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Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies

Sadettin Orhan [a,*], Nizami Aktürk [b], Veli Çelik [a]

[a] *Faculty of Engineering, Kırıkkale University, 71400 Kırıkkale, Turkey*
[b] *Faculty of Engineering and Architecture, Gazi University, 06570 Maltepe, Ankara, Turkey*

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Abstract

Vibration monitoring and analysis in rotating machineries offer very important information about anamolies formed internal structure of the machinery. The information gained by vibration analysis enable to plan a maintenance action. In this study, the vibration monitoring and analysis case studies were presented and examined in machineries that were running in real operating conditions. Failures formed on the machineries in the course of time were determined in its early stage by the spectral analysis. It was shown that the vibration analysis gets much advantage in factories as a predictive maintenance technique.

Keywords: Vibration monitoring; Rolling element bearing defects; Predictive maintenance

1. Introduction

The failures of rotating machineries 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 its initial stage. The predictive maintenance by vibration analysis is the best tool for this purpose. The vibration analysis is a technique, which is being used to track machine operating conditions and trend deteriorations in order to reduce maintenance costs and downtime simultaneously [1]. The vibration analysis technique consists of vibration measurement and its interpretation. Firstly, vibration signals are collected by means of the vibration analyzer equipped with a sensor in the time domain then, these signals are converted into frequency domain by processing FFT, and the information gained from the vibration signals can be used to predict catastrophic failures, to reduce forced outages, to maximize utilization of available assets, to increase the life of machinery, and to reduce maintenance costs related to health of machinery [2]. The vibration measurements are taken periodically, one time per month in general and vibration is monitored by comparing previous measurements to new ones. The vibration monitoring is based on the principle that all systems produce vibration. When a machine is operating properly, vibration is small and constant; however, when faults develop and some of the dynamic processes in the machine change, the vibration spectrum also changes [2]. There are many studies on the vibration monitoring of the rotating machinery. Great amount of them concentrate on ball or cylindrical element bearing vibration monitoring [3–6]. In these studies a test rig, includes ball or cylindrical roller bearing, is used and either an artificial defect is formed on bearing parts or the test rig is running until a desired defect arise on the bearing in laboratory conditions. These studies were partly realized by ideal condition assumption. However, under conditions of real environment there are many factors that affect the actual running state of the machinery. Thus, these factors must be taken into consideration. Studies related to real operating conditions of machineries were quite few. Gluzman [7] monitored vibration of motor-generator system supported by ball and cylindrical roller bearings to predict impending bearing failures. He successfully identified impending failures of the bearing outer and inner races. Al-Najjar [8] observed many bearing vibrations in paper mills for many years to predict remaining bearing life accurately. He also investigated effectiveness of vibration-based maintenance and proposed some findings.

In this study, the application of vibration monitoring and analysis was carried out on the machineries in a petroleum

* Corresponding author. Tel.: +90 318 357 3575; fax: +90 318 357 2459.
E-mail addresses: orhan@kku.edu.tr, sadettinorhan@yahoo.com (S. Orhan).

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refinery. The vibrations of the machineries were monitored for a certain period and diagnosing of defects arised on the bearings of the machineries during this period was aimed. The study includes three different case studies that were obtained from the machineries, which run under real operating conditions.

2. Vibration measurement

Vibration data were gathered and processed using CSI 2110 [9] machinery analyzer. It is well known that a machinery analyzer generally consists of a sensor, a memory in which the signals are stored, electrical circuits that convert time domain signals to frequency domain signals (FFT process) and a port by which vibration signals were transfered into a computer. The sensor used was an accelerometer (CSI 350) with a sensitivity of 0.1 V/EU. Parameters for collecting of vibration signals were given in Table 1. Vibration was measured in axial, horizontal and vertical directions. Obtained data from the vertical direction was dominant compared with the other two directions so the vibration data measured in the vertical direction was used to characterize the health of the machinery.

