ACOUSTIC EMISSION CONDITION MONITORING: AN APPLICATION FOR WIND TURBINE FAULT DETECTION

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Abstract

Low speed rotating machines which are the most critical components in drive train of wind turbines are often menaced by several technical and environmental defects. These factors contribute to mount the economic requirement for Health Monitoring and Condition Monitoring of the systems. When a defect is happened in such system result in reduced energy loss rates from related process and due to it Condition Monitoring techniques that detecting energy loss are very difficult if not possible to use. However, in the case of Acoustic Emission (AE)technique this issue is partly overcome and is well suited for detecting very small energy release rates. Acoustic Emission (AE) as a technique is more than 50 years old and in this new technology the sounds associated with the failure of materials were detected. Acoustic wave is a non-stationary signal which can discover elastic stress waves in a failure component, capable of online monitoring, and is very sensitive to the fault diagnosis. In this paper the history and background of discovering and developing AE is discussed, different ages of developing AE which include Age of Enlightenment (1950-1967), Golden Age of AE (1967-1980), Period of Transition (1980-Present). In the next section the application of AE condition monitoring in machinery process and various systems that applied AE technique in their health monitoring is discussed. In the end an experimental result is proposed by QUT test rig which an outer race bearing fault was simulated to depict the sensitivity of AE for detecting incipient faults in low speed high frequency machine.

Index Terms: Low speed rotating machine, and Condition Monitoring Systems, Acoustic Emission (AE)

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1. INTRODUCTION

The efficiency of the wind turbine performance could be improved due to the implementing of different maintenance practices and they can reduce the maintenance cost if they are continues and automated. Therefore research in fault diagnosis and condition monitoring is in high importance. Various methods have been applied in fault detection of wind turbines such as vibration analysis [1], [2], [3], [4], [5], oil analysis [6], [7], [8], noise analysis [5], [9], data analysis [9], [10], [11], [12], [13] and acoustic emission (AE) analysis [14], [15].

Acoustic Emission (AE) as a technique is more than 50 years old and in this new technology the sounds associated with the failure of materials were detected. Acoustic wave is a non-stationary signal which can discover elastic stress waves in a failure component, capable of online monitoring, and is very sensitive to the fault diagnosis. The Acoustic Emission (AE) technique is very adequate to detecting extremely miner energy release rates [16]. In the case of wind turbine there are limited researches regarding AE condition monitoring that are presented bellow and listed in table 1.

Condition monitoring through applying vibration analysis is a confirmed and efficient technique for detecting the lack of mechanical impeccability of a wide range of rotating machinery including wind turbine. Since conventional vibration measuring materiel is not qualified for measuring the fundamental frequency of operation and also there is no obvious change in vibration signature in components that fluster at low operational speeds, the authors in [17] represented a study of high-frequency stress wave analysis as a means of detecting the early stages of the loss of mechanical integrity in the rotating biological contactor (RBC) which is used for sewage treatment in small communities. Results of the implanted mechanical faults on their test rig indicated that Stress Waves generated from rubbing of mating components were of a complex pattern, expressive of their different transmission paths.

J.Holroyd in [18] introduce a new signal processing approach based on AE in a very slowly rotating machine that can be supplement by or supplement to other signal processing methods. Their algorithms are not available for commercial reasons but they were successful to implement AE technique in heavy industry under noisy site condition and reduced the impact of background noise. Using vibration analysis in rolling element bearings is an established method while this approach was not successful at rotational speed under 16 r/min. The energy that released from failed bearing at this speed generally enables to appear as an obvious signature in conventional vibration measuring equipment. In [19] they represent the an investigation into the applicability of stress wave analysis for detecting early stages of bearing damage at a rotational speed of 1.12 r/min. They applied a bearing test rig which consisted of a motor/gearbox system, two support slave bearings, a test bearing and a hydraulic cylinder ram.

