Procedures for a Long Term Retention Data for the Analysis and Design of a Rudder for a Marine Vessel: STEP Documentation

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ABSTRACT

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Franklin Aaron Montejo

The process of mechanical design involves many steps, starting from a customer need. Then the engineer estimates the possible solutions until an optimal product is achieved. Through these design steps, information is created and exchanged among different design activities. Currently the industry lacks a means to preserve this information flow for future use.

In the end, much of the information generated in the design process may not be available due to obsolete software used to create the design; one missing part of the process; a missing link between the design tasks; unknown context of the design, and some other possibilities.

The present study is intended to create a digital repository in which all the data generated during the design process is preserved in order to establish a Long Term Retention Design Documentation. As an example, the analysis and design of a rudder are carried out to understand the design process and to address a possible solution for the loss of context in the design process.

The work started analyzing an actual rudder by taking all the information contained in a repository provided by the Navy. After this analysis, possible improvements were addressed and a new design was proposed. All the process of analysis and redesign helped to create a document in which all the design activities were linked to each other in order to preserve the context of this particular design.

DEDICATION

To my Mom

ACKNOWLEDGEMENTS

First, I would like to thank my mother for her support, encouragement, and understanding through all this phase in my life.

I would like to thank my committee members: Dr. Victor Mucino, Dr. Bruce Kang, Dr. Kenneth Means, and Dr. James Mooney. I would like to give especial thanks to my advisor Dr. Victor Mucino who helped me since I got into this project and for his patience during this entire time I was involved in it.

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LIST OF SYMBOLS, ABBREVIATIONS, AND NOMENCLATURE

Abbreviations

AP	Application Protocols
CAD	Computer aided design
CFD	Computational fluid dynamics
IDEF0	Integration Definition for Function Modeling
JPEG	Joint Photographic Experts Group
LTM	Long Term Memory
NARA	National Archives and Records Administration
STM	Short Term Memory
STEP	**St**andard for the **E**xchange of **P**roduct Model Data
TWR	Torpedo Weapons Retriever

List of symbols

A	Profile area
AR	Aspect ratio
AR_e	Specific aspect ratio
AR_G	Geometric aspect ratio
C_D	Drag coefficient
C_{Di}	Induced drag coefficient
C_L	3D coefficient form theoretical equations
C_l	2D-3D Lift coefficient conversion
C_N	Normal force coefficient
CP	Center of pressure
D	Drag force, diameter of propeller
J	Advance ratio
L	Lift force
N	Normal force
R	Resultant
TR	Taper ratio
V	Speed
c	Mean chord
n	revolutions per second (rps)
t	Thickness
s	Mean span

α	Angle of attack
μ	Viscosity
ρ	Density
Ω	Sweep angle

Chapter 1. INTRODUCTION

1.1 Background

Long term preservation of important engineering information in digital form is a daunting and elusive task for many engineering systems. In mechanical engineering design practice for example, several engineering scenarios may occur that prompt a series of specific engineering tasks and data transactions, whose preservation is the focus of this research. The nature of the tasks and data transactions generally carries contextual information on the rationale of the design, its changes and its evolution. However, in many situations this information becomes obsolete or is lost altogether leaving systems only partially documented. Because of the generality of the problem described, the emphasis in this thesis will be placed on the specific tasks of a mechanical engineering design scenario and the problems associated with preserving relevant engineering information and documentation for future reference.

Engineering design typically involves a process that starts with a customer requirement (or need). The engineer takes this need and initiates a process of conceptualization until an idea comes across to address that need. Several tools are used to get from the concept to a prototype and then a final product, through a series of analysis and redesign tasks. At the end, the customer only sees a tangible object, and is typically oblivious to the process that ensues before the final product. For the most part, only the people involved in the design know the process that leads to the final product. And is part of their job to document all the process and data produced to reach the final solution. Yet, the following questions can be asked; are engineers documenting every decision made in the design process? Will this documentation be accessible in 30 or 50 years? Will the tools used (for instance, CAD software) be available in 30 or 50 years? Will the product be still in operation in 40 years? There have been cases of existing systems requiring modifications, adaptations and repairs, in which the original information, data and design rationale have been lost, requiring expensive and inefficient re-engineering of an existing system.

Typically, information and data are generated in various forms, using different types of software tools and various media platforms including digital pictures, CAD drawings and various elements that form a data base from analysis software, experimental data, and more. This wealth of information is then typically stored in disjointed sets of data with connectivity that is difficult to trace, except for those engineers who produced them.

Some tools offer their own means to deal with part of this problem. CAD software like Solidworks, Inventor, ProE, etc, typically have their own management system that handles the design process through its whole life cycle. But all these packages manage their own kinds of files and are not necessarily compatible. What if for any reason the company decides to change software or any of they become obsolete in the future? In that case, the data is compromised.

Technology changes continuously. So the problem of how to store data in a consistent and reliable manner is a challenge in today’s technology.

1.2 Problem Statement

As described above, many industries are dealing with the problem of how to store their own data so it can be accessible later in the future or even in the present. As time passes by, new engineers are being hired and the old ones are leaving the job. So, when new engineers try to manage already existing products they encounter the elusive task to understand those products and collect all the data. But part or whole of this information is often gone along with the retired engineer.

To address this problem, the present thesis is taking one specific engineering scenario, the *Subsystem Replacement Scenario*. The objective is to develop a systematic organizational structure allowing engineering tasks and data transactions to be mapped out, so that data preservation tools, namely STEP Application protocols can be applied. This scenario is one of four generic scenarios established in a Design Taxonomy currently under development in the context of this project. The other design engineering scenarios are for new designs (technology development), for trouble shooting and for design evolution, which are beyond the scope of this thesis.

The case and problem selected here involves redesign and replacement of a rudder for a 120’ Torpedo Weapons Retriever. NAVY owns certain amount of these marine vessels; and the premise is that it is necessary to replace the rudders for the existing units before the rudders fail while in service. Presumably some problems have been reported and a performance concern is calling for replacement. Now, the question is: should the current design be used for replacement?

This particular design process starts with a performance analysis for the actual rudder. Then a new rudder is proposed to replace the former. Once all the design process is complete, the idea is to keep it in a standard format, so in the future that the information is needed there is not going to be necessary to have the original software to access to it. With that in mind, ISO 10303, mainly known as STEP, is to be used as a way to exchange data throughout the whole life cycle of a product. STEP is a family of application protocols (AP). Each of these applications is in charge of describing a particular activity in the design process.

It is important to mention that the effectiveness and accessibility of these protocols is questionable. There are many AP for each design activity. The problem is the current tools existed in the market do not take into account those AP. So far, AP203 and AP214 are the only application protocols that the CAD software vendors use as part of their program. Both of these applications only deal with the geometry of the model. Meaning that any part or assembly model created in a “X” CAD software can be stored as a STEP AP203 or 214 and the same files can be imported into a different “Y” CAD software and start working with them.

1.3 Objective of the Thesis

The main objective of the thesis is to develop a roadmap for archiving the information generated in a design process designated as the “subsystem replacement” case. For this it is necessary to establish the difference between storing and archiving data. Storing means keeping objects in a specific place. Meanwhile, archiving means to document, in an orderly manner, so that the information contained is preserved.

Standard archiving tools will be used to achieve this goal, such as the use of STEP application protocols (AP) in the archiving of electronic files; and the use of IDEF0 to show the various engineering tasks involved in the design process. IDEF0 is a standard modeling tool used to show the activities involved in a structured process.

1.4 Scope of the Thesis

This thesis is divided into 7 chapters. The first chapter deals with the background and the explanation of the problem that is tried to be solved.

The second chapter is about the mechanical design process and describes the design process itself and the problems among its development. A brief description of the different engineering scenarios is described in order to locate the main direction of this thesis.

The third chapter deals with the many different ways of characterize a watercraft and the possible types of rudders that can fit the design requirements. It also describes the parts of a rudder and the phenomenon involved in the forces around it.

The fourth chapter talks about the design and analysis of a rudder taken from an existing Navy repository. We will start describing the problems in trying to rebuild the entire context of the previous design. This chapter will be focused on the analysis of the current rudder, starting from a simple case until getting to the rudder itself. After that, a proposed of an airfoil will be studied and compare the results with the actual rudder. Since this is a sample case, the entire design will be focused on the drag and lift coefficients. No stress or failure analysis will be performed.

The fifth chapter deals with the use of STEP Application Protocols (AP) in the design and development of the whole rudder design. We will use all the AP as long as they are accessible to us, in order to preserve the data generated in a standard manner, so this repository would be accessible as a future reference.

The sixth chapter contains the discussion of the procedure taken in the development of the design of the subsystem replacement scenario and the contributions of this work frame related to the same scenario and the applicability for any particular case of design that falls into the category of replacement of a subsystem.

In order to deploy the use of STEP as a tool for long term preservation, it is necessary to establish the types of data exchanges that occur in engineering scenarios. There are several types of scenarios that have been proposed:

- Technology development
- Subsystem replacement
- Troubleshooting
- Design evolution

The first one has been studied and developed by Sarovar [11] and consisted of documents to illustrate the design procedure and tasks for a Cryogenic Vessel.

This thesis deals with the subsystem replacement scenario. In this case, the subject of study is the analysis and possible replacement of a subsystem, the rudder of a marine vessel. For this matter, two repositories have been available containing several documents about this particular subsystem. One repository is from the National Archives and Records Administration (NARA) and the other one is from the NAVY. The first one contains files in different format: STEP files, Inventor, Autocad, Rhino, TIF and JPEG files. The second repository consists of TIF format documents which are pictures of blue prints of the entire ship.

Chapter 2. MECHANICAL DESIGN PROCESS

When engineering projects are carried out, a number of engineering tasks are conducted in which information is created, transformed, retrieved and transferred within specific tasks, to ultimately generate the detailed description of what is to be built and how it is to be built, installed, operated, serviced and disposed.

Several scenarios can also be cited as “typical,” in which a series of information exchanges and engineering tasks ultimately result in a “system change”, which may well be the product of redesigns, repairs and adaptations, which in turn, may be needed in order to maintain a system or unit in proper operation through its lifecycle.

When a system is designed, redesigned, modified or adapted to comply with prescribed operating conditions, documentation of the engineering tasks is not customarily conducted in a systematic way to ensure comprehensive technology archival preservation. In most cases, a series of documents in various formats and media are generated, which have some relation to the final characteristics of the system but without a clear intent on the part of the engineers involved, to provide a structured roadmap of documentation generated through the project development. The ultimate result of this practice is often the “reinvention of the wheel” due to the lack of “engineering context” in typical documentation available at the end of a project.

In this thesis, a generic engineering scenario is proposed that can serve as the basis for establishing a roadmap, conducive to a structured documentation with “engineering context” for the “Subsystem Replacement” case. The main objective is to identify engineering tasks, document types and data classification, which can be supported by STEP application protocols.

2.1 Generic Engineering Scenarios as Procedural Roadmaps

The problem being addressed here is the lack of a systematic approach to capture the majority of the data transactions and the sequence in which they occur, in order to provide context to the final design characteristics for archival purposes. This problem is being addressed by defining clusters of engineering tasks that are typically developed in various engineering scenarios.

When we look at any engineering project, whether it involves design from scratch, redesign, replacement of sub-parts, etc, we notice that each project is nothing but the same steps being used in different sequences, with variations among the input, output, and controlling operations from the same pool of steps used in the completion of the project. The fundamental building blocks of design and development of any product are thus identified as follows.

1. Geometric synthesis

This implies any task aimed at defining the geometric features (2D or 3D) of physical systems, structures or components, at the single or multi-component system level. Any task that involves obtaining/calculating dimensions, drawings, or any other properties and detail that define the shape/structure of the model, component, structure, or any physical system can be classified as Geometric Synthesis.

2. Material properties characterization

This involves the determination of material properties that are necessary to include in mechanistic models for analysis, simulation purposes or for design formulas. Any task that involves anything related to the material used, its properties, behavior, applications in any part of the model, component or system can be classified as Material Properties Characterization.

3. Loading and boundary conditions definition

This involves the definition of loads from prescribed operating conditions and application site. Any kind of forces on the model, component or system, its working conditions, limiting conditions can be classified as Loading and Boundary Conditions.

4. Failure criteria

This involves the functional or operational failure criteria to be used in the design, including reliability and life expectancy. When we design any product, we are very concerned about the usage, its life of expectancy, reliability, shelf life, durability, and knowledge of its failure conditions. These are classified as Failure Mode Criteria.

As it can be seen, there would be no definition of any product without the involvement of all of these factors. Any other task can ideally be decomposed or integrated into these four factors.

The bottom line here is that we are moving towards a TAXONOMY for engineering tasks, for modeling and representation of generic mechanical engineering design scenarios, which can be used for several purposes, including planning and management among others. But very specifically in our case, this taxonomy will be useful for long term data preservation with engineering and contextual features.

The engineering scenarios that can be developed by grouping tasks into these clusters and having a flow of information and sequence of tasks will produce the objectives required. The following scenario-constructs can be created.

2.1.1 *Geometric Design Construct*

A scenario which results in the geometric determination of a particular system, given the loads and boundary conditions to carry, the materials to be used and the target failure criteria (safety factor, reliability, life expectancy).

For instance, imagine that it is needed to determine the diameter *d* and length *L* of a round shaft to be made of commercial steel, which should transmit a determined torque *T* and support two gears each at each end of the shaft, with a safety factor of *F* and is not expected to twist more than certain amount of radians.

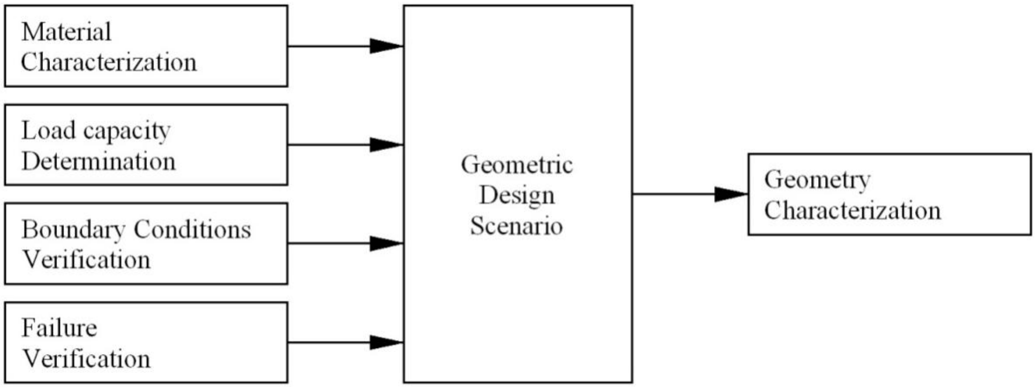


Figure 2-1 Geometric Design Scenario

2.1.2 *Material Selection Construct*

A scenario which results in a material selection based on properties that are relevant to the specific performance requirements, given a required geometry, prescribed loads and boundary conditions and failure criterion.

As an example we made be asked for the selection of an appropriate material for a shaft of diameter *d* and length *L*, which transmits a torque *T*, working with a safety factor *F* and twisting no more than β radians.

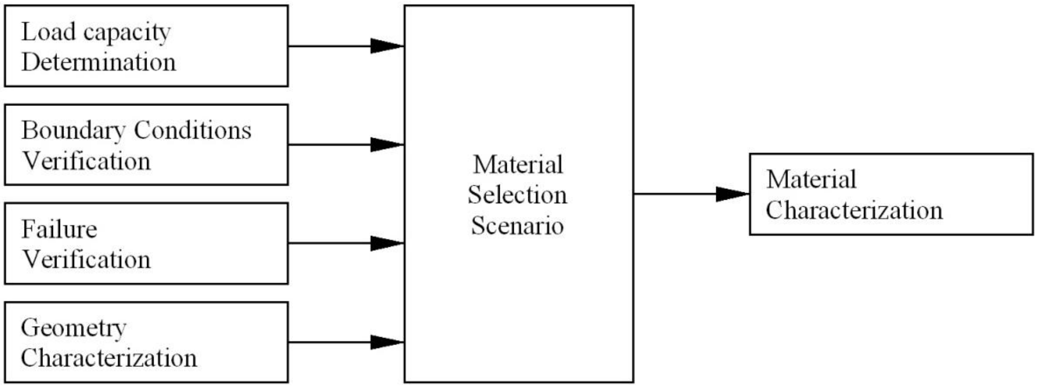


Figure 2-2 Material Selection Scenario

2.1.3 *Load Capacity Determination Construct*

In this scenario, the load capacity of a system or components is sought based on the given geometry, material properties and failure criterion. Sometimes is not necessarily load capacity but some performance measure, for example acceleration capacity, flow or heat rate capacity etc.

Continuing with the shaft example, now it might be desirable to know the maximum torque *T* that is capable to transmit when it has a diameter *d*, length *L*, made of commercial steel, and working with a safety factor of *F*.

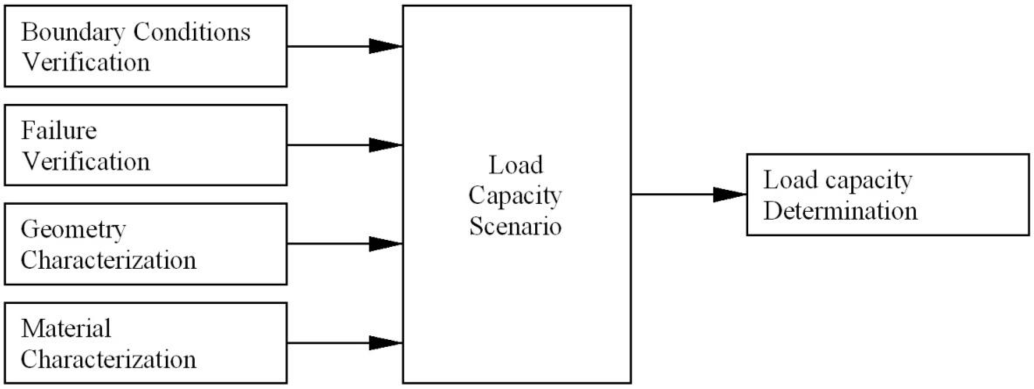


Figure 2-3 Load Capacity Scenario

2.1.4 *Boundary Conditions Construct*

This is a scenario in which the main objective is to determine how a system or component is to be supported, or what interfaces it will have with the rest of the system. These interfaces are the basis for boundary condition definition for mechanistic modeling purposes but also for final configuration of system within its environment.

For instance, to support the shaft mentioned before it is necessary to stablish the type of bearings that will assure a good performance.

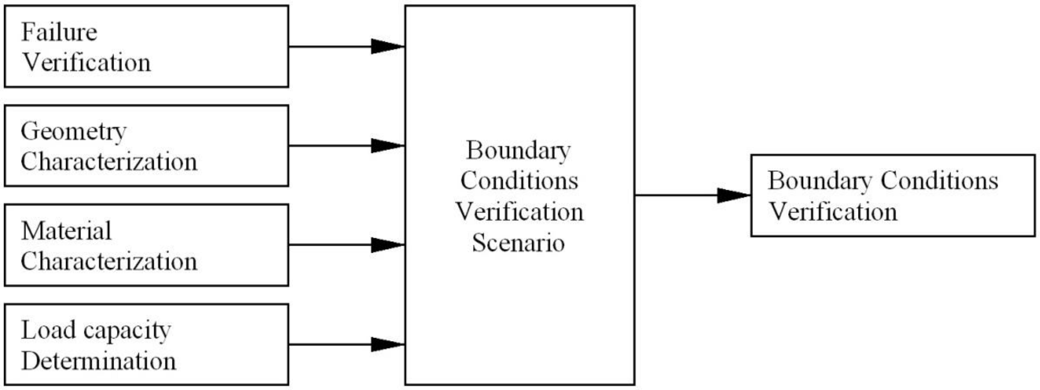


Figure 2-4 **Boundary Conditions Verification Scenario**

2.1.5 *Failure Verification Construct*

This is the scenario that results when all the information is available on geometry, materials and loads and boundary conditions. The main objective is to determine if the failure criterion to be used is satisfied or not. Typically this is the case of computational mechanics models (finite elements) but can also be the result of testing procedures, to verify whether the performance measures are appropriate.

