Investigations of Antifriction bearing defects using Vibration Signatures

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Abstract: Antifriction bearing failure is a major factor in the failure of rotating machinery. As a fatal defect is detected, it is common to shut down the machinery as soon as possible to avoid catastrophic damages. Performing such action typically results in substantial time and economic losses. Therefore it is important to monitor the conditions of antifriction bearings and to know the details of the severity of defects before they cause serious catastrophic consequences. The vibration monitoring technique is the most suitable method to analyze various defects in bearing. This technique can provide early information about progressing malfunctions. Time-domain analysis and frequency domain analysis have been employed to identify different defects in bearing running at three different speeds. Defect-free and defective bearing are used for testing. Time-domain and frequency-domain signals acquired for both good and defective bearings Time waveform indicated the severity of vibration in defective bearings. The frequency spectrum is used to identify the amplitudes corresponding to fault frequencies and enables to predict of the defect presence. The roller bearing is considered for analysis. Three types of defects namely outer race, inner race, and rolling element defect are considered. Experimental data of both defect-free and defective bearings are processed to show the effectiveness of the fault diagnosis using this method. In fault monitoring and diagnostics of bearings, real-time processing and fast on line fault indication are becoming increasingly important. Towards this goal, attention has focused on a search for the use of effective signal processing and signatures extracting methods to realize immediate fault detection.

Keywords: antifriction bearing, frequency domain, outer race defect, rolling element defect, Vibration Signature
1. Introduction

Rolling element bearings are a common component in rotating machinery. The failures of rotating types of machinery can be very critical because these lead to machinery damage, production losses, and personnel injury. So, a very important duty of the maintenance department is to prevent these failures when they are in their initial stage. The Hertzian contact stresses between the rolling elements and the rings are one of the basic mechanisms that initiate a localized defect. When a rolling element strikes a localized defect an impulse occurs and this excites the resonances of the structure.

The vibration signature of a damaged bearing consists of exponentially decaying ringing. These impulses will occur with a period determined by the location of the defect, the geometry of the bearing, and the type of the bearing load. The vibration analysis is a technique, which is being used to track machine operating conditions and trend deteriorations to reduce maintenance costs and downtime simultaneously [1,2]. Since most of the machinery in a predictive maintenance program contains rolling element bearings, it is imperative to understand how to monitor and diagnose problems associated with them. Two-part philosophy concerning rolling element bearing monitoring and diagnostics are: (1) the monitor system will provide adequate warning to avert catastrophic machine failures and (3) diagnostic data will be available so that when the warning is given, the bearings will have visible damage. [1] There are several techniques for condition monitoring of rolling element bearings. Among them, vibration and acoustic measurements are most widely used in [4]. The vibration measurement methods can be classified as in time and in frequency domains. A brief review of the monitoring techniques in time and in the frequency domain can be found in [5]

Honarvar and Martin [6] use the third and fourth moments of the vibration signals known as skewness and kurtosis, respectively, for bearing failure detection. McFadden and Smith [7] present a basic understanding of the high-frequency resonance technique. Lou et al. [8] propose a method based on extracting the dynamic model of the bearing system from the experimental vibration signals to design a proper fault detection filter. The wavelet method is used by the researchers [9, 10, 11, 12] in condition monitoring of rolling element bearings due to its superiority in time and frequency resolution while processing the vibration signals. Recently time-frequency domain analysis has become popular. A component of defects generates specific defect frequencies calculated from equations mentioned by Chaudhary and Tandeon [13].

Hariharan & Srinivasan [14] examined the influence of contamination of lubricant by solid particles on the performance of rolling element bearings. They made the contamination by using the different sizes of silica powder at various concentrations. The authors measured the vibration signals from good and contaminated bearing for analysis. They found that considerable variation in RMS vibration for different particle size and concentration of contamination. An automated approach was utilized to identify and classify the defects in the roller bearings. Eftekharnejad et al. [15] used the AE and vibration signals to identify the naturally damaged bearings.

