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Monitoring Lubrication Regimes in Sliding Bearings

Using Acoustic Emission Analysis

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Sliding contacts at bearings, running surfaces of cylinders or cam transmissions have an essential influence on the mechanical operating conditions of machines, combustion engines or turbines. High value is placed on the construction of compact machines and, therefore, improved thermal and mechanical efficiency is required. This causes a saturation of many machine components, for example, sliding bearings. Under unfavorable circumstances, the minimal lubricating gap becomes so small that a complete hydrodynamic separation of shaft and bearing is no longer guaranteed. Friction and wear increase quickly, leading finally to a failure of the bearing. The failure of a bearing in a ship motor may represent a threat to the machine, ship and environment, as well as to human lives. Failure-free running machines demand efficient and reliable monitoring systems, which can report on the current condition of the bearing arrangement while in operation.

At the Institute of Product Development of the University of Karlsruhe, the procedure of acoustic emission (AE) analysis to detect damage in sliding bearings is being examined. The noise emerging from metallic contacts between sliding surfaces is measured with emission acoustic sensors and further evaluated by spectral analysis. Measurement of the noise level can be done far away from the metallic contacts, even outside of the housing, and therefore requires no type of mechanical changes in the engine compartment.

Acoustic Emission Analysis

The evaluation of machines by noise monitoring in the audible sound range is a commonly used method. Numerous failure symptoms can be identified at an increased noise level or at a typical frequency range.

Figure 1 shows the measured correlation between the average value of the acoustic signal amplitude and the shaft's rotational speed on a 10 kN loaded bearing. The characteristic curve falls to a minimum value and then increases. This course corresponds with the progress of the Stribeck-curve which describes the correlation between sliding speed and friction coefficient in sliding contacts (Figure 2). The region up to the minimum of the Stribeck-curve is determined through boundary and mixed lubrication. To the right of the mixed lubrication regime, the subsequent increasing of the Stribeck-curve is referred to as the elastohydrodynamic regime. In this region, the two machine surfaces are separated by a lubricant film.

Note that the primary contribution to the increase in friction is primarily a function of the lubricant's viscosity. This transition is reflected in increasing noise levels at the measured curve. These results support an argument for the use of AE analysis to be used as a condition surveillance method for sliding bearings based on the correlation between the friction condition and the measuring average noise level.

The spontaneous release of energy from a loaded elastic body is responsible for the

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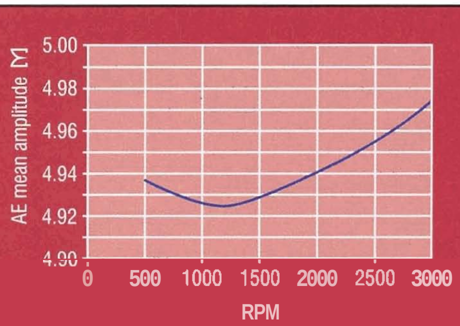

Figure 1. Acoustic Emission Mean Amplitude vs. Shaft Rotational Speed, Loading Force: 10 kN

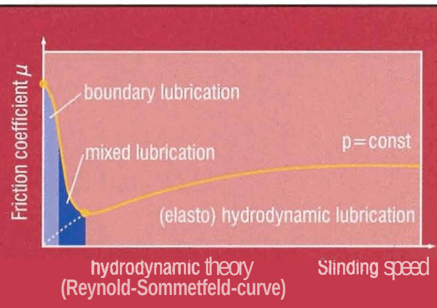

Figure 2. Stribeck Curve

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emission of noise. This can be caused in boundary, mixed or elastohydrodynamic lubrication regimes as well as by the appearance and propagation of cracks, fracture processes, cavitations phenomena and phase changes, or through plastic deformations. The frequency range of the noise emission extends from audible to ultrasonic. In the audible sound range, environmental interferences are so large that the measuring signal is no longer useful. Therefore, it must be measured in an ultrasonic range, at approximately 100 kHz, where normal operating vibrations of machines and engineering equipment have no influence.

