Rolling element bearings are critical components in most rotary machines. When a bearing is damaged, it tends to generate higher vibration than a normal bearing does. Therefore, to prevent machine breakdown due to bearing damage, bearing vibration is generally monitored in critical industrial machines. However, during the early stages of bearing damage, the vibration signal is weak compared to that of other components such as gears, which makes early detection very difficult in most cases. To overcome this problem, AE (acoustic emission) technology was evaluated as a potential condition monitoring technology for rotary machines. The results presented in this paper show that AE can help detect bearing damage at an early stage.

Keywords: acoustic emission, condition monitoring, bearing, rotary machine.

1. Introduction

Condition monitoring is widely used in industry to prevent the catastrophic breakdown of critical machines. As critical components of a rotary machine, bearings are normally the focus in condition monitoring. In most condition monitoring systems, temperature and vibration are used as the indicators of bearing condition. Sharply rising temperatures and vibration indicate that a bearing could be damaged. However, during the early stage of bearing damage, the temperature increase is small and the vibration generated by the bearing damage is buried in the vibration generated by other components such as gears. Therefore, to detect early-stage bearing damage, a new indicator is needed. In this study, AE (acoustic emission) is investigated as one of the potential new indicators.

AE is a transient elastic wave generated by the rapid release of the energy within a material under stress. When the elastic wave propagates to the surface of the material, it can be detected by AE sensors. Traditionally, AE technology has been used to detect cracks in stationary structures such as nuclear pressure vessels, storage tanks, buildings, and bridges, but some research has been undertaken to study the potential of applying AE technology to the detection of bearing damage. Roger [1] proposed the use of AE for detecting damage in low-speed anti-friction bearings in a slewing crane on an offshore production platform. The study of Smith and McFadden [2][3] showed that AE can detect small localized defects and damage on various bearing components at low speeds.

Choudhury and Tandon [4] investigated changes in AE signals for different sizes of simulated defects on the inner race and roller body of cylindrical roller bearings at speeds up to 1500 RPM and under a radial load up to 125 kg. In their research, the simulated defects were across the raceway or the roller body, with widths from 0.15 mm to 1.0 mm. The research found that ring-down count is a useful
parameter for the detection of defects on both the inner race and the roller of the bearings tested. However, it should be pointed out that a vibration measurement with accelerometers should also be able to detect those simulated defects due to their relatively large sizes.

In addition to defect/damage detection, Dykas [5] investigated the potential of using AE to detect degradation and failure of the lubricant in grease-lubricated helicopter drivetrain bearings. The research found that RMS and count rates based on absolute thresholds in the AE signal were able to distinguish a dry bearing from one with fresh grease, but for the degraded grease specimens, these metrics exhibited less clear indications of the distress.

As described above, most of the previous studies investigated the application of AE for bearing damage detection at relatively low speeds and/or under light loads. The varying degrees of simulated bearing damage used in the reported studies were close to final-stage bearing damage. However, it is important that condition monitoring systems be able to detect early-stage bearing damage at high speeds and under heavy loads so they can assist industry in the transition from preventive maintenance to predictive maintenance. Therefore, the purpose of this study is to investigate the capability of AE measurement for detecting early-stage bearing damage at high speeds and under heavy loads. Deep groove ball bearings were used in the study. The early-stage damage was simulated with a tiny dent on the center of the outer ring raceway. The AE tests and analysis results are presented in this paper.

2. Acoustic emission tests

The test rig used in the study is shown in Figure 1. Two AE sensors with 30K Hz and 150K Hz resonance frequencies, respectively, were mounted on the bearing housing with magnet holders. A two-channel digital acoustic emission system was used to acquire data. The sampling rate in the tests was 2M SPS (samples per second). The system was equipped with a high-pass analogue filter with a 20K Hz cutoff frequency and a low-pass analogue filter with a 3M Hz cutoff frequency. For both channels, the AE signals passed through a preamplifier with a gain of 20 dB before the data acquisition.

In the tests, a deep groove ball bearing was used. Table 1 lists the geometry of the bearing.

<table>
<thead>
<tr>
<th>Bore diameter</th>
<th>Outside diameter</th>
<th>Width</th>
<th>Ball diameter</th>
<th>Number of balls</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>72</td>
<td>17.0</td>
<td>11.112</td>
<td>9</td>
</tr>
</tbody>
</table>

![Figure 1: Test rig and AE sensors](image1.png)

![Figure 2: Dent on the outer ring raceway](image2.png)
To simulate early-stage damage, a small dent was created at the center of the outer ring raceway, as shown in Figure 2. Compared to the simulated damage used by Choudhury and Tandon [4], the dent was a much closer representation of an early-stage damage.