3. Defect frequencies of rolling element bearings

The rolling element bearing defect produces certain frequencies that depend on rolling element bearing geometry, which is shown in (Fig. 1), number of rolling element, and shaft speed. These frequencies are expressed in Eqs. (1)–(4).

$$w_c = \frac{n}{2}\left[1 - \frac{d}{D}\cos(\alpha)\right] \quad (1)$$

$$w_b = \frac{n}{2}\left(\frac{d}{D}\right)\left[1 - \left(\frac{d}{D}\right)^2 \cos^2(\alpha)\right] \quad (2)$$

$$w_{bp} = \frac{n}{2}N_b\left[1 - \frac{d}{D}\cos(\alpha)\right] \quad (3)$$

$$w_{bpi} = \frac{n}{2}N_b\left[1 + \frac{d}{D}\cos(\alpha)\right] \quad (4)$$

where n, N_b, w_c, w_b, w_{bp}, w_{bpi} represent shaft speed, number of rolling elements, cage frequency, rolling element spin frequency, rolling element pass frequency outer race, rolling element pass frequency inner race, respectively. Sometimes the defect frequencies computed by above equations deviate to some amount from obtained-ones by measurement. This is because equations use shaft speed by declared manufacturer but real speed of the shaft may be different from this speed in the moment of vibration measurement.

Table 1
Parameters for vibration measurement

Number of spectral lines	400
Number of average	6
Number of gathered data	1024
Window type	Hanning
Spectral average mode	Normal
Frequency range	60–3000 Hz

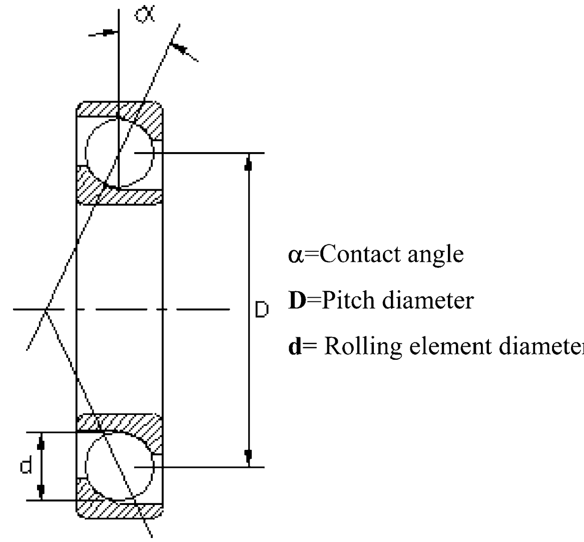

Fig. 1. Rolling element bearing geometry.

When a defect is formed on one of these parts of the bearing, related frequency, its orders, its sidebands, etc. may arise in a spectrum graph. Sometimes these frequencies may exist for healthy rolling element bearing due to some manufacturing errors. The defect frequencies of rolling element bearings used in this study were given in Table 2.

4. Case study I

The vibration of a huge centrifugal pump with nine vaned was monitored. The power and revolution of the pump motor are 160 kW, 2975 rpm, respectively. The reference measurement was taken on 17 October 2001 (Figs. 2 and 3). As shown from reference measurement, vibration behaviour of the pump inner bearing composes of multipliers of the shaft rotation in the spectrum graph and irregular impact signals in the time domain waveform graph.

This situation indicates that rotating equipment, namely ball bearing, is looseness on the housing [10,11]. The vibration amplitudes are in low level. For this reason, maintenance of the pump is not required in this stage. The vibration monitoring was continued and after three weeks, vibration amplitude increased suddenly (Figs. 4 and 5). This situation shows that ball bearing looseness developed. The maintenance was planned and then ball bearing was pulled out on 13 February 2002, finally it was shown that the housing was worn out and the outer race of ball bearing was corroded (Fig. 6). After

