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# Bearing Condition Monitoring with Acoustic Emission Techniques

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***Abstract*—**Monitoring the conditions of rotating machinery, such as bearings, is important in order to improve the stability of work. Acoustic Emission (AE) and vibration analysis are some of the most accomplished techniques used for this purpose. Acoustic emission has the ability to detect the initial phase of component degradation. Moreover, it has been observed that vibration analysis is not as successful at low rotational speeds (below 100 rpm). This because the energy generated within this speed region is not detectable using conventional vibration. From this perspective, this paper has presented a brief review of using acoustic emission techniques for monitoring bearing conditions.

***Keywords*—**Condition monitoring, stress wave analysis, low-speed bearings, bearing defect diagnosis.

## I. Introduction

BEFORE the 21st century, there was a limited amount of research on monitoring the condition of low-speed rotating machines. However, a huge amount of researches was focus on high rotational speed of a variety of components, such as bearings, shafts, gearboxes, etc. Although, a number of industrial applications worldwide use low-speed rotating machines, including steel mills, paper mills, water sewage plants, and wind turbines. Most of the failure in these applications is occur due to stoppages or failures related to the condition of bearings which is one of the vital components.

This paper is focused on monitoring techniques used to oversee the mechanical integrity of these vital components. Monitoring methodologies include the collection of data related to conventional measurements, as well as newer forms of sensing incipient degradation, such as acoustic emission.

## II. Acoustic Emission for Bearing Defect Diagnosis

Materials naturally release elastic energy when they are deformed, which is known as acoustic emission (AE) or stress wave emission. During the past 30 years, many researchers have investigated the development of acoustic emission applications for monitoring the condition of bearings.

One of the earliest documents that addressed the use of AE technology to identify artificially-induced defects in rolling element bearings was published by Balderston (1969), and is considered to be the first application for monitoring bearings [1]. The simulation of the defects included both outer and inner defects, covering the race and ball defects, and the lack of lubrication. The resonant and audible ranges with AE were compared, and the advantages of the resonant range over the audible vibration range were confirmed.

Balerston suggested that, due to the connection and integration of the components, any defect that occurs in between can result in inappropriate frequency, which in turn makes the results difficult to interpret [1]. When rotational speed is low, there is low energy impact, which indicates that the applications for vibration technique would be limited. Two types of AE signatures were detected by Balerston, and certain burst-type emissions also were detected, including defects on the inner race, outer race, and ball element. During drying of the bearing (lubrication starving), continuous type AE signatures were detected. This application was the first assessment of the monitoring of the bearing and some details regarding the characteristics of the equipment used were missing. The vibration technique proved to be successful according to Balertson's report, and a direct correlation was noted between the severity of the defect and the increase in the amplitude of the resonant frequency. He also mentioned, as more sophisticated sensors are developed, AE techniques will become even more important.

Later, the application of AE techniques to monitor low-rotating bearings on cranes used for the production of gas was studied by [2]. Kurtosis technique in signal processing was used to detect the incipient failure of rolling element bearings and the location of fatigue cracks. In this study, the outcomes of AE techniques were compared to the results of the vibration analysis. The detectable sources of AE signatures identified were: grinding of the metal elements in the bearing, rubbing of the crack faces, and damaged parts in the loaded zone.

Rogers stated that it is difficult to apply vibration analysis for online condition monitoring because of the, low rotational speed of the crane. With the use of kurtosis at different frequency rates, AE resonant transducers can become informative for online monitoring of bearings.

Two similar scenarios of detection of bearing defects through the implementation of high-frequency AE were also presented by [3]. The first scenario involved the application of high-frequency signals on hairline cracks on the outer race. The defects identified in this case were not detected by vibration analysis because the defect occurs only at an initial stage, and the bearing still appears to be in a condition of normal operation. The next scenario identified the use of AE technology in detecting the presence of any particulate matter in pump bearings. In this research, the characteristics of the equipment used in the experiment conditions were not made

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clear. Another study was conducted by [4], showing that, before going into the vibration acceleration range, AE parameters identified defects in the bearing. The test bearing in this experiment was lubricated with grease and run at a rotational speed of 660 rpm under a thrust load of 4.2 kN. AE generation sources were identified during fatigue life tests on the ball bearings. In this study, the characteristics of the sensors were not shown clearly. Other researchers, including Hawman and Galinaitis, have agreed with Yoshioka's observations concerning AE's advantage over vibration analysis in detecting bearing faults, and they explained that the bearing defects were diagnosed through the modulation of a high frequency [5]. The speed used in the Hawman and Galinaitis's experiment was fixed at 5700 rpm with a load of 10.7 kN. They used r.m.s. and FFT techniques for monitoring the bearing, and they advised using an adaptive noise cancelling (ANC) technique in order to overcome noise interference. McFadden and Smith also devised and examined the application of acoustic emission transducers for observing the speed of the roller bearing element in the range of 10 to 1850 rpm [6]. The experiment was conducted through the application of sensors on the bearing's housing. Defects originating from a fine scratch on the inner part of the outer race were identified in the frequency spectrum.