In addition to the bearing with the simulated damage, a brand new bearing without damage was also tested as reference. The bearings were tested under two speeds and three different radial loads, as listed in Table 2. The radial load is expressed as percentage of the rated load, which is 5738 N for this bearing. The loads and speeds used in the tests were much higher than those used in the reported studies [2][3][4].

<table>
<thead>
<tr>
<th>Test No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (RPM)</td>
<td>2500</td>
<td>4500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load (% of the rated load)</td>
<td>25%</td>
<td>50%</td>
<td>100%</td>
<td>25%</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>

3. Test results and analysis

3.1 Conventional threshold-based hits analysis

The test data were first analyzed using the conventional threshold-based technique for hits detection and determination. There are two types of thresholds: fixed and floating. A fixed threshold is a constant value, while a floating threshold is automatically adjusted over the time of the test. In this study, a floating threshold was used. Figure 3 shows the hits at 25%, 50% and 100% of the rated load calculated based on the AE measured using the 30K Hz sensor in Channel 1. (Note: In the legend, GB stands for “Good Bearing” and DB stands for “Dented Bearing.”)

At 2500 RPM, the hits for GB are zero or close to zero at the three load levels, but the hits for DB are much higher. At 4500 RPM, however, the hits for the DB at 50% and 100% of the rated load are zero, meaning that at the higher speed and higher load, the hits generated by the dent on the outer ring raceway cannot be isolated from the background noise.

![Figure 3: Hits of GB and DB based on the 30K Hz sensor](image)

![Figure 4: Hits of GB and DB based on the 150K Hz sensor](image)
Figure 4 shows the hits at 25%, 50%, and 100% of the rated load calculated based on the AE measured using the 150K Hz sensor in Channel 2. The observation from Figure 4 is the same as that from Figure 2. The results show that it is difficult to detect the hits generated by the tiny dent on the outer ring raceway, regardless of the sensors used, because of the high background noise generated by a rotating bearing at high speed and heavy load.

There are three types of AE signals: bursts, continuous and mixed [6]. Bursts have short durations relative to the other types of AE signals and are generated by localized damage. Continuous AE signals are formed by multiple signals emitted from different emission sources that overlap in such a way that their amplitudes do not fall below the threshold level.

The background noise and rubbing in a structure are the main sources of continuous emission. In a rotating bearing, because the rollers and the rotating ring enter and exit the load zones, they are subject to varying stress and emit AE even though they have no defects. The AE emission from this source increases at higher speeds and heavier loads — so, when the background noise is high, the AE from the bearing damage may become “buried” in the noise and thus be undetectable. It explains why the hits for the DB are zero when the load increases to and above 50% of the rated load at 4500 RPM. In fact, even for stationary structures such as CFRP (carbon fiber reinforced plastics) under dynamic loads, the noise is so high that the hit detection is challenging [7][8].

Acoustic emissions from a rotary machine are more complex because of the multiple rotating parts, such as shafts, gears and bearings. Therefore, the conventional threshold-based hits detection method is not suitable for rotary machines. Further, even if at low speeds and light loads the irregularities of a rotary machine could be detected based on hits, it is impossible to pinpoint which components have been damaged. Therefore, spectral analysis of AE waveforms is needed for condition monitoring in rotary machines.

### 3.2 Spectral analysis

Figure 5 shows the waveform from the 30K Hz sensor at 2500 RPM under 25% of the rated radial load. The vertical axes in Figure 5 and all other figures in Section 3.2 show the sensor output in volts. The equally-spaced spikes were acoustic emissions every time when a ball is in contact with the tiny dent. One can do an FFT (fast Fourier transform) to convert the data from the time domain to the frequency domain. The frequency spectrum in Figure 6(a) shows that the dominant responses occur around 26K Hz. Since the dent is a localized defect, envelope analysis can be used to further analyze the data.

![Figure 5: Waveform measured by the 30K Hz sensor at 2500 RPM under 25% of rated load](image-url)
The envelope spectrum is shown in Figure 6(b). The three dominant peaks are at 147.5 Hz, 297.5 Hz, and 447.5 Hz, respectively. The theoretical BPFO frequency for this bearing at 2500 RPM is 148.6 Hz. The frequencies of the three dominant peaks are very close to the BPFO and its second and third harmonics. The existence of the BPFO and its harmonics in an envelope spectrum indicates that the bearing outer ring may have localized defects. As the envelope analysis shows, one can not only detect bearing damage, but can also pinpoint the damaged bearing component.

