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Vibration Based Condition Assessment of Rolling element Bearings with Localized Defects

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Abstract:- Rolling element bearings are one of the major machinery components used in industries like power plants, chemical plants and automotive industries that require precise and efficient performance. Condition monitoring of these bearings is important to avoid failures. Several vibration monitoring techniques are available. Vibration analysis gets much advantage in factories as a predictive maintenance technique. In this study, vibration response of the rolling bearings to the defects on outer race, inner race and the rolling elements is obtained and analyzed. It shows that every defect excites the system at its characteristic frequency. The location of the faults is indicated by the FFT spectrum. Additionally, kurtosis, one of the statistical parameters is evaluated for the above cases of the bearing. The results reveal that vibration based monitoring method is successful in detecting the faults in the bearing.

Index Terms:- condition monitoring, FFT,kurtosis,predictive maintenance,rolling element bearings, statistical parameter, vibration.

1. INTRODUCTION

Rolling element bearings find widespread domestic & industrial application which includes all types of bearings that make use of the rolling action of balls or rollers to permit minimum friction, from the constrained motion of one body relative to another. In industrial application, these bearings are considered as critical mechanical components and defect in such bearing, unless detected in time cause malfunctioning and may even lead to catastrophic failure of the machinery. The initial detection of rolling bearings of is important from view point of system maintenance and process automation. The typical failure mode of rolling bearing is fault or scratch on surface which is the result of surface fatigue, caused by the repeated loading of the shaft and it is difficult to avoid in operating conditions. Thus the main problem of malfunction detection of bearing is to examine whether there is a surface defect on the bearing. When a defective surface contacts with its matching surface it will produce a short pulse that may excite the resonances of the bearing assembly. If the bearing is rotating at a constant speed, the contact pulse will occur periodically with a frequency which is a function of a bearing geometry, the rotational speed and the crack location. A lot of researchers published various work on the detection & diagnosis of bearing defects by vibration and acoustic methods. Tandon and Choudhury [1] presented a details review of vibration and acoustic measurement methods for fault detection of rolling bearings.

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By considering the defect into two categories, localized & distributed defect the detection of it can be measured by vibration and noise generation in bearings [2]. The rolling elements, the outer ring and the inner ring are in contact under heavy dynamic loads and relatively high speeds. The Hertzian contact stresses between the rolling elements and the rings are one of the basic mechanisms that initiate a localized defect [3].When a rolling element strikes to a defect on one of the races, an impulse is generated. Since the rolling element bearing rotates, those impulses will be periodic with a certain frequency. A model to describe the vibration pattern produced by a single point defect on the inner race is described by McFadden and Smith [4]. In this study, vibration response of the rolling bearings to the defects on outer race, inner race and the rolling elements is obtained and analyzed.Kurtosis one of the statistic indicator is also evaluated for different condition of bearing. This paper is organized in this manner: Section 2 presents the techniques of vibration based condition monitoring of rolling bearing. Section 3 discusses the experimental set up, instrumentation and measurement condition. Section 4 presents the result of analysis. Section 5 concludes the paper.

2. TECHNIQUES OF VIBRATION BASED CONDITION MONITORING

There are so many methods developed to monitor the condition of machines. Although a variety of approaches may be used in condition monitoring applications, the vibration monitoring and analysis is the most widely used technique to determine the mechanical condition of machinery and their parts since last 50 years [5]. Vibration signals collected from bearings carry rich information on machine health conditions. Therefore, the vibration-based methods have received intensive study during the past decades. It is possible to obtain vital characteristic information from the vibration signals through the use of signal processing techniques [6]. A number of transducer types exist for measuring machine vibration signals, including proximity probe, velocity transducers, accelerometers etc. The measurement of machine casing acceleration is the most common method used for bearing fault detection. This is normally achieved by mounting piezoelectric accelerometer externally on the machine casing, preferably near or on the bearing housing, or on the portion of the casing where relatively rigid connection exists between the bearing support and transducer. Piezoelectric sensors are less sensitive to temperature which is important since most machinery fault results in temperature increase. This will allow the bearing vibration to transmit readily through the structure to transducer. Sawalhi and Randall [7] have discussed the Vibration response of spalled rolling element bearings, Observations, simulations and signal processing techniques to track the spall size and investigated vibration signatures of seeded faults at different speeds. The acceleration signals resulting from the entry of the rolling element into the spall and exit from it are of different natures. Accelerometers have the advantage of providing a wide dynamic range and a wide frequency range for vibration measurement. They have been found to be the most reliable, versatile and accurate vibration transducer available. Many researchers [8, 9]have used differentapproaches and different descriptors under different environments to investigate the relationship between the tested bearing and changes in vibration response under operating condition.

