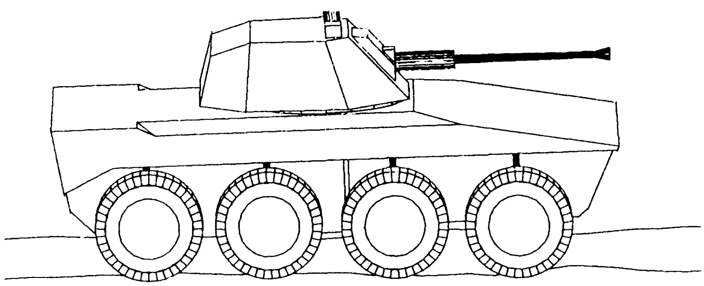
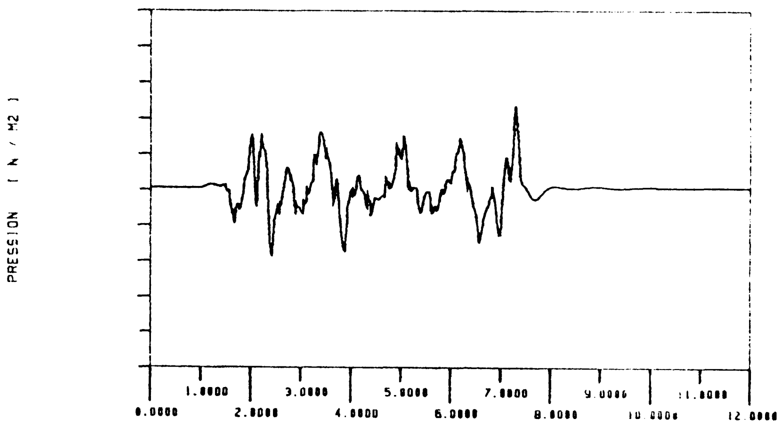


Figure 3 Examples of ADAMS output for an 8 x 8 vehicle. Load on the anchor point of one of the shock absorbers



These results can be used for:
- Fatigue analysis (not detailed herein)
- Local analyses (calculation of the strength of a suspension limit switch attachment, for instance)
- Hull structure dimensioning, discussed in the following section.

3.3. CALCULATING THE TIME-VARIABLE DYNAMIC STRESSES

The phenomena of interest to us are calculated over short periods. The terrains used for the analysis are selected according to;

- The instantaneous loads recorded
- The inertial accelerations observed.

The computations are made by dynamic finite-element codes which are either implicit (such as MEF-MOSAIC) or explicit (such as PAMCRASH which was automatically interfaced with ADAMS for this case).

A map of the time-variable stresses and strains in the hull is thus obtained for each time step.

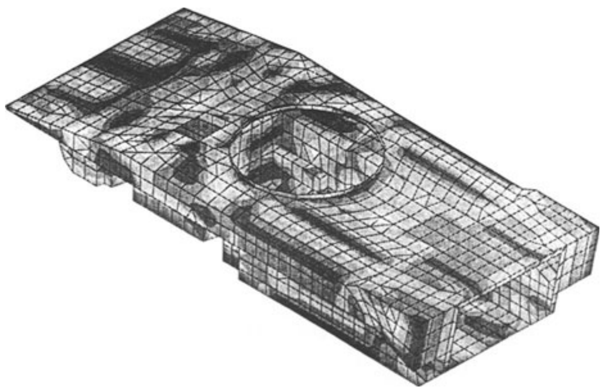


Figure 4. Examples of finite-element computation output for an 8 x 8 vehicle hull.

The stresses are then analysed based on the admissible performance capabilities of the material considered. It should be noted in particular that the analysis takes the amplification phenomena related to the natural modes of vibration of the hull plates into account.

The method as described requires approximately six man-months excluding mesh generation. It should theoretically be repeated at each stage in design, for instance when optimising the plate thicknesses or installing stiffeners. However, it cannot be integrated as such in a design office. But there is another solution, described below, rather than overdimensioning the hull plate thickness which is very costly for parts of such a size, or retrofitting additional stiffeners, which is costly during manufacture.

4. Definition of Equivalent Static Cases

4.1. INTRODUCTION

Design offices generally have static finite-element and modal analysis computation codes that are interfaced with a CAD system. Everything should therefore be done to make use of these tools. From inception, it should be attempted to express the cross-country mobility need through computation cases that are accessible for this software.

Few changes can be made to the overall architecture once the need has been defined (number of people to be transported, weapons carried, ballistic protection level, etc.). All vehicles in a given category have a maximum width and height imposed by their specification (road, rail or air transport), an overall outline guided by optimal survivability rules, and an internal layout determined by the intrinsic function of the vehicle. In other words, not much can be done to the architecture to modify the general hull modes. Although this may appear as a handicap to the designer, it is the very basis of the methodology described below.

4.2. DETERMINING THE MAXIMUM STRESSES

After calculating the instantaneous dynamic stresses on an ideal hull for each type of reference terrain identified in the mobility specification, an algorithm calculates the maximum stress in each cell of the finite-element mesh of the hull. For each cell, we therefore have:

$$\sigma max(i) = max(\sigma i(ti))$$

where:
i = cell no. ($1<i<n$)
σ = stress
t = time

This produces a finite-element map of each terrain sample specified or each group of terrains of the same difficulty. The goal is then to define the computation conditions allowing this map to be approached as closely as possible. It is therefore necessary to define:

- the appropriate stresses, and
- the structure blocking conditions

which will give the closest approach to the desired map.

4.3. DETERMINING THE REFERENCE LOADING CASES

It is attempted to define the optimal computation case as a linear combination of a series of N reference static computation cases which will induce $\sigma ref\ (i)$ in the i cells with $1<ref<N$. These reference cases are of three types:

- A static or quasi-static real case: vehicle stopped under 1 g or vehicle quasi-statically crossing a ditch with steep banks (only the front and rear axles are loaded)
- A static laboratory reference case: for instance the hull under pure torsion or a unit load under a single suspension, etc.
- A case derived from the designer's experience.

A second computation module then tests a linear combination of the reference loading cases causing the maximum stress defined above in the N critical cells.

j = number of the cell used to calculate the reference loading case with $1<j<N$

ref = reference loading condition with $1<ref<N<n$

a = coefficient of the linear combination

To select the N values of j out of the n mesh cells, we use:

* j = the first N cells such that ...
* j = the N cells selected by the user based on the areas where his attention is focused

$\sigma opt(i) = \Sigma \alpha j\ \sigma ref(i)$

$j = 1$ to N and $i = 1$ to n

The correction solution is obtained subject to satisfying several conditions:

- A limited number of reference loading cases of the same nature are submitted to the tool (for instance a linear combination of the unit loading cases on the wheels)
- The method is calibrated by analysing the static stresses in relatively unstressed regions to avoid artificially creating highly stressed areas which risk leading to overdimensioning. This is done using an automatic module which calculates the residual safety margin C for each cell, i.e.:

$\sigma opt(i) = C.\sigma max(i)$

Mapping of the residual safety margin allows rapid interpretation of this validity criterion. It is obtained by directly reading the file associating the cell number and margin C in place of one of the stresses in the MOSAIC finite-element software post-processor.
- The final design is subjected to modal analysis to evaluate the risks related to amplification of the stresses by local vibration of a plate. This is done by comparing the stress spectra on the hull with the local computed modes.

The approach is summarised in the following diagram:

Reference static loading cases
real static cases
theoretical unit case
modal analysis
specified static loading cases + limit of validity
multilinear equations to be solved

Generally, between five and seven equivalent static computation cases are sufficient to cover all the cross-country mobility specifications.

5. Conclusion

Using equivalent static cases to express the cross-country mobility specification during the design stage gives reason to expect:
* A savings in design time: the dynamic computations made at the end of the design stage show that this approach allows satisfactory placement of the most suitable reinforcements. The complete design process now involves only two dynamic computation stages - one at the beginning to express the cross-country mobility specification and the other at the end to check the result
* A savings on the weight by using reference loading cases. This allows the plates to be dimensioned accurately with no risk
* A savings on the production and maintenance costs: evaluation on operational vehicles of hull stresses induced by driving over rough terrain still all too often results in adding reinforcements after the fact or making later repairs.

This numerical method is already demonstrating its worth as an aid for specifying hulls subjected to large amplitude multiple stresses. The design engineer must however be capable of correctly defining the unit load cases to be used. Otherwise, the tool will not be able to produce a multilinear combination of loading cases which does not cause local exceeding of the elastic limit of the material, and which thereby provides a satisfactory safety margin.

Although the method has been validated theoretically, it will be a few years before a production hull dimensioned using it is driven cross-country.

A METHODOLOGY FOR THE DESIGN OF SERVO-SYSTEMS DEDICATED TO MACHINE-TOOLS

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Abstract : In this article, we present an analysis of the problems encountered during the design of machine-tools so as to obtain a synthesis of the design of controlled mechanical systems. This synthesis represents the foundation of the design methodology that we develop and apply on the pre-design of machine-tools servosystems.

1. Introduction

The success of a product depends mainly on how quickly it can be developed and renewed, and on its cost. Even if the performances of machine-tools (MT) are decisive to develop a product, the fact remains that MT are products themselves and therefore submitted to the same contraints as others. MT are among the most difficult controlled mechanical systems (CMS) to design and manufacture as they are submitted to strong constraints due to required performances, reliability and cost. This explains why MT manufacturers keep using traditional methods of design [1].