Now is vital to determine whether or not the shaft is going to fail when it has a diameter d, length L, is made of commercial steel, transmitting a torque T.

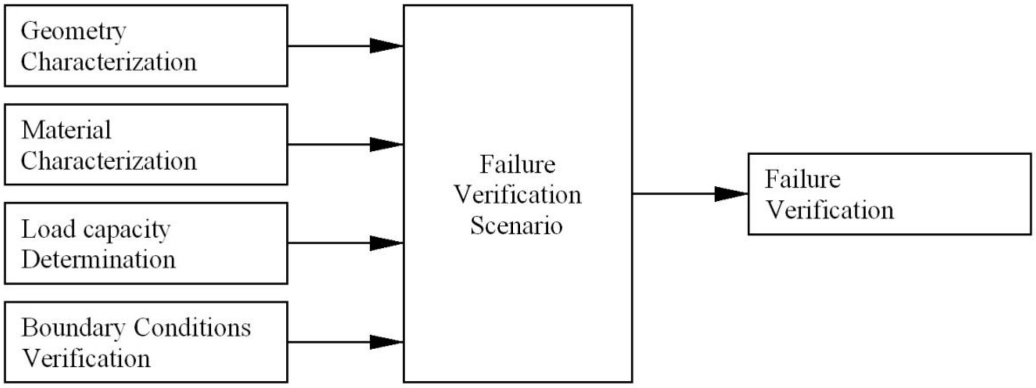


Figure 2-5 **Failure Verification Scenario**

Combinations of these scenarios can give rise to more practical and typical engineering scenarios, which can be captured through information flow diagrams involving input/output data requirements in connection with tasks, functions and possibly resources, tools equipment etc.

The main difference in the four cases above is the way in which the information flows. Consequently, it is possible to establish a generic scenario which can be used for any of these cases with three additional tasks: the mechanistic modeling task, *the system response task* and *the redesign iteration task,* as illustrated in Figure 2-6

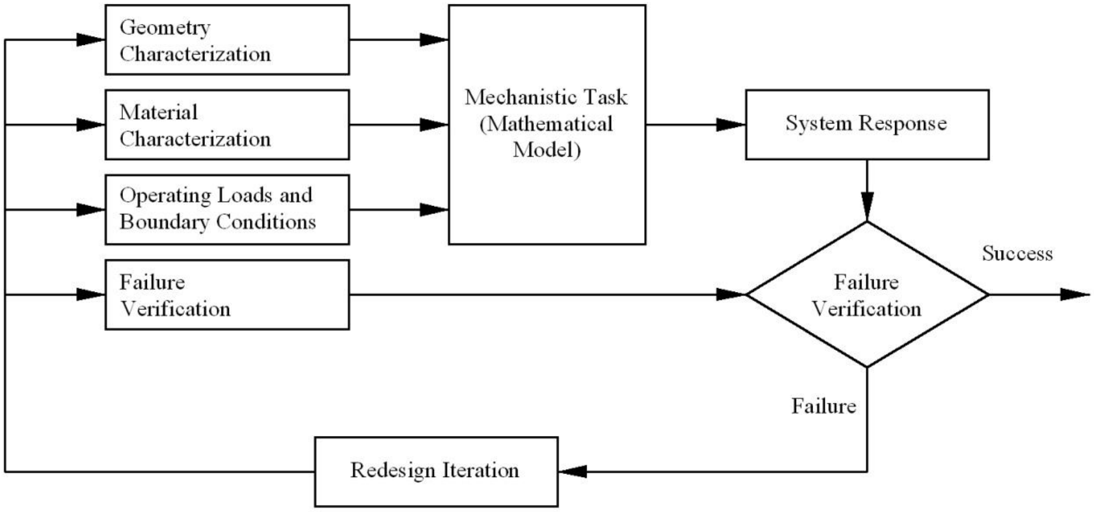


Figure 2-6 Generic Engineering Scenario

Several scenarios can be developed for some cases that are typically encountered in the design of mechanical engineering systems and structures. These cases are described next.

2.2 Engineering Scenarios and Various Beginnings and Ends

The engineering scenario for different cases can be characterized by the way they begin and end. For example, there are several possibilities as follows:

2.2.1 *Technology Development*

It is also known as *design from scratch*. This case is about the design of a particular system to satisfy specific performance requirements. No previous designs exist to satisfy the requirements that can be used as the initial design. The tasks in this case go from the documentation of specific design requirements to conceptual design alternatives to system synthesis based on engineering knowledge from previous practices.

An example would be the design of a pressure vessel to be used to supply liquid nitrogen for a super conductor application. The pressure vessel operates must be under external high vacuum pressure to provide adiabatic insulation. One inlet and three outlets at equal pressure and flow rate are the basic performance measures in addition to the structural soundness. Superconductor applications are all different and they all require manifolds tailored to the specific requirements. ASME pressure vessel code would be required in the design. A design from scratch would be needed in this case, perhaps a design developed for a unique application. This case was studied by Sarovar [11].

2.2.2 *Design Evolution*

In this case the design of a system or component is based on an existing previous design which, if properly modified, it can satisfy the new operational requirements. Previous geometric configurations already exist, which are either modified or emulated in the new design and the details of codes and standards used are documented. For this matter, the design-analysis-redesign cycle is used to finalize the design and the reviews of manufacturing tasks are also performed based on previous designs.

As an example, just take a look at the new Boing 787. The initial point of start is the previous airplanes. They decided to employ composite materials in the structure to reduced weight and this led them to a reduction on the fuel consumption. A basic design is the initial point and an objective function is set forth, for instance reduction on weight or cost, each way can lead to different solutions.

2.2.3 *Troubleshooting*

This is the typical scenario where problems on the field are analyzed and fixed. In this case the system is in current operation, with problems reported by field engineers, by users or by customers. Generally, this scenario lead to a product recalls for permanent fix, but before that an anticipated functional failure must be assessed and preventive measures are conducted. Technical information and geometric descriptions are already exist an it is necessary to extract the relevant information to determine the cause of the malfunction to generate a corrective action.

For instance take the case of the analysis and repair of a leaking flange in a heavy duty transmission that leads to early system failure due to loss of lubrication in the transmission bearings. The leaks take place at some flange joint where a gasket is used to maintain sufficient dealing pressure to prevent leaks. The design fix requires a simulation and virtual modeling of the failure in such way that the assembly procedures and the manufacturing characteristics of the flange are reflected in the performance. Tests needs to be conducted to determine bolt tension relaxation of the joint and flatness of the contacting surfaces in order to determine the compliance of the gasket and produce parametric predictions of leak rates for various extreme operating conditions. Redesign recommendations are then produced to prevent failures in the future.

2.2.4 *Subsystem Replacement*

This scenario consists in the reconstruction of the design context of a system from an existing archival data. This case involves the rehabilitation of data stored in various formats that pertains to an engineering system. The information stored is retrieved with the single purpose of retracting the information related to the various engineering tasks in the development of the technology contained in the system. Geometric specifications, materials processing, failure criteria and load capacity are of particular interest, as well as manufacturing and fabrication processes.

An example is the replacement and redesign of a rudder for a 120’ Torpedo Weapons Retriever Ship from the US NAVY. Two repositories are available containing scans of blue prints, CAD files of some blue prints, STEP documents of some components, and JPEG files of components. While it is conceivable to create solid geometric models from the set of blue prints (which are 2D projections of an actual 3D objects) this can be an impractical approach to rehabilitate the technological package of the system or subsystem. An alternative is to capture the contextual intent of the design to provide performance requirements and operational limits, as well as maintenance expectations. This can be traced from archival information that goes beyond geometric descriptions of parts and systems, and for which some STEP application protocols (AP) are available or in process of being develop. A relevant question is if currently available STEP AP’s are readily supported by commercial CD packages and to what extent these AP are reliable.

Chapter 3. DESIGN CONSIDERATIONS FOR A RUDDER

Since an access to a repository of technical information is available for a 120' Torpedo Weapons Retriever vessel, a plausible scenario has been identified to illustrate the *Subsystem Replacement/Adaptation* engineering scenario. This is the case in which a specific subsystem of this watercraft needs to be replaced for a certain number of ships and a whole engineering scenario unfold: "the rudder replacement", which calls for an assessment of the current design and offers the opportunity for design improvements.

Before starting the rudder design process, it is necessary to understand some of the concepts and theories involved in the specification of a control surface.

We also need to know and understand the type of vessel that is going to use this rudder. It is also necessary to know the requirements and conditions in which this ship will be working.

After knowing the type of ship and the conditions of operation, we can select the type of rudder that is suitable for this purpose and describe the forces around it.

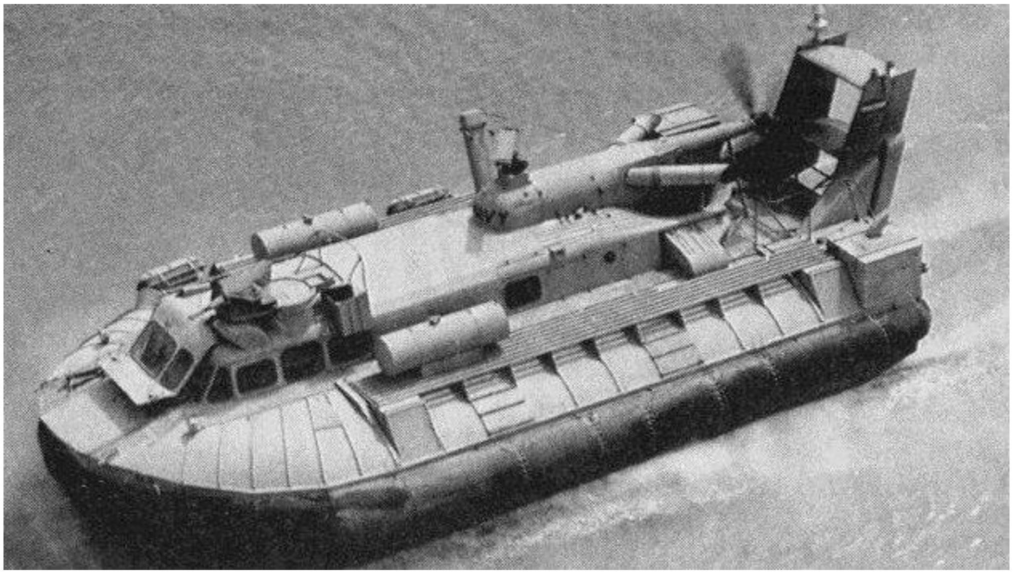
3.1 Types of Ships

Everybody knows the innumerable amount of ships that exist nowadays. Their appearance can change depending on the use and requirements. There are those enormous cruisers, or the ones that carry armor, even oil. But none of these shapes gives us an idea of how to classify them.

There are several ways to classify a ship. Some use the architectural structure, others use their physical support. Another way to classify a ship design is considering their cost, their payload, speed, purpose, etc.

Taking into account the way they support themselves, they are classified as ships with aerostatic support, hydrodynamic support and hydrostatic support. Since our 120' ship Torpedo Weapons Retriever belongs to the third category, we are going to focus on this one.

The former classification contains the watercraft that is supported above the surface of the sea. This support is made by air cushion and they are capable to develop high speeds. Since air is less dense than the water, it makes the watercraft travel without touching the sea. This makes no contact with waves and other types of drag development that is why the capability to achieve high speeds. Figure 3.1 shows an air cushion vehicle that was built and operated in North Korea. These kinds of vehicles are amphibious for their capacity to drive on the ground too.



(http://www.globalsecurity.org/military/world/dprk/images/acv_Image26.jpg)

Figure 3-1 Kongbang class Air-Cushion Vehicle (ACV), built in North Korea

The hydrodynamic ships use the principles of the airfoil (in this case hydrofoil). This principle states that when a shape in movement can produce a difference in pressure around it, it is capable of generate a lift force when moving through the water. This makes the entire ship to rise from the surface of the sea. Figure 3.2 shows an example of this kind of boats. In this picture it can be notice the hydrofoil that makes the boat to elevate from the water. These ships can achieve relative high speeds.

(http://commons.wikimedia.org/wiki/File:Hydrofoil_old.jpg)
Figure 3-2 Example of a Hydrofoil Ship

. The last type of support, the hydrostatic, it is the most known and the oldest of all. As said before, the rudder that is investigated belongs to this category of ships. Their support it is due to the flotation phenomena. According to Archimedes, the force for which a body is supported in the water is equal to the weight of the liquid displaced. Due to this, they are also named displacement hulls. This kind of ships can carry high payload in contrast with the air cushion vehicles. Figure 3.3 shows a torpedo weapons retriever vessel, like the one it is been putting into context to determine the type of rudder we are going to analyze and redesign.

Among this last category of watercraft, there is a sub classification as mention before. Taking the purpose of the ship, it is possible to classify them as commercial, naval and pleasure ships.

(http://www.archives.gov/ncast/navsea/)

Figure 3-3 Torpedo Weapons Retriever 841

3.2 Rudder Functions

Before starting to present the equations and symbols used to describe the characteristics of a rudder, it is useful to understand the importance of these control surfaces. The rudder, as a maneuverability means, is the most important part in a ship. It is placed as further back as possible in order to produce the couple moment capable of turn the ship.

When a ship is moving it should be capable to control its velocity and keep its course. And sometimes, for specific applications, the ship needs to position itself accurately.

One of the obvious functions of the rudder is to make the ship turn. The rudder is responsible to develop the necessary forces to make the vessel change its trajectory.

When the rudder rotates its angle of incidence, α, respect to the center line of the ship, it generates a force P acting on the center of pressure of the rudder (see figure 3.4). This force can be translated to the center C of the ship and generates a moment Pd. As the ship starts to turn, its velocity V rotates describing an angle β. This creates a reaction force *R* on the hull, on the outer side of turning direction. This force is due to the translation of the vessel with the angle *β*. Again, this reaction is resolved to the point *C* generating a moment *Re*, which helps the ship to turn.

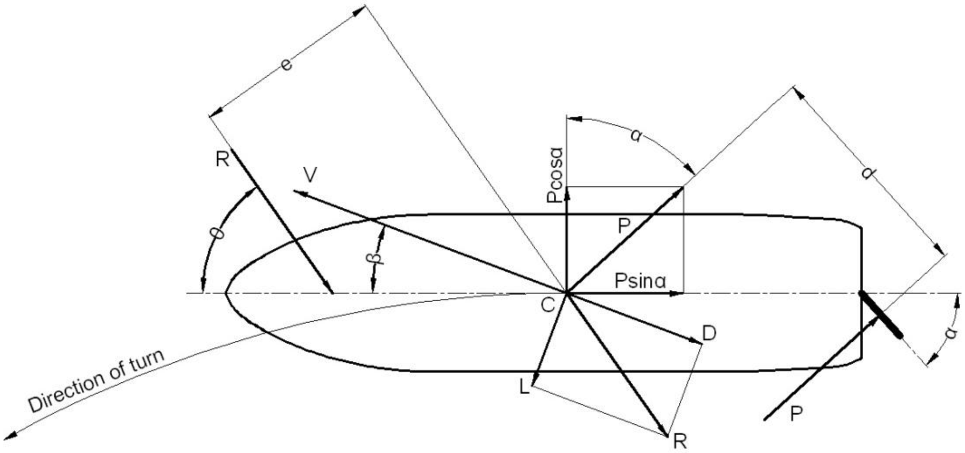


Figure 3-4 Forces on a ship while turning

Another function is to maintain stability in the direction of the craft. Keeping the course of the trajectory is important when moving against or in the same direction as the wind blows.

In cases like in sailing craft, the rudder provides side forces against forces off-course coming from a side. When the ship is moving, it experiences lateral forces that tend to changes its straight line of movement. Thus, the rudder provides a directional stability against yaw motions.

Of course, these three functions are going to conflict depending on the requirements in the design. If what is needed is a high course keeping vessel, it is most likely that the rudder is not going to be very efficient turning the ship. Too much directional stability in a ship makes it hard to turn. What is important is to focus on the requirements of the ship and try to obtain a satisfactory efficiency in the watercraft performance.

3.3 Rudder Definitions and Characteristics

As mentioned before, the rudder is the most important part in a ship and the oldest. It is an important control surface due to the functions mentioned earlier. They are located at the stern of the ship, normally behind the propellers. As their counterpart, the airfoil, the rudder or hydrofoil, share the same characteristics.

Basically, the rudder is compounded of two parts: the flat part, or blade, on which the flow acts impinging pressure; and the stock or shaft which is in charge of impart the movement of the rudder from the steering mechanism of the ship.

In order to understand the actuating forces over this hydrofoil, it is important to know some characteristics about its geometry. Figure 3.5 illustrates these important features that help to describe a rudder.

1. **Mean Span (*s*)**. It is the height of the rudder. The mean span is the average of the leading edge and the trailing edge.

2. **Mean Chord (*c*)**. It is the distance between the trailing edge and the leading edge. The mean chord is the average of the tip chord and the root chord.

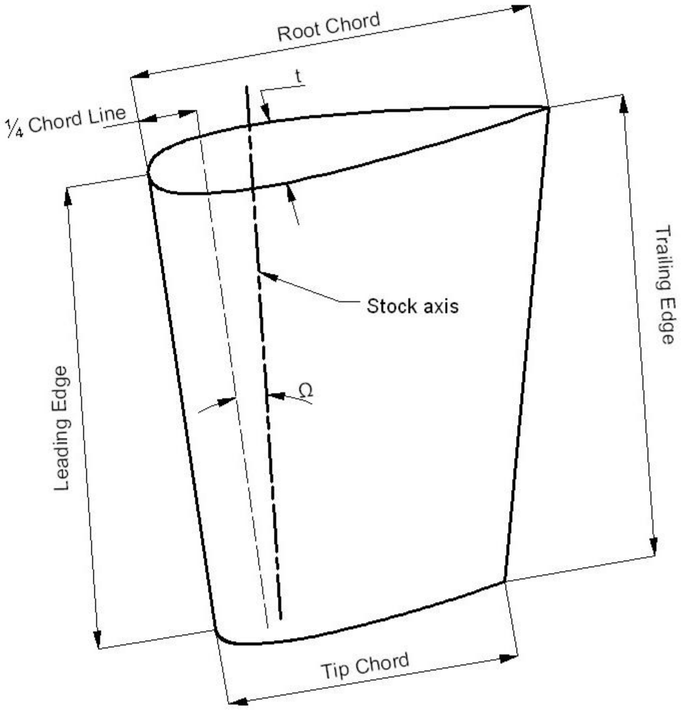


Figure 3-5 Basic rudder characteristics in a balanced spade rudder

3. **The Profile Area (*A*)**. It is the area of the projection of the rudder. Can be taken as the product of the mean chord and the mean span. Although there is no standard rule that determines how much area should be needed in a rudder, it is usual to consider it as a fraction of the product between the length and the draft of a similar ship with similar maneuverability requirements. There is a formula that suggest the minimum area for rudders that work behind propellers:

$$A = \frac{LT}{100}\left[1 + 25\left(\frac{B}{L}\right)^2\right] \quad (3.1)$$

Where L=length of the ship, B=beam, and T=draft

4. **The Aspect Ratio (*AR*)**. The geometric aspect ratio (AR_G) is the ratio of the mean span over the mean chord. In order words, the ratio of the squared span over the profile area. It is the most significant parameter of the rudder. It is important to mention that when the rudder is located close to the hull, which is our case, it behaves as a mirror plane and the effective aspect ratio (AR_e) can be considered as twice the geometric ratio.

5. **Taper Ratio (*TR*)**. Ratio between the tip chord over the root chord.

