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An Experimental Study on Condition Monitoring and Fault Diagnosis of a Cooling Water Pump using Vibration Analysis

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Abstract

Nowadays condition monitoring and fault diagnosis based on the vibration data is one of the most common approaches in minimizing the maintenance and repair costs of industrial machines. The current paper represents the results of the condition monitoring and fault diagnosis of a cooling water pump using the vibration analysis. In this regard, the machine under study is described, and its operating condition is investigated based on the existing charts and standards. The measured vibration signals, i.e. velocity in the low frequency range and acceleration in the high frequency range, are quantified and analyzed to find the defective component of the machine, while the frequency analysis is utilized to detect the type of the fault. The vibration signals and the frequency analysis predict some faults in the inner race and rolling elements of one of the bearings of the machine. Finally, some experimental observations are reported to validate the results obtained from the vibration analysis.

Keywords: Condition Monitoring; Fault Diagnosis; Vibration Analysis; Bearing Fault Detection.

1. Introduction

Nowadays condition monitoring (CM) is considered as an effective maintenance strategy to increase the reliability, health, and optimal performance of industrial machines. The purpose of condition monitoring is to detect faults at early stages, protect machines from sudden failures, and subsequently prevent production loss [1–2]. In this regard, many destructive and non–destructive methods have been suggested. The non–destructive methods are those that are based on relatively easy and cheap measurements and do not need the structure of the machine to be manipulated. In condition monitoring based on the non–destructive methods, several parameters, such as vibration, temperature, sound, etc., can be measured to determine the general condition of the machine [3–4]. Vibration–based condition monitoring (VCM) is one of the most common approaches in minimizing the costs of the maintenance and repair of industrial machines. To evaluate the reliability, health and optimal performance of machines, it is necessary to use the measurable data, such as vibration parameters, in order to inspect and understand the internal conditions of the machine. The analysis of vibration signals measured from various points of the machine is one of the most effective methods that has attracted a lot of attention from researchers and engineers [5].

Pumps are one of the most commonly–used machines in industry, and are composed of several components, including an electromotor, impeller, bearings, etc. Failure in each of these components can result in production loss as well as an increase in repair costs. Diagnosis and amendment of faults at early stages prevent sudden failure and production loss. Furthermore, in recent years, different signal processing techniques have been found to detect the location of the fault and estimate its intensity [6–8].

Aydın et al. [9] used wireless sensor networks to propose new combined intelligent methods for the condition monitoring of electric machines. Both motor current and vibration signals were used to estimate the faults. Amplitudes of three phase current signals and phase space analysis of vibration data were considered as the features in the proposed combined intelligent classifiers. Finally, the accuracy of the proposed system was confirmed by experimental data. Zarei et al. [10] employed artificial neural networks to introduce an intelligent method for the bearing fault detection and classification of induction motors based on vibration data. The method, which uses time–domain features, is composed of two neural networks. The first neural network removes non–bearing fault components, while the second one classifies the fault into four categories of healthy, inner race defect, outer race defect, and double holes in outer race. Experimental results indicated that the method is able to successfully classify the fault in spite of noisy vibration data. Jiang et al. [11] used the improved ensemble empirical mode decomposition to design a condition monitoring and fault diagnosis algorithm for rolling element bearings based on vibration signals. To extract the statistical features from the decomposition results, the correlation analysis and data fusion technology were applied. Experimental data demonstrated that the algorithm is able to detect both known faults and unknown faults with strong robust performance. Lei et al. [12] developed two new features, including accumulative amplitudes of carrier orders and energy ratio based on difference spectra, for condition monitoring and fault diagnosis of planetary gearboxes. The vibration signals measured from a planetary gearbox test rig under different motor speeds and various types of faults on gears and bearings were used to investigate the efficacy of the features. Lu et al. [13] proposed a new method for the condition monitoring and fault diagnosis of motor bearings based on the under–sampled vibration signals acquired from a wireless sensor network. To implement the method, the demodulated resonance technique, bandpass sampling, analogue domain bandpass filtering, and kurtogram were applied, and experiments showed a significant decrease in the length of the sampled data and the transmission time of the proposed method in comparison with traditional methods. Nirwan et al. [14] employed acoustic emission and vibration analysis for the condition monitoring and fault diagnosis of roller bearings. They designed a bearing test rig to study the influence of the fault size on the vibration amplitude. The fault was located on the outer race of a radially loaded cylindrical roller bearing, and the experiment was conducted at different speeds and loads. It was shown that the acoustic emission approach has better performance to identify faults in roller bearings.