Frequency domain approach

Energy in sound signal is distributed over a range of frequencies. Frequency analysis separates individual frequency components in a complex signal and indicates amplitude of each. There are various techniques available under non real time analysis. e.g. fixed filter, sweeping filter, high speed analysis etc. In real time analysis, the analysis is made so quickly that results are provided almost immediately. One of methods under real time analysis is FFT analysis which makes use of FFT (Fast Fourier Transform) algorithm to calculate spectra of blocks of data. The FFT algorithm is an efficient way of calculating the Discrete Fourier Transform (DFT). The basic relationships used to transform information from time domain to frequency domain, or vice versa, are Fourier transform pair.

$$S_X(f) = \int_{-\infty}^{+\infty} x(t) e^{-i 2\pi f t} dt \quad (1)$$

$$x(t) = \int_{-\infty}^{+\infty} S_X(f) e^{i 2\pi f t} df \quad (2)$$

Where *x(t)* is time history of a function x and Sx(f) is Fourier transform of x, a complex quantity. The discrete Fourier transform (DFT) pair equivalent to equation (1) and (2) become

$$s_x(m\Delta f) = \Delta t \sum_{i=0}^{n-1} x(n\Delta t)\, e^{-i 2\Pi m \nabla f n \Delta t}, \quad m = 0, \ldots\ldots\left(\frac{N}{2}\right) \quad (3)$$

$$x(m\Delta t) = \Delta t \sum_{m=0}^{n-2} s_x(m\Delta f)\, e^{i 2\Pi m \Delta t n \Delta f}, \quad n = 0, \ldots\ldots(N-1) \quad (4)$$

The basic indicator is the characteristic defect frequencies in the frequency domain analysis. Spectral analysis of vibration signal is widely used in bearing diagnostics. It was found that frequency domain methods are generally more sensitive and reliable methods [10]. The characteristic defect frequencies depend on the rotational speed and the location of the defect in a bearing. The existence of one of the defect frequencies in the direct or processed frequency spectrum is the main indicator of the fault. The interaction of defects in rolling element bearings produces pulses of very short duration whenever the defect strikes or is struck owing to the rotational motion of the system. These pulses excite the natural frequencies of bearing elements and housing structures. These frequencies depend on the bearing characteristics and are calculated according to the relations as shown below [1, 5, 6, and 8].

$$fs = N / 60 \quad (5)$$

$$fid = (n/2)(N/60)[1 + (bd/pd)\cos\Phi] \quad (6)$$

$$fod = (n/2)(N/60)[1 - (bd/pd)\cos\Phi] \quad (7)$$

$$fcd = (1/2)(N/60)[1 - (bd/pd)\cos\Phi] \quad (8)$$

$$fcd = (pd/2bd)(N/60)[1 - (bd/pd)^2(\cos\Phi)^2] \quad (9)$$

Where,

n = Number of balls, Φ= Contact angle, pd = pitch diameter. bd = ball diameter, N= rotational speed in rpm.

fs=Shaft rotational frequency, *fcd*=Cage defect frequency*fod*=Outer race defect frequency, *fid*=Inner race defect frequency, *fbd*=Ball defect frequency.

