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FFT ANALYSIS OF BALL BEARING FAULTS USING AE

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ABSTRACT

Early detection of bearing faults in rotating machines plays an important role in industrial plants since it avoids the occurrences of serious failure in many parts of the machinery that causes plant failure. It allows the detection of abnormalities and problems at incipient stages which helps in the early of intervention of maintenance and production personnel to keep the plant running and to avoid serious accidents. Therefore, the ability to predict the bearing failure at incipient stage is of great importance. This paper implements the fast Fourier transforms to analyze the acoustic emission time domain signals obtained from acoustic sensor mounted on the bearing housing of an experimental test. Bearing with various health conditions were used in the test. The acquired time domain signals were processed using Lab View and Mat Lab. The results obtained clearly differentiate between the different health conditions of bearings.

INTRODUCTION

Although the technology and application of condition monitoring is continually evolving, its conceptual basis can be traced back to the earliest development of machinery. The use of human senses to monitor the state of industrial equipment is still valid, although currently augmented by scientific advanced instrumentation. The use of such instrumentation permits to quantify the health or condition of industrial equipment, so the problems can be diagnosed early in their development, and corrected by a suitable maintenance before they become serious enough to cause a plant shutdown. Condition monitoring therefore involves the design and use of sensing arrangements on industrial plants, together with data acquisition and analysis systems in addition to predictive and diagnostic methods, with the objective of implementing equipment maintenance in a planned way using actual condition knowledge (Rao, 1996). Rotating machines are those in which the main working components rotate about a fixed centre in a regular manner. They are very complex devices that involve electrical, mechanical and control systems. Although there are various types of rotating machines, they can be classified into three basic groups in terms of their functions; driving machines, transmission machines and driven machines (Electron, 2003).

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The first group comprises all machines purposely designed to drive other machines. These include electrical motors, steam turbines, diesel engines, etc. The common characteristic of these machines is to convert the sources of energy input into a mechanical output in the form of a rotating drive shaft. Transmission machines transmit the mechanical energy from a driving machine to a driven machine. These include gearboxes, differentials and variable speed drives. The transmitted mechanical energy undergoes a speed transformation; therefore these machines incorporate some means of driving disengagement such as a clutch. The third group of machines needs to be coupled to a driving machine through appropriate coupling element.

They include pumps, compressors, generators, blenders and fans. The energy input is commonly in the form of a rotating drive shaft while the output may include electrical energy, kinetic or potential energy of fluid or solid materials, etc. Rotating machines are recognized as the core and fundamental equipment of most engineering systems such as petrochemical plants, automotive industry, power stations, oil and refinery that necessitate precise and ingenious performance. Bearings are of supreme importance to approximately all types of rotating machinery, and are among the most common machine elements. Bearings have three main purposes in rotating machinery: they locate the rotational axis, reduce friction and carry radial and thrust loads.

Because of their wide spread use, major problems in the machinery are due to bearing faults and failure. These failures are one of the foremost causes of breakdown in rotating machinery and can be catastrophic (Mukherjee, 2006; Kauschke and Eggert, 2002). It is therefore necessarily to monitor and diagnose the bearing health condition to avoid serious problems that can lead to catastrophic machine failure.Rotating machines are recognized as the core and fundamental equipment of most engineering systems such as petrochemical plants, automotive industry, power stations and oil refinery that necessitate precise and ingenious performance. Bearings are of supreme importance to approximately all types of rotating machines, and are among the most common machine elements (Mukherjee, 2006; Kauschke and Eggert, 2002; Yang, 2007).

Because of their wide spread use, major problems in the machines are due to bearing faults and failure. It is therefore necessary to monitor and diagnose the bearing health condition in order to avoid serious problems that can lead to catastrophic machine failure (Kauschke and Eggert, 2002; Yang, 2007). A particular problem associated to rotating machines in manufacturing industry is the rolling element bearings. The deterioration and malfunctioning in bearings lead to catastrophic machine failure and human injury. Therefore the performance of the machine can be maintained by monitoring and diagnosing bearings health condition. In this study rolling elements bearings are used in the experimental setup to demonstrate the viability of the technique. Figure1 represents the structure of the ball bearing (Kauschke and Eggert, 2002; Yang, 2007).

