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Acoustic Response of 100 Cr 6 (SAE 52100 chrome steel) Material Ball Bearing in Experimental Oil Starvation Failure Modes

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Abstract

Bearing is the most active rotating element in dynamic mechanical systems. Materials which are used in rotating elements face with faster deterioration due to vibration and acoustic emissions. Frictional effect on bearing components may have different characteristics in acoustical response with respect to surface and micro-structure features. Particulary, oil starvation occurs in bearings by the time; and the material of the inner race, outer race, balls requires higher priority for preventing internal and external failures. In this study, some failure modes are experimented with a ball bearing made of 100 Cr 6 (SAE 52100 chrome steel) and evaluated with respect to the material's acoustic response. Oil starvation single failure mode, oil starvation-horizontal misalignment double failure mode and oil starvation-unbalance-horizontal misalignment triple failure mode are studied in various levels. As rotational speed, failure amount and failure level increase; acoustic signal response and acoustic RMS intensity increase as well, which may lead to deterioration on the material of the bearing. According to the conclusion; characteristic failure signals are achieved in time-domain and frequency-domain at various rotation speeds, and also found that overall root mean square (RMS) values of the acoustic signals are in an increasing trend with respect to the energy on material deterioration. Each failure has characteristic features and they become more prominent with respect to the failure intensity in synchroneus failure modes.

Keywords: steel, acoustic, oil starvation, misalignment, condition monitoring, unbalance

1. INTRODUCTION

The purpose of this study is researching single, double and triple failure modes through acoustics analysis with respect to the overall sound pressure. Sound waves carry energy that is absorbed by the materials which may lead to deterioration consequencing in vibrations. The importance of the study is working on identification of simultaneous failures by acoustics analysis and assessing the efficiency of the technique for simultaneous failures.

Condition monitoring based maintenance spreads among industrial areas with an increasing trend in order to reduce the maintenance cost and increase the health sustainability in mechanical systems.

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Analysing and comparing the data gathered in faulty and non-faulty conditions brought more sensitive decisions for maintenance activities within developments in electronics and computer technologies.

Condition Based Maintenance (CBM) is the model base on collection of physical data, interpretation of the data and taking precautions in order to keep nominal functions of the machine in the desired level [1].

Some parameters are in broad use to detect mechanical failures such as acoustic, temperature, oil, vibration or energy consumption [2]. Acoustic emission technique is a non-destructive condition monitoring approach for identifying failures on rotating elements [3].

Detection of the defect size on bearings is possible with analysis of acoustic emission. This technique is especially useful for bearing manufacturers in identifying homogeneity of bearing material [4].

Nagata and others studied tribological effects on plain bearing by acoustic emission technique in two conditions as lubricated and non-lubricated on an experimental test setup. They found that acoustic emission is quite useful for detecting lubrication condition of frictional surfaces and wear-out features of bearing's material [5].

Al-Ghamd and Mba, in experiments of surface roughness on bearing rings, they concluded that acoustic analysis detects failures earlier than vibration analysis. Also, they declared that it is possible to detect size and development of the failure by acoustic analysis, which can not be accomplished by vibration analysis [6].

Tandon and Choudry declared in their study that acoustic response method is successful in non-destructive testing of bearing materials; particularly for surface properties and some other structural defects such as cracks [7].

Elforjani and Mba practised experiments with ball bearing and roller bearing on an experimental setup consisting of electrical geared motor coupled with shaft that is connected to hydraulic load system. They evaluated spectrum and root mean square (RMS) data of the acoustic measurements and eventually declared that the technique is very useful for testing homogeneity of the bearing material [8].

Faris et al. conducted a research on bearing defects with comparison of acoustic emission and vibration techniques. They declared that vibration technique is suitable for big defects on bearing and acoustic technique is successful for detecting both big and small defects on bearing [9].

Sun and others experimented wear properties of ball bearing steel on an experimental setup in different time intervals in three wear regimes. They concluded that acoustic emission method is very useful detecting the correlation between acoustic emission RMS and wear mechanism [10].

Tan et al. studied the pitting phenomenon on spur gears by acoustic emission, vibration and oil analysis. They reported that RMS levels of acoustic emission is directly interacted with the scale of the pitting and acoustic emission technique is a good indicator for following machine health [11].