Time domain approach

Signal analysis in the time domain has been used to monitor the machine conditions. However, complex signals are difficult to analyze, when frequently encountered in industrial equipment. Some of the time domain techniques can be used or applied for condition monitoring, such as root mean square (RMS), mean, peak value, crest factor, kurtosis, and shock pulse counting.The mean acceleration signal is the standard statistical mean value. Unlike RMS, the mean is reported only for rectified signals since for raw time signals, the mean remains close to zero. As the mean increases, the condition of the bearing appears to deteriorate. Peak value is measured in the time domain or frequency domain. Peak value is the maximum acceleration in the signal amplitude. Crest factor is the ratio of peak acceleration over RMS. This metric detects acceleration bursts even if signal RMS has not changed.The shock pulse method has been used successfully in the detection of defects in rolling element bearings [15].Tandon [13] has shown that defect detect ability of overall power to be the best followed by peak and RMS measurements. However, crest factor can be counterintuitive. At advance stages of material wear, bearing damage propagates, RMS increases, and crest factor decreases. But crest factor is unreliable tolocate defects in rolling elements.

$$RMS(x) = \sqrt{\frac{x_i^2}{N}} \quad (10)$$

$$Mean(x) = \frac{1}{N} * \sum_{i=1}^{N} x_i^2 \quad (11)$$

$$Crest\ Factor = \frac{Peak\ acceleration}{RMS(x)} \quad (12)$$

$$Skewness = \frac{1}{N-1} \sum_{i=1}^{N} (x - \bar{x})^3 \quad (13)$$

The forth moment, normalized with respect to the forth power of standard deviation is quite useful in fault diagnosis. This quantity is called kurtosis which is compromise measure between the intensive lower moments and other sensitive higher moments. It was reported that kurtosis is the good criterion to distinguish between damaged and healthy bearings [11]. A healthy bearing with Gaussian distribution will have a kurtosis value about 3.When the bearing deteriorates, this value goes up to indicate damaged condition which reduces again when the defect is well advanced. One of the advantages of this method is that there is no need to know time history of the signal and bearing condition can be monitored by observing kurtosis.

$$Kurtosis = \frac{(N-1)\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left(\sum_{i=1}^{N}(x_i - \bar{x})^2\right)^2} \quad (14)$$

There are several methods of follow-up in time and frequency domain and their results on rolling element bearings have been presented [4]. Spectral subtraction is a method based on Short Time Fourier Transform. It allows removing the stationary noise of a signal. Estocq et al. [12] have shown that the method improves the sensibility of temporal indicators such as the kurtosis and the crest factor. Su and Lin [14] suggested need of time domain analysis along with frequency signature of vibration for monitoring of bearings reliably.

3. EXPERIMENTAL SETUP AND MEASUREMENTS

3.1Test rig

The test rig used in the present work consists of 1Hp, 1400 rpm.Crompton Greaves three phase induction AC motor.The test bearing is mounted at the end of the shaft and is loaded in radial and axial directions. Vibration isolation rubber sheets were placed under the frame of test rig to reduce the vibration transmission from ground to the test bearing. In order to obtain vibration response of rolling element bearing for detection of fault, four types of 6205 (SKF) deep grove ball bearings were tested. The specification are listed as follows, No of balls are 9, diameter of the ball is 8.5mm, Pitch diameter is 38.5mm, and the angle of contact is 0^0. The combination of defects with same size of 1mm in diameter is introduced on one of the bearing on its outer race and ball. Also the line defect of 1mm is introduced on other bearing on its inner race to acquire its vibration data.The schematic diagram of experimental set-up is shown in Fig. 1

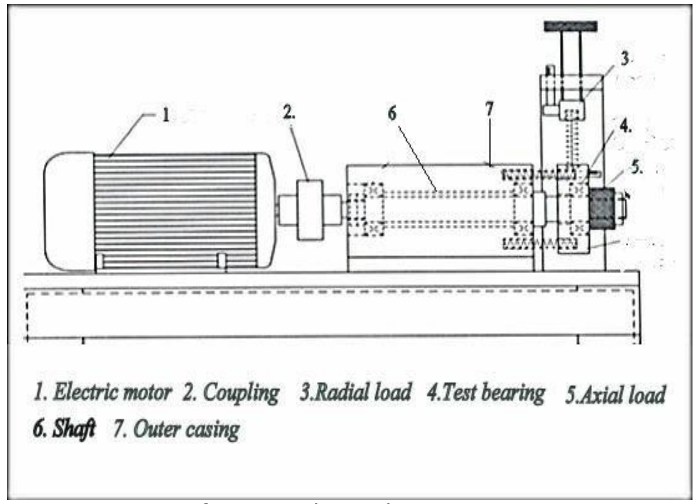

Fig.1 Experimental setup

3.2 Instrumentation

Vibration signal from bearing was acquired with a tri-axial accelerometer of sensitivity 5mV/g mounted on bearing housing. The time domain waveform is acquired in radial and axial direction at different speeds. These vibration signals were analyzed in LabVIEW software. Fig. 2 shows the Lab View program for spectral analysis of vibration signal and evaluating kurtosis.