These methods based on experience remain the most suitable when compared to required performances. However experience would be greatly improved were it completed by rules of design and supported by a design methodology. Scientific studies are being carried out in this direction. Design methodologies include everything from the stated performance requirements to manufacture [1] [2]. Local problems of design are solved on CMS [3] [4]. We will suggest a methodology limited to the design of servo-systems whose process is identical to one used by design departments. Based on the CMS stated performance requirements we will suggest the design of CMS thanks to the management of each of the two stated performance requirements : that of the mechanical part and that of the automatic part.

P. Chedmail et al. (eds.), Integrated Design and Manufacturing in Mechanical Engineering, 515–524.

2. Problems encountered during the design of controlled mechanical systems.

2.1 SUGGESTED ANALYSIS OF PROBLEMS ENCOUNTERED DURING DESIGN.

2.1.1 Process of machine-tools design.
Three phases can be determined during the design process, each step being the implementation of the guidelines established in the previous phase :

1) *Structural choice of design* : The designer makes the first choice concerning the type of standard mechanical components : motricity, cinematics, the mechanical architecture for the mechanical part, the measure location and type of control for the automatic part. This first phase is often ***carried out*** during technical meetings prior to the beginning of the project. It constitutes the guidelines given to the mechanical designer. Often made in an empirical way from the existing machine analysis, it characterizes however the spirit and innovation of a MT manufacturer.

2) *The design proposition* : This is a validation of the feasability of the structural choice of design through a constructive proposition based on drawings and simulations. Additional choices have to be made : as regards some of the components (fixing of a feed screw, choice of guidance..) the design of some bodies to obtain a given dynamic behavior (calculation of a framework...) and calculation of control parameters. This design step which corresponds to a juxtaposition of local resolutions can be sustained by optimization tools.

3) P*rototype manufacturing* : The prototype is manufactured and a testing compaign is carried out. These tests constitute the real validation of design.. This phase is the longest and the most expensive. If the prototype does not meet requirements, the fact of answering these 2 questions « How and where should the prototype be modified ? » means that the design process has to start all over again.

2.1.2 Emergence of the interdisciplinarity in design.
In this difficult design context, the growing increase of dynamic performances (simultaneous velocity and precision increase) entails the interaction between the mechanical and automatic choices during design. Thus these two disciplines can no longer be taken into account separately as this was the case previously. Design management then becomes more and more complex and requires an interdisciplinary approach of mechanics and automatics, which could be called : mechatronic design. An interdisciplinary approach in design means phenomena need to be understood in their specific context (monodisciplinary approach), in their simultaneity (pluridisciplinarity) and their interactions (interdisciplinarity). New modeling approaches have to be developed because detailed modeling are non-efficient to get a global comprehension of all the phenomena.

2.2 SYNTHESIS PROPOSITION OF DESIGN PROBLEMS

2.2.1 Proposition of synthesis of the design process including the inversion problem. We will illustrate this proposition with the CMS control synthesis. A mechanical system MS_1 which is modeled by a rigid body with a mass M, slipping without friction on a horizontal plan and activated by a force F_c.The position control PC_1 contains a velocity loop and the desired position is $x_0(t)$. The whole set is called CMS_1 and is presented on figure 1. Its dynamic behavior is given in equation (1).

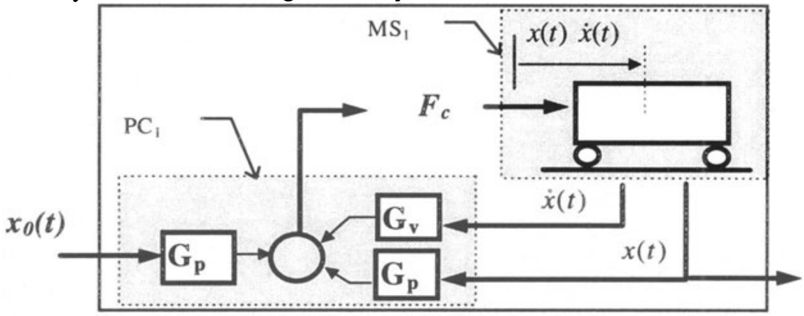

Figure 1 Position controlled rigid mechanical system

$$M.\ddot{x}(t)+G_v.\dot{x}(t)+G_p.x(t) = G_p.x_0(t) \qquad (1)$$

2.2.1.1 *Analysis-direct problem, synthesis - inverse problem.* The analysis phase consists in the development of knowledge that solves and explains a concept without communicating new information [5]. It is obtained thanks to the direct resolution (direct problem) of ordinary differential equations (ODE), i.e. : the simulation and description of the temporal behavior x(t) for $x_0(t)$ and M and Gv and Gp given. The synthetic process is informative and links different concepts [5]. It is connected to the inverse resolution of ODE (inverse problem). In the proposed example this resolution consists in finding control parameter values G_v, G_p so as x(t) has a given temporal behavior for set $x_0(t)$ and M. An analogy with the linear system resolution clearly shows the level of difficulty. Given a linear system c=A.b where b and c are two vectors and A is a matrix. In analogy, the direct resolution consists in calculating c knowing A and b while the inverse resolution corresponds to calculating A knowing b and c. The level of difficulty is at least equivalent to the one of the linear system inversion problem.

2.2.1.2 *System structure.* According to the theory of systems, the structure of a system is a notion linked to organization. It can be considered at different levels [5]. An example given by the CMS_1 would be the use or not of the velocity measure in the control. This measure modifies fundamentally the possible behaviors of x(t) whatever the control parameter Gp and the mechanical parameter Mr may be. The analogy with the linear system resolution is significant. The structural properties of the matrix -the existence of a column or a line of zero- are one of the causes of its noninversibility.

2.2.1.3 *Optimization tools problems*. The development of computer tools -the calculation method and optimization method improvements and computer improvements- has led to think that a global optimization of CMS could be done. But two difficulties come up around the structure of the non-optimized system part:

- behaviors of optimized solutions are linked to this structure;
- the number and nature of parameters to optimize are also linked to it.

Thus to obtain a global optimization, the structure optimization and that of its associated parameters must be carried out simultaneously. Now the only optimization techniques used are limited to choices of parameters for a given structure. A structure optimization entails inevitably the existence of redundant parameters. Therefore it often leads to the local minimum. If optimization tools perfectly solve local calculation problems of mechanical structures and control parameters, they solve only in part problems of structural choice.

2.2.2 Proposition of synthesis of the problems linked to interdisciplinarity.
This proposition of synthesis is based on the design process used in the aerothermal domain (exchanger design). Indeed, it constitutes a typical interdisciplinary field. The physical laws used are those of aerodynamics (Navier-Stocks equations and Euler equations) and those of thermal (Fourrier equations). Each of these fields is, in itself, a source of difficulty even during direct resolutions (analysis step). However managing the interaction between these two fields can be achieved by a purely interdisciplinary approach. It is restricted to the dominant phenomena of this interaction. The exchanger design is controlled for each problem to solve, thanks to invariants or numbers without dimension (Nusselt number, Prandlt number, Reynolds number) whose coefficients or parameters are obtained by experimental correlations. Monodisciplinary improvements are carried out only at the end of the design process. These correlations are often necessary to offer initial conditions of direct resolutions. Through the latter, correlations can be explained more accurately than through experimental techniques. The design process used in the aerothermal field clearly underlines the need to develop new interface disciplines compared to those that already exist and also the need to manage them prior to any other.

2.2.3 Suggested principles and rules concerning the design process.
It seems that two principles constitute implicitly the limits of our ability to understand and design.

1) *The extrapolation principle* : it characterizes how difficult it is to imagine other objects than those that exist. Thus progress can only be based on experiments and it corresponds to an extrapolation of these experiments (under multiple forms). The accumulation and the need for new experiments constitute one of the best means to lessen the problem of imagining new things.

2) *The hierarchy principle* : this is not a property of physical phenomena which are often parallel and independent, but is a tool and a subterfuge that shows how difficult it is to apprehend complex and multiple objects. The development of new hierarchies set up to help in the understanding and the systematic doubt, as regards their

efficiency, seems to be the only artificial way to lessen this impossibility to control complexity.

From these two principles, rules can be infered to implement design. Thus an efficient desig process can be offered.

From the extrapolation principle the following needs can be infered :

- *The analysis of the systems to be designed* i.e. a clear understanding of the behavior of existing CMS. This is the preliminary step in any design.
- *Modelling* : it constitutes the tool and support of this analysis. It formalizes the experiments that enable their extrapolations.

From the hierarchy principle the following needs can be infered :

- *Design process* : it is unavoidable and adds up to organizing priorities and to suggesting a way to handle priorities.
- *Structural choices prior to any other choice* : they correspond to design guidelines adopted obviously from the beginning. They are implicitly organized and, if possible, they should be reexamined through the consequences of the next step.
- *The separation of objects handled has to becarried out,* the classification of scientific disciplines being the most significant example.
- *Reduction of physical phenomena to their essential features as regards their uses and the problem to solve* : this reduction is needed to extract design rules. Thus these design rules amount to local inversions of the analysis as [6] [1] suggest.

To these design rules, it is necessary to add those due to the interdisciplinarity of design problems :

- The development of interdisciplinary disciplines is essential to handle discipline interaction;
- The interdisciplinary approach has to be dealt with before tackling the pluridisciplinary aspect.

3. Suggested methodology in the design of machine-tools servo-systems

In this third part, we will present first of all the CMS design process that we develop and then the applications on the design of high speed machine-tools.

