Classification of Wear by Means of Acoustic Emission and Signal Processing Techniques

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ABSTRACT

Usually inner material effects damage the system internally before those effects can be detected visually at the material. Hence, an optical (surface) inspection cannot reveal the inner state-of-damage. Once the surface is affected e.g. by a crack, the normal reactive monitoring and maintenance procedures may not prevent the systems' failure. Therefore a need to develop reliable and efficient condition monitoring systems able to detect damage, determine the actual state-of-damage, realize diagnostics and predict the remaining use time occurs. The goal of this paper is to introduce a system for online classification and examination of wear phenomena in metallic structure based on the application of the acoustic emission (AE) technique and time-frequency analysis. In this purpose, short-time Fourier transform (STFT) and wavelet transform (WT) were applied to AE signals indicating tribological effects occurred during the process. The results obtained from the two signal processing techniques were compared, good results with respect to advanced applications for fault detection as well as diagnostic purposes are obtained.

INTRODUCTION

Tribological effects (e.g. friction) often define the functionality of typical mechanical elements and mechanical engineering structures. If friction processes does not work well due to bad tribological conditions, sliding surfaces may be destroyed and the components functionality may be reduced up to a complete loss of functionality. The definition of this damage level depends on the particular application and the related tolerable level of deterioration. Hence, this is an individual characteristic that has to be quantized and quantified beforehand, so that the related knowledge can be used for automated supervision, for example in the

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context of condition-based maintenance concepts etc. In the tribological context the surface of the considered individual component is usually evaluated by visual inspection, which is time-consuming and a subjective measure. Furthermore, material displacements, inner cracks… might not be detected by visual inspection. Therefore, an automated and continuous monitoring of safety relevant structures affected by wear effects may be useful to improve SHM- or CM-related goals. This is only possible with non-destructive testing (NDT) methods, which observe/measure those signals that indicate the fatigue progression.

The most efficient technique among the NDT methods is the Acoustic Emission Technique (AET). Advantage of AET is that the application of this method is usually realized during loading, while most other methods are applied before or after the loading of structure. Other advantage is that the frequency range of AE signals is much higher than that of the vibration and environmental noises [1]. Therefore, AET have been considered for many years as the prime approach for the detection, microstructural characterization, and monitoring of damage processes. As shown in [2], [3], and [4] specific properties of AE signals can be used as an indicator for different effects affected by material changes due to aging, wear, etc. Those signals obviously occur due to different wear sources (twinning, slip, deformation glide, etc.), which seems to be the main sources for failure caused by tribological effects. To analyze AE signals, advanced and modern signal processing techniques are required. Here the STFT, and the discrete WT (DWT) were selected to extract, relevant features related to damage.

The aim of this contribution is to detail the developed concept with respect to the hardware realization, the applied new sensor system, as well as the implementation of the diagnostic approaches for detecting and monitoring signals indicating tribological effects with AE analysis, mainly by online realization based on spectrum analysis utilizing Xilinx Field programmable gate array (FPGA) board. Therefore a new sensor technology is applied, FPGA implementation of STFT and WT is used, simulation results are compared, and advantages and disadvantages of each transform are discussed.

SOURCES OF ACOUSTIC EMISSIONS

The tribological system used for first experiments using this technique is based on an oscillating sliding tribo-system. Two contact partners, each consisting of a "wear resistant" plate, are sliding against each other (driven by a hydraulic cylinder) with an adjustable applied normal load. By analyzing several material samples using a Scanning Electron Microscope (SEM; see Figure 1) the occurred wear mechanisms are identified, which lead to the failure of the system. The crack propagates cracks after a certain number of cyclic events through the wear plate and deteriorates it.