In this paper, the results of the condition monitoring and fault diagnosis of a cooling water pump using the vibration data are represented. The measured vibration parameters are velocity in the low frequency range of 5–1000 *Hz*, and acceleration in the high frequency range of 500–8000 *Hz*. First of all, the machine under study is described with full technical details, and its general condition is investigated based on the existing charts and standards. Then, the values of the vibration parameters are used to find the defective component of the machine, and the frequency analysis is applied to detect the type of the fault. Finally, some experimental observations are given to validate the results obtained from the vibration analysis.

2. Machine description

The technical specifications of the cooling water pump under study are reported in Table 1. This pump is used and located in the *Smelting Department of Sarcheshmeh Copper Complex*. Fig. 1 depicts the pump along with four reference and standard points for the measurement of the vibration signals. In each point, the vibration signal is measured in the Horizontal (H), Vertical (V), and Axial (A) directions. The STD3300 Vibration Measurement Device is used for the vibration measurement in the indicated reference points.

Table 1. Technical specifications of cooling water pump under study.

Parameter (Unit)	Value	Parameter (Unit)	Value
Electromotor: WEG Manufacturer			
Motor Power (KW)	132	Motor Current (A)	228
Motor Voltage (V)	400	Line Frequency (Hz)	50
DC or AC	AC	Motor Speed (RPM)	1490
Number of Phases	3	Motor Type	Asynchronous
NDE Bearing	SKF 6316 C3	DE Bearing	SKF 6319 C3
Pump: Pump–Iran Manufacturer			
Pump Type	Centrifugal	Installation Type	Horizontal
Number of Stages	1	Number of Impellers	6
Foundation Type	Rigid	NDE/DE Bearing	SKF 6411 C3
Coupling: IIP Group Manufacturer			
Coupling Type	Flexible	Coupling Size (mm)	200

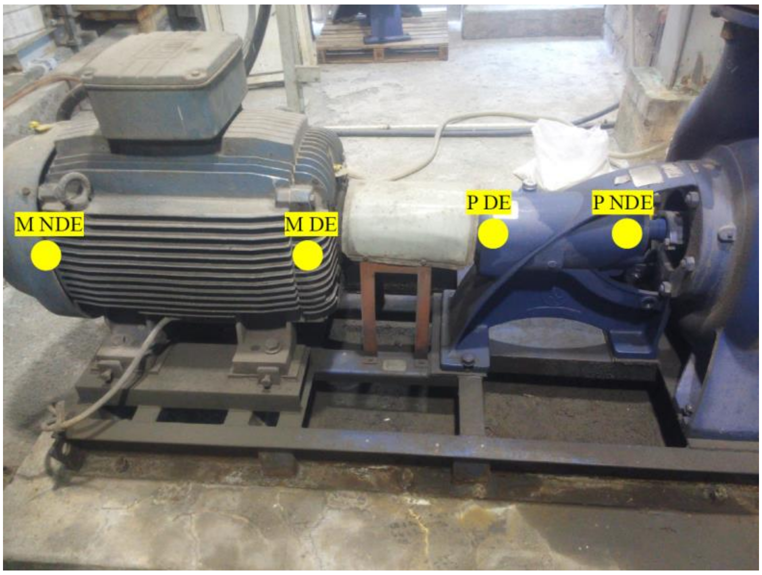

Figure 1. Cooling water pump under study.