6. **Sweepback angle (*Ω*)**. It is the angle described between the quarter chord line, from the leading edge, and the line perpendicular to the centerline of the ship.

7. **Thickness (*t*)**. Is the maximum thickness in the root of the rudder.

3.4 Types of Rudders

There is a vast classification of rudders. Generally, we can classify them as balanced, unbalanced and semi-balanced rudders as shown in Figure 3-5.

3.4.1 *Balanced Rudders*

Part of the rudder in disposed forward of the stock along its height. This makes a reduction in the torque, making stocks with big diameters and thicker rudders. As the angle of attack increases, the center of pressure moves toward the trailing edge. This makes impossible to coincide the C.P and the stocks at all angles. It is a good practice to design the stock to coincide with the C.P at 15 degrees. This type of rudder has been used a lot in single and double screw ships, including small boats, commercial and merchant ships, naval vessels, etc.

3.4.2 *Unbalanced Rudders*

The whole rudder is behind the stock. There is no portion that is forward the stock. Ii is applied in hydrodynamics support watercraft and some old ships.

3.4.3 *Semi-balanced Rudders*

This is combination of the two previous types. The upper part of the rudder is unbalanced and the lower part is balanced. Its use has been seen in merchant ships provided with single and twin screw.

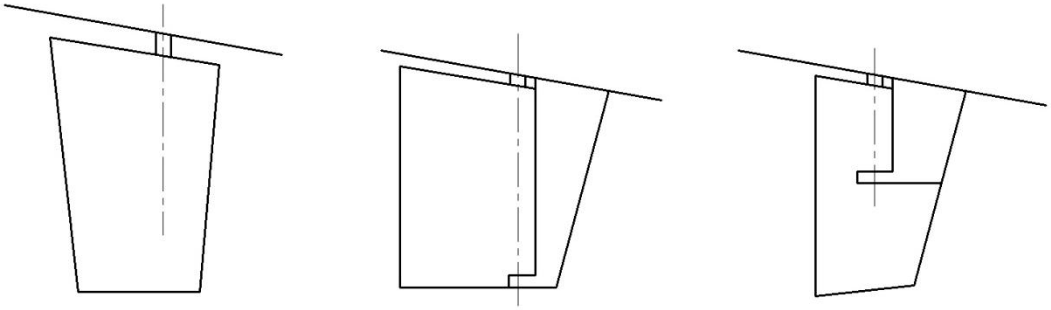


Figure 3-6 Types of rudder: (a) Balanced rudder, (b) Unbalanced rudder; (c) Semi-balanced rudder

3.5 Forces in Rudders

Rudders are devices designed to generate a difference in pressure of the fluid around them. Due to this difference, a resultant force is produced which can be resolved into a lift and a drag forces. Figure 3.6 illustrates the forces around the rudder.

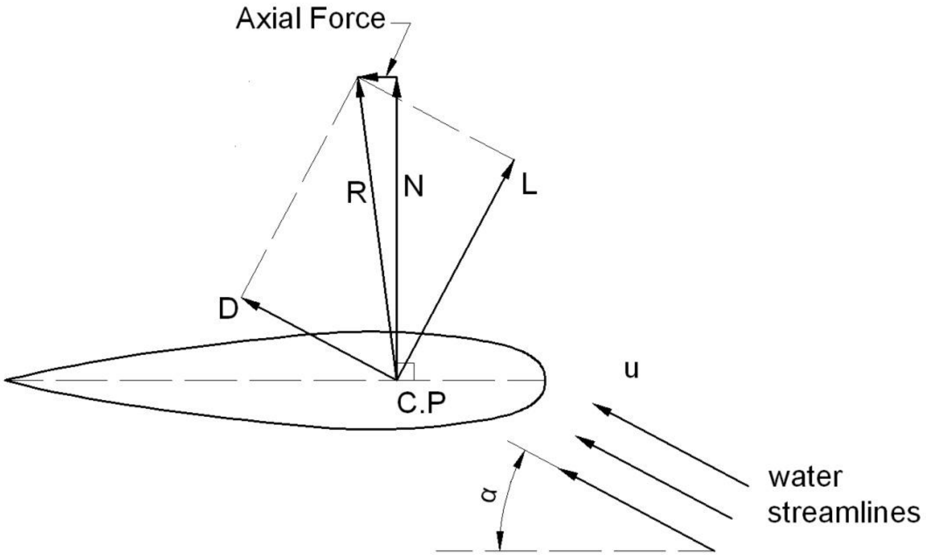


Figure 3-7 Forces in a rudder

1. **Angle of attack (*α*)**. It is the angle described by the chord line of the rudder and the streamlines of the water.

2. **Center of Pressure (*CP*)**. It is the point where the resultant force (*R*), due to pressure on the rudder, is believed to be acting over the rudder. Its location varies as the angle of attack changes.

3. **Lift (*L*)**.It is the component of the resultant force (*R*) that is perpendicular to the water streamlines.
4. **Drag (*D*)**. It is the component of the resultant force (*R*) that is parallel to the water streamlines.
5. **Normal force (*N*)**. Component of the resultant force (*R*) that is perpendicular to the chord of the rudder.
6. **Axial force**. Component of the resultant force (*R*) that is parallel to the chord of the rudder.

As mentioned before, rudders are located as further back as possible of the ship, aligned to the water stream. The main objective of the rudder is to generate high lift forces with minimum drag. Rudders have symmetrical profile since they have to produce the same forces no matter what direction the rudder turns. Forces in a rudder are directly proportional to its cross section shape, its area, the angle of attack, the density of the fluid, and the speed of the water.

$$force = (const)(0.5)\rho A u^2 f(\alpha) \tag{3.2}$$

The constant is function of the geometry of the rudder. The aspect ratio is the most significant characteristic in defining the constant.

Although, it was mentioned lift, drag, and normal forces, it is more practical to talk about lift coefficient (C_L), drag coefficient (C_D), and normal force coefficient (C_N). All the data about lift and drag forces around a hydrofoil (airfoil) is presented in terms of their respective coefficients, as shown in Figure 3-7.

Although, the previous figure shows the lift and drag data from a particular airfoil, all these data is a 2D study case. It is known that the rudder has a 3D geometry and its behavior is in 3D. This and others issues such as hull influence over rudder and rudder-propeller interaction, will be discussed in the next section within this chapter.

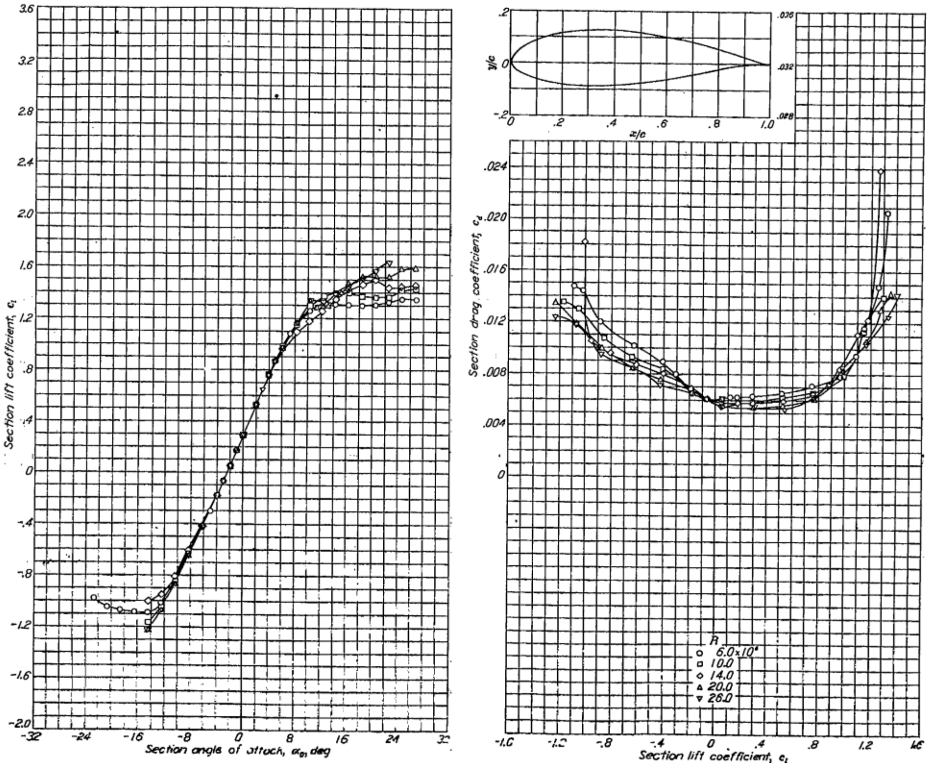


Figure 3-8 Lift and drag coefficient data from a NACA profile. Extracted from Abbot and Von Doenhoff, Theory of Wings Sections [1]

3.6 Induced Drag

3.6.1 *2D Hydrofoils*

This airfoils have an infinite span, thus the fluid motion is 2D and perpendicular to the span. These kinds of control surfaces are studied to collect 2D data which is related to the profile shape rather than the shape of the win. All the pressure distribution, drag and lift data come from these 2D wins.

3.6.2 *3D Hydrofoils*

The difference here is that the flow motion is not only perpendicular to the span but also along it. The motion is 3D. These airfoils have a finite span. Since there is a difference in pressure in the upper and lower sides of the rudder, due to a lift generation, the flow starts moving in a spanwise direction from the side with the greater pressure to the side with the lower pressure. This creates vortices at the tip of the rudder. Assuming that the lower side of the rudder has the greater pressure, what these vortices do is to create a downward flow, thus the angle of attack is altered by an angle ω, as shown in figure 3.8. This generates a sort of effective angle of attack (α-ω), which creates a lift *Lo* that can be resolved into the original lift *L* and an induced drag D_i. This induced drag can be evaluated as:

$$C_{Di} = k_i \frac{C_L^2}{AR_e} \tag{3.3}$$

Values of k_i depend on the shape of the foil. According to Molland [8], a good design practice is to consider k_i between 0.35 and 0.37.

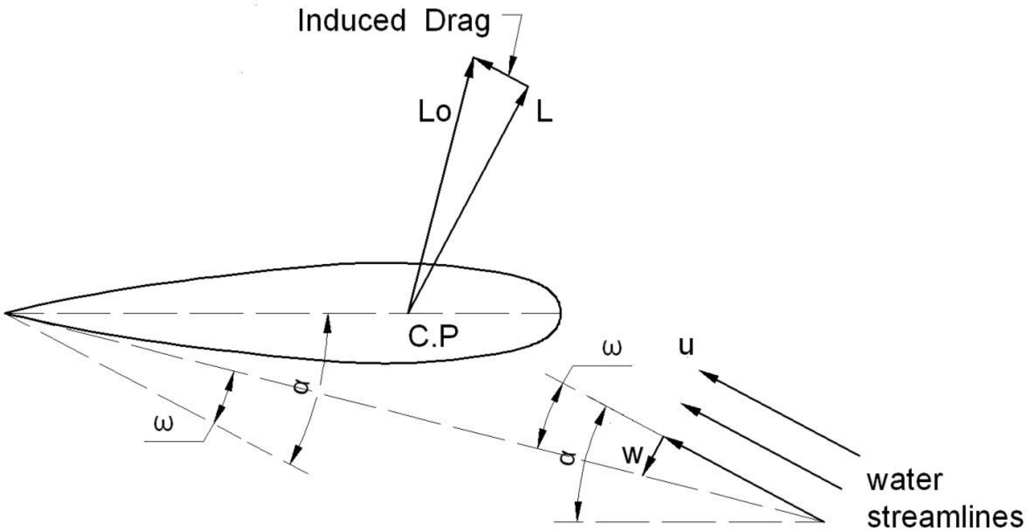


Figure 3-9 Induced drag due to a finite span

The total drag coefficient is now expressed as the sum of the 2D part with the 3D:

$$C_D = C_{D0} + C_{Di} \tag{3.4}$$

$$C_D = C_{D0} + k_i \frac{C_L^2}{AR_e} \tag{3.5}$$

3.7 Rudder-Propeller Interaction

It is necessary to determine the parameters that affect the performance on the rudder. These parameters can be categorized into four groups that will affect the lift, drag, and speed flow on a rudder. These groups are:

1. **Flow variables**. This group defines the forces due to time dependant parameters: speed (*V*), propeller rps (*n*); fluid characteristics, density (ρ), and viscosity (μ). Speaking in no dimensional way, these variables can be treated as the Reynolds number *Re* and the advanced ratio *J*.

$$\mathrm{Re} = \frac{\rho V c}{\mu} \tag{3.6}$$

$$J = \frac{V}{nD} \tag{3.7}$$

2. **Rudder geometry**. This is controlled by the angle of attack (α), the stock position (X_1), thickness (*t*), section shape, taper ratio (*TR*), and sweep angle (Ω). All these parameters determine how the flow goes through the rudder.

3. **Propeller geometry**. This defines how the propeller transmits the flow over the rudder. The parameters that control this are the diameter of the propeller (*D*), its pitch (*P*), the number of blades, the blade area ratio, etc.

4. **Location and size of the rudder and propeller**. The location is defined by the three coordinates *X* (the longitudinal length), *Y* (the lateral distance), and *Z* (the vertical distance). The size is defined as a proportion of how much of the span of the rudder is in the way of the propeller thrust.

We are going to focus on the velocity of the flow imparted by the propeller over the rudder.

For simplicity, consider the propeller as a disc of diameter *D* and area A_1. This disc is going to impart an axial motion to the fluid, as shown in Figure 3-9. This motion will create a thrust (*T*) on the disc that can be evaluated as the rate of change of momentum:

$$T = \rho A_1 V_1 (V_2 - V_0) \tag{3.8}$$

or

$$T = A_1 (P_1^{'} - P_1) \tag{3.9}$$

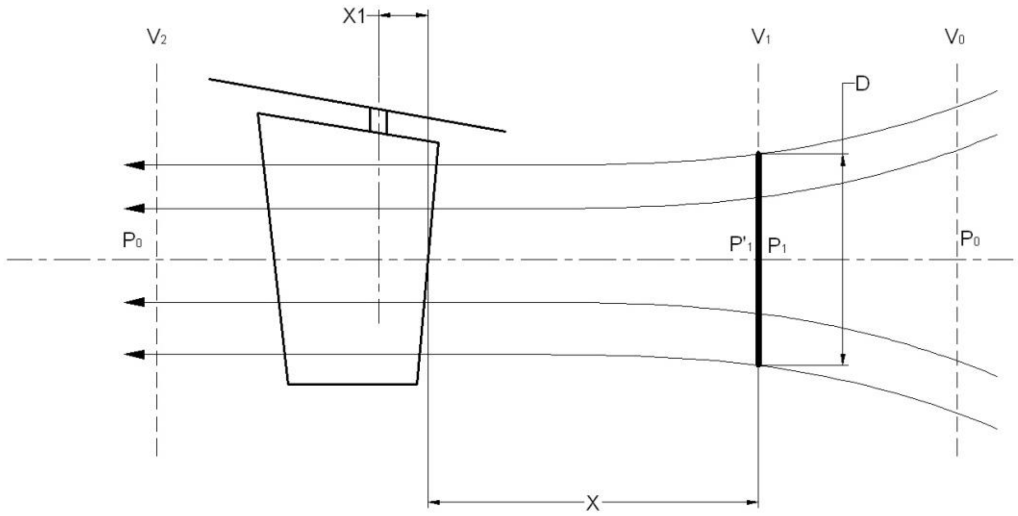


Figure 3-10 Speed and pressure diagram around the rudder due to the propeller action

According to Bernoulli's equation:

$$P_1 - P_0 + \frac{1}{2}\rho(V_1^2 - V_0^2) = 0 \qquad \text{and} \qquad P_0 - P_1^{'} + \frac{1}{2}\rho(V_2^2 - V_1^2) = 0$$

Adding up the above equations and using equation (3.9), we have:

$$T = \frac{1}{2}A_1\rho(V_2^2 - V_0^2) \tag{3.10}$$

Then V_2 can be expressed as:

$$V_2 = \left(V_0^{\,2} + \frac{2T}{\rho A_1}\right)^{1/2} \tag{3.11}$$

Introducing the propeller thrust coefficient K_T, and the propeller advance ratio J, we have:

$$V_2 = V_0\left(1 + \frac{8K_T}{\pi J^2}\right)^{1/2} \tag{3.12}$$

where $K_T = \dfrac{T}{\rho n^2 D^4}$ and $J = \dfrac{V_0}{nD}$ n is the revolutions per second of the propeller

Also, we notice that from equation (3.8) and (3.10) the increment on the velocity in the flow is produced at the propeller:

$$V_1 = \left(\frac{V_2 + V_0}{2}\right) \tag{3.13}$$

Since what is wanted to know is the velocity of the fluid arriving at the rudder V_R, and not V_2, which is too far downstream; it is necessary to add a correction factor K_R, extracted from Molland [8], to evaluate this velocity. Then,

$$V_R = V_0 + V_{increment} \tag{3.14}$$

$$V_{increment} = K_R(V_2 - V_0) \tag{3.15}$$

where $K_R = 0.5 + \dfrac{0.5}{\left(1 + \dfrac{0.15D}{X}\right)}$

Using equation (3.12) we have:

$$V_R = V_0\left[1 + K_R\left\{\left(1 + \frac{8K_T}{\pi J^2}\right)^{1/2} - 1\right\}\right] \tag{3.16}$$

As it is noticed, the velocity in the rudder depends on the propeller advance ratio, the propeller thrust coefficient and the distance between the rudder and propeller.

When these parameters are unknown, it is recommended to use the following relation, Molland [8]:

For propeller with velocity up to 500rpm:

$$V_R = 1.15V_0 \tag{3.17}$$

For propellers with velocity up to 1500rpm:

$$V_R = 1.25V_0 \tag{3.18}$$

For high speed watercrafts:

$$V_R = 1.20 V_S \tag{3.19}$$

V_S is the velocity of the ship, (see section 3.8).

3.8 Hull Influence over Rudder-Propeller Performance

The hull produces two effects over rudder-propeller performance. It slows down the flow to the propeller and rudder to a value V_0 compared to the ship speed V_S. And the hull affects the angle of attack in a rudder when turning, decreasing its value and make the use of an effective angle of attack.

It will be considered only the first effect for simpler calculations.

The effective speed V_0 can be evaluated using the following relation:

$$V_0 = V_S(1 - \omega_T) \tag{3.20}$$

Where ω_T is the wake fraction of the ship and depends on its type. For a twin-screw naval ship, which is this case study, ω_T can be approximated as:

$$\omega_T = 0.71 - 2.39 C_B + 2.33 C_B^2 \tag{3.21}$$

$$C_B = 0.55 - 0.75 \tag{3.22}$$

Where C_B is the block coefficient that depends on the type of ship.

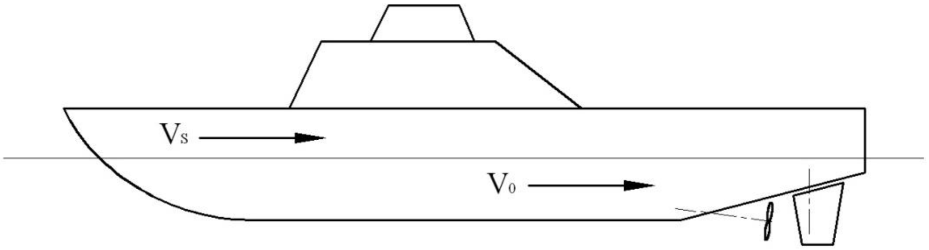


Figure 3-11 Influence of the hull over incoming speed of the rudder

3.9 Summary of the equations to be used

A list of equations taken from Molland [8] is displayed.