Due to the heat development during the shaping process a thin coating can be found on the surface of the wear plates. Even before a load is induced, some tensile cracks can be seen in the coating. During the first hours with applied load this coating is eroded, particles scratch the surface leading to abrasive wear. After loading the system with a constant normal force, fatigue cracks appear and may grow into the ground material. So the main wear mechanism is surface fatigue which initiates and propagates cracks after a certain number of cyclic events [5]. These cracks can be

induced through some gliding dislocations change into hollow dislocations, which become cracks and propagate in the metal usually in the direction of applied stress. According to [6], pressures, forces, and acceleration signals generated from the tribo-system can be related to changes of the surfaces conditions such as changes of lubrification and temperature, etc. indicating friction and wear processes which has to be determined and analyzed. As known e. g., from [7] the source of ultrasonic waves (structure borne sound) lies within the material and results from local inner micro displacements. As shown in [9], as soon as the system is stressed by external mechanical loads, material activities will take place and emit acoustic waves with characteristic properties, which strongly depend on the used material and measuring equipment. For supervision purpose it is necessary to classify the measured signals and correlate them with the causing effects (material change etc.). During the deformation of material usually several effects occur in parallel. Up to now this makes it impossible to clearly connect these signals and related sources. Therefore it is necessary to excite each important material changing effect separately and to sense its characteristic elastic wave.

MEASUREMENT AND SIGNAL PROCESSING

The process of in situ crack growing is hardly measurable by classical measuring techniques. As known from literature [10], [11] material deformations emit elastic waves with small amplitudes, high frequencies lying beyond the audible frequency range and propagating through the material. Those emissions can be detected by special measurement techniques. It can be shown in [9] that this kind of measurement is principally able to sense material changes of relative small dimensions.

As proposed in [9] the sensors are glued to the surface. The coupling between the surface and the material is permanent and can be assumed as very stiff. The sensors used are discs with a diameter of 10 mm and a thickness of 0.55 mm. The measured voltage is fed to an impedance converter and the high-speed AD-converter of the FPGA board. Hence, special care (shielding, grounding, etc.) has to be taken for the transducer, cable, and other hardware. The measured signal is subsequently analyzed by various signal processing methods. The signals detected by the piezoelectric material have to be measured with appropriate sample size and measurement duration to raise the probability of detecting related emissions. For identifying AE properties specific filtering among STFT and WT are developed and implemented onto a Xilinx FPGA. The signal processing chain is shown schematically in Figure 1.
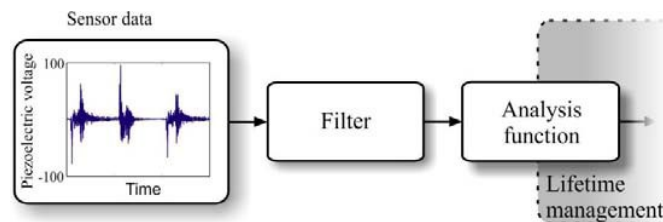

Figure 1. The sampled sensor data are filtered and analyzed to extract damage inherent information.

This paper uses a design of a filter module combining relevant software (Matlab, Simulink, and the System Generator from Xilinx) and hardware (FPGA board) to analyze the digitized piezoelectric signals. The use of FPGA is especially effective for data-intensive applications such as spectral analysis. Here, the STFT and the WT are realized. The STFT is a known method of time frequency analysis. It provides information about the specific characteristics of signal events occurring and allowing a signal representation in the time-frequency plane. Indeed, this information can be obtained with limited precision. The precision is determined mainly by the width of the window which is restricted for all frequencies and the accuracy of solution is limited by the time-frequency resolution tradeoff [12]. In recent years, additionally to the STFT, the WT has been successfully used and became the most informative in analysis of AE signals. This method provides excellent time-frequency localized information, which are analyzed simultaneously with high resolution and in different frequency range [13]. The superiority of the wavelets is more tangible in the case of non-stationary nature of the measurements and the existence of sudden changes in time direction [14].

