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Research Article

Analysis of Vibration Signals of Rolling Element Bearing with Localized Defects

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Abstract

The rolling element bearing is one of the most critical components in a machine. Prompt diagnostics of rolling element bearing fault is important to avoid failures. In the present study, defects in rolling element bearings are detected using frequency domain approach. Time domain parameters such as Kurtosis, crest factor etc. have been compared for defect free bearings and defective bearings. The effect of shaft speed on the performance of kurtosis and crest factor is studied. Results from the study shows that these parameters are affected by the shaft speed. Also Performance of kurtosis, crest factor and cepstrum is studied for different conditions of operation of SKF 6205 bearing.

Keywords: *Cepstrum, condition monitoring, kurtosis, rolling element bearings, vibration.*

1. Introduction

Rolling element bearings are widely used machine components in the vast majority of rotating machines. It is often under high load and high speed running conditions. Most rotating machine failures are often linked to bearing failures. Failures in rolling bearings often result in lengthy industrial downtime that has economic consequences. Prompt diagnostics of rolling element bearings fault is critical not only for the safe operation of machines, but also for the reduction of maintenance cost. Different methods are used for detection and diagnosis of defects; they may be broadly classified as vibration and acoustic measurements, temperature measurements and wear debris analysis. Among these the most fundamental tool is vibration analysis. This technique is based on the fact that components of rolling bearings interact to generate complex vibration signatures. The strength and weakness of vibration represents the location of defects.

Tandon and choudhury presented a detailed review of vibration and acoustic measurement methods for detection of defects in rolling element bearings. McFadden and Smith presented a model to describe the vibrations produced by a single point defect on the inner race of a rolling element bearing under constant radial load. Several condition monitoring techniques such as vibration monitoring, acoustic emission and shock pulse method etc. for bearings have been compared by Tandon *et al*. Sunnersjo have carried out studies on the effect of varying compliance on vibrations of rolling bearings with emphasis on radial vibrations with positive clearance. It was reported that varying compliance gives rise to both radial and axial vibrations. The geometrical shape and surface properties of a real bearing always deviate to some extent from the theoretical design. For bearings of standard tolerances these deviations are large enough to cause measurable levels of vibration. Sunnersjo have studied the effect of geometrical imperfections and wear on vibrations of rolling element bearings.

Tandon compared vibration parameters such as overall RMS, peak, crest factor, cepstrum etc. for the detection of defects in rolling element bearings. The Fourier transform works by first translating a function in the time domain into a function in the frequency domain. The signal can then be analyzed for its frequency content because the Fourier coefficients of the transformed function represent the contribution of each sine and cosine function at each frequency. Other frequency domain techniques are the calculation of power spectral density, band pass analysis and envelope analysis. In envelope analysis, signals are filtered through band-pass filter and the filtered signal is demodulated with the help of full wave rectification of Hilbert transform and then the spectrum analyzed. McFadden and Smith explained the influence of multiple defects by the reinforcement and cancellation of spectral lines due to differing phase angles.

These studies show that vibration is one of the most important tools for the successful diagnosis of rolling element bearings. However majority of the studies are carried out at lower constant speeds. In the present

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study, emphasis is on analyzing the vibration signal in frequency and time domain for fault diagnosis of rolling element bearings running at variable speeds under varying radial and axial loading.

The structure of this paper is as follows. In section 2 description of frequency domain approach for fault diagnosis is presented while time domain approach is discussed in section 3. The data used for monitoring and diagnosis is described in section 4, whereas the detailed fault diagnosis procedure based on frequency and time domain is discussed in section 5. The last section concludes the paper.

2. Frequency domain approach

Frequency analysis plays an important role in the detection and diagnosis of machine faults. The Fourier transforms utility lies in its ability to analyze a signal in the time domain for its frequency content. 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 (Orhan Sadettin *et al*) and are calculated according to the relations as shown below:
The shaft rotational frequency (fs) which is equal to the speed of shaft:

$$fs = (N/60) \tag{1a}$$

The outer race defect frequency (FOD) is given by:

$$FOD = (n/2)(N/60)[1-(bd/pd)\cos\phi] \tag{1b}$$

The inner race defect frequency (FID) or the ball pass frequency of the inner race is given by:

$$FID = (n/2)(N/60)[1+(bd/pd)\cos\phi] \tag{1c}$$

The ball defect frequency (FBD) or ball spin frequency is given by:

$$FBD = (pd/bd)(N/60)[1-(bd/pd)^2\cos^2\phi] \tag{1d}$$

Where
ϕ = contact angle
pd=pitch diameter
n=no. of balls
N= rotational speed in rpm

These bearing characteristic frequencies are approximate as they will be affected by slipping of the elements within the bearing and spinning of the races on the shaft or in the housing.

