Inherent Mechanical Data Storage on Micro-Structured Surfaces

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Abstract

The Collaborative Research Centre "Gentelligent Components in their Lifecycle" deals with the development of techniques for the creation and usage of innovative mechanical components. Developing manufacturing methods which enable data storage on the component itself is one major aspect. Here an approach using micro structures on component surfaces to carry the coded information is presented. These micro structures are created by a fast-tool-servo during a longitudinal turning process. Data, that has been stored in this way, can be read out by a newly developed optical method using directed illumination. The complete data storage system is described with an emphasis on micro-structuring and the readout process.

Keywords: Production Process, Surface Structuring, Mechanical Information Storage, Surface Reconstruction

1. Introduction

In the context of the Collaborative Research Center (CRC) 653 "Gentelligent Components in their Lifecycle", components with novel properties as well as concepts, methods and techniques for their manufacturing and utilization in production engineering are developed [1]. The interdisciplinary CRC's long-term objective is the integration of components with their corresponding information for reproduction as well as stress information from their lifecycle. The term "gentelligent component" was introduced for these components in order to refer to the genetic and intelligent character of these innovative components.

A gentelligent component inherently stores all information necessary for its distinct identification, reproduction as well as for its manufacturing process. Unlike exherent data storage like on centralized servers or attached RFID tags, information on a gentelligent component is stored during the whole component lifetime. Thus, the information cannot be mixed up or get lost. Furthermore, inherent data storage provides an excellent basis to secure from plagiarism. By using adequate materials and sensors, gentelligent components are enabled to detect, process, store and interpret specific information collected during their use. Examples of these pieces of information are applied loads, accelerations and temperatures. Having both the initial state as well as information about the component's lifetime, it will be possible to replace the component on the eve of its failure and not after a certain age. Thus, storing and gathering information is the main focus of the CRC.

In this paper, a system for inherent data storage

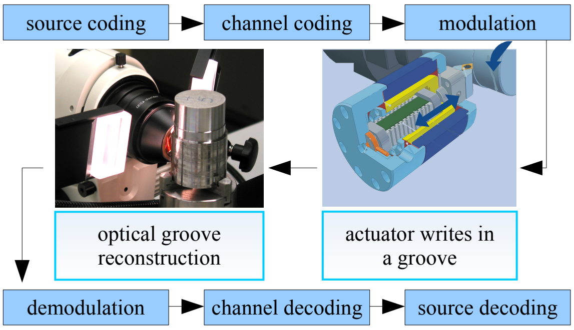

Fig. 1: Procedure for digital data storage.

is presented. The information is saved inside the micro-structured surface of a component. Typically, surface structuring in mechanical engineering is used for functional reasons such as reduced flow resistance [2], improved tribological characteristics [3, 4] or optimized mechanical properties. The structures mentioned in this paper are generated during a turning process by a fast-tool-servo. This tool technology is characterized by high tool acceleration and is usually used in machining precisely contoured and structured optical surfaces [5, 6, 7]. By variation of the excitation of the tool in phase and amplitude, different surface micro structures are produced. In this way a macroscopically non-visible groove is inserted into the surface which can be read out by optical means later. It is the same principle as gramophone records or the first video data media like the capacitive electronic disc [8] are using. As the storage principle is designed for simple and fast writing during the production and insensitivity to mechanical load, data density is quite low but sufficient for gentelligent components.

2. System Overview

For the whole storage system, the standard model for digital data transmission over a channel is used (Fig. 1). Only the channel, where data may be disturbed or corrupted, differs from ordinary data transmission. Here it consists of the actuator's writing, the transmitted signal on the component's surface and of the optical readout, which represents the reconstruction of that signal. The advantage of using this standard model is that source coding, channel coding and the modulation method may be re-used from existing systems.

Source coding is the efficient digital representation of the information being transmitted. For portability, this could be a string list representation in the form *keyN*=*valueN* to assign the *N*th key a value. If hierarchical data is used, xml [9] would be a flexible standard solution for source coding. The data size can be reduced by an additional compression using e.g., the bzip2 algorithm [10].

Following, redundancy is added during channel coding to protect the data against corruption during the transmission. Here, *Turbo-Codes* [11] are used which make sense for high data rates in combination with low signal-to-noise ratios.

Modulation is the step from the digital to the analog domain. Digital symbols are converted to analog signal runs according to the characteristic of the data transmission. The analog signal is used to control the piezo actuator cutting in a groove with varying depth.

Now, the component's surface is characterized by a groove with varying depth containing the stored data. To reconstruct it during the readout process, optical methods were examined using a microscope with small magnification.

