Vibration-Based Power Spectral Density Analysis for the Detection of Multiple Faults in Rolling Element Bearings

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***Abstract*—The traditional industry is shifting towards fourth industrial revolution called "Industry 4.0" that includes automatic fault detection of machinery. The detection of mechanical faults mainly depends upon accurate condition monitoring of the rotating machinery that requires effective predictive maintenance techniques. The modern industry focusing on predictive maintenance techniques so that these faults can be detected automatically. This article proposed vibration-based power spectral density analysis to detect multiple faults in rolling element bearings. The power spectral density plots were computed at 16.7, 25, 40, and 50 Hz operating speed with a bearing loader and without installing a bearing loader on the vibration data taken from SpectraQuest's Machinery Fault Simulator™ through the accelerometers mounted on inboard and outboard bearing housing. The four various types of faults: outer race, inner race, ball, and combined fault have been analyzed separately in this study. The power spectral density plots of damaged rolling element bearings showed high amplitude vibrations with harmonic behavior. This research article proposed that vibration-based power spectral density is an excellent measurement to detect faults in rolling element bearings that endows technical support to Industry 4.0.**

Keywords-fault detection; industry 4.0; power spectral density; rolling element bearings; vibration

I. INTRODUCTION

In rotational machinery, bearings play an important role by carrying the loads at high operating speed. As the bearings start to fail, complications occur in quality and operating conditions. There are three fundamental techniques to perform maintenance on machinery: (1) the maintenance activities are performed after the part is failed is known as run to failure maintenance; (2) the maintenance is performed on the specified time length using the mean time to failure measurement that is known as periodic maintenance; (3) the operating conditions of a machine are monitored through the analysis of the data and on the basis of this data maintenance is performed which is known as predictive maintenance [1]. The poor maintenance practice can allow the bearing to deteriorate further and that will end with catastrophic failure. So, modern industry is focusing on predictive maintenance techniques so that the maintenance activities can be performed before the failure happen. For that, vibration-based fault diagnostics techniques have proved very effective.

The fault mechanism, sensor techniques and signal acquisition, signal processing for feature extraction, and fault diagnosis using intelligent methods are the four basic parts to diagnose the machinery faults. Bearing, gear, and rotor are three basic rotating components that are working in critical operating conditions but they are the backbone of the mechanical industry. Among these components, the most important is a rolling element bearing that is widely used and can lead to catastrophic failure more rapidly [2]. Sometimes bearing faults also serve as the indicator for other mechanical faults like unbalance or misalignment can affect the bearing conditions [3]. In this article, some related work are explained in the next section. The fundamental theories related to roller element bearing are discussed in section III. As this study is based on experimentation that is described in section IV and results have been discussed in section V.

II. RELATED WORK

Numerous researchers have focused on the diagnosis of faults in rotating machinery. Several authors studied the transverse crack based on the dynamic modeling of rotors [4, 5]. A modal based analysis was performed to identify and investigate the cracks, the modal was also validated through the experiments performed on a test rig that proved suitable for industrial machines [6]. Different studies were summarized for double/multi-cracks and identification methods for pipes, rotors, and beams were noted [7]. The strain energy release approach (SERP) was also reviewed for the diagnosis of cracks in rotating machinery and concluded that as the number of cracks increases the dynamic response becomes more complex [8]. The transverse crack for one

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disc rotor (Laval rotor) was also studied and concluded that two-sided spectral order analysis is an effective tool in analyzing the dynamic behavior of one disc rotor (Laval rotor) with a transverse crack [9]. The shaft bend was studied by analyzing the Fast Fourier Transform (FFT) spectrum and it showed higher vibration at 1X and 2X frequency components, if the 1X frequency component is higher, the bend is near to the shaft center and if the 2X frequency component is greater, the bend is near to the end of the shaft [10]. The vibration-based order analysis was performed to detect bent shaft experimentally and results proved that it is an effective technique for bent shaft [11].

The vibration-based dynamic modeling of rolling element bearings were presented and concluded that it is an effective way for fault diagnosis and condition monitoring [12]. The multiple and single fault were compared by developing a dynamic model for deep groove ball bearing and results revealed that vibrations are high for multiple faults as compared to the vibration produces from a single fault [13]. Wavelet-based approach was proposed to diagnose the inner race, outer race, rolling element, and compound fault for rolling element bearings. The vibration signals were analyzed by restraining the ambient noise which concludes that the proposed approach is feasible for the fault detection of rolling element bearing [14].

Nowadays, the Industry 4.0 is becoming more popular because it proposes the predictive maintenance and manufacturing techniques. And it requires advance prediction tools so that automatic fault diagnostics and prognostics can be implemented. The smart predictive tools for managing the big data in Industry 4.0 were studied and concluded that an intelligent prediction of machinery health conditions largely reduces the machine downtime [15]. Smart manufacturing systems for Industry 4.0 were reviewed, a conceptual framework was demonstrated and their future work was presented [16].