Kankar et al. [16] executed the fault analysis of ball bearings with vibration signals using machine learning (ML) algorithms like ANN and SVM. Vibration signals were captured from ball bearing with different defects and the statistical features were extracted. Kankar et al. [17] focused on the defect diagnosis of ball bearings with spalls. The authors acquired the vibrations signals for different fault conditions of the bearing and extract the features using WT. Fayyadh & Razak [18] evaluated
the condition of elastic bearing supports using vibration signals. The authors used the natural frequencies and shapes of different modes for detecting the defects in the elastic bearing supports. They investigated the good, partial defect, and entire defect bearings. Prieto et al. [19] used a novel CM to analyze the defects in bearings. The authors considered the single-point ball and raceway defects along with the local defects.

Taplak et al. [20] analyzed the faults of a direct-coupled rotor-bearing system with vibration signals. Vibration monitoring with pattern analysis and spectral analysis were used for diagnosing the sources of extreme vibrations. Guo & Peter [21] proposed a novel method to compress the large volume of vibration signals used in bearing defect diagnosis. The proposed method was based on ensemble empirical mode decomposition (EEMD), which was an efficient approach to adapt decomposing the vibration signal into various bands of signal components, Dybała & Zipro [22] diagnosed the faults of rolling bearing with vibration signals using the EMD method. The authors decomposed the vibration signals into several IMFs using EMD and divide the vibration signals into three parts. The amplitude of bearing fault-related signals was estimated empirically.

Zarei et al. [23] detected and classified the bearing defects with vibration signals using an intelligent filter based on ANN. They removed the non-bearing fault components by passing the vibration signals by removing the non-bearing fault component (RNFC) filter. Chen et al. [24] analyzed the generator bearing faults using vibration signals with EWT. They extract the intrinsic features of fault bearing using EWT. Saxena et al. [25] proposed a new approach to generate the patterns connected with the vibration signals of bearing faults using continuous wavelet transform (CWT). Mishra et al. [26] conducted the defect analysis of REBs at a slow speed operating condition with wavelet denoising. During low-speed operations, the signal features are associated with faults. Klausen et al. [27] identified the rolling bearing faults by investigating the envelope spectrum of a band filtered vibration signal.

Caesarendra & Tjahjowidodo [28] reviewed the various feature extraction methods for CM of low-speed slew bearing using vibration signals. Lu et al. [29] performed the CM and defect identification of motor bearings with vibration signals. The authors anticipated a novel method which was the mixture of kurtogram, bandpass filtering, bandpass sampling, and demodulated resonance technique. Hoang & Kang [30] performed as a survey on various deep learning (DL) based bearing defect analysis. The accepted DL algorithms like Autoencoder (AE), Restricted Boltzmann Machine (RBM), and Convolutional Neural Network (CNN) were reviewed in the aspects of bearing fault diagnosis.

Bearing are normally classified into two major categories, viz., rotating inner race bearings and rotating outer race bearings. In most of the rotating machines, the outer race is fixed and the inner race rotates along with the shaft. In this chapter, such rotating inner race bearing is considered for the study. The defects in the rolling element bearings may occur in an inner race, outer race, cage and, or rolling element. The typical defects in the bearing are given in Figure 1. Rolling-element defect is the most common defect that causes most machinery failure.
Figure 1 Types of defects in bearings
(a) Defect in the outer race, (b) Defect in inner race, (c) Defect in cage (d) Defect in rolling element

The unique vibration characteristics of each rolling element bearing defect make vibration analysis an effective tool for both early detection and analysis of faults. The specific fault frequencies of the bearing depending on the type of defect, the bearing geometry, and the speed of rotation. In this chapter, vibration signatures of good bearings and defective bearings are obtained using the experimental facility created. Next, there is a discussion of how these signatures can be used for defect identification are discussed. The geometry of the rolling element bearing used for testing is shown in Figure 2.

Figure 2 Geometry of rolling element bearing

2 Experimental Facility
An experimental facility, exhibited in Figure 3, has been developed to obtain the vibration signatures of bearings.