The effect achieved on rotor by unbalance is one of the causes that bring out some physical symptoms. This type of failure will show increasing amplititude in harmonics, but the reason of these harmonics might be some other failures as well [12].

Babak et al. studied shaft breakage with acoustic emission, vibration and current analysis on an dynamic gearbox system. They reported that wear on gear was detected by acoustic and vibration analysis, but not with current analysis [13].

Eftekharnejad et al. worked on condition monitoring of naturally degraded bearings by acoustic emission and vibration techniques. They stated that acoustic emission technique was more sensitive in detection of bearing defects [14].

The most basic diagnostic approach on failures in the time-domain is RMS calculation. Effective power rate of the signal is calculated as root mean square value and helps for detecting various failures. Especially, very useful in detecting unbalance in rotating systems [15].

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + \cdots + x_n^2\right)}.$$

In this research study, acoustic response of 100 Cr 6 (SAE 52100 chrome steel) material ball bearing was investigated on a test setup within two different rotating frequencies under oil starvation failure as the main failure. Misalignment and unbalance are the sub-failures whose characteristics are examined as simultaneous phenomenons in laboratuary conditions.

Material of the tested bearing has been chosen is 100 Cr 6 (SAE 52100 chrome steel) within advanced micro cleaning and reduced containment ingredient. The initial phase of manufacturing begins with hot forging and cold roll forming process. Cages and shields are manufactured through deepen drawn steel strip in many stations, completely automated presses [16].

Overall information about experimental setup, measuring method and findings are given in further sections.

2. EXPERIMENTAL STUDY

This experimental setup system has been inspired from flue gas fan of an cement production factory. Experimental setup consists of AC induction electric motor, two inlet radial fan, five pin flexible coupling and electrical frequency inverter. The experimental setup is mounted on a steel plate and rigid frame system stand which is supported with plastic damping material between the experimental set and the stand, and also the plastic vacuum footings at the base of the stand. The experimental setup is blocked with plexiglass cabin for isolating and protecting the system. Whole system is synchronised with computerized measuring system that has data acquisition card with one acoustic sensor. Acoustic measurement system has relevant software for interpreting the acquised data.

Experiments have been implemented with two different rotational speeds and various levels specified in tested failure types. Acoustic measurements are taken within one direction as vertical on the electrical motor with an omni directional acoustics sensor. Overall view of the experimental setup and other components of the experiment is shown in Figure 1.

Figure 1. Overall view of the experimental setup

3. MEASURING METHOD

Measurements are done in synchronous time for simultaneous failures. For the acoustic signal analysis, every measurement data has been taken from one direction as vertical on the electric motor.

Experimental plan:

Failures: (a) Oil Starvation (OS)

(b) Horizontal Misalignment (HM)

(c) Unbalance (U)

Experiment 1 : Oil Starvation (OS)

Experiment 2 : Oil Starvation (OS) - Horizontal Misalignment (HM) (level I ; level II)

Experiment 3 : Oil Starvation (OS) - Horizontal Misalignment (HM) - Unbalance (U) (level I ; level II)

A clutch degreaser is used in order to build condition of oil starvation. Whole oil removed from the bearing and 0.55 g oil applied in order to create condition of insufficient lubrication. SKF brand various thickness steel shims are placed next to two rear legs of the electric motor with respect to the experimental order to practise misalignment phenomenons. A mass loaded on a wing of the fan for creating unbalance. Basic information is given below;

Oil starvation level : 0.55 g

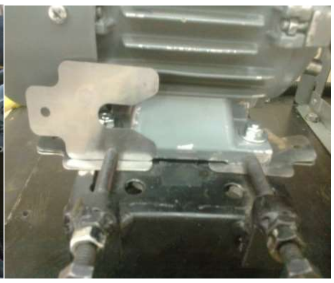
Misalignment levels (deviation) :
0.2 mm (level I) ; 0.5 mm (level II)

Unbalance level (loaded mass) : 23 g

Rotational frequencies (electricity) :
32.7 Hz ; 50 Hz

Overall view of the experimented failures is given in Figure 2.

a)



b)

c)