EXPERIMENTAL RESULTS

As introduced, the main wear effects are related to abrasive wear and wear surface fatigue. According to the results presented in [9] the first goal is to detect transient events and characteristic frequencies for these stochastically appearing effects and to identify a relation between the obtained transient occurring emissions (measured as piezoelectric voltage) and the typical effects (material changes) to reveal a unique connection between both. Accordingly changes in the AE signals indicate a change in the process and surface condition respectively. The severity of the change (wear process) can be indicated by typical transient events, amplitudes, etc., which appear in the distribution of AE energy over the time (see Figure 2).
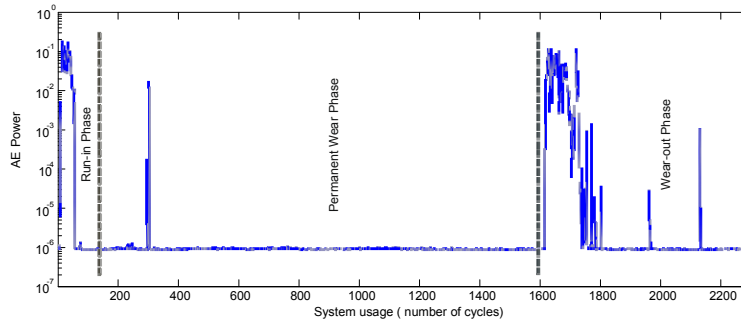

Figure 2. Acoustic emission energy over system usage during run-in phase, permanent wear phase, and wear-out phase.

Referred to [15] the AE energy distribution allows the distinction of the three major phases of system failure. Within the run-in phase, systems have a high probability to fail. This region is also called the early failure region. In the phase of permanent wear the useful life is obtained. The failure rate within this region is ideally constant until the wear-out phase begins. Within the last region, the systems fail due to

the exceedance of their designated life time. In this (time-) representation it is possible to detect the significant regions of the process but it is not possible to distinguish between signals measured during the run-in phase and signals measured during the wear-out phase. Therefore STFT and WT were used to extract relevant frequency components showing the differences of the signals occurred in the several phases.
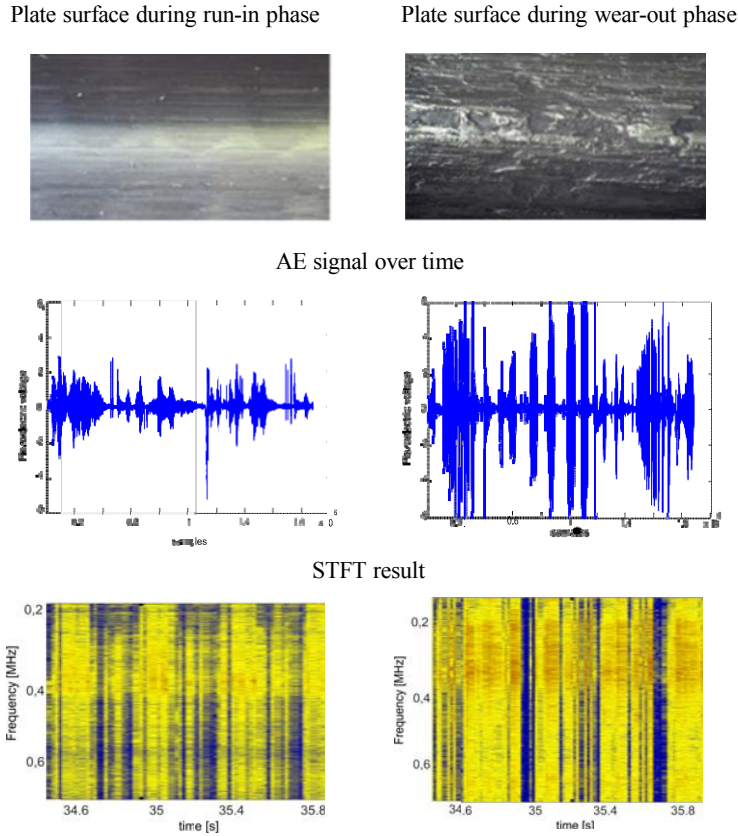
Plate surface during run-in phase   Plate surface during wear-out phase

AE signal over time

STFT result

Figure 3. STFT analysis of plate during run-in and wear-out phase of plate during run-in and wear- out phase.