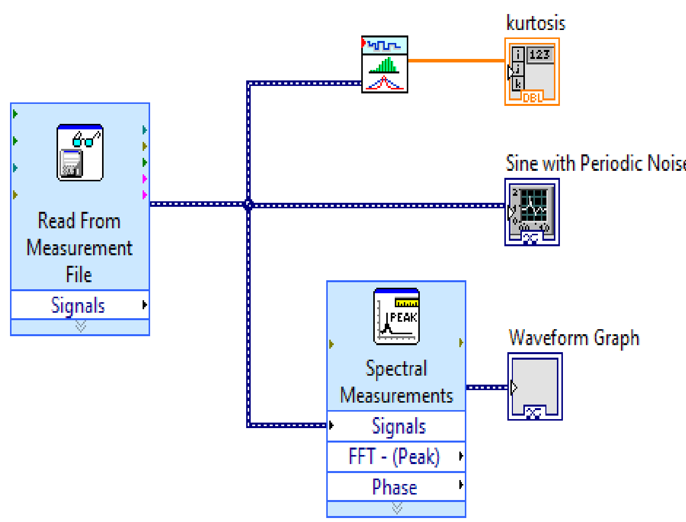

Fig.2 Lab VIEW Program for spectral analysis and kurtosis.

3.3 Measurement Conditions

Vibration data from the bearing was acquired at different speeds such as 1800, 2100, 2400, 2700 and 3000 rpm. The load on the bearing was varied in steps on defect free bearing. It is observed that with variation of load on bearing, the amplitude of the vibrationchanges. Hence it was decided to keep radial and axial load on bearing constant as 60 kg and 15 kg respectively for all defective bearings. The defects were created by electro discharge machining on inner race, outer race and balls.Fig. 3 shows a deep groove ball bearing with defect on outer race of the bearing.

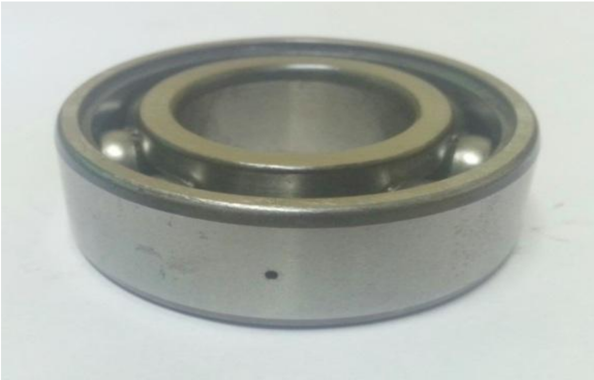

Fig.3 Defective Bearing with 1mm defect on outer race

4. RESULTS AND DISCUSSION

The following section shows the time domain waveform and the FFT spectrum for the measurement conditions mentioned in section 3.3.

Frequency Domain approach

Combined defect on outer race and ball

To start with, the vibration signals were acquired from faulty bearing having combined defects on outer race and ball of 1 mm diameter**.**

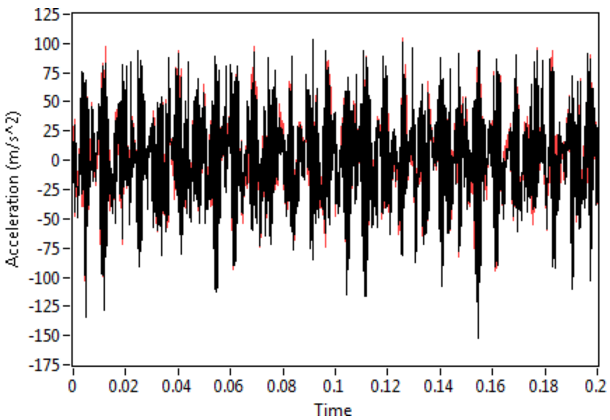

Fig. 3a) Time domain signal for defective bearing at 1800 rpm (Outer race & Ball)in radial and axial direction