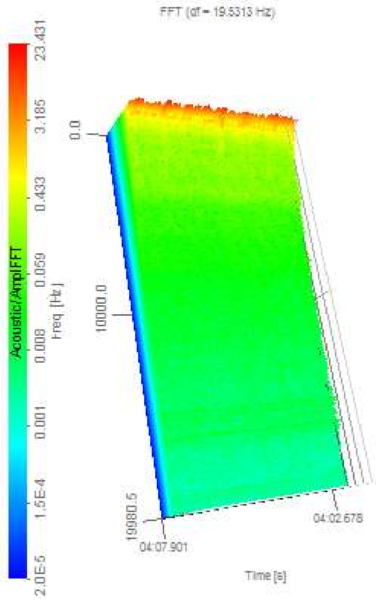
Figure 2. Experimented simultaneous failures; a) Bearing oil starvation, b) Creating horizontal misalignment, c) Loading mass (Unbalance)

3.1. Acoustic Measurement

The data belong to measurements are processed with time-domain and frequency-domain graphics. Resolution: 24 bit; Sound pressure unit: Pascal (Pa); FFT options: 1024 line (amplititude) resolution; window type: blackman; sample rate: 40000/s

3.2. Waterfall Projection

This projection demonstrates the variance of the acoustic response intensity in experimented failures. Overall FFT spectrum (frequency-domain) projection of the acoustic signal data in experimented failures is given in Figure 3. It is concluded that signal amplitude severity increase gradually in terms of experimental conditions that leads to higher deterioration energy on bearings.



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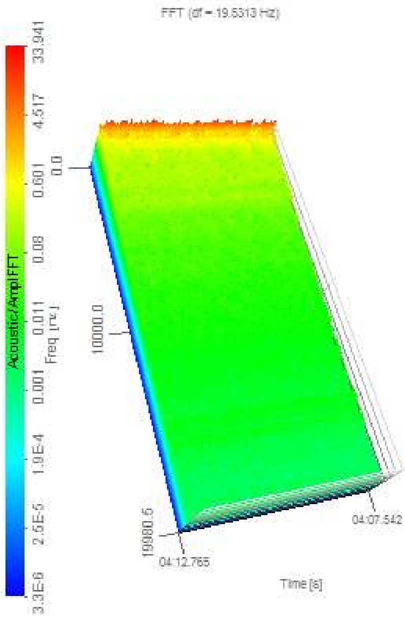

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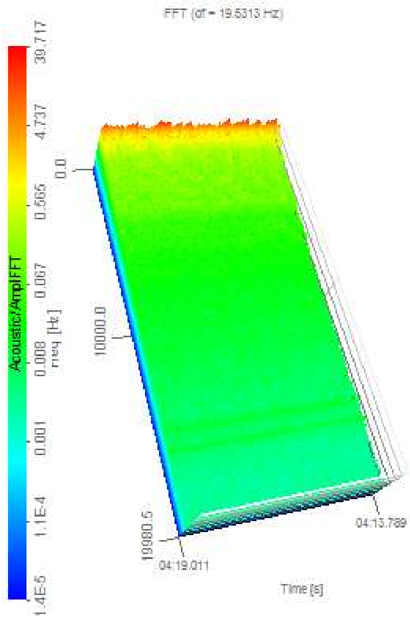


c)

Figure 3. FFT waterfall diagrams; a) Oil starvation, b) Oil starvation - Horizontal misalignment, c) Oil starvation - Horizontal misalignment - Unbalance

3.3. Experimental Setup Components

Motor: 0.37 kW; 1.1 A ; tri-phase AC induction motor with nominal frequency 50 Hz

Bearings: ORS brand ball bearing built of 100 Cr 6 (SAE 52100 Chrome Steel) material

Driven system: Yilida brand SYQ 200R - double inlet centrifugal radial fan

Coupling: Cast iron flexible pin coupling with five pins

Data Acquisition Card (DAQ): In order to transfer acoustic signals to the computer system, Dewe-Orion (model:*0424-200)* brand data acquisition card has been used. This DAQ has four simultaneous sampled channels and 24 bit resolution. It uses Dewesoft software.

Sensor: ICP® microphone with integral preamplifier (PCB brand 130E20) ; sensitivity:45 mV/Pa; Frequency Range: (±5%) 20 to 10000 Hz. Overall view of the acoustic sensor is given in Figure 4.

