VIBRATION ANALYSIS BASED LOCALIZED BEARING FAULT DIAGNOSIS UNDER DIFFERENT LOAD CONDITIONS

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Abstract: Condition monitoring of bearings is one of the vital problem in predictive maintenance. If the bearing failure is not diagnosed in time, it may lead to catastrophic results on the machining operations and may cause downtime. In this study, a diagnosis scheme for bearing faults under different load conditions have been examined using vibration signals. A shaft-bearing setup was designed for acquiring vibration data via a data acquisition system. Artificial local faults have been implemented on the inner and outer race of the bearing. By applying constant axial load and various radial loads, the bearing setup was run under constant spindle speed. Then vibration signals are analyzed in the frequency domain. The fault frequency component was obtained and observed that it increases as the size of bearing fault and the radial loads increase. This study can be considered as a preliminary work for developing more advanced condition monitoring techniques.

Key words: Bearing faults, vibration analysis, radial load effects.

I INTRODUCTION

Predictive maintenance is an important problem for the machining operations having roller bearing elements. If the condition of roller element bearing is not monitored and diagnosed in time, the defects occurred on the bearing may lead to catastrophic results on the rotating machinery operations or at least they may cause downtime. Because bearing parts could be defected during the production or installation, and it is also impossible to avoid abrasion due to steady friction of mechanical components, condition monitoring based on bearing fault diagnosis should be applied to the rotating machinery in automation systems. In literature, one can find many reports for the importance of condition monitoring of roller element bearing defects. It was reported that, bearing faults are widely responsible of many loss of production and expense of maintenance in rotational mechanic components [1]. In another study, it is claimed that the malfunctions are about 40% bearing sourced [2].

For monitoring bearing faults, many models have been developed based on the characterization of bearing signals in vibration, current etc. analysis. McFadden and Smith [3-5] have developed a model for the vibration produced by a single [3] and multiple defects roller element bearings [4], and a monitoring system using high frequency resonance technique [5]. Ocak and Loparo [6] managed to predict rotational speed and the bearing fault frequencies of an induction motor by analyzing vibration data.

As seen from the literature, condition monitoring techniques based on frequency analysis is very common. Because bearing defects at inner race and outer race generate impulses as the roller elements pass the defect at each turn. The frequency of these impacts can easily be estimated from the geometry of the bearing and the running speed. These estimated frequency components should appear in the frequency spectrum when methods like Fast Fourier Transform (FFT) are used. One big disadvantage of this method is that the impulses caused by the defects could be covered by noise or resonance. To eliminate this disadvantage, techniques like high frequency demodulation (HFD) or envelope analysis (EA) should be used. McInerny and Dai [7] have described the relation of fault frequencies with amplitude modulation/demodulation using envelope analysis. Kunle and Yunxin, tried to determine the location of fault frequencies that are concentrated using the vibration signals acquired from locally defected bearing [8]. Besides the pure frequency analysis techniques, more advanced signal processing methods such as wavelet analysis have been also employed. Botsaris and Koulouriotis developed a preliminary estimation analysis methods of vibration signals at fault diagnosis in ball bearings based on wavelet method [9]. Quan-Li et al. [10] have made failure analysis of vibration signals using wavelet transform. In literature, artificial intelligence techniques such as neural networks and fuzzy logic have been used for more sophisticated monitoring techniques. Chow et al. [11] built a neural network system with a support of simulation results to optimize strategies.
for fault diagnosis. Kowalski and Kowalska [12] dealt with diagnosis of rotor, stator and bearing faults by applying neural networks. In [13], the authors used the vibration signals in the frequency domain for classification of faulty bearings based on a Neuro-Fuzzy approach system. In that paper, a special attention is focused on the analysis of the rules obtained by the final neuro-fuzzy system for better classification performance.

In this study, a frequency analysis was employed for the detection and diagnosis of bearing faults under different radial load effects. In order to carry out a diagnosis system, an experimental setup composed of a shaft-bearing mechanism was constructed. The system was operated with a brand new bearing and artificially defected bearings with various defect sizes. Vibration data was collected through a data acquisition system. The experimental setup was run under 2400 rpm and various load rates with 0.4 bar, 0.6 bar and 0.8 bar for a brand new bearing and roller element bearings with 0.5 mm, 1 mm and 2 mm sized local defects in depth that corresponds to incipient, moderate an severe faults, respectively. Defects were artificially introduced to inner race and outer race of the bearing by a technique called Electrical Discharge Machining (EDM). The acquired data were processed on a computer with MATLAB software. The experimental setup that the bearing was mounted was operated at 0.4, 0.6 and 0.8 bar radial load effects. The vibration signals from the setup were acquired and exposed to high frequency demodulation to determine the fault frequency component at the spectrum. Finally, it was observed that the fault frequency components are increasing as the depth size of fault on bearing parts and the effect of radial load get larger.