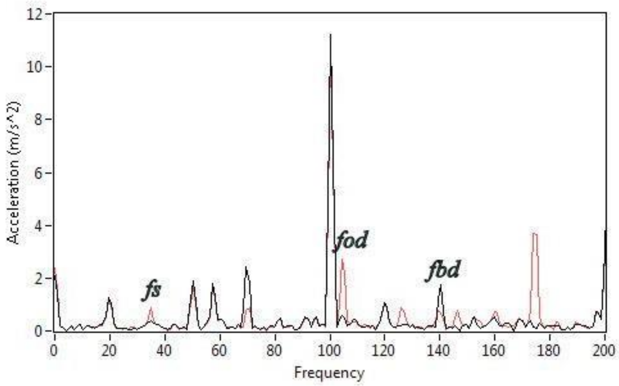

Fig.3b) Spectrum of defective bearing at 1800 rpm (Outer race & Ball)

Fig. 3a) and 3b) shows the time domain waveform for the defective bearing with defect on outer race and ball at 1800 rpm and FFT spectrum respectively in axial and radial directions. It is observed that the spectrum clearly shows the presence of fault on the outer race and the balls. The theoretical frequency 104Hz and 144Hz, obtained by equations mentioned in section 2.1 closely matches with the fault frequencies. Hence the frequency domain approach gives precise estimation of location of defects.

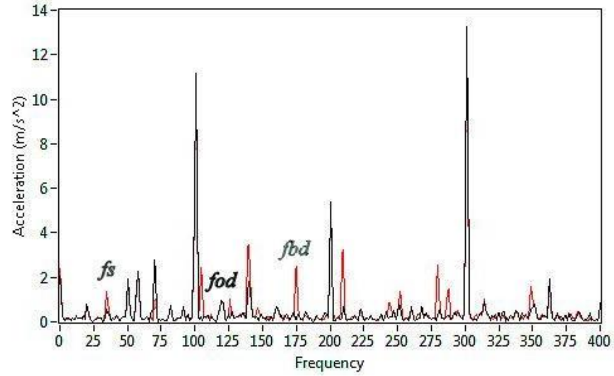

Fig.4a)Spectrum of defective bearing at 2100 rpm (Outer race & Ball)

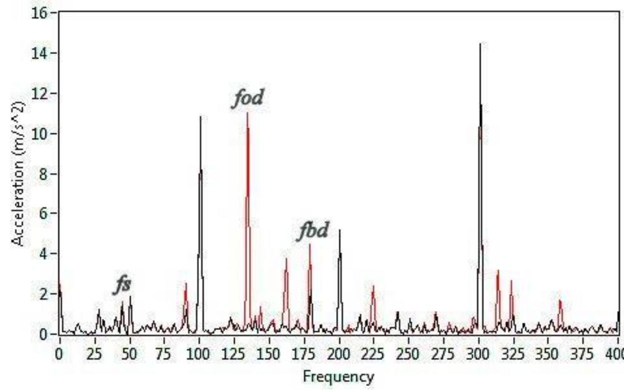

Fig.4b) Spectrum of defective bearing at 2400 rpm (Outer race & Ball)

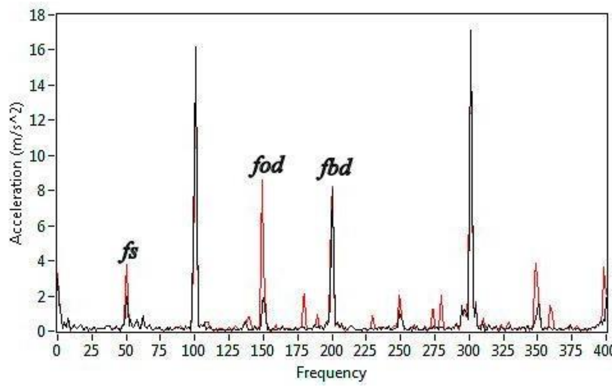

Fig.4c) Spectrum of defective bearing at 2700 rpm (Outer race & Ball)