Generally, rotating machines faults are due to rotor imbalance or shaft misalignment, overload, over-speed, high or low temperature, humidity and a number of other hazards. These defects produce vibration signals on the structure of the machine at frequencies ranging from 50 Hz to 20 kHz. Bearings failure and deterioration associated to these faults produce flaking, spalling, pitting, seizure, fluting, etc. All these types of defects generate stress waves with high frequencies that propagate to the structure of the machine. Detection and analysis of these signals are the basis of acoustic emission testing (Kauschke and Eggert, 2002; Yang, 2007). AE is the elastic energy spontaneously released by material undergoing deformation. AE is thus a wave phenomenon and AE testing uses the attribute or characteristics of these waves to characterize the material/ process. AE waveform is the convolution results of three effects; generation at the source, propagation and measurement. Two of the most common waveform parameters are frequency and amplitude (McFadden and Smith, 1999; Grosse, 2008; Hardy, 2003). AE refers to a group of phenomenon where transient elastic waves generated due to rapid release of energy from localized source or sources within a material. The generation of AE is a mechanical phenomenon, and can originate from a number of different mechanisms. Mechanical deformation and fracture are the primarily sources of AE, but phase transformation, corrosion, friction, and magnetic processes among others also give rise to AE. The energy thus released travels as a spherical wave front and can be picked up be from the surface of material using highly sensitive transducers.

The transducer element is always a piezoelectric crystal. The piezoelectric effect occurs when pressure applied on a crystal with unit cells that exhibit no centre of symmetry will develop an electric field. The majority of AE equipment is responsive to movement in its typical operating frequency range of 30 kHz to 1 MHz (McFadden and Smith, 1999; Grosse, 2008; Hardy, 2003).

Experimental Setup

AE technique is based on the detection and conversion of the high frequency elastic waves to electrical signals. This is accomplished by firmly mounting a sensitive piezoelectric transducer on the surface of the structure under test. An essential requirement in mounting a sensor is sufficient acoustic coupling between the sensor face and the structure surface. Application of a couplant layer should be thin, so it can fill the gaps caused by surface roughness and eliminate air gaps to ensure good acoustic transmission. This can be attained by using glue, holding device such as tape, elastic bands, spring and magnetic hold-downs. The transducer converts the mechanical energy carried by the elastic waves into an electrical signal. An emblematic AE system includes a sensor; signal conditioning electronics, measuring devices, signal processing and data analysis equipment. Figure 1 represents a principle of AE together with the sensor and AE instrumentation (McFadden and Smith, 1999; Grosse, 2008; Hardy, 2003).

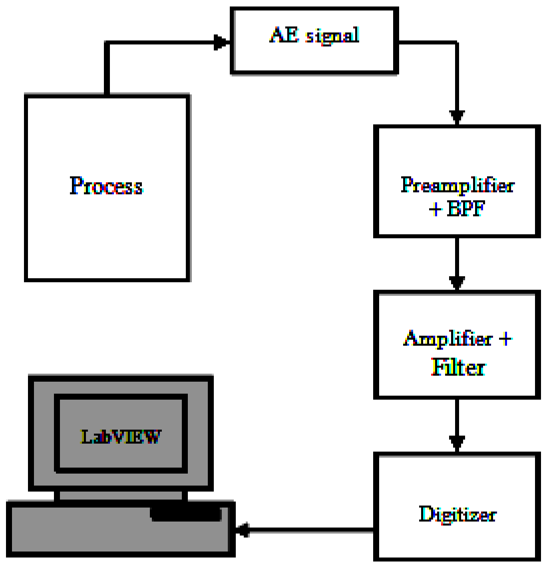

Fig. 1. Principle of AE

The setup shown in Figure2 is developed to perform the laboratory experiments and mainly it comprises of three parts: process part, signal conditioning electronics, signal processing and data analysis. The setup is designed to be operated for various motor speeds, different loads and bearings of various operating conditions. The mechanical part of the test rig consists of a three phase electrical motor coupled to a steel shaft through flexible coupling element. The coupling helps prevent vibrations originating in the motor structure. The shaft is supported on two bearings assembly and driven by the motor.

AE sensor (model WB DIFF AE sensor/ 1m integral cable) is mounted on the roller bearing. A thin layer of couplant grease is applied between the sensor face and the bearing housing in order to fill the gaps caused by surface roughness and to eliminate air gap to ensure good acoustic transmission. This type of sensor is used to get high fidelity and frequency analysis of AE signals as well as providing useful information about the bearing condition and for noise discrimination (Hardy, 2003; Physical Acoustics Corporation, 2003). AE signal is amplified and filtered and amplified using the signal conditioning electronic circuitry. The resulting high-frequency AE analog signal output is connected to TEKTRONIX TDS3012B digital storage scope in order to view a cause and response relationship (Tektronix, 2005).

