International Journal on Advanced Science Engineering Information Technology

Vol.7 (2017) No. 5
ISSN: 2088-5334

Observation of Changes in Acoustic Emission and Vibration Signals to Transverse Crack on Rotating Shaft: An Experiment Investigation

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***Abstract*— This paper focuses on the observation of changes in acoustic emission and vibration signal to transverse crack on rotating shaft. The fundamental difference to other studies is the use of a microphone as acoustic emission sensor placed no direct contact with the part examined. The result of measurements of the acoustic emission signal compared with the vibration signal indicates that the acoustic emission signal apparently was seen and displays the number of maximum spectral peak fewer and amplitude values more consistent. Increasing the shaft speed and the depth of crack increases the magnitude of amplitude.**

***Keywords*— acoustic emission; transverse crack; rotating shaft; vibration; depth of crack; amplitude**

I. INTRODUCTION

There are some condition monitoring machines which are well known and have been used and proven to work well. Some industry already has a well-established machine condition monitoring. The engineer must be good at choosing the right method to get the results established. Condition monitoring is a process of machine condition monitoring through certain physical parameters associated with working operations observed to determine the current status of the device to take action. Each condition monitoring techniques require special features for decision-making algorithms such as neural networks, artificially intelligent, statistical analysis, finite element analysis and others. The data analyzed by various methods, one of which is a method of multilevel I-Kaz [1] to monitor the progression of flank wear during the turning process. A 3-channel Kistler force sensor was assembled to measure the force on the cutting tools. The I-Kaz multilevel method was used to identify and characterize the changes in the signals from the sensors under two different experiments. By applying the decision-making algorithm, the status of flank wear can be predicted and provide an early indication when used in the cutting tool without disassembling it to measure the actual flank wear. The Algorithm of decision making such as finite element analysis applied to engineering as the computational tool to performing analysis planning using technique mesh generation for dividing a complex problem into small elements and the use of software program coded with algorithm Finite Element Method (FEM). Reference [2] using FEA to investigate the fatigue behavior of aluminum alloy 6082. The test conducted for various specimen subjected to the cyclic tensile load to characterize the evolution of the damage, fatigue strength and crack growth sample aluminum alloy 6082. The results showed that the fatigue strength increases with values of stress ratio R. However, the fatigue life a decreases significantly as the pressure ratio lowered. Fatigue cause in the presence of defects and reducing the lifetime of each component.

Acoustic emission analysis increasingly used to monitor the condition of engineering structures such as industrial machinery, vehicles, civic buildings, highways, etc. Railway wheels continuously increased speed and used to work in hazardous environments have a high risk of failure. Reference [3] describes the experimental investigation by applying the Acoustic Emission Technology to monitor the presence of the natural fatigue cracks in the operation of the high- speed shaft. The research showed that the classical AE parameters such as energy, hit and amplitude may indicate failure of the shaft crack. Recent developments encourage movement towards integration algorithm in the diagnosis and prognosis health management system integrated machine of the future. Based on these considerations, acoustic emission technique is one of the effective means of monitoring of rolling element bearings during industrial processes [4]. A linear regression classifier and multilayer neural network models used to correlate AE features selected through appropriate cushioning throughout the laboratory experiments. The results obtained show that the proposed model prediction performance was good and the selection of appropriate signal processing techniques can significantly affect the identification of defects.

Acoustic emission technology is also used to monitor the four-point flexural fatigue crankshaft made of 42CrMo [5]. The specimens divided into two categories, namely, pre-existing cracks and non-existing cracks, which simulates the crankshaft and the new crankshaft. The method parameter analysis technique based on AE, wavelet transform (WT) and SEM analysis are combined to identify the stages of fatigue failure. The results show that the fatigue crack propagation is a transgranular fracture and the fracture is a brittle fracture. The difference is mainly dependent on the shape of crack initiation. AE signal detected by a variety of methods of analysis parameters.