3.1 PRESENTATION OF A GENERAL METHODOLOGY OF DESIGN.

The methodology presented here stems from the rules stated in paragraph 2.2.3. It is therefore progressive and organized into a hierarchy. It starts from the global to go to the local but also from interdisciplinarity to pluridisciplinarity. It results implicitly in the formalization of the process used by mechanical and thermal design departments. It is limited to the CMS pre-design based on stated performance requirements carried out in a preliminary phase. Pre-design enables to establish structural choices of design among compatible mechanical automatic parts. We suggest to deal with these choices using design rules in the form of emnedded stated performance requirements. Considering the formalization of design rules obtained, this process is likely to be supported and completed by decision-assistance tools.

This methodology is divided into three steps :

1) Identifying problems to solve

a) Global analysis of problems of the CMS to design in order to distinguish the large systems.

Notions of system analysis with Bond-graphs, for example [7], could be used so as to identify systems and flows of energy between them. The use of impedance and admittance notions should help to deduce a causality between systems [8].

b) Analysis of scientific disciplines to determine their interactions.

After having underscored an interaction between two scientific disciplines, it is necessary to develop a study to control this interdisciplinarity. These studies will precede monodisciplinary studies connected to them.

Thanks to this first step, the problems encountered in a hierarchy can then be organized to offer a procedure for the pre-design study.

2) Developing interdisciplinary design rules

Although the described approach is presented to develop interdisciplinary design rules, it also applies to the development of monodisciplinary design rules which is already set up in most cases.

a) Modelling of dominant interdisciplinary phenomena.

After having identified and characterized the dominant phenomena of the interaction, modelling will have to be made by a reduction in physical terms. The model reduction must preserve the physical meaning of what has been reduced.

b) Local inversions for the development of design rules.

On the basis of models in the analytical form, local rules on design can be established. The hierarchical management is similar to an inversion by part. This inversion is inevitably rough, but it is operational to offer a pre-design.

3) Predesign.

a) *Predesign proposition.*

The research of the design optimum based on proposed rules and processes will be made by hand or by decision-assistance tools. This pre-design proposition will only concern interdisciplinary choice and monodisciplinary choices with an influence on structural choices. The design optimum will be even better than usual because design rules are not redundant. The cost aspect can be taken into account during the predesign. The cost of each design proposition will be calculated from databases. Therefore cost will intervene as a choice criterion to obtain either a servo-system on a minimal cost basis or the best design at a given cost.

b) *Predesign validation.*

The validation of structural choices decided in the previous phase can be carried out by classic analysis tools (simulation, test beds for local problems...). They contain mechanical structural choices (from technological components to dynamic behaviors of mechanical structures) and automatic structural choices (development of a control based on the supposed behavior of the mechanical system). The behavior models used will be more sophisticated than those that have been used to establish the design rules. Thus some hypotheses used to elaborate the design rules could either be validated or invalidated.

c) *Establishing the mechanical and automatic stated performance requirements.*

Thus, following the structural choice validation, various monodisciplinary stated performance requirements will be presented to each discipline specialist (monodisciplinary designer). The stated performance requirements of a mechanical structure calculation is similar to that of a technological component. When one of the designers cannot meet the stated performance requirements, with design rules, some decisions may be changed and passed on to modify the other monodisciplinary stated performance requirements.

Besides the fact that this methodology is applied to the machine-tools design, this process to handle design in its whole is close to that of F. Pruvot [1]. The most significant differences seem to concern justifications and application areas. In this Study we use a necessary hierarchical organization of disciplines and we have limited our study to the CMS design.

3.2 PROJECT OF HIGH SPEED MACHINE-TOOLS DESIGN.

We will apply the method for high speed machine-tools design and we will present new design rules. Stated performance requirements includ congestion, rapidity, precision, acceleration capacity and chips rate. Design management is presented on figure 2.

3.2.1 Presentation and justification of the sequence of studies

If a machine-tools is considered in terms of CMS, two CMS that interact with other can be noticed : the servo-system that gives the cutting motion and the CMS that gives feed motion. From the studies carried out on flexible manipulator force controls [10], it is common knowledge that the dynamic interaction between CMS is all the more important as their bandwidths are wide. Thus, a dynamic interaction study between the spindle and the feed motion system (FMS), through high speed cutting phenomena, has to be done. This study will then help to determine the performances to each of the two CMS have to reach: these are respectively the stated performance requirements of the spindle and the of FMS.

The FMS is a multi-axis system whose performances are directly connected to those of each of its servo-system (one degree of freedom CMS or axis for MT). A study of the multi-axis system has therefore to be led so as to establish the necessary conditions on each servo-system to obtain the required performances of the multi-axis system. Thus a coordinated management of stated performance requirements for each servo-system is obtained.

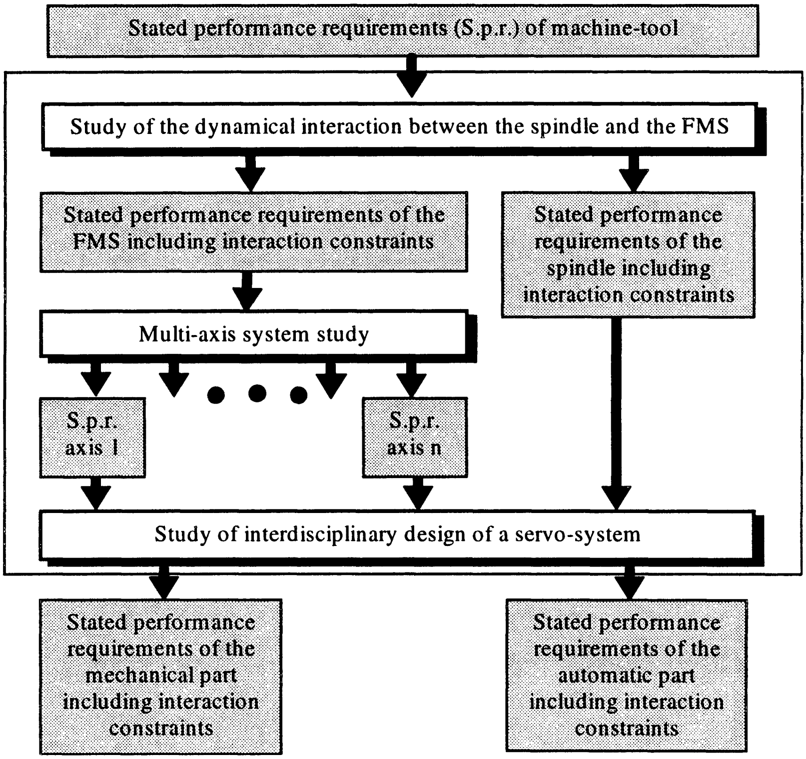

Figure 2 : Machine-tools design process

The machine-tools design being broken down in the sum of servo-systems, the interdisciplinary design of a servo-system will have to be carried out. Based on the stated performance requirements of each servo-system, a predesign of each of them is determined and the stated performance requirements of the mechanical part and that of the automatic part will be drafted. Therefore interdisciplinary design rules are developed.

3.2.2 Description of developed studies

3.2.2.1. Study of the dynamic interaction between the spindle and the feld motion system.

If the direct dynamic interaction between CMS is a problem partly solved thanks to the passivity approach [9], [10], the coupled CMS through non-linear phenomena can be the source of coupled system dynamic instability. The dominant phenomenon in the interaction between the spindle and the FMS is therefore linked to the cutting phenomenon. To ***carry out*** the interaction study, each CMS must possess at least an elasticity, an amortization and a mass. Each CMS having an impedant behavior opposite the cutting phenomenon, a cutting model in the form of an admittante two-port system [8] [7] has to be developed. Based on the case of an orthogonal machining, the behavior model of the whole spindle-cutting phenomenon-FMS in the form of a system of non-linear ordinary differential equations can then be infered. A stability condition of the global coupled system is developed. The condition is similar to a non-chatter condition.

3.2.2.2 Study of multi-axis systems.

The dominant behaviors of the servo-system produce the most important CMS tracking errors. Thus these errors can be correctly approximated thanks to the errors of servosystems which have a second order behaviour. A first study shows that the homogeneity of thedynamic behavior (rapidity, overshoots, acceleration) of each servo-system in a three axis MT is required to obtain segments of a straight line without geometrical tracking errors. A first maximal tracking error quantification has been characterized.

3.2.2.3 Study of the interdisciplinary design of a Servo-system.

The problem of the position measure location and of the velocity measure location on each servo-system can be solved, thanks to the colocation concept, with the measure location problem for the reduced mechanical system [11], [10],shown in figure 3 and witch includes one spring, one damper and two masses. After having deduced the reduced mechanical system which corresponds to the rigid-body and the first flexible mode of the mechanical system, a connection between the mechanical system behavior (M_1, M_2, K and D) and the measure location (the 4 possible cases are as follows $(x_1, \dot{x}_1);(x_1, \dot{x}_2);(x_2, \dot{x}_1)$ or $(x_2, \dot{x}_2)$) can be determined enabling the servo-system to reach a given dynamic performance (precision and rapidity). On account of the present developments, we suggest to deal with the following performances : the static error (traking error for a simple given position, for example) and rapidity (bandwidth, amortization).