The literature concluded that vibration-based fault detection techniques for Industry 4.0 are effective for predictive maintenance in mechanical machinery. Most researchers focus on the harmonics generated at the characteristics fault frequencies for rolling element bearing fault diagnosis but these harmonics are buried in the noise and difficult to monitor in reality. This research article proposes vibration-based power spectral density analysis for the detection of faults in rolling element bearings. In-depth and detailed experimentations have been performed to demonstrate the proposed method.

III. ROLLING ELEMENT BEARING FAULTS

In most of the industry, rolling element bearing is commonly used. The rolling element bearings worked mostly under extreme operating conditions e.g. high operating speed, great load. The pro-active technique is required to detect the bearing faults so that the maintenance cost can be decreased as well as machines can be operated safely. The rolling element bearings are those bearings that bear loads and reduce friction with their rolling elements. These rolling elements have a shape like a barrel instead of spherical. Mainly, there are three components of rolling element bearings: outer race, inner race, and ball.

The disturbances occurring in the vibration-based time and frequency domains of a machine can be regarded as faults. Because whenever the ball touches a defect or discontinuity, it generates impulsive forces that result in a disturbance. In this paper: inner race, outer race, ball, and combined fault of rolling element bearings are simulated. The characteristic fault frequencies can be calculated from the following formulas (1-4). Where, $BPFO$ is Ball Pass Frequency Outer Race, $BPFI$ is Ball Pass Frequency Inner, BSF is Ball Spin Frequency and FTF is Fundamental Train Frequency with Ball Diameter D_B and Pitch Diameter D_P at number of balls n and angle of contact θ. The characteristic fault frequencies of the rolling element bearings used in this study are calculated from (1-4) and shown in Table I.

$$BPFO = \frac{n}{2}\left[1 - \frac{D_B}{D_P}\cos\theta\right] \quad (1)$$

$$BPFI = \frac{n}{2}\left[1 + \frac{D_B}{D_P}\cos\theta\right] \quad (2)$$

$$BSF = \frac{D_P}{2D_B}\left[1 - \left(\frac{D_B}{D_P}\right)^2 \cos^2\theta\right] \quad (3)$$

$$FTF = \frac{1}{2}\left[1 - \frac{D_B}{D_P}\cos\theta\right] \quad (4)$$

TABLE I. THE CHARACTERISTIC FAULT FREQUENCIES OF ROLLING ELEMENT BEARINGS USED IN THIS STUDY

Ball Pass Frequency Outer (BPFO)	Ball Pass Frequency Inner (BPFI)	Ball Spin Frequency (BSF)	Fundamental Train Frequency (FTF)
3.572	5.43	2.322	0.402

To obtain the fault frequencies at the operating speed the multipliers calculated in Table I are used. If the vibration spectrum analysis shows peaks at these characteristic fault frequencies (BPFO, BPFI, BSF, and FTF), then the bearing is often considered as a damaged bearing. But it is not true all the time due to the nature of the failure and loading condition. The Power Spectral Density (PSD) is computed from the following formula (5):

$$PSD = \frac{(Power\ Spectrum)^2}{\Delta f \times Noise\ Power\ Bandwidth\ of\ Window} \quad (5)$$

where the Power spectrum is calculated by taking the average of the magnitude squared of multiple frequency spectra.

IV. EXPERIMENTAL SETUP

In order to detect faults in bearings, a set of experiments were performed through SpectraQuest's Machinery Fault Simulator (MFS). The MFS is consist of three phase 1 H.P. induction motor that drives the rotor assembly with L-type standard jaw coupling. The coupling is made of sintered iron with a length of 54.6 mm.

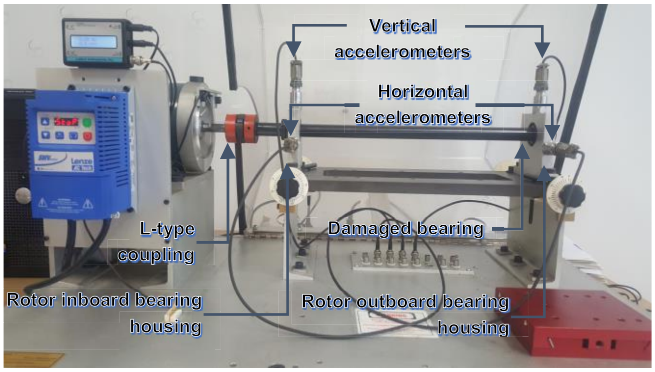

Figure 1. Experimental setup for bearing faults.