3.9.1 *Lift Coefficient*

$$C_L = \left[\frac{dC_L}{d\alpha}\right] \times \alpha + \frac{C_{Dc}}{AR_e}\left[\frac{\alpha}{57.3}\right]^2 \tag{3.23}$$

$$\left[\frac{dC_L}{d\alpha}\right] = \frac{1.95\pi}{57.3\left(1+\dfrac{3}{AR_e}\right)} \tag{3.24}$$

$C_{Dc} = 0.1 + 1.6TR$ for square tips (3.25)

$C_{Dc} = 0.1 + 0.7TR$ for faired tips (3.26)

3.9.2 *Drag Coefficient*

$$C_D = C_{D0} + k_i \frac{C_L^2}{AR_e} \tag{3.27}$$

3.9.3 *Normal Force Coefficient*

$$C_N = C_L \cos\alpha + C_D \sin\alpha \tag{3.28}$$

Chapter 4. ANALYSIS AND DESIGN OF A RUDDER

As an example of a design process and how to preserve the data generated from this process, we are going to consider the analysis and possible improvements of a rudder for a 120’ Torpedo Weapons Retriever Vessel. This design is part of the Subsystem Replacement Scenario.

As was said before, every design process begins with a customer requirement. In our case, these needs and requirements are assumed. We are going to start collecting the existing data provided by Navy in order to reconstruct the context in which the actual rudder was designed. First, the actual rudder will be analyzed in order to obtain the data that will be compared with the possible new rudder.

4.1 Problem Statement

The Navy requires evaluation of the performance of the rudder in its torpedo retrievers with a possibility of an improvement on it. For that matter, they provided a repository in which is contained all the information related to this marine vessel.

4.2 Given and Assuming Data

After looking over the documentation provided by the Navy it was possible to obtain some features from the marine vessel. Table 4.1 presents all these characteristics that are going to be used for analysis and design purposes. The ship possesses two Caterpillar Model 3512 V12 with 1140 shp at 1800 rpm each. Assuming there is no transmission between propellers and each engine, the propeller speed is also 1800 rpm. Both propellers have a diameter of 54 in, posses 4 blades and are made of manganese bronze and have 4 blades. The pitch is 46.8 in. The distance of 24 in between rudder and propeller is assumed.

Table 4-1 Features from the 120’ Torpedo Weapons Retriever obtained from Navy

Ship vessel features					
		Units			
		English		SI	
Length	L	120	ft	36.576	m
Beam	B	25	ft	7.62	m
Draft		89	in	2.261	m
Thrust	T	248	LT	2.47	MN
Speed	v	14.7	knots	7.567	m/s
Power		1140	shp	850.097	kW
Propeller diameter	D	54	in	1.3716	m
Propeller-rudder distance	X	2	ft	0.6096	m
Propeller speed		1800	rpm		

4.3 Determining the effective speed V_0

Using equations (3.20), (3.21) and (3.22) it is possible to estimate the effective speed that goes into the propeller. Taking C_B as 0.65 and V_S=7.567 m/s we obtain:

$$\omega_T = 0.71 - 2.39(0.65) + 2.33(0.65)^2 = 0.141$$
$$V_0 = 7.56(1-0.141) = 6.5 m/s$$

Using the total range of C_B from 0.55 to 0.75 we can find different values of ω_T which will give us several speed values that go into the propeller. Table 4.2 shows these values for the given range of C_B in increments of 0.01.

Table 4-2 Different values of v_0 depending on the values of C_B

C_B	ω_T	v_0 [m/s]
0.55	0.100325	6.807841
0.56	0.102288	6.792987
0.57	0.104717	6.774606
0.58	0.107612	6.7527
0.59	0.110973	6.727267
0.6	0.1148	6.698308
0.61	0.119093	6.665823
0.62	0.123852	6.629812
0.63	0.129077	6.590274
0.64	0.134768	6.547211
0.65	0.140925	6.500621
0.66	0.147548	6.450504
0.67	0.154637	6.396862
0.68	0.162192	6.339693
0.69	0.170213	6.278998
0.7	0.1787	6.214777
0.71	0.187653	6.14703
0.72	0.197072	6.075756
0.73	0.206957	6.000956
0.74	0.217308	5.92263
0.75	0.228125	5.840778

4.4 Determining the speed arriving at the Rudder V_R

From section 4.2 we have:

T=248 LT=2.47 MN
n=180 rpm=3 rps
D=54 in=1.3716 m

Assuming the distance between the propeller and the rudder as 2ft and the density of the water at 5 ^{0}C equal to 1000 kg/m^3, we have from section 3.7:

$$K_R = 0.5 + \frac{0.5}{\left(1 + \frac{0.15 \times 54}{24}\right)} = 0.874$$

$$K_T = \frac{2.47 \times 10^6}{1000 \times 3^2 (1.3716)^4} = 0.776$$

$$J = \frac{6.5}{(3)(1.3716)} = 0.158$$

Then it is possible to calculate V_R from equation (3.16):

$$V_R = 6.5 \left[1 + 0.874 \left\{ \left(1 + \frac{8(0.776)}{\pi (0.158)^2} \right)^{1/2} - 1 \right\} \right] = 51.71 m/s$$

Now it is seen that while the vessel is traveling at a speed of 7.56 m/s, the speed of the water flow passing through the rudder is 51.71 m/s.

Again, taking into account the different values we got from table 4.2, it is easy to find values for the speed passing through the rudder. Table 4.3 shows values for J and v_R

Table 4-3 Different values of J and v_R

J	v_R [m/s]
0.165448	51.77962
0.165087	51.77623
0.16464	51.77204
0.164108	51.76706
0.16349	51.76128
0.162786	51.75471
0.161996	51.74735
0.161121	51.73922
0.16016	51.73031
0.159114	51.72063
0.157981	51.71019
0.156763	51.699
0.15546	51.68706
0.154071	51.67439
0.152595	51.66098
0.151035	51.64686
0.149388	51.63202
0.147656	51.61649
0.145838	51.60027
0.143935	51.58337
0.141946	51.56581

According to Table 4.3, the speed of the water passing through the rudder is about 51 m/s. For the entire analysis the value of 51.71 m/s has been chosen.

4.5 Design of New Rudder

The main idea is to see whether is feasible to improve the performance of the rudder by changing it for an airfoil profile. Since the stock has a diameter of 7 1/8 in (180.975 mm) it is necessary to find a NACA profile which maximum thickness is larger than 7 1/8 in. For that matter, the NACA0030 is chosen because it has a maximum thickness of 300 mm.

Considering the same conditions, density of water 100 kg/m3, viscosity of water 0.001003 kg/m-s, speed of 51.71m/s, the results obtained are shown in the following figures.

As any design procedure, the analysis should involve three different paths: numerical analysis, experimental tests and virtual simulation using a CFD software. Due to limitations on this assignment, there is no experimental part.

Let us begin with the numerical analysis part. The software used is Matlab and all the equations and approximations used are described in Chapter 3. The equations are defined in part 3.9.

4.5.1 *Analytical Part*

Since we are starting from almost zero, we need to know the required area for the rudder. From table 4-1 it is possible to calculate the approximate area needed using equation 3.1:

$$Area = \frac{120 \times 7.417}{100}\left[1 + 25\left(\frac{25}{120}\right)^2\right] = 18.558\,ft^2 = 1.724m^2$$

Same table 4-1 specifies that the ship vessel carries two engines, thus it uses two propellers. Then, each rudder should have $0.862m^2$ at least.

To make things simpler, we are going to begin with an area of $1m^2$. Things would be farther simpler if all the definitions explained in section 3.3 were equal to one. This means the chord, the span, the aspect ratio and the taper ratio are taking the value of one.

Using Matlab to solve equations in sections 3.9.1 and 3.9.2 we can calculate the lift and drag coefficients. Figures 4-1 and 4-2 show the results of this analysis. According to figure 4-1 the lift coefficient increases as long with the angle of attack. This is not actually happening. Remember that the equations are an approximation of what is happening in 3D.

Figure 4-2 shows the behavior of the drag around the hydrofoil. The value at zero angle of attack means the profile develops drag due to its shape. The rest of the values are related to the drag generated by lift. Greater the lift, greater the induced drag.

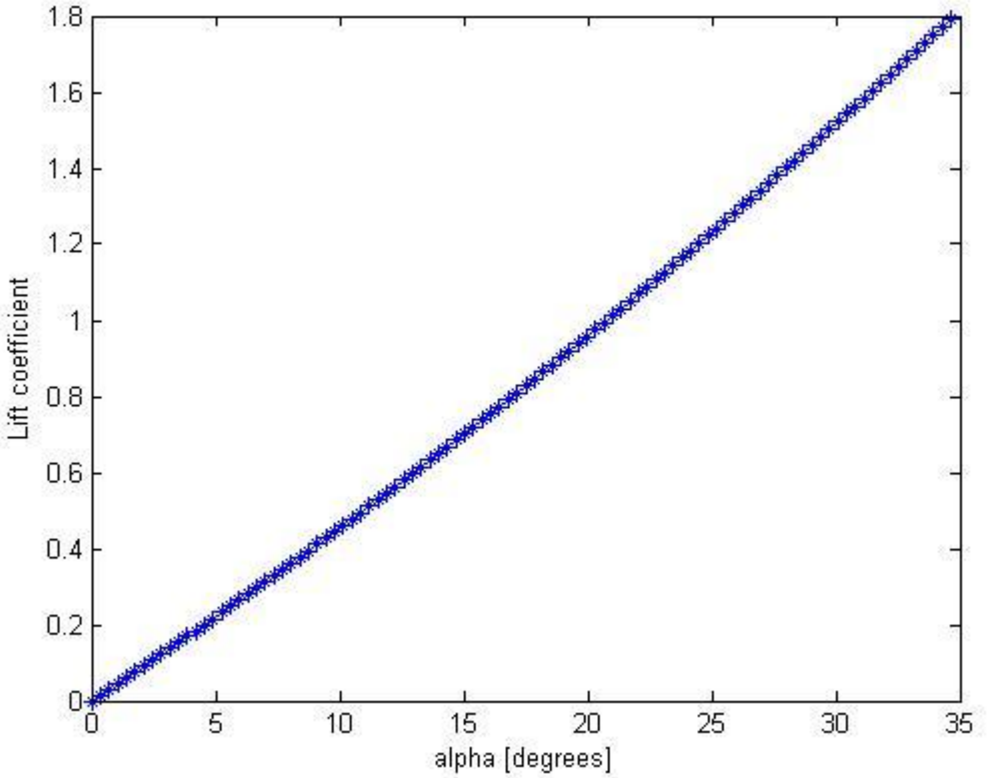


Figure 4-1 Matlab results for lift coefficient for a NACA0030 profile

Since the line defined by the lift coefficient is not accurate after certain angle of attack, then what is the point of doing the Matlab analysis? The answer is to establish a tendency on the results in order to know that what it is being doing on Fluent makes sense and we are in the correct path.

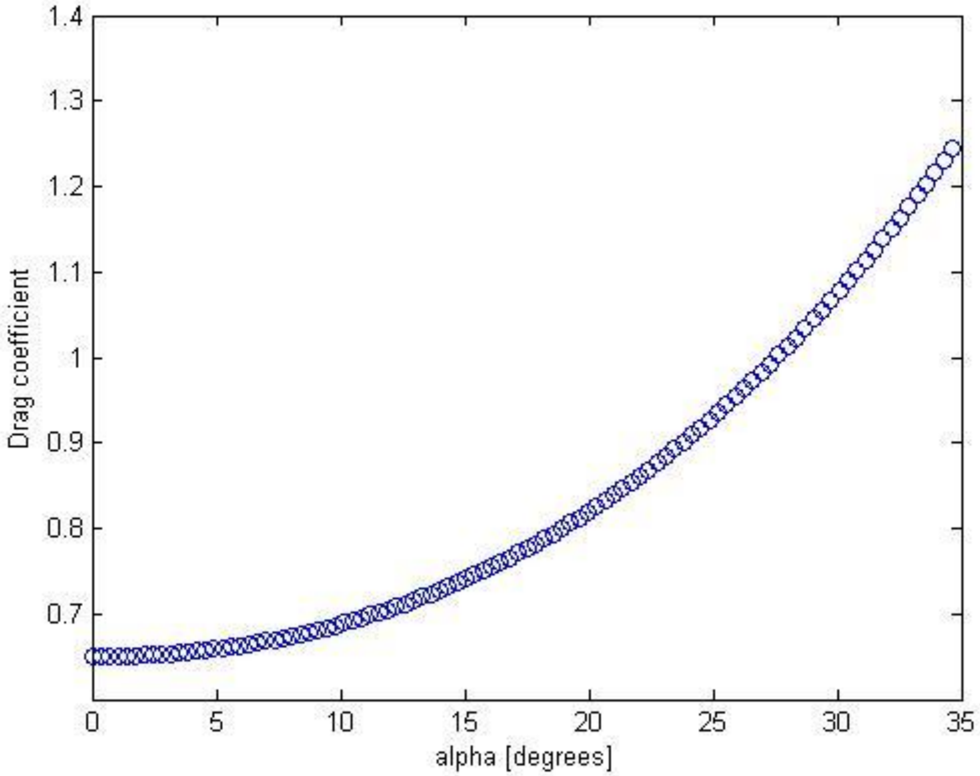


Figure 4-2 Matlab results of drag coefficient for a NACA0030 profile

4.5.2 *CFD Simulation in Fluent®*

In this section, a 2D airfoil profile was generated in Gambit® and draw the grid over the entire area of analysis. After that, import the file in Fluent and start the simulation for the range of angles of attack from 0 to 35 degrees with increments of 5 degrees. The whole simulation is in 2 dimensions.

Figure 4-3 shows the lift developed around the rudder under each angle of incidence. It can be noticed that the lift increases as long with the angle until certain point where the rudder stalls. Remember that what it is being looked for here is large amount of lift.

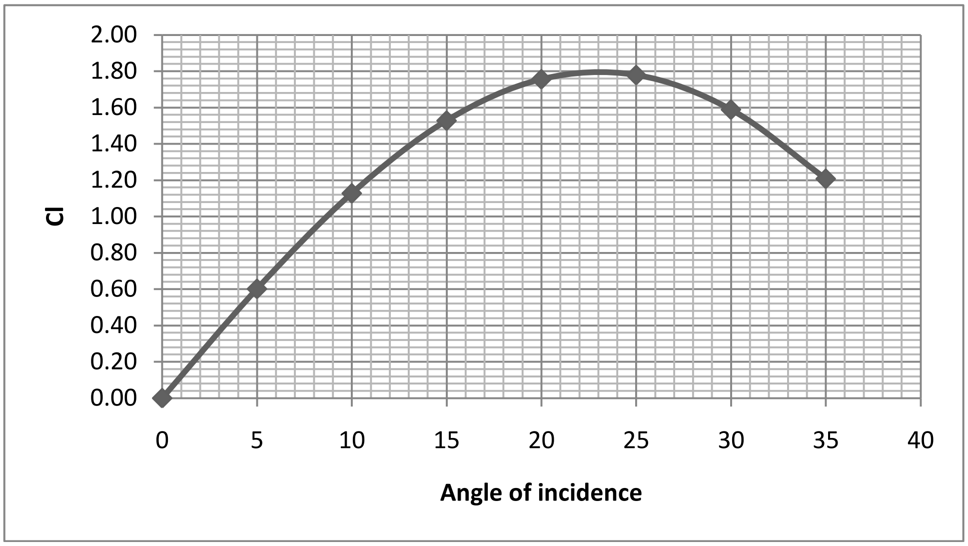


Figure 4-3 Lift coefficient for a profile NACA0030

The results of the drag coefficient analysis are presented in figure 4-4. This chart shows the increase of drag due to the rotation of the rudder.

Figure 4-4 Drag coefficient for a profile NACA0030

It is also possible to evaluate the pressure coefficient around the rudder for a certain rotation on the rudder. Figure 4-5 presents these pressure coefficients when the angle of attack is 25 degrees.

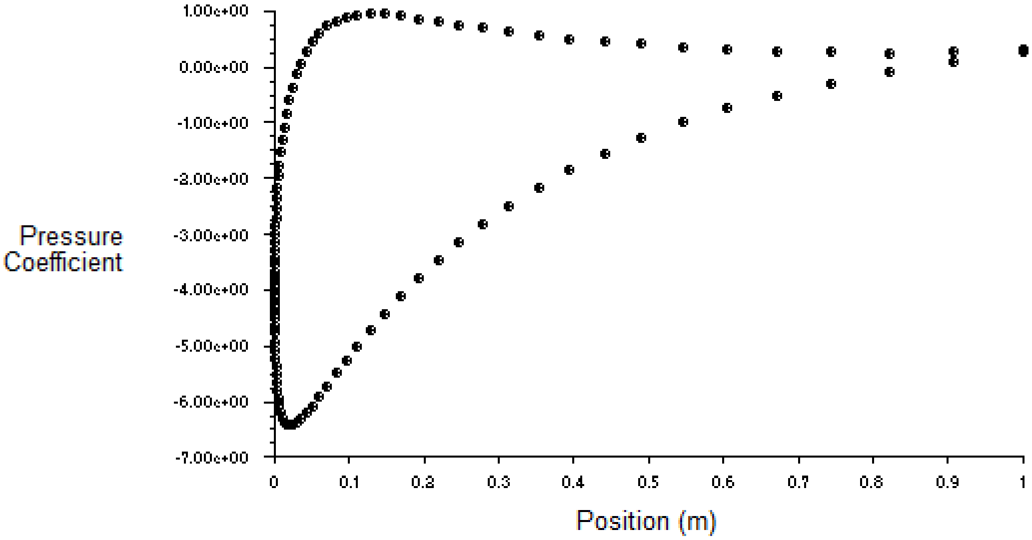


Figure 4-5 Pressure coefficients around airfoil at 25 degrees

4.5.3 *Comparing Matlab results with Fluent results*

In order to figure out if what it was done on Fluent is correct is comparing these results with the ones obtained on Matlab. But, how is possible to compare something in 2D with 3D data? The only way is to translate the 2D data into 3D information. For that matter it is useful to use the equation found on Bertin[3]:

$$\frac{dC_L}{d\alpha} = \frac{\frac{dC_l}{d\alpha}}{1+\frac{57.3\frac{dC_l}{d\alpha}}{\pi e AR_e}} \tag{4.1}$$

This means that the slope of the 3D lift curve (related by upper L) can be approximated by dividing the slope of the 2D lift curve by a factor involving the same 2D lift slope. The *e* is an efficiency factor which values varies from 0.6 to 0.95. Since the denominator in the equation is greater than one, the 3D lift slope will be lower than its correspondent 2D data.

The way of doing this is fitting a curve throughout the values of the 2D data. Using Matlab we fit a curve for the values presented on figure 4-3. This curve is shown in figure 4-6.

