Development of Acoustic Emission Technology for Condition Monitoring and Diagnosis of Rotating Machines: Bearings, Pumps, Gearboxes, Engines, and Rotating Structures

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ABSTRACT—One of the earliest documented applications of acoustic emission technology (AET) to rotating machinery monitoring was in the late 1960s. Since then, there has been an explosion in research- and application-based studies covering bearings, pumps, gearboxes, engines, and rotating structures. In this paper we present a comprehensive and critical review to date on the application of AET to condition monitoring and diagnostics of rotating machinery.

KEYWORDS: acoustic emission, condition monitoring, machine diagnosis, rotating machines

1. Introduction

Acoustic emissions (AEs) are defined as transient elastic waves generated from a rapid release of strain energy caused by a deformation or damage within or on the surface of a material (Pao et al., 1979; Mathews, 1983; Pollock, 1989). In the application to rotating machinery monitoring, AEs are defined as transient elastic waves generated by the interaction of two media in relative motion. Sources of AE in rotating machinery include impacting, cyclic fatigue, friction, turbulence, material loss, cavitation, leakage, etc. For instance, the interaction of surface asperities and impingement of the bearing rollers over a defect on an outer race will result in the generation of acoustic emission. These emissions propagate on the surface of the material as Rayleigh waves and the displacement of these waves is measured with an AE sensor. Rayleigh waves are a combination of longitudinal and transverse waves (Viktorov, 1967). It should be noted that surface defects such as cracks and scratches attenuate Rayleigh waves; in addition, the surface finish of metals can also influence attenuation (Viktorov, 1967).

Judicious application of well-tried and tested acoustic emission technology (AET) can provide powerful diagnostic capabilities, which are safe, efficient and cost-effective. In this paper we review the research and development activities that are being pursued in the following subject areas: bearings (roller and hydrodynamic), gearboxes, pumps, machinery, and mechanical seals.

AE was originally developed for non-destructive testing of static structures; however, over the last 35 years its application has been extended to health monitoring of rotating machines, including bearings, gearboxes, pumps, etc. It offers the advantage of earlier defect/failure detection in comparison to vibration analysis due to the increased sensitivity offered by AE. However, limitations in the successful application of the AE technique for monitoring the performance of a wide range of rotating machinery have been partly due to the difficulty in processing, interpreting, and classifying the intelligent information from the acquired data. The main drawback with the application of the AE technique is the attenuation of the signal, and as such the AE sensor has to be close to its source. However, it is often practical to place the AE sensor on the non-rotating member of the machine, such as the bearing or gear casing. Therefore, the AE signal originating from the defective component will suffer severe attenuation, and reflections, before reaching the sensor.

AE covers a wide frequency range (100 kHz to 1MHz), and time domain waveforms associated with AE are of two types: burst and continuous. A continuous-type AE refers to a waveform where transient bursts are not discernible (Miller and McIntire, 1987). Both waveform types are associated with rotating machinery; for instance, a continuous-type emission may be a result of turbulent fluid flow within a peep while a burst type could be associated with the transient rolling action of meshing bears. On rotating machinery, typical background operational noise is of a continuous type. Traditionally, the most commonly measured AE parameters for diagnosis are amplitude, rms, energy, kurtosis, crest factor, counts and events (Mathews, 1983). Observations of the frequency spectrum, whilst informative for traditional non-destructive evaluation, have only found limited success in machinery monitoring. This is primarily due to the broad frequencies associated with the sources of generation of AE in rotating machinery. For example, the transient impulse associated with the breakage of contacting surface asperities

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experiencing relative motion will excite a broad frequency range.

2. Acoustic Emission and Bearing Defect Diagnosis

From the moment bearings leave the factory, they encounter many harsh environmental hazards, which in turn induce a number of failure modes. It is well known how these failure modes reduce the life expectancy of the bearings. Some of the events responsible for the bearing failures include incorrect applications, poor maintenance, poor lubrication, overload, over-speed, misalignment, imbalance, harsh environmental conditions (temperature/humidity/dust/dirt/altitude), etc. Bearing failure modes include friction/wear processes producing flaking, brinelling, fluting, spalling, pitting, seizure, etc. All these modes are known sources of AE. However, the most widely employed technique for condition monitoring and diagnostics of bearings is vibration monitoring. This method has been successful where the energy from other components (shaft, gears, etc.) does not overwhelm the lower energy content from the defect bearing. In addition, by the time a significant change in vibration has been observed, the remaining operational or useful life of the bearing is very short. This is where AET offers a significant advantage. The formation of subsurface cracks due to the Hertzian contact stress induced by the rolling action of the bearing elements in contact with the inner and outer races and the rubbing between damaged mating surfaces within the bearing will generate acoustic emission activity. Other reasons for the generation of AE include the breakdown of the oil film, foreign matter in the lubricating medium, and excessive temperatures. It must be noted that the propagation of the AE is affected by material microstructure, non-homogeneities, geometrical arrangement of free surfaces, loading conditions, and the number of component interfaces. Almost all research on the application of AE to bearing defect analysis has been undertaken on experimental test-rigs specifically designed to reduce AE background noise.

Catlin (1983) reported that AE activity from bearing defects was attributed to four main factors including numerous transient and random AE signals associated with bearing defects. Furthermore, it was stated that the signals detected in the AE frequency range represented bearing defects rather than other defects such as imbalance, misalignment, looseness, shaft bending as well as the other major structural component resonances. In addition, Catlin noted that high-frequency AE signatures attenuate rapidly; therefore, if the transducer was placed close to the bearing, it was possible to detect the high-frequency content induced mainly by the bearing fault since signatures originating from other machine components are highly attenuated upon reaching the sensor. Balerston (1969) published the first document that applied AET to the identification of artificially seeded defects in rolling element bearings. Interestingly, this is probably one of the earliest applications of AE to monitoring bearings. Defects simulated included outer and inner race defects, ball defects, and lack of lubrication. Balerston compared vibrations in the audible range, resonant range and AE, commenting on the advantages that monitoring of the resonant frequency range offered over the audible vibration range. The resonant technique involved measurement of bearing component natural frequencies initiated by shock excitation associated with minor structural irregularities. These resonant frequencies are a function of the mass configuration and type of material involved. The frequencies and amplitudes at resonance are much higher than bearing element rotations, so they are ideal under conditions of high background noise. Moreover, the resonant frequencies are independent of rotational speed; however, their amplitudes will vary directly with rotational speed, as will the impact energy. Resonant frequencies can be as high as 300 kHz for ball rollers, and up to 140 kHz for the inner race, depending on the mode of vibration (Rogers, 1979). Balerston suggested that the "free" resonant frequencies of the individual components were not changed significantly after assembly, although the assembly created a damping effect. Furthermore, it was suggested that because of the interaction between the components of a bearing, a defect in any component would cause resonant frequency ringing in all components, making interpretation difficult. Moreover, at low rotational speeds the impact energy generated will be very low, and this might explain why there have been limited applications of this technique to low-speed bearings. The principle of the shock pulse meter (SPM) is similar to the resonant technique as both respond to minute transient pressure waves generated from fault impacts in regions of contact; however, the SPM resonates itself.

Balerston noted that two types of AE signatures were observed during experimental testing: burst-type emissions, associated with the seeded defects on the inner, outer race and ball element, and continuous-type AE signatures, noted when the bearing was run dry (starved of lubrication). In one particular bearing defect simulations (dry run) AE counts were noted to increase prior to bearing failure. In summary, Balerston stated that the resonant frequency technique was very successful and it offered a direct correlation between defect severity and increase in amplitude level of the resonant frequencies, although it was concluded that the AE technique would become important with the development of sensors. This was the earliest assessment on the application of AE to bearing monitoring.