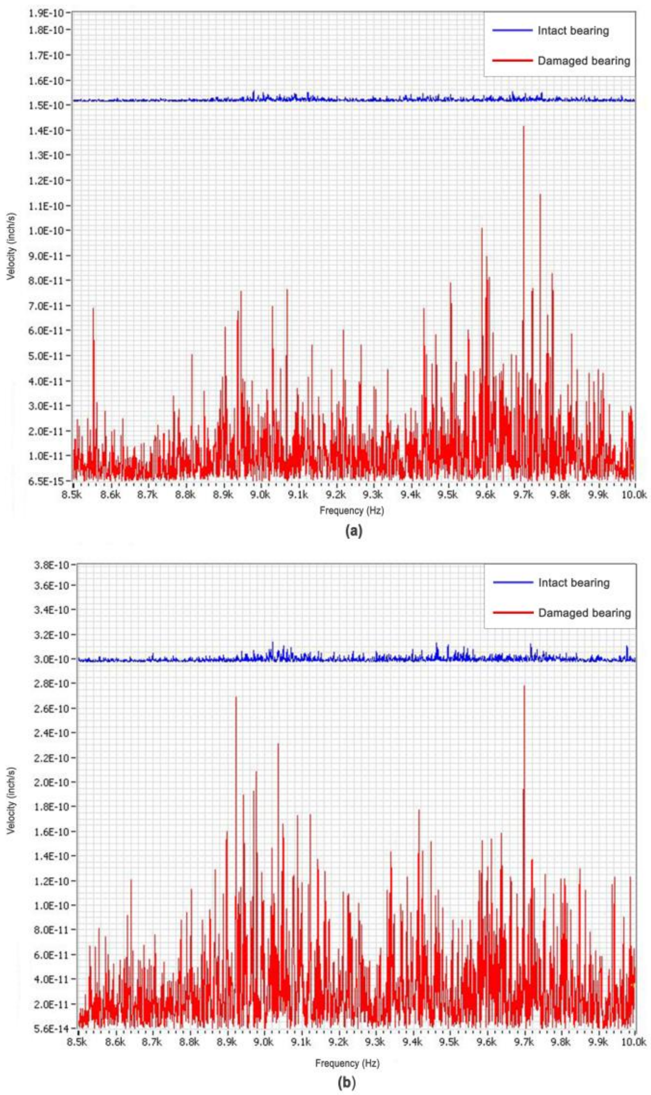

Figure 2. Power spectral density for an outer race fault with a bearing loader at (a) 40 Hz and (b) 50 Hz.

The diameter of rotor assembly shaft is 25.4 mm and it is made of polished (TGP) steel. The operating speed was recorded by built-in tachometer with LCD display and controlled by Variable Frequency Drive (VFD) with short duration from 0 to 6000 RPM. The accelerometers were mounted on rotor inboard and outboard bearing housing to record the vibration data and then it is transferred to the computer through 8-channel data acquisition card for analysis. The accelerometers have the ability to record vibration with the measurement range of ± 490 m/s2 and 10.2 mV sensitivity. The complete experimental setup is shown in Figure 1.

The same MFS was used to detect unbalance on the basis of vibration data acquired through piezoelectric strain sensors at an operating speed of 20 Hz [17] and accelerometers at 15, 30, and 45 Hz operating speed [18], transducers sensitive location was analyzed for a misaligned and cracked case [19]. This paper focuses on the detection of bearing faults with power spectral density, the intact and damaged bearings' power spectral density plots have been compared by performing in-depth and systematic experimentation.