Application of Acoustic Emission (AE) technique to analyze the dynamic response of a different axle cracked performed on the bump test by designing six fractured transverse axis and high-frequency data acquisition system [6]. A wideband transducer AE used to capture the AE signal generated by the bump test models. The signal treated by using statistical moments, wavelet transformation, and time-frequency domain. The results showed that the values of kurtosis and skewness estimated for AE signal could be used to identify the size of the crack shaft.

Technique for detecting crack in the rotating shaft has done with relying on vibration technology but can not be denied that acoustic emission technique was also growing very rapidly as one of nondestructive measurement method to engine condition monitoring. Crack is the beginning of failure due to material fatigue, factory defect, the influence of the chemical environment. A transverse crack is a common form to rotating shaft torque loads experienced repeatedly and continuously. A transverse crack on the shaft tested through research conducted by [7], a test of changes the frequency axis, harmonic components of dynamic system response, and evolution of the orbit as the primary effect because of crack in rotating shaft. Crack that occurred slow moving but significant influences on the reliability of the shaft itself. Crack can lower rigidity and lower resonance shaft speed.

Research related to transverse crack was done by [8] in which the results showed that the presence of crack reduces the critical speed and increase the amplitude of vibration of the rotor system. 2X harmonic vibration cues are visible. The result showed that the crack produces vibration amplitude changes 1X and 2X harmonic vibration and changes more clearly in 3X harmonic vibration. Changes in vibration caused by the presence of cracks on the shaft have also investigated by several researchers [9, 10, 11, and 12]. Changes in vibration response also cause sound changes. Sound changes can be exploited to detect cracked shaft. The rotating shaft interacts with bearing support and produce acoustic emission. Acoustic emission defined as transient elastic wave derived from the interaction of two moving surfaces in relative term.

Acoustic emission technology has been used by [13] to make a critical review of acoustic emission technology application for condition monitoring and diagnostic of rotating machinery. Reference [13] revealed that AE technology offers significant opportunities for development of new technology to overcome a lot of unsolved problems in condition monitoring and diagnostic industry machinery applications. With the speed of technological intelligence development, sensor and data acquisition technology combined with advances in signal processing techniques have widely applied in the fields of engineering, manufacturing, processing and medical. The application of AE technology is growing by using machine condition monitoring, as done by [14] to detect natural crack initiation and crack growth in rotating shaft at slow speed. This study is the first known attempt to correlating AE activity and physical defect in the condition of shaft speed slow and health monitoring of the mechanical integrity of the rotating shaft. Elforjani and Mba present two experimental cases under two load conditions. The results showed that there was a correlation between energy level AE, natural propagation and defect formation of the shaft.

Development of AE technique is also combining two or three methods to get more accurate measurement result, validated, and further development of instrumentation methods. The use of more than one sensor or multi sensory [15] presents a comparison between AE and vibration analysis. Test carried out on the primary source of acoustic emission was concluded that AE offers early detection and identification capabilities over the capacity of vibration analysis. Also, AE technique also indicates the size of the defect, which allows a user to monitor the level of degradation in the bearing which can not achieve with vibration analysis. The combination of the ultrasonic and acoustic emission technique [16] to be a method to monitor crack initiation and growth in the steel pipe straight. The result obtained showed that the acoustic emission technique determines the initial crack earlier than the ultrasonic technology. Initiation crack characterized by acoustic activity higher and higher amplitude peak. While the crack growth cycle, the cumulative number of AE and the right level of correspondence between crack growth and AE signals. This research led to superior sensitivity and reliability of acoustic emission technique to detect crack initiation fatigue and crack growth monitoring for test on specimens pipe. The incorporation of multi-sensor monitoring the development of an increasingly diverse method.

The combination of vibration and acoustic emission method [12] to identify the location and the depth of the crack. Acoustic emission signal is applied in the form of wavelet transform to decompose the signal in the time domain series, where each signal covered with an octave frequency band. Then increased to unity on the boundary and cross-correlation method to detect the location of the cracked shaft. The finite element method is used to create a model rotor cracks, and the depth of crack identified by comparing the response of vibration through experiment and simulation. The research showed that acoustic emission (AE) signal is efficient and able to determine the location of the shaft crack and the vibration signal feasible to establish the depth of the crack.