Table 2
Defect frequencies of rolling element bearings

Bearing type	Shaft speed (Hz)	N_b	w_c (Hz)	w_b (Hz)	w_{bp} (Hz)	w_{bpi} (Hz)
SKF NU 224	12.35	17	5.385	43	91.55	122.14
SKF 6222	16.41	10	6.78	43.56	67.82	98.48

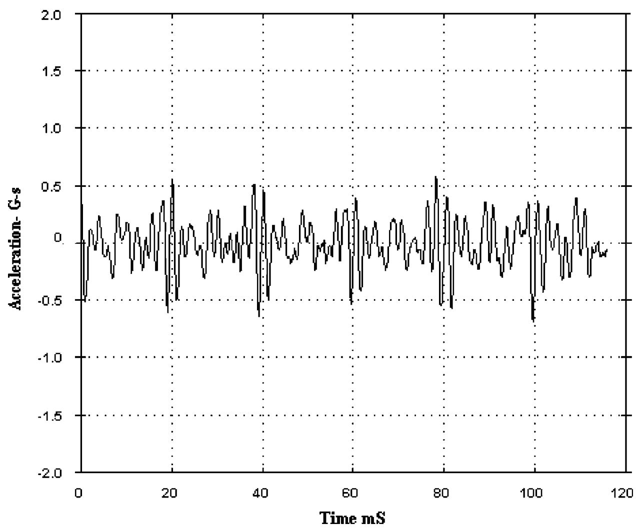

Fig. 2. Reference time waveform graph of the pump inner bearing.

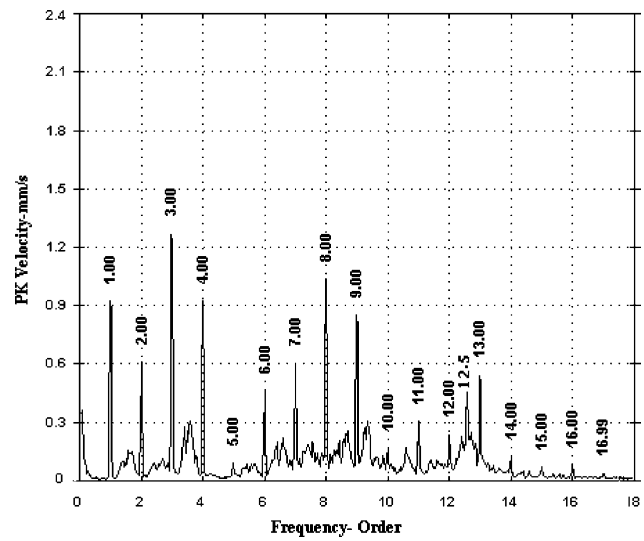

Fig. 5. Vibration time waveform graph resulted from increasing of looseness.

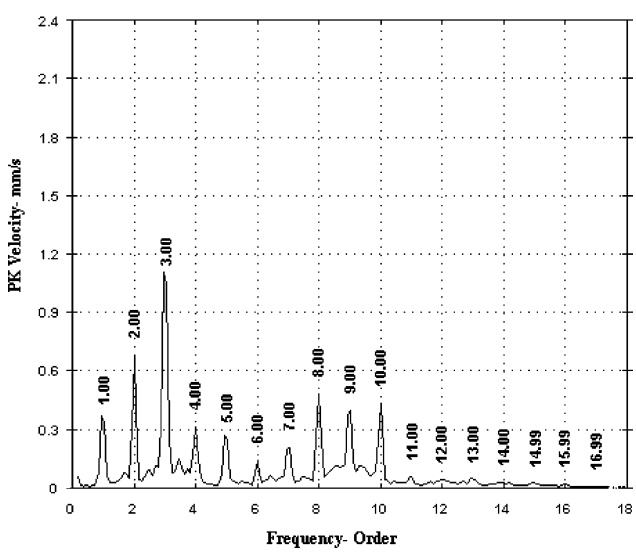

Fig. 3. Reference spectrum graph of the pump inner bearing.