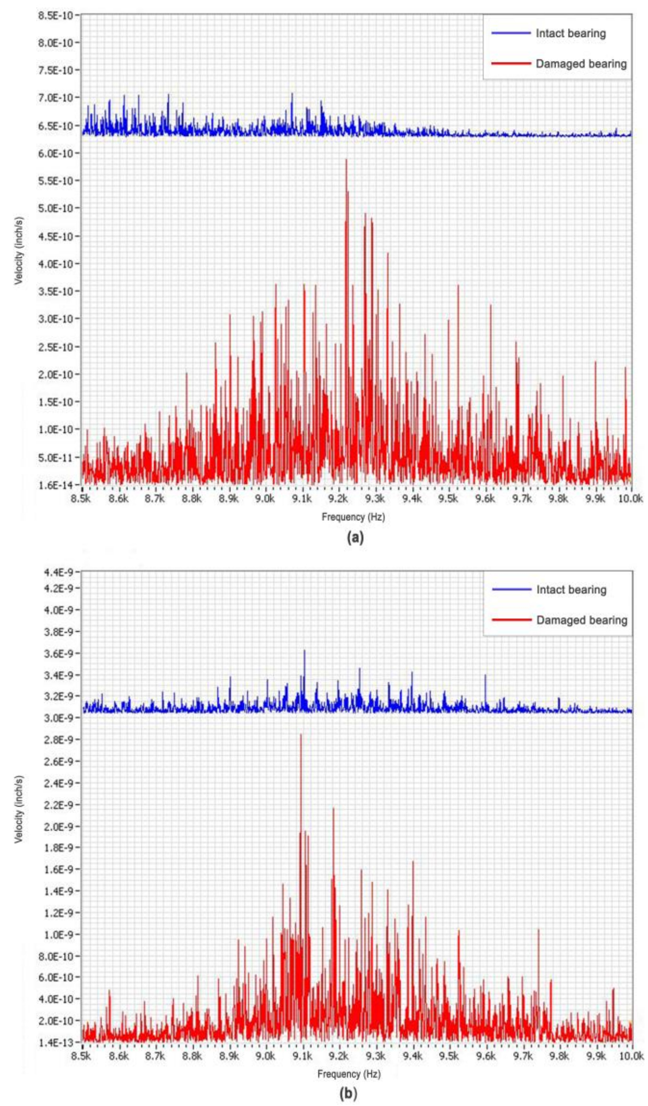

Figure 3. Power spectral density for an outer race fault without installing a bearing loader at (a) 40 Hz and (b) 50 Hz.

The following four bearing faults have been analyzed at 16.7, 25, 40, and 50 Hz operating speed with two different loading conditions: (1) outer race fault; (2) inner race fault; (3) ball fault; and (4) combined fault. Firstly, the vibration data were acquired with intact bearings without applying any load on the rotor assembly and compared with various damaged bearings by replacing the intact bearing with a damaged bearing at outboard bearing housing. Secondly, a bearing loader was placed at a distance of 5 cm from outboard bearing housing and again intact bearing data is compared with damaged bearings. The BPFO, BPFI, BSF and combined fault bearings were installed at outboard bearing housing. The vibration data were collected with 12800 spectral lines and a maximum frequency of 10 kHz, and analyzed with hanning window.

Before placing the damaged bearings, the overall velocity-RMS values with a bearing loader and without installing a bearing loader were collected, and it is listed in Table II and Table III respectively so that the ISO 2372 standard can be followed as it was followed in our previous study for unbalance detection [18]. The ISO 2372 standard categories the vibrations of machines into four sections starting from 'A' and ended with 'D' on a vibration severity chart: if the vibrations generated from a machine belongs to 'D' that means this machine has high vibration and is not permissible. And if a machine's vibration lies in 'A', that means it is in excellent working conditions. As our MFS has 1 H.P motor so it belongs to class 1 according to the ISO 2372 standard. For all intact bearing experiments, the maximum overall velocity-RMS value is 2.7166 mm/s at 50 Hz rotor inboard bearing housing in horizontal direction that is less than the value 2.80 mm/s of the vibration severity chart defined by the ISO 2372 standard, so our MFS belongs to 'C' that means vibrations are within tolerable limits. Hence, our MFS can be used for bearing experiments.

V. RESULTS AND DISCUSSION

The effects of the multiple faults: outer race, inner race, ball, and combined fault on power spectral density have been analyzed separately in the following sections:

TABLE II. OVERALL VELOCITY-RMS (MM/S) VALUES WITH A BEARING LOADER AT NO FAULT CONDITION

Operating speed (Hz)	Rotor inboard bearing housing		Rotor outboard bearing housing	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
16.7	0.3557	0.1557	0.2675	0.1548
25	0.6291	0.2669	0.4674	0.2990
40	1.1643	0.9012	0.7484	0.5704
50	2.7166	1.5035	1.7238	1.4493

TABLE III. OVERALL VELOCITY-RMS (MM/S) VALUES WITHOUT INSTALLING A BEARING LOADER AT NO FAULT CONDITION

Operating speed (Hz)	Rotor inboard bearing housing		Rotor outboard bearing housing	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
16.7	0.2757	0.1337	0.2771	0.1741
25	0.5939	0.3116	0.6544	0.5724
40	1.2863	0.7680	1.2607	1.0588
50	2.0655	1.1951	2.6264	2.3558

