Detection of rotor imbalance in rotor bearing system using multi sensor vibration signature

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Abstract- Rotor imbalance is most common source of vibration in rotating machines such as turbine. This fault generates excessive vibrations and excitation forces, which may cause premature failure of critical parts of the machine. The present work deals with experimental investigations, performed on a rotor bearing test rig to identify the unique signature of vibration spectrum for rotor imbalance under varying operating speed. The experimental frequency spectra were obtained at five different speeds for two conditions i.e. healthy condition and rotor imbalance condition. Fast Fourier Transform (FFT) is used for this purpose. The results of present work provide the valuable information regarding detection of machinery imbalance through vibration analysis.

Keywords – Imbalance, Fast Fourier Transform, Orbit plot, Proximity sensor, Rotor

I. INTRODUCTION

Rotating machinery is widely used in a range of mechanical transmission systems and has important role in industry. Increased complexities of rotating machinery and demands for higher speeds, greater power, heavy loadings and continuous operations have created complex design of rotor with increased vibration problem. Vibration in rotating machinery is mostly caused by imbalance, misalignment, mechanical looseness, shaft crack and other malfunctions[1]. The additional vibration caused by these faults may destroy critical parts of the machine, such as bearings, gears and couplings. Rotor imbalance is a condition, when center of mass (inertia axis) of rotor is out of alignment with the center of rotation (geometric axis). Imbalance causes a moment, which gives an object the wobbling movement characteristic of the vibration of rotating structures [2]. It can cause decrease in efficiency and in the long run may cause failure of machine. Imbalance is very important factor to be considered in modern machine design, especially where high speed and reliability are important consideration

Many researchers have presented their studies for diagnosis of imbalance. Hili et al. [3] presented a model study of a complete motor flexible-coupling rotor system capable to quantify the effects induced by the simultaneous presence of shaft misalignment and imbalance. The authors concluded that imbalance and misalignment can be characterized primarily by one and two times the shaft running speed in corresponding spectra. Jalan and Mohanty [4] identified imbalance and misalignment in a rotor bearing system using model based method. Study concluded that the presence of residual force at node of coupling caused by misalignment while residual force observed at node of disc showed the presence of unbalance. Hariharan and Srinivasan [5] performed a study on a rotor dynamic test apparatus having a self-designed 3-pin type flexible coupling and an over hung rotor to predict the vibration spectrum for rotor imbalance. Both experimental and simulation results spectra concluded that imbalance can be characterized primarily by first harmonics of shaft running speed. Sudhakar and Sekhar [6] investigated a rotor bearing system for the identification of imbalance using two different approaches; equivalent load minimization method and vibration minimization method. The authors concluded that (i) equivalent load minimization method with modified theoretical model and vibration minimization method were more effective than equivalent load minimization method in identifying imbalance and (ii) imbalance fault was identified by measuring transverse vibrations at only one location by both methods. Kumar et al. [7] performed experimental studies on a rotor bearing setup to predict the imbalance in overhung rotor. Study results showed that the presence of high 1X peak of horizontal and vertical spectrum is an indication of unbalance and also there is 90° phase difference in between horizontal and vertical signals. Recently, Pathan and Khaire [8] presented an experimental study to identify the effect of various type of coupling such as jaw coupling, flexible flange coupling and rigid coupling on imbalance. It was found from the experimental study that presence of dominant peak at 1X was independent of type of coupling. It was also observed that rigid coupling was more prone to vibrations as compared to other two couplings (jaw coupling and flange coupling). There is a growing tendency to extract information about the prognostic parameters based on system analysis through various diagnostic techniques. Vibration based condition monitoring is a useful technique for application to rotating machines and provides valuable information regarding symptoms of machinery failures which in practice may avoid costly breakdowns [9]. By using the signature of vibration extracted from the machinery due to defect, a condition monitoring system for defect detection might be developed for rotor system.

In the present work rotor imbalance is detected with the help of two proximity sensors. Fast Fourier transform (FFT) and orbit analysis are used to explain the imbalance in rotor bearing system in presence of a flexible coupling.

