Experimental study on enhancement of defect detection and defect size estimation in deep groove ball bearing

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Abstract. Rolling elements bearings are widely used in rotating equipment and machines to support load and to reduce friction. The presence of micron sized defects on the mating surfaces of the bearing components can lead to failure through passage of time. The large size defects on bearing elements can be detected/identified by time domain and frequency domain analysis of its vibration signals. However, it becomes difficult to detect local bearing defects at their initial stage either due to their smaller size or presence of noise. In the present experimental study, detection of local defects like crack and pits on bearing races have been carried out. Vibrations generated by healthy bearing and bearing having circular or rectangular defect on either race of bearing have been analyzed using MATLAB software. Signal to noise ratio of vibration signal has been enhanced through self-adaptive noise cancellation. Moreover, width of rectangular defects and diameter of circular defects have been estimated through ‘db5’ wavelet. The estimated defect sizes have been compared and validated through measured actual crack width or pit diameter. Accuracy of results proves that wavelet analysis of time domain signal can be used with confidence to estimate the width of fatigue crack and pit of the bearing races.

Keywords: Rolling Element Bearing, Local Defects, Vibration analysis, Wavelet, Adaptive Filtering

1. Introduction:

The performance of any rotating machine is very much dependent on the dynamic behavior of rolling bearings. As rolling element bearing plays a crucial role in the rotating machine it becomes very important to monitor the health of the bearing to avoid breakdown and accidental losses.

Most of the time bearing defects may emerge due to the excessive transferred load on the bearing, corrosion, wear or due to the improper installation of bearings. Broadly researchers have classified
bearing defects as local defects and distributed defects. Localized defects are comprising of cracks, pits, spall whereas distributed defects are comprising of surface roughness, waviness, misalignment, off-size rolling element. Detection of these defects is very much necessary for condition monitoring of the bearing as well as quality inspection.

Different types of condition monitoring techniques have been used by the researchers. Different vibration and acoustic analysis methods, such as vibration measurement in time domain, vibration measurement in frequency domain, vibration measurement in combined time-frequency domain, sound measurement and acoustic emission have been used to detect the defects in rolling element bearings. Initially time domain approach has been used to detect the defect detection with limited success ratio. Root mean square (RMS) value and crest factor have been used to measure the local defects on the rolling elements of bearings. Statistical parameters like kurtosis value and probability density have been used. Defect free bearing gives a gaussian distribution. Due to the relative increase in the number of high levels of acceleration defective bearing have non-gaussian distribution. Frequency domain analysis has been used widely as it gives results very efficiently. Whenever the rolling element strikes on the defects it produces pulses of very short duration. These pulses excite the natural frequencies of rolling element bearing which can be calculated experimentally and theoretically.

Condition monitoring technique such as Proximity transducer technique has been used as this technique uses non-contact type transducer. The main advantage of non-contact type transducer is it eliminates the noise of the housing structure. Due to this reason the signal to noise is improved in this condition monitoring technique. The main disadvantage of this condition monitoring is the difficulty in the installation/mounting of probe at proper location. Signal transmission error can be avoided with proper mounting of accelerometer during vibration capture. Condition monitoring technique such as acoustic noise response has been used to diagnosis the bearing health in the modes of sound pressure measurement and sound intensity measurement. The diagnosis of bearing defects becomes difficult as it also contains surrounding noise other than bearing defect sound. Literature review shows that vibration measurement in time domain and frequency domain gives more precise and better results than other condition monitoring techniques.

Researchers [1-2] have reviewed the various methods which were used for the purpose of health diagnosis and detection of bearing defects. The purpose of condition monitoring, sound measurement, the shock pulse method, and acoustic emission techniques have been used. For the purpose of vibration and wear debris analysis some techniques are used namely as shock pulse, ferrography, spectrography, oil analysis, spike energy and chip detection. To diagnose the bearings defects most of the researchers have used vibration measurement techniques. Many techniques have been applied to measure the vibration response of the bearings which is having local defects. But the problem about these signal processing techniques is they depend on the result of each other and works as complimentary for each other. Time domain and frequency domain are used to study and analyze the vibration signals.