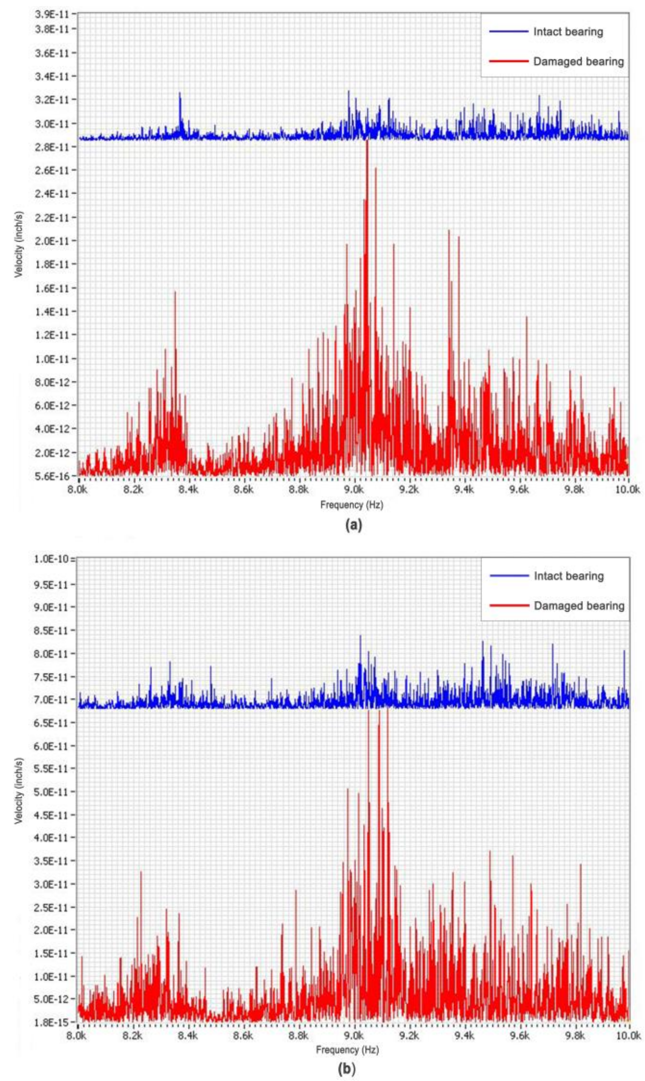

Figure 4. Power spectral density for an inner race fault with a bearing loader at (a) 40 Hz and (b) 50 Hz.

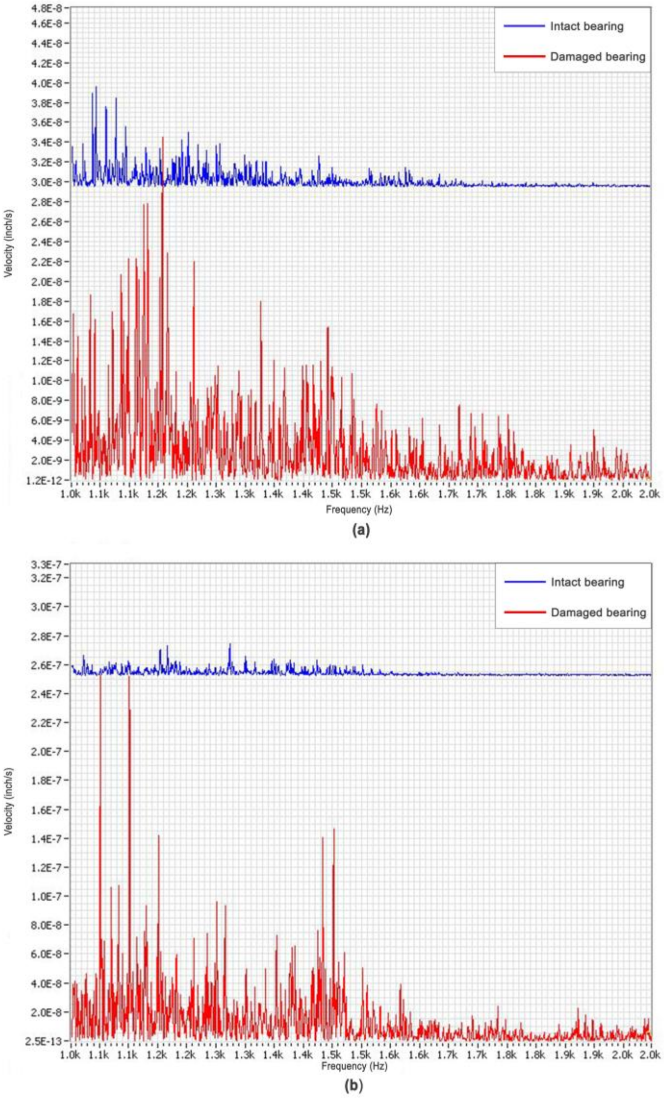

Figure 5. Power spectral density for an inner race fault without installing a bearing loader at (a) 40 Hz and (b) 50 Hz.

A. *Outer Race Fault*

An intact bearing was replaced with a bearing that has a fault in its outer race at outboard bearing housing. These experiments were performed at 16.7, 25, 40, and 50 Hz operating speed with a bearing loader as well as without installing a bearing loader. The power spectral densities for each operating speed were computed. The power spectral density at 40 Hz and 50 Hz operating speed shows a better picture of the damaged bearing as compared to the results obtained at 16.7 Hz and 25 Hz. The power spectral density plots for outboard bearing housing in the horizontal direction with a bearing loader and without installing a bearing loader are shown in Figure 2 and Figure 3 respectively.

