Journal of Scientific & Industrial Research
Vol. 76, May 2017, pp. 308-313

Experimental Investigation of Misalignment and Looseness in Rotor Bearing System using Bartlett Power Spectral Density

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Received 19 December 2015; revised 15 July 2016; accepted 27 January 2017

This paper explains Bartlett Power Spectral Density (BPSD) based analysis to identify the faults in a rotor system from spectral density of vibration signal. Misaligned rotor increases vibration and generates abnormal forces at the coupling and transmitted the bearing. In this study, the dynamic response of a rotor bearing system with angular misalignment and looseness are investigated using the BPSD approach. The fault signals are then compared with baseline vibration signals. Angular misalignment was diagnosed from axial vibration and looseness from sub-harmonics signals at 1X, 1-1/2X, 2X, 2-1/2X, 3X.

Keywords: Bartlett Power Spectral Density, Rotor Bearing System, Vibration Signal Processing, Looseness, Misalignment.

Introduction

Faults in rotating machinery are diagnosed using condition monitoring techniques. In recent years, many researchers have focused to develop new methods for identifying misalignment and looseness in rotor bearing system. The measured vibration signal normally contains more information about the state of a rotor system. This signal can be processed to extract the information by several methods. The noisy observation y(n) can be modelled as,

$$y(n) = x(n) + n^*(n) \qquad \ldots (1)$$

Where x(n) is a signal, n*(n) is noise and n is the discrete time. Filtering of signals is being done using many techniques to extract information. This research paper deals more accurately with Bartlett power spectral density based angular misalignment and looseness fault identification. The looseness rotor creates abnormal vibration signal; therefore, the time and frequency waveform could be used to identify the faults with the help of Bartlett power spectral density. Smoothing periodogram method used to analyze the fluctuation arithmetically in signal processing[1]. Modified maximum likelihood method (MLM) was also introduced to estimate the PSD for many applications[2]. Welch method was also proposed by Sebastian *et al*. for the automatic commissioning of electrical drives[3]. The probability density function of spectral density has calculated for supporting the automatic commissioning of electrical drives using Welch's method[4], which was based on an arbitrary number of frequency bins, the amount of overlap, overlap data segments. The proportionality of harmonics have also obtained from current signal using the accelerometer for monitoring sensor-less on-line vibration monitoring of induction machines[5]. Partial rubs and looseness faults of rotor systems with clearance were distinguished by Seung *et al*.,[6] from non-linear and non-stationary signal by Hilbert-Huang Transform (HHT). However, it needs higher samples to extract information. Looseness at the bushing could be identified from implied impact and friction[7]. Spectral method was developed by Molka *et al*.[8] for the misaligned and unbalance flexible rotor to diagnose the failure state. The transfer matrix has also been proposed by Chao-Yang *et al*.[9] for the shaft coupler with parallel misalignment. Effect of coupling misalignment forces and moments were studied from the FEM model for the rotor coupling system, the study reported that the axial and torsional vibrations of 2X running frequency affected due to change of phase[10]. Tejas *et al*.,[11] reported that the application of vibration waveform, orbit plots and conventional one-sided and two-sided spectrum; forces of coupling misalignment have induced higher harmonics like 3X frequency. Al-Hussain[12] studied the potential energy and kinetic energy dissipation of two rotor system with angular misalignment. Few researchers were focused on a model based study to analyze for fault

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diagnosis of unbalance, angular and parallel misalignment[13,14]. Arun *et al*.[15] have studied the 1X running speed components present in the frequency domain of a healthy rotor system.]

Bartlett power spectral density

The outputs from vibration measuring sensors are analog in nature; these signals are converted into digital signals using the analog to digital converter (ADC) in the data-acquisition boards in which sampling the signals is done at constant intervals of time. Peaks of discrete samples were represented as numbers in a binary form. The curve was generated from the discrete sampled data points (digital). High sampling rate with more points gives better representation of the signal than that of low sampling rate. Sampling frequency must be greater than two times of its maximum frequency for reconstructing an original signal. It is very common to sample the signal five to ten times the maximum frequency of the input signal as the real signal contains noise. Noise frequency is often higher than the Nyquist frequency (anti-aliasing filter). Windowing techniques are used on the finite time record to reduce the amplitude along with spectral leakage. Continuous or analog signals are measured from the rotating machinery. Machinery analysts are familiar with the terms commonly encountered in signal conditioning such as filters, integrators and AC to DC conversion. Vibration transducers convert the physical vibration motion of a machine into an electrical signal. However, this signal in the raw form is of no use unless it is processed to provide meaningful information that can be related to rotor condition. There is a need for monitoring the equipment through electrical signals from a transducer and process it into meaningful data. Averaging the periodogram of the signal presents the power among the individual frequency contents during the process. In BPSD method, several periodograms from different segments of a signal are averaged in order to reduce the variance of the periodogram. N point signal *x(n)* in Bartlett Method is divided into K non-overlap segments with each segment having length L=N/K[16].

