Classification of wear phenomena by specific ultrasonic emission detection for prognostic purposes

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ABSTRACT

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 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. Destructive testing concepts reveal the level of deterioration of a component at a discrete point of time. Though, the progression of fatigue is hardly reconstructable and the process cannot be continued with the same component. This is only possible with non-destructive methods, which observe/measure those signals that indicate the fatigue progression. Hence, the destructive testing provides the reference damage level at discrete operating times while the non-destructive testing fills the gap between those discrete information with the damage progression in between.

This contribution deals with the problem of detecting and monitoring signals indicating tribological effects with a non-destructive concept. Therefore a new sensor technology is applied and first considerations about the related data filtering technique are considered. The main idea is to monitor ultrasonic emission properties of the tribo-system. For first experiments using this technique a test rig for wear examination with variable lubrication, and normal force has been developed. This tribological system is equipped with several sensors, amongst others several piezoelectric materials. The transducers are used as ultrasonic sensors, measuring the structure-borne noise. The goal is to connect the characteristic signals unambiguously to their unique sources, e.g., abrasive wear and surface fatigue. This contribution details the possibility and application of structure-borne noise measurements, and shows preparative results for determination of deterioration and for distinguishing different wear-related effects.

1 MOTIVATION

A test rig consisting of two plates, sliding against each other, with variable lubrication, friction, and normal force is used to test runs producing several kinds of signals. As shown in (Friesel and Carpenter, 1984), (Heiple and Carpenter, 1987), (Kaiser, 1950), and (Woodward and Harris, 1977) the measurement of Acoustic Emission (AE) signals can be used as an indicator for different effects effected by material changes due to aging, wear, etc. Those signals occur due to different wear sources (twinning, slip, deformation glide, etc.), which are the main sources for failure due to fatigue. Usually inner material effects damage the system internally before those effects can be detected visually at the material surface or become effective respectively. Hence, an optical (surface) inspection can not 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.

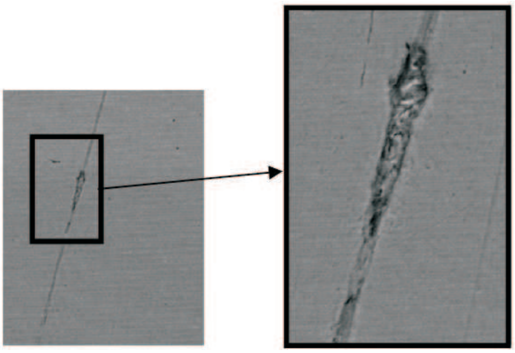

Figure 1: SEM exposure of plate surface with microcrack; left: overview; right: zoomed in.

The contribution is structured as follows: in the first section relevant research results concerning structure borne sound are discussed. The limitations of those are shown and the novel aspect of this contribution is emphasized. In the following section the measurement chain is introduced. The last section sums up and discusses the experimental results. An outlook to future work is shown in the final part of the contribution.

2 STRUCTURE-BORNE SOUND

The tribological system analyzed for this contribution is a oscillating sliding tribo-system. Both contact partners consist of a “wear resistant” plate with a martensite microstructure, with a riffle structure on both plates surfaces. Two plates of different sizes (with area ratio 1:5) are sliding against each other under an adjustable normal load. By analyzing several material samples under a Scanning Electron Microscope (SEM; see Figure 1) the occurred wear mechanisms are identified.

The depicted microcrack results from overstress applied to the surface. The crack propagates through the wear plate and deteriorates it. The process of crack growing is hardly measurable by classical measuring techniques e.g., acceleration measuring. In the context of the proposed new approach several piezoelectric materials are bonded to the structures, realizing the continuous measurement of relevant signals during the wear process. It can be shown that this measurement is principally able to sense material changes of relative small dimensions. A sketch of the used test rig is shown in Figure 2. The upper part depicts the whole test rig with the cylinder, the lever arm, and the tribological system. A detailed scheme of the upper wear plate, equipped with the piezoelectric material, is shown on the lower left side. The photo depicts the assembled tribo-system (upper and lower plate).

2.1 Sources of acoustic emissions

A thin coating with a very brittle microstructure can be found on the surface of the wear plates whereas the microstructure under the surface is lamellar martensite. Even before a load is induced, some tensile cracks can be seen in the coating. According to (Bobrov, 1993) a martensitic microstructure may lead to a propagation of cracks with the initiation on the surface. During the first hours with applied load this coating is eroded, particles scratch the surface and lead to abrasive wear.

