Ball Bearing Fault Detection Using Vibration Parameters

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***Abstract*—Bearing is an indispensible element of almost any rotating machinery. These bearings in due course of time undergo damage which may be confined to inner race, outer race, ball, cage, or all of these. Using various state of the art technologies like Vibration Analysis, Shock Pulse Method, and Acoustic Emission, these bearing faults can be identified, without dismantling the machine. Among all these vibrational analysis of bearing signature is a classical technique. This paper presents an experimental study of bearing vibration and application of FFT spectra as a smart tool for diagnosis and identification of bearing faults like inner race defect, outer race defect and ball defect.**

***Keywords*— Vibrational Signal, FFT spectra, Ball bearing, Ball defect, Inner race defect, Outer race defect.**

I. INTRODUCTION

Bearing is an indispensible element of almost any rotating machinery and as such bearings play a critical role in safe and reliable operation. Frequency of bearing failure is high in any machinery as compared to its other components and hence they are often responsible for the machine breakdown. In fact the majority of the maintenance capital expenditure is spent on bearings. Bearing faults if detected at an early stage can prevent such failures and reduce downtime of equipment. In the last few decades many state of the art technology like vibration measurement, shock pulse method and acoustic emission techniques have been developed.

This paper focuses on vibration measurement technique and use of Fast Fourier Transformation (FFT) to obtain vibration amplitude versus frequency spectra for the study of bearing fault frequencies to detect and characterize different bearing faults. All vibration occurs at some frequency. Knowing the frequency of the vibration is paramount in diagnosing the problem. This is especially true for bearing. All roller bearings give off specific vibration frequencies, or tones, that are unique. A spectrum from FFT (Fast Fourier Transform) is an incredibly useful tool for machinery vibration analysis. If a machinery problem exists, FFT spectra provide information to help determine the source and cause of the problem. While the presence of certain defect frequencies in bearing spectrum confirms the presence of faults, the amplitude of these frequencies is an indication of bearing condition. A comprehensive review of research papers and articles related bearing fault diagnosis has been presented to showcase various techniques and methods developed in the past few decades.

Early research papers on bearing have mostly concentrated on deriving the kinematics and dynamics relationships between the different rotating elements of a bearing. The equations so derived by early researchers like Palmgren, Eschmann and Harris have proved to be very useful for scholars and industrial engineers working in the field of machinery maintenance.

When a bearing spins, any defect or irregularities in the raceway surfaces or the rolling elements such as indentation, spalls, crack, flaking or irregularities in roundness of the rolling element excites periodic frequencies called fundamental defect frequencies. A machine with a defective bearing can generate at least five frequencies [4]. These frequencies are:

1. Rotating unit frequency or speed (f): This is the frequency at which shaft on which bearing is mounted rotates. It is expressed in RPM, cycle per second (cps) or hertz (Hz)

2. Fundamental train frequency (FTF): It is the frequency of the cage. FTF seldom appears in vibration spectrums as the train hardly carries any load.

3. Ball pass frequency of the outer race (BPFO): It is the rate at which the ball/roller passes a defect in the outer race

4. Ball pass frequency of the inner race (BPFI): It is the rate at which a ball/roller passes a defect in the inner race. The level of BPFI is often slightly lower than BPFO as the vibration is generated further away from the transducer.

5. Two times ball spin frequency (2 X BSF): It is the circular frequency of each rolling element as it spins. When one or more of the balls or rollers have a defect such as a spall (i.e., a missing chip of material), the defect impacts both the inner and outer race each time one revolution of the rolling element is made. Therefore, the defect vibration frequency is visible at two times (2X) the BSF rather than at its fundamental (1X) frequency.

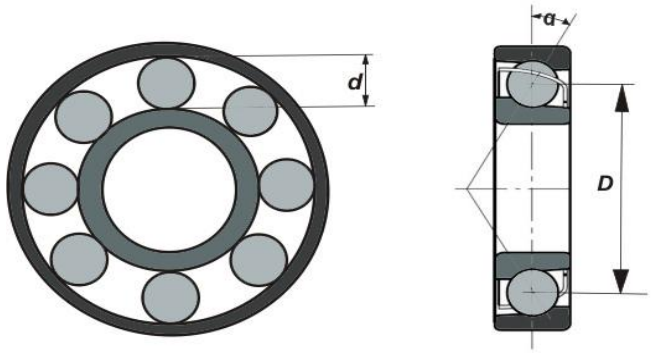

Fig.1 Figure showing bearing element parameters

The equations related to bearing fault frequencies are presented below [1],[2],[3].These equations are used for Calculating Frequency Factors.