$$x_i(n) = x(n + iL)\ x_i \qquad \dots (2)$$

where, i = 0,1,2,3……..K-1, n = 0,1,2,3……..L-1, j = √-1
$x_1(n), x_2(n), \dots\ x_i(n)$
$x(0), x(L), x(2L, \dots\ x(N-1)$

Computed periodogram of each segment is then averaging for K segment. Periodogram for each segment

$$P_{xx}^{i}\left(e^{jw}\right) = \left(\frac{1}{L}\right)\left|\sum_{n=0}^{L-1} x_i(n) e^{-jwn|2}\right. \qquad \dots (3)$$

i = 0,1,2,3…….K-1

Average the Periodogram for K segment

$$P_{xx}^{BT}\left(e^{jw}\right) = \left(\frac{1}{K}\right)\left|\sum_{i=0}^{K-1} P_{xx}^{i} e^{jw}\right. \qquad \dots (4)$$

The Bartlett periodogram is obtained from the average of K periodograms. Vibration Signals exhibit the dynamic behavior of a mechanical system. Signal processing is concerned with the representation, transformation and manipulation of signals and the information contained therein. This information will be useful wherever the system function changes. Energy or power spectral density is concerned with the distribution over the signal energy or power over the frequency domain.

Angular misalignment and looseness

Misalignment is being the most serious problem for a rotor system like unbalance. Basically, there are two types of misalignment existing in the rotor system *viz.*, (i) angular misalignment and (ii) offset misalignment. Force frequency is generated once in every revolution due to angular misalignment during the running speed in the axial direction. Maximum