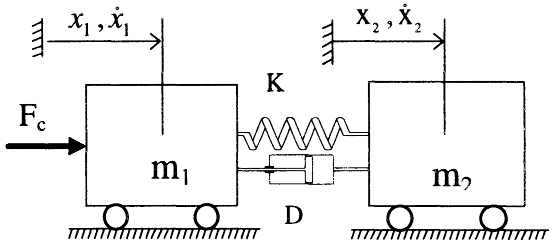

figure 3 : Two degree of freedom mechanical system

Interdependence rules between the mechanical structure of the machine (mechanical architecture, position of the slides in relation to external forces, external torques and the percussion point, and the cantilever-beam distribution), the maximum torque motor and the servo-system accuracy are now being developed.

4. Conclusion

In this article we have offered a methodology to design servosystems of controlled mechanical systems. The setting up of a process and the development of interdisciplinary design rules allows the implementation of a predesign step, that leads to simultaneous and coordinated management of the automatic and mechanical stated performance requirements for the design of CMS. We have shown the feasibility of such a methodology through its application to the design of high speed machine-tools. Additional design rules will obviously need to be added to the design rules presented succinctly here.

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METHODOLOGY FOR INTERACTIVE DESIGN OF A PRODUCT AND ITS ASSEMBLY LINE.

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Abstract. This paper describes a methodology for the interactive design of a product and its assembly line. The main originality of this approach is to investigate heterogeneous lines, comprising manual, automatic and robotized workstations. The discussed methodology is based on the observation that essential characteristics of an optimal product design can be determined regardless of production conditions.
In the first step, performances of all the assembly operations are evaluated for different assembly methods leading to an optimized product design and information for the assembly line design. The second step concentrates on the balance of the assembly line taking into account the required production volume.

1. Introduction

In today's rapidly moving market, manufacturing firms are compelled to greatly reduce the time to market and in particular the development time in order to develop new products at an increasingly rapid pace. It is now widely admitted that many decisions taken at the design stage are decisive for the entire product life cycle.[1] Studies have shown that large portions of manufacturing costs are determined at the early stage of the design and that any change at a later stage dramatically increases the production costs.[2,3] Assuming that product functional requirements are met, the problem is to consider ease of manufacturing and assembly. The best results are achieved when product design is performed interactively with the production line design. Some years ago Professor Boothroyd and his collaborators proposed a new Design For Assembly method [3] which is certainly the most popular and interesting approach available in the marketplace. In this method, the a priori choice of an homogenous assembly line simplifies the product analysis and requires only relative comparison of the design efficiency without any line considerations, leading to a design optimized for only one particular assembly method. However, real assembly lines are rather heterogeneous (e.g. containing manual and robotized stations) than homogeneous. Furthermore, the

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considered mounting chronology is simply the reverse dismantling order and the receptor (base part) is usually the last part of this dismantling. It will be shown that it can be useful to modify the mounting order and/or the receptor choice. This method only focuses on product design and not on assembly line design and, for this reason, cannot be considered as an interactive procedure. DFA methods are often used as the first stage of an iterative approach [4,5]. The second stage is the process planning which consists of developing the liaison diagrams, then all the possible assembly sequences are determined and compared. It usually leads to a limited number of eligible assembly sequences which will be balanced at the next step. Finally, based on environmental constraints such as equipment available in the workshop, the physical assemoly line can be generated (Resource Planning). Many efforts have been made to ensure quick complete iterations of the whole procedure. However, this widely used approach does not always lead to an optimal solution. Product revisions occur only if no acceptable balanced solution can be found. Sometimes a small product modification will make a rejected assembly sequence very attractive.

The aim of the approach presented in Figure 1 is to interactively design the product and its assembly line.[6] The approach is composed of three steps: in the first one, the initial design of the product is performed based on product functionality and Direct DFA (general DFA rules). This initial design will be optimized during the second stage. The comparison between different product designs is performed by calculating an economic indicator CIC (Comparable Indicative Cost) for each operation and for different assembly methods (manual, robotized and automated). The result of this second step is an optimized product design and an operating chart with the corresponding assembly method. The third step concerns the assembly line balancing problem and, in general, minor product design adaptations are still allowed at this stage.

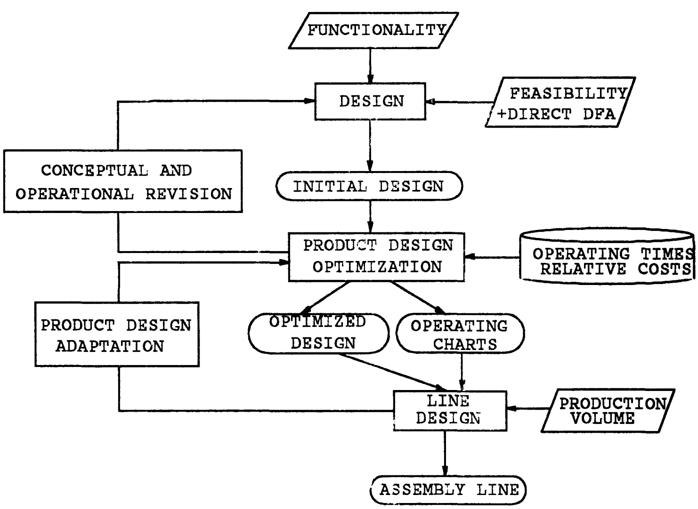


Figure 1. Flowchart of interactive methodology

2. Product Design Optimization

2.1. ASSEMBLY SEQUENCES

The first stage of the procedure presented in Figure 1 is to analyse the product design in order to single out subassemblies. A simple factor complexity has been defined to determine whether a redesign is recommended in order to create subassemblies [6]. Then each subassembly is analysed separately. As mentionned above, the mounting chronology may be an important factor in the cost analysis, we recommend to start with the reverse disassembly order. If this order gives overall satisfaction it becomes the final mounting strategy. Otherwise it is possible to select another base part or another mounting order mainly to eliminate some useless handling or reorientation: this is what we call an operational revision of the subassembly. Sometimes such a modification also implies a conceptual revision. Assembly sequence evaluation is made in a qualitative way; the aim is to choose one good mounting order (and not necessarily the best one) and to redesign the product in order to obtain a design which will allow proper line balancing. Such an optimal design can be characterized by very simple operations, short in time and independent of the type of equipment. It is quite obvious that such a goal will generally be difficult to reach, chiefly with stacked products.

2.2. CIC ANALYSIS

When the first assembly sequence has been determined, the CIC computation can begin. This evaluation criterion has the dimension of a cost but is not a real assembly cost and is mainly used to summarize the operation characteristics of a given assembly method. At this stage only the necessary equipment and operators during production time are considered [7] and the production volume is not yet taken into account.

2.2.1 CIC Structure

The Comparative Indicative Cost (CIC) is defined as the cost to prepare and insert a part (or to perform an assembly operation). For each assembly operation, the following cases are considered, that is to say :

a) Full manual operation (M+M) : Handling and insertion are performed manually by an operator using, if needed, a hand tool.

b) Assisted manual operation (A+M*) : An assisted manual operation means that the part preparation is performed automatically using a vibratory bowl feeder.

c) Automatic preparation followed by an automatic insertion (A+D) or (A+R) : The reference case consists of an automatic preparation using vibratory bowl feeder followed by an automatic insertion performed either by a dedicated machine (A+D) or a robot (A+R).

d) Automatic insertion from manually loaded magazines (K+D) or (K+R) : The reference case (known as "kitting") is a part tray in which parts are manually inserted without effort in order to prepare an automatic insertion.

2.3 CONSTITUTION OF CIC TABLE

After computation, all the information related to a product is summarized in a table (See Figure 2 for the case study table). This chart contains the operation order number (N), operation name, 0/1 index which indicates if the operation is a candidate for suppression (0) or not (1), the number of repetitions of this operation (NR) and the CIC. By looking at this table the designer can immediately identify the parts that cause trouble and see where to concentrate his efforts (high CIC). A conceptual redesign of the product can be performed in order to suppress superfluous parts or to reduce the CIC for each operation and assembly method.

				PREPARATION (1)			INSERTION (2)				COMBINATIONS OF (1) AND (2)					
N	OPERATIONS	0/1	NR	K	A	M	M	M*	D	R	M+M	A+M*	K+D	K+R	A+D	A+R
0	STATOR	1	1	1.51		0.75	0.91		0.13	0.64	1.66		1.64	2.15		
1	BCK FLANGE	1	1	1.51		0.75	0.91		0.17	0.57	1.66		1.68	2.18		
2	SCREWS M6	0	2	1.21	0.19		6.04		0.95	2.31	6.04		2.16	3.22	1.14	2.2
3	BCK FLG BEARING	1	1	1.29	0.15	0.57	3.62	4.22	0.36		4.19	4.37	1.65		0.51	
13	VALVES	1	2	4.06	1.53	2.36	3.02	3.55	1.06	2.23	5.38	5.08	5.12	6.29	2.59	3.76
14	STOPS	1	2	4.06		2.36	3.02	3.55	0.69	2.23	5.38	3.55	4.75	6.29	0.69	2.23
15	COVERS	1	2	3.56	5.11	1.95	1.81	2.18	0.69	2.23	3.75	7.29	4.25	5.79	5.8	7.34
16	SCREWS M4	0	14	8.46	0.54		42.28		6.64	9.74	42.24		15.1	18.2	7.18	10.28
			44				114	39	20	39	126	61	62	79	41	59

Figure 2. *CIC (in BEF, 1 US $ = 30 BEF) for the case study.*

The best design is obtained when (i) the superfluous, or too complicated, operations are eliminated and (ii) for an assembly method the CIC of each operation is equal to a minimal value A (e.g. in manual assembly, A is equal to 1.5 in Belgian currency)

It might be interesting to obtain equivalent CIC for the different assembly methods leading to a product that can be assembled either manually, automatically or using a robot. This is not always possible, furthermore, some operations cannot be performed using a particular assembly method. For example, the stator (case study) cannot be prepared automatically using a vibratory bowl feeder but only manually or using kitting. If all the conceptual revisions have been exploited without a significant improvement in assembly performances, the designer can reconsider the mounting chronology chosen at the previous step of the analysis. If any improvement can be made, the last possibility is to make a complete product conceptual revision. The results of this stage analysis are: a redesigned subassembly, an operating chart containing the succession of the necessary assembly operations with their possible assembly methods and a chart with assembly time operations.