Frequency Factor for inner race:

$$F_{IR} = \frac{Z\left(1+\frac{d}{D}\cos\alpha\right)}{2} \qquad \text{....................................(1)}$$

Frequency factor for outer race:

$$F_{OR} = \frac{Z\left(1-\frac{d}{D}\cos\alpha\right)}{2} \qquad \text{....................................(2)}$$

Frequency factor for cage or train when inner race rotating:

$$F_{CIRR} = \frac{Z\left(1-\frac{d}{D}\cos\alpha\right)}{2} \qquad \text{....................................(3)}$$

Frequency factor for cage or train when outer race rotating:

$$F_{CORR} = \frac{Z\left(1+\frac{d}{D}\cos\alpha\right)}{2} \qquad \text{....................................(4)}$$

Frequency factor for ball spin:

$$F_{BS} = \frac{1}{2}\frac{D}{d}\left(1-\left(\frac{d}{D}\cos\alpha\right)^2\right) \qquad \text{..............................(5)}$$

Above factors when multiplied with Shaft speed (f) gives Specific Bearing Vibration Frequencies:

$$BPFI = f \times F_{IR}$$
$$BPFO = f \times F_{OR}$$
$$FTF = f \times F_{CIRR}$$
$$BSF = f \times F_{BS}$$

Where,

f =Shaft Rotational Speed (Hz)

$BPFI$ =Ball pass frequency inner race
$BPFO$ =Ball pass frequency outer race
FTF =Fundamental train frequency
BSF =ball spin frequency
Z =Number of Rolling Element or Ball
D = pitch circle diameter of the bearing
d =Rolling Element or Ball Diameter
α =Contact Angle

A complex bearing dynamic models was developed, by P.K. Gupta using the generalized equations of motion for the rolling elements, cage, and raceways. The dynamic models include effects such as roller-race interaction, roller-cage interaction, cage –raceway interaction, lubricant drag and churning, roller skew, cage instabilities, material properties of the bearing components, operating conditions such as speed, load, misalignment and preloads. His models were capable of handling geometrical imperfections such as variations in rolling element size, race curvature, and bearing element imbalance and cage geometry, allowing various bearing defects to be simulated. However, experimental verification of the results has not been undertaken except for limited examples[5]-[8].

McFadden and Smith developed have a single-mode vibration model to explain the appearance of various spectral lines owing to different defect locations in the demodulated spectrum. They have suggested that the sidebands around the defect frequency are a result of the modulation of carrier frequency by loading and transmission path[9]–[14]. This model has been extended by Su and Lin to characterize the vibrations of bearings subjected to various loadings[15]. Martin and Thorpe have suggested 'normalization' of the envelope-detected frequency spectra of the faulty bearing with respect to the healthy bearing to give greater sensitivity to the detection of defect frequencies[16].

Acoustic Emission Techniques and Shock Pulse Method are another two techniques being widely used for bearing fault diagnosis .The use of this technique traces back to 1969 when Balerston used it for the defect diagnosis of rolling element bearings and proposed the acoustic emission(AE) source mechanism[17]. Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors. The early research pretending to shock pulse method is by Boto. The Shock Pulse method involves measuring the shock signal on a decibel scale. He developed a simple model of the contact action when a ball encounters a spall and measured the energy released during the impact[18] .However these techniques have very recently become popular, with the advent of researchers like Hawman and Galinaitis have carried some research on acoustic emission monitoring of faulty bearing[19].Tandon has worked on statistical methods of bearing fault diagnosis including RMS, crest factor, kurtosis, statistical methods, and probability density function[20].Mba,D., Raj, B. K., and Rao have carried out extensive research on the development of Acoustic Emission Technology for Condition Monitoring and Diagnosis of Rotating Machines: Bearings, Pumps, Gearboxes, Engines, and Rotating Structures[21].

II. EXPERIMENTAL SETUP

The experimental setup used in this research work is a Spectra Quest's Machinery Fault Simulator^{TM} as shown in figure 1. This is a versatile setup for studying signatures of common machinery faults. Its robust yet flexible design allows for easy installation and removal of bearings and loaders .The setup has a variable speed motor to provide wide range of speeds as per the demand and suitability of particular experiment. The vibrational signal was collected and analysed using PRÜFTECHNIK VIBXpert 2-channel FFT data collector and signal analyser. The VIB 5.436 accelerometer was mounted on the faulty bearing housing using magnetic mount attachment.

