ON VARIOUS SPECIALIZED VIBRATION TECHNIQUES FOR DETECTION OF BEARING FAULTS

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ABSTRACT

Detection of bearing faults from raw time domain or frequency domain data is extremely difficult in view of the fact that there are a very large number of frequency components present in these signals. For this reason, other specialized signal processing techniques have been tried out. Experiments were carried out on a specially fabricated bearing test rig with variable speed drive and hydraulic loading arrangement. Faults were induced in an SKF N 307 roller bearing and the bearing housing vibrations were sensed by piezoelectric accelerometers. These signals were fed to a personal computer through a Data Acquisition System (DAS) and processed using MATLAB software. The enveloping spectrum, cepstrum and the auto regressive model based spectrum have been presented for the case of bearings with inner race (IR) and outer race (OR) defects. These results prove that the above methods have an edge over conventional methods for fault diagnosis.

1 INTRODUCTION

The majority of problems in machinery are caused by faulty bearings. The techniques that have been employed in the recent past for fault diagnosis of rolling element bearings are shock pulse method (SPM), spectrum analysis, analysis of kurtosis and root mean square (rms) values, etc. Bentley [1,2] used a rolling element bearing activity monitor (REBAM), which measures the very small deflection of the bearing outer ring with respect to the shaft as an indication of bearing condition. He pointed out that the vibrations produced by machines equipped with rolling element bearings always have components in rotor vibration region, prime spike region and high frequency region. McFadden and Smith [3] proposed that defect frequencies modulate the resonance frequencies of the bearing components. Prashad et al. [4] carried out experiments on cylindrical roller bearings at various speeds and diagnosed faults using high frequency resonance technique. Mathew et al. [5] carried out experiments at low speeds (less than 100 rpm) under different load conditions and analyzed the data with demodulation resonance technique and concluded that the technique is more sensitive in detecting damage under virtually no load condition. The work of Martin and Thorpe [6] on envelope analysis was a breakthrough in frequency domain vibration analysis. They emphasized that the amplitude of the rotational frequency component is often much larger than that of the defect frequency and pointed out the difficulty in distinguishing the defect frequencies from the rotational frequencies. Mechefske and Mathew [7] had carried out experiments on a defective cylindrical bearing at low speeds at constant load. They concluded that auto regressive (AR) model based spectral estimates showed a clear difference between a defective bearing and a good one. They described the procedure for monitoring of low speed rolling element bearings by parametric models and concluded that successful fault detection and diagnosis can be achieved from shorter signal lengths than in the conventional fast Fourier transform (FFT) spectra.

Most of the reported research has been carried out using individual techniques like acceleration enveloping, parametric spectra, etc. and have been compared with the FFT technique. Each method has its own advantage and disadvantage. Based on past experience, it is seen that several different techniques should be applied to identify bearing problems, because the results based on one or two alone may be misleading and can be counter productive. Hence, the need for a simple, cost effective multi-technique approach, which can effectively analyze different types of bearing faults for various operating conditions. This paper describes such a procedure, which increases the effectiveness of detecting different types of bearing failures over a wide range of operating speeds and loads using a simple program in MATLAB.

2 TEST SETUP AND DATA ANALYSIS

The schematic drawing of the bearing test rig used for carrying out experiments is shown in Figure 1. This rig consists of a short shaft supported between two bearings and driven by a variable speed (0-3000 rpm) d.c. motor. The test bearing is mounted in the non-drive end. The shaft is provided with a hydraulic loading arrangement (0–10000 N) as shown in Figure 1. Cylindrical roller bearings SKF N 307 and SKF NU 307 are chosen. Their specifications and characteristic frequencies are given in Tables 1 and 2 respectively. The geometry of the bearing is shown in Figure 2a. A cylindrical roller bearing is selected because creation of defects is easy. Bearings with defective outer and inner
races and a good bearing are used for carrying out experiments. Defects of size 8 x 0.5 x 0.5 mm are induced along the width of the bearing using spark erosion technique. Typical defective bearings with inner and outer race defects are shown in Figures 2b and 2c respectively.