II. EXPERIMENTAL SETUP

The experimental setup consists of a motor, two deep groove ball bearings, split type bearing housing, shaft, rotor disc, coupling and a variable speed drive in order to get different RPM of motor. Schematic of experimental apparatus on which experiments were conducted is shown in Fig. 1.

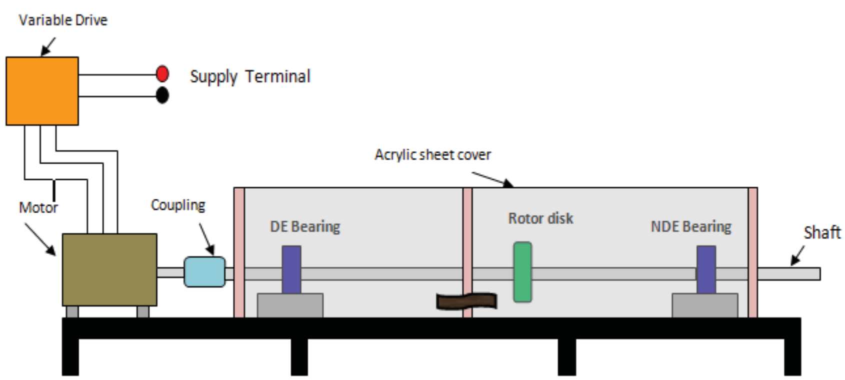


Figure 1. Schematic diagram of experimental setup

In the experimental setup, the rotor shaft (Material: EN8) is supported by the two identical deep groove ball bearings fitted in split type plummer block housing. The shaft has a length of 1400 mm and span of shat between bearings is 1000 mm. The diameter of rotor shaft is 15.52 mm. A three phase alternating current motor of 0.5 HP capacity is used to drive the rotor shaft connected through the flexible coupling. A balanced rotor disc of outer diameter 97.81 mm and thickness 8.82 mm is mounted at the center of the shaft. The rotor disk has eight equally spaced holes of 6 mm diameter at 40 mm radius to create an imbalance by fixing a mass. In order to get speed variation, a variable drive is connected to the motor that controls the RPM of motor in the range from 0 to 2810 RPM, through frequency variation. The speed of the shaft is measured by using a proximity switch with digital display. In the experiment, two proximity probes are used for acquisition of vibration response of shaft displacement. The proximity probes are mounted on an attachment placed near the centrally mounted rotor disc. A data acquisition system (NI-USB-4431) is used to acquire the vibration signal using proximity sensors.

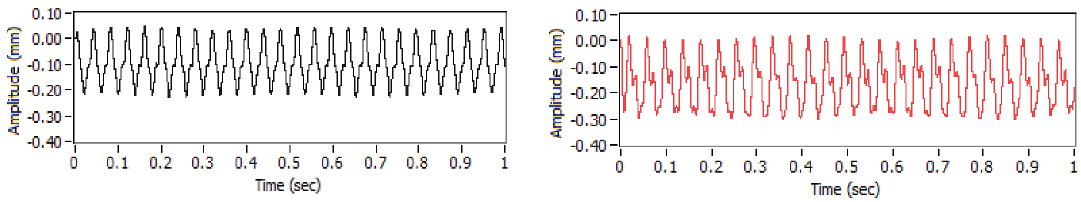
III. EXPERIMENTAL PROCEDURE

Experimental setup shown in Fig. 1 is used for imbalance test. Experimentation is performed for two conditions, i.e., fault free condition and rotor imbalance condition. Imbalance is introduced in healthy system by placing a mass of 9 gram in the disc at a radius of 40 mm. Initially the setup is allowed to run for few minutes to settle down all minor vibrations. Sensors are placed in a way so that they can acquire proper vibration signal. Vibration response of shaft is measured through proximity sensors at five different speeds i.e., 300 RPM, 600 RPM, 900 RPM, 1200 RPM and 1500 RPM for fault free and faulty conditions. A personal computer based data acquisition system is used to acquire the vibration signal obtained from proximity probes. A program has been developed in Labview environment to acquire and display the signal. Sampling rate for data acquisition was set at 70000 samples per second. There is provision to record/store the signal in the hard disk of the computer for subsequent processing and analysis.