About 10 years after Balerston, Rogers (1979) utilized the AE technique for monitoring slow rotating antifriction slew bearings on cranes employed for gas production, and obtained some encouraging results compared to vibration monitoring techniques. Rubbing of the crack faces, grinding of the metal fragments in the bearing, and impacts between the rolling elements and the damaged parts in the loaded zone were identified as sources of detectable AE signatures. Roger stated that "because of the slow rotational speed of the crane, application of conventional vibration analysis (0–20 kHz) was of limited value for on-line condition monitoring." AE resonant transducers between 100 and 300 kHz were found to be informative for on-line monitoring of bearings using kurtosis at different frequency bands.

Yoshioka and Fujiwara (?, 1984) have shown that AE parameters identified bearing defects before they appeared in the vibration acceleration range. In addition, sources of AE generation were identified during fatigue life tests on thrust loaded ball bearings. Hawman and Galinaitis (1988) reinforced Yoshioka's observation that AE provided earlier detection of bearing faults than vibration analysis and noted that diagnosis of defect bearings was accomplished due to modulation of high-frequency AE bursts at the outer race defect frequency. Hawman and Galinaitis placed the AE receiving sensor directly onto the bearing outer race. The modulation of AE signatures at bearing defect frequencies has also been observed by other researchers (Holroyd and Randall, 1993a; Holroyd, 2001). In addition, Bagnoli et al. (1988) investigated the demodulation of AE signatures at the defect rotational frequency (outer race) of a bearing. It was noted that when the defect was absent, the periodicity of the passage of the balls beneath the load could be readily identified by observing the frequency spectrum of demodulated AE signatures; however, it was reported that the AE intensity was less without the defect present. There was no mention of trigger levels employed, load applied on the test bearing, method of attaching the transducers to the rig, or any information on background noise.

Tandon and Nakra (1990) investigated AE counts and peak amplitudes for an outer race defect using a resonant-type transducer. It was concluded that AE counts increased with increasing load and rotational speed. However, it was observed that AE counts could only be used for defect detection when the defect was less than 250 μm in diameter, although AE peak amplitude provided an indication of defects irrespective of the defect size. Loads applied ranged from 8% to 50% of the bearing static load rating. Choudhary and Tandon (2000) employed AE for bearing defect identification on various sized bearings and rotational speeds ranging from 500 to 1500 rpm. It was observed that AE counts were low for undamaged bearings. In addition, it was observed that AE counts increased with increasing speed for damaged and undamaged bearings whilst an increase in load did not result in any significant changes in AE counts for both damaged and undamaged bearings.

Tan (1990) used a variation of the standard AE count parameter for diagnosis of different sized ball bearings. In addition to the difficulty of selecting the most appropriate threshold level for standard AE counts, Tan cited a couple of other drawbacks with the conventional AE count technique. This included dependence of the count value on the signal frequency. Secondly, it was commented that the count rate was indirectly dependent upon the amplitude of the AE pulses. Tan's variation to the standard AE counts technique involved computing the accumulated area under the amplitude–time curve of the AE waveform over a specified time period. This was accomplished by setting four trigger levels with amplitude multiples of 1, 2, 4, and 8, and calculating the area under the amplitude–time AE waveform. The final count assigned was weighted by the multiple of the amplitude ratio between these levels. It was concluded that the "new" count rates increased exponentially with increasing defect sizes and increasing rotational speed. The dependence of AE counts on threshold levels was also noted by Huguet et al. (2002) during investigations on the use of AE for identifying damage modes in specific materials; in this instance, a trigger level of 10% of the maximum amplitude was employed.

Yoshioka et al. (1999) undertook an investigation of vibration and AE on naturally fatigued deep groove ball bearings (bore diameter 20 mm). By removing the groove on the inner race, Yoshioka claimed the stresses in the area of contact were increased and this accelerated fatigue failure. Vibration rms levels were recorded continuously through the fatigue tests which lasted approximately 130 h. The presence of spalls on the inner race resulted in a rapid increase in vibration rms levels. However, AE (counts per minute) showed a steadily increasing value at least 5 h before the observed rapid increase in vibration. A total of 16 fatigue tests were undertaken and the authors commented that they could predict the appearance of a spall by observing the AE response.

Whilst AE counts may highlight changes in machine state, they will not be able to identify the origins of defect, e.g. outer race. The successful use of AE counts for bearing diagnosis is dependent on the particular investigation, and the method of determining the trigger level is at the discretion of the investigator. Moreover, it has been shown that AE counts are sensitive to the level and grade of lubricant within the bearing, adding to the complexity of this measure. Morhain and Mba (2003) undertook an investigation to ascertain the most appropriate threshold level for AE count diagnosis in rolling element bearings. The results showed that values of AE maximum amplitude did correlate with increasing speed but not with load and defect size. In addition, it has been shown that the relationship between bearing mechanical integrity and AE counts is independent of the chosen threshold level, although a threshold of at least 30% of the maximum amplitude for the lowest speed and load operating condition was advised. Furthermore, Morhain and Mba commented that unlike the results reported by Tandon and Nakra (1990) it was observed that AE counts could be used for defect size detection for lengths of up to 15 mm and widths of 1 mm. In addition, Morhain validated the observations of Choudhary and Tandon (2000).

Kakishima et al. (2000) undertook a comparative experimental study on the assessment of AE and vibration for monitoring/detecting seeded defect simulations on the inner race of a roller and ball bearing. Defects were seeded with an electron discharge machine (EDM). Analysis of the AE was based on the spectrum of the enveloped AE signals. It was concluded that the threshold at which the AE technique was able to identify the defect was similar to that for vibration monitoring. Furthermore, for both AE and vibration, it was noted that an increase in defect size resulted in an increase of both AE and vibration levels on the envelope spectrum. Kaewkongka and Au (2001) applied the AE technique on a rotor dynamic system onto which multiple defects were seeded, including a seeded defect on one of the bearings. It was shown the AE technique offered high sensitivity, thereby allowing for discrimination of the multiple defect conditions. Success was based on minimum distance classifier. Schoess (2000) presented the results of an assessment of six different but relevant technologies for onboard monitoring of a railcar bearing. It was concluded that the AE technique offered the highest potential payoff. Schoess successfully evaluated the AE technique on an artificially damaged bearing on a railcar, concluding that the AE technique offered the potential for condition-based maintenance in the railroad industry. Price et al. (2001) assessed the vibration and AE techniques for monitoring rolling element bearing failures. Their experimental study focused on a four-ball machine from which AE activity, vibration, temperature, friction, etc., were monitored as a function of time. It was noted that AE could detect distress within the test balls before the friction in the contact area increased noticeably. It was stated that increasing damaging results in increasing friction at the contact area.