Tavakoli examined the implementation of AE transducers to needle bearings at low rotating speed [7]. The experiment was conducted with the following three conditions: 1) the use of fully-lubricated, defect-free bearings, 2) the use of defect-free, unlubricated bearings, and 3) the situation in which two nearby needle elements were missing. Moreover, a radial load was applied on the bearing that rotated at 80 rpm. Tavakoli examined both the time domain and the frequency domain features by applying the three conditions. The experiment demonstrated that the mean spectral density of the r.m.s. voltage was different for all three conditions. In addition, it also was shown that the main source of AE in the bearings for all three conditions was friction.

Yoshioka conducted the first known attempt to identify natural degradation in bearings in 1992 [8]. With the use of AE technology, the identification of rolling contact, subsurface, and fatigue cracks remained the major focus of the study. It was demonstrated that AE can locate the source of a defect. This can be achieved by time-delay analysis, which is related with AE events acquired by different sensors. Furthermore, Yoshioka stated that the size of cracks can be identified using the AE technique. A bearing with three rolling elements, not a typical operational bearing, was used in this test. In addition to this, the test was completed after AE activity increased. Hence, the distribution of subsurface defects relative to surface defects was not observed properly. The results of this study indicated that AE was more sensitive and detected faults earlier than vibration analysis. Furthermore, for monitoring the condition of low-speed rotating machinery, a laboratory study was conducted by Mba with the use of stress waves (SW) [9]. He built a test rig for the simulation of mechanical defects, e.g., frame looseness. His study consisted of two parts, the first of which was an analysis of high-frequency stress waves to detect the early stages of the loss of mechanical integrity in low-speed rotating machines. In the second part, Mba enhanced and improved on a monitoring system for RBCs (rotating at 1 rpm). In addition, he also evaluated the possibility of using SW to monitor low-speed bearings with diameters between 80 and 125 mm. On the test rig, signs of SW were found for every fault condition.

Autoregressive coefficients were considered instead of traditional AE pattern identification techniques, such as energy, counts, r.m.s., and amplitude. He concluded that the application of high-frequency SW analysis to the monitoring of low-speed rotating machines has been proven to be successful. Further, this technique can be used for all kinds of low-speed machines, not just rotating machines.

Miettinen and Pataniitty conducted research in which they monitored the faults in extremely low-speed bearings using acoustic emission techniques [10]. The outcomes of the AE measurements were presented in this work for shaft rotational speeds ranging from 0.5 to 5 rpm with an applied load of 70 kN. The measurements were taken using a laboratory test rig and a spherical roller bearing lubricated with grease. Before the tests began, the bearing to be tested was damaged naturally on its outer race. In the same test setting, the outcomes of acoustic emission measurement and vibration measurement methods were compared. The vibration measurement methods included peak value, the envelope spectrum, the acceleration signal derivation, and the vibration acceleration time signal. They used the pulse count method and the time signal as methods of AE measurement. From this study, it was concluded that the acoustic emission technique is a highly sensitive method in low-speed rotating machines for detecting bearing defects. Furthermore, the advantage of using the pulse count method is that the measurement file stays reasonable, while in the AE time signal method, the data file becomes very large. From the AE signals, the cycle time of the bearing fault frequency can be detected in better ways if the speed of the rotational signal is higher. This is because high emission energy is generated at high rotational speeds when the rolling element crashes on the fault. Therefore in this case, the background noise cannot distribute the fault cycle time identification. However, when the rotational speed is high, it is difficult to identify the fault cycle time using the pulse count method. Furthermore, it was noted that the features of AE emission depend on some parameters, including the size and shape of the defects on the rolling surface. With low-frequency vibration methods, the envelope-based spectrum measurement was the most sensitive method. Furthermore, the speed of the rotational machine in vibration methods was set between 10 and 20 rpm; errors can be detected accurately at these speeds [10]. Further research was conducted by Jamaludin et al., showing the application of the stress wave technique for identification of the early stages of damage to a bearing at a rotational speed of 1.12 rpm. Several attempts by various fatiguing measures were made to generate natural defects in the bearing's components. The test bearing was allowed to operate for 800 hours without lubrication, and no defects were detected visually on any bearing components. It was concluded that, through the use of the autoregressive coefficient, the classification of the defect's signature helped to monitor the mechanical integrity of the bearings in both time and frequency domain [11]. Additionally, it was proven that AE was more sensitive than vibration analysis for these types of applications. In addition, the simplicity of using the AE technique and the use of commercially-available equipment make the monitoring system effective [12].