Then, the signal read out is demodulated. This is not inverse to the modulation as the actuator adds (mostly linear) distortion to the signal which needs to be compensated. Knowing the actuator's characteristic i.e. by also writing in an impulse or a chirp, the distortion can be removed. The demodulation then recovers digital symbols as well as an estimation of the bit error rate. As there is redundancy, the channel decoder may use this to find the most probable decoding of the symbols. Finally, source decoding recovers the original information.

3. Micro-Structuring - Writing Data

3.1. Fast-Tool-Servo

In many occasions fast-tool-servos are used to finish free-formed optical surfaces but another application in turning operations is active vibration control as described by Denkena in [12]. Thus, they are designed to withstand relatively high cutting forces in comparison to the needs of a pure structuring tool. So the first natural frequency in advance direction is low, which does not allow high data density storage. In order to realize a significantly higher frequency range, a new tool called *Structool* has been developed with a first natural frequency of 6 kHz. This was mainly achieved by a guiding unit out of titanium, which contributes a significant reduction of the moving masses. The link between the static part and the moving part of the titanium frame is of flexure hinge design, thus reducing additional membranes and screw connections (Fig. 2).

The tool design allows the use of different configurations of piezo-electric elements with up to

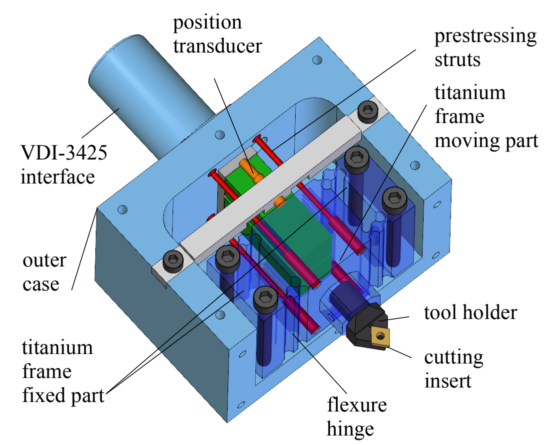

Fig. 2: The Structool.

four elements used at a time. Each element has a dimension of 14 x 14 x 20 mm and a stiffness of 500 N/µm. The maximum force generation per element is 11 kN, the resonance frequency is 32 kHz. The tool can be used with only one piezo-electric element, with two elements mechanically connected in series or in parallel as well as with a combination of these. The first structuring results were achieved with only one piezo-electric element and may thus be improved by amplitude or bandwidth.

3.2. Modulation Method

For best data transmission, the coded data have to be modulated according to the channel‘s characteristic, which is nearly the characteristic of the actuator in this case as the readout hardly adds systematic distortion. It was found out that the actuator behaves as an linear time-invariant system that can be described by its impulse response or by its transfer function.

In Fig. 3, the actuator‘s transfer function is displayed. The resonance at the first natural frequency of approximately 6.5 kHz can be seen clearly. Also important is another smaller resonance at around 5 kHz. Until that frequency, the phase difference lowers linearly from -90° near 0 Hz. The reason for the 90° phase offset is that the actuator‘s input signal is a control current

$$I = C\frac{dU}{dT}$$

and the measured excitation is proportional to the impressed voltage U. So without any mechanical restrictions, an input cosine will become an output sine wave.

For digital data transmission, there are two constraints that have to be fulfilled. First, the amplitude of the transmitted signal should be clearly distinguishable from distortions to achieve a good signal-to-noise ratio. Until 5 kHz the baseband would be sufficient with the lowest amplitude at about 1 µm. The amplitude could be further improved by using two piezo-electric elements and pre-emphasis on higher frequencies.

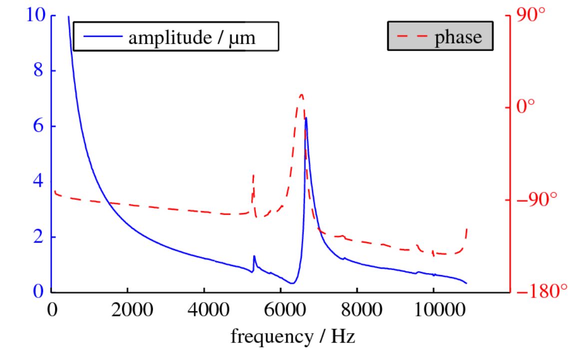

Fig. 3: Transfer function of the acutator.

The second constraint is that there should not be any phase distortion that jams digital data transmission. Phase distortion is generated by a non-constant group delay, which is the negative deviation of the phase response. Because of the 90° phase offset around 0 Hz baseband signals would disturb the transmission. This means that the modulated signal run has to be mean-free. The same occurs with signals over the resonance frequency of around 5 kHz. In the residual band with approximately 5 kHz bandwidth, 5 kBit/s may be stored with a binary modulation method. That bandwidth could be extended using two piezo-electric elements in parallel. Further bandwidth extensions could be achieved using multi-carrier modulation methods which are able to occupy a second frequency band e.g., from 7 to 9.5 kHz, for data transmission.