Figure 3 Experimental test rig
1-Accelerometer, 2- Steady rest, 3- Roller bearing, 4- Shaft, 5- Bearing support, 6- Lathe bed, 7- Vibration analyzer, 8- Computer, 9- Chuck, 10- Headstock.
The experimental facility consists of a precision toolroom lathe, shaft, and bearing system with necessary instrumentation. The toolroom precision lathe is a versatile machine tool used in almost all the manufacturing industries. Such a lathe has been chosen for conducting experiments to achieve a variable speed drive; to have an exact co-axial setup. Shafts are supported by steady rest which sits on a rigid bed. A mild steel solid shaft of 35 mm diameter and 450 mm length is used between the bearings to accommodate the bearing. Five roller bearings (SKF N307) with 35 mm inner diameter are used for testing. Two bearings are defect-free. The other three bearings contain defects in an inner race, outer race, and rolling element respectively as shown in Figure 1. The defects in the bearings are artificially created using the electrical discharge machining (EDM). The specification of the bearing used in the present study is given in Table 1.

| Parameter                  | Value   |
|----------------------------|---------|
| Make                       | SKF N307|
| Number of rollers           | 11      |
| Outer diameter, mm         | 80      |
| Inner diameter, mm         | 35      |
| Pitch diameter, mm         | 57.5    |
| Roller diameter, mm        | 11      |
| Contact angle, $\beta$     | 0       |

The measuring instruments and measurement settings used in this study are as follows:

- Piezoelectric accelerometer (CTC, Type: AC102-A, S.No. 66760)
- Dual-channel vibration analyzer (ADASH 4300–VA3/ Czech Republic make)
- Number of samples for time-domain measurement: 8192
- Sampling frequency: 8192 Hz
- Signal length: one second
- Frequency band: 0-3000 Hz
- Number of spectral lines: 1600
- Number of averaging: 4

3. Experimental Procedure

Two defect-free bearings are tested under the no-load condition to obtain reference signatures. Before experimenting, the lathe spindle vibrations are measured and verified to check the ovality and misalignment. After correcting misalignment and ovality (if any), the defect-free bearings are carefully fitted into the shaft at a specified distance (450 mm). One end of the shaft is firmly fixed in the lathe chuck and the bearings are rigidly supported on the two steady rests shown in Figure 3.3. The setup is run for 15 minutes to stabilize the vibration. An accelerometer having a magnetic base is directly mounted over the bearing support to acquire the vibration signals. The accelerometer output signal is directly fed into the dual-channel vibration analyzer and is stored as vibration signatures. Time-domain and frequency-domain signals are acquired at three different speeds. The stored data in the vibration analyzer is retrieved through an RS232 cable connected to the computer for further analysis using DDS 2007 software. After obtaining necessary signatures with the defect-free bearings,
the defect-free bearing at the tailstock end is replaced with a defective bearing (one by one) and the experiments are repeated.

4 Vibration Signatures of Bearing with Defect-free Bearing

Figure 4 represents the amplitude of vibrations obtained with time, in the time domain mode, and the RMS velocity of the vibrations at various frequencies during the frequency mode. The data shown are obtained at 740 rpm, 1150 rpm and 1600 rpm, which are the speed settings available at the test facility.

In the case of time-domain signals, with an increase in time, the amplitudes vary between ± 0.05 µm, ± 0.1 µm, and ± 0.13 µm at 740, 1150, and 1600 rpm respectively. The waveforms are repeated overtime without many deviations.

In the frequency domain, plots vide Figure 4 (b₁-b₃), at all the three speeds, the values of RMS velocities obtained are less than 0.004 mm/s, which indicates that the bearings are defect-free. This means that the minute imperfections during the manufacturing process give low amplitude vibration signatures that cannot be eliminated.

![Figure 4](image-url)
5 Vibration Signatures of Bearing with Outer Race Defect

5.1 Fault Frequency Calculation

In the case of a defective bearing, the interaction of the defect in the rolling element bearing produces pulses of very short duration. This happens when the defect strikes the rotational motion of the system. These pulses excite the natural frequency of the bearing elements, resulting in an increase in the vibration energy at these high frequencies. With a particular defect on a bearing element, an increase in the vibration energy at element rotational frequency may occur. This defect frequency can be calculated from the geometry of the bearings and element rotational speed as given in Table 2. For the present bearing geometry (shown in Table 1) and the speeds at which the bearings are tested, such fault frequencies are calculated and the values obtained are listed in Table 3.