Acoustic emission measurement result leads to decision-making about the state of the material tested. With only rely on acoustic emission, an instrument is not enough to meet the standard size of AE, but it is necessary to add variables such as load testing. This method used in determining the location and extent of the crack as result of torsional loads as done by [17], where the measurement of crack in some loading conditions that bending load combined a steady torsion influence on the crack length and propagation. Furthermore, [18] also researching with stable torsion on short and long crack in rotating bending treatment. A short crack growth was tested with range factors modifications to strain to see the correlation proportional or non-proportional to provide multi axial loading then made some regular torsion mode to see the crack growth both in the short and length the crack. During the process of crack propagation, crack generating acoustic emission energy. The amount of acoustic emission energy is minimal compared to the surface energy that can produce during crack propagation. For example, in PMMA (Poly Methil MethaClarity), the maximum energy of acoustic emission is only 5% of the surface energy. It has been known for the dynamic theory, that a small disturbance can produce large changes in the dynamics of the system unstable. So the interaction between crack and sound that arise can not be ignored. In the experiment, testing done by [19] showed that there is two Rayleigh wave speed is static Rayleigh wave speed for low frequency and speed for the Rayleigh wave high frequency. This second wave Rayleigh relevant to describe the movement of cracks which depends on high-frequency acoustic waves. These waves emitted by crack.

Based on the literature review some previous studies that apply acoustic emission technology, there are four issues related to the AE sensor. First, the AE sensor is a sensor used in direct contact with parts of the investigation. Second, the AE sensor attached to rotating portion and approaching the location of crack on rotating parts of the machine [12], [14], [20] - [22]. Third, if the AE sensor placed in direct contact with parts that investigated then indeed no different from the accelerometer. Fourth, the failure of fatigue, such as the crack on the rotating shaft can not be measured using an accelerometer. This weakness can only fulfill by placing the AE sensor at a certain distance to record cues acoustic signals emitted by the cracked shaft. This paper is an experimental investigation performed in the anechoic chamber to test the ability of acoustic emission technique to record acoustic emission energy emitted by the crack of rotating shaft. AE sensor used is cardioid type microphone placed at a particular distance from the location of the crack. The selection and placement of AE sensor differ from other AE sensors are applied directly to the object observed.

II. Material and Method

A. Material

This paper is an investigation to observe changes in signal amplitude due to increased shaft speed and depth crack. The technique used is a method of acoustic emission. Accuracy and precision of acoustic emission technique using microphone sensor need to validated by another method that has been proven to detect gestures crack at the machinery rotating. Therefore, the vibration technique also used in this study. Microphone and accelerometer used simultaneously in this study. Tests performed on a test model. This paper is an observation of the experimental investigation of research that has been done before [23]. This article explains the changes in acoustic emission and vibration signals on testing of transverse cracked shafts due to changes in shaft speed and the depth of the crack. This paper also shows the actual conditions of repeated measurements made that lead to the value of relative uncertainty.

B. Experimental Setup

The test model consists of one unit electromotor, coupling, test shaft, roller bearing and radial load. The test shaft is used deliberately in some circumstances shaft. The test shaft consists of three shafts are the healthy shaft (without cracked), the shaft with the depth of crack 25% and 50% of the diameter of the shaft. These shafts named as the healthy shaft, the cracked shaft 0.25D, and the cracked shaft 0.5D, D is shaft diameter notation. Wire cutting produces the transverse crack of the shaft, with length 800 mm, width 14 mm and location of crack on the region of keyway as it has high-stress concentration. The test shaft made of steel DIN 17315A ST 41.