Among all the monitoring systems, the structural health monitoring (SHM) system [20] is of the principal importance because it is the structure that provides the integrity of the system. Considering wind turbine as a low speed rotating machine, acoustic emission (AE) monitoring during loading of wind turbine blades has provided remarkable advantages towards the realizing of the damage mechanisms which arise on a turbine blade, and has upgrade the analyzer ability to evaluate damage. In [21] a fatigue test of a wind turbine blade was conducted at the National Renewable Energy Laboratory and the author shows that the fatigue test of large fiber-reinforced plastic wind turbine blades can also be monitored by AE techniques. They used Physical Acoustics Corporation (PAC) Spartan AT acoustic emission system. They have conducted the test with exceeding the load in different levels and the acoustic emission data showed that this load exceeded the strength of the blade.

The authors in [22]inquire the effectiveness of Acoustic Emission (AE) system for initial detection of faults regarding rotating components in machinery. They designed and developed a system to provide an opportunity to test this concept and the AE real time measurement as well. They utilized the Time and frequency domain analysis to analyze the accumulated data using Labview. A comprehensive test was done in [23] on gear fault detection for split torque gearbox (STG) using AE sensors. They applied wavelet transform to analyze AE sensor signals in different locations to specify the arrival time of the AE bursts which leads to determine the gear fault location. Li Lin in [15] applied acoustic emission (AE) techniques based on Hilbert-Huang transform (HHT) for charactering the AE signals that released from wind turbine bearing. Hilbert-Huang transform is appropriate to nonlinear and non-stationary methods and immediate frequencies based on local properties of the signal is consider as functions of time and energy.

Existing reports indicate that few researches have been done on wind turbine vibration monitoring whilst on AE is more confined. In [24] authors present combined vibration and AE monitoring performed over a continuous period of 5 days on a wind turbine gearbox and generator. The vibrational and AE signatures were collected as a function of wind speed and turbine power for recognition of fault signals related to shaft and gearbox defects. They used Similarity analysis using Euclidean distance which is a simple algorithm for the distinction of substantial differences between data sets.

2. WIND TURBINE FAULTS AND CONDITION MONITORING SYSTEMS

2-1.Wind turbine major components and prevalent failures

Wind turbines are mostly located in remote areas and unlike traditional power plants are not very protected facing with highly variable and harsh weather conditions, severe winds, tropical condition, lightning stroke, icing, and etc. These reasons reveal the importance of fault detection techniques in the maintenance of wind turbines. It is obvious that the majority of electrical and mechanical faults in such systems that have high correlation between their components may cause different failures and fatigues. Figure 1 shows the major components of a typical wind turbine that are faced all the above concerns. Further studies showed that the most conventional failures has root causes in subsystems which include gearbox, main shaft and bearings, blades, electrical control, yaw system, generator and rotor brake. Figure 2 has depicted the failure rate of wind turbine components [7].

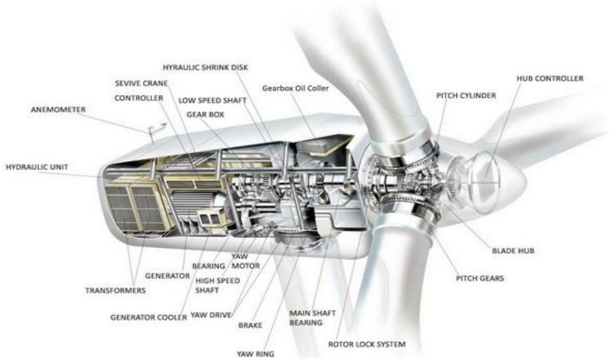


Figure1. The major component of a wind turbine

The wind turbines operate until the failure made it to stop working [8] and then based on the nature or severity of damage, it should be maintained or replaced (reactive maintenance). Through the development of wind turbines and increasing their capacity, preventive maintenance (PM) became more approved. This method requires periodic inspections for condition assessment based on empirical measures which are generally very expensive and not very comprehensive. With the improving technology and implementing condition monitoring and fault detection techniques, predictive maintenance (PdM) and condition-based maintenance (CBM) have gained for condition assessment based on empirical measures which are generally very expensive and not very comprehensive. With the improving technology and implementing condition monitoring and fault detection techniques, predictive maintenance (PdM) and condition-based maintenance (CBM) have gained highly attention from wind farm holders and academia [8]. In the following part we first elaborate the major parts of the wind turbine that frequent faults would happen and then we describe different methods of monitoring and fault diagnostic in wind turbines.