3. Machine condition

In this section, the machine condition is investigated. Fig. 2 shows the general machinery vibration severity chart prepared by the *IRD Mechanalysis Inc. Colombus, Ohio* and presented by Nicholls in [15]. In this chart, the vertical axis is the peak–to–peak vibration displacement in micrometres, while the horizontal axis is the machine speed in revolutions per minute or RPM. The inclined lines in the chart indicate the regions related to different levels of vibration and general condition of the machine. According to Table 1, the speed of the pump under study is 1490 RPM. The maximum peak–to–peak vibration displacement of the pump is measured about 32 micrometres. Based on these data, the condition of the pump is indicated by a red circle in Fig. 2. Therefore, the general machinery vibration severity chart implies that the general condition of the pump under study is “Fair”.

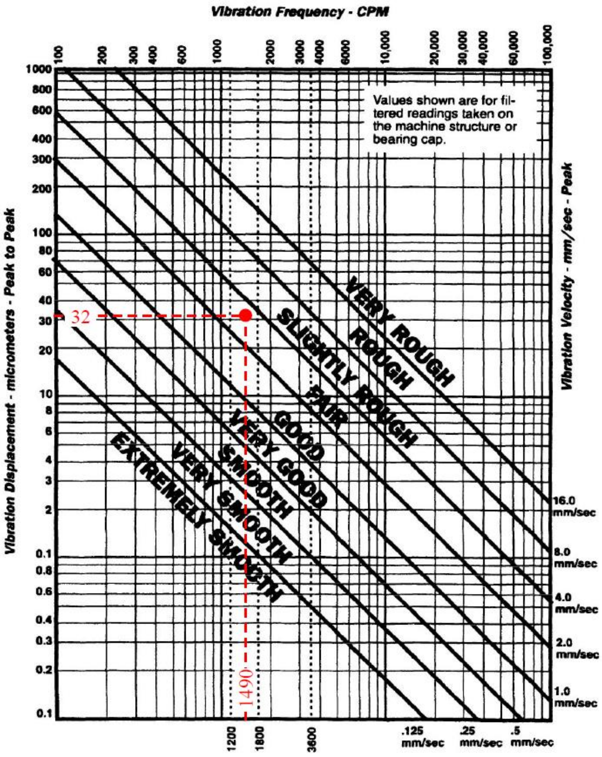

Figure 2. ENTEK IRD general machinery vibration severity chart.

Fig. 3 indicates the changes in the vibration parameters, i.e. the RMS of velocity in the low frequency, the RMS of acceleration in the high frequency, and the peak of acceleration in the high frequency, over the measurement points in the horizontal direction. In these graphs, for each vibration parameter, the unsatisfactory limit and the risk of damage limit are also shown according to the ISO 10816 and ISO 13373 standards.

From Fig. 3, it can be observed that the RMS of velocity in the low frequency for the “P DE” and “P NDE” measurement points exceeds the unsatisfactory limit meaning that closer inspection of the machine is necessary. The values of the RMS and peak of acceleration in the high frequency for the “P DE” and “P NDE” measurement points exceed the risk of damage limit meaning that the machine is suffering from a high–frequency fault. Moreover, the graphs show that all of the three reported vibration parameters experience an upward–downward trend. From the “M NDE” measurement point to the “P DE” measurement point, the trend is upward implying that it is approaching the location of the possible fault, the maximum value happens at the “P DE” measurement point, and after that the trend is downward. Since the maximum value for all of the three reported vibration parameters over the measurement points occurs at the “P DE” measurement point, this point is a suitable candidate for further investigation.