IV. RESULTS AND DISCUSSION

A. Fault free condition

As a first step in study of rotor baring system, it is essential to acquire vibration response of healthy system (fault free system). Fault free condition results will help to identify the effect of the fault introduced in the system. In fault free condition, the system is well balanced and properly aligned with minimum possible imbalance error. The lateral vibration response of shaft (duration 1 sec.) in time domain recorded by proximity sensor at 1500 RPM is shown in Fig. 2.



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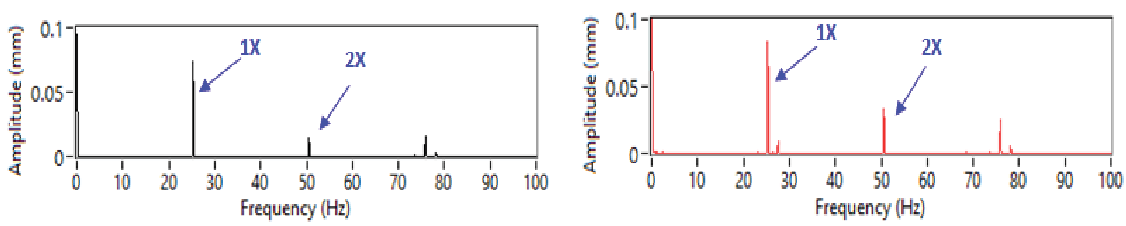
(i) (ii)

Figure 2. Vibration responses of healthy system at 1500 RPM in (i) horizontal direction, (ii) vertical direction.

It may be noted that vibration response along both the lateral directions (i.e. horizontal and vertical) are almost equal. The frequency spectrum of both displacement signals was computed through FFT corresponding to all operating speed, in order to characterize the displacement of the shaft in the frequency domain and link it to the rotational speed. Fig. 3 shows the frequency spectrum of the vibration signals acquired from the proximity sensors in healthy condition at 1500 RPM (25 Hz) in horizontal and vertical direction. The X-axis indicates the normalized frequency and the Y-axis denotes displacement (mm).



(i) (ii)

Figure 3. Frequency spectrum of healthy system at 1500 RPM in (i) Horizontal direction, (ii) Vertical direction

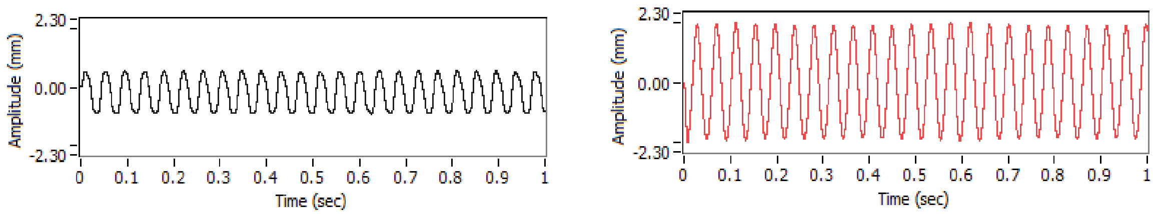
In Fig. 3, the FFT plot for vibration response in both directions shows strong 1X and 2X component magnitude. In some cases small higher harmonics such as at 3X and 5X components are noticed that may be due to presence of some unknown mechanism in the actual system such as residual misalignment, bearing nonlinearity etc. Table 1 shows the magnitude of 1X and 2X component corresponding to five different operating speeds in fault free condition.