2-2. CONDITION MONITORING

Condition monitoring (CM) as a term is widely used and many CM commercial instruments are available. We all know the meaning of ‘condition’ as a phrase, but scientifically we cannot measure or allocate unit to it like for example the temperature’ that its unit(s) of measurement have been very carefully defined; we cannot consider the machine to be in 100% condition or 0% condition Consequently there is no CM instruments are calibrated in terms of ‘condition’ so they measure related characteristics of an operation system which can interpret the condition of the machine. When a failure is occurred in a machine it increases energy loss and results in the transformation of sound, heat and the whole performance. These various features construct the basis of most CM techniques.

Since a special CM technique usually consider itself with only one of these features it is obvious that the use of different CM techniques provides a more complete investigation to extract the better conclusion of machine condition. Meanwhile, the achievements of CBM must preponderate the costs related to its performance and these are strongly dependent on the costs of CM, purchase cost, training costs and running costs. On the contrary, failures and degradations in the condition of static structures generally are associated with fatigues like crack growth, plastic deformation and corrosion. Structural condition monitoring which usually called Structural Health Monitoring or Structural Integrity Monitoring is a pioneer concept and is currently less established than machinery condition monitoring

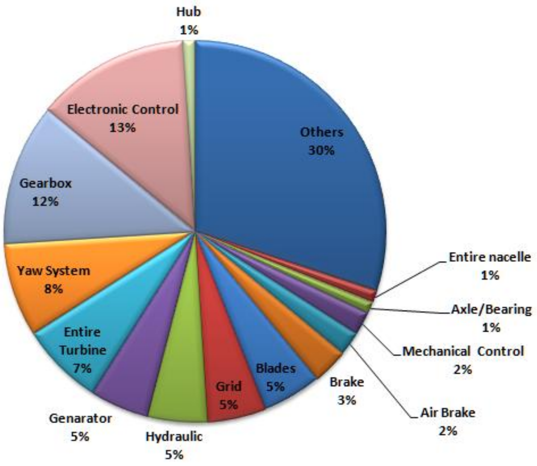


Figure2. Failure rate of wind turbine components

Table 1- specification of references in AE techniques

Number	Year of publication	Data base source	Applied Component	Method
1	1997	Wind turbine in NREL	large fiber-reinforced plastic wind turbine blades	AE monitoring
2	1999	A sewage treatment in small communities	Bearing &Stub shaft	stress wave analysis
3	2001	MHC-Memo portable CM instrument	Bearing & shaft	-
4	2001	Test rig	Bearing gearbox	stress wave analysis
5	2008	Test rig	Bearing NACHI (6203-2NSE) and Koyo (6203ZZCM FG)	Time and frequency domain
6	2010	split torque gearbox (STG)	gearbox	wavelet transform
7	2010	wind turbine bearing test	bearing	Hilbert-Huang transform(HHT)
8	2013	Real wind turbine	Shaft & gearbox	Similarity analysis using Euclidean distance

Vibration analysis is one of the most known and popular approach in condition monitoring of wind turbines which is surveyed comprehensively in [25], [26]. There are two major groups of vibration analysis: 1) broadband analysis, and 2) analysis based on the selected spectral lines. . Basic broadband analysis parameters are: root mean square, peak values, crest factor and kurtosis. Analysis techniques based on selected spectral lines reflect specific frequencies generated by certain components and some of them are gear mesh, low shaft harmonics and characteristic bearing harmonic [27].