In 2003, an investigation to ascertain the application of standard acoustic emissions (AE) parameters was undertaken by Morhain and Mba on a radially-loaded bearing [13]. A test rig was designed to allow seeded defects on both the inner and outer races of the split Cooper spherical roller bearing. The rationale behind this choice of bearing was its property of disassembly without removing the slave bearings. In this experiment, three different rotational speeds were used: 600, 1500, and 3000 rpm, with three loads for each of them; 0, 2.4, and 4.8 kN. The results achieved showed that AE parameters, e.g., r.m.s. and counts, made it a strong technique for detecting damage to bearings. Furthermore, it was found that the relationship between AE counts and the mechanical integrity of the bearing is independent of the selected threshold level. These results were in agreement with the published results of researchers such as [14]-[16], and it became the foundation of studies on the effect of threshold levels for AE counts.

Price et al. compared vibration analysis and AE techniques in the context of monitoring bearing failures [17]. Their study focused on four ball machines, which were monitored as a function of time. In this experiment, vibration, AE activity, temperature, and friction for these four ball machines were monitored. A variable speed DC motor was used, in which the speed could be varied from 500 to 3000 rpm, and a load between 3.5 to 7.8 kN was applied. Price observed that AE can detect distress presented in the test balls before friction increases in the contact area. Furthermore, the damage increased while the friction was increasing. Another comparative study was conducted by Al-Ghamdi and Mba to identify bearing defects and to analyse defect size using acoustic emission and vibration analysis [18]. Four speeds were used in this experiment: 600, 1000, 2000, and 3000 rpm, with three load conditions; 0.1, 4.43, and 8.86 kN. The experiment was divided into two test programes, the first of which determined the AE activity source from the bearing's seeded defects. The second programe defined the size of the defect using the AE technique and vibration technology. It was concluded that AE r.m.s., maximum amplitude, and kurtosis are more sensitive to the initiation and defect growth than vibration techniques. Furthermore, a relationship was noted between defect length and AE burst duration. In order to confirm the findings of Al-Ghamdi and Mba, Al-Dossary et al. conducted an investigation to determine the relationship between the AE burst duration and the actual size of the defect in a roller bearing [19]. Furthermore, they investigated how the defect size affected specific AE parameters. Different bearings were tested in this experiment with seeded faults at 1500 and 3000 rpm under loads of 2.7, 5.3, and 8 kN. This step was taken in order to recognise the influence of defect size on the AE waveform at deferent loads and speed conditions. Besides, several parameters were used for the detection of bearing damage, including AE maximum amplitude and energy values. In the context of this investigation, a strong relationship was found between the actual sizes of the defect on the bearing's inner and outer race with AE burst duration. Furthermore, the energy parameter can be used to identify the severity of the defect in both the inner and outer race of the bearing. However, AE max amplitude could be used only to monitor defects on the bearing outer race, as the signal attenuates on the transmission path from the inner race to the AE sensor. Finally, this study agreed with Al-Ghamdi and Mba, proving AE techniques to be effective in monitoring the condition of the outer race.

Later, Elforjani and Mba conducted a study to validate the application of acoustic emission measurements in order to identify, monitor, and locate the initiation and spread of natural defects in a thrust rolling bearing [20]. In order to speed up the initiation of a natural crack, a combination of thrust ball bearing and a thrust roller bearing was used. An electric-geared motor with a speed of 72 rpm was used. To monitor the integrity of bearings, traditional parameters were used in this study, such as counts, amplitude, energy, and ASL. It was concluded that AE parameters such as energy are sufficiently strong and sensitive to detect the crack's initiation in low-speed bearings. Moreover, it was shown that the source of acoustic emission can successfully be located during the operation using the AE technique. This was the first known attempt to correlate AE with the generation of a natural defect and locate the defect in low-speed bearings.