Table -1 Amplitude of 1X and 2X component (in mm) in fault free condition at different speed

Speed (RPM)	FFT of signal in horizontal direction		FFT of signal in vertical direction	
	1X	2X	1X	2X
300	0.036463	0.023648	0.036463	0.033567
600	0.038888	0.022218	0.038888	0.048676
900	0.044408	0.060451	0.044759	0.016428
1200	0.043286	0.014302	0.042508	0.031023
1500	0.066697	0.014276	0.074402	0.03332

B. Rotor imbalance condition

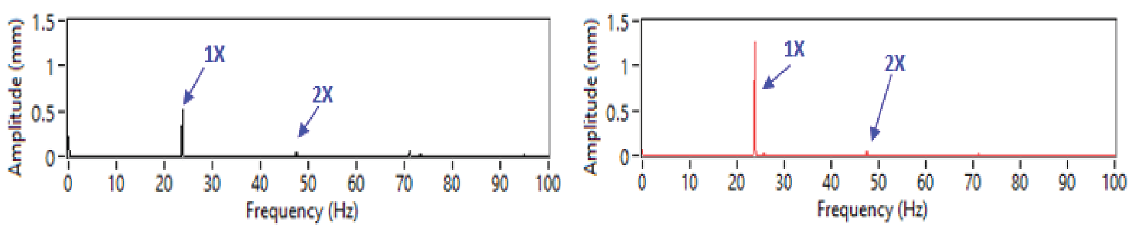
In order to introduce imbalance in a healthy system, a mass of 9 gram is placed in the threaded hole of the rotor disc. This will result in shifting of center of mass of the rotor disc. In rotor imbalance condition, the lateral vibration response of shaft in time domain recorded by proximity sensor at 1500 RPM is shown in Fig.4.



(i) (ii)

Figure 4. Vibration responses of imbalanced system at 1500 RPM in (i) horizontal direction, (ii) vertical direction.

From Fig. 4, it is clear that vibration responses obtained in rotor imbalance condition have higher levels of vibration which is different from the vibration response in fault free condition (Fig. 2). In imbalance condition, the rotor vibration level along vertical direction is more compared to the horizontal direction. This disturbance in vibration response is resulted from the presence of imbalance effect. Fig. 5 shows the frequency spectrum of lateral vibration in rotor imbalance condition correspond to 1500 RPM (25 Hz) in horizontal and vertical directions.



(i) (ii)

Figure 5. Frequency spectrum of imbalanced system at 1500 RPM in (i) Horizontal direction, (ii) Vertical direction.

Fig. 5 clearly shows that imbalance effect results in higher amplitude vibration response in vertical direction compared to horizontal direction with increase in speed and higher harmonics also become obsolete at higher speed. It is also observed that FFT of vertical direction has dominant 1X component peak at all operating speed. Some higher harmonics with weaker magnitude and noise is reported in the FFT at slow speed. Also the effect of imbalance makes orbit (shown in Fig. 6) inclined and elliptical which is almost circular in fault free condition.

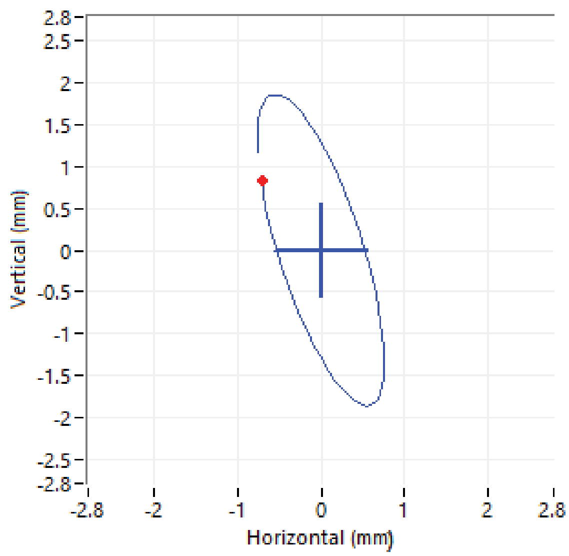


Figure 6. A typical shaft centerline orbit plot under imbalance condition at speed of 1500 rpm

Table 2 and Fig. 7 shows the magnitude of 1X and 2X component corresponding to five different operating speeds in imbalance condition.