For the gearbox and bearing faults that are the most frequent faults in wind turbine wavelet and the Fourier transformation are the two widely used techniques. Chu et al present a novel morphological undecimated wavelet (MUDW) based on morphological coupled wavelet theories. In [2], [3] the authors used the rotor modulating signals spectra for the stator and rotor fault diagnosing. H. Douglas et al. [4] utilized wavelet analysis for detection of the stator faults and [28], [29] have used wavelet analysis for distinguishing of fault signals and the background noise in wind turbine. Mohanty and Kar[5] represent fault detection of a multistage gearbox by applying discrete wavelet transformation to demodulate the current signal. In [15] the authors describe acoustic emission (AE) techniques based on Hilbert-Huang transform (HHT) that were applied to defined the AE signals released from the wind turbine bearing.

3. Background on AE:

3-1. History and Fundamentals:

The research on AE technology has incepted in the middle of the 20th Century. Two historical articles have been already published [30] , [31] and also a comprehensive summary on AE history [32]. One of the AE phenomenon is creaking of timber before breaking that the first report on a scientifically planned AE experiment was done in [33]. F. Forster in 1936 [34] measured very small voltage changes owing to resistance fluctuations and the AE phenomena had occurred by martensite transformations. In the geological field, L. Obert in [35] presented the discovery of micro-seismic emissions in rock and In 1938, he was operating seismic velocity tests in the lead-zinc mines of northern Oklahoma. During the test, spurious signals kept triggering the interval time between two geophones and finally he found out that the self-generated signals of the rock were created the triggering [36].

3-1-1. STAGES IN AE HISTORY

1. Age of Enlightenment (1950-1967)

In the first period in AE history, which is called the Age of Enlightenment, [37]significant improvements were conducted inresearches regarding the fundamentals of AE phenomena and studying AE behavior during deformation and defeat of different materials. The first major effort in AE research in the world was incepted in the U.S. in 1954 by Bradford H. Schofield at Lessells and Associates and various basic reports publications entitled "Acoustic Emission under Applied Stress" [38]. In 1956 Dr. Clement A, Tatro and his graduate students at Michigan State University were performed the second major effort. Harold L. Dunegan started a comprehensive research in *AE* in 1963 At Lawrence Radiation Laboratory (now Lawrence Livermore National Laboratory), after notifying of the paper published by Tatro and Liptai the previous year [39]. His work directly influenced the inception of major efforts in AE research in the U.S., particularly at a number of U.S. Atomic Energy Commission facilities. There were several other research projects conducted during this period which accelerated ongoing work throughout the world.

2. Golden Age of AE (1967-1980)

The *Golden Age* of *AE* initiated in the late 1960s by organizing the acoustic emission working groups and continued to the decade of the 1970s. The working groups gathered all the scientists of AE technology and provided forums for the exchange of ideas and information. They provided a peer review system and a set of awards for identifying prominent work in the field of acoustic emission. One of the more noticeable areas of research strongly followed during this period which was proposed by W.P. Mason, H.J. McSkimin, and W.Shockley in 1948 by B.H. Schofield in 1961, and by P.P. Gillis in 1971, was the study of dislocations being the source of AE that is the most cited research papers in AE by D.R. James and S.H. Carpenter [40].

3. Period of Transition (1980-Present)

Deterioration of heavy industry in the 1980s and driven by economic change the reason for inspection - the practice of inspecting every part provided no added value, only added cost. This change in thinking has concluded into *process control* and *total quality management* which release nondestructive test (NDT) technologies like AE expecting for new fields of application. Today theapplication of AE is very vast in the aerospace and petrochemical industries. Br. Timothy J, Fowler at Monsanto Co. started the AE inspection program of fiber reinforced plastic vessels and piping [41]**.** In this stage the wa*veform-based analysis* has produced a revolution in signal analysis, source characterization, and source location [42]. With the restructuring going on in many European countries, it seems to grow moderately in industrial AE applications and academic research at a number of universities.

