Fault Diagnosis of Rolling Bearing Based on Feature Extraction and Neural Network Algorithm

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Abstract: - The rolling element bearing is a key part in many mechanical facilities and the diagnosis of its faults is very important in the field of predictive maintenance. Till date, the resonant demodulation technique (envelope analysis) has been widely exploited in practice. In complex machines, the vibration generated by a component is easily affected by the vibration of other components or is corrupted by noise from other sources. Hence, the fault-related vibration must be recovered from among those sources for accurate diagnosis. In this paper, envelope analysis and FFT analysis used for feature extraction. Back propagation neural network algorithm used for fault diagnosis on rolling bearing.

Key-Words: - Rolling bearing, fault diagnosis, back-propagation artificial neural network algorithm, envelope detector, Fast Fourier Transform

1 Introduction

Rolling element bearings find widespread domestic and industrial applications. Bearing fault detection is a typical problem in rotating machinery fault diagnosis [1].

Bearing failures can sometimes cause both personal damage and economic loss, if the fault cannot be detected and diagnosed well in advance. Proper functioning of these appliances depends, to a great extent, on the smooth and quiet running of the bearings [2]. Material fatigue, faulty, installation, or inappropriate lubrication may cause localized defects of rolling bearings. Each time the rolling element passes over the defect, An impulse of vibration is generated [3].

Different methods are used for detection and diagnosis of bearing defects; they may be broadly classified as vibration and acoustic measurements, temperature measurements and wear debris analysis. Among these, vibration measurements are the most widely used. Several techniques have been applied to measure the vibration and acoustic responses from defective bearings; i.e., vibration measurements in time and frequency domains, the shock pulse method, sound pressure and sound intensity techniques and the acoustic emission method [2].

Bearing failures have received much attention in the field of vibration analysis as they represent an area where much can be gained from the early detection of faults. Burchill [4] presented the method of resonance demodulation to diagnose the fault of rolling element bearings in the 1970s, and the SPM Company later developed an instrument to detect rolling element bearing faults based on the measurement of resonant responses of an accelerometer excited by the faults. Many approaches have been developed in recent years, such as wavelet analysis, empirical mode decomposition (EMD), cepstral analysis and so on [5-7].

For example, the detection of a localized defect in early stages is still a problem because the measured signal is affected by the harmonics from rotating components of the machine and the impulses generated by defects [8].

Envelope analysis, originally known as the high frequency resonance technique, is the most commonly used frequency analysis technique for the detection and diagnosis of bearing faults. Time-frequency domain techniques use both time and frequency domain information allowing for the investigation of transient features such as impacts. A number of time-frequency domain techniques have been proposed including Short Time Fourier Transform (STFT), the Wigner-Ville Distribution (WVD), and the Wavelet Transform (WT) [9, 10]. Bi-coherence spectra are used in [11] to derive features that relate to the condition of a bearing. The application of bi-spectral and tri-spectral analysis in
condition monitoring [12]. Neural networks are also applied to bearing fault detection and diagnosis [13, 14]. The traditional envelope analysis method, the fault is identified through the peak value of envelope spectrum. On the one hand, FFT method is widely used in the spectrum analysis of envelope signals [15]. Statistical data shows [16] that 90% of faults which occur in rolling bearings are due to cracks in inner and outer race and the rest are cracks in balls or cage [17].

The aim of the paper is to investigate the potential of vibration analysis in fault diagnosis of roller bearing. In this paper, envelope analysis and FFT analysis used for feature extraction. Back propagation neural network algorithm used for fault diagnosis on rolling bearing.

2 Experimental Setup and Test Bearing

Experimental bearing test rig worked for this study had an effective speed range of 250-5000 rpm via 3 phase AC servo motor with a maximum load capability of 5kN by a pneumatic cylinder. The split-type cylindrical roller bearings FAG N208-E-TVP2 and NU208-E-TVP2 were used in test bearing and they allowed defects to be planted onto inner and outer races, are presented in Fig 1. Bearing is a faulty component with a defect in the outer and inner race. The motor shaft was connected to the bearing shaft with a coupler.

2.1 Measuring Equipment

The accelerometer employed for vibration data acquisition was placed directly on the housing of the bearing. The accelerometer (Endevco 7253B-10) used has a frequency band of between 10Hz and 25.6kHz and a voltage / vibration sensitivity is 10mV/ms². The accelerometer was connected directly to a Pulse Type 7533 data acquisition and analyzer for data logging and analyzing. A total of 2048 data points were recorded per acquisition at a sampling rate of 2048Hz. The recorded data was analyzed Matlab with Intel i5 2.53GHz processor.
and 4GB RAM. Matlab was used for FFT analyze, envelope detector, ANN application and fault diagnosis of the bearing test system.