The AE sensor used is Super Cardioid Microphone Type S 1800 XM. Microphone connected to the breakout box of PCI sound card (M-Audio Delta) program Adobe Audition. The sampling frequency of recording process is 44.1 kHz, mono, and 32 bits. The frequency of sampling taken by observing that the electromotor maximum frequency is 5000 Hz, to meet the Nyquist criterion, the sampling frequency must be greater than equal to twice the maximum frequency. The sensor microphone placed at distance 2 cm from the crack location. Determination of microphone distance from the crack location based on the results of the study [24] where the microphone placed at several points of measurement where the microphone position is 2 cm from the crack location. The measuring point 30 and 40 cm is the point that produces spectral signals have an approximately equally amplitude value. The crack location is between 30 and 40 cm measurement points. Data recorded in the sound.wav file extension. In this test, the use of an accelerometer sensor attached to the casing of electromotor. Accelerometer with PCB 352C33 models associated with Lab View program-Ni. The recording process is done in duration 5 seconds and acceleration g = 32.3 ft / s2. Recording sound source can effect of noise environment, and the experiment has done in an anechoic chamber.

C. Experimental Procedure

The procedure begins with the experimental setup of the sensor as shown in Fig.1. The microphone placed horizontally with a distance of 2 cm from the crack location while accelerometer attached to the casing of electromotor at axial direction. The variables used the shaft of the speed from 500 to 1000 rpm and variation of the depth of the crack. Test carried out on the healthy shaft, the cracked shaft 0.25D, and the cracked shaft 0.5D. The first test conducted on the healthy shaft. The shaft of the speed set at 500 rpm and then the model test was run for 15 minutes to reach a stable condition, and the recording done for 5 seconds. Sensors connected to the instrument program. After 5 seconds, the test model stopped, and the next step is to raise the shaft of the speed to 600 rpm. The procedure of loading and acquisition system AE repeated at the shaft speed of 600 rpm to 1000 rpm. The second test on the cracked shaft 0.25D with a variety of the shaft speed as in the first test. Moreover, the last testing on the cracked shaft 0.5D with the same procedure.

Fig.1 Setup of sensor

III. Results and Discussion

Data recording processed through signal processing in time-domain and displayed in graphs Fast Fourier Transform (FFT).

A. Observation of changes in Acoustic Emission Signals and Vibration for Various Shaft Speed

The first observation on the healthy shaft tested at the shaft of the speed 500 rpm to 1000 rpm. The result of the test performed on the shaft speed of 500 rpm is shown in Fig. 2 and Fig. 3.

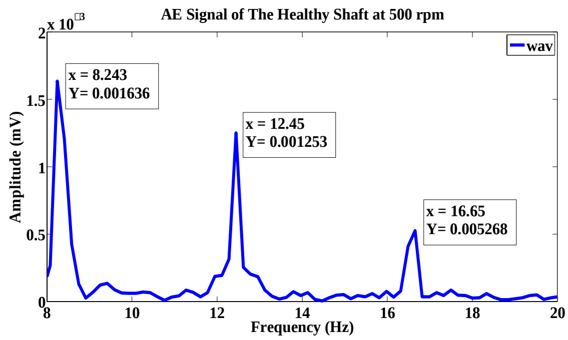

Fig. 2 AE signal of the healthy shaft at 500 rpm

Fig. 2 display the acoustic emission signal (the healthy shaft) at the shaft speed 500 rpm. The acoustic signal that shows in FFT, the peak of spectrum signal not only appear on the frequency harmonic but peak spectrum signal also appears at some frequency. The figure shows, there is three peak amplitude spectrum and the highest peak amplitude at the frequency of 8.243 Hz. If the shaft speed of 500 rpm converted to a unit of frequency, then 500 rpm is equivalent to 8.33 Hz. This deviation is meaningful enough so can be concluded that measurement of acoustic capable of capturing acoustic emission signal. While in Fig. 3 show there is four peak amplitude spectrum. The peak maximum of the vibration signal does not look at the frequency of the shaft speed measured and the number of the peak spectrum more than the acoustic signal. The frequency close to the frequency of 8.33 Hz is frequency 8.399 Hz. There is a deviation 0.069, and this also shows that the vibration technique capable of capturing the vibration signal at the shaft speed of 500 rpm. Striking differences demonstrated by the chart of acoustic emission signal, peak amplitude is fewer in number, and consistent mean amplitude peak has magnitude consistent from high to low. While the chart of the vibration signal is not consistent, that indicates the magnitude of each spectral peak appears randomly and more numerous spectrum peak than the spectrum peak of the acoustic signal. Caused by accelerometer capable of recording vibration at high frequency to low. So it is seen that the emergence of the acoustic emission signal spectrum more clearly and fewer in number. However, it easier to identify the signal.