During operation, process, position, and wear specific frequencies appear in the measured signal. For reasons of consistency and comparability the analysis of the AE signal is always performed at the same position, identical duration, and direction of movement of the cylinder. The points in time of AE measurement are at the beginning of the cylinder movement. The information resulting from frequency content (see Figure 3), duration, and position of occurrence of the transient event can be seen in the STFT results. By monitoring those events/patterns over the whole experiments, features like the emitted energy per cycle (minute/speed/...), count rate of emission, etc. information about the level of deterioration can be achieved for the determination of wear related properties in upcoming considerations. As expected, the STFT results of the signals in run-in- and wear-out phase are nearly identical in comparison to the STFT results of the signal measured during the permanent wear phase (see figure 4).
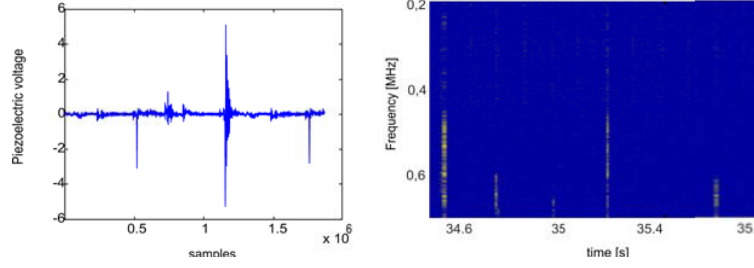
Figure 4. Signal analysis of plate during permanent wear phase.

In summary, the increasing of wear rate over system usage can be observed by the STFT. Unfortunately this specific signal processing method is not efficient to distinguish differences between relevant frequency components indicating transient events occurred in the run-in phase or in the wear-out phase. This lack could be remedied with the application of the DWT. In figure 5 the decomposition of run-in-and wear-out signals in three levels is shown. Here level 1, 2, and 3 represent the constituent parts of the AE signal at frequency band [0, 155], [155, 312.5], and [312.5, 625] kHz, respectively. So it can be deduced that frequencies between 155 and 312.5 kHz dominate over the two operation phases. Frequencies characterizing AE signals measured in the run-in phase are located in level 3 (312.5, 625 kHz), while relevant frequencies indicating the wear-out phase are situated in the first level (< 155 kHz). Therefore compared to the STFT, WT can better represent the state of damage and allow advanced wear diagnostic maintenance applications.
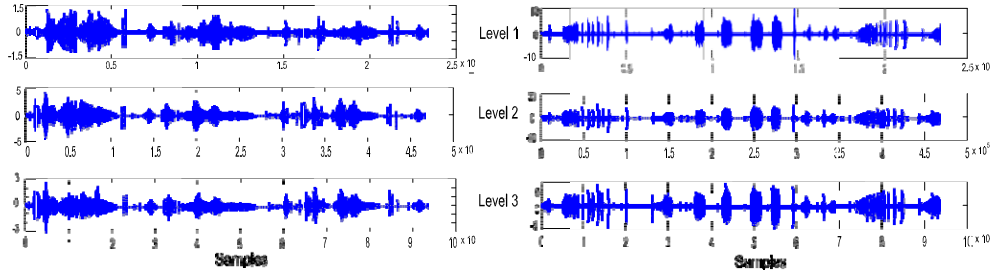

Figure 5. DWT analysis of plate during run-in and wear-out phase of plate during run-in and wear- out phase.

SUMMARY AND CONCLUSION

The goal of the contribution is the automated supervision of tribo-systems with wear. As demonstrated, the AE technique is efficient to detect transient events due to inner system mechanisms. For this reason a new measurement chain for ultrasonic emissions has been developed and tested. It could be shown that the waves generated by material changes were also initiated by the wear test-rig runs and can be detected by the proposed sensor technology and the measurement chain. In this context the STFT and the WT could reveal the point in time and as well as the energy content of the transient event of deterioration. The new result from this

contribution is that now wear-state dependend AE-signals are obtained and a related measurement chain is realized. It can be concluded that now wear-state supervision can be realized based on automatically running routines. In the next steps to detail the introduced concept of detection and quantification of the state-of-damage of a tribological system, the stimulation of the wear effects as well as the unambiguous determination of characteristic frequencies occurring during the different phases of the process will be examined. Additionally to the presented new results, it is observed that compared to STFT, the WT has more advantages and can also reveal a relationship between frequencies and actual state-of-damage.

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