3. Line design

The main problem in the line design is the line balancing which consists of allocating assembly operations to homogeneous stations. Ideal line balancing is reached when the cycle time of all the stations are equal to the throughput time of the line which is a productive constraint, leading to an ideal continuous flow of products. CIC analysis is performed on the assumption that equipment is always in a productive state, i.e. the required production volume reaches the full equipment capacity. At this stage, the required production volume is taken into account. Capacity of the equipment being greater than the required production volume, the equipment is not fully used and the production costs increase. Furthermore, operation allocation in the stations further reduce the equipment occupation rate of the fastest stations. As mentioned above, the assembly line can be heterogeneous: all types of assembly methods (manual, automated, robotized) have to be considered for each station. As a consequence, line balancing is not trivial due to the number of possible solutions. It should be kept in mind that the station should be homogeneous: operations can be clustered into a station only if they are of the same method type, although not always the most optimal.

3.1. PROCEDURE

The line balancing problem can be broken down into the following steps :

1. Evaluation of operation cost and time at the optimal production volume,
2. Determination of the throughput time (cycle time T_{cl}).
3. Selection of an admissible dispersion rate for the stations (π_j).
4. Operation allocation on homogeneous stations according to the dispersion rate allowed. Different line configurations are possible.
5. Cost evaluation for each possible solution.
6. Selection of the most economical balanced line.
7. If no solution can be found, partial redesign of the product design or assembly equipment.

The cycle time of an operation T_i is the technical time necessary to carry out the operation. The most useful data are given in the literature [3] or can be experimentally determined for a specific product [8, 6]. The associated costs (*CIC)* are generally determined at the optimum capacity of the equipment [6, 9].
The throughput time of the line T_{cl} is inversely proportional to the expected annual production volume *Vt*. According to the annual number of seconds available per shift-year (*6 10*^{6}) and the number of shifts per day *Npt* , the throughput time is as follows :

$$Tcl = \frac{6.10^6 \times N_{pt}}{V_t} \qquad (1)$$

3.1.1. Dispersion rate

The dispersion rate of a station π_j is the relative difference between the station cycle time Tj (=ΣT_i) and the line cycle time T_{cl} . The dispersion rate of station *j* realizing operations *i* is given by :

$$\pi_j = \left| \frac{(\sum T_i) - T_{cl}}{T_{cl}} \right| \quad (2)$$

For example, with a cycle time of 12 sec. and a dispersion rate of 20%, the cycle time of each station must be in the range 9.6 to 14.4 sec.

3.1.2. Operation allocation

In our study, the stations can be manual, dedicated or robotized. In order to lower the dispersion rate of each assembly station, successive operations are grouped on homogeneous stations until the determined cycle time is reached. The number of operations per station will vary with its nature. If no solution can be found, the station must be split into two or more identical stations of the same or different natures.

During this analysis, different factors have to be taken into account, for example :

- The combination of operations with quite different cycle times usually leads to an unavoidable over-cost of the under-employed equipment.
- Some operations cannot be carried out on a manual, dedicated or robotic station.
- Some very typical operations cannot be coupled with others on the same station due to technical or timing constraints. Those operations create a common node for all the configurations of the line presented in the tree.

Several configurations can be extracted from this analysis by pointing out the continuous paths from the first to the last operation. Different paths could have the same configuration for more than one station. When a common node is found, all the following stations are of the same two configurations.

When no acceptable solution can be found due to the imposed dispersion rate or the specific technical constraints; several solutions can be proposed :

- Redesign the product in order to optimize the components design (suppression, combination, redesign,...).
- Permute operations with different cycle time, if allowed in the assembly sequence.
- Design assembly equipment more efficiently in order to decrease the cycle time of specific operations (ex.: multi-screwdriver).
- Work with a higher dispersion rate, which introduces an unavoidable over-cost due to lower quality of the line balancing.

3.1.3. Cost evaluation

The cost computation described in the previous step must be used in order to choose the most economical line configuration. All equipment costs must be weighted depending on their under-use. The operation cost of each station now depends on the cycle time of the slowest station. Furthermore, equipment clustered in a station is used only during a fraction of the station cycle time corresponding to its specific operation and is idle for the remainder of the time cycle.

3.1.4. Selection of the most balanced line

Based on the time and cost evaluations, the most balanced lines can be selected, by summing up the various individual stations. The line balancing defines a logic line which can be materialized according to other criteria, such as : available space, type of transfer pallet, type of circulation among the stations,...

3.1.5. Reconsideration of the product design or assembly equipment

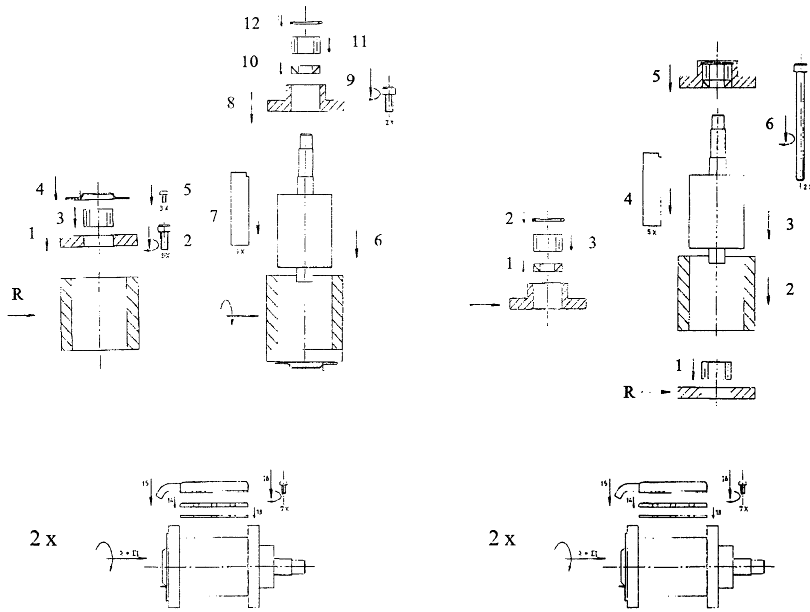
Several operations can penalise the line design due to their assembly cycle time, their equipment cost or other specific characteristics. The line balancing described above highlights the most expensive operations and focuses on a possible redesign of the product or of the equipment for those operations. In the case study, a screwdriver carrying out 7 successive operations is replaced by a multi-screwdriver performing these operations simultaneously.

4. Illustration of the interactive methodology : vane compressor

Considering the capsulism containing rotor and vanes of a vane compressor, see [6], the first step in the procedure is to choose the receptor and the assembly sequence. The last part in the dismantling is the stator. This seems to be a good choice because it is a stable container and choosing any flange would introduce too many useless turnovers. Figure 3(A) presents the first mounting chronology. The first operation is to place the back flange on the stator (1) and secure it by two screws (2), insert the bearing (3) and the deflector (4) and secure it by three screws (5). These operations can easily be performed by a top-down movement and constitute a temporary subassembly which should be turned over in order to facilitate assembly of the rotor (6) and the vanes (7), the front flange (8) secured by 2 screws (9), a seal (10) and a needle bearing (11) secured by a circlip (12). Then two valve plates with their stops and covers are screwed on the sides of the stator. Figure 2 presents the CIC table for this initial mounting chronology. It should be noted that in this mounting chronology assembly of the needle bearing (11) requires a double adjustment respectively with the front flange and the shaft; such situations should be avoided. The third column of CIC table shows that screws (2) and (9) are candidates for suppression but, because of functional requirements, cannot be eliminated. However, these four screws may be replaced by only two longer screws as depicted in Figure 3(B). This conceptual revision shortens the necessary amount of operations but still contains too many turn overs. So, to eradicate them, we decided to consider the back flange as the base part (operational revision). To be acceptable, this new receptor choice requires an induced conceptual revision which consists in incorporating the deflector with the bottom of the housing (enrichment of the housing functionality).

4.1. LINE BALANCING

With a throughput time of 12 sec (which is equivalent to 500.000 unit/shift-year) and a dispersion rate of $\pi = 0.1$, the time rate for each station has to be in the range 10.8 to



(A) Initial assembly sequence

(B) Final assembly sequence

Figure 3. First and final assembly sequences

13.2 sec, but no solution can be found. Figure 4 presents distribution of operations per station for the manual (M), dedicated (D) or robotized (R) solution for an admissible dispersion rate of 0.2 (9.6<Tj<14.4 sec). An appropriate cell is represented by a continuous vertical arrow.