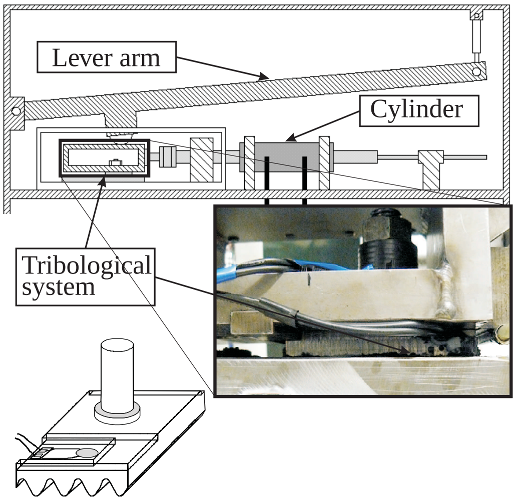

Figure 2: Wear test rig at the Chair of Dynamics and Control, SRS, U DuE

After loading the system with a constant normal force, fatigue cracks appear and may grow into the ground material. Additionally some small cracks appear under the surface starting at the cone end of deformed inclusions and spreading parallel to the surface. So the main wear mechanism is surface fatigue which initiates and propagates cracks after a certain number of cyclic events (Sly, 2002). These cracks can be induced through some gliding dislocations change into hollow dislocations, which become cracks and propagate in the metal in the direction of applied stress. Because of the oscillating movement in the current tribological system the cracks can propagate in two directions, which could be seen in the areas near to surface. According e. g., to (Rogers, 1985) the source of ultrasonic waves (structure borne sound) lies within the material and results from local inner micro displacements.

Those displacements emit a displacement specific wave that travels through the material (van Bohemen *et al.*, 2005). By sensing these signals, the occurrence and rate of occurrence directly correlates to the activities within the material system. Assuming a system in idle mode no ultrasonic activities due to material change are observed. As soon as the system is stressed by external mechanical loads, material activities will take place and emit waves with characteristic properties, which strongly depend on the used material and measuring equipment. For purpose of supervision it is necessary to classify the measured signals and correlate them with the causing effect (material change etc.).

During the deformation of material usually several effects occur in parallel. This makes it impossible to clearly connect unambiguously signals and effects. Therefore it is necessary to excite each important material changing effect separately and to sense its characteristic elastic wave.

2.2 Test setup

In the material and application considered here, the generated waves have small amplitudes and high frequencies which lie beyond the audible frequency range. Therefore sensors with high sensibility and wide bandwidth have to be chosen to detect even small surface movements. For this reason piezoelectric materials are chosen and used as flat response transducer (sensors).

As proposed in (Rogers, 1985) and (Zaitsev *et al.*, 2000) the sensors are glued to the surface. The coupling between the surface and the material is permanent and very stiff. Hence, a low signal attenuation of the stress waves is obtained. The sensors used for the shown results are discs with a diameter of 10 mm and a thickness of 0.55 mm. The measured voltage is directly feed to a high-speed analog/digital-converter (ADC). Hence, special care (shielding, grounding, etc.) has to be taken for the transducer, cable, and other hardware. This aspect is addressed below.

The measured signal is subsequently analyzed by various signal processing methods. A simple and easy to realize threshold supervision and analysis is widespread in the literature but not applied here. This contribution focuses on the analysis of the signals frequency content. According to e.g., (Zaitsev *et al.*, 2000) and (Nam *et al.*, 2001), special attention is paid to higher frequencies ($>$ 300 kHz) and their source. The phenomenon of stochastically occurring material changes can be observed in higher ranges (see (Nam *et al.*, 2001)). Those wave emissions are transient and have a high energy content. Hence, the signals detected by the piezoelectric material have to be measured with an appropriate sample size and measurement duration to raise the probability of detecting such emissions.

Due to the novelty of the proposed approach no detailed information are available for proposed frequency ranges of those relevant effects in combination with the material used for examination. Therefore wide frequency range (up to 1 MHz) is covered by the measurement chain. An appropriate sampling rate of the ADC is chosen. This assures a high resolution (horizontally and vertically) of the discretized piezoelectric voltages.

The test rig and the measurement setup are operated in a rough surrounding (in terms of electro-magnetic emissions). A hydraulic pump and a valve, driving the test rig, emit mechanical vibrations and electrical interferences. The signal-to-noise ratio (SNR) of the piezoelectric voltage is not determined accurately because the relevant frequencies are not yet determined exactly. Due to electro magnetic compatibility (EMC) problems (see below) further work has to be done in the field of shielding and grounding.