2.2 Experimental procedure
In this study, the experimental study has been performed on 108 experiments of which healthy bearing and faulty bearing faults are classified into three groups:

- 36 were fault-free
- 36 had inner race bearing fault
- 36 had outer race bearing fault.

All test recordings were undertaken for 12 running conditions; two load conditions (2 and 3kN) and six speeds (600, 900, 1200, 1500, 1800 and 2100rpm). The experimental data was collected eight times at the considered cases.

3 Signal Process and Artificial Neural Network
Each bearing element has a specific rotational frequency. These specific defect frequencies can be calculated from the geometry of the bearing and its rotational speed. For a bearing with a stationary outer and inner race, these frequencies are given by Table 1 and characteristics of the bearing parameters are given Table 2 and shown in Fig 2.

![Fig. 2. FAG N208 -E-TVP2](image)

### Table 1. Specific Defect Frequencies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Diameter (D)</td>
<td>80</td>
</tr>
<tr>
<td>Diameter of Roller (Rb)</td>
<td>11</td>
</tr>
<tr>
<td>Diameter of roller centers (dm)</td>
<td>62.1</td>
</tr>
<tr>
<td>Width (w)</td>
<td>18</td>
</tr>
<tr>
<td>Number of roller (N)</td>
<td>14</td>
</tr>
</tbody>
</table>

Depends on these geometric properties the outer race defect (ORD) frequency was settled at 5.7596 times of rotation shaft speed. Because of inner ring is bonded to the shaft rotation, inner race defect (IRD) frequency was settled at shaft rotation frequency. Fig. 3 shows the fault free, inner and outer race of bearing with localized defects with (0.5mm width and 0.5mm depth). The speed of motor shaft is 600rpm, that rotating frequency \( f_r = 10 \text{Hz} \). Based on the geometric parameters and rotating speed, the specific frequency of the ORD is calculated 57.6Hz. For outer race defects, the period of specific impulses is 17ms. The specific frequency of the IRD is equal to rotating frequency. So, IRD frequency is 10Hz and the period of specific impulses is 100ms.

### 3.1 Envelope Detection
Vibration analyze in the frequency domain can detect the location of the defect. But, vibration spectrum of the defective bearing may not point the defect at the beginning stage. Therefore, some signal processing techniques like envelope detection are used. Envelope detection is a significant signal processing technique which assists in the identification of bearing defects by extracting specific defect frequencies from the vibration signal of the defective bearing. In envelope detector processing, the vibration signal is bandpass-filtered around one of the resonant frequencies. Bandpass filter removing most of the unwanted vibration signals from other sources. This bandpass-filtered signal is rectified for demodulated by an envelope detector. Then rectified signal is smoothed by low-pass filtering to remove the bandpass-filtered resonant frequency. The specific defect frequency of the bearing is obtained from the spectrum of the envelope signal in the low frequency range [2]. The envelope detection of the vibration signal is represented in Fig. 4.

![Fig. 4. Envelope Detection](image)

### 3.2 Fast Fourier Transform
The frequency contents of the signal are calculated by the Fast Fourier Transform (FFT). For a discrete signal, FFT is calculated by the equation given below [18].

\[
X(k) = \sum_{n=1}^{N} x(n) e^{-2\pi i (k-1)(n-1)/N} \quad 1 < k < N
\]

Fig. 5 shows the frequency spectrum of the fault free, IRD and ORD vibration signal which is shown Fig. 3. In Fig. 5, rotating speed is 600rpm and fault
free, IRD and ORD frequencies are settling 10Hz, 10Hz and 57.9Hz respectively. Fig. 5 clearly shows that the component at specific frequencies and its harmonics differ substantially.

![Fault Free Vibration Time Waveform](image1)

![Inner-race Fault Vibration Time Waveform](image2)

![Outer-race Fault Vibration Time Waveform](image3)

**Fig. 3.** Vibration time waveforms for all defects at speed of 600rpm with 2kN load

For feature extraction, envelope detection and FFT have been applied to raw bearing vibration signal. Shaft rotation speed, peak frequency, IRD, ORD and their two harmonics and amplitudes were used for training ANN.