Shiroishi et al. (1997) compared vibration and AE on seeded defective bearings operating at 1200 rpm. Interestingly, Shiroishi et al. defined the industry bearing failure criteria as being reached when a defect size reached 6.45 mm^2; this value was cited from Hoeprich (1992). Defects of varying sizes were seeded on the outer and inner races. Shiroishi et al. noted that the vibration offered better detection than the AE technique, and that the AE sensor was insensitive to inner race defects. In addition, on the parameters extracted from vibration and AE measurements, Shiroishi et al. (1997) noted that the peak ratio was the most reliable indicator of the presence of a localized defect with the rms, kurtosis and crest factor showing decreasing reliability. The most significant observation from the investigation of Shiroishi et al. was the correlation between acceleration peak value and defect width. This correlation was first noted by Balerston (1969) employing a monitoring system based on observations of bearing resonant frequencies. The most recent correlation between defect size and measuring parameter (AE) was noted by Al-Ghamdi et al. (2004) and Al-Ghamdi and Mba (2005). A direct correlation between defect length (circumferential, along direction of rolling) and AE burst duration was observed under varying simulated defect cases. In addition, a correlation between the amplitude of the burst-type AE signature (associated with the bearing defect) to the underlying continuous-type emission was noted to increase with increasing defect width (perpendicular to rolling direction).

Li et al. (1998) undertook bearing fatigue failure tests at 1600 rpm and 167% of the rated radial load. To accelerate failure, an initial defect was seeded with an electric discharge machine. Li et al. commented that vibration and AE rms increased with increasing defect severity. An adaptive scheme was proposed to predict conditions of defective bearings based on vibration and AE techniques. Bansal et al. (1990) applied AE as a quality control tool on reconditioned bearings. Bearings were tested at 3% of the load rating. It was noted that as the load increased there was little increase in the peak-to-peak amplitude level for standard (operational) and reconditioned bearings; however, the peak values of the reconditioned bearing were in some instances five times that of a new bearing.

Li and Li (1985) presented a pattern recognition technique for early detection of bearing faults using AE. Faults were seeded on an outer race, a roller and multiple outer race defects. It was noted that the occurrence of AE events at a rate equivalent to a bearing characteristic defect frequency was evidence of the presence of a localized defect. Li et al. presented such a case with the seeded outer race defect but no results on the roller defect were presented. This was rather disappointing as Li and Li are the only investigators to attempt to diagnose roller defects with AE.

Sundt (1979) detailed two cases where high-frequency AE was applied to bearing defect detection. For the first case study, high-frequency signals associated with a hairline crack in the outer race the defect frequency were detectable above 100 kHz. This defect condition was not observed with vibration analysis. It was stated that the defect was at an early stage of development and the bearing clearances had not deviated from the normal operating condition, explaining why vibration monitoring was unsuccessful in this particular study. The second case study showed the ability of AET to detect the presence of foreign matter (sand) in the bearings of a pump unit. Sundt commented on the use of AE to defect defective bearings utilizing race resonance for amplification, noting that this could enhance detection sensitivity. However, it was stated that the mechanical “Q” (dynamic magnification factor) of the race was an unpredictable function of the bearing type, housing constraint, etc. Furthermore, it was noted that race resonances could be excited by normal background noise. Also, similar readings could be obtained from a good bearing with a high “Q” and a bad bearing with a low “Q”. The difficulty with monitoring bearings at the element resonating range (20–100 kHz) was also discussed by Barclay and Bannach (1992). It was noted that wavelengths of vibration at these frequencies are often comparable with the dimensions of parts in the bearing or bearing housing which may create standing waves with nodes and antinodes. The consequence of this makes sensor position critical. Barclay and Bannach (1992) presented the spectral emitted energy (SEE) method, which combined the high-frequency AE detection within the 250–350 kHz range with the enveloping technique. The source of AE activity was attributed to the metal-to-metal contact as a result of lubricating film breakdown. It was concluded that the SEE method was a viable technique for detecting rolling element bearing defects and compliments the present-day low-frequency vibration.

Badi et al. (1990) investigated the condition of automotive gearbox bearings using stress waves (also known as AE). These sensors were used on a bearing test rig with simulated faults. All the artificially seeded faults were identified by employing the stress wave sensor method. The sensors were easy to install and needed simple signal processing to evaluate bearing faults. The only drawback was that the sensors were bulky. Sturm et al. (1992) employed AE to investigate damage processes (pitting and mixed friction) of sliding and rolling element bearings under laboratory and field conditions. Analysis revealed that the amplitude behavior observed from the envelope analysis of the AE signals yielded essential information about the damage processes. Javed and Littlefair (1993) presented some general aspects of the application of AE for detecting the early development of failures in rolling element bearings. Some results of the experimental investigation of the basic relationship between ball bearing failures and the resulting change in AE signal were presented. Neill et al. (1998a) described the relative sensitivities of accelerometer and AE sensors to a range of defects and assessed their merits in an industrial environment, where ambient noise and/or other faults were highly influential. It was revealed that the AE signals preserve the impulsive nature of defect-element interactions, yielding characteristic harmonics of the defect frequencies in the spectrum. These harmonics distinguished bearing defects from other periodic faults induced by imbalance or misalignment occurring at the same frequency. Also, Neill et al. concluded that the AE sensors were more sensitive to small defects.

Salvan et al. (2001) adopted a triangulation technique by employing two AE sensors with fuzzy neural networks on a high-speed post office mail sorting machinery, which contained a large number of bearings. The investigation was limited to the detection of a simpler source and the authors were unable to obtain a precise location, presumably due to incorrect parameters in the sound velocity equation and the use of an inefficient technique. Parikka et al. (2002) reported their findings on the operation of paper machines, which were equipped with a number of oil-lubricated rolling bearings. They assessed information on the effects of higher or significantly lower than intended bearing loads on its service life, as the lubricant conditions or movement changes with time. It was commented that the possibility of using AE for monitoring critical operating situations of rolling bearings was very promising. Based on this investigation, a window-based diagnostic system (prototype) was developed. Morhain and Mba (2002) investigated the application of standard AE characteristic parameters on a lightly radially loaded bearing. An experimental test rig was designed to allow seeded defects on the inner/outer races. The test rig also produced high background AE noise providing a realistic test for fault diagnostics. It was concluded that irrespective of the high levels of background noise and low radial load (between 2% and 70% of the bearing rating), standard AE parameters provided adequate early indication of bearing defects. Fan et al. (2005) presented data streaming technology for non-interrupted acquisition of AE waveforms. In addition, Fan et al. reiterated that modulation of the AE waveforms could identify the defective part (race, roller) within the bearing. Holroyd (2000) detailed laboratory studies on rolling element bearings in which AE signals were processed in terms of their dynamic envelop (i.e. rectification and low pass filtering). Tests showed that the periodicity of the enveloped signal corresponded to a bearing defect frequency. A proprietary method of characterizing the AE time waveform was proposed. Several successful applications of the proprietary method were also presented.

Finley (1980) developed an incipient failure detection (IFD) system based on high-frequency AEs generated from shock pulses as a rolling element (ball) passes a defective race. A couple of industrial case studies were presented. Finley noted that AET has been proven to be more effective than conventional low-frequency sound and vibration measurements.

Jamaludin et al. (2002) presented research findings on the lubrication monitoring of low-speed rolling element bearings (1 rpm). A test rig was designed to simulate the real bearing used in real-life situations. Using a newly developed method called the pulse injection technique (PIT), the variation of lubricant amount in the low-speed bearing was successfully monitored. This technique was based on transmitting a Dirac pulse to the test bearing in operation via an AE sensor. The AE data were processed using a clustering technique based on the autoregressive (AR) coefficient to differentiate between properly and poorly lubricated bearings. The AE technique has also been employed by Miettinen and Salmenperä (2002), Miettinen and Andersson (2000), and Holroyd (2000) to monitor the lubricant condition in rolling element and plain bearings.

Whilst monitoring bearing degradation by AE and vibration analysis is relatively established at speeds above 600 rpm, at low-rotation speeds there are numerous difficulties with vibration monitoring that have been detailed (Berry, 1992; Murphy, 1992; Canada and Robinson, 1995; Robinson et al., 1996). The difficulty of monitoring at low rotational speeds was summarized by Kuboyama (1987).