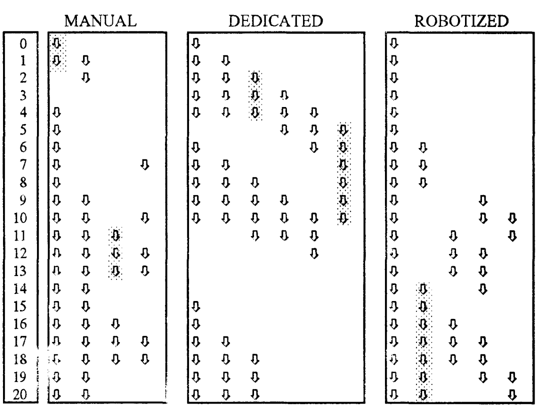
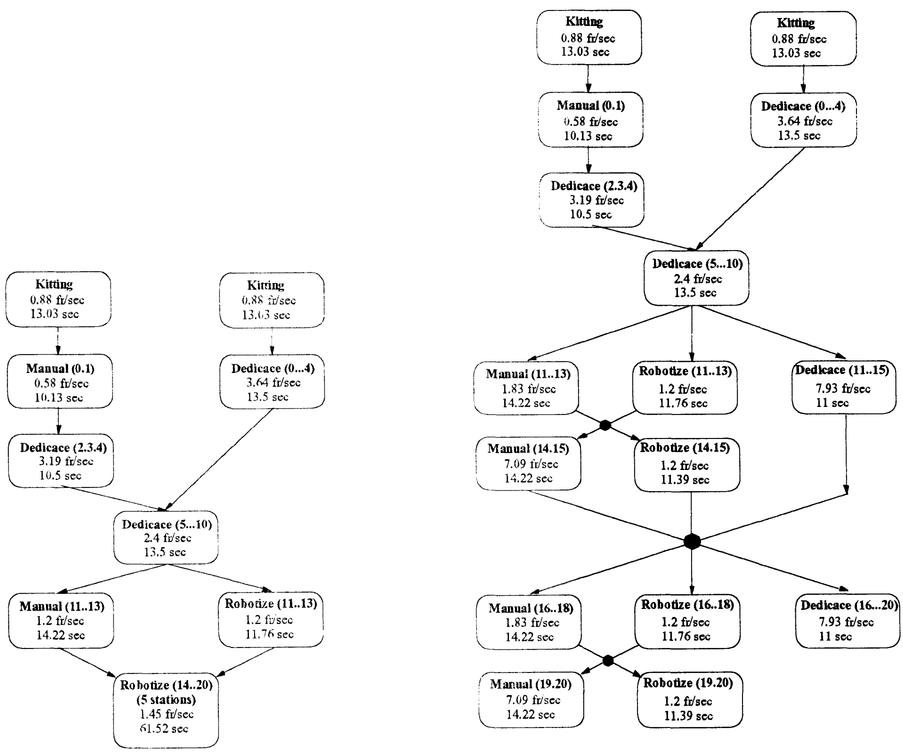


Figure 4. Operation allocation

In order to visualise all the combinations, the different solutions are presented in a simplified graph (figure 5,A) where we can observe that :

- Operations 0 to 4 can be performed either on a dedicated station or on the combination of a manual and a dedicated station.
- Operations 5 to 10 can only be performed on a dedicated station.
- Operations 11 to 13 can be performed either on a robotized or manual station.
- Operations 14 to 20 can be performed on a multi-robotized station. 5 parallel stations are needed to obtain the desired time rate.
- A kitting station must be inserted at the beginning of the line in order to place the components n° 2, 5, 7, 14 and 19 on the transfer pallet.

Figure 5 also indicates the optimal time rate of the individual stations and the equivalent cost per second. If operations 11 to 13 are perform on the manual station, the throughput time of the line is 14.2 sec. On the other hand, if they are perform on a robotized station, the throughput time is 13.5 sec. This means that all the stations have the same time rate, even if they could work faster.



(A) First balanced workstations (B) Balanced workstations after reconsideration

Figure 5. Combination of balanced stations

4.1.1. Selection of the most efficient line

Comparison of the cost of one compressor assembled on the 4 heterogeneous lines described above, is presented in table 1.

Table 1. Cost comparison for different line configurations

Line configuration	Time rate (sec)	Cost rate (fr/sec)	Cost (fr)
1 / K-M-D-D-R-5*R	13.5	15.5	209.25
2 / K-D-D-R-5*R	13.5	15.4	207.90
3 / K-M-D-M-M-5*R	14.2	15.8	224.36
4 / K-D-D-M-5*R	14.2	15.7	222.94

The first two lines are equivalent with a preference towards the second one, with no manual station included. The technical reason is that the manual operations (0..1) of the first station can be performed on the dedicated station (2..4) and so produce a better occupation rate. The most manual line (3) is the less economical one due to a greater cycle time and a bad occupation rate for stations (0.1) and (2...4) introducing a excessive cost due to the under-usage of the corresponding equipment and/or operator.

4.1.2. Reconsideration of the product design or assembly equipment.

Operations 15 and 20 related to the 7 screws are the most expensive in the line. We decided to introduce a multi-screw driver performing those operations simultaneously. The cost of this equipment is considered to be 7 times that of a simple screw-driver and the corresponding time cycle is divided by 3. This leads to a new station combination as presented in figure 5,B. It can be observed that several possibilities now exist for operations 11 to 20. Eighteen different configurations are possible from the balancing point of view but the most efficient configuration is :

K - D (0..4) - D (5..10) - R (11.13) - R (14.15) - R (16..18) - R (19.20),

with a global cost of 158.6 fr /unit (compared to the 207.9 of the first optimal line).

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MODELLING AND ANALYSIS OF THE STAMPING AND CLAMPING OF A CYLINDER HEAD GASKET

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Résumé. Après avoir défini la formulation de notre problème: élastoplasticité en grandes transformations avec contact unilatéral et frottement, nous proposons une méthodologie permettant de construire un modèle numérique de joint de culasse métallique. La validation de ce modèle est réalisée à l'aide d'essais d'écrasement du joint. L'étape finale consiste à simuler le serrage de ce dernier dans le moteur. La technique du super-élément est exploitée dans les zones à comportement totalement linéaire. Les ovalisations, mesurées et calculées, des cylindres du bloc moteur sont comparées puis analysées.

Abstract. After defining the formulation of our problem: elastoplasticity during large deformations with unilateral contact and friction, we propose a methodology allowing the construction of a numerical model of a metallic cylinder head gasket. To validate this model, we experimentally crush the gasket. Finally, we simulate the clamping of the gasket to the engine. The superelement technique is used to represent the parts with totally linear behaviour. The measured and calculated distortions of the cylinders in the engine block are compared and analysed.

1. Introduction

The aim of the research work presented here is to control geometric distortions of engine cylinders, which involve both noise and oil consumption. The final goal is then to limit the pollution from engines.

The simulation initially deals with stamping and crushing operations of a cylinder head gasket, large deformations with plasticity and contact with friction, a solid finite element model developed using the Abaqus computer code. In addition, experiments have been carried out in order to identify the plasticity rule for the materials used, and measure

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the crushing of the cylinder head gasket under a given normal pressure representing the clamping operation.

The main difficulty with this work is to correlate the cylinder head gasket behaviour and cylinder distortions with the main function of the gasket : gas sealing.

The cylinder head gasket is a complex multi layer structure made of three spot welded metal sheets. This assembly has many different shaped holes.

Around the cylinder hole, on both outer layers of the gasket, there is an embossment of small size to ensure gas sealing between the engine block and cylinder head. This rib is not circular because of the combustion chamber.

2. The incremental formulation of the discrete boundary value problem

In order to take into account non linearities involved in such a problem, for instance large deformations including plasticity and contact, we use a Lagrange configuration. In addition, the elastoplastic behaviour formulation is based on an unstressed intermediate configuration. As only metals are used in this work, the assumption for small elastic strains is maintained. $\mathbb{D}$ being the strain rate tensor, we write $\mathbb{D} \approx \mathbb{D}^e + \mathbb{D}^p$ where $\mathbb{D}^e$ and $\mathbb{D}^p$ are, respectively, the elastic and plastic portions of the strain rate tensor. The materials are plastic-incompressible and with the above assumptions $\det\left(\mathbb{F}^e\,\mathbb{F}^p\right) \approx 1$, where $\mathbb{F}^e$ and $\mathbb{F}^p$ are the elastic and plastic parts of the geometric transformation gradient [LeM80]. The Kirchhoff stress tensor τ is then near that of the Cauchy, σ, and therefore $\tau \approx \sigma$.