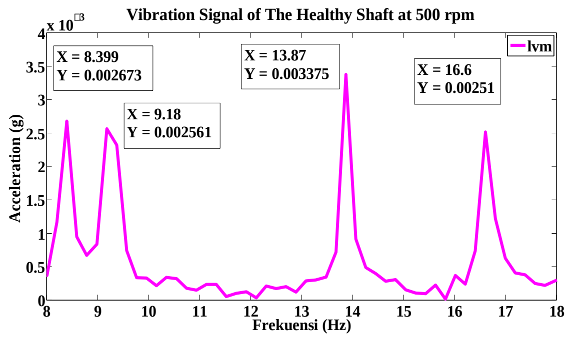

Fig. 3 Vibration signal of the healthy shaft at 500 rpm

To clarify the condition of change signals that appear at the shaft speed of 500 rpm - 1000 rpm, the test result shown in Table I and Table II and plotted in the chart changes in the acoustic and vibration signal in Fig. 6 and Fig. 7.

TABLE I
Changes in Acoustic Emission Signal at The Shaft Speed Variation

Measurement of Acoustic Emission				
Shaft Speed (rpm)	**Frequency (Hz)**	**Amplitude (mV)**		
		The Healthy Shaft	**The Cracked Shaft 0.25D**	**The Cracked Shaft 0.5D**
500	8.243	0.001636	0.002498	0.002929
600	9.925	0.001999	0.0023	0.003154
700	11.61	0.002225	0.002679	0.003823
800	13.29	0.002937	0.003588	0.00407
900	14.97	0.003117	0.003302	0.004439
1000	16.65	0.003711	0.003605	0.004881

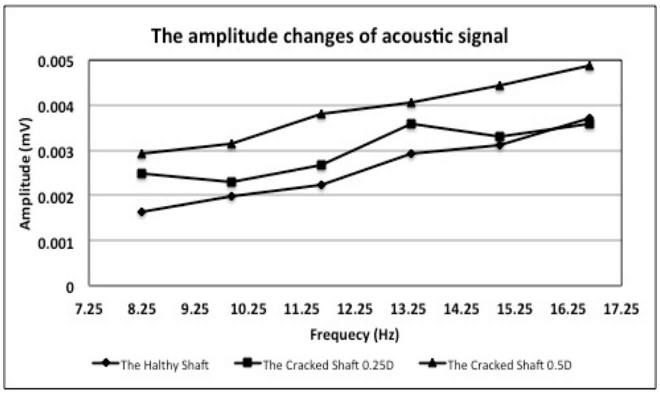

Fig. 4 Amplitude changes of AE signal at the healthy shaft

From the chart on the shaft test (Fig. 4) show that the value of the amplitude change ranging from 500 rpm increased significantly at 1000 rpm. The chart of changes in vibration signal fluctuated diverse (Fig.5).

TABLE II
CHANGES IN VIBRATION SIGNAL AT THE SHAFT SPEED VARIATION

Measurement of Vibration Signal				
Shaft Speed (rpm)	Frequency (Hz)	Acceleration (g)		
		The Healthy Shaft	The Cracked Shaft 0.25D	The Cracked Shaft 0.5D
500	8.399	0.002673	0.002134	0.003407
600	9.961	0.003651	0.002843	0.003829
700	11.72	0.002662	0.00258	0.00262
800	13.28	0.003554	0.003057	0.003413
900	15.04	0.003849	0.003362	0.003812
1000	16.65	0.003004	0.003073	0.003742