The AE signal measured by the 150K Hz sensor was also analyzed. The waveform is shown in Figure 7. Similar to Figure 5, a number of equally spaced spikes can be observed. Those spikes are the acoustic emissions when a ball is in contact with the defect. The frequency spectrum is shown in Figure 8(a). Because of the high resonance frequency of the sensor, the frequency range is extended to 200K Hz. This frequency response is different from that of the 30K Hz sensor. The dominant response for the 150K Hz sensor is at around 23K Hz — instead of at around 26K Hz, as was the case for the 30K Hz sensor — therefore, the band pass filter for the envelope analysis is different.

Figure 8(b) shows the envelope spectrum. The envelope spectrum is similar to that shown in Figure 6(b). It has three dominant peaks at 147.5 Hz, 297.5 Hz, 447.5 Hz, which are the BPFO and its harmonics. It indicates that the outer ring may have localized defects. Another significant difference between the acoustic emissions measured by the 30K Hz sensor and the 150K Hz sensor is that the amplitude of the acoustic emissions measured by the 30K Hz sensor is much higher than that measured by the 150K Hz sensor.

Figure 7: Waveform measured by the 150K Hz sensor at 2500 RPM under 25% of rated load
As revealed by the analysis in Section 3.1, it is difficult to detect the defect/damage using conventional hits analysis under heavy load and high speed conditions. Therefore, the author was interested to see whether the spectral analysis could detect the defect when the bearing was rotated at 4500 RPM and under 100% of the rated load — the most challenging condition among the tests conducted.

Figure 9 shows the waveform measured by the 30K Hz sensor at 4500 RPM and under 100% of the rated load. Although the pattern of equally spaced spikes can still be observed, some irregular spikes also are present. The irregular spikes are acoustic emissions from sources other than the simulated damage.

The frequency and envelope spectra are shown in Figure 10. From the frequency spectrum, one can see the dominant responses are at around 28K Hz. There are three dominant peaks at 265.0 Hz, 530.0 Hz and 800.0 Hz in the envelope spectrum. The theoretical BPFO of the bearing at 4500 RPM is 267.4 Hz. Therefore, the dominant peaks represent the BPFO and its harmonics. The discrepancy between the theoretical BPFO and the actual value is mainly due to the frequency resolution. The existence of the BPFO and its harmonics indicates that the outer ring raceway may have localized defects.

The waveform measured by the 150K Hz sensor at 4500 RPM under 100% of the rated load is shown in Figure 11. Although some spikes can be observed, there are no clear patterns. Figure 12 shows the frequency and envelope spectra. The frequency spectrum shows that the acoustic emission amplitudes is the highest at around 24K Hz. There are no dominant peaks observed in the envelope spectrum, indicating that with the 150K Hz sensor, one cannot detect the defect on the outer ring raceway under the high speed and heavy load condition.
4. Conclusions

Acoustic emission tests were conducted under various speeds and loads to investigate the feasibility of using AE for the detection of early-stage bearing damage. To simulate early-stage bearing damage,
tiny dent was created on the outer ring raceway of a deep-groove ball bearing. Two AE sensors with 30K Hz and 150K Hz resonance frequencies were evaluated. The test data were analyzed using conventional threshold-based hits analysis and spectral analysis.

The hits analysis was able to detect the simulated damage under low speed and light load conditions. However, it could not pinpoint which bearing component had been damaged. Further, under high speed and heavy load conditions, the hits analysis could not effectively detect the damage at all. This is because the background noise, for example, the acoustic emissions generated by the rollers and the inner ring as they enter and exit the load zone, increases with the increase in speed and load. In this case, the hits analysis was unable to separate the AEs generated by the defect from the background noise.

With the 30K Hz AE sensor, under all the test conditions, the spectral analysis effectively detected the simulated damage and pinpointed the component on which the damage was located. With the 150K Hz sensor, however, the spectral analysis was unable to detect the damage under the most challenging high speed and heavy load condition. It can be concluded that AE sensors used for rotatory machine condition monitoring must be carefully selected based on the structure to be monitored.

5. Acknowledgments

The authors would like to thank The Timken Company for permission to publish the paper and Alex Lemus and Richard Phillips for conducting the AE tests.

REFERENCES