Unlike vibration monitoring there has been considerable success in the development and application of AE to monitoring slow-speed bearings. McFadden and Smith (1983) explored the use of AE transducers for the monitoring of rolling element bearings at speeds varying from 10 to 1850 rpm. The sensors were placed on the bearing housing. A fault, simulated by a fine scratch on the inner raceway, formed the basis of this experiment. It was commented that the AE transducer, with a frequency response beyond 300 kHz, failed to perform as expected at the higher end of the rotational speed range (850 rpm) and was inferior to the conventional high-frequency accelerometer. However, at low rotational speeds (10 rpm) the AE transducer appeared to respond to minute strains (local distortions) of the bearing housing caused by the concentrated loading of each ball in the bearing. These minute strains appeared as spurious spikes superimposed on the ball pass frequency. It was concluded that at low speeds with steady loads, the base bending/strain of the bearing housing could enable the AE transducer to detect signatures from very small defects in rolling element bearings, while at higher speeds base bending appears as low-frequency noise.

Smith (1982) was involved in the experiment mentioned above and, in a separate paper, reiterated the findings of McFadden and Smith (1983), although puzzled at the behavior of the AE sensor used, stating “the form of response of the AE sensor was puzzling since the transducer was responding to once-per-ball distorting in the casing at frequencies as low as 1 Hz. AE transducers are not supposed to respond to frequencies as low as these.”

Tavakoli (1991) investigated the application of AE to needle bearings. Interestingly, the rotational speed for this investigation was 80 rpm, which some might classify as a low-speed application. Three simulations were undertaken: defect-free fully lubricated, defect-free unlubricated, and a condition in which two adjacent needle elements (rollers) were missing. The frequency domain characteristics of the AE rms voltage were examined in relation to the simulated conditions. It was shown that the mean spectral density function of the rms voltage distinguished all three simulations. It was also noted that the source of AE in bearings was attributed to friction and impacting.

Holroyd (1993) described in this application note the results of AE measurements on four heavily loaded roller bearings rotating at 60 rpm. The operation of these bearings in the slowly rotating machine was critical indeed. This case study clearly demonstrated the ability of this innovative and profitable technology to prevent secondary damage and to minimize production loss due to machine failures. Miettinen and Pataniitty (1999) described the use of the AE method in monitoring of faults in an extremely slowly rotating rolling bearing, whose rotational speed varied from 0.5 to 5 rpm. This investigation revealed that the AE measurement was very sensitive and the fault was easily identified under laboratory conditions. Jamaludin et al. (2001) reported the results of an investigation into the applicability of AE for detecting early stages of bearing damage at a rotational speed of 1.12 rpm. A bearing test rig was used with seeded localized surface defects induced by spark erosion on the inner/outer races and on a roller element (which resembled pitting). The paper concluded that AE parameters such as amplitude and energy provided valuable information on the condition of a particular low-speed rotating bearing.

Sato (1990) investigated the use of AE to monitor low-speed bearing damage by simulating metal wipe in journal bearings at 5.5 rpm. It was observed that acoustic bursts were generated as a result of slight metallic contact and the amplitude of the waveform became larger with increasing metal wear. Sturm and Uhlemann (1985) also investigated the application of AE to plain bearings, noting the instantaneous response of AE to the changes in the frictional state of hydrodynamic fluid film.

Williams et al. (2001) noted that the majority of bearing diagnosis experiments were undertaken with seeded defects and, as such, undertook bearing experiments without seeded defects; in essence, fatigue tests. The test bearings, roller, and ball were run at 6000 rpm at 67% of the dynamic rated load, although some tests were undertaken at varying speed conditions. Vibration and AE techniques were compared, and in one particular instance Williams et al. stated that the AE sensor showed an increase 10 min after an increase in vibration. It was also noted that the AE sensor was unresponsive to outer race failures. This is rather surprising considering the number of publications confirming the ability of the AE technique to diagnose outer race defects.

The development of AE in bearing monitoring and fault diagnosis is the most established application of AE in rotating machinery and this is reflected in the number of commercially available systems on the market today. Needless to say, more detailed investigations are still required and there are opportunities for applying AET for prognosis.

3. Application of Acoustic Emission to Monitoring Gearboxes

Whilst vibration analysis on gear fault diagnosis is well established, the application of AE to this field is still in its infancy. In addition, there are limited publications on the application of AE to gear fault diagnosis. Irrespective of the numerous publications on the application of vibration analysis to monitoring gearboxes, it still meets with great challenges that monitoring and diagnosis of gearboxes present. AET offers a complementary tool in this instance.

Miyachika et al. (1995) presented a study on AE in a bending fatigue test of spur gear teeth. Three different gears with common module, pressure angle, and number of teeth were used. Two of the gears were case hardened to different case depths. These gears were made from SC415 steel with a face width of 10 mm whilst the second gear (face width of 8 mm) was made from S45C steel without any case hardening. An AE sensor was fixed on the gear with a clamp arrangement. AE measurements, such as frequency spectra, cumulative event count, event count rate, and peak amplitude, were recorded during the fatigue process under different tooth load conditions. In addition, crack length measurements were made. However, the type and characteristics of the sensor, the sampling rate employed, and the loading frequency were not presented in this paper. During the fatigue test, it was observed that there was a marked increase in AE cumulative event count and event count rate just before crack initiation for both case hardened gears. For the normalized gear, such an observation was not noted. It was also found that as the tooth load decreased, the number of cycles until the marked cumulative event count occurred increased. Miyachika et al. drew the conclusion that the prediction of crack initiation using the AE technique was possible for case hardened gear but difficult in the case of the normalized gear.

Miyachika et al. (2002) extended their investigations to supercarburized gear material. The investigation was performed under the same test set and procedures as detailed above, with additional analysis techniques: AE cumulative energy count and wavelet transforms of AE signals. From the results, Miyachika et al. concluded the prediction of crack initiation by means of the AE method was possible for the various carburized gears tested.

Wheitner et al. (1993) performed a series of gear tooth bending fatigue tests to verify the effectiveness of AE and system stiffness measurements for monitoring the crack initiation and propagation. The tests and instrumentation employed were to standards detailed in the Society of Automotive Engineers (SAE) gear geometry, testing procedure and fatigue test fixture. The AE senor had a resonant frequency of 300 kHz and was attached to the gear at the root of the tooth with superglue. The tooth stiffness measurements were made through an accelerometer mounted to the base of the fixture. The test gears were of various materials, surface finishes, and surface treatments. All the testing was performed by applying sinusoidal load of 10 Hz and load ratio of 0.1. A run-out life of 10^6 cycles was employed for all the test cases. Wheitner et al. noticed non-zero AE counts before the initiation point of the gear tooth root fatigue crack, which was attributed to the background noise of the test machine. In general, AE activity increased with crack propagation and very rapidly at the failure point. All the test gears exhibited similar trends in stiffness measurements. At high load and low fatigue lives, crack propagation life contributed a significant proportion of the gear total life as compared to crack initiation life. Wheitner et al. went further to conclude that both the AE and system stiffness measurements were effective in monitoring the cracking processes of the gear tooth. However, in most cases, AE activity was detected before the first change in stiffness compliance was registered.