Four faulty MB ER-10K bearings were used for experimental purpose. The first one having inner race defect, the second one having outer race defect, the third one having ball defect and the fourth one having multiple defects-inner race defect ,outer race defect and defective ball. Experimental tests were conducted on shaft speed of 16.6Hz for each bearing fault case. The signals collected were analysed on VIBXpert. The FFT of corresponding signals were plotted and peak frequency compared with Calculated Fault frequencies given in table III, to identify particular faults in bearings.

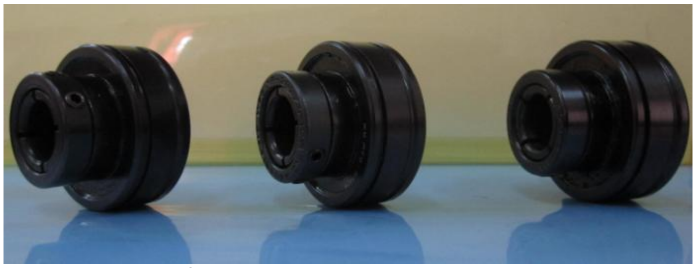

Fig.2 Photograph of MB ER-10K bearings used in experiment

Fig.3 Figure showing Spectra Quest Fault Simulator Setup and PRÜFTECHNIK VIBXpert 2-channel FFT data collector and signal analyse

TABLE I
MB ER-10K BEARING PARAMETERS

Bearing Parameters	**Value**
Number of rolling elements	8
Rolling element diameter	7.9375mm
Pitch diameter	33.5026mm
Contact angle	0 degree

TABLE II
ANALYZER MEASUREMENT SETUP

Measurement quantity	Acceleration
Δf	0.1000 Hz
Filter type	Software
HP/LP filter[Hz]	500/10000
Upper frequency	1500.00 Hz
Number of lines	15000
Window type	Hanning
Average type	Linear

TABLE III

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SENSOR SETUP

Measurement quantity	Acceleration
Signal type	LineDrive
Sensitivity	1.000µA/m/s^2
Offset	0.00 µA
Linear from	1.00 Hz
Linear to	20000.00 Hz
Res. frequency	36000.00 Hz

TABLE IV
DEFECT FREQUENCY FACTORS FOR MB ER-10K BEARING

Factor/Multiplier	**Value**
Train frequency factor	0.381
Ball pass frequency factor for outer race	3.052
Ball pass frequency factor for inner race	4.948
Ball spin frequency	1.992

TABLE V
DEFECT FREQUENCY FOR MB ER-10K BEARING AT DIFFERENT SPEEDS

Speed(Hz)	**FTF**	**BPFO**	**BPFI**	**BSF**
16.66	6.325	50.663	82.137	33.067

TABLE VI
HARMONIC FREQUENCY AT DIFFERENT SPEEDS

Speed(Hz)	**2X**	**3X**	**4X**	**5X**
16.66	33.2	49.8	66.4	83

III. RESULTS AND ANALYSIS

Analysis of Vibrational FFT spectra of faulty bearings mounted on shaft rotating at 16.6 Hz.

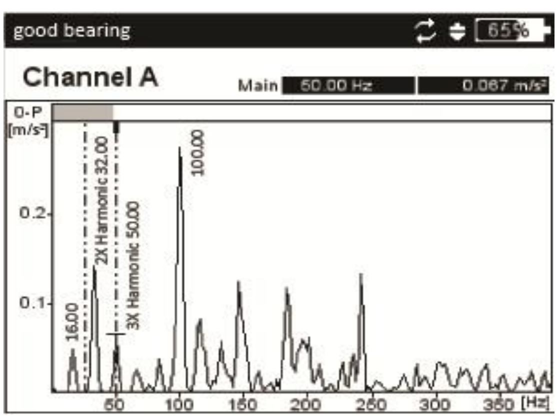

Fig.4Figure showing FFT spectrum of good bearing

Analysis: The peak at 16.00Hz is the shaft rotating frequency, also called the fundamental frequency. Peak at 32.00 is the 2X harmonic and peak50.00Hz is the 3X harmonic of fundamental of frequency. Presence of the fundamental peak and harmonic peaks indicate imbalance and looseness in setup. The amplitudes of all these peaks are however under the permissible limit as per the ISO 2372 vibration severity chart.