Figure 4. Acoustic sensor

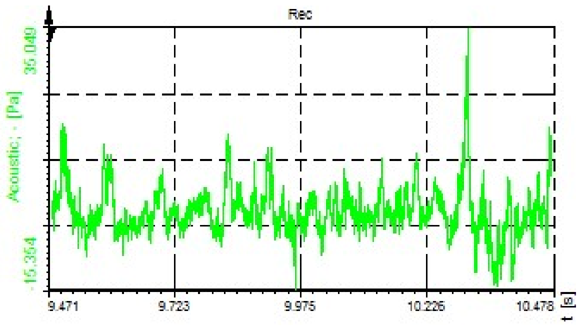
Electrical frequency inverter: ABB brand frequency converter.

4. EXPERIMENTAL FINDINGS

4.1. Oil Starvation Single Failure Mode (OS)

4.1.1. Acoustic Response Signals

In the time-domain and frequency-domain figures; bearing acoustic response is given for oil starvation (OS) failure at rotational frequencies of 32.7 Hz and 50 Hz in Figure 5 and Figure 6.



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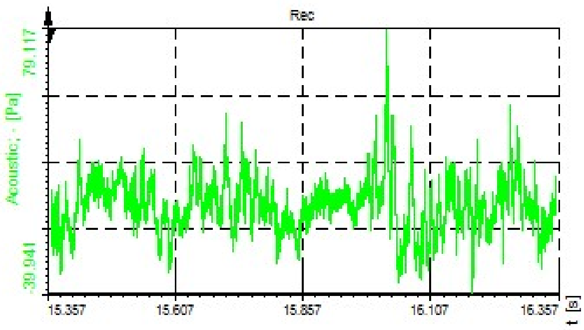

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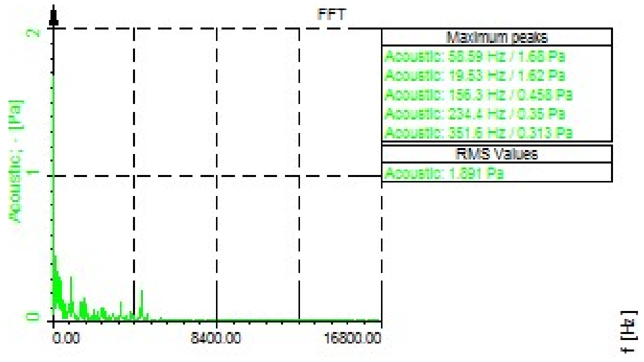
Figure 5. Time domains of oil starvation; a) at 32.7 Hz, b) at 50 Hz



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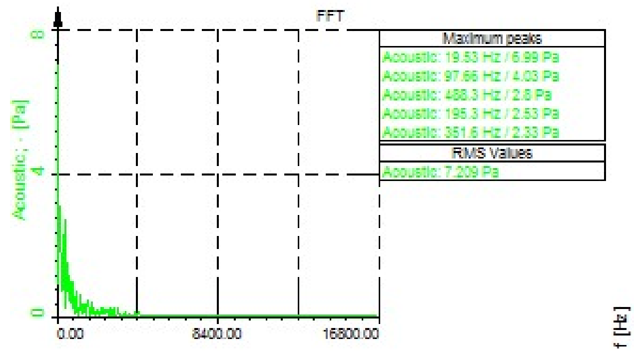


b)

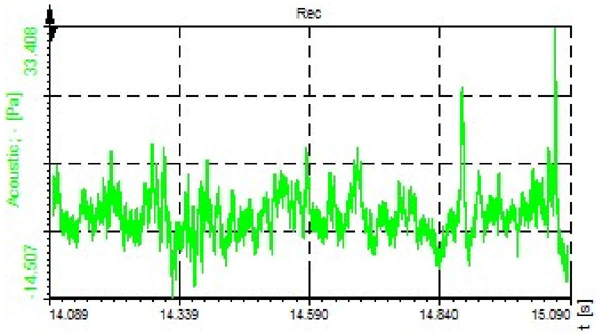
Figure 6. Frequency domains for oil starvation; a) at 32.7 Hz, b) at 50 Hz

In the oil starvation experiment, high frequency acoustic responses occur at 50 Hz that leads to increasing frictional forces of balls in the bearing with an increase in RMS comperatively at 32.7 Hz that release the deterioration energy on surface of the bearing material. RMS values increased from 1.891 Pa at 32.7 Hz to 7.209 Pa at 50 Hz. Sum of five dominant amplitudes is 4.421 Pa at 32.7 Hz and 18.68 Pa at 50 Hz which means higher deterioration energy on bearing components.