Cepstrum is anagram of spectrum. Cepstrum is obtained by taking Fourier transform of the logarithm of the mean square density as shown in Fig.1.

Fig.1 Cepstrum of a signal

Cepstrum is a function of independent variable frequency having the dimensions of time. The advantage of using cepstral analysis is that the periodic harmonics can be detected even when they are covered within a high noise level (B. K. N. Rao).

3. Time Domain Approach

In time domain analysis, statistical parameters are normally used for fault detection. Treating the monitored signal as a random variable, statistical parameters such as probability function and its moments are often used. The paper in (R. B. W. Heng) presents a series of statistical moments to indicate the shape of probability function. The first and the second moment are the mean and the variance respectively. Odd moments relate the information about the position of peak density relative to the median value. Even moments indicate the spread in the distribution.

Kurtosis is fourth moment, normalized with respect to the fourth power of standard deviation of probability distribution. It is given by:

$$\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu/\sigma)^4 \tag{2}$$

Where x_i is the vibration amplitude in time history, σ is the mean of the data and N is the total number of data points. Kurtosis can be good criteria to distinguish between a damaged and a healthy bearing. Healthy bearing with a Gaussian distribution will have a kurtosis value about 3. When the bearing deteriorates this value goes up to indicate the damaged condition. The effectiveness of kurtosis versus shaft speed has been considered. It is observed that in a particular speed range the trend of kurtosis is diverted. Crest factor is the ratio of maximum peak of the vibration signal to the rms value. It is a modified quantity of rms.

4. vibration data acquisition

In the present work, the vibration signatures were collected from bearing of an experimental set up as shown in Fig.2. The shaft of the experimental setup is driven by an AC motor through a gear coupling. The test bearing SKF 6205 was mounted in the bearing casing on the shaft and loaded by screw and nut arrangement in radial and axial direction. To obtain variation in speed, a variable frequency drive (VFD) is used. Radial and axial vibration of the bearing was recorded using PCB tri-axial shear accelerometer with NI 9234 sound and vibration module. Vibration signals are acquired at different speeds up to 3000 rpm of system for both defect free and defective bearing. The defects are created on inner race, outer race and rolling elements by electric discharge machining. The radial and axial load on defect free bearing is varied while acquiring the vibration signal to study the effect of load on the vibration pattern.

Fig.2 Experimental Set-up

5. Experimental Results

5.1 Frequency Domain Analysis

The parameters of SKF 6205 bearing are: Number of balls 9, diameter of balls 7.94 mm, pitch diameter 39 mm and contact angle 0^0. The vibration signal is acquired for analysis of four test bearings. The details about the test bearings and sizes of defects are shown in table 1.

Table 1: Defect Details for Test Bearings

Sr. No.	Bearing Defect	Defect Size	Remark
1	------	------	No Defect
2	Outer Race	1mm	Two defects
3	Inner Race	1 mm	One Defect
4	Ball+Outer Race	1mm each	Two defects

The theoretical characteristic frequencies for above cases of defect are calculated according to equations 1a to 1d. These frequencies are shown in table 2 for different speeds.

Table 2: Theoretical Characteristic Frequencies (Hz)

Speed in rpm	fs	BPFO fod	BPFI fid	BPFR fbd
2100	35	125.4	189.5	164.8
2400	40	143.4	216.6	188.5
2700	45	161.2	243.7	211.8
3000	50	179.1	270.8	235.4

To know the effect of load on vibration behavior of rolling bearing the radial load was varied from 212 N to 636 N. The axial load is varied from104 N to 156 N. Fig. 3 and Fig. 4 shows the vibration spectrum obtained for test bearing SKF6205 under different radial and axial loading respectively. The results reveal that the vibration spectra with variation in loading follow the same trend.