Table 2. Amplitude of 1X and 2X component (in mm) in imbalance condition at different operating speed

Speed (RPM)	FFT of signal in horizontal direction		FFT of signal in vertical direction	
	1X	2X	1X	2X
300	0.091337	0.051861	0.031283	0.026614
600	0.06379	0.080222	0.052967	0.044231
900	0.023116	0.727454	0.133271	0.027888
1200	0.111109	0.076178	0.399417	0.08108
1500	0.458295	0.047529	1.13244	0.047529

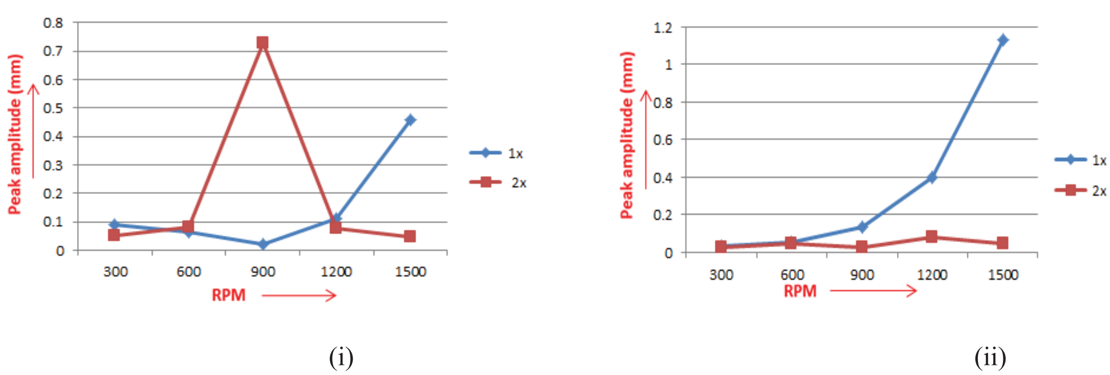


Figure 7. Magnitude of 1X and 2X component in imbalance condition correspond to different operating speed in (i) horizontal direction, (ii) vertical direction.

From Fig. 7 it is observed that only 1X component in vertical direction is important and can be noticed because this component is dominant over other peaks corresponding to all operating speed. As speed increases, its magnitude also increases due to increase in centrifugal force. Fig. 8 shows the variation of 1X peak of vertical spectrum over different speed in fault free (shown by blue) and rotor imbalance condition (shown by red).

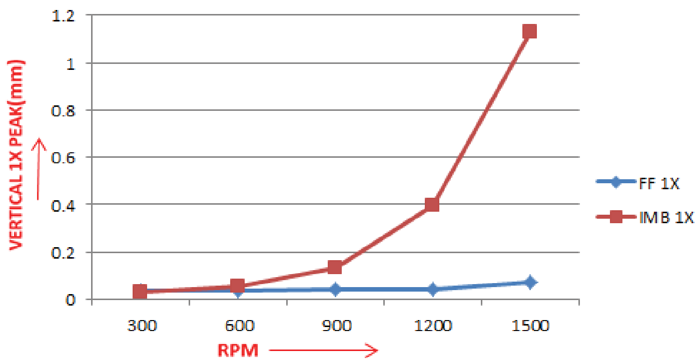


Figure 8. Variation of 1X peak of frequency spectrum in vertical direction over different speeds in fault free (FF) and imbalance (IMB) conditions.

Centrifugal force due to imbalance mass is directly dependent on operating speed. Imbalance doesn't show significant effect at slow speed. Therefore, there is only small difference in magnitude of 1X component in fault free and imbalance condition at 300 RPM. As speed increases, magnitude of 1X component in imbalance condition also rapidly increases due to increase in centrifugal force. Therefore at 1500 rpm difference between magnitude of 1X component in fault free and imbalanced condition is large. It is clear that presence of strong 1X component in vertical direction at all operating speed indicates presence of imbalance fault in the system.

V. CONCLUSION

Present work reveals that when any fault initiates or develops in machine then vibration signature deviates from the standard condition. On the basis of experimental results and observations, the following conclusions are drawn:

- Maximum vibration amplitude at first harmonics (1X) in vertical direction at all operating speed is an indication of presence of imbalance in the rotor system. A small 2X component is also noticed at all speed. But other higher harmonics are very weaker in magnitude or become obsolete at higher speed.
- In imbalance condition, as speed increases, magnitude of 1X component also rapidly increases due to increase in centrifugal force. At lower speed imbalance doesn't show much effect.

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