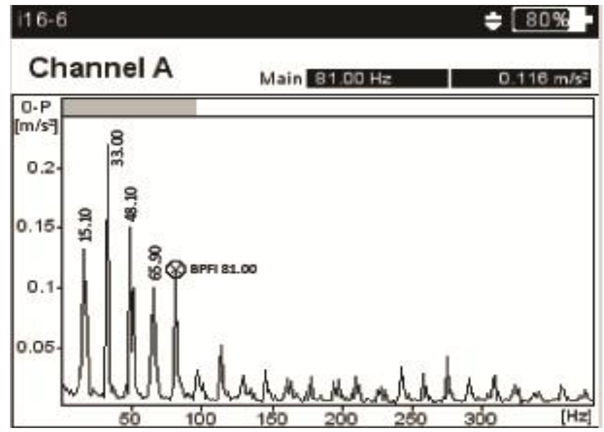

Fig.5 Figure showing FFT spectrum of faulty bearing with inner race defect

Analysis: The peak at 81.00Hz is the bearing fault frequency of inner race (BPFI).

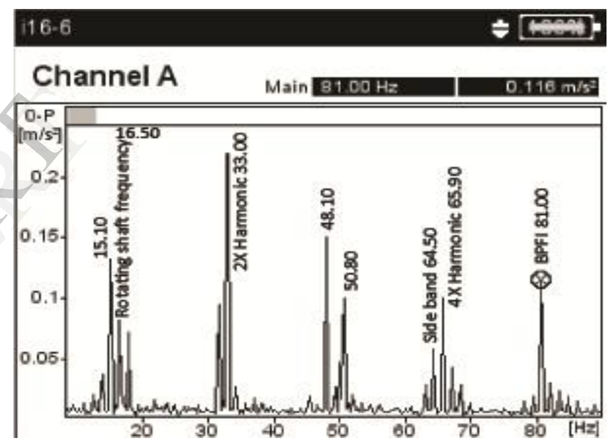

Fig.6 Figure showing FFT spectrum of faulty bearing with inner race defect. The spectrum has been zoomed to show harmonics and side band around BPFI

Analysis: Peak at 81.00Hz is the BPFI. The motor was set to run at 16.60Hz.However the motor actually speed was 16.50Hz as shown by the presence of the fundamental frequency peak at16.50Hz. The presence of this fundamental this peak and its harmonics at 33.00Hz, 50.80Hz indicate imbalance and looseness in setup. However it is under permissible limit. The side band to the left of at 64.50 Hz is the difference frequency (81.00-16.50=64.50Hz) between BPFO and motor speed. This side band indicates that the defect is large enough to permit movement of shaft.

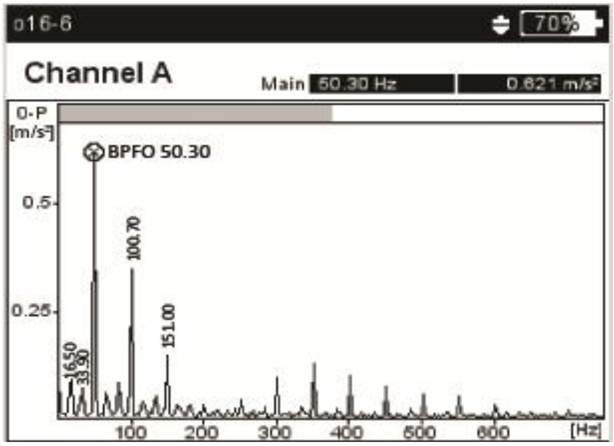

Fig.7 Figure showing FFT spectrum of faulty bearing with outer race defect

Analysis: The peak at 50.30 Hz is the bearing fault frequency of inner race (BPFO).The spectral line at 100.70Hz is the second harmonic of BPFO. In this case second harmonic is probably caused by fragment denting.

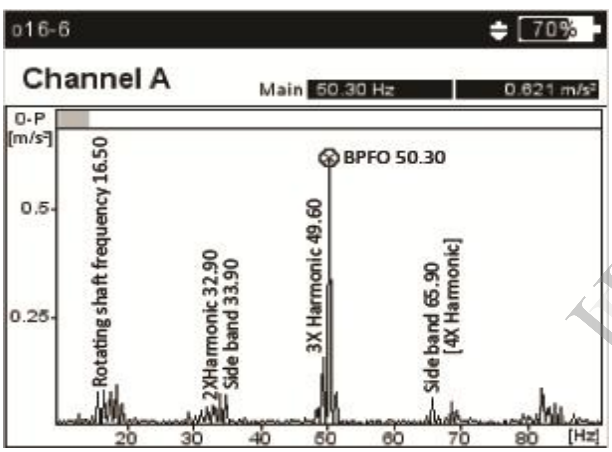

Fig.8 Figure showing FFT spectrum of faulty bearing with multiple defect. The spectrum has been zoomed around BPFO to differentiate it from other peaks nearby