The test bearing is mounted on the shaft. Two piezoelectric transducers are mounted on the bearing housing in the vertical and horizontal directions using a magnetic base. The speed of the motor is gradually adjusted to the required value. The vibration signals sensed by the pickups are fed to charge amplifiers and the output signals are recorded on a tape using an FM tape recorder (tape speed 3 ¾ inches per second to suit the frequency range of 0 to 5000 Hz covering the outer race resonance frequency of 3.7 kHz).

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**Table 1: Specification of Test Bearing**

<table>
<thead>
<tr>
<th>Bearing type</th>
<th>N 307/NU 307</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Rollers (n)</td>
<td>12</td>
</tr>
<tr>
<td>Contact angle (β)</td>
<td>0º</td>
</tr>
<tr>
<td>Roller diameter (d)</td>
<td>11 mm</td>
</tr>
<tr>
<td>Pitch circle diameter (D)</td>
<td>57.5 mm</td>
</tr>
<tr>
<td>Cage material</td>
<td>Polyamide Plastic</td>
</tr>
</tbody>
</table>

**Table 2: Characteristic frequencies of test bearing**

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>100</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>shaft rotational frequency (f_s) Hz</td>
<td>1.66</td>
<td>8.33</td>
<td>16.66</td>
<td>25.00</td>
<td>33.33</td>
</tr>
<tr>
<td>Defect frequency for inner race (f_{i_{r}}) Hz</td>
<td>11.91</td>
<td>59.55</td>
<td>119.10</td>
<td>178.65</td>
<td>238.20</td>
</tr>
<tr>
<td>Defect frequency for outer race (f_{o_{r}}) Hz</td>
<td>8.09</td>
<td>40.45</td>
<td>80.95</td>
<td>121.35</td>
<td>161.80</td>
</tr>
</tbody>
</table>
The experiment is conducted at zero load and loads of 2500 N, 5000, 7500 N and 10000 N and at speeds of 100 rpm, 500 rpm, 1000 rpm, 1500 rpm and 2000 rpm respectively. The recorded analog signal is replayed on the FM tape recorder and converted to a digital signal using the Data Acquisition System (DAS) and the data files are stored in a personal computer. Using MATLAB 5.3 signal processing toolbox, acceleration enveloping, parametric spectral estimation and cepstrum analysis are done.

3 Acceleration enveloping

Defects in rolling element bearings produce a series of impacts at a constant time interval which excite resonances in the races, rolling elements and other structural elements. The magnitude of impact depends on the load and defect. A vibration from a defective bearing is made up of low frequency signals from rotational components, defect impulse signals and machine noise. When a frequency spectrum of a real bearing is measured, it is found difficult to detect the defect frequencies from amongst the many frequencies present due to the presence of dominant background machine noise. Side bands in rolling element bearings occur at the resonant frequency of machine component or structure as the carrier frequency $f_r$ plus one of the bearing defect frequencies as the modulating frequency. The bearing defect frequencies include ball pass frequency-outer race (BPFO), ball pass frequency-inner race (BPFI), ball spin frequency (BSF) and fundamental train frequency (FTF). Amplitude modulations are common in rolling element bearings because the vibration amplitudes vary when the defects on inner race or rolling elements rotate in and out of the bearing load zone. Acceleration enveloping (Figure 3) enables the bearing fault detection in the incipient stage itself. Here a band pass filter is designed with a bandwidth of $\pm 2f_d$ around $f_r$ (resonance frequency). Using the band pass filter, all the low frequency signals are eliminated and the filter output signal contains only the resonance frequency along with the side bands of defect frequency. The filtered signal is demodulated to eliminate the carrier frequency. The demodulated signal is filtered using a low pass filter to eliminate the high frequency vibration and its power spectrum is obtained.