In experiments carried out with axial and radial bearings, a density of impulses was determined in order to evaluate the acoustic signal at high frequencies. By calculating the impulse density, conclusions on the existence of damages in bearings can be determined. The adjusted limiting of noise level plays a central role in this procedure, while amplitudes too high or too low can generate incorrect diagnostics.

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These analyses use only part of the information contained in the AE signal. In the case of the impulse density measurement only the frequency is used, and in the case of the effective value measurement only the amplitude is used. The new procedure principle proposes the use of both frequency and amplitude to prematurely detect bearing failures.

Sliding Bearing Test Methods and Apparatus

The test bench consists of a steel shaft supported by two bearings. The test bearing is located between both supporting bearings, which can be loaded using a hydraulic cylinder with a static loading force of up to 60 kN (13,490 pounds) (Figure 3). The test bench enables testing with half- and complete shells. Speed of the shaft can vary between 150 and 3,000 rpm. Preheating the lubricant from 40°C to 60°C is an option, which would enable the bench to run tests at different hydrodynamic conditions based on the viscosity change.

For the tests, lead-copper-tin-bearings of the type Glyco 40 and bronze-bearings with a diameter of 61.5 mm and a width of 9.5 mm were used.

Measured parameters such as speed, driving torque, loading force, bearing rear temperatures and inlet lubricant temperature were determined. The AE-sensor was mounted on the outside of the housing (Figure 3).

