Viability of the Application of Acoustic Emission (AE) Technology for the Process and Management of Maintenance in Industries: Defect Detection, On-Line Condition Monitoring, Diagnostic and Prognostic Tools

Shuib Husin[1], D.Mba[2] and R.I. Raja Hamzah[3]

Abstract--- This paper reviews the success of the application of Acoustic Emission (AE) technology in rotating elements which can be adopted as a tool for the maintenance strategy, "Condition Based Maintenance". Preventive maintenance needs data to be supplied in order to plan the maintenance schedule. On-line condition based monitoring offered by AE technology, provides a complimentary assessment of the current condition of machines whereby outage schedules can be planned for proactive maintenance. Research into the feasibility and viability of AE technology at Cranfield University, which was started in 1984, on rotating elements has shown encouraging results and it is evident that AE technology can be employed as a tool for defect detection, on-line condition monitoring, diagnosis and prognosis. All these capabilities of AE are of benefit to the process and management of maintenance in industries.

Keywords: **Acoustic Emission (AE), Condition Based Maintenance (CBM), Condition Monitoring, Defect Detection.**

I. Introduction:

AE Technology as a Special Tool to Complement theProcess and Management of Maintenance

Employing special tools for maintenance purposes in anticipating and heading off failures significantly contributes to improving reliable plant capacity in industry [1]. It leads to the effective implementation of proactive work whereby attention would be given to preventive and predictive maintenance. Vibration analysis and acoustic emission (AE) technology are among the special tools that are being referred for the process and management of maintenance.

The vibration technique has been reported widely in its use and is well established as a diagnostic technique for rotating machinery in industry compared with AE which is still in its infancy [2]-[5]. However, a numbers of researches show that vibration analysis is incapable of early fault detection [6]- [8], [11]. The application of AE technology as a diagnostic tool for rotating elements, particularly gears and bearings, is now get attention in maintenance system based on its capabilities in early fault/defect detection, on-line and condition monitoring, and diagnosis and prognosis which is noted better over vibration analysis. Comparative work between vibration techniques, AE and spectrometric oil analysis was done by Tan (2005) in his thesis programme and can be found in Tan et al., (2005). The capability to detect and indicate the incipient defect and defect size progression by AE technology allows the maintenance people to monitor the rate of degradation on the rotating elements. In that aspect, it is unachievable using vibration analysis **[**4], [6]**,** **[**7]**,** [9]-**[**12]

Based on the encouraging results of the employment of AE technology on side and test-rigs, it is concluded that AE technology offers a complementary tool for defect detection and is viable in the condition monitoring of rotating elements; gears, bearings and shaft seals [4]. Furthermore, it is gaining acceptability as a diagnostic tool.

Active-observing benefits from the on-line monitoring technique offered by AE technology; for instance, it provides early warnings of serious equipment problems. It is interesting to note that the term "diagnosis and prognosis" used in machinery maintenance has always been referred to as the effort required in detecting and understanding of incipient defects/problems of a machine's parts which later might cause a casualty or catastrophic failure. Gears and bearings have a high risk of problems which affect a machine's performance and safety, and eventually cause money loss. They are widely used in the gearbox and transmission of various engineering systems.

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[1] Universiti Kuala Lumpur Malaysian Spanish Institute , Department of Mechanical Engineering, Kulim Hi-Tech Park, 09000 Kulim, Kedah, Malaysia.
[2] Cranfield University, School of Engineering, Cranfield, Beds MK43 0AL, UK.
[3] University Teknologi Malaysia, Appplied Mechanics Dept, UTM, JB, Malaysia.
Corresponding author. Fax: +44(0) 1234 754681
E-mail address: d.mba@cranfield.ac.uk

"Diagnosis and prognosis" is the art of foretelling based on the recognised symptoms that are indicative of forthcoming severe problems, and is normally used for cases which are concerned about high safety requirements.

In any production type of industry, outage time means money loss where it involves productivity and labour planning. Hence, emphasis on a proper and observed maintenance system in industry is receiving attention in order to achieve the so-called reliability maintenance. According to Palma (1999), reliability maintenance is defined as an effort that is concerned with keeping equipment from failing in the first place. AE is feasible and viable in achieving the reliability of plant capacity.

In the aerospace industry, particularly for the helicopter platform, it is important to detect incipient defects/damage in the rotating components before catastrophic failure occurs, e.g. the gears crack within the gearbox. The gearbox is the most critical and complicated component on both the helicopter platform and the landing gears for aeroplanes; part failure such as gear tooth breakage will lead to loss of life and assets. This means that reliability maintenance is of paramount important in the aerospace industry. Awareness of the importance of proactive maintenance to avoid catastrophic occurrences in the aerospace industry has yielded the development tools for on-line and condition monitoring for maintenance systems and health monitoring; e.g. a system called "Helicopter Health and Usage Monitoring System" (HHUMS) [13]. The implementation of the active-observing and on-line techniques for supporting the preventive maintenance system in the aerospace industry has facilitated the modern maintenance philosophy, such as condition based maintenance.