4.2. Oil Starvation - Horizontal Misalignment Double Failure Mode (OS-HM)

4.2.1. Acoustic Response Signals

In the time-domain and frequency-domain figures; acoustic responses are given for horizontal misalignment (HM) failure in oil starvation (OS) at rotational frequencies of 32.7 Hz and 50 Hz in Figure 7, Figure 8, Figure 9 and Figure 10.



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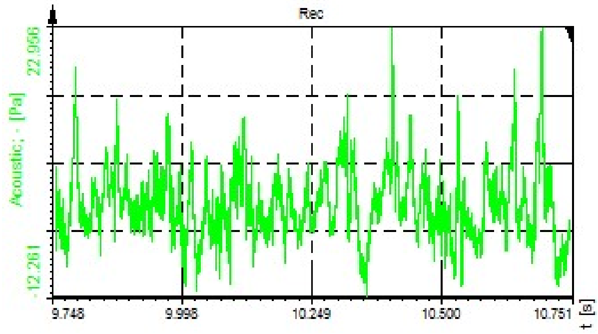
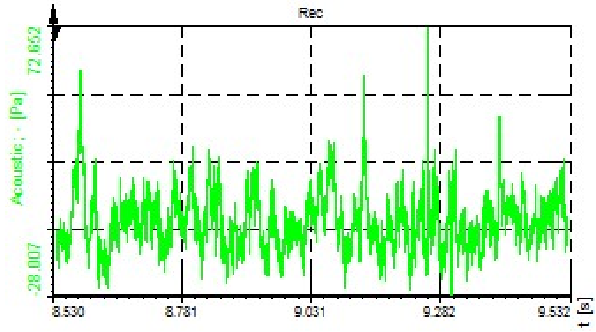


b)

Figure 7. Time domains at 32.7 Hz (oil starvation - horizontal misalignment); a) Level I, b) Level II



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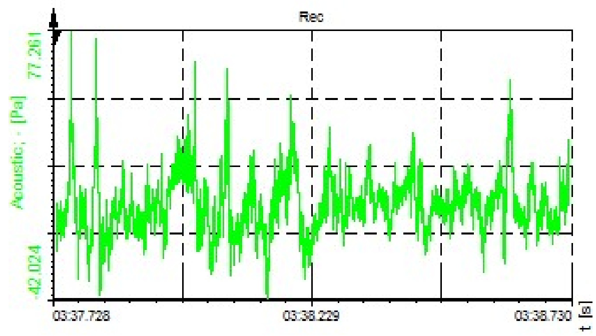
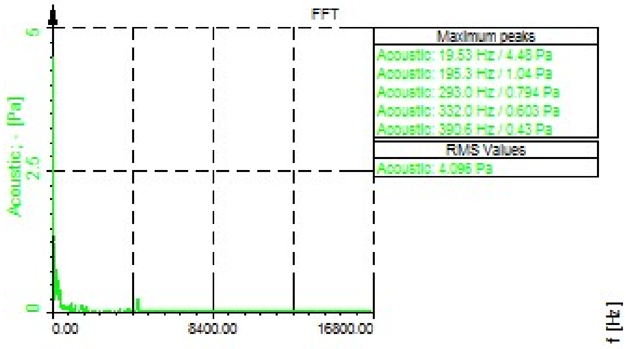
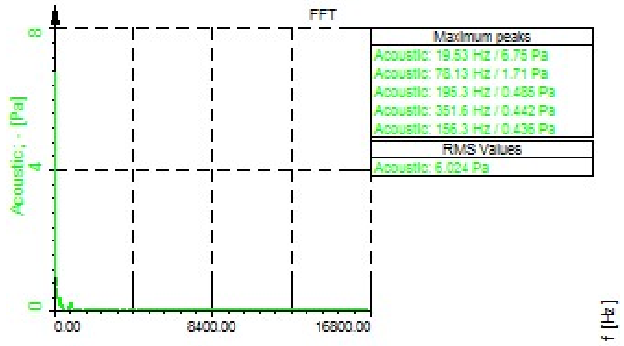


b)