Singh et al. (1999) explored an alternative AE technique to the more widely used vibration and debris monitoring methods for detection of gear tooth crack growth. They employed a single tooth bending machine with the load on the tooth varied sinusoidally at 40 Hz frequency. An AE sensor and accelerometer were mounted on a spur gear near to the loading tooth. The test terminated when the loaded tooth broke off. Raw AE waveforms and fatigue cycles were recorded during the test. There was no information given on the type of gear, sensors, the applied load, and the sampling rate used. The test revealed that AE detected the first sign of failure when the gear reached 90% of its final life. As the crack progressed, AE amplitude increased. During the final stage of gear tooth fracture, a significantly high amplitude AE burst was detected. On the other hand, the vibration level did not change significantly in the initial stage of crack initiation and propagation until the final stage of failure. Hence, Singh et al. concluded that AE method offered an advantage over vibration monitoring techniques.

In order to study the practical aspects of sensor placement in a real-life gearbox situation, Singh et al. (1999) performed an assessment of the transmissibility of an AE signal within a gearbox. The tests were performed with different torque levels using lead pencil breaks to simulate AE activity in the gearbox. This technique is known as the Nielsen source test. First, various individual interfaces with varying torques were studied and quantified. Following this, Singh et al. evaluated the total loss of strength of the AE signal across multiple interfaces and compared with the sum of losses obtained from individual interfaces. Several AE transmission paths were examined. From the results obtained, Singh et al. concluded that the attenuation across the gearbox was an accumulation of losses across each individual interface within the transmission path, and that the optimum path of propagation will be that with the smallest cumulative loss.

The investigations detailed earlier (Wheitner et al., 1993; Miyachika et al., 1995, 2002; Singh et al., 1999) have indicated that the AE technique was able to detect bending fatigue failure. In addition, the AE technique was capable of detecting the fault condition in advance of the vibration monitoring technique. This conclusion is encouraging and motivating for the AE technique to be the new condition monitoring tool. However, to ensure that this technique is robust, the defect detection capability on the other modes of gear failure (surface damage and fatigue) has to be explored.

Siores and Negro (1997) explored several AE analysis techniques to correlate possible failure modes of a gearbox during its useful life. The gearbox employed for the failure interrogation includes two gear sets (input and output), a DC shunt motor, and a variable speed controller to alter the motor speed for the tests. The AE sensor employed was mounted on the gearbox casing and has a resonant frequency of 175 kHz. Prior to the start of the test, the gearbox was allowed to wear-in at 1200 rpm for four 1 h intervals at full load condition. Common gear failures, such as excessive backlash, shaft misalignment, tooth breakage, scuffing, and worn teeth, were seeded on the test gears. All the seeded defect conditions were tested at 300 and 600 rpm whilst AE parameters such as rms, standard deviation, and duration of AE were measured. Siores and Negro concluded that the monitored AE parameters exhibit identifying qualities for the respective failure modes.

Singh et al. (1996) performed two experiments to study the feasibility of applying AE to detect gear pitting. Both simulated and natural pits were used to evaluate this detection technique. The first experiment employed a UH1H generator drive offset quill, which consisted of the driver, driven, and idler gears. In this experiment, the idler gear contains the simulated pit of width and depth of 1.25 mm. This pit was simulated by removing a thin strip of material from the pitch-line on one of the teeth of the idler gear by the EDM process. A resonant type AE sensor with a resonant frequency of 280 kHz and an accelerometer were mounted on the gearbox housing near the output shaft bearing. A tachometer was used as a trigger to ensure each cycle of the measurements started with the same idler tooth in contact. The test gearbox was first run with no pit on the idler gear and then replaced by the idler gear with simulated pits. AE and vibration data were recorded during the run. This procedure was repeated for several combinations of load and speed. From the test results, Singh et al. concluded that both detection techniques were able to pick up the simulated defect but the AE technique exhibited much greater signal-to-noise ratio. He also suggested that both detection techniques were unable to detect the simulated pit at extremely high speeds or unloaded conditions as the noise level increases whilst the amplitude of the defect signal arising from contact of the pitted region decreases.

Singh et al. (1996) performed the second experiment using a back-to-back gearbox to study the detectability of natural pits. Similar acquisition systems to the first experiment were employed with both the AE sensor and accelerometer mounted on the housing of the test gearbox. The input speed to the gearbox was 1775 rpm with an unknown torque loading. During the early stage of the test, there were no defects on the mating gear teeth surfaces and the signals (both AE and vibration) showed no significant peaks above the operational noise level. After 30 min of operation, pits started to develop on the pinion teeth and periodically occurring peaks were observed from the AE signals. A further 15 min run saw pitting on multiple teeth and the detected AE signals revealed more frequently occurred peaks above noise level. There was no visible peak noted for the accelerometer signal. During the test, the AE sensor was also placed at the slave gearbox housing and bearing location between the two gearboxes to assess the detectability of the natural pits from the mentioned locations. Singh et al. concluded that the AE sensor should be as close to the monitored part as possible in order to maximize the detection capability of pits using AE technique.

Raad et al. (2003) illustrated the application of the AE monitoring technique for gear fault detection by employing an industrial gear rig. No information on the gear test rig, applied torque, and speed was given in the paper. The experiment was performed above the rated load of the gears for two weeks until near breakage of two teeth. Various types of AE sensors (resonant and wide band) and accelerometers were mounted on the bearing. Measured signals were taken at regular intervals and visual inspection of gears was performed at the end of each day. The recorded AE and vibration data were analyzed using four different methodologies: visual comparison, Kurtosis, spectral density, and envelope analysis. The visual comparison revealed that AE bursts appeared with spalling. However, these AE bursts disappeared after the defect was established. There was no clear indication from vibration signatures. The Kurtosis values were correlated to spalling defects after 3000 cycles. However, this method was unable to localize the spalling defect to individual tooth. The first sign of spalling observed from the vibration technique was at 5000 cycles. Using the spectral density analysis method, the increase in energy before and after the spall detection was common to both AE and vibration signals. In the final analysis of the AE and vibration signals, the spectrum of the squared envelope was used. The vibration technique was able to pick up the defect by displaying peaks at twice the shaft frequency. However, these peaks were not visible in the AE spectrum until the logarithm of the squared envelope was employed. The observed peaks occurred at the same frequency for both AE and vibration techniques. Raad et al. concluded that this first evaluation of AE as condition monitoring tool was promising.

Sentoku (1998) presented an investigation on tooth surface failure with AE measurements. A power circulating type gear testing machine was employed. The testing machine consisted of a pair of test and power return spur gears with a forced lubrication system that supply oil directly to the engaged teeth surfaces from the side of the gear pairs. It is important to note that the oil temperature was maintained constantly at 40 ± 2^{o}C. This eliminated the effect of oil film thickness on AE activity. An ultracompact AE sensor of resonant frequency 350 kHz was mounted on the gear wheel using screws. The AE signature was transmitted from the sensor to the data acquisition card via a mercury slip ring. A strain gage was also adhered to the tooth root to correlate the extracted AE parameters with tooth root strain waves. During the tests, the roughness of the gear teeth surfaces and pitting size were measured at regular intervals.

The first test was performed under applied stress of 960 MPa and pinion speed of 992 rpm using hardened gears. From the results obtained, Sentoku observed no change in AE amplitude except that the unevenness of AE wave lines was smaller with an increasing number of cycles. At this stage of the test, no surface damage was noted. Subsequently, Sentoku performed the second test using heat-treated ground gears. During the early stage of the test, both AE amplitude and the pitting area ratio remained unchanged. However, when pitting on the three monitored gear teeth began, AE wave lines started to change. Subsequently, AE amplitudes increased with both the pitting area ratio and the numbers of cycle. Sentoku explained that the increase in AE amplitude was caused by friction due to increasing pitting. Similar observations were noted for AE energy. Hence, with the results obtained from the test, he drew conclusion that the AE technique could detect gear teeth pitting.