From the Figure 2 and Figure 3, the damaged bearing who has a fault at outer race shows harmonics and high amplitude vibrations at high frequencies greater than 8.5 kHz as compared to the intact bearing. The power spectral density clearly revealed the outer race fault at the frequencies ranges from 8.5 kHz to 10 kHz. It is concluded that vibrations from an outer race damaged bearing are high in amplitude and shows clear harmonics at the frequencies greater than 8 kHz in power spectral density plots.

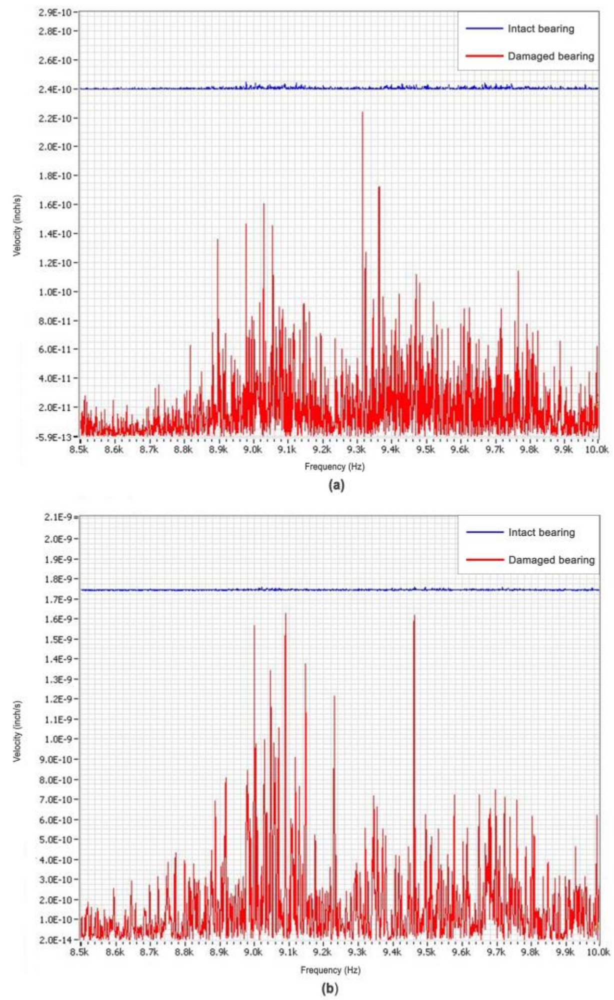

Figure 6. Power spectral density for a ball fault with a bearing loader at (a) 40 Hz and (b) 50 Hz.

B. *Inner Race Fault*

These experiments were performed for inner race fault detection at 16.7, 25, 40, and 50 Hz operating speed with a bearing loader as well as without installing a bearing loader. An intact bearing was removed from outboard bearing housing and a bearing that has a fault at its inner race was installed. The power spectral densities for each operating speed were calculated and at 40 Hz and 50 Hz operating speed it shows a better picture of the inner race fault bearing as compared to the results obtained at 16.7 Hz and 25 Hz operating speed. The power spectral density plots for outboard bearing housing in the horizontal direction with a bearing loader and without installing a bearing loader are shown in Figure 4 and Figure 5 respectively.

The Figure 4 and Figure 5 shows the power spectral density plots for inner race fault, in comparison with intact bearing it is concluded that the vibrations are high in magnitude at high frequency. The plots of without installing a bearing loader didn't show clear peaks as compared to the plots of with a bearing loader due to the fact that greater load generates greater vibration when the ball hits with the defect or discontinuity.