In production or process industries which depend on machines, there are always arguments about which maintenance philosophy should be adopted to achieve reliable plant capacity [1]. Too much focus on corrective maintenance with no time allocated to proactive planning, the problems still seem never to stop. While too much on the proactive planning sometimes causes wastage; e.g. changing critical and expensive parts of a machine based on the manufacturer's recommendation period although the part is still in good condition is a type of waste. Hence, a new technique to solve this argument is suggested; Condition Based Maintenance (CBM).

It can be concluded that the benefits of on-line and "active-observing" lead to condition monitoring where diagnosis and prognosis have been established and recognised: (1) reduction in maintenance costs, (2) early warning of incipient component failure, (3) improved safety, (4) greater machine availability, (5) lower insurance cost (in aerospace industry).

The aim of this paper is to review the successful application of AE technology in detecting the incipient defects and indicating defect size. In addition, the paper will discuss the viability of AE technology for on-line and condition monitoring tools which eventually lead to diagnostic and prognostic tool for rotating elements, especially gears and bearings in industry. Most of the research results and evidence of the successful application AE technology on rotating elements discussed in this paper are based on previous and current works at Cranfield University.

2. Adoption of AE Technology as Condition Monitoring Tool for Maintenance Strategy in Industries

In the CBM concept, overhaul is done based on the actual condition of the machine where any deterioration or symptom in the machine is observed and checked either by on-line monitoring or interval monitoring/checking.

Condition monitoring is defined as the detection and collection of information and data that indicate the state of machine [14]. Condition monitoring provides an early indication of many potential problems which helps in the process and management of maintenance strategy to maximise machine life and avoid unplanned outages.

The advantages of the effective condition monitoring approach in maintenance systems are: (1) it might not need previous data history from "mini files" for prognostic defects/faults, (2) it provides a means for decision making on the right time to change a part or outage time planning to repair a machine, (3) the usage of critical part machines which are normally expensive and limited could be maximised, (4) improved safety since condition monitoring enables machines to be stopped before a critical condition is reached, (5) fully optimised machine operation by obtaining a better compromise between the outputs and operating life of the machine. The devices or method of analysis that are available in the market which can be used as condition monitoring are, for example, vibration analysis, ultrasonic testing, oil-debris analysis (spectrometric oil analysis) and the latest technology is AE technology [2], [4], [6], [15].

Prognostic capability, which benefits from condition monitoring results, not only would provide the prediction of failure time, but would allow for the adjustment of the maintenance schedule in order to reduce downtime and maintenance costs.

Condition monitoring enhanced with on-line monitoring such as that offered by AE technology definitely maximises the machines' operation and is maintained at the minimum possible cost without compromising the necessarily high safety standards. It is apparent that the cost of maintenance could therefore be reduced. The target to fully utilise machinery in industrial plant while maintaining the high standards of safety requirements such as those in the aerospace industry has placed condition monitoring at the centre of attention [6].

3. Brief of AE Technology

Acoustic emission (AE) is a term where transient elastic waves are generated by the rapid release of energy within a material [16]. It has been reported that the first AE was used in 6500 BC, in the making of hard fired pottery, as a means of quality checking [17]. Later, an Arabian alchemist Jabir Ibn Hayyan (8th century) documented the observation that tin gives off a harsh sound when a bar of tin is bent. It is postulated by him that the crackling sound may be heard as crystals in the inner parts of the bar breaking against one another [17]. Significantly, in 1950, Joseph Kaiser performed the first comprehensive investigation into the phenomenon of AE. In his report, Kaiser suggested that crystalline solids would emit sound when under a mechanical load. Kaiser systematically used high frequency sensors and electrical amplifiers to listen to a range of engineering materials under controlled loading. These experiments were published in Kaiser's thesis in 1950, where he stated *"engineering materials in general emit low amplitude clicks of sound when they are stressed"*. Furthermore, the most significant discovery of his work in the AE field was the irreversible AE phenomenon which has since been known as the 'Kaiser Effect'. A simple definition of the 'Kaiser Effect' is that given by Holroyd (2000): *"Material does not start to re-emit AE activity until the applied stress exceeds that which it has previously experienced"*. From that moment a new technique for non destructive testing technology was developed.

Sensors (or transducers) are the backbone of the AE technique and are usually made of piezoelectric material such as Lead Zirconate Titanate (PZT) and Polyvinylidene Fluoride. The function of the AE sensor is to detect mechanical movement or wave stress and convert it into a specific usable electrical signal [17]. A typical AE transducer configuration is shown in Fig 1. It has been acknowledged that AE technology is deemed to be the most sensitive method in acoustic detection. The frequency range for the AE sensor is beyond the human hearing threshold of 100 kHz to 1MHz. The high frequency content of the AE signatures which enable typical mechanical noise (less than 20 kHz) is eliminated.