Badi et al. (1996) performed an investigation on the use of AE and vibration monitoring techniques for condition monitoring of a typical drive line. A test rig comprised of a drive and simple spur gearbox, loaded by a pneumatically operated brake disk, was employed to simulate the essential part of this drive line. The rotating components were connected by flexible couplings and supported by bearing blocks. The rig was instrumented with both accelerometers and AE sensors at several locations along the drive line. However, Badi et al. only reported the results from the sensor which gave the optimum location for fault detection. Seeded defects such as “blip” and “shaved” gear faults were introduced on the test gears to simulate scuffing and pitting defects on gear tooth. There was no further information on the testing procedures used in this experiment. Analysis techniques such as the crest factor and kurtosis were employed for both AE and vibration techniques. For the “blip” gear fault, both monitoring techniques were able to identify the defect through the analysis techniques employed. As for the “shaved” gear fault, only the AE technique was able to detect the defect. Badi et al. concluded that the analysis techniques used were ideally suited for identifying faults with an impulsive nature. However, for a more comprehensive methodology, other analysis techniques should be explored.

Tandon and Mata (1999) performed seeded defect tests on spur gears using an IAE gear lubricant testing machine to assess the fault detection capability of the AE technique and to make a comparison with the more widely used vibration technique. Both hardened and ground spur gears were employed for the tests. The test gears were lubricated by a jet of oil. The AE sensor and accelerometer employed had resonant frequencies of 375 and 39 kHz, respectively. Both the AE and vibration signals were measured closed to the bearings of the test gearbox. All the tests were carried out at a single speed (1000 rpm) and varying load conditions (0–10 kg). AE and vibration measurements were first taken for gears that have no seeded defect, which were treated as reference signals. Subsequently, a simulated pit of constant depth (500 μm) and variable diameter (from 250 to 2200 μm in incremental order) was introduced on a gear tooth pitch-line by spark erosion. From the tests, Tandon and Mata made these observations. (a) There was some increase in AE with increase in load. (b) The AE parameters increased as the defect size (diameter of pit) increased. (c) The AE (ring-down) counts showed slightly better results than the other AE parameters measured. (d) The AE technique detected the seeded defect at a smaller size (500 μm) compared to the vibration technique (1000 μm). (e) In general, the distribution of AE events, counts, and peak amplitude became broader due to the presence of a defect in the gear.

Finley (1980) presented an industrial case study on the application of an AE developed system (IFD) for gearbox monitoring. Al-Balushi and Samanta (2002) introduced energy-based features extracted from AE signatures for monitoring and diagnosing gear faults. This feature, called the energy index (EI), was defined as the square of the ratio of the rms value for a segment of the signal to the overall rms value of the entire signal. Various different forms of EI were derived and compared with existing statistical methods for early fault detection. Experiments were undertaken on a back-to-back spur gearbox. Three miniature ultrasound transducers were implanted onto the rolling element bearing adjacent to the gear wheel for collection of AE data. A triggering system was used to ensure all the acquired data have identical starting locations on the gear. The tests were performed using brand new gears and terminated at the 40th hour when the gear failed. AE signals were acquired for one revolution of the test gear at hourly intervals. However, information such as the characteristics of the sensors, the applied load, and the reason for the varying rotational speeds was undisclosed. Al-Balushi and Samanta illustrated that the proposed EI and the various derived forms were able to locate the broken and pitting teeth more effectively than the traditional kurtosis and crest factor methods. By employing the proposed analysis technique, the defective tooth was picked up in a helicopter gearbox.

In a separate report Al-Balushi and Samanta (2000) presented a procedure for fault diagnosis of gears through wavelet transforms and artificial neural networks (ANNs). The time domain AE signals of a rotating machine with normal and defective gears were processed through wavelet transform to decompose in terms of low-frequency and high-frequency components. The extracted features from the wavelet transform were used as inputs to an ANN-based diagnostic approach. The procedure was illustrated through the experimental AE signals of a gearbox.

Tan and Mba (2005a, 2005b) noted difficulties in identifying the location of a defective tooth during an experimental investigation. It was noted that the lubricant temperature had an influence on the levels of AE activity/strength during the gear mesh. This has far reaching consequences as it implies that whilst other researchers have stipulated the effect of load/speed on AE activity, the time of data acquisition, in effect the temperature of the lubricant, will influence the levels of AE obtained.

While exploring the applicability of the AE technique to gear health diagnosis, Toutountzakis and Mba (2003) made some interesting observations of AE activity due to misalignment and natural pitting. The test was performed on a back-to-back spur gearbox with the AE sensors placed on the pinion and bearing casing of the pinion shaft. The AE sensors used have a relative flat response in the region between 150 and 750 kHz. A silver contact air-cooled slip ring was employed to transmit the AE signal for further processing.

AE parameters such as rms and energy values were recorded during the tests. Prior to the test proper, AE measurements for defect-free gears were first recorded. As the rotational speed increased, measured AE parameters increased for both AE sensor locations. Furthermore, Toutountzakis and Mba observed that change in speed resulted in changing AE parameters. During one of the tests, Toutountzakis and Mba noted increasing AE rms (at pinion location) for 6 h before the gearbox was paused for inspection. The results of the inspection revealed signs of pitting and scuffing, which indicated a misalignment in the gearbox. The gearbox was reassembled and the test continued. An interesting observation was made: "a reduction in AE parameters was noted initially, but these values gradually increased to values which did not depart from the initial gradient of the increasing trend." Toutountzakis and Mba concluded that there is a potential application of the AE technique for gear health diagnostic.

Price et al. (2005) investigated the detection of severe sliding and pitting with AE. The experimental results presented were based on a "four-ball machine" test-rig. It was observed that scuffing and pitting were easily detectable by observing changes in AE energy, principally due to changes in contact friction. More interestingly, Price et al. noted changes in the frequency patterns of measured AE signals prior to pitting and stated that AE monitoring was capable of detecting wear events prior to either vibration monitoring or wear debris analysis. Building on this statement, very recently Tan et al. (2004, 2005a, 2005b, 2005c) have presented results of an experimental investigation in which natural pitting of spur gears was allowed to occur. Throughout the test period, AE, vibration and spectrometric oil samples were monitored continuously in order to correlate and compare these techniques to the natural life degradation of the gears. It was observed that the AE technique was more sensitive in detecting and monitoring pitting than either the vibration or spectrometric oil analysis (SOA) techniques. It is concluded that as AE exhibited a direct relationship with pitting progression, it offered the opportunity for prognosis. From the results presented it was clearly evident that the AE monitoring indicator could be linearly correlated to the gearbox pitting rates for all torque conditions, with detection of onset of pitting as early as 8% of the pitted gear working face area. This offered much earlier diagnosis than vibration analysis, where only after between 20% and 40% of pitted gear working face did this technique offer capability for defect identification. This near linear relationship between AE and pit progression offers great potential, and opportunities, for prognostics in rotating machinery.

Tan and Mba (2004a, 2004b, 2005a, 2005c) ascertained the AE source mechanism through a series of experimental programs. These experimental programs consisted of isothermal tests on undamaged gears to explore the effects of rotational speed and applied torque on AE levels. From the isothermal test results, it was observed that variation of the applied torque had a negligible effect on the AE rms levels, similar to the negligible effect of load on film thickness under elastohydrodynamic lubrication (EHL) of non-conforming mating surfaces. It was noted that the variation in rotation speed had a more pronounced effect on AE rms levels relative to the load. Tan and Mba concluded that the source of AE during gear mesh was asperity contact under rolling and sliding of the meshing gear teeth surfaces.