4. Application of AE monitoring to process machinery

4.1. Rolling element bearings

The impact of inner and outer races in the rolling action of the bearing elements and rubbing between surfaces within the bearing generates various degradations such as flaking, brinelling, fluting, spalling, pitting, and seizures. The traditional technique for fault detection in rolling bearing is vibration monitoring that measures the response of the structure to the developing fault while AE sensors measure the actual fault mechanism itself especially in low bearing speeds (less than 100 rpm) where AE is substantially more effective than vibration [43]. Furthermore, because of the sensitivity of AE to surface roughness, researchers have found that the lengths of the defect can be estimated from AE spectrum [44](Fig. 3). In industrial applications, signals are more complicated and maybe additional diagnosing techniques may be required is special occasions. However, sufficient indication of early stage faults is possible in the presence of noise [45] .

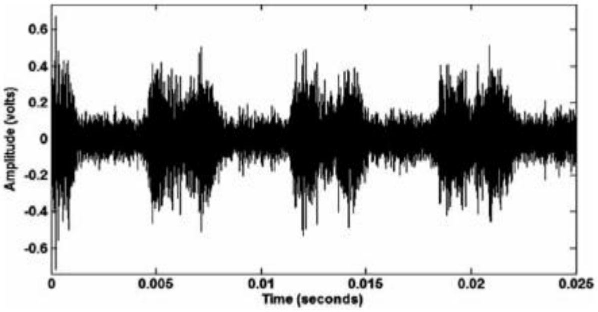


Figure3. Duration of AE burst is indicative of the circumference outer race defect length (width13 mm by length 10 mm) [44]

4.2. Mechanical seals

As industrial studies shows the AE is an effective technique for detecting incipient failures of mechanical seals. With fluctuations in AE energy, features like leakage, dry running, and cavitations in the seal gap have been detected successfully [46-50]. At present some difficulties in fault generating in a controlled environment caused inconclusiveness in development of a strong diagnosis and prognosis for mechanical seals [51]. On the other hand the high sensitivity of AE makes the interpretation become difficult. Previous researches widely reported that AE signals taken from different parts of a system are remarkably larger on star-up when the surfaces face ‘bed-in’ and when the test is restarted signals return to their prior stage [52]. This drawback probably occurred owing to minor changes in process conditions which made the faces adjust to their former positions. When tests were stopped and seals removed for inspection, no faults or anomalies were detected.

4.3. Journal bearings

Albeit one of the most manifest applications for the rotating elements is AE monitoring, it was taken to consideration at a very late stage of investigations. Previous publications have represented that fluctuation in several AE features such as RMS, envelope, kurtosis, impulse density, and etc. have correlation with lubrication regime (full/ mixed/boundary lubrication) and failures [53-55]. The location of AE sensors is one of the common challenges associated with the monitoring journal bearings to capture the signals with less affect of flow noise generated by the bearing’s parent machine (e.g. high speed compressor, steam turbine, engine etc.).

4.4. Gearboxes

Tooth cracking, gear wear, and lubrication breakdown are frequent faults in gearboxes which can successfully captured and detected using different traditional and advanced AE signal analysis methods [56]. Moreover, AE is able to detecting faults and failures in the earlier stages in compare with vibration or wear debris analysis [14]. Unfortunately researches indicate that, as an disadvantage of AE technique, after a defect is established or when monitoring AE levels form rolling bearings, AE bursts have disappeared and caused an increased background level [57]. Applying AE sensors on the rotating gear and the bearing pedestal through a precise study has resulted much greater sensitivity that contributed to developing miniature AE sensors telemetric capabilities [58].

5. Experimental results:

5.1. Low speed test rig

In rolling element component such as bearing and gearbox generally defects occurred during a large period, hence it is necessary to simulate their typical faults in a controlled manner to have a better understanding of the signal characteristics regarding each fault. For this purpose, a low speed machine test rig was developed in the laboratory as shown in Figure 4. The major components of the test rig include: an electric motor, a flexible coupling, three sets of interchangeable rolling element bearings, a speed reduction gearbox, and a variable speed drive and the safety control device. The AE sensors applied in the experiment are the resonance type ‘R6a’ sensors from Physical Acoustics Corporations (PAC).