Time domain analysis technique like root mean square (RMS), crest factor, kurtosis, spectral kurtosis, and probability density have been used by researchers [3-7]. The signal processing techniques like kurtosis, spectral kurtosis, kurtogram and band kurtosis are the extensively used signal processing techniques to determine the impulsiveness of the signal. The frequency domain is the most widely used and accepted approach to find bearing defects and to perform the higher level of signal processing techniques. Bearing elements have a characteristic rotational frequency which lies in a specific range, due to this phenomenon whenever rotating elements pass through defect on bearing elements, the vibrational energy at that characteristic defect frequency increases.

To remove the external vibration of the signal using signal processing techniques are discussed by researchers [8-9]. Some of them are: envelope analysis, adaptive noise cancellation, self-adaptive noise cancellation, high-frequency resonance technique (HFRT), wavelet analysis, stochastic
resonance, cyclostationary analysis, spectral subtraction and blind source separation. It is difficult to retrieve important peaks at defect frequencies in presence of noise [9].

The bearing defects have been detected by researchers of references [10-15] with the help of adaptive noise cancellation technique (ANC). Adaptive noise cancellation requires primary signal and reference signal. Primary signal includes bearing signal and noise. Reference signal is related to the noise signal. The signal to noise ratio has increased marginally in each of the experiments performed by researchers. As a result of ANC signal to noise ratio (SNR) increased and time domain techniques like kurtosis, power spectrum, RMS values have been determined. The self-adaptive noise cancellation technique (SANC) is capable to enhance SNR with only primary signal. Khemili and Mnaouar [10] have used self-tuning adaptive filters also known as self-adaptive noise cancellation (SANC) for their theoretical and experimental study for bearing defect detection. They have concluded that SANC filters have provided better SNR than adaptive noise cancellation for simulated data as well as experimental data.

Defect size estimation has always remained challenging task for researchers. The literature survey discloses that very few researchers [16-25] have estimated the size of the faults in the rolling element bearing. Most of the researchers have used wavelet analysis for defect size estimation due to the simplicity of wavelet analysis. Khanam and Tandon [16] have estimated the bearing outer race defect size using Symlet wavelet. Symlet wavelet has identified entry and exit events of rolling elements at outer defect.

The acoustic emission burst duration has been found out by the Kumar [20]. Authors have concluded from the experimental study that the duration of burst increases with width of outer race defect. Experiments have been performed to estimate the size of outer race defects [20]. The bearing vibrational signals have been decomposed by Barszcz [23] into deterministic and non-deterministic components to detect the fault on the outer race of the ball bearing. Adaptive filter has been used to remove the noise from the vibrational signal.

Literature review reveals that a lot of research work has been carried out in the field of defect detection of rolling element bearings in absence of external vibrations. Most of researchers have estimated defect size of outer race. However, it is difficult to estimate the bearing defect size in presence of noise at the initial/beginning stage i.e. when the size of the fatigue crack or pit is minute in size. Hence, the main objective of the present experimental study is to estimate the width of fatigue crack and diameter of pit on bearing races. Moreover, self-adaptive noise cancellation technique has been adopted to improve signal to noise ratio of bearing vibration signal. Vibration signals of deep groove ball bearings having crack or pits (on either race) of varying size have been captured. Statistical parameter like kurtosis has been computed from time domain signal, while defect characteristic frequencies have been identified in frequency domain. Defects size has been estimated through ‘db5’ wavelet analysis of time domain signal. Estimated defect width and defect diameter has been validated with actually measured defect size. Paper has been organized as follow: section 2 discusses experimental set up, vibration responses of bearings have been presented in section 3, self-adaptive signal processing technique has been discussed in section 4, while defect size estimation and signal analysis has been carried out in section 5 and section 6, respectively.

2. Experimental details: -

Vibrations generated by healthy and defective deep groove ball bearings (SKF BB1 B420206) have been captured by accelerometer. A photographic view of experimental setup used for vibration study is shown in Figure1. A shaft is supported on two deep groove ball bearings. It receives power from motor through V-belt and pulley, attached on right hand end of the shaft. While, the test bearing (SKF BB1B420206) was mounted on cantilever portion of left-hand end of shaft. The radial load of 10 kg was hanged at the bottom of specially designed test bearing housing and accelerometer (603C01 NI) was mounted on top of this housing to capture vibration data. Data acquisition card (9234 NI) was used to transfer captured data to the computer through LAB-VIEW software. The
vibration data were captured at the sampling rate of 1k. The test bearing specifications are provided in the Table 1. The collected vibration signal of the test bearing has been analyzed in time domain and frequency domain using MATLAB software.