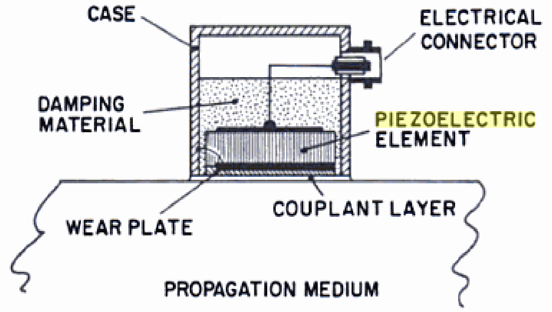


Fig 1: Construction of a simple AE transducer [20].

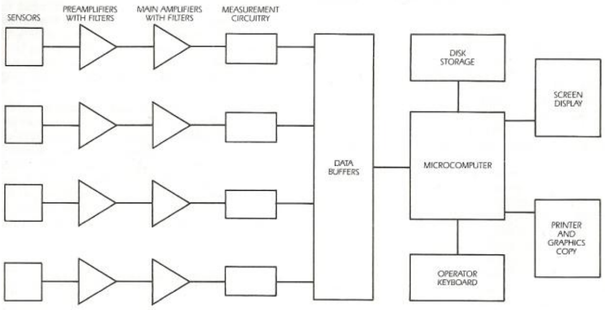


Fig 2: Schematic diagram of AE Technology [17].

4. Stages Progress in AE Application

Work using AE technology was reported as being done at the Boeing and Phillips Petroleum Companies in 1965 [17], and since then many works of application of this technology as condition monitoring of bearings and gears have been published. For example, it was reported that AE technology had been applied to condition monitoring for failure detection in bearings and gears as early as 1970 where AE rms voltage was used as the primary means of signal processing [21].

Generally, from the number of investigations at Cranfield University into the applicability of AE technology in identifying defects in bearings and gears which have subsequently been published, indicates the reliability and practicality of the usage of AE technology for condition monitoring. Even though AE technology is still in its infancy, this technology could be adopted for the maintenance strategy approach, namely Condition Based Maintenance.

The research activities in the AE field that have been done at Cranfield University since the mid 1980s, show the established application of AE in rotating machinery [2]-[9], [11]-[13], [15], [19], [22]-[41]. In general, from the phase of initial investigation (detection AE generated signature) to the well established phase (acceptability in diagnosis and prognosis) that we are at now, the growing and development of AE application in rotating elements, particularly gears and bearings, can be divided into 5 stages:

i) Stage 1: Application of AE in detecting defects/faults.

ii) Stage 2: Observation of AE signature and trend of the series of simulation defects.
iii) Stage 3: Establishing correlation between the AE activity and seeded defects.

iv) Stage 4: Establishment of AE as a condition monitoring tool.

v) Stage 5: Actualisation in diagnosis and prognosis of the defects/faults using AE technology.

4.1. Stage 1: Application of AE in Detecting Defects

It has been shown that many branches of industry employ AE technology in detecting defects/faults; e.g. in the machining industry, the AE was used in detecting tool wear [22]-[25]; in process industrial machinery AE was employed in detecting the defects of rotating elements such as pitting, cracking, scuffing, rubbing and tooth breakage in gears, bearings and shaft-seal rubbing [2], [4], [6], [9], [11], [15], [19], [26], [28], [29], [35]; in the rail transportation industry where AE was employed in assessing surface integrity of rail track [30]-[32],[36]; in the liquid transportation industry, it has been used for detecting cavitation and determining BEP in centrifugal pumps and gas void fraction measurement in piping transportation [12], [33], [34].

In general, the results of the attempt to detect defects/faults using AE technology by the aforementioned researchers in their investigation are respectively:

i) Markovic (1978) employed the AE technology in machining process and showed that the total ringdown counts have good correlations with the total wear.

ii) Wilson (1979) concluded that event counting (ringdown count) and amplitude measurement has proved successful for the measurement of AE for grinding process wear.

iii) Macey (1995) has obtained constant results for all tool bits showing a characteristic peak on the frequency spectra which has a high amplitude if the tool is worn.

iv) Robert (1981) has shown that the technique of the AE energy rate detection has potential for the "*in-process*" of grinding in a production situation, especially for the early warning of wheel pick up and likelihood of burning.

v) Spenser (1988) highlighted the concept of fault detection by AE in gear teeth meshing where a fault condition would be highlighted by change to the amplitude distribution.

vi) Yaghin (1991) showed very convincing results in that the AE signatures of a faulty gear tooth in mesh were high frequency spiky signals.

vii) Tan (2005) has proved that AE technology is capable of detecting faults in gear teeth.

viii) Pedersen (2005) identified gear failure with AE technology. He found that the cross-over count and energy were increased with the amount of surface pitting on gear.