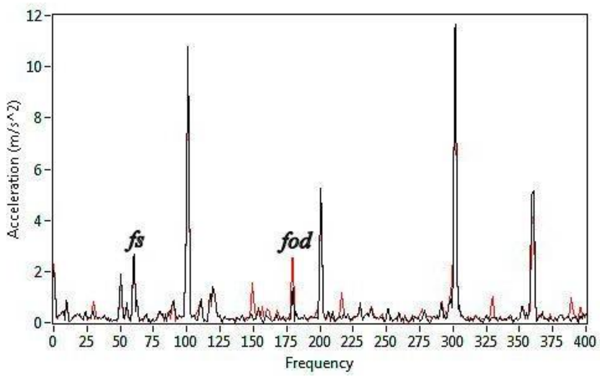

Fig.4d)Spectrum of defective bearing at 3000 rpm (Outer race & Ball)

Similar results were obtained at 2100, 2400, 2700 rpm respectively. At 3000 rpm it is observed that the spectrum do not indicate the presence of fault on the ball. This is due to the fact that the defect on ball may not be in the loading path. Additionally all the spectrum shows peak at 100, 200 and 300 Hz.

Line defect on Inner race.

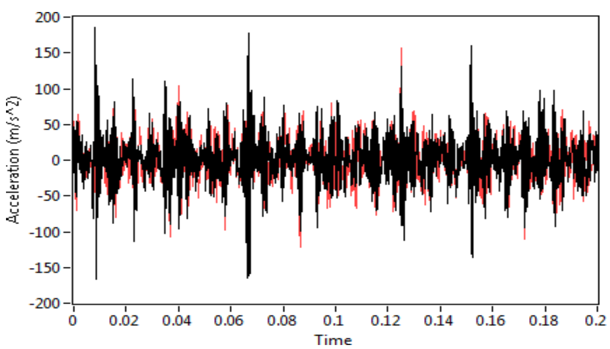

Fig.5a)Time domain signal for defective bearing at 1800 rpm (Inner race line defect)

Figure 5a) and b) shows the time domain waveform for the defective bearing with defect on inner race at 1800 rpm and its FFT spectrum respectively. The theoretical frequency for the inner race defect closely matches with the experimental one.

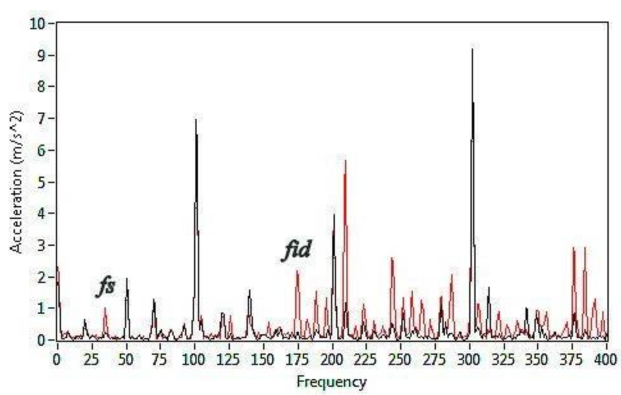

Fig. 5b) Spectrum of defective bearing at 1800 rpm (Inner race line defect)

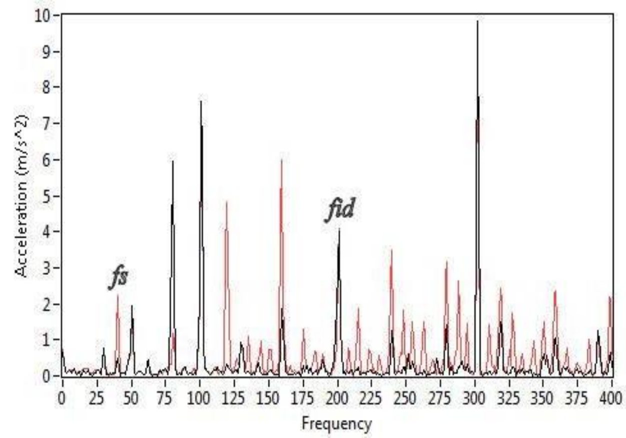

Fig.6a)Spectrum of defective bearing at 2100 rpm (Inner race line defect)