Fig. 6. Corrosion on the ball bearing outer race due to looseness.

maintenance, on 7 March 2002 and following measurements, vibration amplitude decreased to the normal value (Fig. 7). By means of vibration monitoring ball bearing looseness, which may lead to break up bearing, later the pump, was easily determined, thus, possible damage and production loss was prevented.

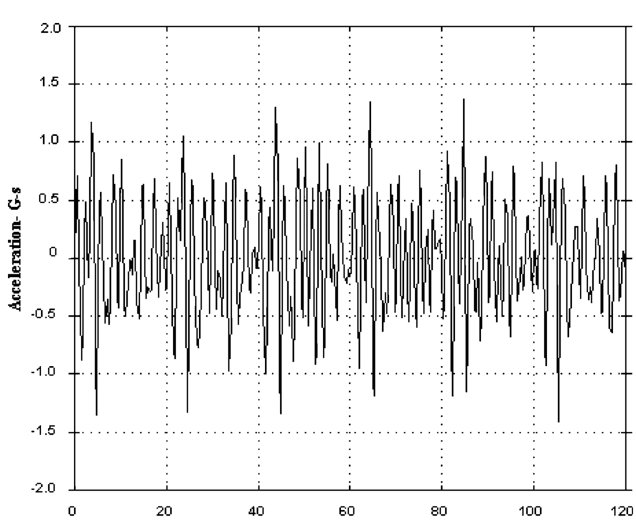

Fig. 4. Vibration time waveform graph resulted from increasing of looseness.

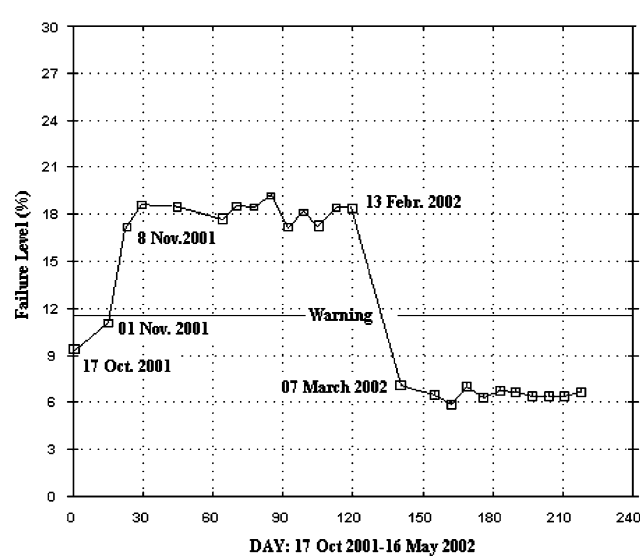

Fig. 7. Overall vibration level trend of the pump inner bearing.

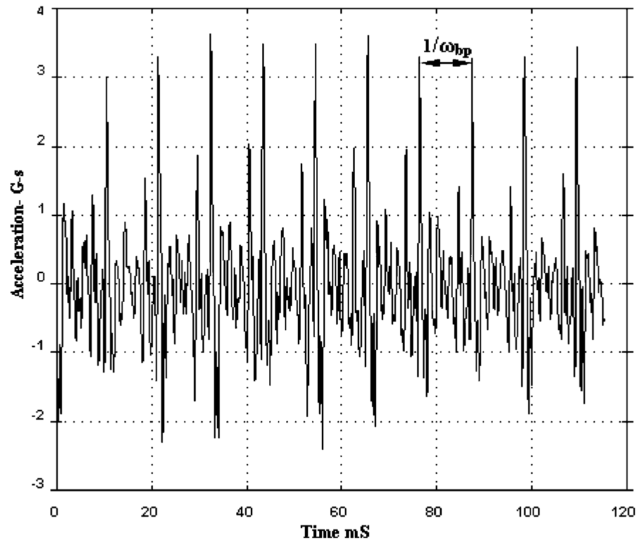

Fig. 8. Reference time domain waveform graph of the fan motor inner bearing.