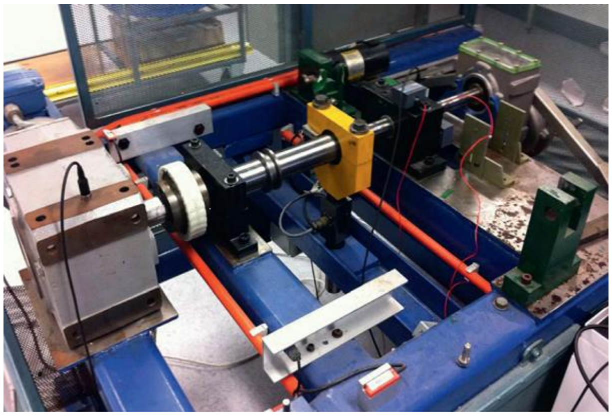


Fig.4. QUT test rig

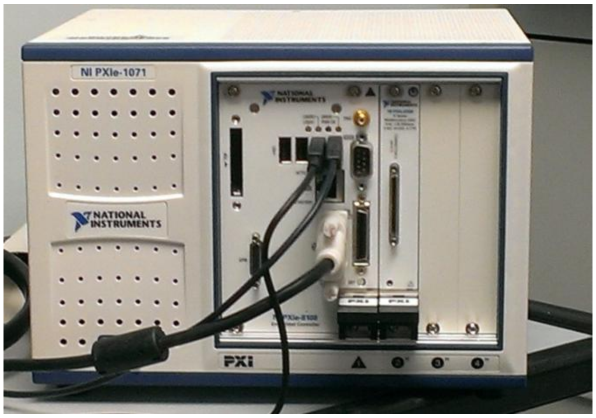


Figure5. PXI data acquisition system

The operating frequency range of the sensors is between 35 kHz and 100 kHz. The signal generated by the sensors was amplified by matching (PAC) pre-amplifiers before being recorded by a National Instrument PXI data acquisition system (fig 5). In the simulating fault experiment A single row cylindrical rolling element bearing (type NSK-NF307) with removable outer ring was used. The bearing has 12 rolling elements, an inner diameter of 35 mm and an outer diameter of 80 mm. to simulate an incipient bearing fault onto the outer race of bearing a very thin scratch was indented as depicted in fig. 6. The AE signals captured from the measurement are used for analyzing on the following section.

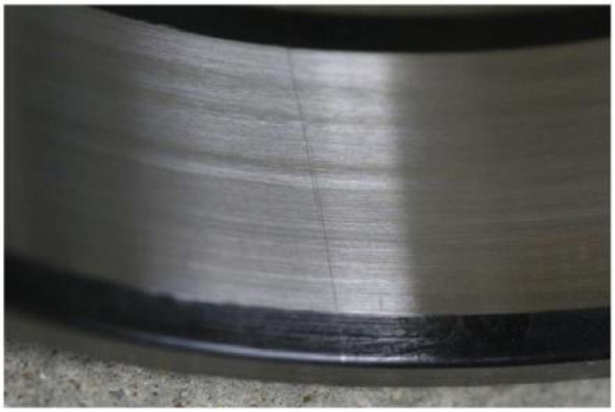


Fig.6. Graphical illustration of the simulated incipient bearing outer race defect

5.2. Time domain statistical parameters

Various methods can be applied for fault detecting and failure diagnosis by analysis the acoustic data obtained from the data acquisition system. Time domain statistical methods are traditional methods which widely used for signal processing and drawing different features of signals [59]. One of the important aspects is be able to summarize the data to extract meaningful and useful features. The principal statistical features are: root mean square (RMS), skewness and Kurtosis. When damage occurs, a pickup in these values should observe. The bearing time domain metrics are calculated based on the following equations where the time signal x(t) having N data points.