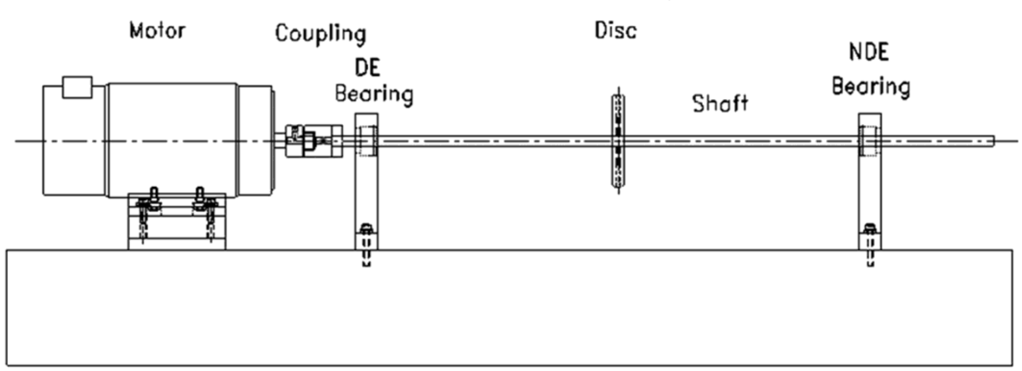

Fig. 1—Rotor-coupling-bearing test rig

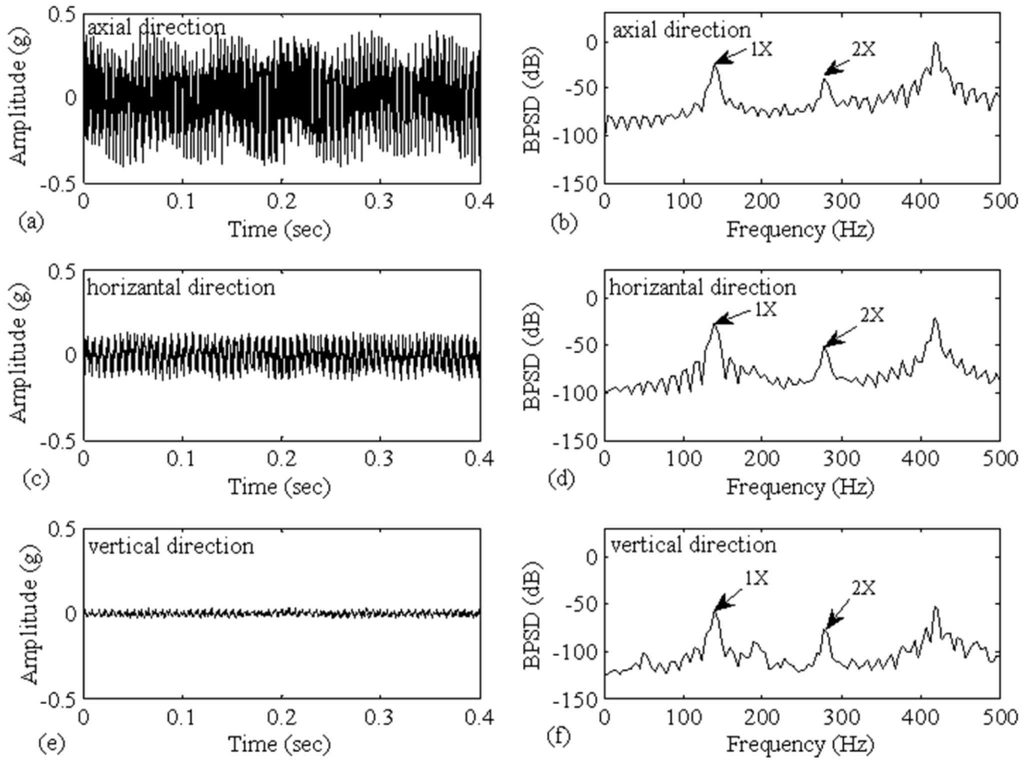

Fig. 2—The original vibration signals and Bartlett power spectral density of angular misalignment at 8400 rpm

displacement presents in the axial direction. Induced force (1X running speed in axial direction) increases proportionally with angular misalignment. Amplitude of these components is high when compared with baseline signature. 1X component in the axial vibration is the best indication for angular misalignment. The looseness is another common problem in rotating machinery. Presents of Looseness due to loose-mounting bolts between bearing pedestal or machine to base structure creates more abnormal vibration. Vibration signature is induced in both vertical and horizontal planes due to loose fit between component parts or bearing pedestal with foundation, which produces more harmonics signals. A truncation of the time waveform appears in the time signal due to harmonics.

Experimental set-up and data collection

Experiment is performed with an angular misalignment and looseness fault. The rotor disc is mounted at the mid-span of the shaft. There are two self-align bearing at both the ends for support (Drive end bearing and Non-drive end bearing). Flexible jaw coupling is used to connect the shaft and motor shaft. Rotor system can be run by DC motor with the speed control device for varying the field voltage. The shaft is perfectly straight and circular in diameter. Vibration isolator is also placed between motor and bed to diminish the vibration. Tri-axial accelerometer is attached to the bearing stand to measure the impulse response. Dial gauge method is used to make a system fault free condition. Figure 1 shows the schematic diagram of rotor-coupling-bearing test rig. Vibration signals are observed from the rotor system at different speeds using Tri-axial accelerometer and it is sent to the spectrum analyzer through a condition amplifier. The rotor shaft is then gradually rotated to reach the desired speeds. These measured signals at different speeds are considered as baseline signatures. For angular misalignment, axis of the Motor shaft and the rotor shaft, are made at about 18 minutes by suitably moving NDE bearing stand in the horizontal direction, so that the excited residual forces are transferred to bearing stand and performed for dynamics analysis. To characterize the vibration signatures upon the looseness, an experiment is performed by loosening bolts at bearing housing. Discrete time signals are transformed into Bartlett power spectral density for investigation using MATLAB tool. Taking periodograms for each section, the mean value is calculated by averaging these periodograms from which BPSD is estimated,