Taking into account all of these hypotheseses, it may be demonstrated that body and surface forces are given on updated geometries, while the internal stresses refer to the initial geometry. Thus, the final discrete weak formulation of this problem is given by :

$$[G]\,(q) = \int_{\cup V_0^h} [\beta]^T\,[\tau]\,dV_0 - \int_{\cup V^h} [N]^T\,[f]\,dV - \int_{\cup S_F^h} [N]^T\,[F]\,dS = [0] \qquad (1)$$

where $[f]$ and $[F]$ are, respectively, the volume and surface loads, $\cup V_0^h$ and $\cup V^h$ are, respectively, initial and actual domain mesh of the structure, and $\cup S_F^h$ its actual boundary where the surface load $[F]$ is applied. In equation (1), if classically $[u^h]$ being the displacement and $[q]$ the vector of degrees-of-freedom, we have:

$[u^h] = [N]\,[q]$ and $[D^h] = [\beta]\,[q]$, $[N]$ being the interpolation matrix. (2)

In order to find the configuration (C_{n+1}), the discrete weak form is linearised round q_{n+1}^i at i^{th} iteration and within the $n+1^{th}$ increment. The consistent linearised expression of the discrete weak form is then expressed as follows :

$$[G]\left(q_{n+1}^{i+1}\right) \approx [G]\left(q_{n+1}^{i}\right) + \left(\frac{\partial[G]}{\partial[q]}\right)_{n+1}^{i} \left([q]_{n+1}^{i+1} - [q]_{n+1}^{i}\right) = [0] \tag{3}$$

The directional derivative in equation (3) is given by :

$$\frac{\partial[G]}{\partial[q]} = \int_{\cup V_0} \left([\beta]^T \frac{\partial[\tau]}{\partial[q]} + \frac{\partial[\beta]^T}{\partial[q]}[\tau]\right) dV_0 - \int_{\cup V} [N]^T \left(\frac{\partial[f]}{\partial[q]} + \frac{1}{J}[M_v]\right) dV$$
$$- \int_{\cup S_F} [N]^T \left(\frac{\partial[F]}{\partial[q]} + \frac{1}{\alpha}[M_S]\right) dS \tag{4}$$

where $\alpha = \frac{dS}{dS_0}$, $J = \frac{dV}{dV_0}$, $[M_v]$ represents $\frac{1}{J}\vec{f} \otimes \frac{\partial J}{\partial \vec{q}}$ and $[M_S]$ represents $\frac{1}{\alpha}\vec{F} \otimes \frac{\partial \alpha}{\partial \vec{q}}$.

Note that contact with friction has been included using the Lagrangian multiplier method to assure a non-penetrating condition [Par89], and the penalty method to take into account Coulomb friction [ChC88].

The constitutive law has now to be written under the incremental form $\Delta \sigma = \tilde{\mathbb{H}} : \Delta \varepsilon$, where $\tilde{\mathbb{H}}$ is the consistent tangent operator for rate-independent elastoplasticity. In addition, the Von-Mises equivalent stress type is kept with an isotropic hardening. It has been established that the constitutive tangent operator is then of the following form in plasticity :

$$\tilde{\mathbb{H}}^p = Q\,\tilde{\mathbb{J}} + \frac{K - Q}{3}\,\mathbb{I} \otimes \mathbb{I} - R\,\sigma_D \otimes \sigma_D \tag{5}$$

where expressions for K, Q, R, $\tilde{\mathbb{J}}$, ... in equation (5) are given by [HKS93] and [SiT85].

Given the known configuration (C_n), displacements and geometry are deduced for the configuration (C_{n+1}) from equation (3). Therefore, in order to preserve the objectivity [HuW80], stresses are computed in the last configuration as :

$$\sigma_{n+1} = \Delta\mathbb{R}^T \sigma_n \Delta\mathbb{R} + \Delta\sigma^J;\ \Delta\sigma^J = \sigma_{n+1}^J - \sigma_n^J;\ \ \Delta\mathbb{R} = \mathbb{R}_{n+1} - \mathbb{R}_n \tag{6}$$

where $\mathbb{R}$ is the rigid body rotation tensor within the polar decomposition and σ^J the Jaumann stress tensor

Finally, the utilized yield stress σ_Y for the experimental characterisation of the plastic behaviour is given by the uniaxial Ludwick law [MoF90] according to the following dependency of the uniaxial plastic strain ε_p :

$$\sigma_Y(\varepsilon_p) = \sigma_{Y_0} + K\,\varepsilon_p^N \tag{7}$$

Traction bench tests conducted on samples permit deducing the following characteristics of the tested metals :

TABLE 1. Plastic characteristics of gasket metals

Steel Z3 CT 12: (internal layer)	σ_{Y_0} = 278 MPa K = 1028 MPa N = 0,754	Steel Z11 CN 17 08 (external layer)	σ_{Y_0} = 1093 MPa K = 2186 MPa N = 1

Note that these experiments are very difficult to achieve due to the fact that the samples are taken from actual cylinder head gasket layers which are very thin (external layer: 0,5 mm, internal layer: 0,7 mm).

3. Simplified ribbed portion study of a cylinder head gasket

The ribbed portion is the main functional part of a gasket. We have therefore carried out a local study of this part. This study is very difficult in three dimensional modelling. We therefore start by a simplified local study on an annular three layered structure as shown in figure 1, using a two-dimensional axisymmetric model.

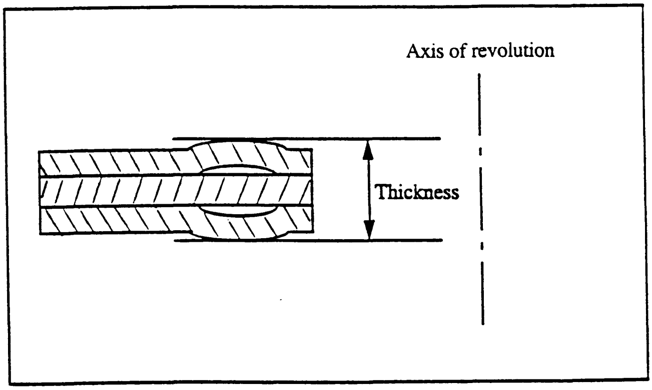

Figure 1. Geometry of the annular structure

The model for stamping and crushing a rib contains solid axisymmetric four node elements with reduced integration (CAX4R) to represent the embossment, and interface elements (IRS21A: two node rigid line element) to assure the interactions with rigid surfaces. We begin by forming the rib, then the tools (rigid bodies) are removed and replaced by rigid plane surfaces. The crushing operation is simulated by prescribing a normal global load under the rigid plane surfaces which is equivalent to a clamping load applied to a gasket portion associated with one internal cylinder. After examining convergence of stresses with the meshes, we deduce that residual stresses due to stamping of the rib have no significant effect on its global behaviour (figure 2). Hereafter, all computations to measure global parameters are such that the clamping thickness will be achieved starting with the given geometry of the ribs resulting from the stamping.

To validate the axisymmetric model (figure 3) for the annular structure, calculation and experiment are compared, see figure 4.

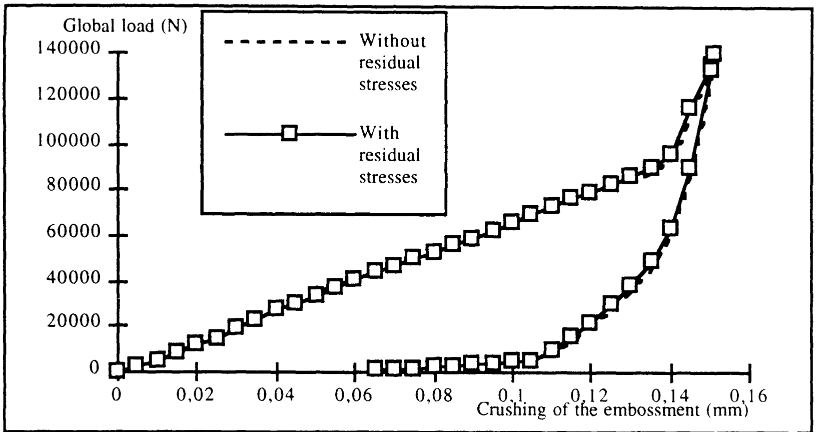

Figure 2. Global behaviour of the simplified rib

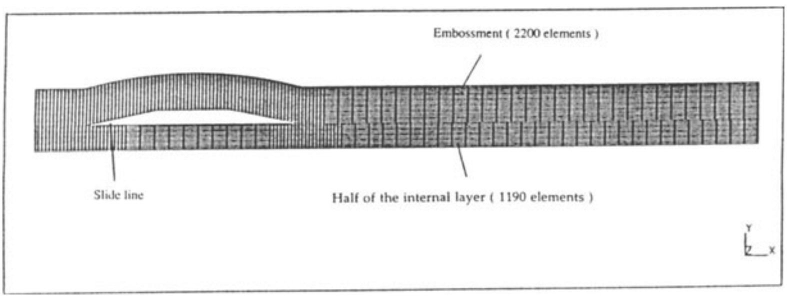

Figure 3. 2D mesh of the annular structure

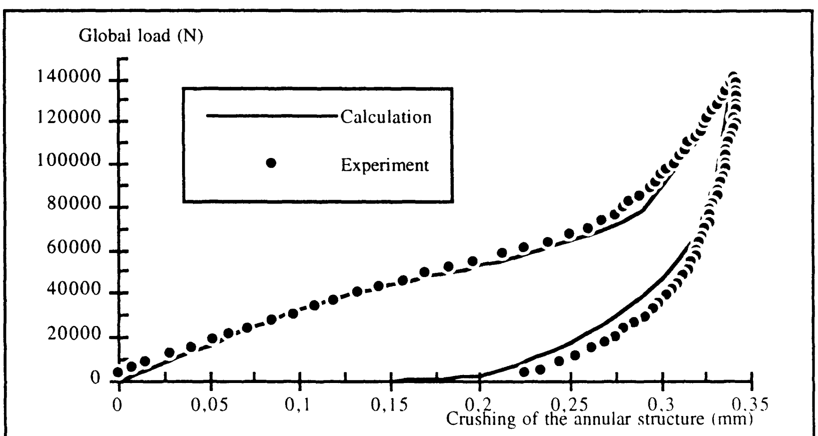

Figure 4. Global behaviour of the annular structure

4. Three-dimensional cylinder head gasket model

A three-dimensional solid finite element model is developed to represent the above three layered annular structure. This model is a compromise between the number of elements used in the mesh and the global response of the structure. Our aim is to prepare the mesh of the real three-dimensional shape of the cylinder head gasket. The retained mesh for the finite element model is shown in figure 5. To represent the layers, eight node solid elements with reduced integration C3D8R have been used. Interactions between ribs and rigid plane surfaces are assured by IRS4 four node rigid surface elements, and interactions between different layers are assured by ISP4 four node contact plane elements. Since residual stresses do not have any significant effects on the global response which we want to analyse in this study, geometric data of the rib are "a priori" given. Hence, only the crushing phase is studied.