Eftekharnejad et al. later investigated the application of AE and vibration techniques in monitoring naturally-degraded roller bearings [21]. This study was the first known attempt to determine the efficiency of using the Kurtogram and spectral kurtosis (SK) to increase signal noise ratio to assess the bearing fault features. An axial load of 50 kN was applied with a rotating speed of 1500 rpm. The findings of the study indicated that, by identifying the incipient damage, AE was more sensitive than the vibration method. Furthermore, Kurtogram and SK were shown to be effective methods for improving bearing fault features. Furthermore, various experiments using grease-lubricated thrust bearings have been conducted by Nohal et al. In these experiments, dents were created artificially in order to initiate rolling contact fatigue [22]. To monitor the conditions of the bearings, three parameters were taken into consideration: temperature, AE parameter (r.m.s., count, and event), and level of vibration. A comparative study was conducted for the acoustic emission signal on dented and non-dented bearings. In Nohal's study, the potential of acoustic emission is presented for identifying the damage on the incipient surface. In addition, the ability of acoustic emission was compared with common vibration analysis. The results of this study indicated that the acoustic emission approach was the better methodology for motioring the bearing conditions. Further comparison between acoustic emission and vibration signal in detecting defects on the bearing's outer race was conducted by Feng et al. Both techniques, AE and vibration, were processed by wavelet transform, Hilbert envelope transform, and FFT transform [23]. A radial load was used in this experiment, but Feng did not clearly mention the characteristics of the tools used, nor did they detail speed and load conditions. Based on the analysis, it was concluded that acoustic emission was superior to vibration in the diagnosis of bearing faults.

Niknam et al. undertook another experimental study, using the acoustic emission technique to differentiate between dry and lubricated rolling bearings [24]. Eight speed levels from 1800 to 6000 rpm were applied in this work with four radial loads (between 2268 to 9073 N). Various AE time domain parameters were used: skewness, kurtosis, max. and min. amplitude of the AE, variance, mean value, and standard deviation. It was found that AE parameters showed a difference between dry and lubricated bearings, so these techniques could be used to distinguish between dry and lubricated bearing. Nevertheless these parameters were non-sensitive at all conditions. Thus, they advised using both time and frequency domain parameters to get better results.

Towsyfyan et al. published a paper in which they presented AE measurements for evaluating the features of self-aligning journal bearings [25]. The characteristics were measured at various rotational speeds (362–1450 rpm), lubrication conditions, and loads (0, 1, and 2 kN). In this study, two signal processing methods were discussed: time domain and frequency domain analysis. Based on the outcomes obtained, the features of AE are dependent on the lubricant used, rotational speed, and radial load. The results indicated that, for high-speed and high-load conditions, the level of AE energy increases because of the high elastic energy emitted from the asperity contact. Bearings work better with more viscous lubricant (as chances of asperity contact are eliminated with higher viscosity, resulting in small amplitude AE responses), therefore lubricant degradation in journal bearings can be identified using AE. This agreed with the outcomes of the Niknam et al. experiment [24].

Parizi et al. created a comparison by subjecting one good bearing and one naturally-damaged bearing to acoustic emission tests in normal operation conditions at a rotational speed of 60 rpm [26]. From this study, it was realised that the counting method is influenced by the experience of the user. In addition, other statistical tools, including crest factor, kurtosis, and energy factor, were used. This study provided evidence that statistical parameters are more effective in detecting defects in a low-speed bearing if the data are transformed by removing low-frequency noise using a wavelet packet.

In 2014, an experiment was conducted by Ruiz-Cárcel et al. to detect bearing fault features from an acoustic emission signal while emphasising the application of spectral kurtosis (SK) as a de-noising tool [27]. This study implanted defects of various sizes on a roller bearing to study the noise generated from it. With the implementation of spectral kurtosis, background noise was reduced, and the burst visibility of the AE signal obtained from the defective roller bearings improved. This substantiates the recent findings of Eftekharnejad et al. [21], who suggested that SK is helpful in the detection of the degradation of bearings using acoustic emission in the early stages. This study applied the same tools used by Eftekharnejad et al. [21]. Nonetheless, Ruiz-Cárcel et al., applied only one load condition to the bearing; 5.3 kN with a rotating speed of 1500 rpm. An electric engraver with a carbide tip was used to seed nine different defect sizes on the outer race of the bearing. It was found that acoustic emission bursts, without the use of SK, were less visible, but with the use of SK, a higher percentage of improvement in the detection of smaller defects was observed. In addition to this, the signal-to-noise ratio was also proportional to the size of the defects in the bearings. However, little improvement was observed in the signal-to-noise ratio for AE using SK, which was when the bearing was in the advanced stages of damage. Thus, according to the findings of Ruiz-Cárcel et al., it can be said that an improvement can be observed with the application of SK in acoustic emission signals in the detection rate of a bearing fault at the early stages of degradation. This will also help in reducing the detection time of bearing faults.

## III. CONCLUSION

A great amount of research has been carried out in recent decades in the context of the application of condition monitoring technologies for monitoring the integrity of rotating bearings. However, more research should be undertaken in this area in order to improve the monitoring condition of bearings. Changing the work path into using acoustic emission techniques to monitor rotating machinery becomes necessary to improve the monitoring accuracy and earlier detection of defects.

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