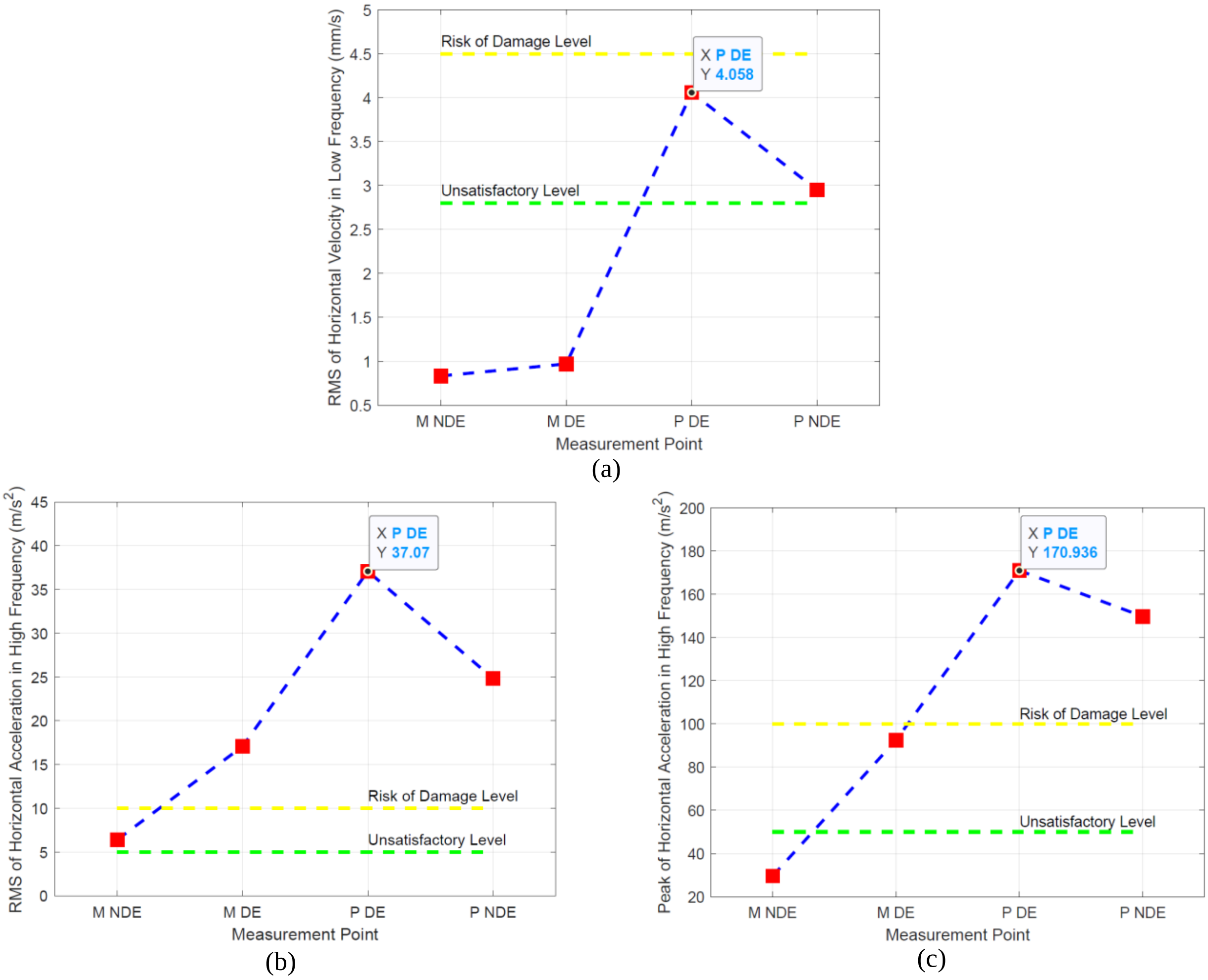

Figure 3. Change in vibration parameters over measurement points in horizontal direction: (a) RMS of velocity in low frequency, (b) RMS of acceleration in high frequency, (c) Peak of acceleration in high frequency.