![Assumed method of signal generation](image)

**Figure 3: Representation of the enveloped technique**

4 Parametric spectra and Estimation of Model Order

Vibration based machine condition monitoring strategies have long depended on the FFT to transform raw vibration signals into more easily interpreted frequency spectra. The speed of the FFT allows large amount of vibration data to be processed quickly resulting in useful frequency spectra. However, when only a short length of vibration signal is
available, or if the vibration signal is of low energy, the FFT often yields poor results. Parametric methods can yield higher resolutions than non-parametric methods in cases when the signal length is short. In this method, instead of trying to estimate PSD directly from the data, the data are modeled as the output of a linear system driven by white noise and then the parameters of that linear system are estimated. The output of the filter for white noise input is an auto regressive (AR) process. The estimation of parameters for an AR model results in linear equations. Therefore, it has a computational advantage over other modeling techniques such as the auto regressive moving average (ARMA) and moving average (MA) techniques, which require highly non-linear equations to be solved. An AR model is one where the present value of the signal generated by a process is expressed as a weighted sum of the past values plus a noise term. In equation form it is represented as:

\[ X(t) = a_0 X(t-1) + a_1 X(t-2) + \ldots + n(t) \]  

where \( X(t) \) is the present data value, \( X(t-1), X(t-2), \ldots \) are the previous data values, \( a_0, a_1, a_2 \ldots \ldots \) are the model parameters and \( n(t) \) is the noise term.

Designing the model involves finding the optimum model order and calculating the model parameters. The Yule walker AR method (auto correlation method) in the MATLAB signal processing toolbox has been used for spectral estimation. This method computes the AR parameters by forming a biased estimate of the signal’s auto correlation function by minimizing the forward prediction error in the least squares sense. Along with estimating the model parameters, the modeling error is also calculated. When the modeling error reaches a minimum value, the optimum model order is found. A model of too high an order will result in spectral estimates containing spurious peaks, while spectral estimates with insufficient resolution are the result of models with too low an order. Since the best choice of model order is not known beforehand, several models of increasing orders are usually designed. The computation of the final prediction error (FPE) involves calculating the residual sum of squares error between the sample data and the model generated data. By minimizing the error, an optimum model order may be determined. The FPE loss function continues to decrease as the model order increases. No relatively large variation occurs after a particular model order is reached. The power spectral density (PSD) of the signal vector \( X \) is determined using Yule Walker AR method.

5 Cepstrum analysis

One of the ways an expert system detects bearing tones is by looking at the spectrum of logarithmic spectrum. This process is called cepstrum analysis, "cepstrum" being a play on the word "spectrum". This means that cepstrum analysis can be used as a tool for detection of periodicity in a spectrum, e.g. families of harmonics and uniformly spaced side bands. Its side band spacing, which contains the basic diagnostic information as to the source of modulation can be extracted using the cepstrum. The cepstrum has the twin advantage of being able to detect periodicity not immediately apparent to the eye and of being able to measure it very accurately because it gives the average side band spacing over the whole spectrum. Other terms involved in cepstrum analysis, like “quefrecency”, “rahmonics”, etc. have been derived from terms used in spectrum analysis, like “frequency”, “harmonics” etc. The peaks in the cepstrum result from families of side bands; the quefrecency of the peaks represents the periodic time of the modulation, and its reciprocal the modulation frequency. The mathematical representation of cepstrum was originally given by

\[ C(\tau) = |\Im \{\log F_{xx}(f)\}| \]  

The new definition of the power cepstrum is the inverse transform of the logarithm of the power spectrum i.e.

\[ C(\tau) = \Im^{-1} \{\log F_{xx}(f)\} \]

where \( F_{xx}(f) \) is the power spectrum of the time domain signal \( f(t) \). \( \Im \{ \} \) represents the FFT of the quantity in brackets.

6 RESULTS AND DISCUSSIONS

Figure 4 shows a typical raw spectrum of a bearing with outer race defect at 2000 rpm and no load condition. From the spectrum, it is seen that there are frequency components in the low frequency region (running speed and multiples up to around 120 Hz), structural resonance of the test rig (peak 150 Hz), a component due to outer race resonance (3.538 kHz) and side bands corresponding to defect frequency about the resonant frequency. The defect frequency as such is not visible in the 0-500 Hz range.