![Experimental setup](image)

**Figure 1 Experimental setup.**

**Table 1. Test bearing (SKF BB1B420206) specification.**

|                         |     |                               |     |
|-------------------------|-----|--------------------------------|-----|
| Bore of bearing, mm     | 30  | Ball diameter (d_b), mm        | 10.4|
| Inner race diameter (d_i), mm | 34.52| Diametric clearance (P_d), μm  | 10  |
| Outer race diameter (d_o), mm | 54.92| Grooves radii, mm              | 5   |
| Pitch diameter (D_P), mm | 44.72| Number of balls (N_b)          | 8   |

Vibration signals of defect free test bearings (considered as healthy bearing) and test bearings having circular defect (considered as pit) or rectangular defect (considered as fatigue crack) on its either race have been captured for analysis. Artificial defects were created through electro discharge machining. Figure 2 shows the photographic view and microscopic images of circular and rectangular defects on inner race and outer race of the bearing.
It is worth to mention here that four artificial circular defects of different diameter on inner race and three artificial circular defects of different diameter on outer race were created. Four artificial rectangular defects of different width on inner race and three artificial rectangular defects of different width on outer race were created. Hence vibrations generated by these fourteen healthy bearings before defects creation and after defect creation were studied.

3. Vibration response of deep groove ball bearing: -

The vibration responses of all test bearings before and after defect generation have been captured and analyzed. It is worth to mention here that time domain and frequency domain analysis have been performed for healthy and defective bearings using MATLAB software. Statistical parameters like Kurtosis and Root Mean Square (RMS) value have been computed from time domain data through equation 1 and equation 2 respectively.

\[
kurtosis = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{x_i - \mu}{\sigma} \right)^4
\]  

(1)
Root mean square = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2} \quad (2)

Kurtosis gives insights into the shape of the distribution of the data. Skewness is a measure of the symmetry in a distribution. A symmetrical dataset gives zero skewness. Skewness measures the relative size of the two tails. Kurtosis also measures the amount of probability in the tails. The value is many times compared with the kurtosis of the normal distribution, which is equal to 3. If the kurtosis is greater than 3 for given dataset, then the dataset has heavier tails than a normal distribution. If the kurtosis is less than 3, then the dataset has lighter tails than a normal distribution. Generally, root mean square value of defective bearing increases with the increase in the size of the defect.

3.1 Vibration response of healthy bearing

The vibration response of one of the healthy bearing has been presented here. Vibration data in form of acceleration captured by accelerometer has been presented in Fig. 3 in form of time domain and frequency domain. As shown in Figure 3(a) vibration signal has been captured for 2.5 millisecond for 4096 samples. A computed kurtosis value is 2.8246 and RMS value is 0.3887 for this healthy bearing. The shaft was rotating at 1600 RPM. The rotation speed was measured by digital tachometer. The peaks at shaft rotational frequency ($F_s = 26.66$ Hz) and its harmonics ($2 \times F_s = 53.32$ Hz, $3 \times F_s = 79.98$ Hz) can be noticed in frequency domain of signal (refer Figure 3(b)). Additional dominant frequency peaks observed around 100 Hz are due to natural frequency of the system, which were observed in all captured vibration signal irrespective of shaft rotational speed.

![Figure 3 Vibration response of healthy bearing at a shaft speed of 1600 RPM.](image)
Same methodology has been adopted for all healthy bearings (i.e. before artificial defect creation). The frequency peaks at shaft rotation speed along with their harmonics were observed in vibration acceleration spectra of all bearings. The kurtosis value was around 3 for all cases, while the maximum RMS value was 0.4774 for healthy bearings.

3.2 Vibration response of bearings having defects on its inner race:

As discussed in section 2, rectangular and circular artificial defects were created on inner race of healthy bearings to capture vibration responses of defective bearings. In first stage rectangular slot of 0.77 mm width on one bearing and circular blind hole of 0.77 mm diameter on another bearing were created. Vibration data in form of acceleration were captured and analyzed for both bearings separately. To study the effect of defect size and shape of inner race defect on vibration response, circular hole and rectangular slot were enlarged upto 2.07 mm diameter and 1.91 mm width respectively and vibration signals were captured.