Figure 8. Time domains at 50 Hz (oil starvation - horizontal misalignment); a) Level I, b) Level II

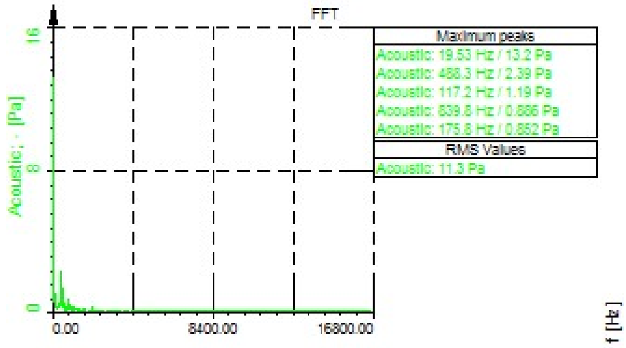


a)



b)

Figure 9. Frequency domains at 32.7 Hz (oil starvation - horizontal misalignment); a) Level I, b) Level II



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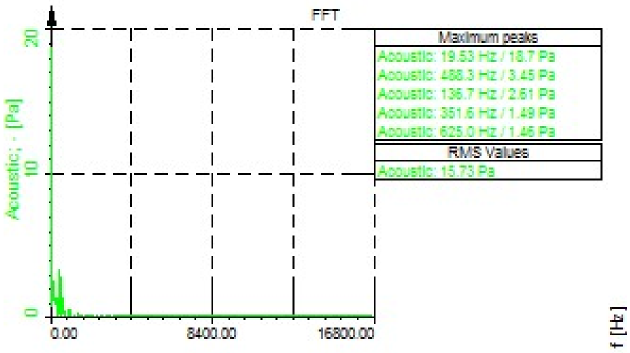


b)

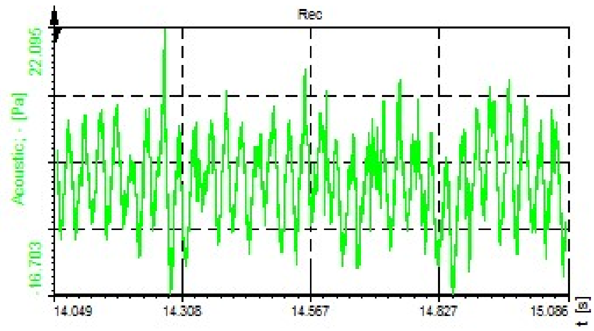
Figure 10. Frequency domains at 50 Hz (oil starvation - horizontal misalignment); a) Level I, b) Level II

At both frequencies of 32.7 Hz and 50 Hz; higher frequencies are detected in acoustic responses at level I than level II. RMS intensity is higher in level II at both frequencies and all RMS values are higher than the first experiment of oil starvation failure. RMS values obtained as 4.096 Pa at 32.7 Hz in level I, 6.024 Pa at 32.7 Hz in level II, 11.3 Pa at 50 Hz in level I, 15.73 Pa at 50 Hz in level II.

4.3. Oil Starvation - Unbalance - Horizontal Misalignment triple failure mode (OS-U-HM)

4.3.1. Acoustic Response Signals

In the time-domain and frequency-domain figures; bearing acoustic responses are given for oil starvation (OS) – unbalance (U) - horizontal misalignment (HM) failure at rotational frequencies of 32.7 Hz and 50 Hz in Figure 11, Figure 12, Figure 13 and Figure 14.



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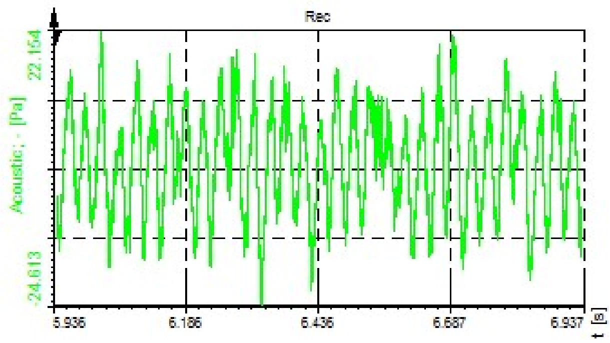
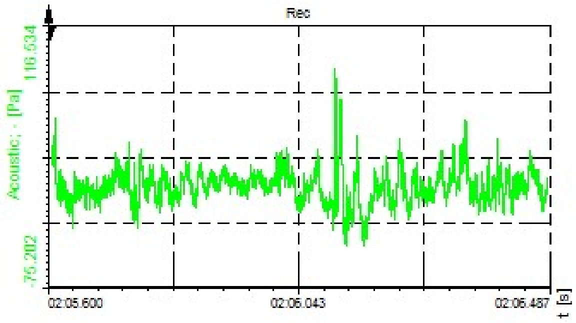