II THEORETICAL INFORMATION

Frequency analysis technique that is the most common analysis method for bearing fault detection in literature was used in this study. It can be found many spectrum analyzers designed for vibration analysis. One can easily detect the faults on balancing, wrong alignment with frequency analysis of time series signals. It is well-known that a specific defect or damage on bearing causes a certain frequency component on the frequency spectrum. In other words, it is possible to determine the type of fault by analyzing the frequency spectrum of the vibration signals. Besides, defects on inner race, outer race and rolling component (ball) generate various independent frequency components [14].

Figure 1 shows the geometric structure of the ORS 6205 bearing for 9 rolling component. The parameters for this bearing are namely D = 52 mm, dm = 38.95 mm, Rb = 7.895 mm, w = 15 mm and contact angle (θ) = 0º.

A. Bearing Fault Frequencies

A bearing generates vibrations when it gets defected or abraded due to steady manner of mechanical friction. Vibration causes strong harmonics and sidebands. Given the geometry of the bearing and the frequency of the running speed of the rotating machinery, fault frequencies could be distinguished from other frequency components. For a bearing shown in Fig. 1, with the outer ring being stationary, bearing fault or key frequencies are as follows:

\[ BPFO(Hz) = N \frac{f_s}{2} \left( 1 - \frac{R_b}{d_m} \cos \theta \right) \]  \hspace{1cm} (1)

\[ BPFI(Hz) = N \cdot f_s \left( 1 - \frac{1}{2} \left( 1 - \frac{R_b}{d_m} \cos \theta \right) \right) \]  \hspace{1cm} (2)

\[ BSF(Hz) = f_s \left( \frac{d_m}{R_b} \right) \left( 1 - \frac{R_b}{d_m} \cos \theta \right) \]  \hspace{1cm} (3)

where, \( BPFO \) is the Ball Pass, Frequency Outer Race, \( BPFI \) is the Ball Pass Frequency Inner Race, \( BSF \) is the Ball Spin Frequency, \( N \) is the number of balls, \( f_s \) is the revolutions per second of the inner race or the shaft, \( \theta \) is the contact angle [15]. The contact angle for the ball bearings carrying no thrust is assumed to be zero. Manufacturers often provide these frequencies in the bearing data sheet. The measured values for the characteristic frequencies might not match the theoretically calculated ones especially when the ball bearings have significant thrust loads and internal preloads.

B. Fourier Transform

In the frequency analysis, Discrete Time Fourier Transform (DTFT) technique was used. DTFT depends on the principle that estimates the Fourier transform from finite numbered sample points of a function. The approach used today in determining the Fourier transform is Fast Fourier Algorithms (FFT).
The FFT algorithm, built in 1965 by Cooley and Tukey, is not different from DTFT. It is an effective and perfect algorithm for determining DTFT. DTFT’s significant role in like spectrum analysis, convolution and correlation in digital signal processing is based on FFT algorithms. FFTs of experimental vibration data were determined in MATLAB.

Fourier transform can be applied to continuous time signals and discrete time signals as shown in the Eqn.4 and Eqn.5, respectively.

\[ F(iw) = \int_{-\infty}^{\infty} f(t)e^{-jwt} dt \]  
\[ X(k) = \sum_{i=1}^{n} x(i)e^{-j2\pi(k-1)\frac{(i-1)}{n}} \quad 1 < k < n \]

where \( n \) is the total number of points in the signal.

C. High Frequency Demodulation

When a bearing has a defect, shock pulses are generated as the rolling elements pass over the defect. These shock pulses excite the resonance frequency of the mechanical system and produce vibration and the energy of this vibration is mostly centered around the resonant frequency. The vibration signal can be considered as an amplitude modulated signal with carrier frequency being the resonance frequency of the mechanical system. Therefore, it is reasonable to demodulate the signal to separate the modulation signal (shock pulses) from the carrier frequency.

Demodulation or envelope analysis involves three steps:
1-) Band Pass Filtering,
2-) Half-wave Rectification,
3-) Low Pass Filtering [15].

The center frequency of the band pass filter must be chosen as the resonance frequency of the system. Low pass filtering is used to cancel high frequency components and retain bearing defects associated low frequencies. Figure 2 shows an envelope analysis example on a simulated vibration signal for an inner race defective bearing. The shock pulses and the vibration signal along with the output of each step are shown in Fig. 2. Figure 3 depicts the magnitude FFT of the final envelope signal. Inner race frequency (IR) was simulated to be 162 Hz. The peaks at the defect frequency and its harmonics along with the side bands are clearly visible.