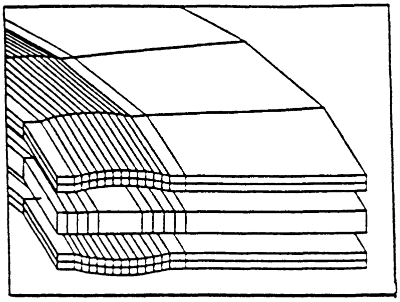

Figure 5. 3D mesh of the annular structure

This step permits us to develop a model for the gasket (figure 6). This model can be used to simulate engine clamping. An updating of the rib geometry has been achieved. This updating has been conducted with respect to experimental global behaviour. It is to be noted that the rib geometry updating phase involves sizes for the rib between tolerances given by the gasket manufacturer. The geometry without water and oil holes is complex because of the particular rib shape near the combustion chamber figure 6. In figure 7, we compare the global behaviour obtained from simulation and experiment of a gasket portion associated with one internal cylinder. We obtain a good correlation between calculation and experiment in the interval [50000 N , 140000 N]. This corresponds to the variation of the global clamping load during engine operation from cold to hot phase.

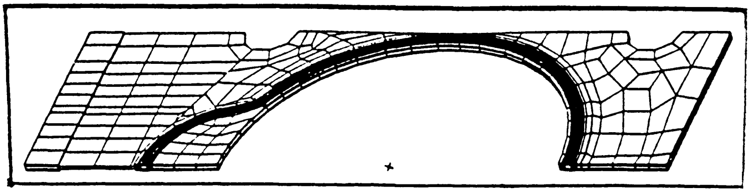

Figure 6. 3D mesh of a half gasket corresponding to one internal cylinder

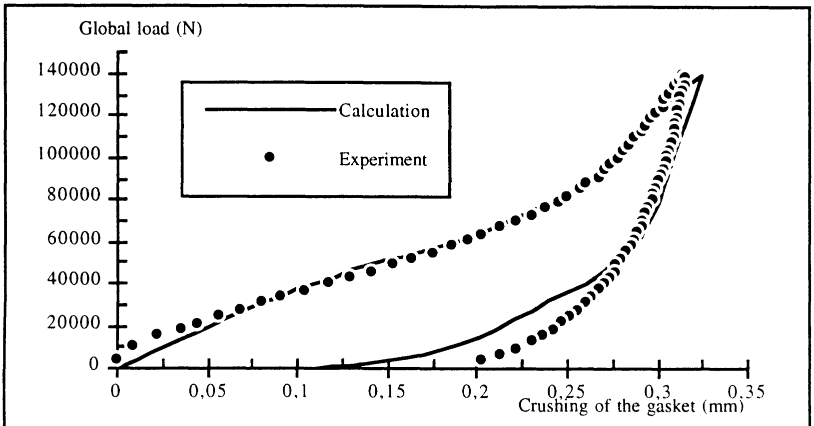

Figure 7. Global behaviour of the gasket

5. Simulation of the gasket clamping in the engine and evaluation of cylinder distortions

Our model concerns the part of an engine associated to an internal cylinder. Only a half part is considered due to symmetries. Figure 8 shows the mesh of the model. It requires many degrees of freedom, and all computations are achieved on a supercomputer. During the clamping operation, cylinder head, engine block, combustion chamber and bolts show a totally linear behaviour (small elastic strains). A superelement technique [HKS93] is therefore used to condense all degrees of freedom from the linear part to the frontier of non linear parts (surfaces in contact with the gasket). The gasket is considered as having an elastoplastic behaviour during large deformations. The interfaces between the different layers of the gasket, and those between the gasket and other parts, are represented by three node ISP3 and four node ISP4 contact plane elements. Numerical simulations are then achieved using a modified Newton-Raphson algorithm. As a lot of contact elements are needed, the convergence of the model is very difficult to achieve.

Cylinder geometric distortions resulting from cold clamping $\left(\Delta R = R_{clamped} - R_{free}\right)$ have been calculated at several levels along the height of the cylinder in order to show the cross-section shape of the cylinder when it is clamped. An example is given in figure 9, and there is good correlation between computations and experiments.

The different points representing distortions at a given level are interpolated by cubic splines. This result is then decomposed into Fourier series [Sou96]

$$\Delta R\left(\theta\right) = Umax_0 + Umax_1 \cos\left[\theta - \phi_1\right] + \ldots + Umax_n \cos\left[n\left(\theta - \phi_n\right)\right] + \ldots \qquad (8)$$

where n is the order, $Umax_n$ the amplitude, ϕ_n the phase, and θ the angle measured around the cylinder axis.

The fourth order is critical for the oil consumption [Dun90], [SBL93]. We therefore represent (figure 10) the evolution of the fourth order amplitude along the cylinder height corresponding to the piston stroke. The maximum values given by experiments are obtained numerically with an error of 8 %.

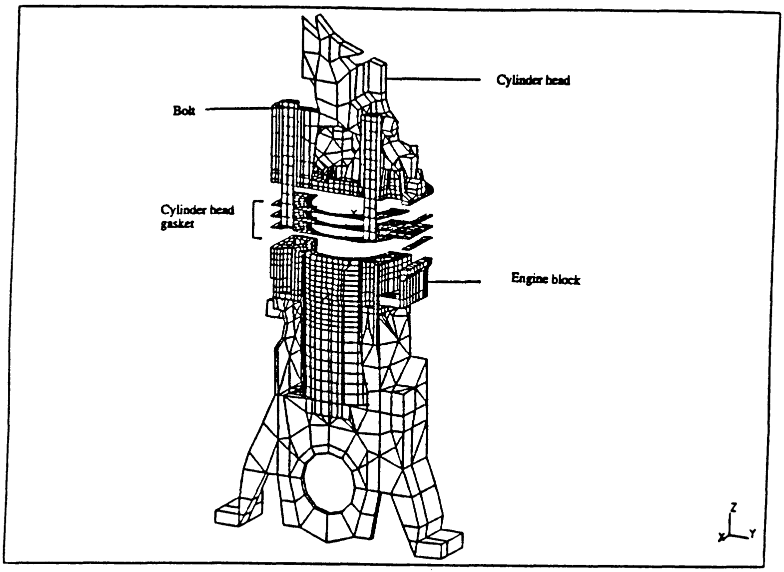

Figure 8. Mesh of the engine model

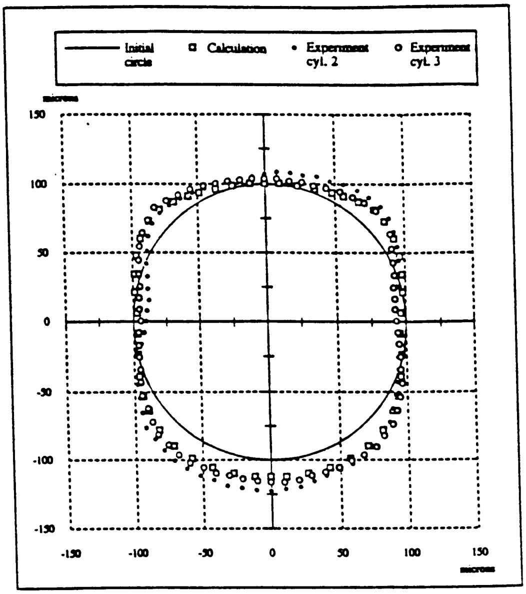

Figure 9. Distortion of the level (- 20 mm). Reference circle radius = 100 E-06 m

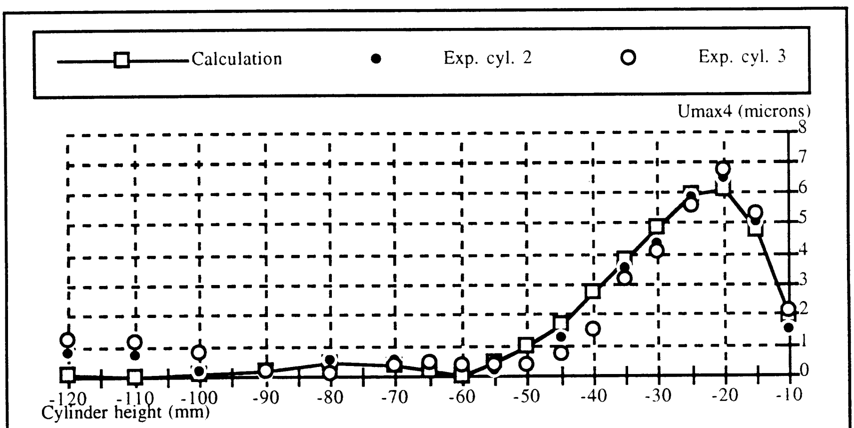

Figure 10. Evolution of the fourth order amplitude

6. Conclusions

The methodology developed in this paper can be applied to model all ribbed metallic gaskets. A good correlation between experiments and calculations has been obtained. Our final model of the engine can be used to analyse oil consumption and noise in order to facilitate the optimisation of the engine design. Future work will be concentrated towards size reduction of the gasket finite element model.

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