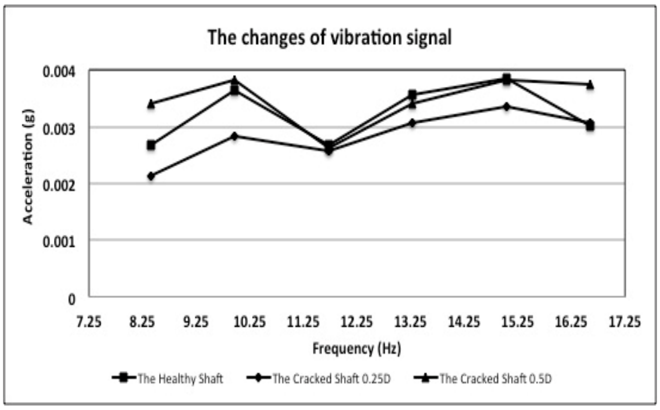

Fig. 5 The changes of vibration signal

B. Observation of Changes in Acoustic Emission Signal and Vibration for Various Depth Crack

The second observation on the cracked shaft with the depth crack of 25% and 50% of the shaft diameter. The result of the test performed on the cracked shaft 0.25D and 0.5D at 500 rpm is shown in Fig. 6 and Fig. 7.

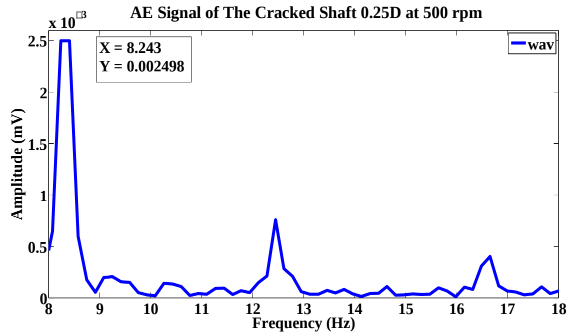

Fig. 6 AE signal of cracked shaft 0.25D at 500 rpm

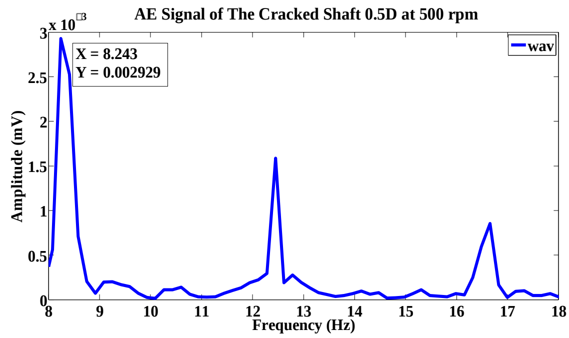

Fig. 7 AE signal of cracked shaft 0.5D at 500 rpm

On the condition of the cracked shaft 0.25D, the chart of the acoustic signal (Fig. 6) at 500 rpm, there is three peaks spectrum amplitude. Likewise, the chart of the acoustic signal, on the cracked shaft 0.5D (Fig. 7), seen three peaks maximum spectrum amplitude. From the two charts can be seen that at the frequency of 8.243 Hz on the cracked shaft 0.25D, amplitude achieved by 0.002498 mV while on the cracked shaft 0.5D mV, amplitude value of 0.002929. Have been changes in the amplitude on two condition of the shaft with different of the depth of crack. The shaft with cracked 50% has values higher amplitude. The pattern of the signal spectrum with the same amount of spectrum peak seen in the chart of acoustic signals on the healthy shaft, the cracked shaft 0.25D and 0.5D. If shaft speed increased to 1000 rpm, amplitude acoustic emission signal at the cracked shaft 0.25D and 0.5D increases, as shown in Table I. It is apparent that the amplitude value of 0.003605 on the cracked shaft 0.25D increased to 0.004881 mV on the condition of the cracked shaft 0.5D. The pattern of the spectrum looks evident and consistent.

The measurement of vibration signal carried on the cracked shaft 0.25D produces a measurable amplitude value of 0.002134 (Fig. 8). If the depth of crack increased to 50%, the amplitude value rose to 0.003407 (Fig. 9). From the result, measurements performed on both the shaft show that the depth of crack affects the amplitude value.