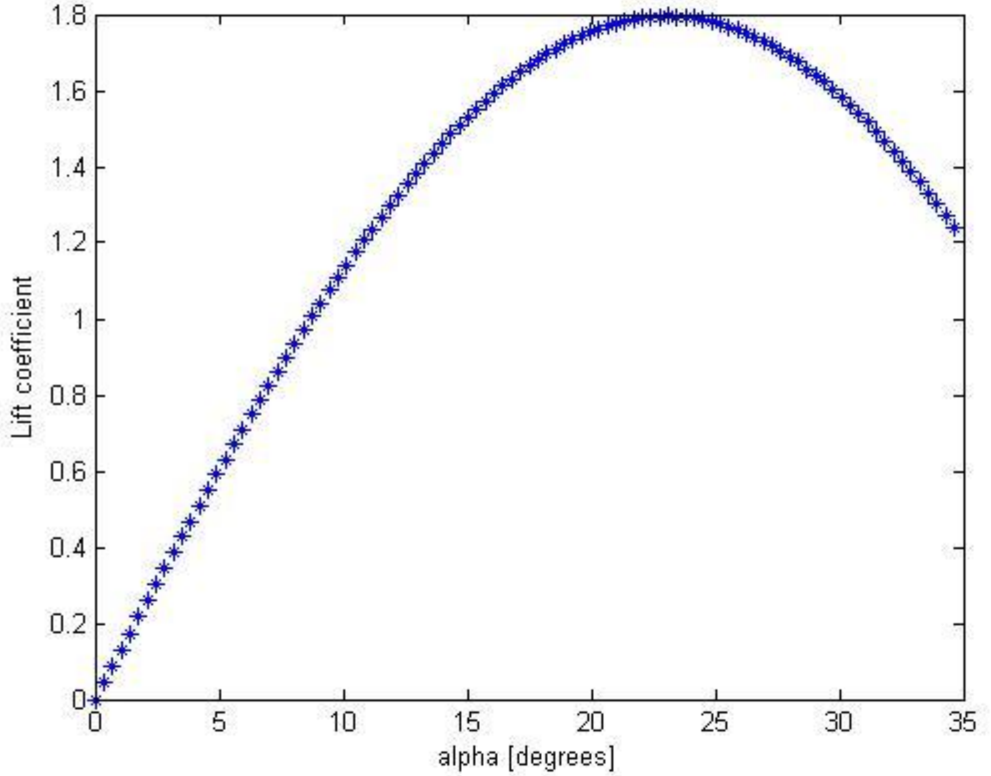


Figure 4-6 Lift coefficient curve fitted in Matlab

Next step is find the slope of the curve for each point and apply equation 4.1 in order to find the correspondent 3D lift slope. After doing the calculation in Matlab, the values of the slop are shown in figure 4-7. It is noticeable that after an angle of attack around 25 degrees the values of the slope are negative. This is due to the curvature of the 2D lift curve. Lift coefficient gets its maximum value at around 25 degrees, after that lift decreases. Now that the values of slope are found it is just matter of multiply them by the values of angles of attack.

Figure 4-8 shows the comparison between the 3D data collected from the equations against the 3D data obtained from the 2D analysis in Fluent. We can see a good approximation between both curves until the angle of 15 degrees. What it is possible to do is fixed a value of slope for the 2D case and approximate the entire new 3D lift curve. The value taken as a fixed slope is the slope correspondent to the angle of 14 degrees.

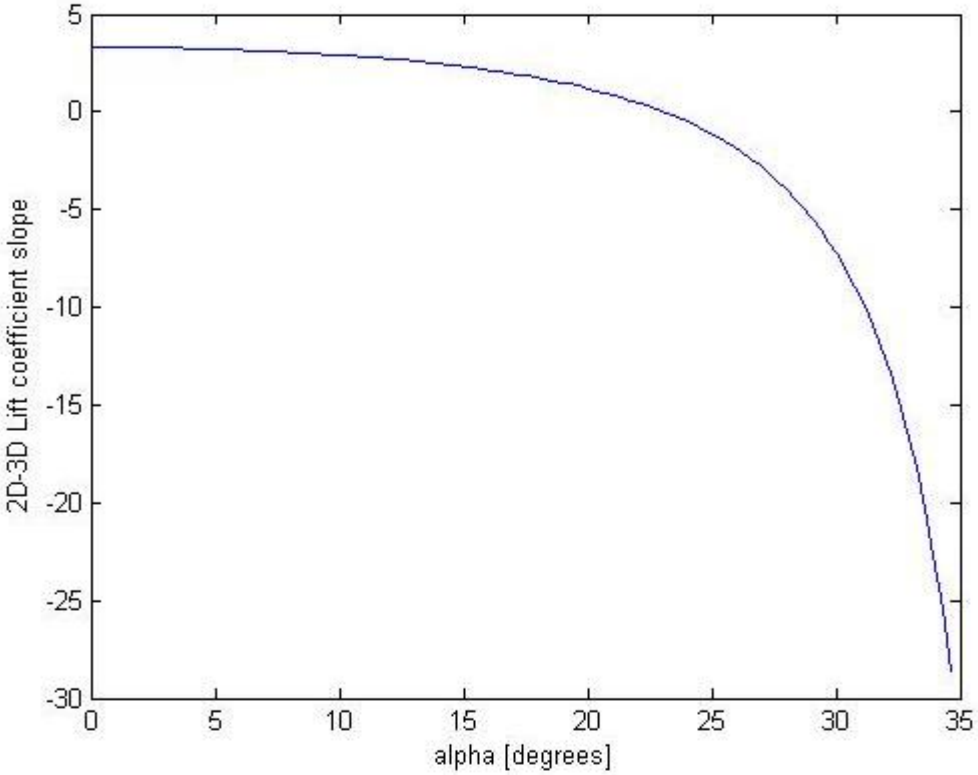


Figure 4-7 Curve showing the slope of the 2D lift curve

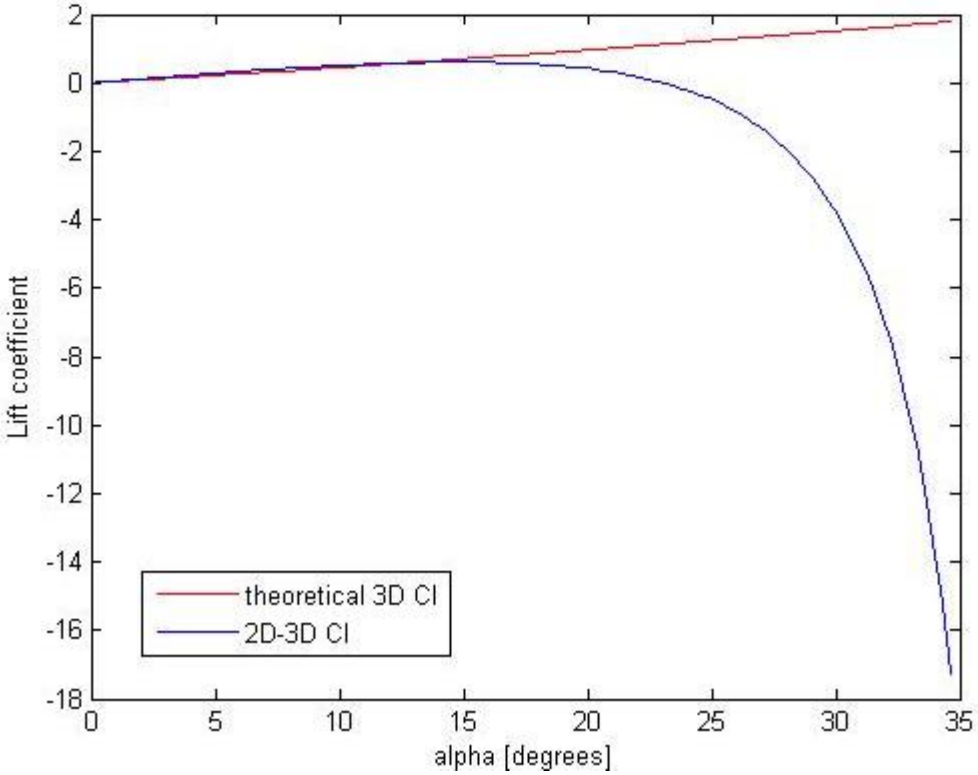


Figure 4-8 Theoretical 3D lift coefficient curve and 2D-3D conversion lift coefficient curve.

After fixing the value of the slope, we compare the new 2D-3D curve to the one obtained from the equation in section 3.9. Figure 4-9 presents both curves. In table 4-4 is presented the values for the theoretical 3D analysis, the 2D-3D conversion, the fixed 2D-3D data and the error for each angle of incidence.

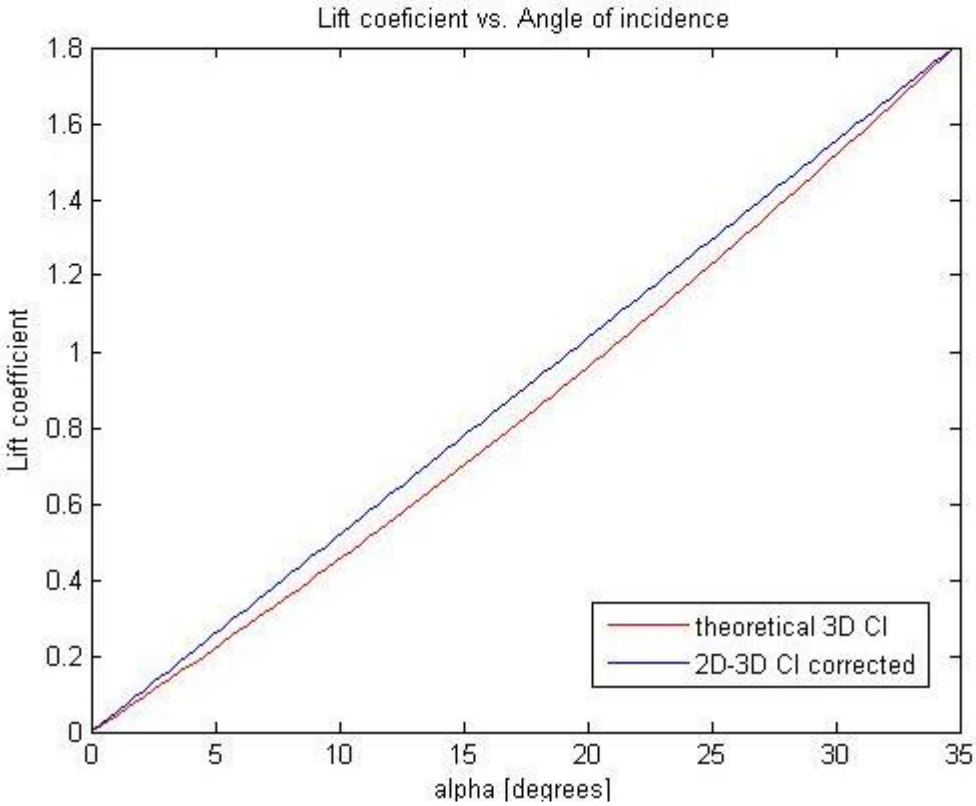


Figure 4-9 Comparison between 3D theoretical curve and the approximated 3D-2D curve.

Table 4-4 Values for lift coefficients for the different cases

Angle	CL	Cl_1 (real 2D-3d)	Cl_2 (fixed 2D-3D)	Cl_1-CL error	Cl_2-CL error
0	0	0	0	0	0
0.35	0.015	0.0204	0.0181	0.0054	0.0031
0.7	0.0301	0.0407	0.0363	0.0107	0.0062
1.05	0.0452	0.061	0.0544	0.0158	0.0092
1.4	0.0604	0.0811	0.0725	0.0207	0.0121
1.75	0.0756	0.1011	0.0906	0.0255	0.015
2.1	0.0909	0.121	0.1088	0.0301	0.0178
2.45	0.1063	0.1408	0.1269	0.0345	0.0206

2.8	0.1218	0.1604	0.145	0.0387	0.0232
3.15	0.1373	0.1799	0.1631	0.0426	0.0259
3.5	0.1528	0.1992	0.1813	0.0464	0.0284
3.85	0.1685	0.2184	0.1994	0.0499	0.0309
4.2	0.1842	0.2373	0.2175	0.0531	0.0333
4.55	0.1999	0.2561	0.2356	0.0561	0.0357
4.9	0.2158	0.2746	0.2538	0.0588	0.038
5.25	0.2317	0.2929	0.2719	0.0612	0.0402
5.6	0.2476	0.3109	0.29	0.0633	0.0424
5.95	0.2636	0.3286	0.3082	0.065	0.0445
6.3	0.2797	0.3461	0.3263	0.0664	0.0466
6.65	0.2958	0.3632	0.3444	0.0674	0.0486
7	0.312	0.38	0.3625	0.068	0.0505
7.35	0.3283	0.3965	0.3807	0.0682	0.0524
7.7	0.3446	0.4125	0.3988	0.0679	0.0541
8.05	0.361	0.4282	0.4169	0.0672	0.0559
8.4	0.3775	0.4434	0.435	0.066	0.0575
8.75	0.394	0.4582	0.4532	0.0642	0.0592
9.1	0.4106	0.4726	0.4713	0.062	0.0607
9.45	0.4272	0.4864	0.4894	0.0591	0.0622
9.8	0.444	0.4996	0.5076	0.0557	0.0636
10.15	0.4607	0.5123	0.5257	0.0516	0.0649
10.5	0.4776	0.5244	0.5438	0.0468	0.0662
10.85	0.4945	0.5359	0.5619	0.0414	0.0675
11.2	0.5114	0.5466	0.5801	0.0352	0.0686
11.55	0.5285	0.5567	0.5982	0.0282	0.0697
11.9	0.5456	0.566	0.6163	0.0204	0.0707
12.25	0.5627	0.5745	0.6344	0.0118	0.0717
12.6	0.5799	0.5821	0.6526	0.0022	0.0726
12.95	0.5972	0.5889	-0.6707	0.0084	0.0735
13.3	0.6146	0.5947	-0.6888	0.0199	0.0742
13.65	0.632	0.5995	-0.7069	0.0325	0.075
14	0.6495	0.6032	-0.7251	0.0463	0.0756
14.35	0.667	0.6058	-0.7432	0.0612	0.0762
14.7	0.6846	0.6072	-0.7613	0.0774	0.0767
15.05	0.7023	0.6073	-0.7795	0.0949	0.0772
15.4	0.72	0.6061	-0.7976	0.1139	0.0776
15.75	0.7378	0.6035	-0.8157	0.1343	0.0779
16.1	0.7556	0.5994	-0.8338	0.1563	0.0782
16.45	0.7735	0.5936	-0.852	0.1799	0.0784
16.8	0.7915	0.5862	-0.8701	0.2053	0.0786

17.15	0.8096	0.577	-0.8882	0.2326	0.0786
17.5	0.8277	0.5658	-0.9063	0.2619	0.0787
17.85	0.8458	0.5526	-0.9245	0.2932	0.0786
18.2	0.8641	0.5373	-0.9426	0.3268	0.0785
18.55	0.8824	0.5196	-0.9607	0.3628	0.0783
18.9	0.9007	0.4994	-0.9788	0.4013	0.0781
19.25	0.9192	0.4767	-0.997	0.4425	0.0778
19.6	0.9377	0.4511	-1.0151	0.4866	0.0775
19.95	0.9562	0.4225	-1.0332	0.5337	0.077
20.3	0.9748	0.3907	-1.0514	0.5841	0.0765
20.65	0.9935	0.3555	-1.0695	0.638	0.076
21	1.0122	0.3166	-1.0876	0.6957	0.0754
21.35	1.031	0.2737	-1.1057	0.7573	0.0747
21.7	1.0499	0.2266	-1.1239	0.8233	0.074
22.05	1.0688	0.1749	-1.142	0.8939	0.0731
22.4	1.0878	0.1184	-1.1601	0.9695	0.0723
22.75	1.1069	0.0565	-1.1782	1.0504	0.0713
23.1	-1.126	0.0111	-1.1964	1.1371	0.0704
23.45	-1.1452	0.0848	-1.2145	1.23	0.0693
23.8	-1.1645	0.1652	-1.2326	1.3297	0.0682
24.15	-1.1838	0.2529	-1.2508	1.4367	0.067
24.5	-1.2031	0.3484	-1.2689	1.5515	0.0657
24.85	-1.2226	0.4525	-1.287	1.675	0.0644
25.2	-1.2421	0.5658	-1.3051	1.8079	0.063
25.55	-1.2617	0.6893	-1.3233	1.951	0.0616
25.9	-1.2813	0.824	-1.3414	2.1053	0.0601
26.25	-1.301	0.9708	-1.3595	2.2717	0.0585
26.6	-1.3207	1.1309	-1.3776	2.4516	0.0569
26.95	-1.3406	1.3057	-1.3958	2.6463	0.0552
27.3	-1.3604	1.4967	-1.4139	2.8572	0.0535
27.65	-1.3804	1.7056	-1.432	3.086	0.0516
28	-1.4004	1.9344	-1.4501	3.3348	0.0498
28.35	-1.4205	2.1851	-1.4683	3.6056	0.0478
28.7	-1.4406	2.4605	-1.4864	3.9011	0.0458
29.05	-1.4608	2.7632	-1.5045	4.224	0.0437
29.4	-1.4811	3.0967	-1.5227	4.5778	0.0416
29.75	-1.5014	3.4648	-1.5408	4.9662	0.0394
30.1	-1.5218	3.8719	-1.5589	5.3937	0.0371
30.45	-1.5422	4.3233	-1.577	5.8655	0.0348
30.8	-1.5628	4.825	-1.5952	6.3878	0.0324
31.15	-1.5833	5.3842	-1.6133	6.9676	0.0299

31.5	-1.604	6.0095	-1.6314	7.6135	0.0274
31.85	-1.6247	6.711	-1.6495	8.3356	0.0249
32.2	-1.6455	7.5008	-1.6677	9.1463	0.0222
32.55	-1.6663	8.3937	1.6858	-10.06	0.0195
32.9	-1.6872	9.4078	1.7039	-11.095	0.0167
33.25	1.7082	-10.5649	1.722	-12.2731	0.0139
33.6	1.7292	-11.8926	1.7402	-13.6217	0.011
33.95	1.7503	-13.4249	1.7583	-15.1752	0.008
34.3	1.7714	-15.2054	1.7764	-16.9768	0.005
34.65	1.7926	-17.2895	1.7946	-19.0822	0.0019

This comparison between the two approaches were made just to make sure what it was done in Fluent is correct. From now on all the study is going to consider the Fluent results for the actual rudder.

4.6 Analysis of Actual Rudder

It was said that the NAVY wants to replace the rudders in all its Torpedo Weapons Retrievers. Figure 4-1 shows the actual configuration of the current rudder in use. Since this rudder is basically a plate with ribs to make it stiffer, the analysis is going to consider only the plate as a first analysis, then the presence of the stock will be consider.

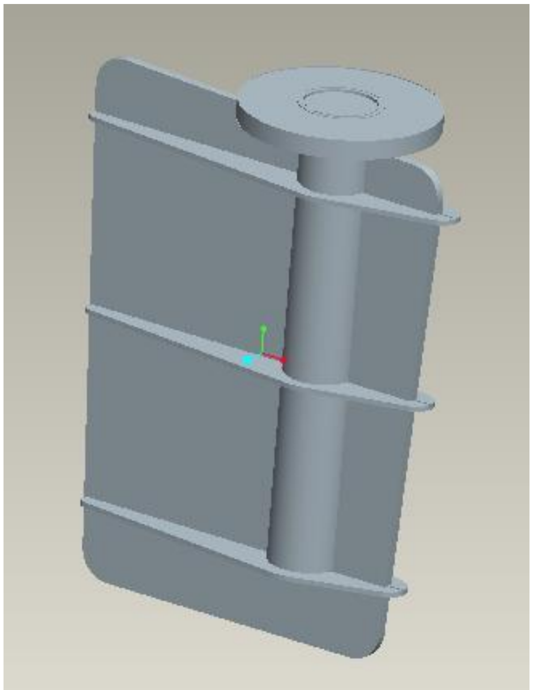


Figure 4-10 Actual rudder. Model made in ProE

4.6.1 *Rudder as a simple plate*

As established before, the simulation of the rudder will be considered it as simple plate. Figure 4-11 shows the blueprint to build the rudder. But this rudder has multiple dimensions to describe its geometry as shown in the Figure 4-12, which is a zoom view of the previous figure.

As anyone can think, it is possible to reconstruct the rudder from this blueprint. But the problem is not how to rebuild the actual piece, but understand why it has the features it has already. But this issue will be taken in detail in the next chapter.