\[
\begin{align*}
\text{BPFO} &= \frac{n}{2} f_r \cos \beta \\
\text{BPFI} &= \frac{n}{2} f_r (1 + \left(\frac{BD}{PD}\right)^2 \cos \beta) \\
\text{BRF} &= \frac{PD}{BD} f_r \cos \beta \\
\text{FTF} &= \frac{1}{2} f_r \left(1 - \left(\frac{BD}{PD}\right)^2 \cos \beta\right)
\end{align*}
\]

Where \(n\) - Number of balls or rollers

\(PD\) - Pitch diameter of bearing

\(f_r\) - Rotational frequency

\(\beta\) - Contact angle

\(BD\) - Rolling element diameter

| Table 2 Fault frequency equations  
(Alfredson and Mathew 1985) |
|--------------------------|

| Ball-Pass Frequency for Outer-Race | BPFO |
|-----------------------------------|------|
| \(BPFO = \frac{n}{2} f_r \left(1 - \left(\frac{BD}{PD}\right) \cos \beta\right)\) |

| Ball-Pass Frequency for Inner-Race | BPFI |
|----------------------------------|------|
| \(BPFI = \frac{n}{2} f_r \left(1 + \left(\frac{BD}{PD}\right)^2 \cos \beta\right)\) |

| Ball-Rotational Frequency | BRF |
|---------------------------|-----|
| \(BRF = \frac{PD}{BD} f_r \cos \beta\) |

| Fundamental Train Frequency | FTF |
|-----------------------------|-----|
| \(FTF = \frac{1}{2} f_r \left(1 - \left(\frac{BD}{PD}\right)^2 \cos \beta\right)\) |

| Table 3 Fault Frequencies at Various Speeds |
|-----------------------------------------|
| Category | Speed, rpm |
|          | 740 | 1150 | 1600 |
| BPFO (Hz) | 54.56 | 85.24 | 118.60 |
| BPFI (Hz) | 80.81 | 125.58 | 174.72 |
| BRF (Hz)  | 31.05 | 48.26 | 67.15 |

5.2 Time Domain Signal

The time-domain signals of bearing with outer race defect at different speeds are indicated in Figure 5 (a1-a3). The time waveform indicates the severity of vibrations for defective bearings. The peak to peak vibration amplitude of bearing with outer race defect from time waveform is around ± 0.15 \(\mu\)m at 740 rpm, ± 0.6 \(\mu\)m at 1150 rpm, and ± 1.1 \(\mu\)m at 1600 rpm. These amplitudes are comparatively 190 %, 489 %, and 775 % higher when compared to the defect-free bearing at 740, 1150, and 1600 rpm, shown in Figure 4 a1-a4 respectively.
5.3 Frequency Spectrum

Frequency spectrums obtained with the outer race defect are shown in Figure 5 (b₁-b₃). It becomes clear that significantly larger RMS velocity values are noticed with the defective bearing when compared to that of defect-free bearing shown in Figure 4  (b₁-b₃). At 740 rpm, the maximum RMS velocity of defect-free bearing is 0.0026 mm/s whereas that for the outer race defective, it is nearly 0.069 mm/s, i.e. about 35 times larger. Similarly, 10 times and 9.5 times larger RMS velocity values are obtained when the speeds are 1150 rpm and 1600 rpm respectively with the defective bearing.

Higher amplitude signatures clearly indicate that the bearing is a defective one. Owing to this defect, the larger amplitudes can be identified by noticing the peaks of the frequency domain signals. At 740 rpm, from Figure 5 b₁, the peaks occur at 55, 110, 165, 220, 275, 330, 385, 440, 495 Hz, and so on. From Table 3, the values of BPFO at 740 rpm match with the peak amplitude-frequency. Thus, the obtained peak value frequency is near the harmonics of the BPFO values as shown in Table 4. It is evident that the defect is due to a fault in the outer race. Similar observations are discernible at 1150 rpm and 1600 rpm as well.