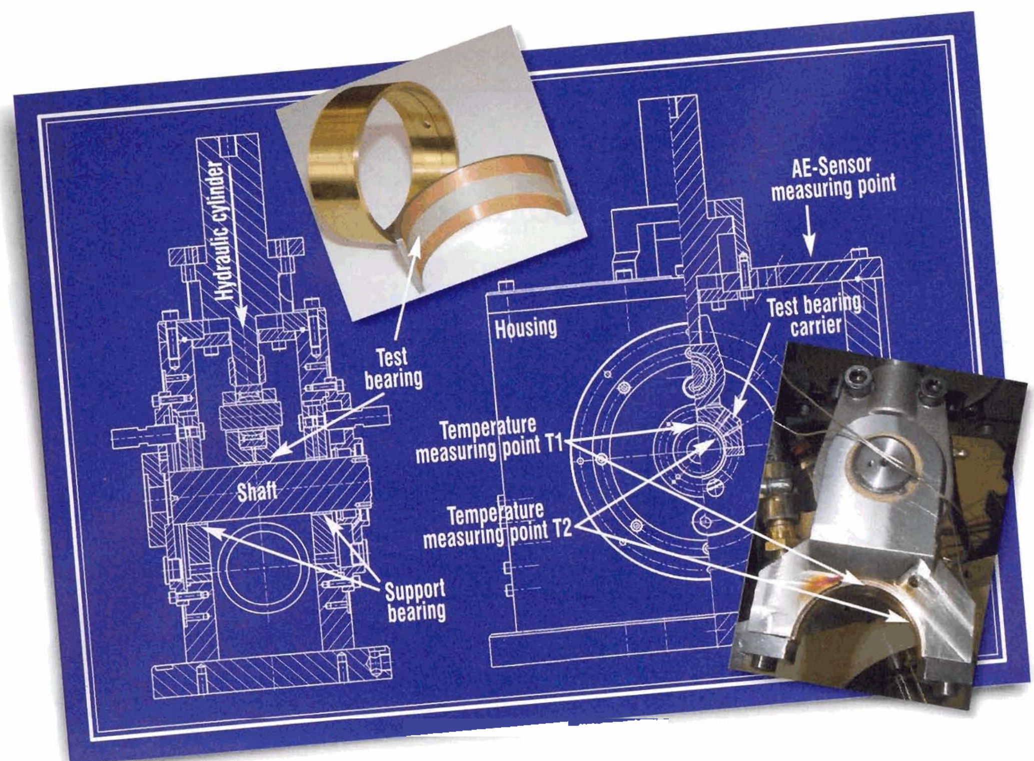

Figure 3. Sliding Bearing Test Bench

Test Procedure and Results

To demonstrate use of AE measurements, the test bearings were run to failure through a combination of means, including reduction of the lubricant volume, a lubricant deficiency, and/or bearing overload. The loading force was increased to the point where asperity contacts began to occur. The possibility of preheating the lubricant facilitated a further reduction of the loading capacity of the bearing due to the viscosity decreasing as temperature rises. In this instance, a bearing failure could be induced by applying slight loading forces.

Figure 4 shows the frequency spectrum for an undamaged surface under hydrodynamic condition and slight load is shown against the frequency spectrum for a failed bearing. An increase of the amplitude in the range between approximately 80 kHz and 140 kHz in the failure can be clearly recognized. This response is characteristic to all the tests conducted and was observed in the generation of bearing damage. In addition, the slight increase of the amplitude between 100 kHz and 120 kHz is characteristic of the intact running bearings.

In spite of the strong attenuation of the sensor's sensitivity at frequencies up to 50 kHz, strong vibrations below 20 kHz are observed. These vibrations are attributed to the noise emitted by the test bench motor. This range of measurements will not be taken into account in the subsequent signal evaluation.

To document the progress of the bearing failure, the acoustic signal was measured and evaluated continuously every second. The result of the measurement using a Glyco 40 half-shell under slowly increasing continuous load, with a speed of 3,000 rpm, is represented in Figure 5. The lubricant for this test was preheated to 53°C. In Figure 5, the variation in time of every frequency spectral analysis is properly arranged. The progress of the bearing damage can be clearly observed. At the beginning of the measurements, the same frequency pattern is consistent with those seen in Figure 4. Starting at the 16th test series, the amplitude in the range between 80 to 140 kHz is clearly pronounced, showing the beginning of metallic contact between shaft and shell, and eventually leading to a bearing failure.

To establish a relationship between these results and the other measured variables at the test bench, the integral of the frequency spectra values in ranges between 80 kHz and 140 kHz was calculated to characterize the AE signal. In Figure 6, the value of this integral is given next to the progress courses of load, torque and bearing back temperature. The initial bearing damage can be recognized where the loading force at the bearing was gradually increased up to 4.5 kN. This corresponds with the abrupt increase of the torque signal. Following a slight delay, the bearing back temperature increases strongly and reaches a maximum value of 215°C. The increase of the composite acoustic spectral emission precedes the increase observed in the torque and temperature curve. This procedure clarifies that with the AE signal a bearing failure can be recognized seconds before it occurs. After testing, the sliding bearing was classified as defective.

Further analysis is required to fully explain the extent to which each of the measured variables influence the acoustic signal. All of the variables - shell material, speed, temperature and lubricant viscosity - are of interest. Further investigations presented similar results although bearing shells with different diameters and materials were used.

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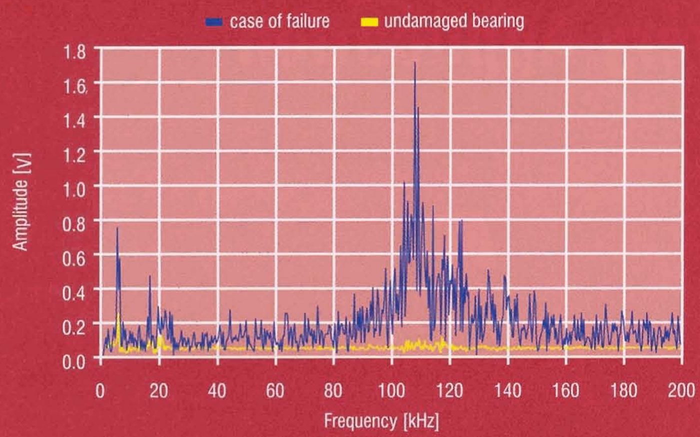