![Envelope Detection](image4)

**Fig. 4.** Envelope detection of inner-race fault

### 3.3 Artificial Neural Network

ANNs have been applied to a large number of problems because of their nonlinear system modeling capacity. ANNs are able to map the relationship between input and output and they store it into their parameters. Most of the ANN applications use simple multi-layer perceptron (MLP) network training with back-propagation algorithm.

![FFT Analysis](image5a)

**a)** Fault free

![FFT Analysis](image5b)

**b)** Inner Race Defect

![FFT Analysis](image5c)

**c)** Outer Race Defect

**Fig. 5.** FFT analyze of vibration signals and its harmonics: a) Fault free, b) IRD and c) ORD

Typical MLP network is settled in layers of neurons, where every neuron in a layer computes the sum of its inputs x and passes this sum through an activation function (f). The output of the network (o) is defined as a matrix form:

\[
o = f^2(W^1 f^1(W^0 x + b^0) + b^1)
\]

(2)

Where W is weight matrices, b is a bias vector and f is activation function (f^1 logistic, f^2 linear).
$W(i,j)$ is the weight between ($i$) the output and ($j$) the input and superscript defines layer number [18]. MLP networks can learn adjusting the weight using back propagation approach. The back-propagation algorithm for the MLP is a generalization of the least mean square algorithm which should adjust the network parameters in order to minimize the mean square error (MSE);

$$e = \frac{1}{2} \sum_{\mu=1}^{P} (t_{\mu} - o_{\mu})^2$$  \hspace{1cm} (3)

Where $t$ is target, $o$ is MLP output, $\mu$ is the sample instant $q$ size [19]. The realized MLP architecture with Matlab ANN toolbox had twelve inputs, two hidden layers and one output. The value of output indicated class of faults.

4 Results

The flow diagram of fault diagnosis is illustrated in Fig. 6. The analog signal of vibration from rolling bearing are digitized by the Pulse type 7533 data acquisition system. Raw bearing vibration signal was filtered by envelope detector and analyzed FFT. Extracted feature of Envelope – FFT data was used to estimation of fault diagnosis by ANN.

In this paper, to fill the input variable space better for diagnosis of bearing fault by ANN, the experiments were repeated three times. The results of 106 experiments were divided for training (%70), validation (%15) and test (%15). ANN is adjusted according to its error with 76 experimental results. 16 experimental results are used to measure ANN generalization and to halt training when generalization stops improving. The trained ANN was tested by presenting 16 experimental results for providing measure of ANN performance during and after training which the ANN has never seen before. The performance of the ANN is presented in Fig. 7 and Table 3.

The performance of ANN was evaluated according the mean square error (MSE) and correlation coefficient (R). Fig. 8 shows the correlation coefficients of ANN which indicated that ANN estimation and target values overlapped similarly.

![Image of Flow Diagram](image-url)
Fig. 7. Training performance of ANN

Table 3. Performance (MSE) of ANN

<table>
<thead>
<tr>
<th></th>
<th>Train</th>
<th>Validation</th>
<th>Test</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSE</td>
<td>0.0277</td>
<td>0.0570</td>
<td>0.0590</td>
<td>0.0370</td>
</tr>
</tbody>
</table>

The experimental data (targets) and the estimation of the ANN are presented in Fig. 9. Fault free, ORD and IRD classes are showed -1, 0 and 1 respectively. The small MSE value (Table 3.), and accuracy of the ANN estimation (Fig. 9) demonstrated the feasibility of the proposed envelope detector, FFT analyze and ANN combination for development of fault diagnostic system for rolling bearing.

Fig. 8. Correlation coefficients of ANN performance

5 CONCLUSION

In this paper, the authors present an approach for diagnosis of rolling element bearings based on the envelope, FFT and back-propagation neural network algorithm to fault diagnosis. The roles of different vibration signals and preprocessing techniques have been investigated. The effects of number of features and generations on the classification success have been studied. The use of six selected features gave 98% test success for most of the cases considered in this work. From the investigation presented in this paper, a few concluding remarks can be drawn, as follows.

- It is computationally efficient to apply the envelope, FFT and neural network method for bearing fault detection and diagnosis.
- Higher values of correlation coefficients (R = 0.9718) and MSE (0.0370) values show that ANN model and its estimated fault classes are close together.
- Envelope detector, FFT and ANN method is able to quantitatively determine the severity of faults.
- Useful information can be extracted from the analysis of vibration signals.

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REFERENCES