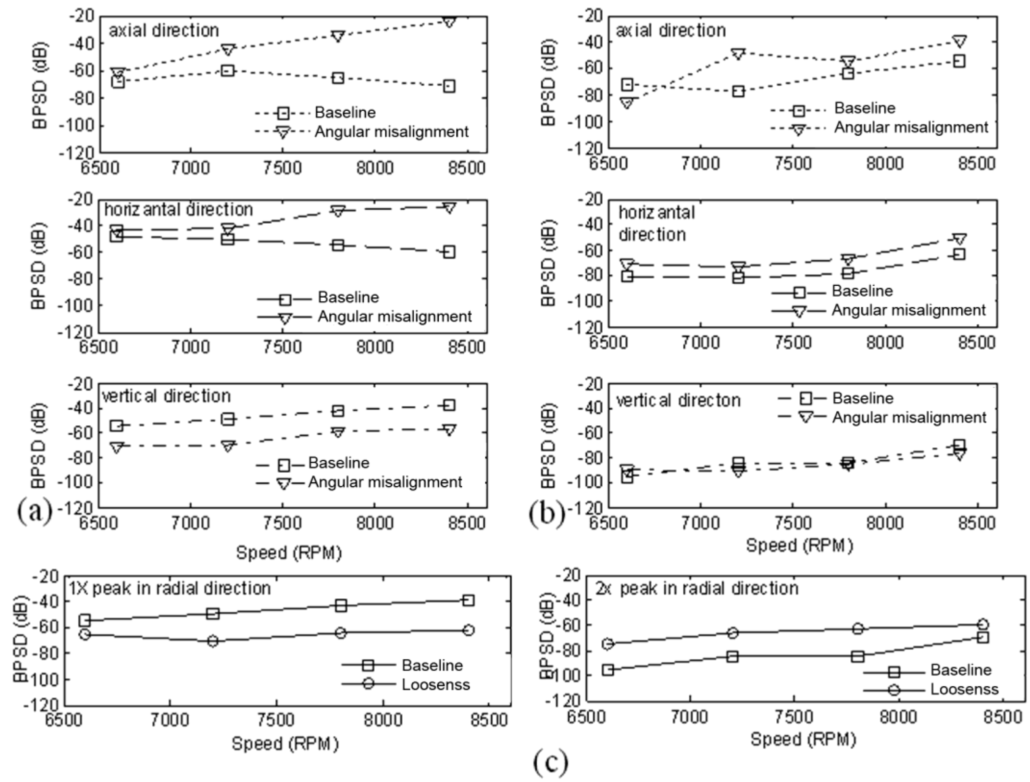

Fig. 3—Bartlett Power Spectral Density: (a) angular misalignment at 1X peak (b) angular misalignment at 2X peak and (c) Looseness at 1X peak and 2X peak

using sampling frequency of 1280 Hz, with six segments. Signals are observed at the sampling rate of 5 kHz and the sensitivity of 100mV/g.

Results and Discussion

Impact test of rotor test rig

The impact test for the shaft of the rotor is performed to find the natural frequencies of the shaft. Tri-axial accelerometer is attached at the end of the shaft and the shaft is impacted with an impact hammer at the centre of the shaft to measure the signals. The signals are stored in the computer through A/D conversion with fast Transform and analyzed with MATLAB software. Natural frequencies (f1, f2 and f3) of the rotor system are observed from impact test (46.3Hz, 173.6Hz and 443.7Hz.).

Angular misalignment

Experiment is conducted to study the influence upon the power spectral density due to angular misalignment in the test rig at different speeds. NDE bearing housing is displaced about horizontal direction of 18 minutes (0.3°) angular misalignment for investigation and analysis. Figure 2(a), (c) and (e) show the original vibration signals with angular misalignment fault, which are measured from the test rig at a speed of 8400 rpm. Prediction of fault is difficult from time domain signal. The frequency spectrums of Bartlett power spectrum density are shown in Figure 2(b), (d) and (f). It can be seen that the 1X and 2X harmonic frequencies are obvious. Vibration signatures are measured using data acquisition with no defect and with angular misalignment as shown in Figure 3. Vibration signatures are compared with base line signatures. The power spectral density are developed at four speeds of 110HZ, 120Hz, 130Hz and 140Hz (6600, 7200, 7800 and 8400 RPM) using Bartlett method in axial, horizontal and vertical directions respectively in a healthy rotor system. It is obvious from the baseline signature that amplitude of 1X running speed in radial direction is always dominated than axial direction. Perfect balance is impossible since there may be any manufacturing fault and unbalance force on the bearing housing. Harmonic signals are generated in every cycle. Therefore, high excitation exists in the radial direction due to unbalance. 1X running frequency peak is always dominated than the 2X running frequencies due to imbalance. Vibration responses from the rotor bearing system with angular misalignment are investigated through power spectral density. An experiment is performed at four different speeds. The position of the tri-axial accelerometer is the same as it was in the baseline experiment. Vibration signatures (Time domain) are first recorded from angular misalignment rotor system then is evaluated using Bartlett Power spectral density responses. It is observed that the power spectral density of axial direction with no defect rotor system is low at 1X running speed than radial direction as shown in Figure 3 (a) and (b). Evidence of unbalance is observed from the 1X running speed with dominant amplitude in radial direction. Further 1X running frequencies are increasing in the vertical direction with increasing speed; however, it is decreasing in the axial directions. In the misalignment rotor system, 1X power spectral density -61.7 dB, -44.9 dB, -34.7 dB and -24.56 dB in the axial direction and -43.7 dB, -42 dB, -29 dB and -25.7 dB in the horizontal direction are increased by the rise in running speed. However, the power spectral density of 1X running frequency peak at an angular misalignment is dominant in the axial and horizontal responses at all speeds and which are compared to baseline signature -68.7 dB, -60 dB, -65 dB and -71.6 dB in axial direction and -48.8dB, -50.5dB, -54.7dB and -59.3 dB in horizontal direction. The baseline signature of 1X running frequency is always dominant than the misalignment peaks -54.6 dB, -48.8 dB, -42.6 dB and -38.3 dB, in the vertical responses due to the presence of horizontal angular misalignment. On the other hand, the axial amplitude of 1X running frequency of angular misalignment is always greater than radial direction. High amplitude at 1X running speed in axial direction is the sign of presence in angular misalignment; nevertheless, 1X peak of vertical direction is low as compared to baseline signature, there is less force in the vertical direction. BPSD responses observed from an angular misalignment