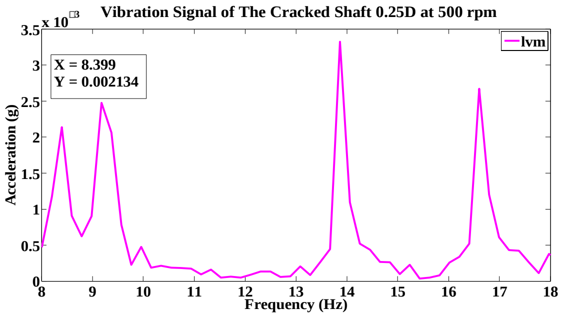

Fig. 8 Vibration signal of the cracked shaft 0.25D at 500 rpm

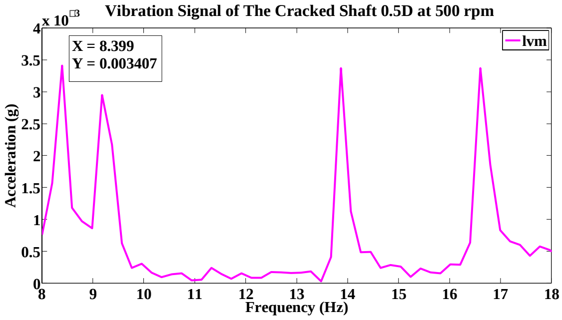

Fig. 9 Vibration signal of the cracked shaft 0.5D at 500 rpm

Changes amplitude of the healthy shaft, the cracked shaft 0.25D and 0.5D with acoustic emission technique shown in Fig. 10.

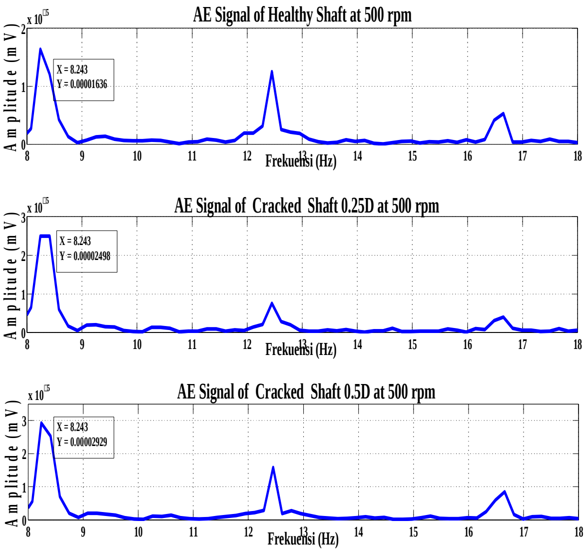

Fig. 10 AE signal of three test shaft at 500 rpm

C. *Observation of Changes in Acoustic Emission Signal and Vibration Based on The Uncertainty*

The vibration measurement used as a reference to validate the measurement of acoustic emissions and determine uncertainty. The results are not in the form of a fixed value but rather a range of values which have the possibility (probability) the correct one another. "True value" of direct measurements expressed as a value - the average of the measurement results.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

Where : $\bar{x}$ = average value
$\sum_{i=1}^{n} x_i$ = the total number of measurements
n = number of measurements

Uncertainty in the value of repeated measurements expressed as standard deviation, which can be calculated by the formula [25]:

$$\Delta x = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n(n-1)}} = \frac{1}{n}\sqrt{\frac{n\sum x_i^2 - (\sum x_i)^2}{n-1}} \qquad (2)$$

Where : Δx = standard deviation

Writing the results of repeated measurements is :

$$x = \bar{x} \pm \Delta x \qquad (3)$$

Given the uncertainty in the measurement, the exactness of the measurement results can see from the relative uncertainty obtained from the quotient value of the uncertainty (Δx) to the actual value multiplied by the formula 100%. Relative uncertainty can be used to determine the degree of measurement accuracy. The smaller the value, the higher the measurement accuracy. In this section, the authors show the value of uncertainty in measuring acoustic emissions and vibrations. Measurements made on the cracked shaft 0.25D on the shaft speed of 600, 700 and 800 rpm. Measurements made three times. For more details, as shown in Table III.