4. Frequency analysis of vibration signals

Generally, the vibration of industrial machines generates complicated time signals that do not have any specific and regular patterns, but are composed of sinusoidal signals with various amplitudes, frequencies, and phases. Since different faults produce sinusoidal signals with specific frequencies, the main tool in fault diagnosis using vibration data is frequency analysis. Frequency analysis separates the harmonic components of the input time signal and facilitates finding the causes of vibration in the machines. One of the most popular methods to detect the fault type and find its location is to transfer the measured vibration signals in the time domain into the frequency domain by applying the Fast Fourier Transform (FFT). The plot obtained from this method is called spectrum. Fig. 4 illustrates the spectrums of the velocity of the "P DE" measurement point in the low frequency of 5–1000 *Hz*.

In Fig. 4, the most dominant peaks related to the frequencies that are not the harmonics or multiples of the machine speed are indicated. These frequencies are 110.469, 134.844, 414.844, 464.531, 634.688, and 684.531 *Hz*. Existing these frequencies, that are not the harmonics of the machine speed, in the spectrums is a warning sign and should be further investigated.

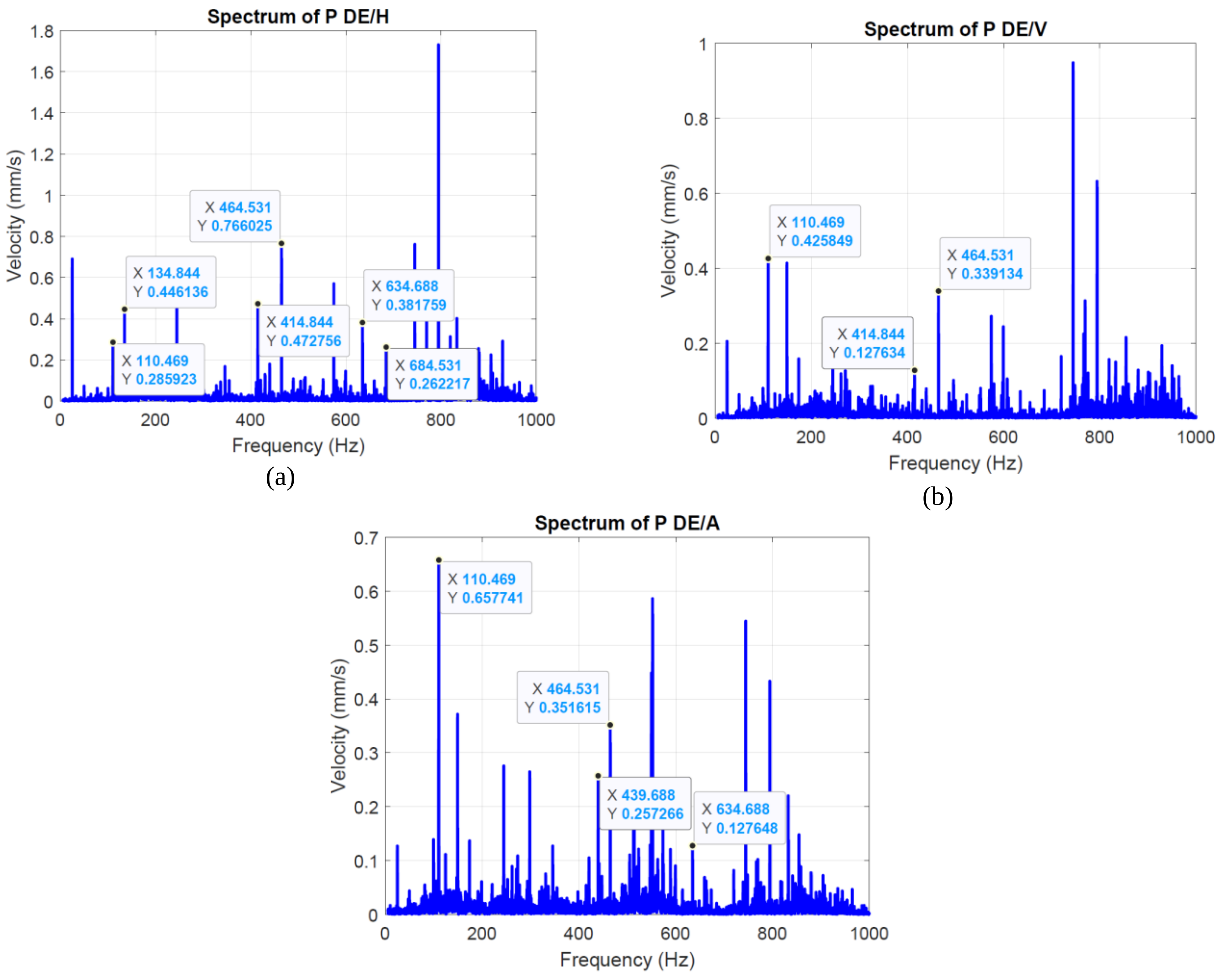

Figure 4. Spectrums of "P DE" measurement point in: (a) Horizontal, (b) Vertical, (c) Axial directions.

Rolling element bearings are composed of different components such as inner race, outer race, rolling element, and cage. A basic idea in the fault diagnosis of bearings is that whenever the rolling element passes across the faulty component of the bearing, an impact signal is produced at the unique frequency related to the faulty component. These unique frequencies, called the characteristic frequencies of bearing defects, are ball pass frequency of inner race (BPFI), which is produced when the rolling elements roll across the