b)

Figure 11. Time domains at 32.7 Hz (oil starvation - horizontal misalignment - unbalance); a) Level I, b) Level II



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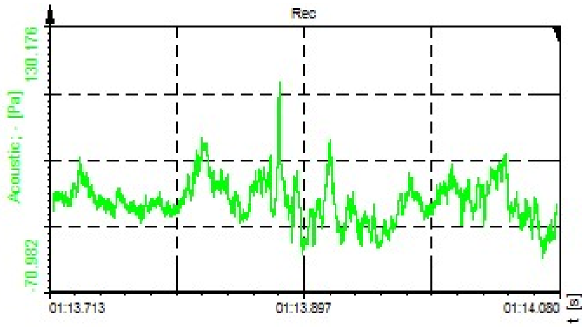
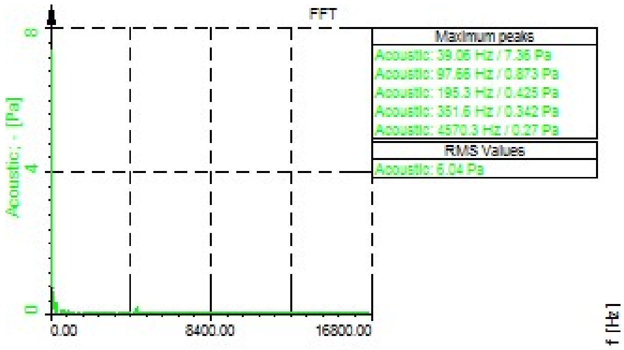


b)

Figure 12. Time domains at 50 Hz (oil starvation - horizontal misalignment - unbalance); a) Level I, b) Level II



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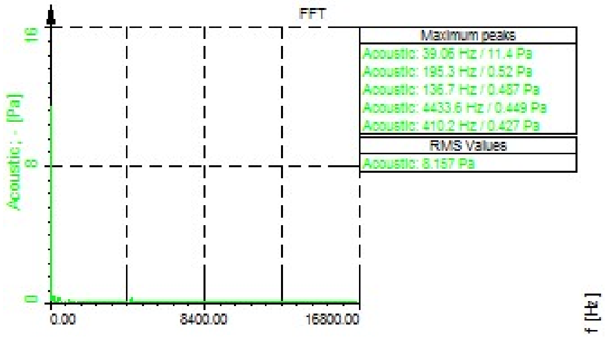
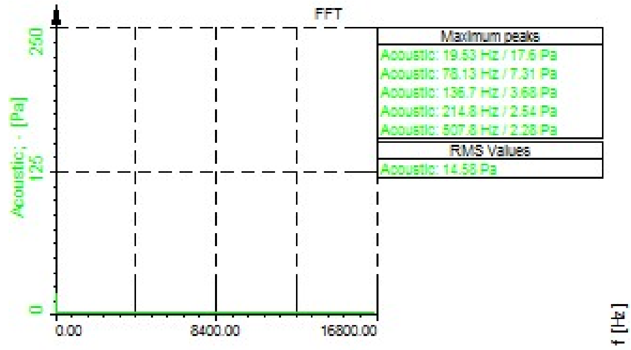
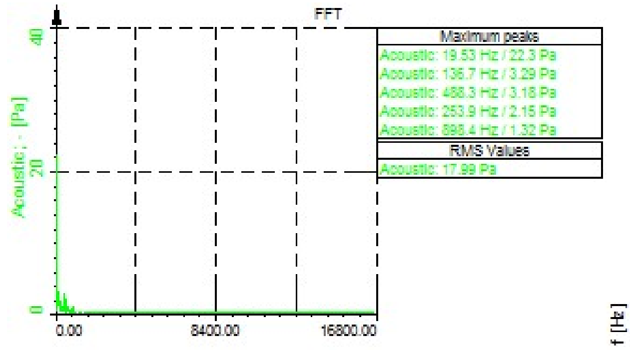


b)