3 EXPERIMENTAL RESULTS

As introduced the main wear effects are abrasive, and wear surface fatigue. According to the results presented in (Woodward and Harris, 1977), the first goal is to detect characteristic frequencies for these stochastically appearing effects and to assign them to their unique wear sources/mechanism. Form literature (e. g., (Bohlan *et al.*, 2002), (Zaitsev *et al.*, 2000)) it is known that several material aspects effect the detected signals (e. g., grain size).

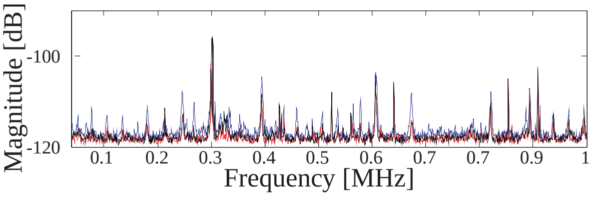

Figure 3: FFT of measured background noise, taken at different points in time; shape stays the same.

The Fast Fourier Transform (FFT) of the unfiltered signal, measured by the equipment while the test rig is in idle mode is shown in Figure 3.

Three signals have been measured over 0.5 seconds at different points in time but identical fixed cylinder position. The obtained and depicted characteristic frequencies appear in every FFT more or less with the same intensity. Hence, the general shape of each FFT stays the same (as depicted). This is considered to be the background noise.

The disturbing frequency parts result from electro, or electro-magnetic environmental interferences and have to be suppressed by enhanced measurement equipment.

Although those frequencies do interfere with the analysis, the information about the constant general shape of the disturbances was used to extract the relevant information from the signal. In a first approach the signal components with a intensity of lower than -120 dB were truncated to -120 dB.

After the evaluation of the disturbances, the test rig starts running. During operation, process, position, and wear specific frequencies appear in the measured signal. The point in measurement is kept identically, so the ultrasonic emissions are taken at identical movements/positions for the whole experiment.

To preserve the time information within the analysis a Short Time Fourier Transform (STFT) spectrum is used for identifying transient ultrasonic emissions. Furthermore the correlation of standard process information (position, velocity, etc.) becomes possible (not depicted in this contribution).

For reasons of consistency and comparability the analysis of the signal is always performed at the same position, identical duration, and direction of movement of the cylinder (highlighted by the four boxes; c.f., Figure 4). The points in time of AE measurement are at the beginning of the cylinder movement. 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 frequencies, amplitudes, etc.

For those reasons the same sections in time are compared in the following in detail to extract the characteristic information from the signal. The contents of the four black boxes of Figure 4 are examined for their transients events.

On the left side of Figure 4 the wear plate in condition “good” is depicted. The surface is not deteriorated. As a result, the wear plate is smoothly moved by the cylinder (position signal shows no ripples, un-