defective inner race, ball pass frequency of outer race (BPFO) which is produced when the rolling elements roll across the defective outer race, ball spin frequency (BSF) which is the circular frequency of each rolling element, and fundamental train frequency (FTF) which is known as the frequency of the defected cage [16]. The values of the characteristic frequencies of bearing defects depend on the shaft speed, bearing pitch diameter, ball diameter, number of balls, and contact angle. Table 2 shows the characteristic frequencies of defects for bearing SKF 6411 C3 at the running speed of 1490 RPM.

Table 2. Characteristic frequencies of defects for bearing SKF 6411 C3 at running speed of 1490 RPM.

Parameter	Value (Hz)
Ball Pass Frequency of Inner Race (BPFI)	111.51
Ball Pass Frequency of Outer Race (BPFO)	62.83
Ball Spin Frequency (BSF)	41.47
Fundamental Train Frequency (FTF)	8.94

From Fig. 4 and Table 2, it is clear that the first frequency that is not the harmonic of the machine speed, i.e. 110.469 *Hz*, is very close to the ball pass frequency of inner race (BPFI), i.e. 111.51 *Hz*. This fact implies that the inner race of the bearing is probably defective. In addition, the third frequency that is not the harmonic of the machine speed, i.e. 414.844, is the tenth harmonic of the ball spin frequency (BSF) meaning that some rolling elements of the bearing are probably defective as well.

5. Experimental Observations

In this section, some experimental observations of the bearing located at the “P DE” measurement point are presented. Fig. 5 illustrates the real images captured from the different components of the bearing. The most important point is that the pittings or holes on the surface of the inner race of the bearing can be clearly seen in Fig. 5(a). There is small corrosion on the surface of the outer race of the bearing given in Fig. 5(b), while the corrosion on the surface of the rolling elements of the bearing is noticeable as can easily be observed in Fig. 5(c).