Figure 4 shows the vibration response of bearing having circular defect of 0.77 mm diameter on its inner race. The RMS value and kurtosis value computed from Figure4(a) is 0.3320 and 3.9139 respectively. Figure 4(b) shows the frequency response of defective bearing. Along with shaft rotational frequency \( F_s = 26.63 \text{ Hz} \), frequency peaks at ball pass frequency of inner race (BPFI) at 131.1 Hz and its harmonics at \( 2\times\text{BPFI} = 263.1 \text{ Hz} \). The computed value of BPFI =131.29 Hz and its harmonics at \( 2\times\text{BPFI} = 262.58 \text{ Hz} \). This can be validated with Figure4(b). The inner race of bearing rotates at shaft rotation, hence side bands at BPFI\( \pm F_s \) are also expected. In Fig.4(b) sidebands at BPFI\( + F_s = 157.8 \text{ Hz} \) and BPFI\( - F_s = 104.9 \text{ Hz} \) for first harmonic and \( 2\times (\text{BPFI} + F_s) = 289.3 \text{ Hz} \) and \( 2\times (\text{BPFI} - F_s) = 236.5 \text{ Hz} \) for second harmonic are clearly observed.

Figure 4 Vibration response of bearing having circular defect of 0.77 mm diameter on its inner race at shaft speed of 1600 RPM.
Figure 5 shows the vibration response of bearing having rectangular defect of 0.77 mm width on its inner race. The RMS value and kurtosis value computed from Figure 5(a) is 0.2560 and 3.1116 respectively. Figure 5(b) shows the frequency response of defective bearing. Along with shaft rotational frequency $F_s = 26.63$ Hz, frequency peaks at ball pass frequency of inner race (BPFI) at 131.6 Hz and its harmonics at $2 \times $ BPFI = 261.5 Hz. The computed value of BPFI = 131.29 Hz and its harmonics at $2 \times $ BPFI = 262.58 Hz. This can be validated with Figure 5(b). The inner race of bearing rotates at shaft rotation, hence side bands at BPFI $\pm F_s$ are also expected. In Fig. 5(b) sidebands at BPFI $+ F_s$ = 158.2 Hz and BPFI - $F_s$ = 104.5 Hz for first harmonic and $2 \times (BPFI + F_s)$ = 289.7 Hz and $2 \times (BPFI - F_s)$ = 236.1 Hz for second harmonic are clearly observed.

![Time domain](image)

(a) Time domain

![Frequency domain](image)

(b) Frequency domain

Figure 5 Vibration response of bearing having rectangular defect of 0.77 mm width on its inner race at shaft speed of 1600 RPM.

Same methodology has been adopted to study vibration responses of bearings having inner race defect of 1.03 mm, 1.1 mm and 1.53 mm defect diameter and 1.03 mm, 1.44 mm and 1.91 mm defect width. The kurtosis value reached to 4 or more for all defective bearings and RMS value reached to 0.5094, determined from their respective time domain signals. Moreover, the expected inner race defect frequency along with side bands at BPFI $\pm F_s$ were observed in their frequency spectra.

Raw signal of Inner race Rectangular defect -1 in which shaft rotating frequency and harmonics of the defective frequency is shown by its relative names as BPFI and its harmonics $2 \times $ BPFI. The sidebands for BPFI are also shown as BPFI $- F_s$ and BPFI $+ F_s$. Unfortunately, defect frequency and its harmonics are not clearly visible due to the noise in the vibrational signal.

3.3 Vibration response of bearings having defects on its outer race: -

As discussed earlier, rectangular and circular artificial defects were created on outer race of healthy bearings to capture vibration responses of defective bearings. In first stage rectangular slot of 0.77 mm width on one bearing and circular blind hole of 0.77 mm diameter on another bearing were created. Vibration data in form of acceleration were captured and analyzed for both bearings separately. To study
the effect of defect size and shape of outer race defect on vibration response, circular hole and rectangular slot were created on different bearings from 0.499 mm, 1.50 mm and 1.87 mm diameter and 0.72 mm, 1.49 mm and 2.16 mm width respectively and vibration signals were captured.