ix) Raja Hamzah (2008) showed that the changes in load, speed, temperature, surface roughness and lubricant viscosity influenced the generation of AE. He concluded that AE technology was capable of the identification of lubrication regime; hence gear failure associated with wear could be eliminated.

x) Bruzelius (2003) investigated the use of AE technology in assessing mechanical integrity in rail track.

xi) Mill (2004) and Jindu (2004) continued the work of Bruzelius and confirmed that AE technology was capable of being used in detecting surface defects in rail track. Both of them produced encouraging results of correlation between AE burst and seeded defects, speed and load.

xii) Al-Maskari (1985) investigated the feasibility of the application of AE technology for the detection of cavitation in a centrifugal pump. He established the correlation between event rate and count rate with cavitation. He concluded that AE is capable of detecting developed cavitation.

xiii) Alfayez and Mba (2004) investigated the best efficiency point (BEP) of a centrifugal pump using AE technology and tried to link with cavitation phenomena and bubble collapse in the system. They found that at a high NPSH value, when incipient cavitation is prevalent, a significant increase in AE was observed. The results obtained prove the successful use of the AE technique for detecting incipient cavitation and the potential for AE technology to be employed in determining the BEP of a pump.

xiv) Al-lababidi et al., (2009) concluded that the gas void fraction (GVF) in liquid of piping transportation could be determined by measurement of Acoustic Emission.

xv) Mba et al., (2004) employed AE technology for detecting and verifying shaft-seal rubbing in their case study on a steam turbine unit. They concluded that AE technology was capable of detecting the sliding contact between rotating and stationary components. They distinguished a continuous and partial rub source of an AE signature modulated waveform. Continuous rub type comes from sustained contact between the rotor and the stator which will generate an AE signature above background noise; whilst the partial rub type comes from any looseness or unbalanced part.

xvi) Bruzelius and Mba (2004) made observations from simulated conditions and identified that progressive wear on the rail track/wheel interface were associated with increasing AE transient bursts.

xvii) Toutountzakis et al. (2005) performed a test to determine an effective AE indicator for seeded gear defect detection. Unfortunately their result from the relationship between AE rms and the defect location introduced was considered unsatisfactory and fraught with difficulty. However, they found the 'side result' where the AE rms varied with time as the gearbox reached a stabilised temperature. In other words, the role of oil film thickness where it is affected by temperature influenced the AE generation activity.

xviii) Abdullah et al., 2006 performed a comparative study between AE technology and vibration analysis (accelerometer) for identifying the size of a defect on a radially loaded bearing. They concluded that AE was capable of detecting an early fault. They investigated the relationship between AE rms, amplitude and kurtosis for a range of defect conditions. The test conditions introduced were: defect free condition, a point defect, a line defect, a rough defect and smooth defect. It was found that for all test conditions, the AE rms value increased with increasing speed and load. The same trend was shown by AE maximum amplitude parameter. The maximum AE amplitude is apparent for line defect compared to the rest of the simulated defects. Finally, they concluded that increasing the defect width demonstrated the burst signal was increasingly more evident above the operational noise levels, whilst increasing the defect length increased the burst duration.

xix) Al-Dossary et al., (2008) attempted to understand the defect size characterisation and the AE waveform generated through establishing the simulation of increasing defect sizes. It was found that energy values increased with increasing defect size and increasing load. Furthermore, they found that the geometric of the seeded defect gives a distinctive AE waveform generation. For defects with increasing width, the AE burst duration remained relatively constant irrespective of load condition. However, for defects with increased length, the AE burst increased with increasing defect size along the circumferential direction of the roller. Their results concluded that the geometric defect size can be determined from the AE waveform.

The aforementioned list of articles has clearly shown the successful application of AE in their research respectively, covering a wide range of industries (power generation turbine, liquid transportation, machining, aerospace and nuclear). It is noted by Miller and McIntire (1987) that the application of the AE technique in test-rig research programmes is well documented and referenced. It would be ready to be commercially employed in industry for defect detection, on-line and condition monitoring, and as a reliable diagnosis and prognosis tool.

4.2. Stage 2 – Stage 5: Effort in Understanding the AE Signature Trend, Establishing Correlation and Viability as Diagnosis and Prognosis Tool.

After AE technology had been proven sensitive to detect defect, efforts have been made to observe the AE signature and trend of the simulated defects, natural defects/natural mechanical degradation [19], [36], [37], and operating parameters such as speed and load [2], [5], [9], [30] surface roughness and temperature [5], [6], [15], [39]. Furthermore, detail experiments have been performed by researchers to investigate the effects of specific film thickness, asperity contact and gear meshing mechanisms on the AE signature [15], [38], [39]. These three parameters are dependent on the operating temperature [5], [6], [28], [38], [39], [42].

In brief, the following stages (stage 2 - stage 5 as aforementioned) were the efforts in achieving confident level by producing the reliability and repeatability of results which makes this technology is viable for prognostic tool which can be employed in the process and management of maintenance in industries.