Analysis: Peak at 50.300Hz is the BPFO. The motor was set to run at 16.60Hz.However the motor actually speed was 16.50Hz as shown by the presence of the fundamental frequency peak at16.50Hz. The presence of this fundamental this peak and its harmonics at 32.90Hz, 49.60Hz indicate imbalance and looseness in setup. However it is under permissible limit. The side band to the left of at 33.90 Hz is the difference frequency (50.30-16.50=33.70≈33.90Hz) between BPFO and motor speed. This side band indicates that the defect is large enough to permit movement of shaft.

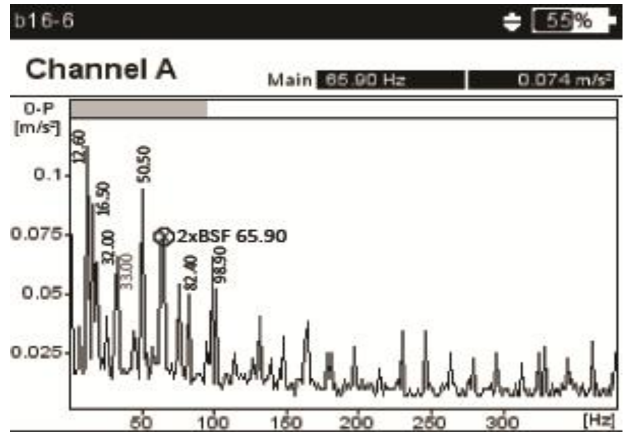

Fig.9 Figure showing FFT spectrum of faulty bearing with ball defect

Analysis: The peak at 65.90 Hz is the ball spin indicating that the ball has a spall. Presence of fundamental frequency at 16.50Hz and its harmonics gave indication of possible imbalance and looseness in the system. However the amplitudes of these harmonics are very low and under prescribed limit of ISO severity chart.

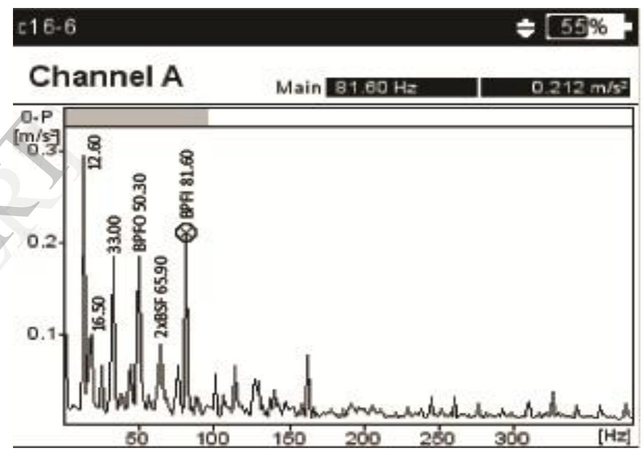

Fig.10 Figure showing FFT spectrum of faulty bearing with multiple defect

Analysis: Peak at 50.300Hz is the BPFO, the peak at 65.90Hz is the 2xBSF and the peak at 81.60Hz is the BPFI. Presence of all these peaks indicates that the test bearing has multiple faults. The motor was set to run at 16.60Hz.However the motor actually speed was 16.50Hz as shown by the presence of the fundamental frequency peak at16.50Hz. Presence of this fundamental peak indicates looseness in setup.

IV.CONCLUSIONS

The objective of this research was to study FFT spectrum of faulty ball bearing having three different defects-inner race defect, outer race defect and ball defect. The salient points of observation made from FFT spectra are presented below:

- The BPFI, BPFO and 2xBSF peaks were observed in FFT spectrum of bearing with inner race defect, outer

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race defect and ball defect respectively. The FFT spectrum of bearing with multiple faults shows BPFI, BPFO and2xBSF peaks.

- The experimental defect frequencies are slightly different from calculated one as the kinematic equations have been developed with taking into account the slip phenomenon.

Defect Frequency(Hz)	BPFO	BPFI	BSF
Calculated	50.663	82.137	66.134
Experimental	50.30	81.00	65.90

- The harmonics of shaft rotating frequency and side band around BPFI and BPFO shows that some looseness and misalignment was there in setup. The amplitudes of those peaks were however under permissible limits as per the ISO Machinery Vibration Severity Chart.

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