Figure 6 shows the vibration response of bearing having circular defect of 0.77 mm diameter on its outer race. The RMS value and kurtosis value computed from Figure 6(a) is 0.4032 and 3.1089 respectively. Figure 6(b) shows the frequency response of defective bearing. Along with shaft rotational frequency $F_s = 26.63$ Hz, frequency peaks at ball pass frequency of outer race (BPFO) at 83.53 Hz and its harmonics at $2 \times \text{BPFO} = 166.7$ Hz. The computed value of BPFO = 81.74 Hz and its harmonics at $2 \times \text{BPFO} = 163.48$ Hz. This can be validated with Fig. 6(b).

![Time domain](image1.png)

(a) Time domain

![Frequency domain](image2.png)

(b) Frequency domain

Figure 6 Vibration response of bearing having circular defect of 0.72 mm diameter on its outer race at shaft speed of 1600 RPM.
Figure 7 Vibration response of bearing having rectangular defect of 0.499 mm width on its outer race at shaft speed of 1600 RPM.

Figure 7 shows the vibration response of bearing having rectangular defect of 0.77 mm diameter on its outer race. The RMS value and kurtosis value computed from Figure 7(a) is 0.3517 and 2.9360 respectively. Figure 7(b) shows the frequency response of defective bearing. Along with shaft rotational frequency $F_s = 26.63$ Hz, frequency peaks at ball pass frequency of outer race (BPFO) at 82.73 Hz and its harmonics at $2 \times$ BPFO = 165 Hz. The computed value of BPFO = 81.74 Hz and its harmonics at $2 \times$ BPFO = 163.48 Hz. This can be validated with Figure 7(b).

Same methodology has been adopted to study vibration responses of bearings having outer race defect of 0.72 mm, 1.49 mm and 2.16 mm defect diameter and 0.499 mm, 1.50 mm and 1.87 mm defect width. The kurtosis value and RMS value determined from their respective time domain signals were increased as compared to healthy bearings. The maximum RMS value reach to 0.9699 for defect width of 1.87 mm.

4. Noise cancellation in vibration signal: -

It has been observed that when defect size is small, the characteristic defect frequencies submerge in noise and its identification in frequency spectra become difficult. In this situation the adaptive noise cancellation techniques are useful. Adaptive filters have the ability to adjust their impulse response to filter out the correlated signal from the input signal. The prior information about signal and noise characteristics do not require in case of adaptive filters. The principle of adaptive noise cancellation is presented in Fig. 8. The primary input signal $S$ (vibration response of defective bearing) is corrupted by the noise $v_o(n)$ (unwanted vibration response). The reference input consists of noise $v_r(n)$ is uncorrelated with the primary signal $S$ but correlated with the noise $v_o(n)$.

![Figure 8 Basic concept of adaptive noise cancellation](image)
The principle of self-adaptive noise cancellation (SANC) is presented in Figure 9. The use of self-adaptive noise cancellation signal processing technique amplifies the important frequencies in the vibration spectra. Self-adaptive noise cancellation technique does not require any reference signal. A delay version of the primary signal is used in the self-adaptive noise cancellation as the reference signal. The adaptive filter has the ability to adjust the parameter of its own and it can minimize the average power of the residual interference present in the output signal which has the error. The adaptive noise cancellation technique is highly depending on the filter length, step size and length of the signal.

4.1 Noise cancellation in defective bearing vibration signal:

The time domain vibration signal of bearing having circular defect (signal shown in Fig. 4(a) has been used as an input signal for SANC filter. The reference signal has been provided with delay of 4 samples of input signal. The filter length was 1024 and step size = 0.036. Filtered vibration response of this signal is shown in Fig. 11. The shaft rotating frequency along with the ball pass frequency of inner race and its sidebands are now visible clearly in Figure 11. The noise in

![Figure 10 Vibration response of bearing having inner race circular defect after noise cancellation at a speed of 1600 RPM](image)

vibration response has suppressed after use of self-adaptive noise cancellation. The time domain vibration signal of bearing having rectangular defect on inner race (signal shown in Fig. 5(a) has been used as an input signal for SANC filter and its vibration spectra has been presented in Figure 11. Selected filter length was 1024 and step size = 0.0135.
The noise present in the vibration response (time domain signal in Figure 6(a)) has suppressed with the help of self-adaptive noise cancellation. Figure 12 shows the vibration response of bearing having outer race circular defect with the use of self-adaptive noise cancellation.