In this section, some results of the AE signature from previous researchers' work at Cranfield University, which show an AE trend under certain conditions, are revisited as a compilation of successful works in application of the AE technology provide evidence to gain its acceptability as a diagnostic tool for maintenance.

It was proven that AE technology is capable in detecting natural surface degradation (scuffing, rubbing, and pitting) in slow speed bearings, the AE waveform clearly shows AE transient and AE periodic transient events as functions of increasing operating time [37]. This proves that natural defect or surface degration is developed as function of operating time. If a system were operate in insufficient oil lubrication, the natural defect will develop faster. The ability of AE technology in detecting the natural defects by simply observing the generated AE waveform proves that this technology capable enough to be on-line and condition monitoring tool.

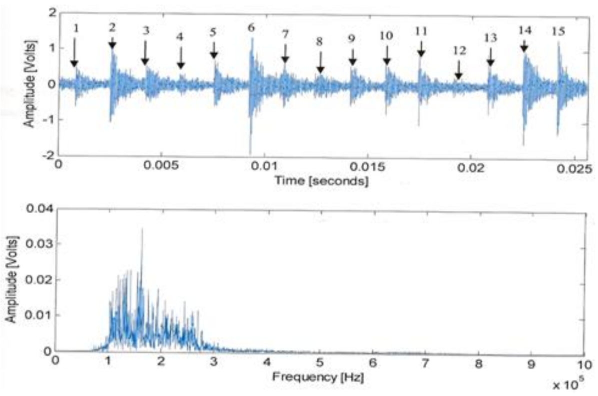


Fig 3: AE signature of every tooth of gear meshing [39].

The generated waveform clearly show AE signature of every tooth in the gears operation [2], [39], [7]. For example, see Fig 3. This shows that that the AE waveform can be used for identifying defects in gears system.

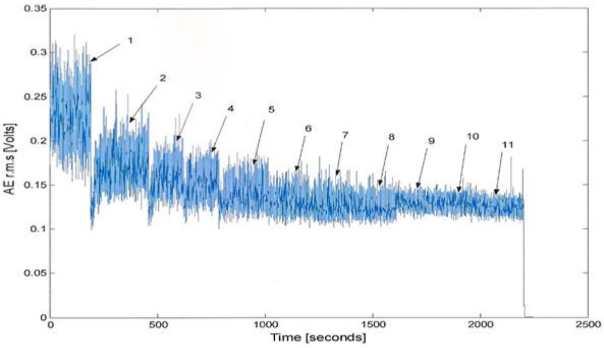


Fig 4: AE signature of different oil level [15].

It was found that AE technology can be used for oil level indication for particular systems that are hard to reach due to their assembly design, such as the oil level in the differential gears or any system [15]. See Fig 4, the AE waveform resulted from different oil levels. This is another prove that AE technology is robust and reliable for oil monitoring in engineering system. Standard data of the AE signature on the system have to be developed and calibarated before it can be use.

AE output is sensitive to the changes of speed and load operating [2], [5], [9], [39]. It is also sensitive to micro-physical condition of system interaction areas such as the different meshing mechanisms in spur and helical gears [39]. Raja Hamzah and Mba (2009) successfully proved this aspect in terms of asperity contact and the role of pure rolling and sliding in gears meshing during operating. Furthermore, they found that the effect of specific film thickness in gears operation affects AE generation. He established correlation amongst AE rms, specific film thickness and load. Raja Hamzah and Mba (2009) concluded that AE is more sensitive to changes in specific film thickness under a combination of rolling and sliding (spur gear) as compared to pure rolling (helical gear). Furthermore, they believe that AE technology could be applied as a tool to identify the lubrication regime (partial elastohydrodynamic or fully elastohydrodynamic mode) within a gearbox during operation which is influenced by many operational parameters; load, speed, temperature and mechanical mechanism of the system.

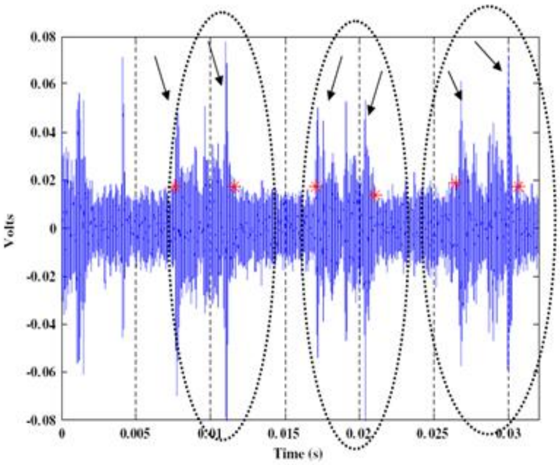


Fig 5: AE waveform shows that 2" large spiky" of big defect at inner bearing race [19].

Fig 6: Example of big seeded line defect [19].