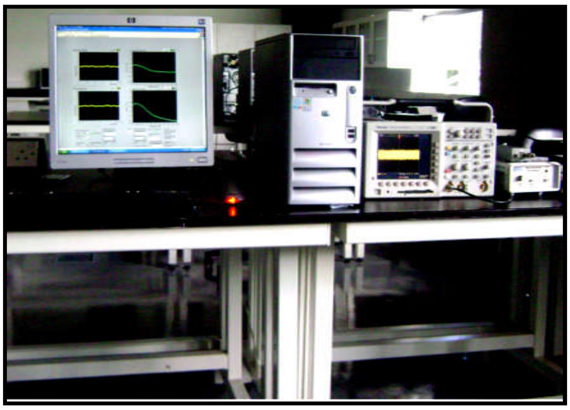

Fig. 2. Proposed experimental setup

The Tektronix oscilloscope is interfaced to PC using the National Instrument general purpose interface bus (NI GPIB 488-2). GPIB is configured using Measurement and Automation Explorer (MAX) (Tektronix, 2005). An AC variable voltage power supply is used to supply the motor. It is properly connected between the motor windings to make the forward and reverse rotation. The voltage supply is varied to set the required motor speed. Prova Tachometer (10 rpm-100000 rpm) is used to measure the speed of the motor.

Fig. 3. EDM Machine

Bearings Defect Creation

The experimental tests are conducted by using bearings type 6203 from different manufacturers. Several measurements are carried out for normal (healthy) bearings, poorly lubricated bearings and defective bearings. The electrical discharge machine (EDM) shown in Figure3 is used to seed defects of different sizes in the bearing assembly. The defects are seeded in the inner race, outer race, rolling element and cage.

Signal Conditioning Electronics

Signal conditioning electronics is a one of the most important parts in the measurement and automation systems. It provides the interface between the sensors output and the measurement system. In general, the output voltages of the transducers are very small accompanied by some sort of noise. Therefore, an appropriate electronic circuitry is required to eliminate the noise and to amplify the output voltage of the sensor. It comprises of three main elements: preamplifier with plug in band pass filters, amplifier and digital storage oscilloscope.

The Tektronix TDS3012B digital phosphor storage oscilloscope with speed of 100 MHz and sampling rate of 1.25 G S/s is configured to interface the process to PC the computer through the general purpose interface bus (GPIB). The oscilloscope automatically selects the normal acquisition which can acquire a maximum of 10000 points to capture and analyse the signal. Time and frequency domain analysis of the acquired data were obtained to provide the information regarding the health condition of the bearing under test (Tektronix, 2005).

Spectrum Analysis

The samples of AE signals obtained from TKT3012B oscilloscope constitute time domain representation of the signal. This representation provides the amplitudes of the signals at the instant of time during which it is sampled. To get the frequency content of the signal a representation in terms of individual frequency components known as frequency domain is required (Nathan and Ciocan, 2003). The frequency domain representation can give more insight about the signal and the system from which it is generated. In this regards spectral measurement using fast Fourier transform (FFT) and power spectral VIs are used to transform samples of AE time domain into frequency domain signals. In order for any FFT to present the correct frequency components of a signal, it is required to ensure that the oscilloscope samples at a rate which does not violate Nyquist theorem which states that: the sampling rate must be larger than two times the highest frequency component required to be detected in the signal. However, a general rule is to sample at 10 times the largest frequency in order to have a nice time-domain representation of the signal (Nathan and Ciocan, 2003). TDS3012B Tektronix oscilloscope automatically sets the proper sampling rate since the AE signal characteristics are within the oscilloscope's specifications (100M Hz, 1.2GS/s).

Signal Processing and Data Analysis

The AE signals captured from bearing housing of the test rig are amplified, filtered and digitized through the signal conditioning electronics mentioned in the previous sections.