Figure 4. Frequency Spectra of Undamaged Bearings

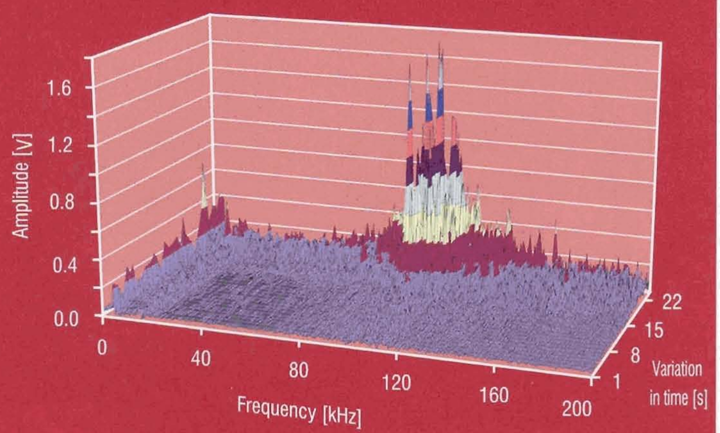

Figure 5. Time Variation of the Frequency Spectra

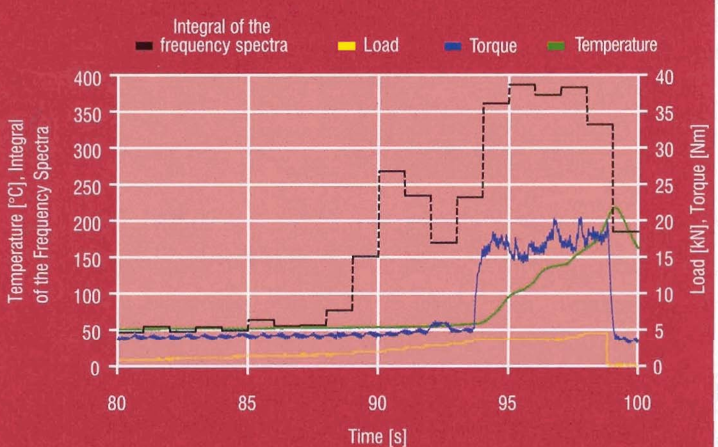

Figure 6. Result of Static Applied Load Test on Half-shell Glyco 40 Bearing

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Conclusions

These studies demonstrated that acoustic emission analysis is an appropriate measurement procedure to detect incipient failures at sliding bearings through the correlation between the emitted acoustic signal and the energy dissipated in the sliding metallic contacts. Damage can be recognized independently of contact geometry, sliding speed, shell-material, rear shell temperature, and lubricant temperature with a significant increase of the amplitude in the frequency range around 100 kHz. A detailed examination of the variables, which are normally involved in the friction process, determined that physical and mechanical parameters of the friction surface, where steel surfaces were involved, did not generate appreciably differing results.

Bearing damage could always be recognized before the initial stage of a failure which was expressed by increasing torque. The monitoring of the bearing back temperature, which is often used to supervise bearings, clearly reacted later than the AE signal. On the basis of these severities, this measurement procedure shows a large potential for a practical use in the early recognition of bearing failures. Acoustic emission analysis also has an extra advantage with the AE-sensor. It can be mounted far away from the metallic contacts and therefore outside of the housing. Relative to engine analysis, there are no changes required for the engine compartment, cabling or housing configurations. The transferability of these results to nonstationary loaded bearings, for example in combustion engines, remains uncertain and its investigation could become the main purpose for further works.

The success of a continuous surveillance system will depend on its configuration relative to the specific mechanical interactions. Machine-specific data collection parameters and data management functions will need to be developed to enable integration of the right criteria, and identification of incipient failure. For continuous surveillance systems, significant storage and processing capacity is required to manage the relatively large amounts of data and processing algorithms. **POA**

Editor's Note:

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