![Figure 4: Typical spectrum of bearing with outer race defect at 2000 rpm and no load condition](image)

6.1 Results of Acceleration Enveloping

The first sign of rolling element-bearing deterioration will generally be an increase in amplitude level of the frequency spectrum in the region of the resonance of the inner or outer race. It is difficult to diagnose the fault by examining the frequency spectrum, but is easy to do so using the envelope analysis technique. Figures 5 a-d show the signals after each step of the enveloping process. Figure 5 a shows the time domain signal for the bearing with outer race defect and Figure 5 b the corresponding spectrum. Figure 5 c shows the spectrum after band pass filtering around the outer race resonance. Figure 5 d shows the spectrum of the demodulated and low pass filtered signal. A low pass filter with a cut off frequency of \( 2f_s \) is used. The defect frequency and its multiples are seen (92.17 Hz, 185.5 Hz) in the enveloped spectrum.
Figure 5: Enveloping process for bearing with outer race defect

Figure 6 shows the enveloped spectra for bearing with inner race defect clearly bringing out the defect frequency and harmonics corresponding to a running speed of 1000 rpm. Figure 7 shows the enveloped spectra of a bearing with OR defect at 100 rpm. From this, it is seen clearly that the defect frequency at low speeds can be pointed out using enveloping technique.

6.2 Results of Parametric Spectra

Though the enveloping process gives good results as far as fault diagnosis is concerned, successful diagnosis can be achieved for shorter signal records using parametric models. An AR model of suitable order was first generated from the low pass filtered signal. The model order was determined (Figure 8) from the various power spectra generated using models of increasing order (50 to 3000). The peaks in these spectra are found to match well with those in the enveloped spectra and are better discernable in the parametric spectra.

Figure 9 shows the parametric spectrum of an OR defective bearing for a speed of 2000 rpm and 10000 N. The AR spectra for outer and inner race defective bearings are shown in Figures 10 and 11 respectively for a speed of 100 rpm.
speed = 2000 rpm; load = 10000 N; OR defect

Figure 9: Parametric spectrum- OR defect-2000 rpm

speed = 1000 rpm; load = 2500 N

Figure 13: Parametric spectrum - OR defect with short length data- 1000 rpm

Figure 11: Parametric spectrum-IR defect- 100 rpm

(a) OR defective bearing

(b) IR defective bearing

Figure 14: Parametric spectra of OR and IR defective bearings with short length data - 100 rpm

6.3 Results of Cepstrum Analysis

Figure 15 a shows the cepstrum obtained from the raw time domain signal for the bearing with outer race defect. A1, A2 and A3 are rahmonics of 0.00766 seconds, which corresponds to a modulating frequency or defect frequency of (1/0.00766) Hz, which is equal to 129 Hz corresponding to a outer race defect frequency at 1500 rpm. This is found to match extremely well with peaks of defect frequency and harmonics as shown in the parametric spectrum in Fig.15 b. Figures 16 a and b show the cepstrum and parametric spectrum of bearing with inner race defect. A1, A2 and A3 are rahmonics of 0.00589 seconds that corresponds to a defect frequency of (1/0.00589) Hz, being the inner race defect frequency at 1500 rpm. With respect to fault detection, the cepstrum, is seen to have the advantage in being able to extract spectrum periodicity not immediately apparent to the eye and in being insensitive to secondary effects such as signal transmission path.
7 CONCLUSIONS

(i) Acceleration enveloping is a very effective technique for pinpointing bearing defects at all speeds. The defect frequencies are very clearly brought out for the case of outer race defect. But in the case of inner race defect, the defect frequency signal is not so apparent.

(ii) Parametric spectra yield high resolution (based on the order) even for short length data and can be used in addition to the enveloping technique.

(iii) Cepstrum clearly indicates the spectrum periodicity and its rahmonics are quite apparent to the eye for inner race defect also.

(iv) All the above techniques can be used in combination with one another to detect all bearing faults over a wide range of operating speeds and loads.

REFERENCES