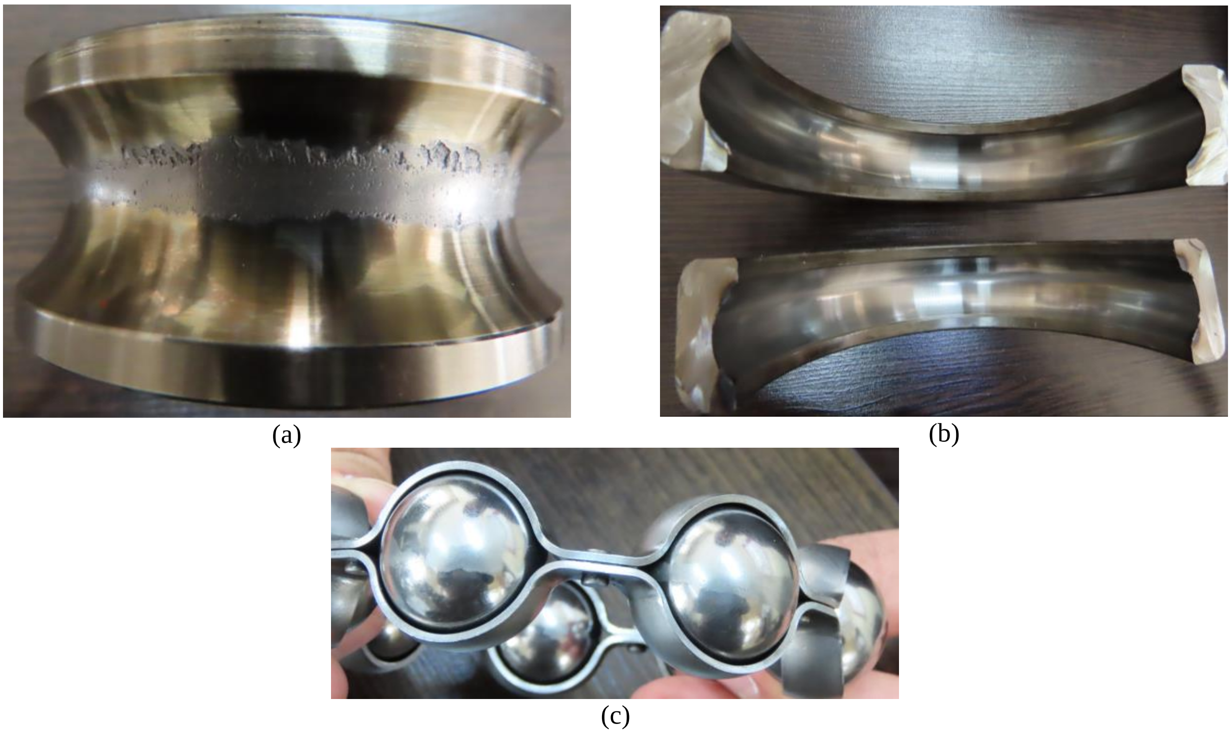

Figure 5. Real images from different components of “P DE” bearing: (a) Inner race, (b) Outer race, (c) rolling elements.

In the previous section, it was conducted that the inner race and rolling elements of the bearing are probably defective as the ball pass frequency of inner race (BPFI) and ball spin frequency (BSF) have dominant peaks in the spectrums of the “P DE” measurement point. According to Fig. 5, the real images taken from the different components of the bearing located at the “P DE” measurement point approve the results obtained in the previous section. In other word, the results obtained from the vibrations–based fault diagnosis are in agreement with the experimental observations.

6. Conclusions

In this paper, the results of the condition monitoring and fault diagnosis of a cooling water pump using the vibration data were represented. The machine under study was technically described, and its operating condition was investigated based on the ENTEK IRD general machinery vibration severity chart as well as the ISO 10816 and ISO 13373 standards. The vibration parameters, i.e. velocity in the low frequency range of 5–1000 *Hz*, and acceleration in the high frequency range of 500–8000 *Hz*, were measured at four standard points along the machine in three directions.

The vibration signals and the frequency analysis predicted some faults in the inner race and rolling elements of the bearing located at the "P DE" measurement point. Finally, the experimental observations and real images captured from the different components of the bearing verified the results obtained from the fault diagnosis based on the vibration analysis.

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