Based on above results, vibration signal from all defective bearings is acquired at 634 N constant radial load and 104 N constant axial load. The spectra for different test bearings are shown in following figures.

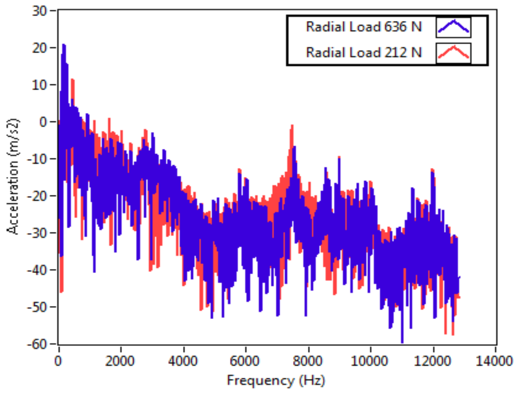

Fig.3 Vibration Spectra under different radial loads

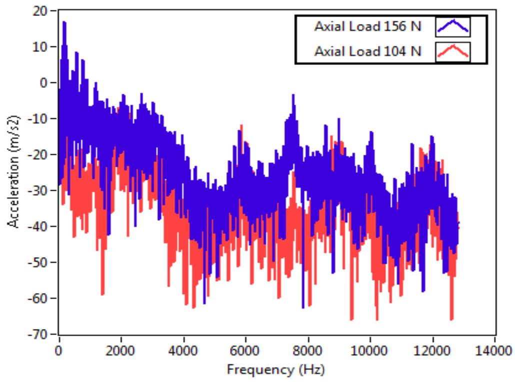

Fig.4 Vibration Spectra under different axial loads

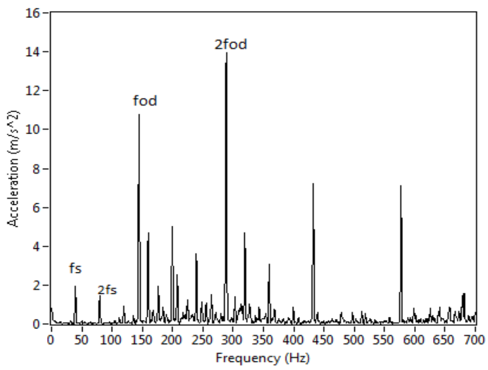

Fig.5 Vibration Spectrum for defect on outer race at 2400 rpm

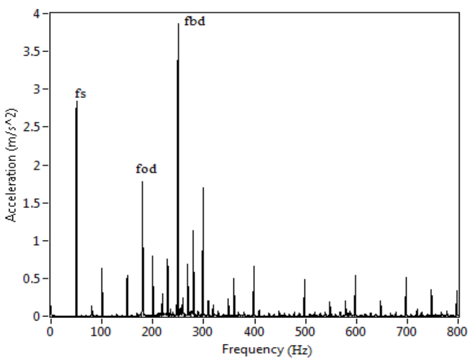

Fig.6 Vibration Spectrum for defect on outer race and ball at 3000 rpm

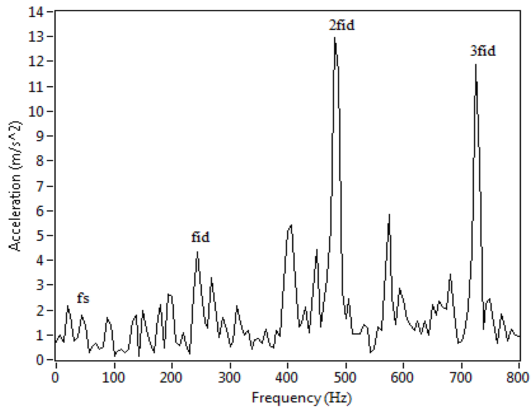

Fig.7 Vibration Spectrum for line defect on inner race at 2700 rpm

Figures 5 to 7 shows the vibration spectrum for SKF 6205 bearing with defect on outer race, defect on outer race and ball, defect on inner race respectively. For all test bearings the first peak is obtained at shaft rotation frequency. For defective bearing with defect on outer race peak corresponding to fod calculated theoretically by equation 1b) is dominating as shown in Fig 5. For bearing with defect on outer race and ball, amplitude level of roller defect frequency is greater than outer race defect frequency shown in Fig 6. For defects on inner race, peaks corresponding to inner race defect frequency and its harmonics are indicated by the spectrum in Fig 7.