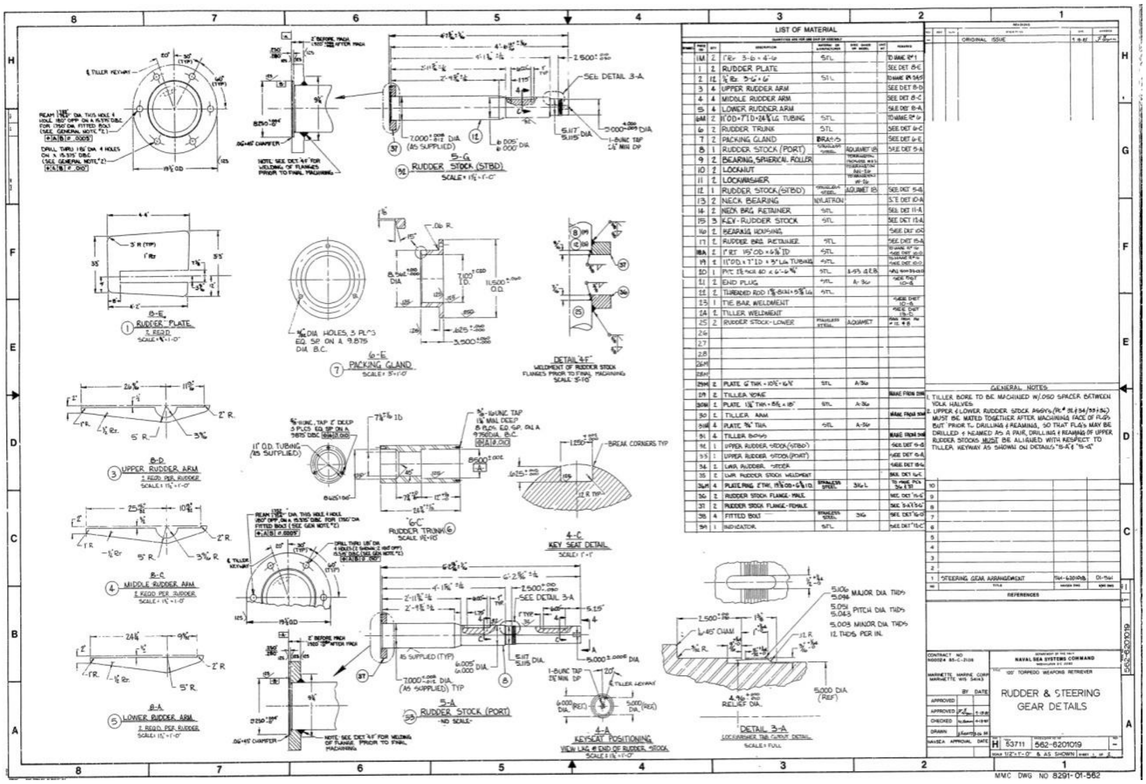


Figure 4-11 Blueprint for the construction of the actual rudder. Extracted from the NAVY repository

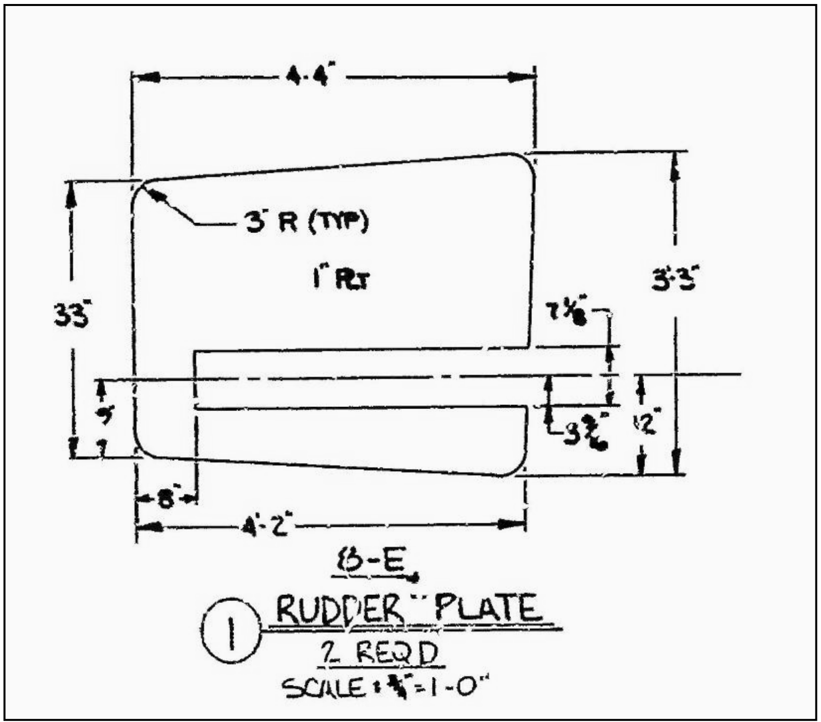


Figure 4-12 Image showing the dimension of the actual rudder

Since the analysis to be performed is in two dimensions, it is needed to work with mean chord. Thus,

$$c = \frac{39 + 33}{2} = 36in = 0.9144m$$

Knowing that the speed entering the rudder zone is 51.71 m/s and that the angle of incidence of work range between 0^{o} and 35^{o} we input these values into Fluent and simulate the behavior of the plate under this range of angles of attack.

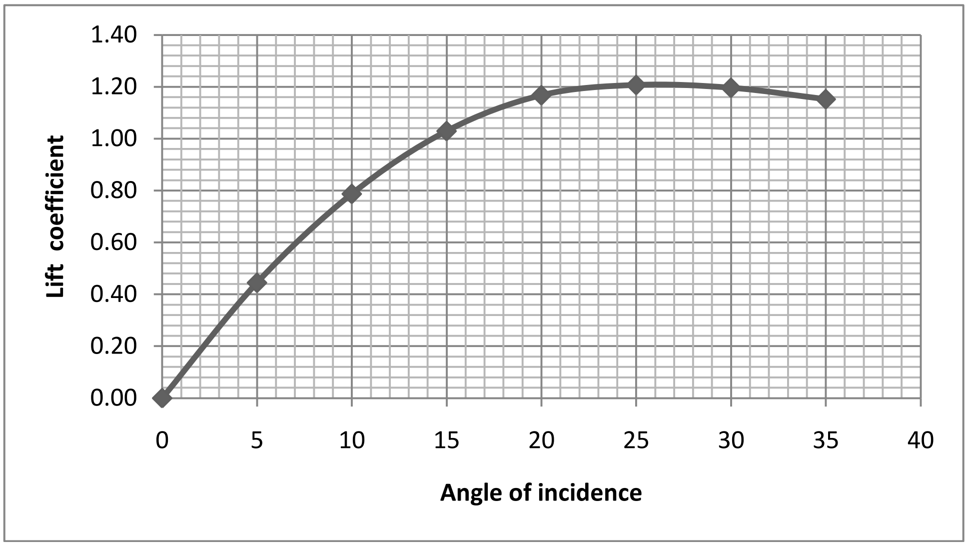


Figure 4-13 Lift coefficient of actual rudder as a simple plate

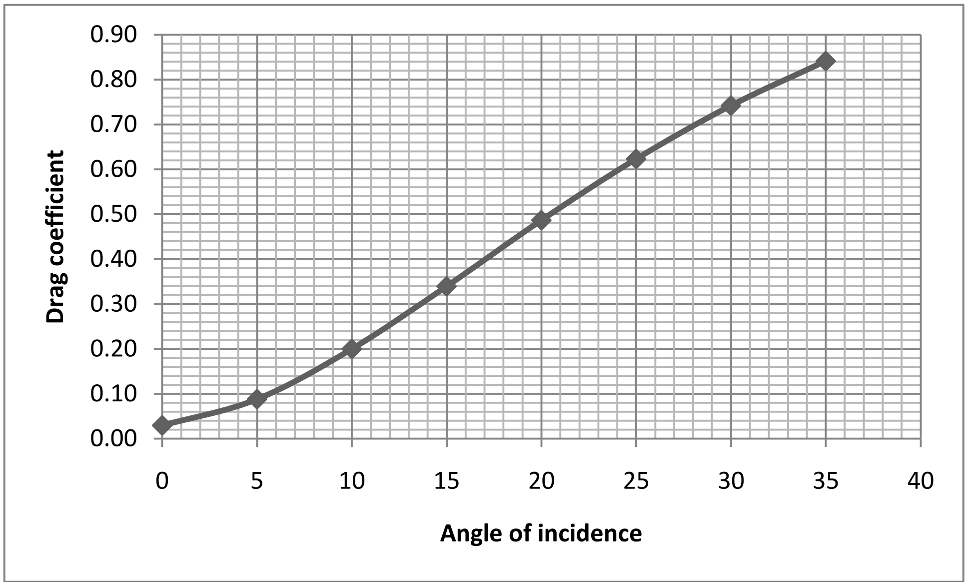


Figure 4-14 Drag coefficient of actual rudder as a simple plate

After running the analysis in Fluent, the drag and lift coefficients have been plot with the correspondent angle of incidence. Figure 4-13 and 4-14 contain the values of these coefficients for each angle.

Figure 4-15 shows the static pressure around the plate for an angle of attack of 25^o. The maximum static pressure is 1.17 MPa at the lower side on the leading edge, while a negative pressure of 2 MPa is developed at the upper side around the trailing edge.

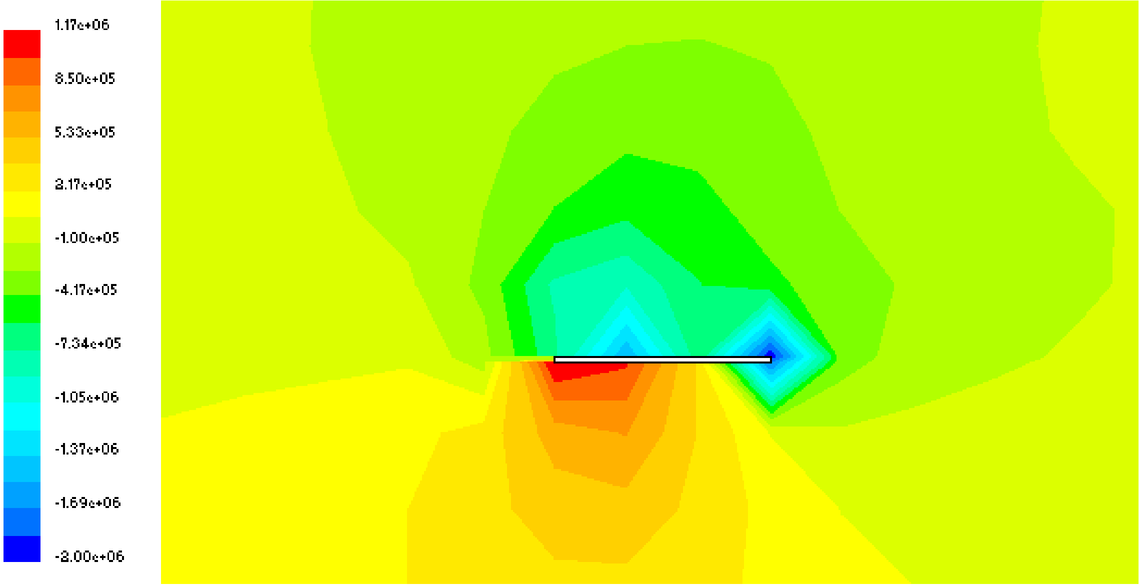


Figure 4-15 Static Pressures around a plate at 25 degrees

4.6.2 *Rudder considering the plate and the stock*

As before, the plate is considering similar as the previous case, but now the influence of the stock is studied. The same entering data is considered here, the speed, the range of angles. The lift and drag coefficients are shown in figures 4-16 and 4-17. Values of lift and drag are a little lower compared to the plate case.

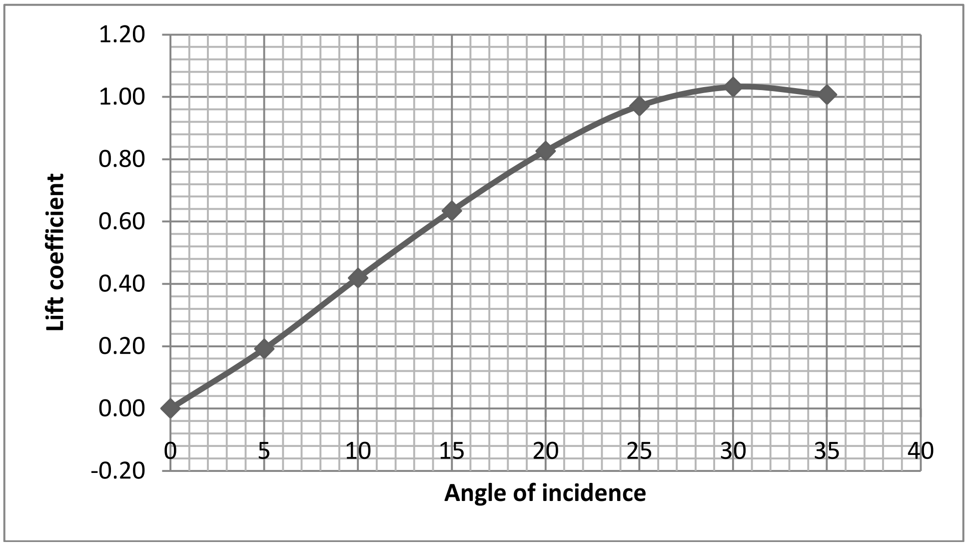


Figure 4-16 Lift coefficients for the actual rudder

Figure 4-17 Drag coefficients for the actual rudder

Static pressure is shown in figure 4-18. The picture shows the pressure distribution when the flow is at 25° respect to the rudder. The red zone under the rudder indicates large pressure which is the area where the water is hitting the rudder. Also, it can be noticed the influence of the stock in Figure 4-19. Because of the presence of the stock the pressure distribution is altered between 0.2 and 0.4 in the x-axis which is the location of the axle.

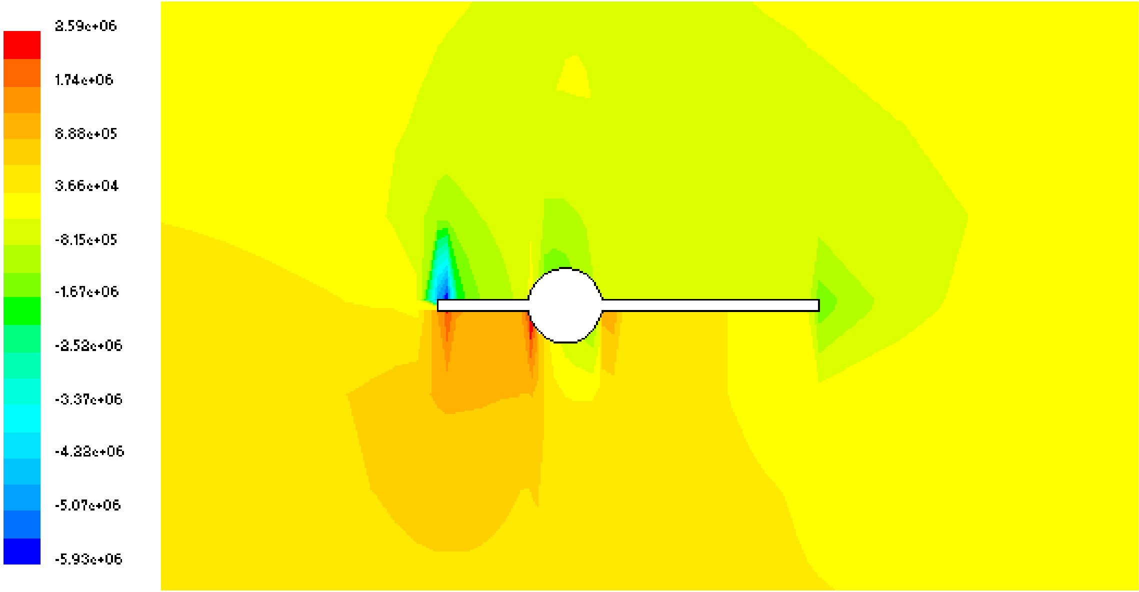


Figure 4-18 Static pressure around rudder at 25 degrees

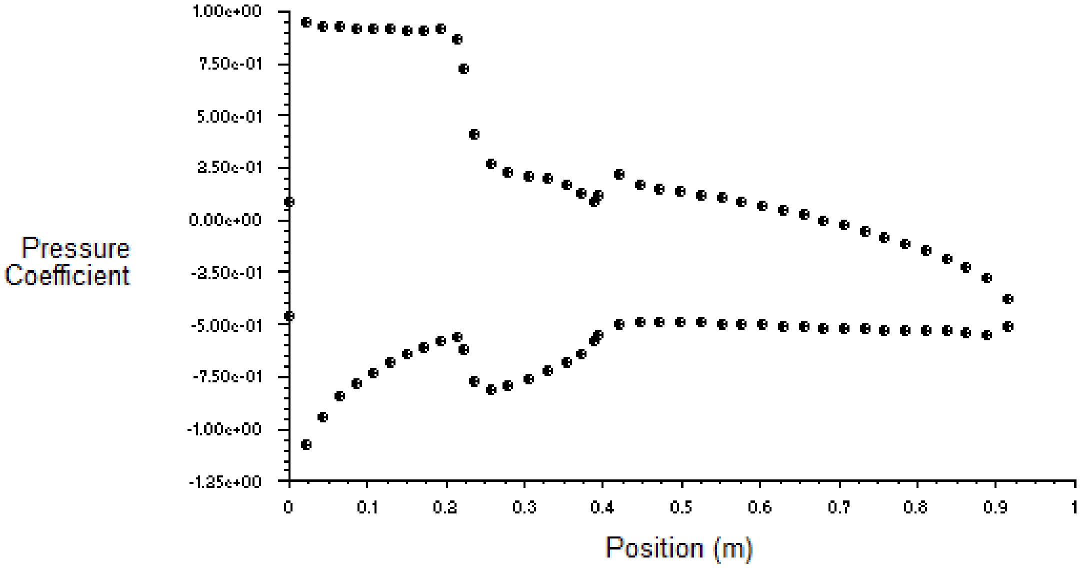


Figure 4-19 Pressure coefficient around rudder at 25 degrees

4.7 Results analysis

Now that we have the analysis for the three cases, it is imperative to decide if it is convenient to change the actual rudder for the new one.

What it is being looked for here is a rudder capable of develop large amount of lift and reduced amount of drag. In order words, the lift drag ratio should be as large as possible.

In Figure 4-20 it is seen that the drag generated by the airfoil is less than the actual rudder. On the other hand, the values of the lift are greater than the other cases, see Figure 4-13. Besides, it can be noticed that the presence of the stock more drag and less lift than the single plate. It is logical to think that the simple plate would have done a better job, but do not forget the presence of stress in the axle of the rudder. That is why the stock has those dimensions. Do not forget that the present thesis is focused only on the calculus of lift and drag coefficients, and it does not consider the analysis of stress on any component of the rudder.