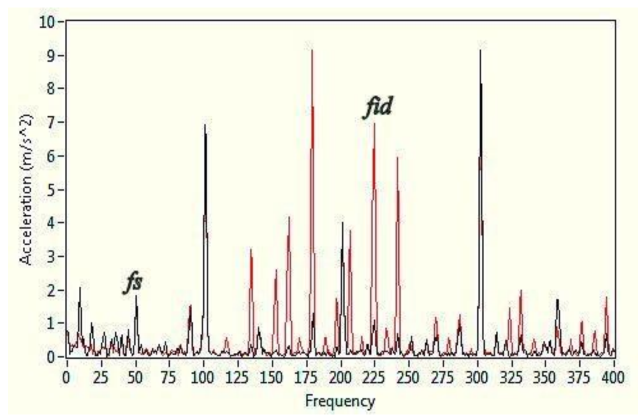

Fig.6b) Spectrum of defective bearing at 2400 rpm (Inner race line defect)

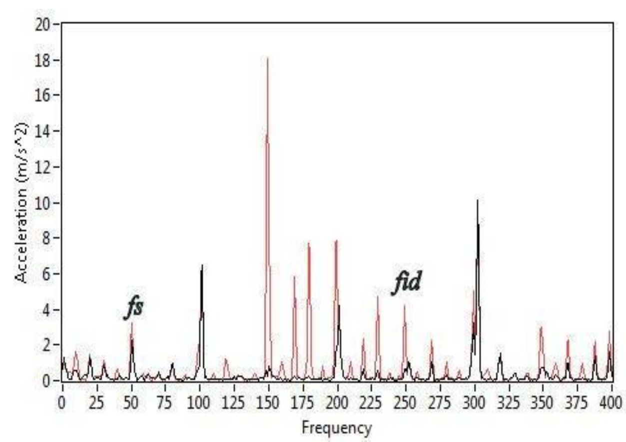

Fig.6c) Spectrum of defective bearing at 2700 rpm (Inner race line defect)

The spectra in Fig. 6a) to 6c) shows the presence of defect on inner race of bearing at 2100, 2400 and 2700 rpm respectively. The shaftrotational frequency is also shown in spectrum. The theoretical frequencies for all the cases of defects and shaft rotational frequency at different speeds calculated by equations (5) to (9) are shown in table 1.

TABLE.1
CHARACTERISTICS FREQUENCIES (HZ) AT DIFFERENT SPEEDS

Speed (rpm)	Shaft Freq. fs	Inner Race Defect Freq. FID	Outer Race Defect Freq. FOD	Ball Defect Freq. FBD
1500	25	137	88	120
1800	30	165	104	144
2100	35	192	122	168
2400	40	220	140	192
2700	45	247	157	216
3000	50	275	175	240

Defect on outer race

Similar to the above two cases, vibration signals are acquired at different speeds for the defect on outer race. However the FFT spectrum is shown at 2400 rpm only to avoid repetition of the results.Fig. 7 shows the spectrum of the vibration signal acquired at 2400 rpm for the defect on outer race. The theoretical fault frequency is 140 Hz as shown in table 1.The

spectrum clearly shows the peaks at 140 Hz and its harmonics.

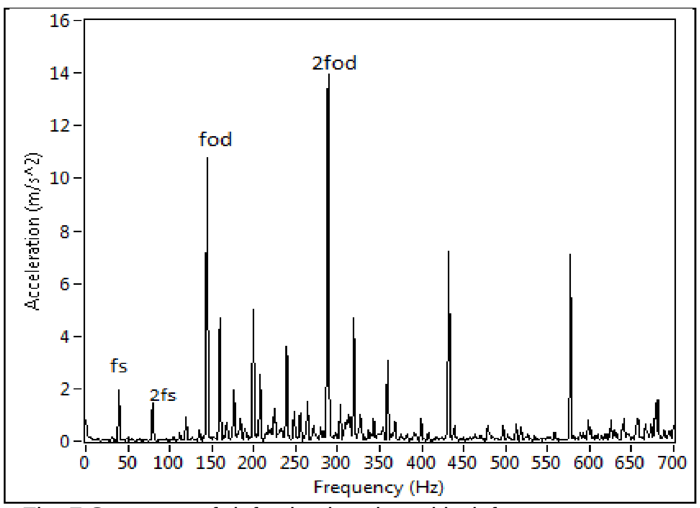

Fig. 7 Spectrum of defective bearing with defect on outer race at 2400 rpm

Time domain approach

As discussed in section 2.2, kurtosis is one of the important statistical indicators for fault detection in rolling bearings. First kurtosis is calculated for defect free bearings at different speeds. Fig. 8 shows the variation of kurtosis for defect free bearing with respect to speed in radial and axial direction.