It was proved that the generated AE signature is dependent on the geometry and size of defect [19], [11]. Al-Dossary et al. investigated the AE signature generated from the seeded defect in inner race bearings; they found that two large AE burst spikes (see Fig 5) were associated with defect geometry. It can be explained by Fig 6 which shows the entry and exit of the roller onto the defect. A similar trend of 'two large AE burst spikes' was also found in the work of Al-Ghamd et al., (2006) (see Fig 12).

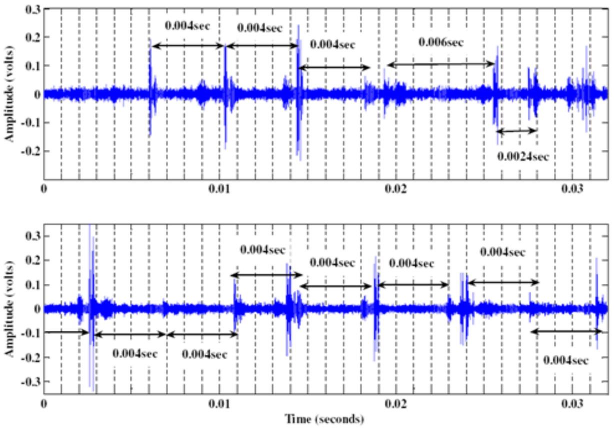


Fig 7: Cage slip can be detected by AE waveform burst duration [19].

A bearing default such as cage slip can also be detected by the AE waveform, based on the time interval between successive AE bursts [19]. Example of AE waveform in detecting this fault using AE burt duration technique is shown in Fig 7.

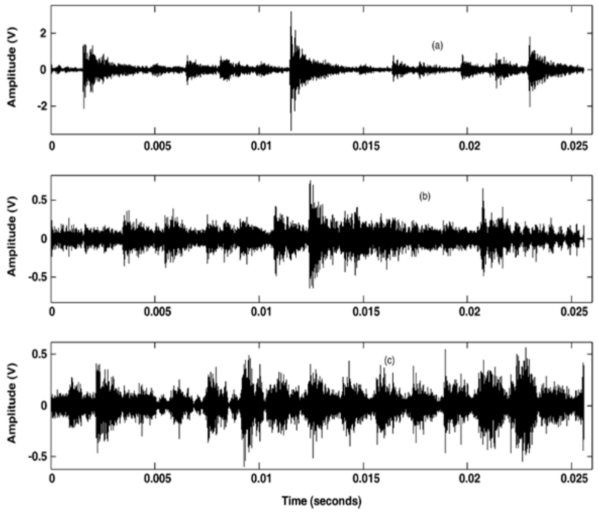


Fig 8: AE signatures of seeded gear defects (small pitch line defect); in increasing load (a) no load, (b) 55 Nm, (c) 110 Nm [2].

Bruzelius and Mba (2004) in the first attempt ever known in the application of AE in detecting surface integrity of rail track, found an association between AE signature and load. The AE waveform changes with operating load on the seeded pitch line defect in gear tooth was recorded in Fig 8.

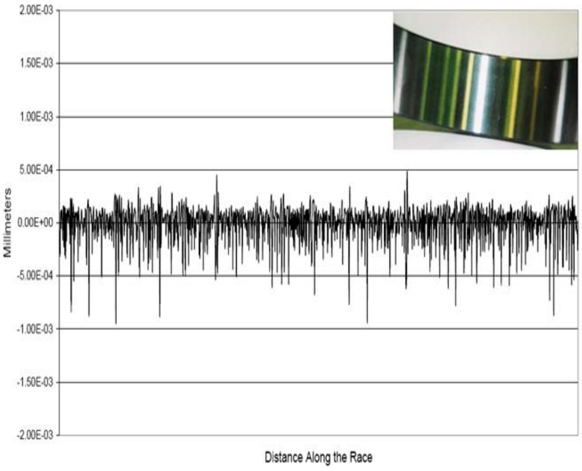


Fig 9: *AE waveform* signature of defect free at bearing race [11]

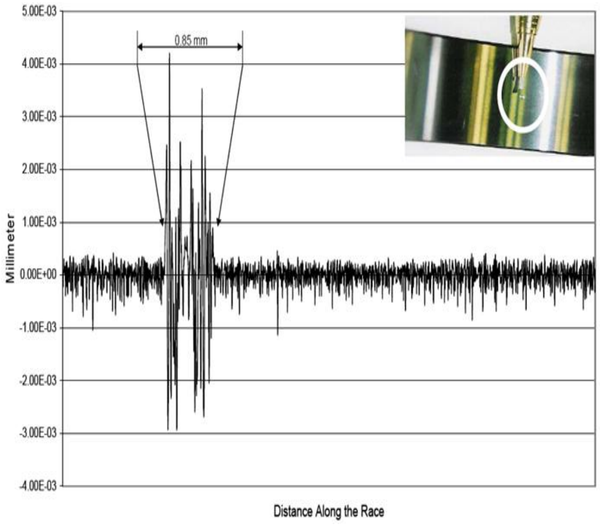


Fig 10: *AE waveform* signature of point defect at bearing race [11]