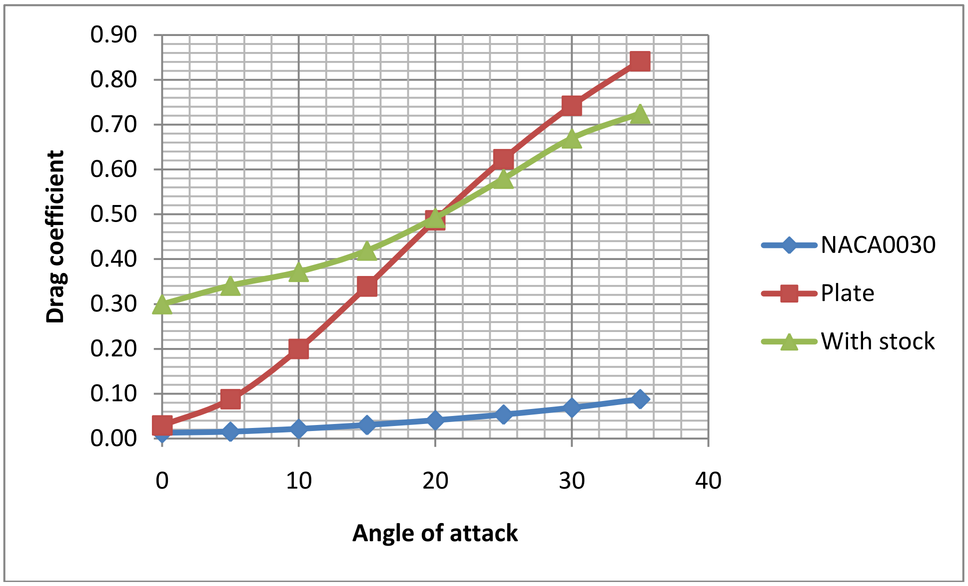


Figure 4-20 Drag coefficients for the three cases

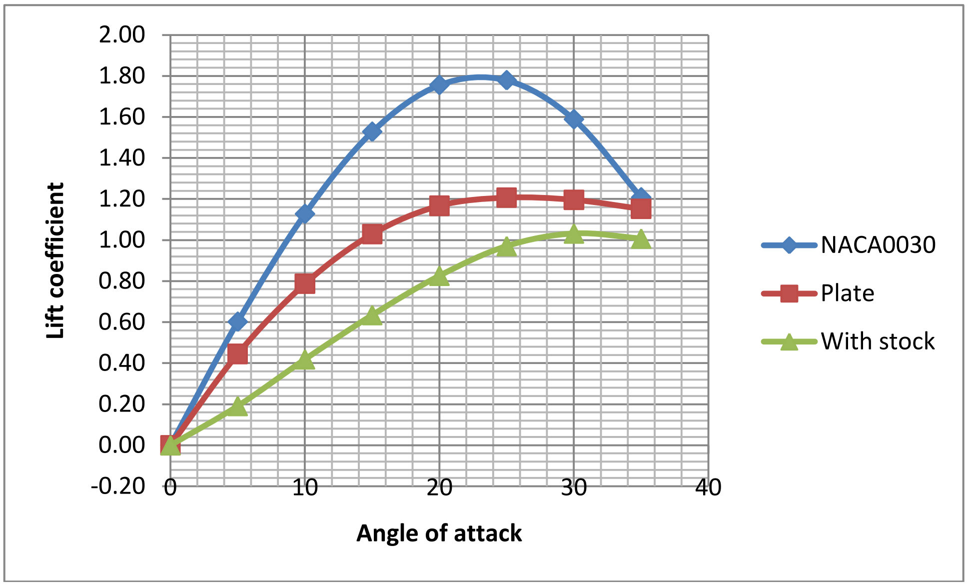


Figure 4-21 Lift coefficients for the three cases

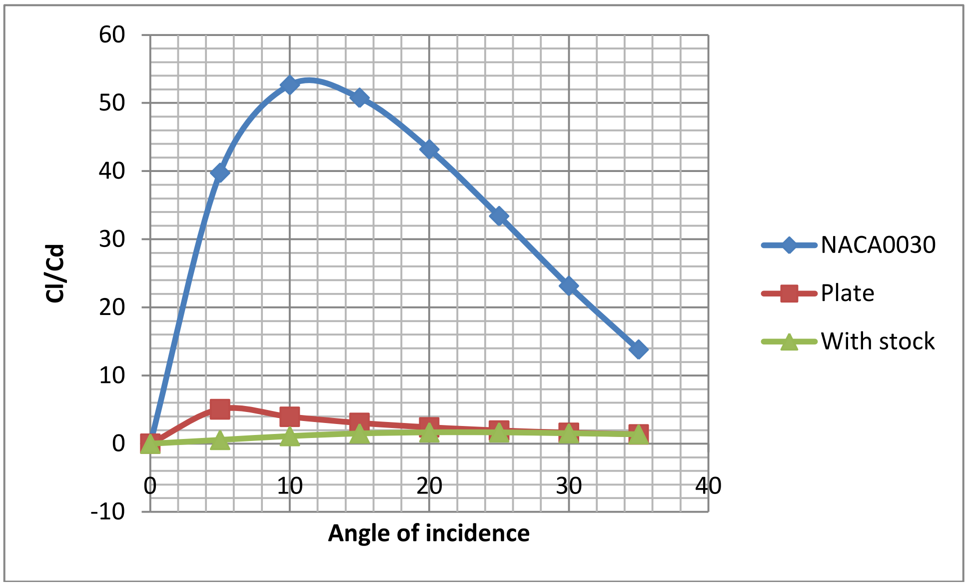


Figure 4-22 Cl/Cd comparison for the three cases

Since what it is being looked for is a high lift/drag ratio, Figure 4-22 tells us that the NACA profile is a good replacement. This advantage is due to the low drag developed for the airfoil.

The next chapter shows the development of a small repository for long term retention for the design of the rudder. We are going to explain the importance of the STEP AP's.

Chapter 5. IN SEARCH FOR LONG TERM RETENTION DATA

Many times it has been said that the design process involves several activities in which a part of the product is elaborated under certain conditions. Each activity presents several tools that use their own way to store the data produced. If geometry is being generated using specific CAD software, the same program has its own format to manage the data created.

5.1 What is STEP?

Its official name is ISO 10303. STEP is the acronym for Standard for the Exchange of Product model data. Basically, it was developed to replace another format: iges [7]. Figure 5-1 presents an example of how this STEP document looks like. As it can be appreciated, the STEP format is a plain text language that describes points and lines in a simple manner.

Step is made up of several parts. Each part is in charge of describing all the aspects of a design procedure. These parts can be classified into five categories [6]:

1. Description Methods
2. Information Models
3. Application Protocols
4. Implementation Methods
5. Conformance Tools

Each category takes part in the entire structure of STEP. As a description method, STEP uses its own language named EXPRESS. It is this language which drives the implementation methods. The structure and constraints of a model are described by the information model and the application protocols [6].

```
ISO-10303-21;
HEADER;
/****************************************************************
 * Generated by software with PDE/Lib inside                    *
 * PDElib Version v51a, created Tue 12/06/2005                   *
 * International Technegroup Inc. (www.iti-oh.com)                *
 ****************************************************************/
FILE_DESCRIPTION((''),'2;1');
FILE_NAME('C:\\Documents and Settings\\SEAP\\Desktop\\TWR Models\\STEP Files\\Rudder
Assembly\\Parts\\Starboard_Rudder_Stock.stp','2007-08-15T07:30:41',('SEAP'),(''),'Autodesk Inventor 11','Autodesk
Inventor 11','');
FILE_SCHEMA(('AUTOMOTIVE_DESIGN { 1 0 10303 214 1 1 1 1 }'));
ENDSEC;
DATA;
#5=APPLICATION_CONTEXT('automotive design');
#6=APPLICATION_PROTOCOL_DEFINITION('Draft International Standard','automotive_design',1998,#5);
#7=PRODUCT_CONTEXT('None',#5,'mechanical');
#8=PRODUCT('Starboard_Rudder_Stock','Starboard_Rudder_Stock','None',(#7));
#9=PRODUCT_RELATED_PRODUCT_CATEGORY('part','description',(#8));
#10=PRODUCT_DEFINITION_FORMATION('None','None',#8);
#11=PRODUCT_DEFINITION_CONTEXT('part definition',#5,'design');
#12=PRODUCT_DEFINITION('None','None',#10,#11);
#18=(NAMED_UNIT(*)PLANE_ANGLE_UNIT()SI_UNIT($,.RADIAN.));
#19=DIMENSIONAL_EXPONENTS(0.0,0.0,0.0,0.0,0.0,0.0,0.0);
#20=PLANE_ANGLE_MEASURE_WITH_UNIT(PLANE_ANGLE_MEASURE(0.017453292500000),#18);
#24=(CONVERSION_BASED_UNIT('DEGREE',#20)NAMED_UNIT(#19)PLANE_ANGLE_UNIT());
#28=(NAMED_UNIT(*)SI_UNIT($,.STERADIAN.)SOLID_ANGLE_UNIT());
#32=(LENGTH_UNIT()NAMED_UNIT(*)SI_UNIT(.MILLI.,.METRE.));
#34=UNCERTAINTY_MEASURE_WITH_UNIT(LENGTH_MEASURE(0.010000000000000),#32,'DISTANCE_ACCURACY_VA
LUE','');
#36=(GEOMETRIC_REPRESENTATION_CONTEXT(3)GLOBAL_UNCERTAINTY_ASSIGNED_CONTEXT((#34))GLOBAL_U
NIT_ASSIGNED_CONTEXT((#24,#28,#32))REPRESENTATION_CONTEXT('None','None'));
#37=AXIS2_PLACEMENT_3D('',#38,#39,#40);
#38=CARTESIAN_POINT('',(0.0,0.0,0.0));
#39=DIRECTION('',(0.0,0.0,1.0));
#40=DIRECTION('',(1.0,0.0,0.0));
#41=SHAPE_REPRESENTATION('',(#37),#36);
#42=PRODUCT_DEFINITION_SHAPE('','',#12);
#43=SHAPE_DEFINITION_REPRESENTATION(#42,#41);
#44=CARTESIAN_POINT('',(132.800000000000010,192.981250000000270,146.115285406458670));
#45=CARTESIAN_POINT('',(135.973999999999990,192.981250000000300,151.397708483439200));
```

Figure 5-1 Extract of a Step document

Each application protocol describes one part of the design process. For instance, AP203 represents the geometry of the model made in certain CAD software. AP239 deals with the entire lifecycle of the design. In table 5-1 are listed several application protocols that conform the STEP standard.

Although STEP contains a large amount of protocols, just two of them are available through CAD software vendors: AP203 and AP214 that manage the description of the geometry of a model. Despite the fact that these previous mentioned Application Protocols describe the geometry of a part or assembly, their efficiency is questionable. Previous experience has shown that different configurations of a same CAD file are lost when translated to STEP format. Imagine a company that uses one type of bolt and the only difference is the length. So, the engineer models that bolt and the three different lengths in Solidworks. Instead of create three different files, the engineer models a bolt and inside the same file creates two more configurations corresponding to the other two lengths. Now there is only one file with three different configurations. When this single file is saved as a STEP file, just one configuration is saved and the other two are lost. Now the question is whether AP203 and AP214 do not support several configurations inside a same file, or the software is not using all the capabilities of these AP.

The same questions could be asked for the rest of AP. This issue questions the capability of STEP to represent each activity in the design process. The only way to clear this issue is to take a complete design process of a product, translate entirely to STEP format and import the whole file into different software and see what is missing. Unfortunately, this cannot be done at the moment due to lack of accessibility to STEP AP.

Table 5-1 Some of the STEP Application Protocols.

Part 201	Explicit Drafting
Part 202	Associative Drafting
Part 203	Configuration Controlled Design
Part 204	Mechanical Design Using Boundary Representation
Part 205	Mechanical Design Using Surface Representation
Part 206	Mechanical Design Using Wireframe Representation
Part 207	Sheet Metal Dies and Blocks
Part 208	Life Cycle Product Change Process
Part 209	Design Through Analysis of Composite and Metallic Structures
Part 210	Electronic Printed Circuit Assembly, Design and Manufacturing
Part 211	Electronics Test Diagnostics and Remanufacture
Part 212	Electrotechnical Plants
Part 213	Numerical Control Process Plans for Machined Parts
Part 214	Core Data for Automotive Mechanical Design Processes
Part 215	Ship Arrangement
Part 216	Ship Molded Forms
Part 217	Ship Piping
Part 218	Ship Structures
Part 219	Dimensional Inspection Process Planning for CMMs
Part 220	Printed Circuit Assembly Manufacturing Planning
Part 221	Functional Data and Schematic Representation for Process Plans
Part 222	Design Engineering to Manufacturing for Composite Structures
Part 223	Exchange of Design and Manufacturing DPD for Composites
Part 224	Mechanical Product Definition for Process Planning
Part 225	Structural Building Elements Using Explicit Shape Rep
Part 226	Shipbuilding Mechanical Systems
Part 227	Plant Spatial Configuration
Part 228	Building Services
Part 229	Design and Manufacturing Information for Forged Parts
Part 230	Building Structure frame steelwork
Part 231	Process Engineering Data
Part 232	Technical Data Packaging
Part 233	Systems Engineering Data Representation
Part 234	Ship Operational logs, records and messages
Part 235	Materials Information for products
Part 236	Furniture product and project
Part 237	Computational Fluid Dynamics
Part 238	Integrated CNC Machining
Part 239	Product Life Cycle Support
Part 240	Process Planning

5.2 What is IDEF0?

IDEF comes from the acronym Integrated Definition for Function Modeling. This is a Federal Information Processing Standard (FIPS), which is issued by the National Institute of Standards and Technology. It is a family of languages in which IDEF0 is part of it. IDEF0 is a modeling language that allows the representation of a system or enterprise by means of developing structured illustrations that correspond to a specific function inside the system. This function can be an activity, an action or a process.

IDEF0 was created to provide a modeling technique of the functions inside a system and the relationship between these functions. IDEF0 can be used in conjunction or separately from CAD software.

According to the *Draft Federal Information Processing Standards Publication 183* [4], the use of IDEF0 is strongly recommended for projects that are involved with analysis, development, re-engineering or acquisition of information. AP239 uses IDEF0 to manage the life cycle of the product.

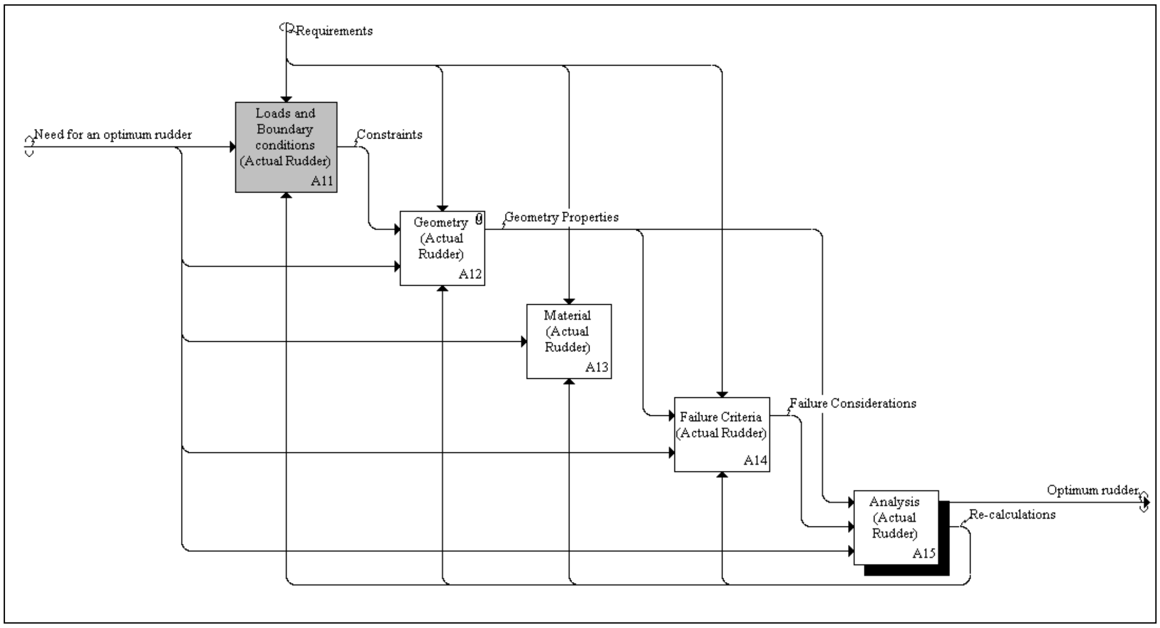


Figure 5-2 Representation of an IDEF0 structure for the analysis of the actual rudder

After all these said, it is obvious why it will be considered the use of IDEF0 in the purpose of this thesis. Figure 5-2 shows how an IDEF0 representation modeling looks like. Each activity is represented in a block and each block is connected to each other through arrows. Each arrow could represent an input (entering an activity to the left), a mechanism (entering a block at the bottom), a control (entering an activity on the top), and an output (leaving the activity from the right side).

Each block represents an activity performed in the design process. The geometry determination activity performs the equations and iterations leading to determine the physical shape of a model. Inside each activity can be linked all the files related to the model geometry. It does not matter in what part of the computer a file is stored; this file can be linked to its specific activity in IDEF0 and either be opened from the same activity or the activity would showed the path for the file.

The arrows in IDEF0 represent functions performed between activities. The input arrow indicates the information known that is pertinent to perform the activity in which it is entering. The output arrow is the response of the activity to the specific input. The control arrow represents the restrictions that limit the response of the activity. These restrictions can be related to the input requirements. The mechanism arrow relates to the tools that the activity uses to perform its function and achieve an output.

5.3 Engineering Design Process Support System

For long time engineers have behaved like if drawings were the most important part or the most significant in the design of a product. When they needed to make some modifications or evaluate possible improvements, they realized the importance of maintain a record of everything that is generated along with the design process itself. The entire content of this part of the thesis is based on the work of David Ullman [13].

In order to understand the process of designing a mechanical system, it is necessary to distinguish all the agents involved in this process and the relationship between both. Specifically speaking, we are talking about the human problem solver, the designer engineer, and the external environment, which is an extension used by the designer to help him support his abstraction.

Inside the designer it is possible to define two types of memory: short term memory (STM) and long term memory (LTM). In comparison with a computer, STM can be seen as the RAM. It is fast accessible since is the conscious mind of the engineer. Its capacity is limited. Within it is found images that the engineer creates in order to solve a problem. LTM it is seen as the hard drive of the computer. Although its accessibility is slow, its capacity is infinite. Here we can find the information learnt by time. It is possible to access this memory via the STM. If the engineer has to deal with some static analysis, he images the structure of the problem using STM and this activates the knowledge stored in the LTM for solving this kind of problem.

After the engineer begins with some abstractions of the design solution, he needs a physical instrument to do some sketches, blueprints, calculations, etc. All the means he uses to support his work is known as the external environment.

Now we know there are two agents involved in the design process: the engineer and the external environment. The engineer uses this external agent as a complement of the STM and the LTM.

So far, the agents of the design process have been identified and the relationship between them. But, what kind of information is developed during the entire design process and how the external environment is going to manage this information? To answer this question it is necessary to describe the types of information created during an engineering design process and the means used by the external environment to help the design engineer to manage this information.

5.3.1 *Type of data generated during an engineering design process*

The engineering design process generates a huge load of information during its development. This information will be itemized in order to get a neat description of what we are dealing with.

5.3.1.1 Form, fit and function

At the end of the mechanical design process, the design engineer presents a product which possesses certain geometry. The product is an assembly of little parts that made up the entire final project. Basically, the whole assembly has a form and it is composed of different parts, that also have their own form, and they need to fit together in order to achieve certain function.

Since we are trying to preserve data in a standard language, STEP AP's that deal with the shape of the design are presented in table 5-2.

Table 5-2 AP's related to the fit, form information

Part 201	Explicit Drafting
Part 202	Associative Drafting
Part 203	Configuration Controlled Design
Part 204	Mechanical Design Using Boundary Representation
Part 205	Mechanical Design Using Surface Representation
Part 206	Mechanical Design Using Wireframe Representation
Part 214	Core Data for Automotive Mechanical Design Processes

5.3.1.2 Material and manufacturing

Once the CAD part of the design process have finished, the manufacturing and assembly activities are in charge of giving the physical body to the product. To do so it is necessary to apply materials to the parts. It is noticeable the link between the development of the form, fit and function with the manufacturing and material activities. The engineer needs to know the manufacturing process available within the company and the materials accessible in order to generate a feasible geometry for a product that is capable of achieve the desirable functions.

As it is seeing, table 5-3 shows STEP AP's that manage the material and manufacturing information.

Table 5-3 AP's related to material and manufacturing information

Part 207	Sheet Metal Dies and Blocks
Part 210	Electronic Printed Circuit Assembly, Design and Manufacturing
Part 211	Electronics Test Diagnostics and Remanufacture
Part 213	Numerical Control Process Plans for Machined Parts
Part 219	Dimensional Inspection Process Planning for CMMs
Part 220	Printed Circuit Assembly Manufacturing Planning
Part 221	Functional Data and Schematic Representation for Process Plans
Part 222	Design Engineering to Manufacturing for Composite Structures
Part 223	Exchange of Design and Manufacturing DPD for Composites
Part 229	Design and Manufacturing Information for Forged Parts
Part 235	Materials Information for products
Part 238	Integrated CNC Machining

5.3.1.3 Cost

When we look at the blueprints of an object we can find information about dimensions, tolerance, finish surfaces, assembly, materials, etc. This information is given by the design engineer to manufacturing department. But nothing is said about the cost of designing and manufacturing. Even when it is necessary to make a modification in the design, the engineer must consider the implications regarding cost.