Although the development of AE in gear diagnosis is in its infancy, the papers reviewed have illustrated the potential and viability of AE becoming a useful diagnostic tool in condition monitoring of gears. However, more detailed investigations are required to ensure this technique is robust and applicable for operational gearboxes. This involves understanding the influences of operational variables on AE generation and investigating the effects of variable load conditions to monitoring with AE.

4. Pumps and Acoustic Emission Technology

Pumps play a significant role in industrial plants and need continuous monitoring to minimize loss of production. Every pump manufacturer supplies characteristic curves for their equipment illustrating pump performance under given conditions. These curves demonstrate the inter-relationship between discharge capacities, pump head, power, and operating efficiency. The ideal operating point for a pump is known as the best efficiency point (BEP). This is the point where pump capacity and head pressure combine to provide the maximum efficiency of the pump. If the pump operates too far to the left or right of the BEP, not only may its efficiency be compromised, but it can also be subjected to increased wear, reducing operational life. Also, the pump manufacturer will undertake net positive suction head (NPSH) tests on supplied pumps; the significance of the latter is to determine the 3% drop in head at which serious cavitations will occur. Cavitation occurs when the absolute static pressure at some point within the pump falls below the saturated vapor pressure of the liquid. It causes a loss of pump efficiency and degradation of the mechanical integrity of the pump. It is generally accepted that the critical pressure for inception of cavitation is not constant and varies with operation fluid physical properties, the surface roughness of the hydraulic equipment, etc. In addition, cavitation is known to begin long before the performance of the pump is affected (McNulty and Pearsall, 1962).

In this paper we review the application of AE for condition monitoring of pumps. Prior to detailing some recent attempts at applying AE to pump health diagnosis, the investigations of McNulty and Pearsall (1962) and McNulty and Deeprose (1978) are worth mentioning. They undertook high-frequency measurements (up to 160 kHz) taken at the suction and discharge sides of the pump and detected incipient cavitation. However, it was noted that the success was dependent on the operational background noise levels. These results relating NPSH to varying noise levels are of great interest, although undertaken at 40 kHz. This clearly relates the audible intensity and high-frequency energy to the varying cavitation stages experienced by a pump as the head drops to the 3% level. It was noted (McNulty and Pearsall, 1962) that during cavitation the high-frequency noise increased. In separate paper, McNulty (1981) showed that the minimum noise intensity levels of a pump were obtained at the BEP. Sources of noise were noted as turbulence, impeller and volute interactions and hydraulic interactions.

Derakhshan et al. (1989) investigated the cavitation bubble collapse as a source of AE and commented that the high amplitude pressure pulse associated with bubble collapse generated AE. When the AE sensor was placed on the actual specimen experiencing cavitation, Derakhshan et al. observed increasing AE rms levels with increased pressure of flow and cavitation. However, with the AE sensor mounted on the tank wall the reverse was observed: decreasing AE rms levels with increasing pressure and cavitation. This was attributed to a visible bubble cloud that increased with pressure. It was commented that this cloud attenuated the AE signature prior to reaching the transducer on the wall casing. In addition to the high amplitude pressure pulse associated with cavitation, pressure pulses associated with centrifugal pumps have been detailed (Guelich and Bolleter, 1992); these include wake flow from the impeller blade trailing edge, vortices generated by flow separation and recirculation. The influence of the latter on pump performance has been presented (Fraser, 1981).

Neill et al. (1996, 1997) assessed AET for detecting early cavitation. It was also noted that the collapse of cavitation bubbles was an impulsive event of the type that could generate AE. These transients cause very high local transient pressure that can damage the internal parts of pumps. It was observed that when the pump was under cavitation, the AE operational background levels dropped in comparison to non-cavitating conditions. To ensure a more direct transmission path between the fluid and the sensors, metal wave guides were put into the venture tube wall at different locations. It is worth stating that prior to, and during cavitation, vibration measurements showed no significant change. In conclusion, Neill et al. stated that loss in NPSH before the 3% drop-off criterion was detectable with AE and evidence of incipient cavitation was detectable in the higher frequency band (0.5–1 MHz). It is interesting to note that Neill et al. (1998b) also successfully applied AET to detect the recirculation in a centrifugal pump. Recirculation is defined as a flow reversal at either the inlet or the discharge tips of the impeller vanes. It occurs in axial, centrifugal shrouded and unshrouded pumps. It is important to detect this phenomenon at the earliest stage and distinguish it from other undesirable phenomena, such as cavitation.

Hutton (1969) investigated the feasibility of detecting AE in the presence of hydraulic noise. It was noted that artificially seeded AE bursts were detected above background operational noise for turbulent flow, with and without cavitations. Furthermore, Hutton noted that the presence of cavitations in the system increased the operational AE noise levels by a factor of 50. In addition, cavitation was found to generate a significant increase in noise level below 500 kHz. Hutton placed AE sensors on the pipe. Darling and Johnston (1991) found that AE from a high pressure hydraulic pump during cavitation was wide band noise, up to 1 MHz. Darling and Johnston noted that during cavitation there was little change in the vibration signature from normal operation, which was not the case with AE observations. It was also commented that the position of the AE sensor was insensitive to mounting position whilst the reverse was observed with the vibration senor.

Al-Maskari (1984) attempted to detect incipient cavitation with AE but concluded that whilst the inception of cavitation was not detectable with AE, fully developed cavitation was detectable. Another interesting observation by Al-Maskari was the variation in AE activity at flow rates below the BEP and it was suggested that investigations on applying AE to cavitation detection should be concentrated at the BEP. Al-Maskari placed the AE sensor on the pump casing. Sundt (1979) detailed a case study on the application of AE for detecting pump cavitation. It was shown that during cavitation AE levels increased whilst vibration levels dropped. Also, Finley (1980) presented an industrial case highlighting the successful application of AE to cavitation detection. Whilst promoting the use of audible acoustics (less than 20kHz) for monitoring pumps, Cudina (2003) cites some applications of AE for detecting broad-band noise associated with cavitation. Al-Sulti et al. (2005) noted that the use of the power spectrum density of AE acquired over a range of flow rates was not effective in detecting cavitation. However, it was noted that the use of higher-order spectral analysis (bicoherence) showed improved sensitivity of AE over vibration for early detection of cavitation. The results are in contrast to nearly all published work on AE for monitoring cavitation where a clear increase in AE levels was noted without the need for advanced signal processing.

The papers reviewed above have clearly associated AE with the collapse of cavitation bubbles. The presence of cavitation has been shown to increase operational AE noise levels. Recently, Alfayez et al. (2005) and Alfayez and Mba (2005) undertook experimental tests on a range of pumps in an attempt to correlate incipient cavitation with AE activity. The results showed a clear relationship between AE activity measured from the pump casing, suction and discharge pipes, and incipient cavitation. At a high NPSH value, when incipient cavitation is known to occur, a significant increase in AE was observed. Experiments were conducted for several flow rates on different sized pumps to validate this assumption. Further reduction in the NPSH resulted in a decrease in measured AE levels due to the presence of bubble clouds. Observations of the frequency content of captured AE time waveforms showed a shift in frequency range for incipient and developed cavitation. The results of this study also showed that the measurement of AE rms levels could be employed for determining the BEP of pumps, which offers enormous opportunities within the industry. Sikorska and Hodkiewicz (2005) reiterated the observations of Alfayez et al. (2005) and Alfayez and Mba (2005), noting that AE was able to detect off duty conditions in double suction pumps. Furthermore, Sikorska and Hodkiewicz noted that AE could be used to detect cavitation and recirculation and postulated that low-flow AE activity was initiated by recirculation whilst high-flow AE activity was due to incipient cavitation. Cavitation is known to occur more easily at higher flow rates (Cudina, 2003).