![Figure 5](image-url)
Table 4 Comparison of fault frequencies (outer race defect)

| Sl. No | Type of defect          | Speed (rpm) | Theoretical frequency (Hz) | Experimental frequency (Hz) |
|--------|-------------------------|-------------|----------------------------|-----------------------------|
| 1      | Outer race defect (BPFO) | 740         | 54.56                      | 55, 110, 165, 220, 275, 330, 385, and 440 |
| 2      |                         | 1150        | 85.24                      | 85, 170, 255, 340, 425, 510, 595 and 680 |
| 3      |                         | 1600        | 118.60                     | 118, 236, 354, 472, 590, 708, 826, and 944 |

6 Vibration Signatures OF Bearing with Inner Race Defect

6.1 Time Domain Signals

The time-domain signals of the bearing with inner race defect at different speeds are shown in Figure 3.6 (a1-a3). The time waveform indicates the severity of vibrations for defective bearings. The peak to peak vibration amplitude of bearing, with inner race defect from time waveform, is around 0.9 μm at 740 rpm, 0.9 μm at 1150 rpm, and 2.2 μm at 1600 rpm. These amplitudes are 700 %, 350 %, and 816 % higher when compared to the defect-free bearing at 740, 1150, and 1600 rpm respectively.

6.2 Frequency Spectrum

Frequency spectrums obtained with the inner race defective bearings are illustrated in Figure 6 (b1-b3). Significantly, larger RMS velocity values are deciphered in the defective bearing when compared to the RMS velocity of defect-free bearing signatures shown in Figure 4 (b1-b3). At 740 rpm, the maximum RMS velocity of defect-free bearing is 0.0026 mm/s, whereas for the inner race defect is nearly 0.0356 mm/s, i.e. about 13.69 times larger. Similarly, 38.61 times and 34.1 times larger RMS velocity values are obtained at 1150 rpm and 1600 rpm respectively with the defective bearing.

Table 5 Comparison of fault frequencies (inner race defect)

| Sl. No | Type of defect   | Speed (rpm) | Theoretical frequency (Hz) | Experimental frequency (Hz) |
|--------|------------------|-------------|----------------------------|-----------------------------|
| 1      | Inner race Defect (BPFI) | 740         | 80.81                      | 82,161,241,323,397,482, 801, 979 and 1200 |
| 2      |                  | 1150        | 125.58                     | 123, 252, 374, 748, 500, 623, 748 and 878 |
| 3      |                  | 1600        | 174.72                     | 176, 352, 528, 699 and 876 |
A higher amplitude signature clearly indicates that the bearing is a defective one. This is because the amplitudes of larger signatures can be identified by noticing the peaks of the frequency domain signals. At 740 rpm, from Figure 6 b1, the peaks frequency distribution occurs at 82, 161, 241, 323, 397, 482, 801, 979, 1200 Hz, and so on. From Table 3, it is understood that the values of BPFI at 740 rpm match with the peak amplitude-frequency. Thus, the obtained peak value frequency is near the harmonics of the BPFI values as vide in Table 5. Thus it is evident that the defect is due to the outer race. Similar observations are noticed at 1150 rpm and 1600 rpm as well.

7 Vibration Signatures of Bearing with Rolling Element Defect

7.1 Time Domain Signals

The time-domain signals of bearing with rolling element defects at different speeds are shown in Figure 6 (a1-a3). The time waveforms indicate the severity of vibrations due to the defect in the bearing. The peak of peak vibration amplitude of bearing with rolling element defect from time waveform is around 0.28 μm at 740 rpm, 0.59 μm at 1150 rpm, and 2.31 μm at 1600 rpm. These amplitudes are 180%, 210 %, and 862% higher when compared to the defect-free bearing at 740, 1150, and 1600 rpm respectively.
118x345 Figure 3.7 Vibration signatures of bearing with rolling element defect
(a1-a3: Time waveform; b1-b3: Frequency spectrum)

Table 6 Comparison of fault frequencies (rolling element defect)

| Sl. No | Type of defect | Speed rpm | Theoretical frequency (Hz) | Experimental frequency (Hz) |
|-------|----------------|-----------|----------------------------|----------------------------|
| 1     | Rolling element defect (BRF) | 740 | 62.11 | 62, 124, 183, 244, 305, 366, 427, 488, 549, 610, 671, and 732 |
| 2     |                | 1150      | 96.40 | 94, 188, 282, ., 376, 470, 564, 658 Hz, 752, and 846 |
| 3     |                | 1600      | 134.13 | 131, 262, 393, 524, 655, 786, and 917 |