- 1X peaks in the axial direction is dominated as compared to radial direction.
- 1X peaks in the horizontal direction are dominated than the baseline signatures with respective speeds due to presence of angular misalignment in the horizontal direction and also baseline signatures are always dominated in the vertical direction.

Looseness

Multiple impact forces are induced due to looseness at the bearings in each revolution. Tri-axial accelerometer is located at the same place as it is in the misalignment experiment. The loose mounting is induced complex sub-harmonics signals due to the impact and friction. The Bartlett power spectral densities of the looseness rotor system are recorded at different speeds. Vibration signatures with looseness at 6600 rpm, 7200 rpm, 7800 rpm and 8400 rpm speeds in radial (vertical) direction are measured to get hold of looseness harmonics from experimental study. Table.1 gives that the looseness harmonics peaks along radial direction, which are captured from Figure 3 (c). However, there are multiple sub-harmonics peaks (1X, 2X, 3X, etc., and 1½X, 2½X, 3½X, etc., in radial direction) are appeared due to the looseness in the rotor system. When rotor speed is increased, peaks of 1X, 2X, 3X etc., are also increased in the form of 3X amplitude greater than 2X amplitude, greater than 1X amplitude and also it can be seen that sub-harmonic peaks of 1½X, 2½X, 3½X, etc., are appeared in the radial direction. BPSD response observed from looseness rotor.

- Multiple harmonic peaks (1X, 2X, 3X, etc., and 1½X, 2½X, 3½X) appeared in the radial direction.
- Side bands appeared at all harmonics and sub-harmonic peaks.
- 3X peak dominated as compared to 1X and 2X peaks.

Table 1—Looseness harmonics peaks in radial direction

		BPSD (dB)					
		1X	1½X	2X	2½X	3X	3½X
Speed (RPM)	6600	-64.97	-88.59	-74.91	-89.63	-71.24	-87.88
	7200	-70.11	-86.88	-65.67	-84.66	-63.69	-82.05
	7800	-63.64	-68.26	-63.02	-72.34	-55.22	-71.57
	8400	-61.78	-68.56	-59.84	-74.57	-53.89	-72.21

Conclusions

This study reveals that the Bartlett power spectral density provides useful information to analyze the angular misalignment and looseness faults in the rotor bearing system. Further BPSD method paves the way to extract the sub-harmonics peaks of angular misalignment and looseness for analyzing the behavior within rotor system under dynamic state. Moreover, axial vibration signature is always dominated due to angular misalignment. In the case of pedestal looseness, multiple sub-harmonics peaks were appeared. From the foregoing analysis, it is proved beyond doubt that the BPSD based condition monitoring method could certainly diagnose the rotor faults if angular misalignment and looseness exist within the rotor bearing system.

Acknowledgement

The research study was conducted in the vibration analysis laboratory in Mechanical Department (Engineering Design), Government College of Technology at Coimbatore, Tamil Nadu, and India.

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