Table 1. The AE data obtained for normal bearings

AE parameter	Bearing type	Test No.1 2000 rpm, 50N	Test No.2 2200 rpm, 50N	Test No.3 2000 rpm, 100N	Test No.4 2200 rpm, 100N
Amplitude , Vpp	FAG	1.3	1.8	1.3	2.1
	SKF	1.5	1.9	1.6	2.2
	KOYO	1.7	2.2	1.7	2.3
	NACHI	1.4	2	1.4	2.1
	MALEX	1.6	1.9	1.5	2.2
Peak Frequency , k Hz	FAG	100	95	100	95
	SKF	100	100	95	100
	KOYO	100	100	100	95
	NACHI	100	100	100	100
	MALEX	95	100	100	100
V2 rms, Db	FAG	-65	-60	-58	-60
	SKF	-10	-20	-60	-58
	KOYO	-15	-18	-55	-60
	NACHI	-55	-60	-60	-60
	MALEX	-45	-55	-60	-60

GPIB is used to interface the oscilloscope to PC. It is configured by Measurement and Automation Explorer (MAX) of National Instruments (NI). The Tektronix oscilloscope instrument driver TKTDS3K is installed to enable the communication between the oscilloscope and Lab VIEW. The data acquired from the measurements are analyzed using NI LabVIEW. Using MAX and oscilloscope utilities, the oscilloscope address1 is selected and LabVIEW is run. By utilizing the LabVIEW programming functions (using front panel and block diagram) a programme called Virtual Instrument (VI) is built. The programme is developed to enable the communication between the oscilloscope and LabVIEW.

Initially, the measurements are carried out using a load of (50 - 100) N and different motor speeds. The motor speed is controlled by varying the supply voltage and checked by Prova Tachometer. The acquired AE signals are displayed on the Tektronix TDS3012B oscilloscope. A LabVIEW programme is started and AE time domain signal is displayed on the PC monitor.

Measurement on the Test Rig

The purpose of the first phase of the experiment is to study the behaviour of healthy bearings. A series of experiments are performed for several sets of bearings to study the patterns of AE signals. The LabVIEW filter VI is also used to filter out any source of unwanted signal that accompanies the AE data before being processed and analyzed using the spectral analysis VI. The AE data obtained from the measurements carried out on the experimental test rig using healthy bearings with loads and motor speeds are summarized in Table.1.

Notably, under the specified operating conditions the AE signals captured from bearing housing have similar characteristics. A continuous type AE signals are observed. The maximum amplitude of the time domain AE signals does not exceed 2.3 Vpp. The amplitudes increase with increasing the motor speed (see the dashed areas in Table 1. On the other hand, it is observed that the increment in loads does not present significant increase in the AE signal amplitudes.

Each test is repeated for several times and the results are used for comparison. The FFT analysis of time domain signals for all types of bearings used shows that no peak signals present for the whole frequency range of the AE sensor. Nevertheless, a peak at 100 kHz persists in all analysis. This peak frequency corresponds to -20 dB of power spectrum (V2rms), for most of the measurements conducted. It is known as the resonant frequency of the sensor.

Measurements on Poorly Lubricated Bearings

The main features of the proposed AE technique are to detect the on-set of failure in bearings. This can be done by having a part of lubrication grease removed from a healthy bearing.
For this condition, the bearing is considered as poorly lubricated. This test is performed in the following manner:

- Completely confiscating lubrication grease using soap solution.
- Lubricating the bearings using a little amount of grease.
- Lubricating the bearings using a reduced amount of grease.

Following the preparation of poorly lubricated bearings as prescribed in the previous steps, several measurements are performed by running the experiments on the test rig. Similar procedures applied for the case of healthy bearings are implemented here. The acquired time domain AE signals and the corresponding frequency spectrum for several test replications are presented. Particularly, sample patterns of the results attained at motor speed of 2000 rpm and load of 50 N were summarized in Table 2. It could be observed that for bearings without lubrication grease, the amplitudes of AE signals are of high values that rises up to 9.3 Vpp. These values decrease gradually with increasing the amount of lubricant. The amplitude of about 2.8 Vpp is observed for bearings being lubricated with reduced amount of grease. On the other hand the FFT analysis doesn't show any peaks except the one at 100 kHz which is the resonant frequency of the sensor. This frequency appears at V2rms of about -20 dB, for most frequency spectrums. Nevertheless, a peak at 125 kHz appeared in the spectrum of KOYO bearing when the lubrication grease is entirely confiscated.

Test No	Amount of Lubrication Grease	Amplitude, Vpp		Peak Frequency , kHz		V2rms, dB	
		SKF	KOYO	SKF	KOYO	SKF	KOYO
1	Without	9.2	9.3	100	100, 125	-20	-20
2	Little	7.2	7.4	110	100	-15	-20
3	Reduced	2.8	2.7	95	95	-18	-20

By comparing the results shown in Table 1 and Table 2, the following conclusions can be summarized.