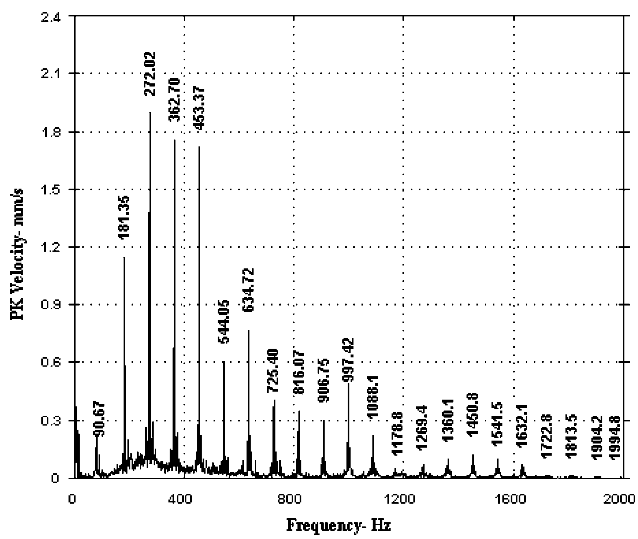

Fig. 9. Reference spectrum graph of the fan motor inner bearing.

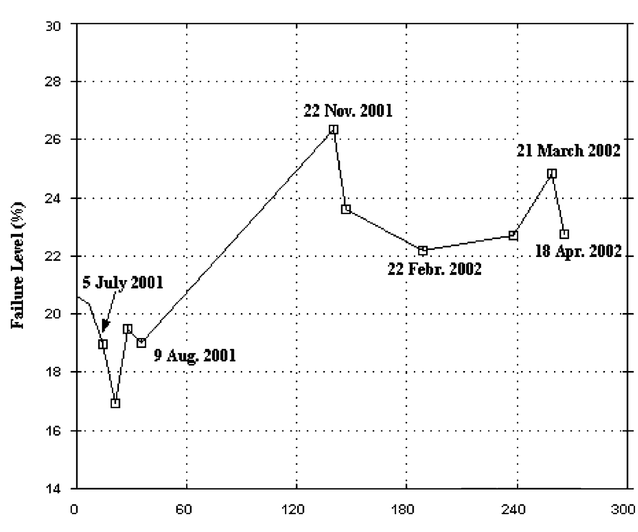

Fig. 10. Overall vibration level trend of the fan motor inner bearing.

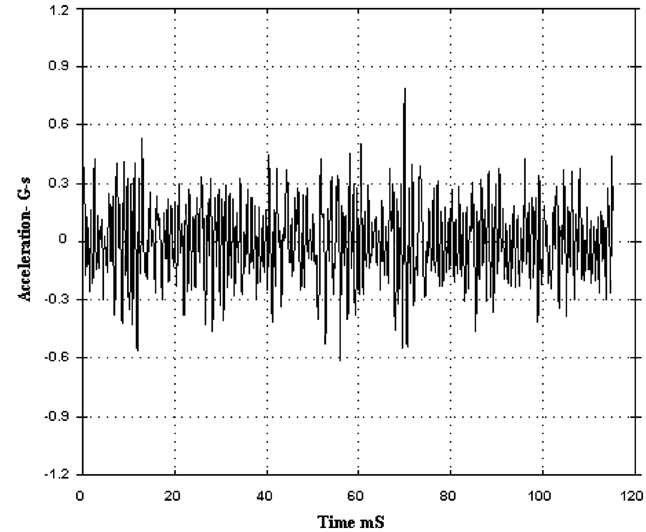

Fig. 11. Reference time waveform graph of the fan motor outer bearing.