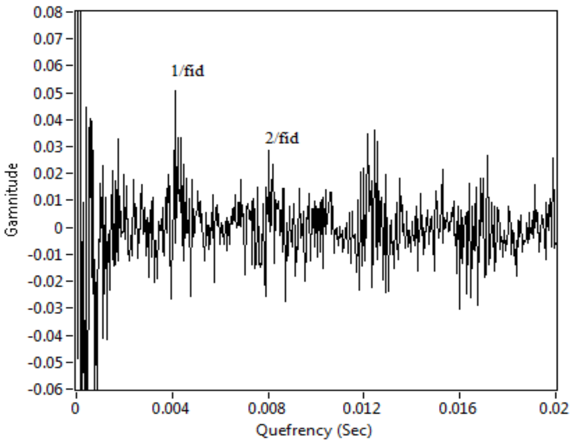

Fig.8 Cepstrum for 6205 bearing with inner race defect at 2700 rpm

Fig. 8 shows the cepstrum of bearing with inner race defect. It indicates major peaks corresponding to inner race defect frequency and its rahmonics. Fig. 9 shows cepstrum of bearing with outer race defects. Major peaks are obtained corresponding to outer race defect frequency and its rahmonics. The cepstrum for defect on ball does not give any clear picture of fault present as seen in Fig. 10.

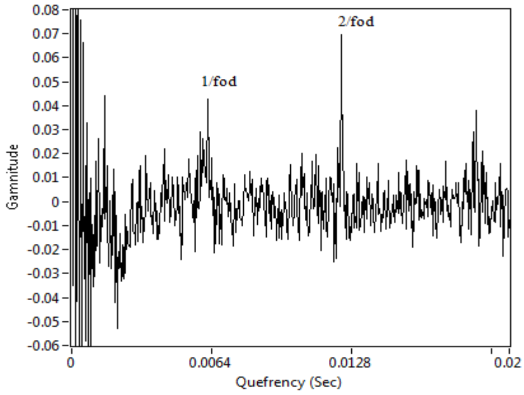

Fig.9 Cepstrum for 6205 bearing with outer race defect at 2700 rpm

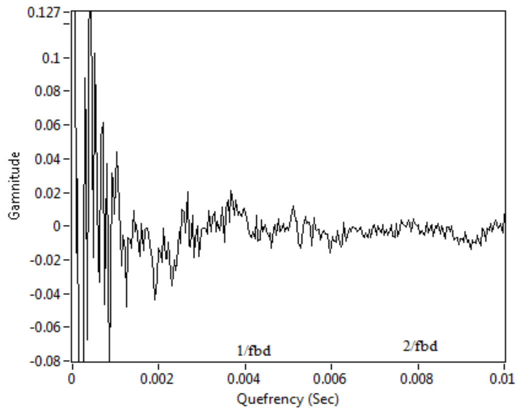

Fig.10 Cepstrum for 6205 with defect on ball at 3000 rpm

5.2 Time Domain Analysis

Variation of Kurtosis for defect free bearings at different speeds is shown in table 3. Kurtosis is high at lower speed at 1800 rpm and tends to increase at higher speed at 3000 rpm shown in Fig 11.

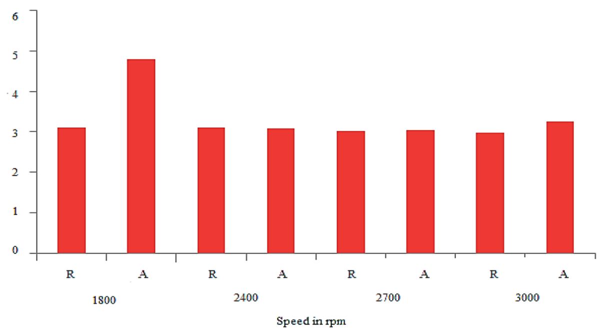

Fig.11 Variation of Kurtosis with speed

Table 3: Variation of Kurtosis with speed

Bearing	Speed in rpm							
	1800		2400		2700		3000	
	R	A	R	A	R	A	R	A
Defect free	3.1	4.78	3.11	3.07	3	3.04	2.98	3.2