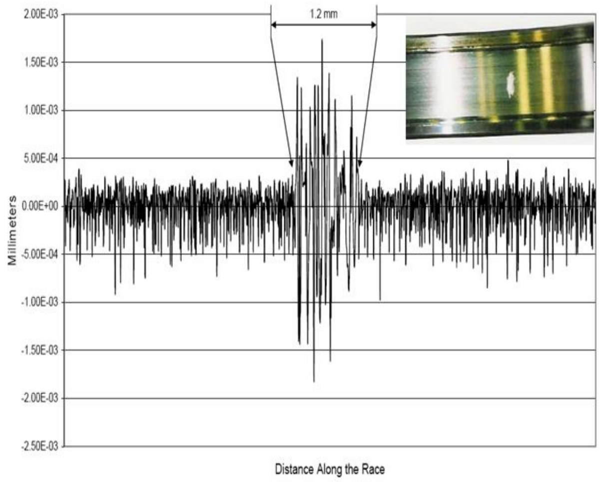


Fig 11: *AE waveform* signature of line defect at bearing race [11]

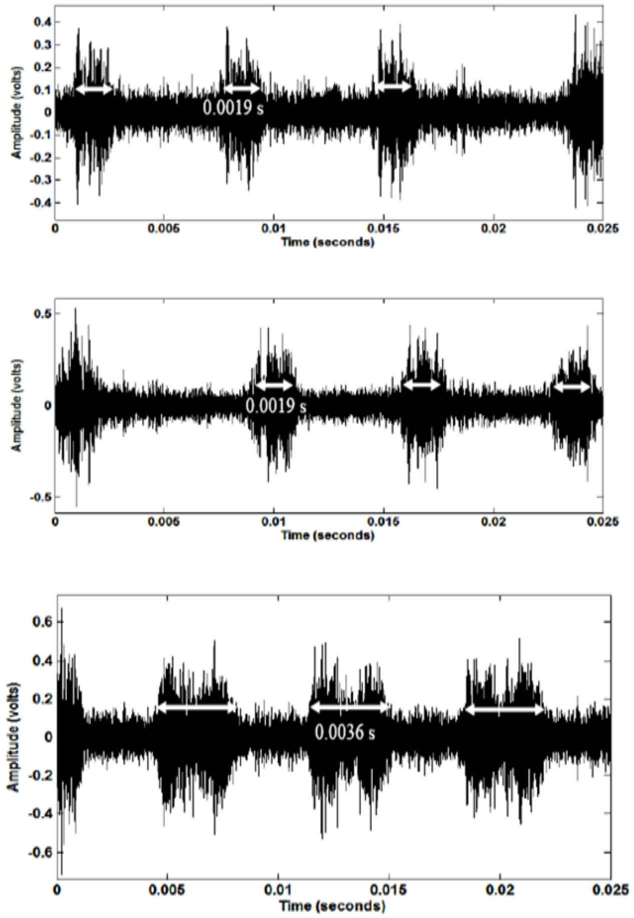
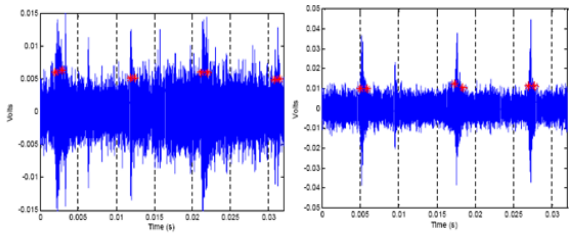
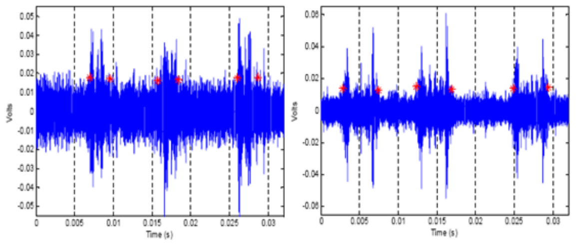


Fig 12: AE Burst Duration from different size of defects (width x length); 8x4 mm defect, 13x4 mm defect and 13x10 mm defect respectively [11]



Defect D2 **Defect D4**



Defect D7 **Defect D9**

Fig 13: Vary AE waveform from varying defect size at outer bearing race; D2=0.9x2.5 mm; D4=0.9x8 mm; D7=5x12 mm; D9=9x12 mm [19].

Al-Ghamd et al., (2006) prove that the AE waveform shows different AE durations for different sizes of defect. Furthermore, the larger the size of defect, the clearer are the two “large spikes” that are associated with AE duration (Fig 13). The result from Al-Dossary et al., (2009) show the same trend of burst duration as function of defect size. In their experiment, four types of defect were seeded in the bearing inner race; smooth defect, point defect, line defect and big rough defect. No defect of bearing race was used as a comparative. Fig 10 – Fig 11 show the defects on inner bearing race and its generated AE waveform. It shows the larger defect size and the longer AE duration obtained. Fig 9 as comparative on no seeded defect. Fig 13 shows clearly the comparative of AE duration signal according to the defect size in their investigation programme.