TABLE III
WRITING THE MEASUREMENT RESULTS AND THE RELATIVE UNCERTAINTY

The AE measurement					
i	Amplitude	$\bar{x}$	Δx	$\bar{x} \pm \Delta x$	$\frac{\Delta x}{\bar{x}}$ x 100%
600 rpm					
1	0.002288	0.002078	0.000185	0.002078 ± 0.000185	8.91 %
2	0.001936				
3	0.002012				
700 rpm					
1	0.002618	0.002629667	0.000044658	0.002629 ± 0.000044	1.69 %
2	0.002592				
3	0.002592				
800 rpm					
1	0.003483	0.003433333	0.000184582	0.003433 ± 0.000184	5.37 %
2	0.003229				
3	0.003588				
The vibration measurement					
i	Acceleration	$\bar{x}$	Δx	$\bar{x} \pm \Delta x$	$\frac{\Delta x}{\bar{x}}$ x 100%
600 rpm					
1	0.002401	0.002252667	0.000141571	0.002252 ± 0.000141	6.28 %
2	0.002238				
3	0.002119				
700 rpm					
1	0.002843	0.002685333	0.000139091	0.002685 ± 0.000139	5.17 %
2	0.00258				
3	0.002633				
800 rpm					
1	0.002969	0.003028	0.0000510979	0.003028 ± 0.000051	1.68 %
2	0.003057				
3	0.003058				

Table III shows the relative uncertainty with the shaft speed of 600 rpm on the acoustic measurement is 8.91%

while 6.28% on the measurement of vibration. In the 700 rpm, the acoustic measurement the relative uncertainty is 1.69% while the vibration measurement is 5.17%. It can see that the relative uncertainty fluctuations provide the reason that the acoustic and vibration measurement is affected by the shaft speed and the depth of crack. Another factor worth noting in repeated measures is the stability of the test model: such as the voltage of the electric motor is stable, the condition of the sensor must survive along with the software.

IV. CONCLUSIONS

Observation to signal changes of acoustic emission and vibration for the transverse crack in rotating shaft presented to know the effect of the variation the shaft speed and the depth of crack. The amplitude will increase when the shaft speed increased ranging from 500 rpm to 1000 rpm. Amplitude change also occurs if the depth of crack has grown. The greater the depth crack, the value of the amplitude will increase. Further, from the measurement result obtained showed that the microphone as the AE sensor could record cues crack emitted during rotating shaft. Problems faced so far, during measurement of rotating engine components such as the cracked shaft by attaching the sensor to the nearest part of the shaft and not rotating, such as the bearing casing. The sensor will record as many spectral signals from different sources of vibration signals as possible. The acoustic measurement by placing the AE sensor at a certain distance without direct contact with the shaft can be suggested to record a sound signal indicating a shaft damage. The signal spectrum obtained through the AE method selects a particular signal, and a low-frequency signal will remove. Striking differences shown by the chart of acoustic signal, peak amplitude is fewer in number, and peak amplitude has magnitude consistent from high to low, the peak maximum always appears at the frequency of the shaft speed measured and has the same pattern at various of the shaft speeds and the depth of crack. While the chart of the vibration signal is not consistent, that means the magnitude of each spectral peak appears randomly and more numerous spectrum peak than the acoustic signal. This condition it makes acoustic measurement an easier assessment to identify the failure or damage to rotating components. Acoustic measurements may be proposed to cover the deficiency of vibration measurements on the rotating parts. However, to enhance performance this measurement, we will try to combine with other techniques to repair some of the disadvantages of this method like appearance the peak undesired. Future research will apply other techniques to rotating engine elements. It should add that acoustic and vibration measurements are fluctuating, so repeated measurements recommended for conditions monitoring of rotating machine.

ACKNOWLEDGMENT

Thank Dr. Dhany Arifianto as Head of Acoustics Laboratory Physical Engineering Institute of Technology (ITS) Surabaya who had provided assistance and permission to use anechoic chamber for research. This research supported by Nuffic Program and The Commodity Research Grant Scheme ITS 2011.

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