- The AE signals for poorly lubricated bearings provide amplitudes which are considerably higher as compared to that of healthy bearings (the dashed areas in Tables1 and 2.
- Generally, under various motor speeds and loads applied to the experimental rig, the FFT analysis of the acquired AE signals do not demonstrate any peak in the frequency spectrums of healthy and poorly lubricated bearings.
- Nevertheless, a peak at 100 kHz persists in all measurements. This peak is due to the resonance frequency of the sensor. Detection of AE signals using the proposed technique gives insight about the recognition of bearings health condition, since it can clearly differentiate between the signal amplitudes of normal bearings and poorly lubricated bearings.

Measurements on Defective Bearings

In evaluating the effect of bearing faults on AE signatures, there are other problems that can be studied. The EDM machine can be used to create faults of different sizes the main parts of bearings assembly. The faults to be generated include the inner race, outer race, rolling element and the cage. Several measurements under loads of 50N and 100N, motor speeds of 1500, 2000, 2200 and 2500 rpm, and bearings of various defects were carried out. Some of the results obtained are shown in Figures 4 and 5.

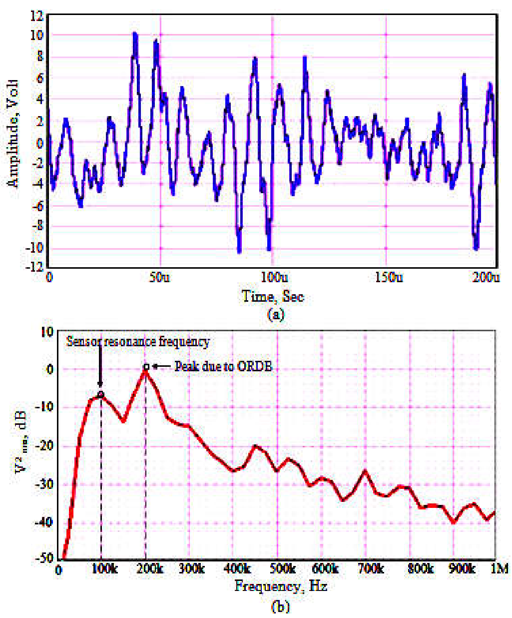

Fig.4. The AE data of ORDB. (a) TD (b) FS

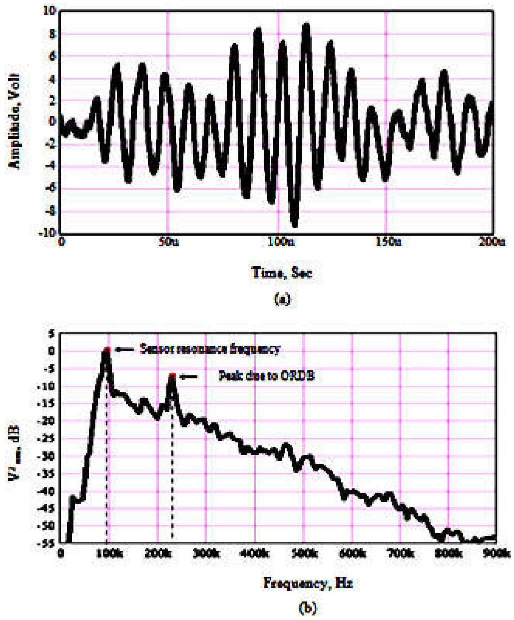

Fig.5. The AE data of ORDB. (a) TD (b) FS

Table 3. Time domain AE Signal Amplitude for Bearings of Various Health Conditions