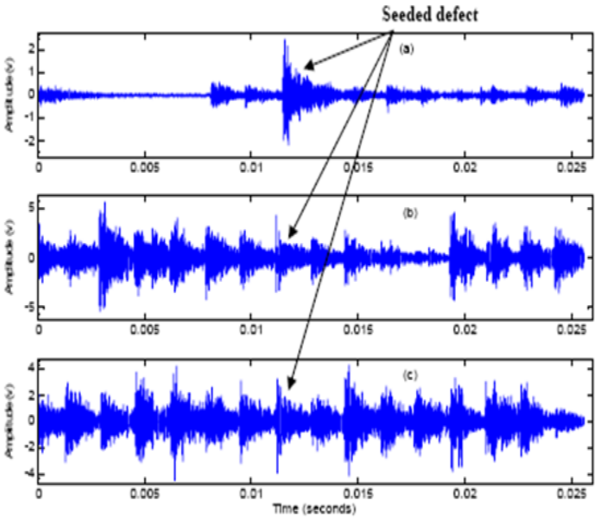


Fig 14 (a): at speed 745 rpm: AE waveform changes with changing in speed and load on the large addendum seeded defect; (a) No load, (b) 55 Nm and (c) 110 Nm [5].

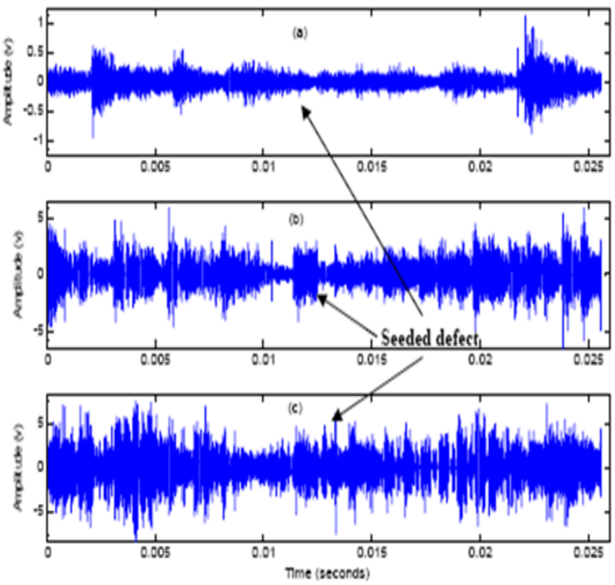


Fig 14(b)- at speed 1460 rpm: AE waveform changes with changing in speed and load on the large addendum seeded defect; (a) No load, (b) 55 Nm and (c) 110 Nm. [5]

In the work of Tan et al., (2005) as shown in Fig 14(a) and 14(b), increases in speed and load changes the AE signature generation. Increasing load and speed affect the gear surface asperity contact. When a test was performed with no load on the seeded defect at a higher rpm of 1460 rpm, it showed that no spikes were picked up by the sensor (Fig 14b). It was postulated that asperity contact is decreased when the bearing is operating at the higher speed. It might caused by the phenomenon of “melting” at the surface protrusion of the bearing race. Al-Dossary et al., (2008) discussed in detail this contribution to the AE generation. It is concluded that suitable speed is needed for AE technology in detecting defect. Fig 14(a) and Fig 14(b) imply the effect of speed on the AE generation on the seeded defect.

The next step in the development of AE as a diagnostic and prognostic tool is the establishment of relationship. For example; Tan and Mba (2005) established correlation between AE activity and asperity contact in gears; Raja Hamzah and Mba (2007) established correlation between AE and specific film thickness of gear surface; Abdullah et al., (2006) and Toutountzakis et al., (2005) established correlation between AE and size, and geometry of bearing and gear defects respectively. However, these established correlations are specific to the used operating temperature. Since the application of AE technology is still in its infancy compared with other technology, nevertheless its capabilities as discussed such as on-line defect detection, being robust for data analysis during the in-process, and having sensitive and reliable detection on the incipient defects and geometrical defects, make AE technology is become more accepted as condition monitoring and as a prognostic tool.

5. Conclusion

The successful applications of AE technology as a on-line/in-proces, condition monitoring and diagnostic tool for rotating elements, particularly gears and bearings in low and high rotating speeds, have been reported. The article and the results reviewed in this paper clearly show the capability and reliability of AE technology in detecting defects, especially incipient defects. Furthermore, convincing arguments have been provided to show that AE technology could be an effective complementary tool for the process and management of maintenance in industries. The robustness and sensitivity of AE technology make it reliable tool for in-process monitoring, condition monitoring and eventually as a diagnostic and prognostic tool for the common critical component defects found in industrial machinery.

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