3.3. An Example for Written Data

In the following, an example for writing data is made. The source-coded information is the uncom-pressed ASCII string “SFB 653” (means CRC 653) of 56 bit data size. There was no channel-coding used for better visibility. As modulation method, a simple mean-free translation from the digital symbols to analog signal runs was chosen. Every logical one physically is assigned a full sine wave leading to a positive sine wave movement of the actuator. A logical zero means no movement of the tool. The run of the actuator is shown in Fig. 4.

The green line shows the position of the tool. The red crosses show the target position in terms of

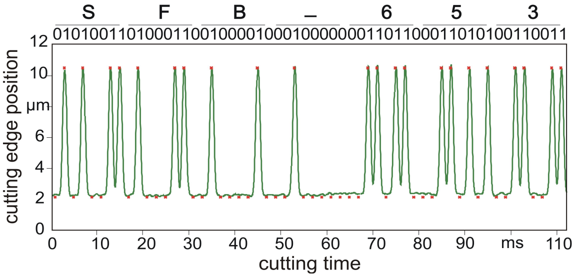

Fig. 4: Example for a signal written as a groove onto the surface.

displacement, which represents either a zero with a position value of 2 µm or a one with a position value of 10 µm. The demodulation in this case is simply distinguishing these two states. It can be seen, that their positions clearly differ at the chosen sampling frequency of 500 Hz and thus the demodulation will succeed. At higher frequencies the maximum movement of the cutting edge decreases. According to the transfer function, a double-amplitude movement of 2 µm can be obtained at a sampling frequency of 5 kHz, so that the resultant structures can be recognized by optical readout methods.

4. Reading Data

4.1. Readout Method

The readout here is the reconstruction of the groove's run. This could be achieved using expensive surface reconstruction instruments. But the readout should be possible in a simple way so that a mechanical component could e.g., be inspected at a service station. Thus, shape reconstruction methods with a customary microscope with low magnification were evaluated, which later can be adapted to cheap hand-held units. As multiple views from the surface are needed for the readout, the setup here includes an apparatus for rotating and translating the mechanical component. A special channel coding could later be used so that the whole information may be retrieved from one view.

The developed readout method uses directed illumination to recover the groove's depth. The surface of the mechanical component here is

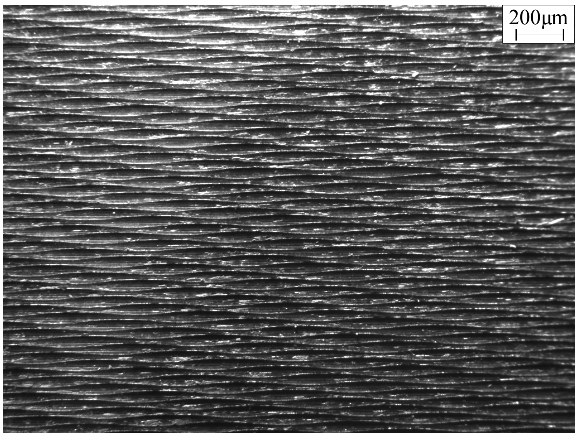

Fig. 5: The surface of the component under directed illumination from the top. The grooves run horizontal. The topmost groove is magnified in Fig. 6.

illuminated with parallel light from the top. As it is highly reflective, it only appears light at positions with a specific surface normal. Here, it is assumed the groove consists of two flanks which meet in the middle of the groove and have a constant surface normal. The angle of the incident light is thus chosen that way, the lower flank reflects into the direction of the camera. The depth of the groove can then be determined from the flank's width which is approximately proportional to its depth. It should be noted that this is just a simple model for the groove. Variations will be corrected during the demodulation as they are included in the system's transfer function. In practice, there are many disturbances which also appear light, but the grooves (Fig. 5) as well as their varying widths (Fig. 6) are clearly recognizable.

4.2. Groove Reconstruction

Under the assumption that the grooves of the components run horizontal in the microscope image, a one-dimensional frequency analysis in vertical image direction is performed. As the feed of the turning process is constant, the vertical offset between the grooves is constant, so a vertical frequency analysis should find a peak at that distance.