7.2 Frequency Spectrum

Frequency spectrums obtained with the rolling element defective bearings are indicated in Figure 6 (b1-b3). Significantly larger RMS velocity values are noticed in the defective bearing when compared to that of defect-free bearing shown in Figure 4(b1-b3). At 740 rpm, the maximum RMS velocity of defect-free bearing is 0.0026 mm/s whereas for the defective rolling element it is nearly 0.0675 mm/s, i.e. about 25.96 times large. Similarly, 8 and 5.89 times larger RMS velocity values are obtained at 1150 rpm and 1600 rpm respectively with the defective bearing.
Higher amplitudes of the signatures clearly indicate that the bearing is a defective one. Owing to this defect, the amplitudes of larger signatures can be identified by noticing the peaks of the frequency domain signals. At 740 rpm, from Figure 6 b1, the peak frequency occurs at 62, 124, 183, 244, 305, 366, 427, 488, 549, 610, 671, 732 Hz and so on. From Table 3, it is seen that the values of BRF at 740 rpm nearly match with the peak amplitude-frequency. Thus, peak values of frequency obtained are near the harmonics of the BRF values vide Table 6. Thus it is evident that the defect is due to the rolling element. Similar observations are shown up at 1150 rpm and 1600 rpm as well.

8 Conclusion

In this study, the bearing with defects in the outer race, inner race, and rolling element defect has been studied. The frequency spectrum and time domain graphs are obtained and drawn for various speeds. The following conclusions are drawn from these experimental results:

1. The time waveform indicated the severity of vibration in defective bearings. Then, the amplitude of the defect-free bearing and defective bearing are compared. The amplitude of vibration obtained is 2-7 times larger for the bearing with outer race defect, 3-8 times larger for bearings with inner race, and 2-8 times larger for bearings with rolling element defect when compared to the defect-free bearing.

2. The frequency spectrum helps in identifying the exact nature of the defect in bearing. From Figures 3.5, 3.6, and 3.7 (b1-b3) the harmonics of fault frequency corresponding to outer race defect, inner race defect, and rolling element defect are noticed. This is a good indication of the presence of the defect at specified bearing elements. These harmonic frequencies are very close to the theoretical fault frequencies.

References

[1] Alfredson R.J. and Mathew J. (1985), ‘Time Domain Methods for Monitoring the Condition of Rolling Element Bearings’, Mechanical Engineering Division, Journal of Institution of Engineers, Australia, Vol.10(2): 102-107.

[2] Renwick JT, Babson PE. (1985) “Vibration analysis—a proven technique as a predictive maintenance tool”, IEEE Transaction of Industrial Applications, 21,(2): 324–332.

[3] Alguindigue IE, Buczak LA, Uhrig RE. (1993) "Monitoring and diagnosis of rolling element bearings using artificial neural networks", IEEE Transactions of Industrial Electronics, 40 (2): 209–217.

[4] Tandon N, Choudhury A.(1999) "A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings", Tribology International , 32: 469–480.

[5] Mathew J, Alfredson RJ. (1984) “The condition monitoring of rolling element bearings using vibration analysis”, Journal of Vibration Acoustics Stress Reliability Design, 106: 447–453

[6] Honarvar F, Martin HR. (1997) “New statistical moments for diagnostics of rolling element bearings”, Journal of Manufacturing Science and Engineering, 119: 425–432.

[7] McFadden PD, Smith JD. (1984) "Vibration monitoring of rolling element bearings by the high-frequency resonance technique—a review", Tribology International, 17: 3–10