Table 4: 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

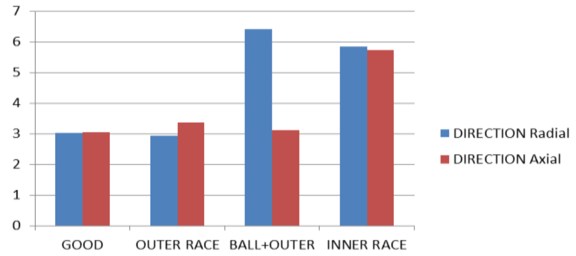

Fig.12 Variation of Kurtosis with defect location

Fig.12 shows the values of kurtosis for different test bearings. For defect free bearing and the bearing with outer race defects the kurtosis values are in the range of 2.9 to 3.2 as shown in Table 4. For defect on ball and inner race defects, the kurtosis values are well above 3 indicating presence of defects. It is observed that kurtosis cannot detect the outer race defect. It is good indicator for detecting defects on inner race and rolling elements.

Crest factor for defect free bearing is less than 4 as shown in table 5. It is observed that there is no definite pattern of crest factor at different speeds. This variation is shown in Fig. 13.

For bearing with outer race defects similar results are obtained as shown in table 5. Therefore crest factor is not a good indicator for outer race defects. For bearing with defects on rollers and inner race, the crest factor values are greater than 5. Thus this clearly indicates the presence of faults. Fig. 14 shows the variation of crest factor values for different defects.

Table 5: Crest Factor for defect free bearings at different Speeds

Condition of bearing	Crest factor					
	2400		2700		3000	
	R	A	R	A	R	A
Defect free	3.76	4.22	3.74	3.53	3.72	4.26

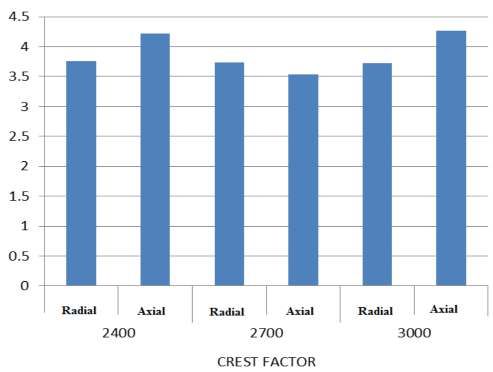

Fig.13 Variation of crest factor with speed

Table 6: Crest factor for different defects

Bearing Condition	Direction	
	Radial	Axial
Defect free	3.74	3.53
Outer race 2x2mm defect	3.33	3.86
Ball+outer race 2mm	7.22	4.42
Inner race line	5.18	5

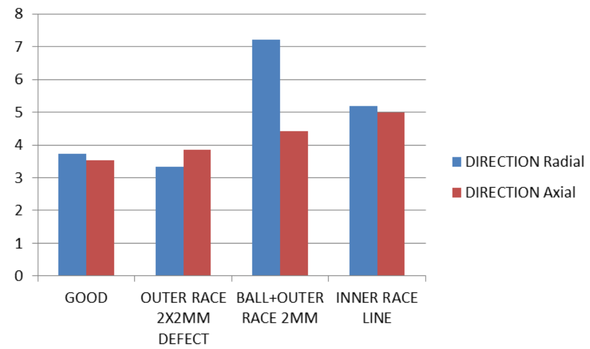

Fig.14 Variation of crest factor with defect location

Conclusion

The characteristics frequencies for different defect locations calculated using equations are observed in the spectrum of bearing. These characteristic frequencies vary with the speed of rotation of bearing. The spectrum is obtained for different locations of the defect on the bearing. The spectrum for defects on outer race and ball shows higher amplitude corresponding to ball defect frequency. Cepstrum for different defects is obtained. The results reveal that it is not possible to detect defect on balls using cepstrum.

Performance of statistical parameters such as kurtosis, crest factor and cepstrum is studied for different conditions of operation of SKF 6205 bearing. Value of kurtosis for defect free bearing is high at low speed and decreases with speed. It is observed that kurtosis is poor indicator of defect on outer race. Crest factor for defect free bearing is less than 4 and there is no definite pattern of crest factor at different speeds. Similar to kurtosis, crest factor is not good indicator for defect on outer race.

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