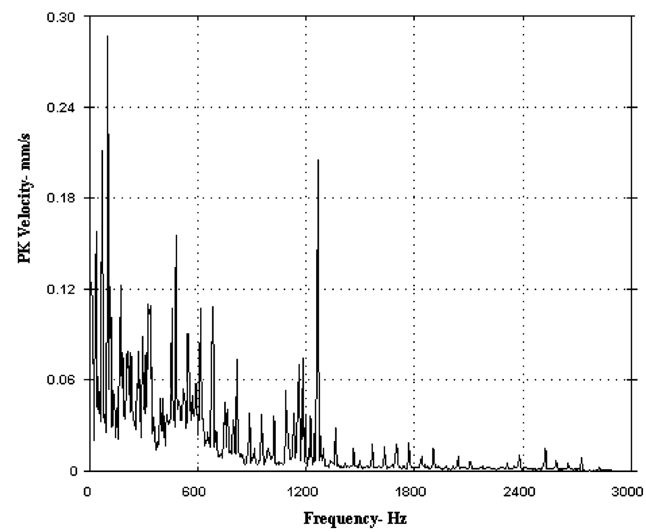

Fig. 12. Reference spectrum graph of the fan motor outer bearing.

5. Case study II

Cylindrical rolling element bearing is often used to support motors in industrial applications. Inner bearing vibration of the fan motor, which supported by SKF NU 224 types cylindrical, rolling bearing, was monitored periodically. The power and revolution of the motor are 345 kW, 741 rpm, respectively. The reference measurement was taken on 20 July 2001 (Figs. 8 and 9). By analyzing the vibration signatures, it is shown that the bearing condition was critical. Existing of multipliers of the cylindrical rolling bearing outer race defect frequency (90.67 Hz) on the spectrum graph and impact signals whose frequency is equal to outer race defect frequency (ω_{bp}), in the time domain waveform graph indicate that ball bearing outer race has a defect but it does not require to take apart the bearing in this stage because the vibration amplitude is on a normal level [13]. This situation continued in this way for 4 months. It is shown from the next measurement that vibration amplitude

Table 3
Frequency compositions of the fan motor outer bearing

Frequency (Hz)	Amplitude (mm/s-Peak)	Corresponding frequency ($\times\omega_{bp}$)
66.69	0.25	1
131.75	0.06	2
202.2	0.1	3
271.91	0.1	4
339.2	0.11	5
406.64	0.04	6
473.84	0.14	7
542.01	0.08	8
609.4	0.1	9
677.75	0.11	10
744.41	0.05	11
812.98	0.064	12
880.62	0.039	13
949.26	0.03	14
1016.7	0.04	15
1084.4	0.04	16
1152.9	0.057	17
1220.8	0.036	18
1292.3	0.032	19
1356.6	0.02	20
1490.7	0.01	22
1558.8	0.02	23
1626.6	0.01	24
1694.9	0.02	25
1761.9	0.02	26
1829.8	0.02	27
1898.2	0.01	28
1961.4	0.0045	29
2311.9	0.1	34
2379.6	0.011	35
2583.5	0.01	38
2652.5	0.01	39
2723.2	0.03	40

suddenly increased (Fig. 10), the vibration level was still normal so not any action was initialized but vibration must be measured regularly from this time on and any increase in amplitude has accurately to be evaluated. In the next and other vibration measurements, vibration levels some varied due to loading conditions. This bearing may be used effectively under the condition that the vibration level is accurately monitored. From this time on, any increase in the vibration level must be carefully evaluated because otherwise the bearing will be brake down at any moment.