5.2.1. Root Mean Square (RMS)

The RMS value illustrates the energy of the signal. Generally the faults are directly detected by the changes in RMS fluctuation level of the signals. In other words, RMS calculated in a certain band frequency indicates a specific value that is almost the same when machine is working under normal condition. Any changes in this value should be considered as a fault. The RMS value is calculated in the following way:

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i)^2} \qquad (1)$$

5.2.3. Skewness

The statistical moment of the third order of the signal is skewness which normalized by the standard deviation to the third power and calculated by the equation bellow:

$$S = \frac{1}{N\sigma^3}\sum_{i=1}^{N}(x_i-\mu)^3 \qquad (2)$$

Where σ is the standard deviation,μ is the average if the signal and $x_i$are the amplitudes of the signal. The skewness of a single point of a signal demonstrates the asymmetry of the probability density function, meaning the deviation degree from the symmetry of a distribution. If it is negative the curve is shifted to the left, if positive the curve is shifted for the right and if it is null the curve is entirely symmetric.

5.2.4. Kurtosis

The other feature that called kurtosis is defined as the fourth statistical moment, normalized by the standard deviation to the fourth power. It represents a measure of the flattening of the density probability function near the average value. Kurtosis is a measure of how outlier-prone a distribution is. The kurtosis of the normal distribution is 3. Distributions that are more outlier-prone than the normal distribution have kurtosis greater than 3; distributions that are less outlier-prone have kurtosis less than 3.

$$K = \frac{1}{N\sigma^4}\sum_{i=1}^{N}(x_i-\mu)^4 \qquad (3)$$

5.2.5. Test rig result

From the comparison of the raw data of vibration signal (Fig.7 a) and AE signal (Fig.7 b) it concluded that the AE technique is more sensitive in detecting the incipient bearing defect than the vibration technique in this experiment[60]. However, the large data size it generate because of the high frequency sampling (i.e., the sampling frequency in this application was

200 kHz) is a major disadvantage of the AE technique for such applications. The following figures show the differences of undamaged and damaged wave form of the Time domain statistical parameters and the increase or changes when the incipient defect was happened. The values were calculated based on a moving window or sub band of the raw signal, the length of the frames is 100 ms which was shifted 50ms.

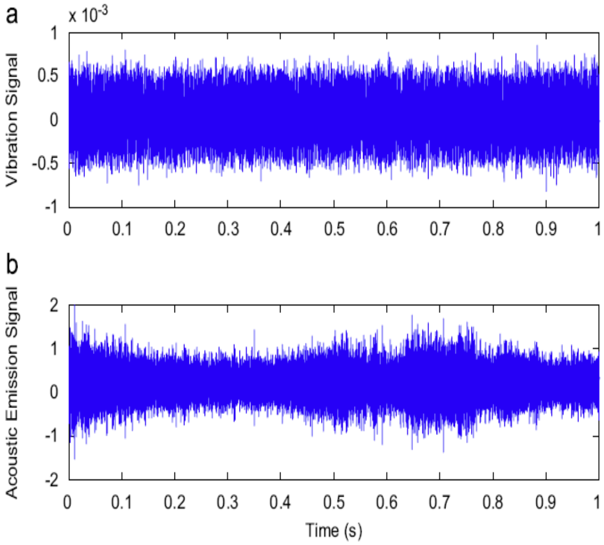
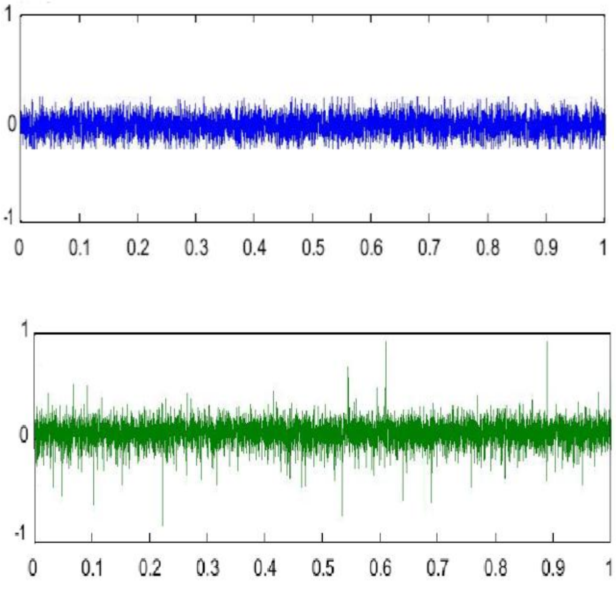