[8] Lou X, Loparo KA, Discenzo FM, Yoo J, Twarowski A. (2000) "A model-based technique for rolling element bearing fault detection", International Conference on Acoustics, Noise, and Vibration, Aug 8–12; Montreal, Quebec, Canada.
[9] Li CJ, Ma J. (1997) "Wavelet decomposition of vibrations for detection of bearing-localized defects", NDT&E International, 30: 143–149.
[10] Robertson AN, Park KC. (1998) “Extraction of impulse response data via wavelet transform for structural system identification”, Transactions ASME, 120: 252–260
[11] Nikolaou NG, Antoniadis IA. (2002) "Rolling element bearing fault diagnosis using wavelet packets", NDT&E International, 35: 197–205.
[12] Tse PW, Peng YH, Yam R. (2001) "Wavelet analysis and envelope detection for rolling element bearing fault diagnosis-their effectiveness and flexibilities", J Vibration and Acoustics., 123:303–310.
[13] Choudhary A and Tandon. N, (1998) "A theoretical model to predict vibration response of rolling bearing to distributed defects under radial load", Journal of vibration and acoustics, Transactions of ASME, 120(1): 214-220.
[14] Hariharan, V & Srinivasan, P.S.S 2010, 'Condition monitoring studies on ball bearings considering solid contaminants in the lubricant', Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 224, no. 8, pp. 1727-1748
[15] Eftekharnejad, B, Carrasco, M, Charnley, B & Mba, D 2011, 'The application of spectral kurtosis on acoustic emission and vibrations from a defective bearing’, Mechanical Systems and Signal Processing, vol. 25, no. 1, pp. 266-284
[16] Kankar, PK, Sharma, SC & Harsha, SP 2011a, 'Fault diagnosis of ball bearings using machine learning methods', Expert Systems with Applications, vol. 38, no. 3, pp. 1876-1886.
[17] Kankar, PK, Sharma, SC & Harsha, SP 2011b, ‘Rolling element bearing fault diagnosis using wavelet transform’, Neurocomputing, vol. 74, no. 10, pp. 1638-1645
[18] Fayyadh, MM & Razak, HA 2012, ‘Condition assessment of elastic bearing supports using vibration data’, Construction and Building Materials, vol. 30, pp. 616-628.
[19] Prieto, MD, Cirrincione, G, Espinosa, AG, Ortega, JA & Henao, H 2012, ‘Bearing fault detection by a novel condition-monitoring scheme based on statistical-time features and neural networks’, IEEE Transactions on Industrial Electronics, vol. 60, no. 8, pp. 3398-3407.
[20] Taplak, H, Erkaya, S & Uzmay, I 2013, 'Experimental analysis on fault detection for a direct-coupled rotor-bearing system', Measurement, vol. 46, no. 1, pp. 336-344.
[21] Guo, W & Peter, WT 2013, 'A novel signal compression method based on optimal ensemble empirical mode decomposition for bearing vibration signals', Journal of sound and vibration, vol. 332, no. 2, pp. 423-441.
[22] Dybala, J & Zimroz, R 2014, ‘Rolling bearing diagnosing method based on empirical mode decomposition of machine vibration signal’, Applied Acoustics, vol. 77, pp. 195-203.
[23] Zarei, J, Tajeddini, MA & Karimi, HR 2014, ‘Vibration analysis for bearing fault detection and classification using an intelligent filter’, Mechatronics, vol. 24, no. 2, pp. 151-157.
[24] Chen, J, Pan, J, Li, Z, Zi, Y & Chen, X 2016, ‘Generator bearing fault diagnosis for wind turbine via empirical wavelet transform using measured vibration signals’, Renewable Energy, vol. 89, pp. 80-92.
[25] Saxena, M, Bannet, OO, Gupta, M & Rajoria, R 2016, ‘Bearing fault monitoring using CWT based vibration signature’, Procedia Engineering, vol. 144, pp. 234-241.
[26] Mishra, C, Samantaray, A & Chakraborty, G 2017, ‘Rolling element bearing fault diagnosis under slow speed operation using wavelet de-noising’, Measurement, vol. 103, no., pp. 77-86.
[27] Klausen, A, Robbersmyr, KG & Karimi, HR 2017, ‘Autonomous Bearing Fault Diagnosis Method Based on Envelope Spectrum’, IFAC-papers online, vol. 50, no. 1, pp. 13378-13383.
[28] Cassandra, W & Tjahjowidodo, T 2017, 'A review of feature extraction methods in vibration-based condition monitoring and its application for degradation trend estimation of low-speed slew bearing', Machines, vol. 5, no. 4, pp. 21.
[29] Lu, S, Zhou, P, Wang, X, Liu, Y, Liu, F & Zhao, J 2018, ‘Condition monitoring and fault diagnosis of motor bearings using undersampled vibration signals from a wireless sensor network’, Journal of Sound and Vibration, vol. 414, no., pp. 81-96.

[30] Hoang, D-T & Kang, HJ 2019, ‘A survey on Deep Learning based bearing fault diagnosis’, Neurocomputing, vol. 335, pp. 327-335.