As mentioned before, AP239 uses IDEF0 to manage the life cycle of a product. And inside IDEF0 we can find tools where to specify the cost of the activities performed by every activity in the engineering design process.

5.3.1.4 Requirements

Requirements are refer to the different constraints and specifications that need to be solved. Each part of information generated by the engineering design process develops its certain requirement, and each requirement could be affect another type of information in the process of design. A low cost in design could implicate less manufacturing process, which could be translated in simple geometry of parts.

5.3.1.5 Issues and plans

The design engineer is going to realized there are several ways to achieve a designing goal. He must plan the design process choosing the tasks that fit the goals pursued. This chosen plan must deal with all the available tools that are on hand to arrive to a define object. Of course in the development of the design process there are going to emerge issues that are going to require changes or adjustments in the design. All this issues and plans must be archived as part of the design rationale.

The STEP AP's that manage the issues and plans information are displayed in table 5-4.

Table 5-4 AP's related to issues and plans information

Part 213	Numerical Control Process Plans for Machined Parts
Part 214	Core Data for Automotive Mechanical Design Processes
Part 220	Printed Circuit Assembly Manufacturing Planning
Part 221	Functional Data and Schematic Representation for Process Plans
Part 224	Mechanical Product Definition for Process Planning
Part 231	Process Engineering Data
Part 232	Technical Data Packaging
Part 236	Furniture product and project
Part 239	Product Life Cycle Support
Part 240	Process Planning

5.3.1.6 Intent

The intent information deals with the decisions made in each step of the design process. The reason why a certain plan has been chosen, the issues emerged during the design and the options taken into account to deal with those issues, are part of the design intent.

All these kind of information are part of the design rationale. Remember that, rationale, as described in Ullman [13], is *"...an information structure that justifies how the implementation (consequences of the design selections) satisfies its specification"*. In other words, to archive the design process of a product it is needed to archive what we are designing, why it has a certain shape, what it is being design for, what changes there have been during the generation of the product, what decisions we have made, etc.

The standard ISO 10303 deals with the intent information using the AP's shown in table 5-5.

Table 5-5 AP's related to intent information

Part 208	Life Cycle Product Change Process
Part 214	Core Data for Automotive Mechanical Design Processes
Part 224	Mechanical Product Definition for Process Planning
Part 231	Process Engineering Data
Part 239	Product Life Cycle Support
Part 240	Process Planning

5.3.2 *Means of the external environment to deal with the information generated in a design process*

The design process begins with a customer need. The design engineer tries to solve that need imagine possible solutions. Once a solution is imagine, the engineer starts defining concepts in his mind using STM and LTM. After some concepts are developed, the design engineer takes use of the external environment to solve equations and make some drawings about all the structure of that possible solution he has in his mind.

Here, we can have an idea of what design is. As Ullman [13] describes it: *"Design is the evolution of information punctuated by decisions. The types of information that are developed during the design process represent both the product being designed, the process by which it is being designed, and other processes in the life of the product such as manufacture, distribution, and retirement."*

Thus, in order to preserve the design process of a product, all the information generated by the design must be supported in some way. An ideal engineering design process support system must capture, archive and inquiry the information generated.

At last, an archival system should be able to communicate what it has in his records and be accessible to people that requires that kind of information. STEP application protocols are made to be accessible for everyone since they intent to generate a standard language and do not depend on specific software. The bad news is there is no software capable of translate every activity and information developed in a design process. But all the efforts are being directed to that goal.

The next step is to apply what we described as an engineering design process support system in a specific design scenario. The analysis and design of a rudder will be considered for this as an example in the section on this chapter.

5.4 Applying the design process to the subsystem replacement case

Now that we have a clear idea of what an engineering design process support system is, we are going to apply our *subsystem replacement scenario: analysis and design of a rudder for a 120' TWR.*

The supposition here is that the customer, the NAVY, has a requirement: it has a certain number of ships vessels whose rudders need to be replaced due to a malfunction after certain hours of operation. They need to know if the improvement is feasible and how well the performance will be.

Doing this we can use IDEF0 to keep track of every step on the design process. Next, we are developing the analysis and design of the rudder.

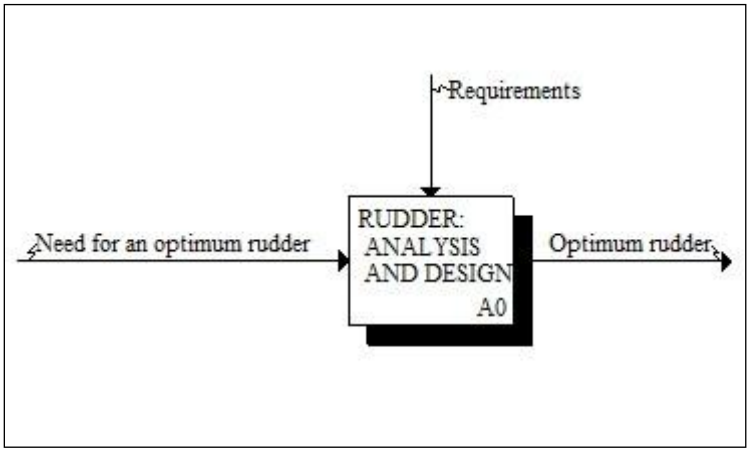


Figure 5-3 Representation of a design summary. Blocks represent an activity. Arrows represent concepts.

In an upper level of design, we can show the customer needs as inputs, the final products that fulfill the need as outputs, and the requirements that control every step on the design. Figure 5-3 shows this design summary. The block defines activities performed along the entire design process. The arrows are concepts that represent results from the activities or some initial conditions to start an activity. Formally there are four types of concepts.

1. Inputs. Arrows that enter to the left of the block. These are like the initial conditions or prime matter to start an activity.

2. Outputs. This is the result of an activity. It is represented as an arrow coming from an activity from its right side.
3. Controls. These are requirements or some restrictions that have to be taken into account to perform the activity. They are represented by arrows going into the top of the activity.
4. Mechanisms. These are the tools that the activity employ to perform a task. They are represented by the arrows going into the block at the bottom.

As noticed on Figure 5-3, the RUDDER: ANALYSIS AND DESIGN activity is shaded. That means that there are more activities performed inside. Going one level inside in the design process we can see the entire design process configuration arrangement, as shown in Figure 5-4.

The process has been divided into analyze the actual rudder and design a new one. After the analysis is done the results are taken to the Analysis of Results activity to compare the information provided by the two previous analyses. Then, we proceed to the manufacturing activity.

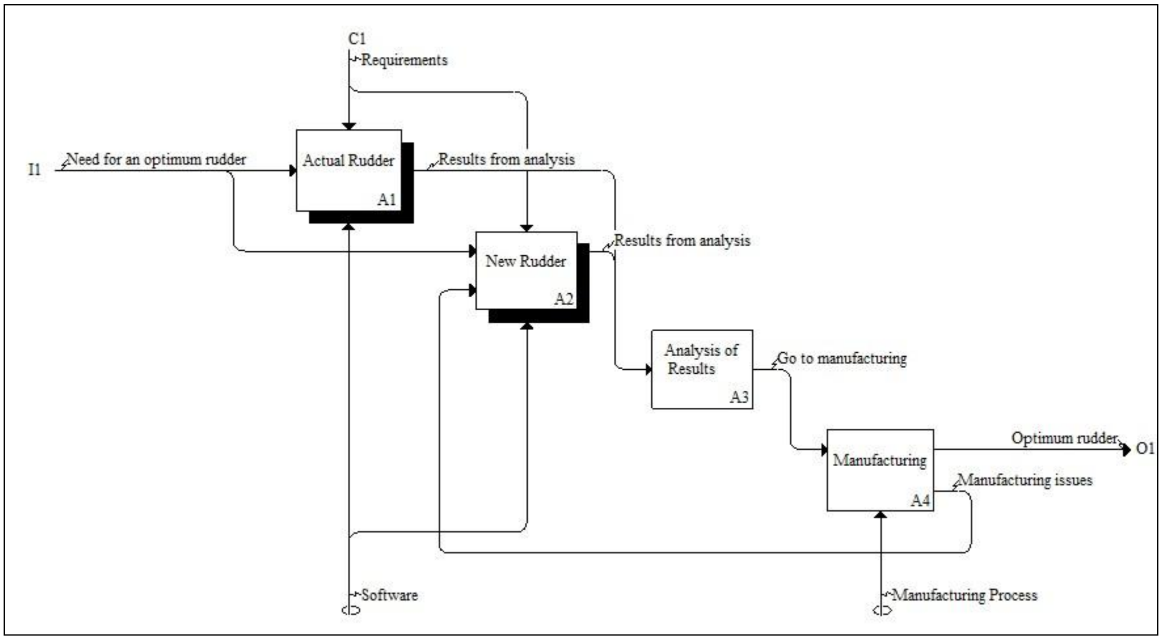


Figure 5-4 Design process configuration arrangement

Figure 5-5 shows the geometric determination construct scenario that was mentioned about in section 2.1. In each activity we can link every file related to that specific activity. For instance, the Geometry activity shows a clip inside the block, as noticed in Figure 5-5. This clip indicates that there are files attached to that activity. These files are related to the geometry definition. In our case, the Figure 4-10 and its respective STEP file are attached to that activity. The same it is done with each activity in the engineering design process. Clicking over the clip shows all the files that are attached to it. Also, every concept has a description. Double click on any concept and it opens a window where the design engineer can enter a series of descriptions and annotations related to the specific concept.

Going further one more level inside the analysis of the current rudder it is noticeable the three kinds of analyses performed: numerical analysis, finite element analysis and experimental analysis. These activities are presented in Figure 5-6. The numerical analysis activity contains the code made in matlab and the results obtained from the same software. In the same manner, in the CFD activity can be found the files generated in fluent.

Just like the whole analysis of the current rudder has been explained using IDEF0, the same procedure was followed to the design of the new rudder.

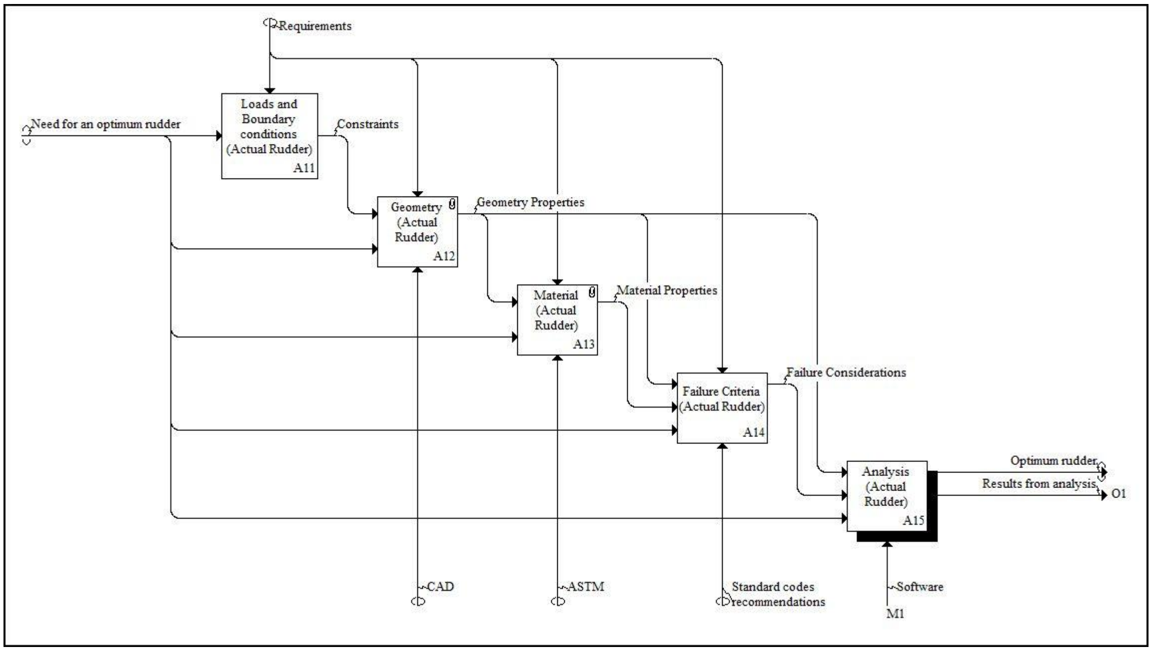


Figure 5-5 **Basic construct scenarios done in IDEF0 for the analysis of the actual rudder**

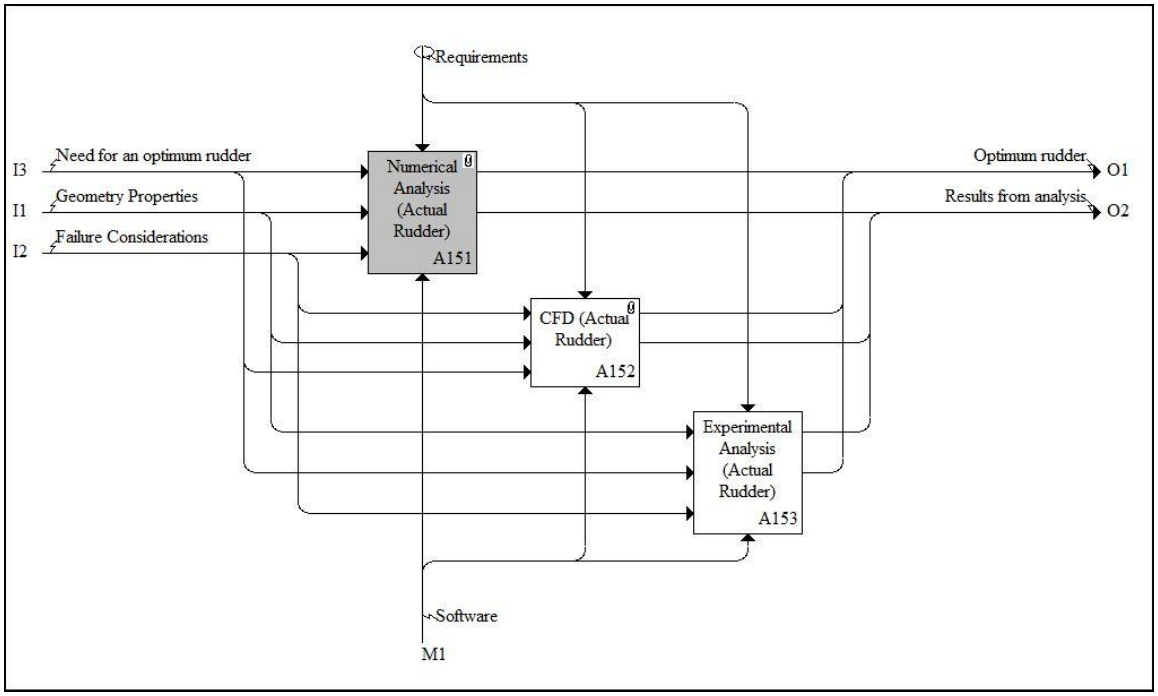


Figure 5-6 The three types analysis performed to analyze the actual rudder.

After doing both analyses, the results are taken into the Analysis of Results activity to be compared and get a decision. After the decision is made, the next step is to go to the Manufacturing activity.

As seen in this demonstration of an engineering design process support system, IDEF0 has been used to manage every type of information generated by design process. The purpose of this is not only to record all the data produced but to show the evolution of the design process and how the design engineer proceeded to manage every task.

Chapter 6. DISCUSSION AND CONTRIBUTIONS

6.1 Discussion

It is obvious that this kind of work frame can be used to analyze different situations that involve the case under study: *subsystem replacement scenario*. It is possible to employ the same procedures to analyze other situations, let us say for instance the analysis of a landing gear of an airplane that needs to be improved, or the improvement of a turbine blade of an aircraft engine that has some issues due to collisions with birds when flying at low altitude. The latter was a case that prompted General Electric to started designing flexible blades for its aircraft engines.

The general idea here is that whatever the specific case of subsystem replacement scenario is; it can be approached in a similar manner as in the case described here for the rudder case.

6.2 Contributions

The study of the possibility of improving the rudder of the 120' Torpedo Weapons Retriever was a simple example of one of the different Mechanical Engineering Design Scenarios that occur in industry. The work done in the present thesis tries to show the procedures an engineer takes when they deals with a case that gets into the category of a Subsystem Replacement Scenario; and how to preserve the entire work developed in order to prevent any lost of information that could be needed in a latter attempt to recover the data of the design. What was developed here is a work frame that can be used as a roadmap when dealing with subsystem replacement scenarios cases.

More specifically, to reconstruct the conditions in which the actual rudder was designed, it was necessary to collect all the data available related to the rudder such as blueprints, images, and CAD files. Also, for the new rudder some data was generated along with various assumptions for the design based on best practices.

After collecting all the data it was necessary to establish a relationship and a correlation between the different pieces in order provide a structure to all the information. Of course, in the case of the rudder there was missing information regarding requirements, calculations, and reasons why of the geometry of the rudder. Some data, like the requirements, were assumed in order to reconstruct the taxonomy of the current rudder.

Once the data was in order, it was crucial to define the possible design activities that were used to generate the different type of data obtained. Each data should be embedded in their respective activity.

Now the design activities are defined, it is just needed to make the interconnection between them and fill the requirements along the network.

Now that the reconstruction of the previous design is done, it is turn of the new option design. The procedure is similar. The gathering of data is the beginning of the process. But this time the information collected is related to requirements from the customer. Then, we come up with possible prototypes that resolve those requirements. After the optimal prototype is established, the definition of the design activities is next. Inside these activities it can be found the data generated and the information that controls each activity.

Chapter 5 shows some IDEF0 diagrams developed in the case studied here. In these diagrams, it is noticeable the design activities defined to proceed with the constructs of the taxonomy of the design scenario as previously discussed. Activities like geometry definition, material definition, etc are the common procedures in a design scenario. Each particular case of Subsystem Replacement will share similar activities. As mentioned before, these activities can come handy for any case like in the case of replacement of a landing gear of a plane, or a turbine blade of aircraft engine and others.

Chapter 7. CONCLUSION

For many years documentation and accessibility to engineering data have been a concern to the engineering community. Electronic neutral format files such as STEP, IGES, PDF have been created to exchange CAD files among and within companies. But, the effort for keeping the taxonomy of an engineering design process goes beyond the simple recording of files. In order to effectively preserve information, the taxonomy of the design process it is needed to provide a context to the design.

IDEF0 has provided an effective tool to keep track of every single step made during the design process, not only storing each file created but showing the evolution of the design process indeed. Using this standard language as a repository maker it was possible to maintain the link between each engineering activity within the design process.

The design and analysis of a rudder has been performed following a methodology beginning from the customer requirements and finishing with a product. All the information generated was managed according to what was said concerning to an engineering design process support system.

Standard languages were used, IDEF0 and STEP. The former was used to generate the repository and to manage the electronic data. STEP AP's were used were it was possible. Although STEP has several application protocols that manage every type of information in a design process, just AP203 and AP214 could be used, since these AP are accessible from about any CAD package. The use of a translator to STEP AP could be handy in this kind of task and a way to test the efficiency of STEP dealing with this sort of process. Yet a large portion of the various data sets, such as worksheet tabulations, MatLab routines and the outputs produced by the engineering software used (Fluent) produced data sets that are not supported by specific STEP AP's. Consequently the opportunity exist to increase the applicability of STEP AP's to preserve a larger portion of the data typically generated in an engineering scenario such as the one presented here.

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