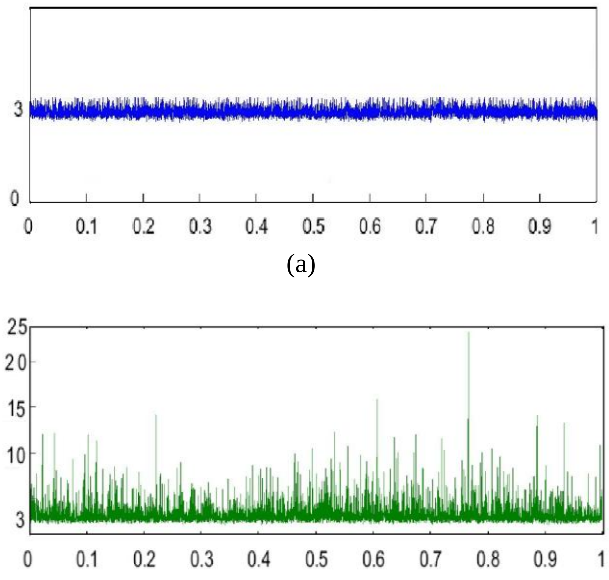
Fig.7. Comparison of the vibration(a) and AE signal(b)



(a)

(b)

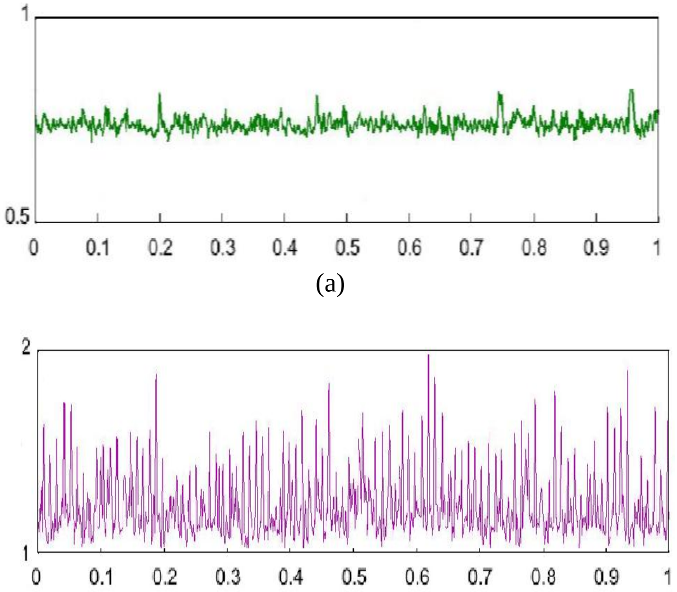
Fig.8. Comparison of the skewness trend of undamaged (a) and damaged (b) signal



(a)

(b)

Fig.9.Comparison of the kurtosis trend of undamaged (a) and damaged (b) signal



(a)

(b)

Fig.10. Comparison of the RMS trend of undamaged (a) and damaged (b) signal

CONCLUSIONS

Acoustic Emission (AE) technique can successfully applied for condition monitoring of low speed rotating components such as rolling bearing and gearbox. This technique is able to detect very small energy released rates from incipient defect in a very early stage. Wide range of signal processing methods can be apply for diagnosing faults and fatigues in AE spectrums and the changes in wave forms are very significant to recognize the failures.

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