Test No.	AE Amplitude in Volts		
	Healthy bearing	Poorly lubricated bearing	Outer race defective bearing
1	1.08	4.2	7.6
2	0.84	7.12	10.2
3	0.84	5.2	7.6
4	1.12	3.56	6.6
5	1.16	2.64	22.2
6	1.84	3.4	19.8
7	2.32	4.8	7.4
8	1.16	3.6	9.6
9	1.76	3.2	8.6
10	1.08	3.4	6.2
11	0.88	5.4	19.2
12	2.6	4.6	11.2
13	1.92	4.48	7.6
14	1.16	5.6	23.4
15	2	4.4	10.2
16	1.96	5.2	7.6
17	0.92	4.2	6.6
18	1.32	3.44	22.6
19	2	6.1	22.2
20	1.48	4.4	7.4
21	1.6	5.6	10.1
22	2.2	3.4	8.6
23	1.28	3.2	19.2
24	1.88	3.84	11.2
25	1.2	4.4	10.4
26	1	4.4	10.6
27	1.68	5.1	13.8
28	1.84	4.4	20.4
29	1.12	3.2	15.8
30	2.12	3.2	6.2
31	2.16	4.24	22.6
32	1.4	3.76	11.4
33	2.32	3.36	13.6
34	1.24	4	6
35	2.04	4.6	22.8
36	1.92	3.36	8.6
37	1.52	4.6	14.4
38	1.16	3.8	10.6
39	2.2	4.8	23.2
40	1.68	3.44	22.6

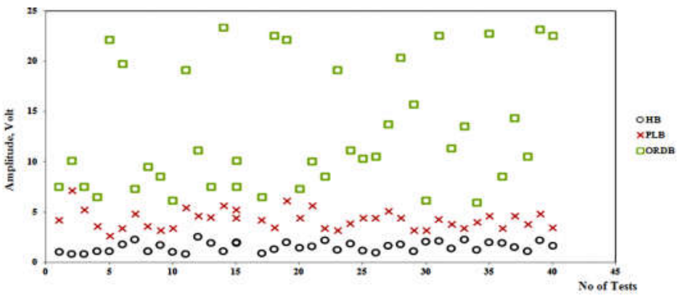

Fig. 6. AE amplitudes for bearings of Different operating conditions

It could be observed that the bearings with small size defect indicate relatively small signal amplitudes (11.4 V and 10.9 V) at the motor speed of 2000 rpm. However, at speed of 2200 rpm the amplitudes are almost doubled. The bearings with defect size 1×1 mm2 produce a high value of AE signal amplitudes at both operating speeds. In comparison to the AE signal amplitudes obtained for the SKF ORDB to those described in Table 1 and Table 2, it can be deduced that the AE measurements performed are able to distinguish between the healthy, poorly lubricated and outer race defect bearings. Unlike the healthy and poorly lubricated bearings, the FFT analysis for outer race defect bearings show peaks of various frequencies. The maximum peak frequency is 525 kHz.

Comparison of the Measurement Results

In order to understand the pattern of AE signals for a set of bearings with various health condition, several tests are conducted at a motor speed of 2200 rpm with a load of 50 N. SKF bearings are used in the tests and each test is repeated for several times. A sample of the maximum amplitudes of time domain AE signals obtained are shown Table 3. Using the data obtained in Table 3, the results are plotted as shown in Figure 14. These show a significant variation in the maximum amplitudes of SKF bearings with different health conditions. It can be concluded that the amplitudes of healthy bearings are quite small in comparison to others. Onset of failures could be observed in the area of poorly lubricated bearings which just preceded the healthy bearings. The ORDB amplitudes are quite distinct as compared to healthy bearings and poorly lubricated bearings and their values in general show the maximum amplitudes.

Using the data obtained in Table 4, the results are plotted as shown in Figure 6. These show a significant variation in the amplitudes of bearings with different health conditions. It can be concluded that the amplitudes of HB are quite small in comparison to others. Onset of failures could be observed in the area of PLB which just preceded the healthy bearings. The ORDB amplitudes are quite distinct as compared to healthy bearings and poorly lubricated bearings and their values in general show the maximum amplitudes.

Conclusion

The experimental test rig results show the capability of the proposed AE technique to distinguish between normal and faulty bearings. It is found that the acoustic signal amplitudes of normal bearings do not exceed 2.2 V_{pp} for the whole measurements. These values are increasing progressively for poorly lubricated, caged defect and rolling elements bearings. The maximum amplitudes are observed for the outer race defect bearings. These results are found in good agreement to the state of art of AE bearings. On the other hand, the spectrum analysis of the time domain AE signals of defective bearings show peaks at high frequencies ranging from 100 to 300 kHz. Also the results shown for bearings with rolling element and cage defects can give more insight for condition monitoring of bearings since not much research is carried out for these parts of bearings. The time domain AE signals shown throughout the results represent the signals which are displayed by LabVIEW at the instant of averaging completion. All other AE time domain signals which are observed during averaging have exactly the same characteristics. The FFT analyses performed by programming the storage oscilloscope are in good agreement with the results obtained using LabVIEW spectrum analysis VI.

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