Application of Wavelet Packet Transform (WPT) for Bearing Fault Diagnosis

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Abstract—The bearings are the most important mechanical elements of rotating machinery. They are employed to support and rotate the shafts in rotating machinery. On the other hand, any fault in bearing can lead to losses on the level of production and equipments as well as creation an unsafe working environment for human. For these reasons, Condition monitoring and fault diagnosis of these bearings has become a fundamental axis of development and industrial research. This paper presents a bearing-fault detection method based on wavelet packet transform (WPT). The results show that the proposed method improves the bearing faults diagnosis compared to other common techniques.

Keywords—Vibration Analysis; Bearing Fault Diagnosis; Fast Fourier Transform (FFT); Wavelet Packet Transform (WPT).

I. INTRODUCTION

The vibration monitoring is a fundamental axis of development and industrial research. Its purpose is to provide knowledge about the working condition of systems at each moment without stopping the production line. The monitoring allows avoiding the production losses related to breakdowns and reducing overall maintenance costs [1-2].

Rotary machines are usually used in various applications. A reliable technique for detection the bearing faults is critically needed in a wide array of industries to prevent machinery performance degradation, malfunction.

There are many techniques which can be used to monitor the bearing health like noise monitoring, temperature monitoring, current monitoring and vibration monitoring etc [3-4], but the most effective technique of them is vibration monitoring. Because the advantage of this method is that it is fast, accurate and robust to employ [3-4].

Many signal processing techniques have been proposed in literature for machinery fault diagnosis like Fourier Transform (FT), Short Time Fourier Transform (STFT) [4]-[5], Wigner-Ville Distribution (WVD) [6], Wavelet Transform (WT) [7-8], and Envelope Analysis (EA) [8-9]. The most of these methods use spectral analysis based on FT, the spectral analysis is the most fundamental and most common technique. Fourier transform is used to project vibration signals from time domain to frequency domain. However, it is not suitable for analyzing impulsive signals such as bearing and gearboxes faults. This incapability makes WT and EA an alternative solution for machinery fault diagnosis. WT can be continuous, discrete and Wavelet Packet Transform (WPT). It is an excellent tool for analyzing the non-stationary vibration signals.

This paper presents a bearing-fault detection method based on wavelet packet transform (WPT). The monitoring results indicate that the proposed method improves the bearing faults diagnosis relatively to other common techniques.

The paper is organized as follows: Section 2 presents system and bearing faults descriptions. Section 3 presents fault diagnosis techniques and monitoring. Section 4 concludes our contributions.

II. EXPERIMENTAL STUDY

A. System Description

The experiments presented in this paper used the vibration data obtained from the Case Western Reserve University Bearing Data Centre [9]. The data were collected from an accelerometer mounted on the motor housing at the drive end of an induction motor system coupled to a load; that can be varied within the operating range of the motor as shown in Figure 1. The data are sampled at a rate of 12 kHz and the duration of each vibration signal was 10 seconds.

The bearings used in this study are deep groove ball bearings manufactured by SKF. Faults were introduced to the test bearings using electro-discharge machining method. The defect diameters of the three faults were the same: 0.007, 0.014, and 0.028 inch. The motor speed during the experimental tests is 1797, 1772, 1750, 1730 rpm. Each bearing was tested under the four different loads: 0, 1, 2, and 3 horse power (hp).

Fig1. The test-bed to simulate the fault of rolling element bearing
### B. Fault Bearing Characteristic Frequencies

Defective bearings generate vibration equal to the rotational speed of each element bearing frequencies. They relate notably to the rotation of the balls, the cage and the passage of the balls on the inner and outer rings.

Frequency associated with defective inner fault is given by equation (1):

\[
BPFI = \frac{n}{2} f_r \left(1 + \frac{d}{D} \cos \alpha \right)
\]

where, \(f_r\) is the rotational frequency, \(d\) the ball diameter, \(D\) the pitch diameter, \(n\) the number of balls and \(\alpha\) the contact angle.