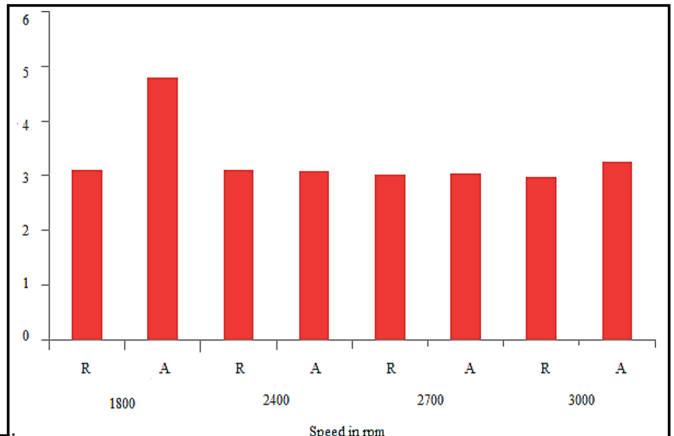

Fig.8 Variation of Kurtosis with speed for defect free bearings

It is observed that kurtosis is high at 1800 rpm, and then it decreases at 2400 and 2700 rpm. At 3000 rpm, it again increases.Then kurtosis is calculated for defective bearings using equation (14)for defect at different locations. Table 2 shows the kurtosis values for different cases.

TABLE 2
KURTOSIS VALUES FOR DIFFERENT DEFECTS

Condition of Bearing	Radial	Axial
Defect free	3.02778	3.04539
Outer race defect	2.93378	3.35999
Ball + Outer race	6.42007	3.12388
Inner race line defect	5.85179	5.73698

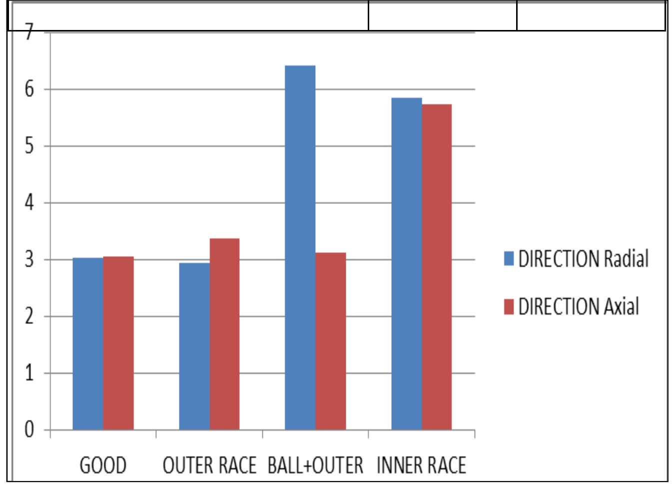

Fig. 9 Variation of Kurtosis with defect location

Fig.9 shows variation of kurtosis with various defect locations. It is seen that the value of kurtosis for good bearing is close to 3. For defects on the inner race and defect on ball the value of kurtosis approaches 6 indicating the presence of fault. However, in case of bearing with outer race defect, kurtosis value equals that of a good bearing. It can be concluded that kurtosis is not a good indicator of fault on outer race of a bearing.

5. CONCLUSION

Based on the studies carried out on vibration monitoring of bearings, it can be concluded that FFT spectrum indicate the location of the fault. Additionally, kurtosis, one of the statistical parameters is evaluated for the above cases of the defects on the bearing. Kurtosis though indicates state of the bearing; it cannot detect the location of fault. Also, it is not suitable for detecting fault on outer race of rolling bearing. The results reveal that vibration based monitoring method is effective in detecting the faults in the bearing.

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