Figure 12 Vibration response of bearing having outer race circular defect after noise cancellation at a speed of 1600 RPM

Figure 13 shows the vibration response of bearing having outer race rectangular defect (for time domain signal in Figure 7(a)) after the use of self-adaptive noise cancellation. The use of self-adaptive noise cancellation signal processing technique has suppressed the noise from the signal.

Figure 13 Vibration response of bearing having outer race rectangular defect after noise cancellation at a speed of 1600 RPM.

5. Defect size estimation: -

Wavelet analysis has gained lot of popularity among the researchers for the condition monitoring of the machine and in diagnosis of bearing faults. Wavelet analysis possesses flexibility and effectiveness in
the computation and implementation. A wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelet has the ability to perform local analysis of the large signal. Wavelet analysis consists of breaking up a signal into shifted and scaled version of the mother wavelet.

Approximation and details are two main part of the wavelet analysis where approximation indicates the high-scale and details indicates the low scale component. Here, high scale refers to the low frequency component whereas low scale refers to the high frequency component. The original signal passes through two given filters and emerges as two signals. Two filters are namely as low pass filter and high pass filter. The signal has been decomposed in lower resolution and reconstruct it without the loss of important information.

Wavelet analysis has the capability to expose the aspects of data of the signal like trends, breakdown points, self-similarity and discontinuities in higher derivatives. Wavelet analysis is used in many different applications which are Detecting Discontinuities and Breakdown Points, Detecting Long-Term Evolution, Detecting Self-Similarity, Identifying Pure Frequencies, Suppressing Signals, De-Noising Signals, De-Noising Images, Compressing Images and Fast Multiplication of Large Matrices.

It has been noticed that when ball passes through defect zone, the dynamic characteristic of bearing elements changes due to change in stiffness [26]. The change in stiffness results in changes in deflection pattern. The impulses generated due to impact correspond to ball position in defect zone can be identified using wavelet analysis of time domain signal.

5.1 Defect size estimation of inner race defect: -

Figure 14(a) presents the entry and exit of rolling element (ball) in defect zone of inner race. The entry point of defect zone has been marked with A (refer Figure 14(a)) and it’s corresponding time when ball just touches point A has been shown with A’ in zoomed view of time domain signal (refer Figure14(b)). The exit point of defect zone has been marked with B in Figure14 (a) and it’s corresponding time when ball just touches point B has been shown with B’ in Figure14(b). The time difference corresponds to B’ and A’ provide information related to time spent by ball in defect zone. Inner race defects have been measured with the help of signal processing technique called wavelet analysis. Daubechies wavelet as a mother wavelet is used. Approximation of the signal is taken up to 3rd level. The same phenomenon has been used for circular defect and rectangular defect. Figure 14(b) shows time domain response at different entry and exit events of the ball when it strikes to the inner race circular defect.

Figure 15 shows the different entry and exit events of the ball when it strikes to the inner race rectangular defect. The time duration of ball at defect can be determined from these entry and exit events.
(b) Corresponding time domain signal and enlarged view of encircled part

Figure 14 Ball position at inner race defect zone.

Figure 15 Approximation by decomposition of signal at 3rd level for entry and exit of ball from inner race defect zone.

5.2 Defect size estimation of outer race defect:

(a) Entry and exit event
Figure 16 Ball position at outer race defect zone.

Figure 16(a) presents the entry and exit of rolling element (ball) in defect zone of outer race. The entry point of defect zone has been marked with C (refer Figure16(a)) and its corresponding time when ball just touches point C has been shown with C/g99 in zoomed view of time domain signal (refer Figure16(b)). The exit point of defect zone has been marked with D in Figure16(a) and its corresponding time when ball just touches point D has been shown with D/g99 in Figure16(b). The time difference corresponds to D/g99 and C/g99 provide information related to time spent by ball in defect zone. Outer race defects have been measured with the help of signal processing technique called wavelet analysis. Daubechies wavelet as a mother wavelet is used. Approximation of the signal is taken up to 3rd level. The same phenomenon has been used for circular defect and rectangular defect for outer race defects.