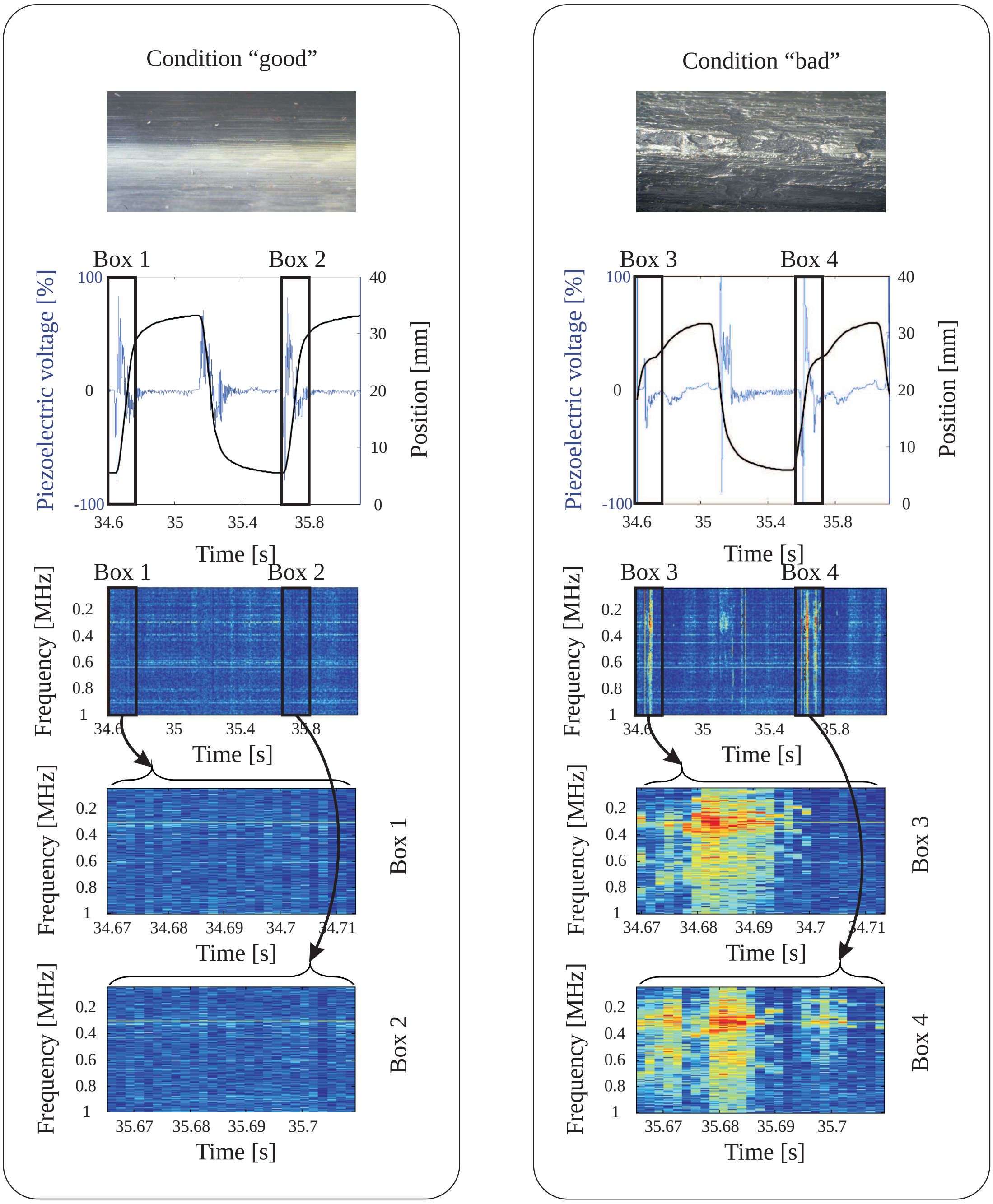

Figure 4: Superposition of cylinder position and recorded acoustic emission signals with examination in time and frequency; comparison of wear plate in “good” and “bad” condition

steady movements, etc.). This represents the starting condition of the test.

After a certain time of operation the surfaces deteriorate. On the right side of Figure 4 the wear plate is shown after being operated. The AE activities increased and therefore the wear increased.

Each signal, transformed by the STFT reveals information about this change. The pathbreaking information (frequency content, duration, position of occurrence) of short time transient events can be seen in the STFT spectrum. A transient event is analyzed for its containing frequencies and amplitudes and is represented as a vertical contour line (comparable with the waterfall diagram). Frequencies indicated by the blue color (-120 dB) are not found in the signal and truncated to -120 dB, whereas red colored frequencies (-80 dB) are dominant in the analyzed signal. The persistent horizontal lines in Figure 4 result from the above mentioned EMC challenges (background noise).

As expected, the STFT information of box 1 and box 2 are nearly identical. Furthermore no transient occurrences are detected. Hence, no detectable wear occurred in this early operation stage.

In comparison to that, boxes 3 and 4 show high AE activities. Beyond that an AE activity is found shortly after box 4, which does not occur after box 3. Obviously an AE emitting event has occurred.

By monitoring those events/patterns over the whole experiments, features like emitted energy per cycle (minute/speed/...), count rate of emission, etc. information about the level of deterioration can be achieved.

4 SUMMARY AND CONCLUSION

The goal of the contribution is the automated supervision of tribo-systems with wear. The development of a related condition monitoring system (as described in (Dettmann and Söffker, 2008)) adequate measurement concepts, sensors and diagnosis approaches has to be developed, applied, and validated. As demonstrated in literature, the acoustic emission due to inner system mechanisms (micro displacements due to overstress or others) seems to fit for this purpose. For this reason a measurement chain for ultrasonic emissions has been developed and tested in this contribution. 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 spectrum has promise to reveal the point in time and energy content of the transient event of deterioration.

The next steps following the introduced concept of detection and quantification of the state-of-damage of a tribological system are the stimulation of the wear effects as well as the unambiguous determination of characteristic frequencies, signal energies, and fault specific properties. The efficiency and reliability of the proposed method has to be validated.

The information can be used for determination of the actual state-of-damage, and for diagnostic and prognostic purposes (lifetime prediction).

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