Thus, the first step is to partition a microscope image $I(x, y)$ such that each part contains only one

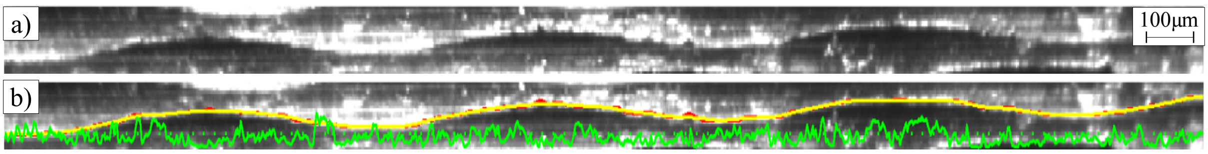

Fig. 6: a) Original image of the groove and b) its reconstructed run (red, smoothed in yellow). Green is the probability density of the Markov model. The images were stretched vertically by two for better visibility.

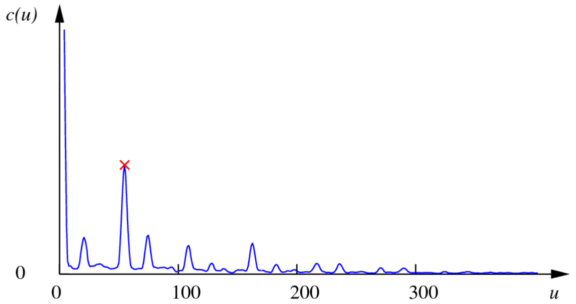

Fig. 7: Amplitude c of frequency components u of Fig. 5 in vertical direction. The peak at $u=54$ *corresponds to a groove distance of 14.2* px.

groove. First, several windowed one-dimensional discrete Fourier transformations are averaged in an appropriate manner to make the algorithm robust with respect to image noise and visible cutting artifacts. The highest amplitude peak $c(u_0)$ besides the mean value at frequency $u=0$ is searched for. A typical example for a frequency distribution is displayed in Fig. 7 where the peak is visible at $u=54$. From the frequency u_0 at that peak, the groove distance may be determined. Finally with the help of the phase offset $\varphi(u_0)$, the exact position of the border between the grooves is computed. A microscope image containing several grooves may now be partitioned into images containing only one groove like displayed in Fig. 6.

It has to be considered that only the lower flank is illuminated and that the flank's width is proportional to the groove's depth. As the middle of the groove is known from the previous step, the lower groove edge has to be tracked to reconstruct its depth. A heuristic p for the edge being at a specific position (x_i, y_i) is the negative discrete deviation of the image in *y*-direction

$$p(x_i, y_i) = -\left.\frac{\partial I(x_i, y)}{\partial y}\right|_{y=y_i} .$$

To enhance the continuity of the found edge, a Markov model with a regular topology is introduced. Each state S_{x_i, y_i} stands for the edge passing the pixel at position (x_i, y_i). Like shown in Fig. 8, state transitions are only allowed from x_i to x_i+1. Their transition probability is assigned a normal distribution with a mean value of y_i. A Viterbi algorithm is then able to find the most probable run of the edge from the left to the right side of the image. It can be seen from Fig. 6 that even in the case of heavy perturbation, the found edge is correct.

Finally, all groove pieces from multiple microscope views are put together. To determine the offset between two images, normalized cross-correlation coefficients are minimized. When the data is rearranged according to the groove- and image offsets, the written signal is reconstructed. Finally, the demodulation- and decoding algorithms will recover the stored data. Redundancy is chosen so that disturbed or destroyed surface regions can be recovered until the readout method itself fails. Tests have shown that oxidation has no influence on the data integrity. So the here-presented readout method is practicable.

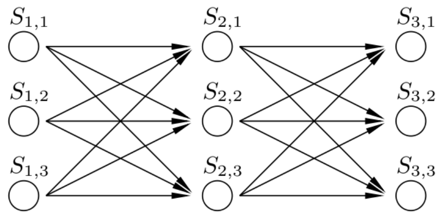

Fig. 8: The Markov model used with a regular topology. To model the run of the groove, transitions are allowed from all states S_{x_i, y_i} *to* $S_{x_i+1, y_{i+1}}$.

5. Conclusion

A complete system for data storage on the surface of mechanical components was presented. The standard model for digital data transmission was applied. The channel of the communication system here consists of a fast-tool servo writing in data during a turning process and of the optical reconstruction of the written groove. The other parts of the communication system, which are source coding, channel coding and modulation, thus do not have to be reinvented.

Only the modulation part which has to take care of the characteristic of the channel has to be adapted. It was shown that for the current configuration a frequency band with a size of 5 kHz may be used for data transmission.

To read the data written in the groove of varying depth, a three-step method utilizing directed illumination is applied. First, the image is partitioned using frequency analysis in vertical direction. Then, the groove is tracked, greatly enhanced by the application of a Markov model with a regular topology. To put the groove parts exactly together to the one-dimensional signal written in by the actuator, overlapping regions of several images are taken.

Thus it was successfully demonstrated that inherent data storage on surfaces using simple means is possible. To determine optimal writing and reading parameters as well as the best-suited modulation method, further investigations are carried out.

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