Figure 17 shows the different entry and exit events of the ball when it strikes to the outer race rectangular defect. All the defect sizes for inner race and outer race have been estimated with the help of the same signal processing technique.

6. **Result and discussion**

Figure 3 shows the vibration response of healthy bearing in time domain and frequency domain. The kurtosis values and root mean square (RMS) values for all the healthy bearings have been computed and tabulated in Table 3. It can be observed that the healthy bearing has kurtosis value around 3. The kurtosis value above 3 indicates manufacturing defect in bearing. However, the kurtosis value of bearing having defect on either race (refer time domain signal of Figure4 – Figure7) are around 4, this is indication of presence of local defect on bearing races. The peaks at defect frequency BPFI and 2×BPFI along with its side bands BPFI-Fs and BPFI+Fs in the case of inner race defective bearings can be observed in frequency domain. It is worth to mention here that the side bands appeared due to rotation of inner race defect at shaft rotation speed. The frequency peaks at BPFO and 2×BPFO in frequency domain of Figure6 and Figure7 indicates defect on outer race of bearing. In case of frequency domain of healthy bearing such characteristic defect frequency peaks are missing.
Figure 17 Approximation by decomposition of signal at 3rd level for entry and exit of ball from outer race defect zone.

The vibration response of defective bearings after the use of self-adaptive noise cancellation signal processing technique have been presented in Figure10 – Figure13. The enhancement of amplitude at defect frequency as compared to amplitude of defect frequency without use of SANC (refer frequency domain signals in presence of race defects) reveals increase of SNR. in the important peaks are massive and observed by comparing the figure without the use of self-adaptive noise cancellation and with the use of self-adaptive noise cancellation signal processing technique.

The defect size has been estimated for both rectangular defect and circular defect (on either bearing race) through wavelet decomposition of time domain signal of Figure14 – Figure17. The average time duration ($\Delta t$) i.e. time spent by rolling element in defect zone for three events has been measured. The time duration ‘$\Delta t$’ has been computed by taking time difference between time of exit of ball from defect and time of entry of ball in defect for same event. The estimation of defect size also depends on shaft rotational speed and bearing parameters like pitch diameter of bearing, number of balls and ball diameter. The defect size has been estimated through Eq. 3 provided by Khanam et al. [16].

$$\text{Defect size} = \frac{D_p \times \omega_b}{4} \left(1 - \frac{d_b^2}{D_p^2} \cos^2 \alpha \right) \times \Delta t \quad (3)$$

Where, $\omega_b$ is the shaft rotational speed of the ball, $D_p$ is the pitch diameter of the bearing, $d_b$ is the ball diameter, $\alpha$ is the contact angle equal to zero for deep groove ball bearing.

The estimated defect width (for rectangular defect) and defect diameter (for circular defect) through Eq. 3 and actual measured defect size have been tabulated in Table 2. It is worth to mention here that the actual defect size has been measured by optical microscope. The error between estimated value and measured value provide accuracy of defect size estimation.

Table 2 : Comparison of measured defect size and estimated defect size.

| Defective race | Type of defect | Defect size (dia. or width) measured using optical microscope (mm) | Defect size (dia. or width) estimated through signal processing | % Error |
|----------------|---------------|-----------------------------------------------------------------|-----------------------------------------------------------------|---------|


7. **Conclusion:**

The vibrations generated by healthy and defective deep groove ball bearings have been captured experimentally and vibrations signals have been analyzed in time domain and frequency domain. It has been observed that the statistical parameters like kurtosis and RMS value increases in presence of local defects on either race of bearing. The peaks at characteristic defect frequency along with their harmonics have been observed in presence of local defect on either race. Thus, the frequency domain analysis of vibration signal can provide information regarding health of bearing. The amplitudes of defect frequency are more in case of rectangular defect as compared to circular defect amplitudes. However, it becomes difficult to identify the defect frequency peaks at the initial stage of defect and in presence of noise. In such cases, signal to noise ratio improved after use of SANC that result in enhancement of amplitude of defect frequencies. The width of rectangular defect (fatigue crack) and diameter of circular defect (pits) have been estimated accurately with maximum error of 6.8%. Authors of this paper believe that the present experimental study will provide guidelines to researchers and practicing engineers in bearing defect detection and defect size estimation.

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