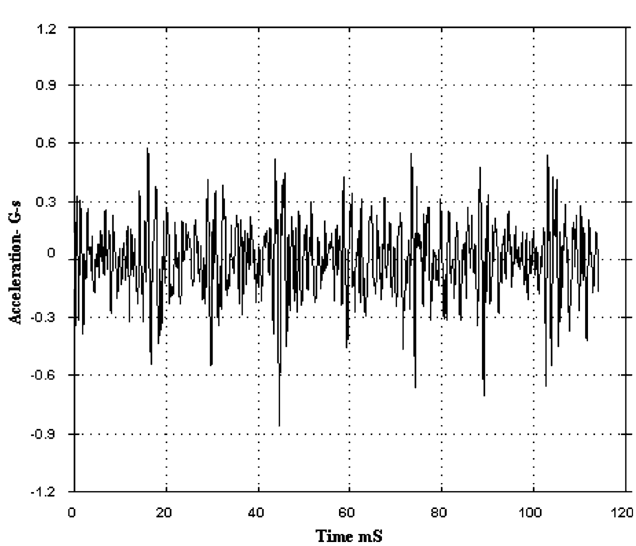

Fig. 13. Time waveform graph of the fan motor outer bearing on 3 October 2001.

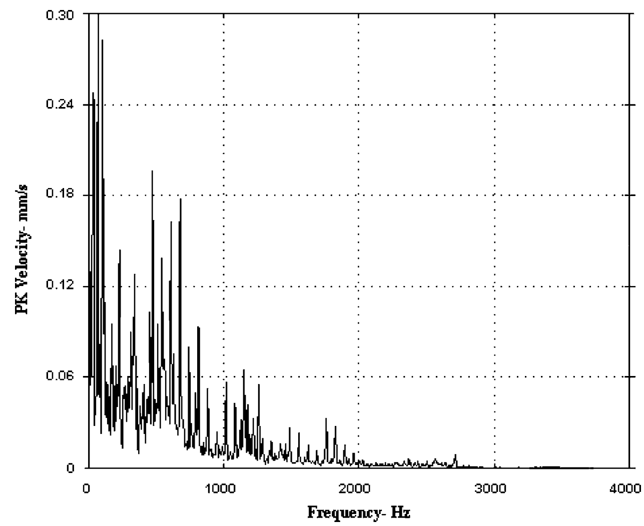

Fig. 14. Spectrum graph of the fan motor outer bearing on 3 October 2001.

6. Case study III

Ball bearings were widely used in any type of rotating machinery. Thus, determining the health of the ball bearings is very important. Outer bearing vibration of a fan motor, which is supported by SKF 6222 type ball bearing, was monitored periodically. The power and revolution of the motor are 200 kW, 985 rpm, respectively. The reference measurement was taken on 6 September 2001 (Figs. 11 and 12). By spectral analysis of vibration signatures, it is shown that the bearing condition was normal. Vibration frequencies on the spectrum graph consist of ball bearing outer race defect frequency and its

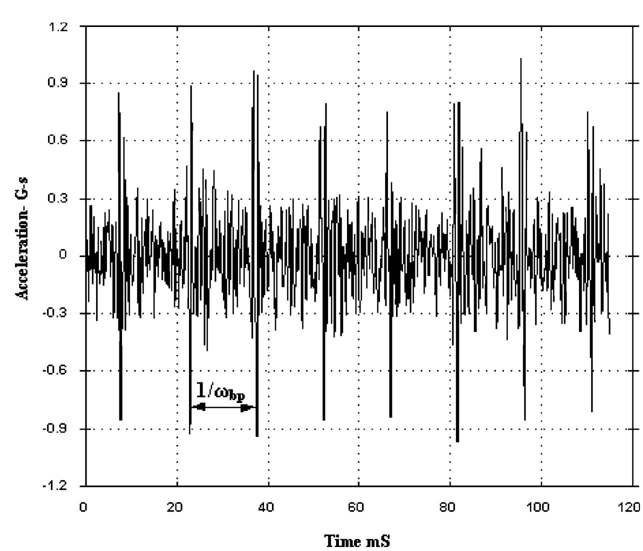

Fig. 15. Time waveform graph of the fan motor outer bearing on 6 July 2002.