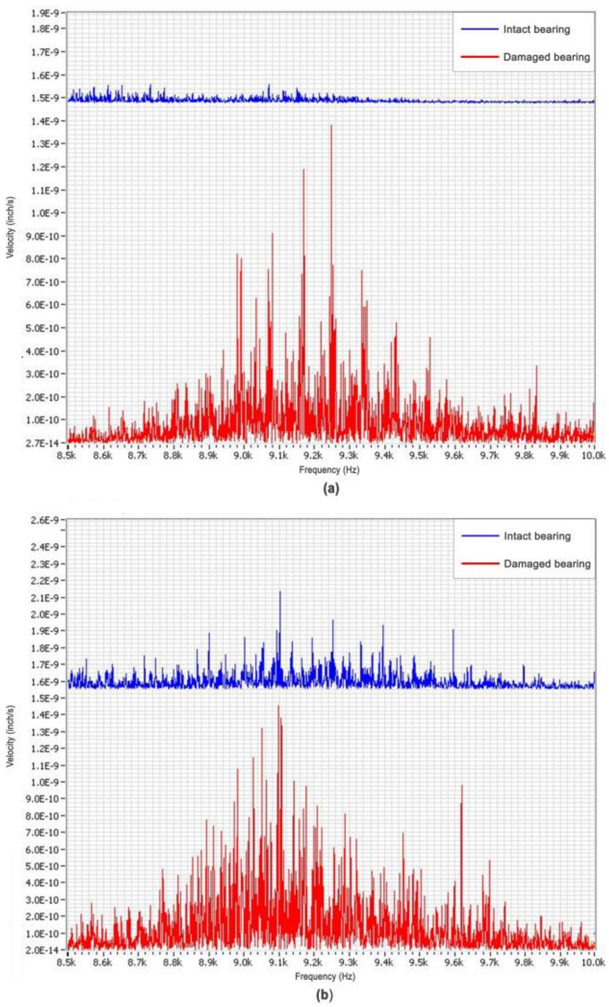

Figure 7. Power spectral density for a ball fault without installing a bearing loader at (a) 40 Hz and (b) 50 Hz.

The power spectral density plots clearly showed spikes and peaks of vibration that point towards the severe fault. Hence, the power spectral density is an excellent indicator for the detection of inner race fault.

C. Ball Fault

The ball fault was analyzed by performing a set of experiments at 16.7, 25, 40, and 50 Hz operating speed with a bearing loader as well as without installing a bearing loader. A ball defected bearing was installed at outboard bearing housing and power spectral densities for each operating speed were computed. But plots at 40 Hz and 50 Hz operating speed demonstrate the fault more distinctly as compare to the plots obtained at 16.7 Hz and 25 Hz operating speed. The power spectral density plots for outboard bearing housing in the horizontal direction with a bearing loader and without installing a bearing loader are shown in Figure 6 and Figure 7 respectively.

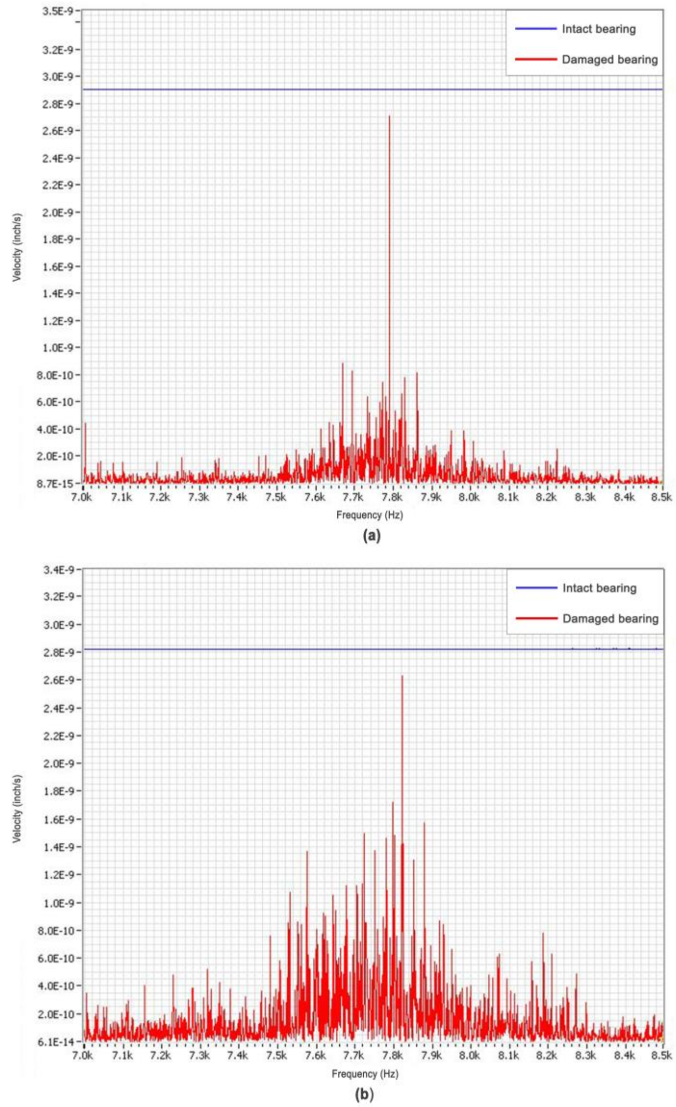

Figure 8. Power spectral density for a combined fault with a bearing loader at (a) 40 Hz and (b) 50 Hz.

From the Figure 6 and Figure 7, it is concluded that the ball fault is easily detectable because the high amplitude vibrations are visible in the power spectral density for both of the loading conditions at the frequencies greater than 8 kHz. The vibrations are high and harmonics are visible in case of the damaged bearing. The plots of power spectral density proved that it is an effective measurement for detecting the ball fault in rolling element bearings.