Figure 13. Frequency domains at 32.7 Hz (oil starvation - horizontal misalignment - unbalance); a) Level I, b) Level II



a)



b)

Figure 14. Frequency domains at 50 Hz (oil starvation - horizontal misalignment - unbalance); a) Level I, b) Level II

Simply, one signal that is at 39.06 Hz displays prominent amplitude in experiments at level I and level II for 32.7 Hz; and signals at other frequencies give very low values. Signals with the highest five amplitude frequencies show considerable amplitude values for deterioration of the ball bearing material at 50 Hz.

Higher frequencies are observed particularly in level II at 32.7 Hz with respect to the triple failure mode of the oil starvation. In the RMS perspective; it is observed that level II RMS intensity is higher than level I. RMS intensity increase in a linear trend with respect to the increase in level of the failure intensity and rotational frequency. RMS values are obtained as 6.04 Pa at 32.7 Hz in level I; 8.157 Pa at 32.7 Hz in level II, 14.58 Pa at 50 Hz in level I, 17.99 Pa at 50 Hz in level II.

5. CONCLUSIONS

In this research; oil starvation, oil starvation-horizontal misalignment, oil starvation-unbalance-horizontal misalignment failures are studied in various levels with two different electrical frequencies (32.7 Hz ; 50 Hz) that are set by an inverter in order to determine the rotational speeds under acoustic investigation. The results are valid for 0.37 kW power AC induction motor with ball bearings that drives two inlet radial fan coupled with flexible pin coupling respect to the acoustic responses for the measured time intervals.

5.1. Acoustic Response Analysis Results

Through the acoustic measurement and analysis, failures of oil starvation, oil starvation-horizontal misalignment, oil starvation-unbalance-horizontal misalignment failures in different levels are clearly diagnosed in 32.7 Hz; 50 Hz. In the similar time interval, time-domain and frequency-domain results indicate that intensity of the acoustic increase in each level at the experiment 1, experiment 2 and experiment 3 as gradually respect to the increase in rotational speed (frequency). Each failure shows characteristic periodical mass acoustic fluctuations in the time-domain (waveform) graphics.

Based on frequency-domain analysis; oil starvation failure displays on the harmonics as clearly at the 32.7 Hz and 50 Hz in all experiments. Misalignment and unbalance failures on oil starvation particularly displays in high amplitudes at low frequencies; signals in bearing frequency zone especially at high frequencies indicate the bearing deterioration. Intensity of the five highest amplitude acoustic signal levels in frequency-domain is higher at 50 Hz than 32.7 Hz in each experiment and amplitude of acoustic signals increases from experiment 1 to experiment 3 as gradually.

One of the important results found at 32.7 Hz is that all frequencies do not give considerable signal amplitudes. At 50 Hz, not only the low frequency but also the higher frequencies represents considerable signal amplitudes.

Reasons of the acoustics in oil starvation failure base on increase at frictioning points. Horizontal misalignment failure causes acoustic signals on orders of the main frequency. Unbalance failure increase the dominance of the main frequency. When the failures are simultaneous, symptoms become more prominent with respect to the failure dominance.

5.2. Root Mean Square (RMS) Analysis Results of Acoustic Signal Data

RMS levels indicate acoustic defect intensity. In each experiment; RMS intensity increase respect to the failure level and rotation frequency. Triple failure mode (oil starvation-unbalance-horizontal misalignment) has RMS intensity slightly higher than oil starvation-horizontal misalignment double failure mode and both failures have more remarkable increase in comparison with oil starvation single failure mode.

5.3. Overall Result

As a general conclusion, it is found that acoustic response analysis is thoroughly helpful for identifying material defect due to friction and wear in this experimental setup within specific features with respect to the specific time intervals. As rotational speed, failure amount and failure level increases; acoustic signal response and acoustic RMS intensity increases as well which may lead to deterioration on the material of the bearing. Acoustic response function is found useful for detecting material homogeneity of rotating elements.

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