5. Monitoring Engines and Rotating Structures with Acoustic Emission

Industries all over the world use various machines and structures to manufacture and distribute various goods and services to global customers. These include rotating and reciprocating machines and mechanical structures of all sizes, shapes, and complexities. Damage assessment of these assets (both old and new) is very crucial as it determines the quality, reliability, availability, maintainability, and the life expectancy. The reliability and health monitoring of both old and new machineries and structures form the subject of extensive research in many academic institutions, government laboratories, defense research establishments, and industrial organizations worldwide. AET is now becoming a widely accepted practice in the field of engine and rotating structural monitoring.

Holroyd et al. (1996) illustrated the background to the AE approach and its technological developments, which enabled it to be used as a means of dynamically probing the operation of machineries and mechanisms, and attempted to clarify the opinions held on the similarities and differences of the AE and vibration monitoring techniques when applied to machinery condition monitoring (Holroyd and Brashaw, 1999). Holroyd and Randall (1993b) illustrated with examples some real benefits of using AE techniques as a highly sensitive, simple to use, and cost-effective maintenance tool.

Gill et al. (1998) described how AE techniques could be implemented as a condition-based maintenance strategy to monitor the inlet and outlet valves of reciprocating compressors. The investigation was based on an eight-cylinder, horizontally opposed, single acting, two-stage compressor used to compress ethylene at a large plastics plant. Gill et al. highlighted the possibility of detecting fluid movement with AET. The sensor required very little space and was non-intrusive, which was a major benefit in the hostile conditions. The results revealed the practical deployment of AE sensors for condition monitoring applications.

Fog et al. (1998) conducted an experimental investigation into detecting exhaust valve burn-through on a four-cylinder, 500 mm bore, two-stroke marine diesel engine with an output of approx. 10,000 BHP. The investigation comprised monitoring three different valve conditions (normal, leak, and large leak). Vibration and structure-borne stress waves (AE) were monitored. The results showed that the AE signals contained more information for identifying valve and injector related mechanical events during the combustion process than time series recorded from other sensors. Features of the AE signals were extracted using principal component analysis (PCA). A feedforward neural classifier was used to discriminate between the three valve conditions. Friis-Hausen and Fog (2001) identified efficient classifiers for the detection of two different failure modes in marine diesel engines: exhaust valve leaks and defective injection (misfire). The purpose of the exhaust valve is to seal the combustion chamber from the surroundings during compression, thus securing maximum pressure in the cylinder during the combustion event. This ensures maximum engine performance in terms of output power. This study identified an efficient classifier, which could discriminate completely between leak sizes in the exhaust valve, based on the recorded rms AE signals. An efficient classifier for detection of misfire was also developed. El-Ghamry et al. (1998) illustrated the potential of AE sensing to determine the strength of the air–fuel mixture in 30.56 liter Perkins four-stroke, eight-cylinder turbocharged gas engine. AE, acceleration, inside cylinder pressure, and timing signals were monitored during the tests. The results revealed that the AE signal showed additional features, which could be used to identify the strength of the gaseous fuel mixture.

Results that showed that indirect measurements of cylinder pressure from diesel engines with AET were presented by El-Ghamry et al. (2005). The AE rms was correlated to the pressure in the time and frequency domains. Furthermore, the complex cepstrum analysis was used to model the pressure readings from the complete combustion phase of the engine. El-Ghamry et al. noted the advantage of employing the cepstral analysis for the model, stating that it used the frequency content of the AE rms signal rather than the energy content, which gave the advantage over signals with low-energy content. The application of AET to modeling the pressure originated from previous studies by El-Ghamry et al. (2003). In the latter investigation El-Ghamry et al. attempted to develop generic techniques for diagnosing faults in reciprocating machines. The generic pattern recognition technique developed was based on the time-domain AE rms signals, statistical feature extraction from the time-domain signal, and correlation of the AE response to specific events in the engines. Steel and Reuben (2005) recently reviewed developments in monitoring engines with AE. It was noted that AE signals could be associated with the actual operational and degrading processes in the engine. Furthermore, this could be accomplished non-intrusively. It was also stated that analysis of AE data could be enhanced with a detailed knowledge of the operating conditions of the engine, such as injector timing, running speed, and valve movement.

Mba (2002) presented a case study on the application of high-frequency AE as a means of detecting the early stages of loss of mechanical integrity in low-speed rotating machinery. Investigations were centered on the rotating biological contactor (RBC), which is used for sewage treatment in small communities and rotates at approximately 1 rpm. The results presented were obtained from an operational unit that suffered a fractured stub shaft retaining bolt head. Evidence to support the inadequacies of vibration analysis and the applicability of AE to detecting this fault condition were detailed. The results of the case study pointed to the potential of AE for diagnosing serious mechanical defects where vibration analysis would be ineffective. The investigation showed that AE activity could be related not only to the fractured bolt but also to loose bolts. The mechanism for generating AE signatures was the rubbing in the threaded bolt within its recess and the rubbing and/or crushing of the fractured bolt shank with wear and rust particles within the clearance hole of the stub shaft. A typical AE parameter such as amplitude can provide valuable information on the clamped condition of a component on a low-speed rotating machine. These observations confirmed the finds of Hanel and Thelen (1995, 1996a, 1996b) where a relationship between AE activity and the tensile stress on a bolt was established. A direct correlation between increased AE activity and plastic deformation of the bolt was presented. Furthermore, the investigators proposed that the low-level AE activity in the elastic range of the bolt corresponded to the friction process in the thread.

Smulders and Loob (1994) employed the use of enveloping and high-frequency AET for monitoring: bearing fault detection, very slow speed bearing, rail car turntables, and lubrication condition in paper mill machinery. Mba et al. (1996) and Mba and Hall (2001) presented the results of a study into the use of stress wave analysis as a means of detecting early stages of loss of mechanical integrity in low-speed rotating machinery. The source of AE was attributed to the breakage, and entrapment, of surface asperities as a result of relative movement of clamped components that had lost predefined tightening torques (loose clamped components). AR coefficients associated with each AE provided an efficient parameter for classification and diagnostics. Holroyd (2002) reviewed some of his development work in applying AET to machinery condition monitoring over the last decade, and also introduced new developments in the field of condition monitoring of structures.

6. Conclusion

AET is a continuously evolving multidiscipline and is now the focus of intense research- and application-based studies. The wealth of knowledge discovered, generated, and disseminated in this evolving discipline is itself proof of its diverse applicability. The interest in developing new technologies to overcome the many hitherto unsolved problems in condition monitoring and diagnostics of complex industrial machinery applications offers immense opportunities for AET to grow unabated. This is also reflected by the significant growth in global demand for AE sensors. With the accelerating speed in the growth of intelligent information, sensor and data acquisition technologies, combined with the rapid advances in intelligent signal processing techniques, a healthy growth in the application of AE in many engineering, manufacturing, processing, and medical sectors is to be expected. The application of AE in prognosis has yet to be fully explored and exploited. We are still a long way away from interpreting and fully understanding the wonderful "sounds of AE" from rotating machines.

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