D. Combined Fault

A combined fault bearing was replaced with an intact bearing at outboard bearing housing. The combined fault experiments with a bearing loader and without installing a bearing loader were performed on four operating speed as 16.7, 25, 40, and 50 Hz. The peaks and harmonics are more visible at 40 Hz and 50 Hz operating speed and only their power spectral density plots are presented in this study. The Figure 8 and Figure 9 showed the power spectral density plots for outboard bearing housing in the horizontal direction with a bearing loader and without installing a bearing loader respectively.

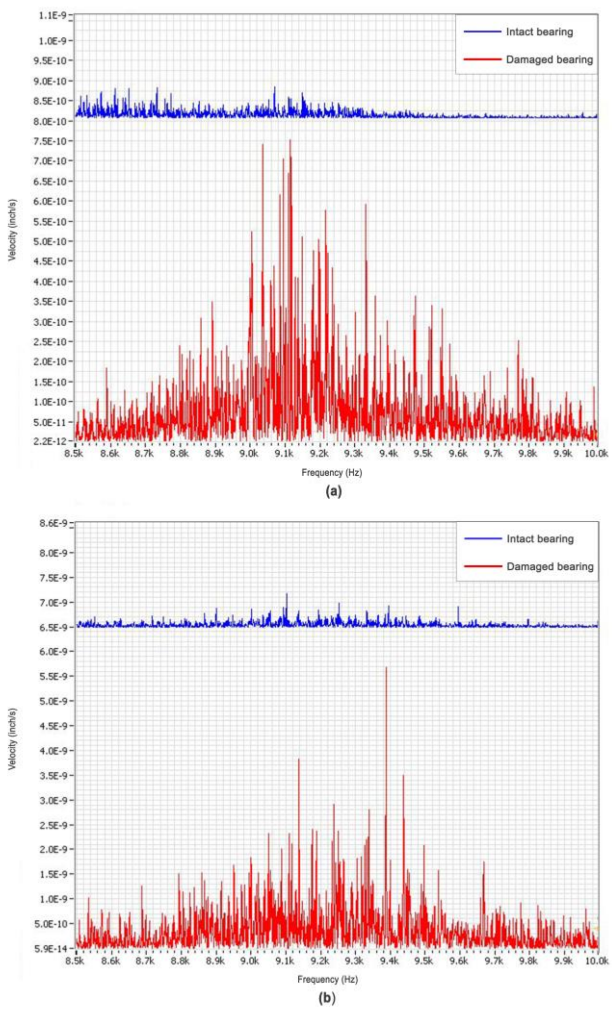

Figure 9. Power spectral density for a combined fault without installing a bearing loader at (a) 40 Hz and (b) 50 Hz.

The presence of high amplitude vibrations and harmonics in Figure 8 and Figure 9 for a combined fault bearing concluded that the power spectral density plots are highly effective in detecting the bearing faults. At lower speeds, the harmonics are not much visible due to the fact that the vibrations generated at lower speeds have low amplitudes. Hence, the power spectral density is an excellent approach for the detection of faults in rolling element bearings.

VI. Conclusions

The four faults of rolling element bearings: inner race, outer race, ball, and combined fault have been successfully detected with vibration-based power spectral density analysis. ISO 2372 standard has been followed in this study before creating any fault, the vibrations were within tolerable limits. The power spectral density plots showed harmonics and high amplitude vibrations for a damaged bearing as compared to an intact bearing for all speeds and loading conditions. The results concluded that the vibration-based power spectral density plots are highly effective in detecting the faults for rolling element bearings. Hence, the vibration-based power spectral density analysis is helpful in condition monitoring and fault diagnosis for the mechanical industry.

All the experimental results revealed that the speed and load didn’t affect the methodology to detect the faults in a rolling element bearing. At low operating speeds the vibrations are lower, and as it increases the vibration also increases. At lower speeds, the harmonics are not much visible due to the fact that the vibrations generated at lower speeds have low amplitudes and it is buried in noise. The power spectral density plots in horizontal direction demonstrate all the faults more clearly.

For a real-world problem, the fault cannot be diagnosed only by performing the analysis at some specific operating conditions due to the fact that the machine’s integral non-linarites vary vibration in a complex way. However, machine learning techniques can be helpful that is our future work.

This study empowers the Industry 4.0 by presenting an effective and simple technique for detecting the bearing faults. The bearing is the most important component of any mechanical industry and the results presented in this study provides better understanding of the faults occurring in a rolling element bearing. This research article endows automatic fault detection and online condition monitoring techniques. In future, we are also planning to detect shaft faults such as misalignment with the help of power spectral density analysis.

Acknowledgment

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