III EXPERIMENTAL SETUP

Experiments were conducted on a bearing-shaft mechanism of an AC electric motor shown in Fig. 4. Equipments used in this study are National Instruments 6211 data acquisition card (DAQ), piezotronics accelerometer, and ORS 6205 polyamide cage deep groove type radial bearings. In the experiments, normal and artificially defected bearings were used to gather vibration data measured by the piezotronics accelerometer. The collected data were transferred to the computer via data acquisition card that collect, sample and digitize the data.
The main cause for bearing faults is the mechanical friction they encounter in every phase of the process. Other than inevitable friction, factors like moisture, load and heat also affect the life of the bearing. Normally this process takes months to occur. But in order to realize a diagnosis system in laboratory conditions, the process should be accelerated. Therefore, artificial defects should be applied. For artificial defects, bearing parts were detached into inner race, outer race and balls. Since the bearing used in the experiments are polyamide cage type, they can be separated into parts and reattached them as shown in Fig. 5.

In addition to artificial faults introduced to the bearing parts, radial loading affect was also applied on the experimental setup. Therefore, one of the purpose of this study is to analyze the loading affects on the bearing life. Because overloading reduces the life of bearings. The load distribution on bearing is depicted in Fig. 7.

An accelerometer was used to get the vibrations. The accelerometer that was used in the experiments was PCB 352C65 of which the details are given in Tab. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (±10%)</td>
<td>10.2 mV (m/s²)</td>
</tr>
<tr>
<td>Measurement interval</td>
<td>±491 m/s² pk</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>≥35 kHz</td>
</tr>
<tr>
<td>Non Linearity</td>
<td>≤ %1</td>
</tr>
</tbody>
</table>

Table 1: PCB Model 352C65 accelerometer.
frequency using DAQ card. Then, MATLAB software was used to process data in frequency domain.

IV. EXPERIMENTAL RESULTS

Many experiments were conducted on the experimental setup using normal bearings and faulty bearings with incipient, moderate and severe fault sizes under different radial loads. In fact, the experimental setup was run under different spindle speed. But, the results with only 2400 rpm speed were reported in this study.

In the experiments, vibration signals were collected from a normal bearing via accelerometers mounted on the setup. Figure 8 shows a sample raw vibration data for a normal bearing.

Since the raw vibration signal is an amplitude modulated signal with resonance frequency of the mechanical system, it is required to apply high frequency demodulation analysis on the signal as explained in Section II.

In order to enhance the effect of artificial faults, radial loads were implemented on the bearings. First, vibration signals were collected from the experimental setup subjected to different radial loads for normal bearing with no faults. Fig.9-11 show the vibration signals applied high frequency demodulation under different radial loads.

The figures emphasize that the amplitude of fault frequency components are increasing with the values of 202.3, 314.4 and 354, respectively.

For bearing with incipient (0.5 mm) outer race fault, the setup was run again under different radial loads and the demodulated vibration signals have been obtained as seen in Fig.12-14.
The amplitude of the demodulated fault frequencies are namely 323.6, 501.5, 718 for bearing with 0.5 mm fault under 0.4 bar, 0.6 bar and 0.8 bar radial loads, respectively.

Similarly, the demodulated vibration signals for bearing with moderate (1 mm) outer race fault under 0.4, 0.6 and 0.8 bar radial loads have shown at Fig. 15-17. The fault frequencies are namely 465, 591 and 759.

When the experiments were repeated for bearing with severe (2 mm) fault under 0.4, 0.6 and 0.8 bar radial loads, the fault frequencies are obtained as 596, 765 and 797, respectively as shown in Fig. 18-20.
In order to summarize all the results shown Fig.9-20, the fault frequencies are depicted in a bar graph at Fig.21. As bearing fault and radial loads increase, the amplitude of the fault frequency component obtained from high frequency demodulation of vibration signals are increasing.

All the experiments conducted for normal bearing and with various outer race faults under different radial loads are repeated for the bearing with inner race fault. Similarly, artificial faults are introduced to inner race as 0.5 mm (incipient fault), 1 mm (moderate fault) and 2 mm (severe fault), respectively. Again, the experimental setup was run for faulty bearing under different radial loads. When the vibration signals were subjected to high frequency demodulation, the fault frequency components are obtained as shown in Fig.22. As expected, the amplitude of fault frequency components get larger as the quantity of fault at inner race and radial load effects are increasing.

V. CONCLUSIONS

In this study, the effect of bearing faults and radial loads on the fault frequency component was investigated. For this purpose, predefined artificial faults were applied to bearings with a technique called EDM. Bearings were detached to its components, and defects with various sizes were introduced to inner race and outer race. Defect sizes were 0.5 mm, 1 mm and 2 mm that correspond to incipient, moderate and severe fault, respectively. The experimental setup that the bearing was mounted was operated at 0.4, 0.6
and 0.8 bar radial loads. The vibration signals from the setup were acquired and exposed to high frequency demodulation to determine the fault frequency component of the spectrum.

As bearing fault size and the radial load increase, the amplitude of the fault frequency components also increases. Therefore, by frequency analyzing of vibration signals, it is possible to determine the level of fault and loading. The study presented in this paper can be extended to vibration based condition monitoring of more complex systems.

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