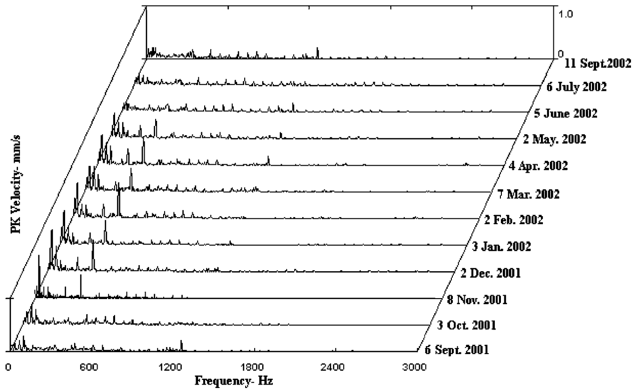

Fig. 16. Multiple spectrum graph of the fan motor outer bearing.

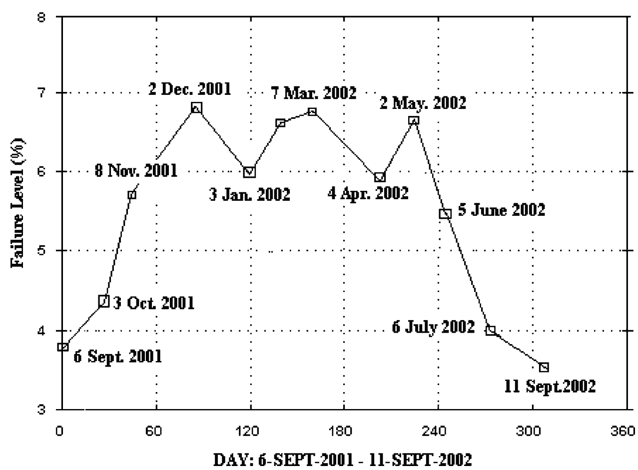

Fig. 17. Overall vibration level trend of the fan motor outer bearing.

harmonics from $1\times\omega_{bp}$ to $40\times\omega_{bp}$ as shown in the Table 3. This situation indicates the sign of a outer race defect but there are no impact signals in the time domain waveform graph. This indicates that the defect did not still formed, namely, is in its early stage. In the time domain waveform graph (Fig. 13) obtained after about one month (3 October 2001) periodical impact signals are formed whose period was related to ball bearing outer race defect frequency (66.69 Hz) and vibration frequencies in the spectrum graph (Fig. 14) were the same as in the previous situation. At this moment, the defect became evident, the amplitude of the frequencies was on a low level, thus a maintenance action was no required. From following measurements, for example 6 July 2002, impact signals were evident as shown in Fig. 15. In contrast to these facts, it is shown that vibration amplitudes had been decreased on 5 June 2002 and in following measurements (Figs. 16 and 17). This indicates that bearing entered a catastrophic stage and due to ‘self-peening’ of the bearing flaws, high frequency amplitude levels often decreased. The occurrence of this ‘self-peening’ phenomenon is especially true for low speed machines [12]. There was no chance to pull out ball bearing, consequently, to see bearing defect because maintenance staff of the refinery did not accept a maintenance action.

7. Conclusions

In this study, diagnosing techniques of the ball and cylindrical roller element bearing defects were investigated by vibration monitoring and spectral analysis as a predictive maintenance tool. Ball bearing looseness, a ball bearing outer race defect and a cylindrical bearing outer race defect were successfully diagnosed. It was shown that ball and cylindrical roller bearing defects were progressed in identical manner without depending on rolling element type. Furthermore, it was experienced that when a bearing defect reaches an advanced stage, high frequency amplitude levels often decrease due to ‘self-peening’ of the bearing flaws. Remaining life of the bearings can be estimated using vibrational behaviour and running time of the bearings. Diagnosing of defects on multiple parts of the bearing may also be investigated in a real running condition. Also, it can be concluded that if vibration monitoring is applied within regular selected periods, capable instrumentation and if vibration analysis is performed by experienced personnel, impending failures can be easily detected.

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