In order to evaluate the suggested method, the measured data are collected at speeds of 1797 rpm (30Hz) for 0-load (0 hp) and 1730 rpm (29Hz) for 3-load (3 hp) in tow cases; normal state, inner races fault. The sampling frequency is 12000 Hz and the number of samples for each signal is 4096 points.

<table>
<thead>
<tr>
<th>Location of the data collection</th>
<th>The Drive-End bearing (DE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault Diameter</td>
<td>0.007 inches</td>
</tr>
<tr>
<td>Faults Types</td>
<td>Inner race</td>
</tr>
<tr>
<td>Motor Load (HP)</td>
<td>0</td>
</tr>
<tr>
<td>Motor Speed (rpm)</td>
<td>1797</td>
</tr>
<tr>
<td>Frequencies Speed of Motor (f_r), (Hz)</td>
<td>29.94</td>
</tr>
<tr>
<td>Frequencies of bearing faults in Hz calculated by equations (1)</td>
<td>162.2</td>
</tr>
</tbody>
</table>

Figures (2) and (3) represent respectively the vibration signals of normal state, inner races fault.

### III. Fault Diagnosis Methods

Many signal processing techniques have been proposed in literature for machinery fault diagnosis. These techniques can be classify as, signal processing based on time domain signal, frequency domain signal and time–frequency domain signal. Each technique is having some advantages and some limitations over each other. We present in this section some signal processing methods appropriate for bearing faults diagnosis.

#### A. Temporal analysis.

One of the simpler detection approaches is to analyze the measured vibration signal in the time domain. This method based on the analysis of the vibration data as a function of time using several parameters or indicators such as peak value, peak to peak value, root mean square RMS, kurtosis, crest factor, impulse factor, shape factor and clearance factor [10-13]. Below is the equation for the crest factor:

\[
CRF = \frac{\text{Peak value}}{\text{RMS Value}}
\]

The equation of impulse factor is defined as:

\[
\text{Impulse Factor, IMF} = \frac{\text{Peak value}}{\frac{1}{N} \sum_{i=1}^{N} |x_i|}
\]

The equation for kurtosis is given by:

\[
\text{Kurtosis} = \frac{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^4}{\left(\text{RMS value}\right)^4}
\]

The temporal analysis of vibration signals of normal state, inner races fault are collected at speeds of 1797 rpm (30Hz) for 0-load (0 hp) using the following indicators: impulse factor, kurtosis, crest factor and shape factor, is shown in the Fig (4).
Fig. 4. Indicators values of vibration signals of normal state and inner races fault at 1797 rpm (30Hz) for 0-load (0 hp).

These indicators are simple to implement. Also, the computed indicator allows the tracking of any abnormal change in condition machine. But, the temporal analysis will not provide any information on which component is faulty. This method represents only a strategy of security.

B. Frequency analysis

Frequency analysis or spectral analysis is the most commonly used method for analyzing stationary signals whose frequency components do not change over time [10-13]. The spectrum $X(f)$ of a given signal $x(t)$ is defined by [10-13].

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi ft} dt$$ (5)

Where: $f$ is the signal frequency.

The spectrums of signal with bearing fault at 1797 rpm and 1730 rpm for inner races fault is shown in Fig (5). Obviously, it is difficult to identify the bearing fault, because the spectral analysis presents some limitations in the analysis of non-stationary signals. This inability makes the Wavelet transform (EA) alternative for machinery fault diagnosis.

C. Wavelet transform (WT)

Wavelet transform can be considered as a mathematical tool that converts a signal in time domain into a different form, it is describes a signal by using the correlation with translation and dilatation of a function called mother wavelet or wavelet function, which is a small wave, possesses oscillating wavelike characteristics and concentrates its energy short in time, is needed to implement the wavelet transform. The wavelet transform can be categorized as Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT), and Wavelet packet transform (WPT) [14-17].

The continuous Wavelet Transform (CWT) of a given signal $s(t)$ is defined by [14-17]:

$$CWT(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} s(t) \psi^*(\frac{t-b}{a}) dt$$ (6)

Where, $\psi^*(t)$ is the conjugate function of the mother wavelet $\psi(t)$. The terms $a$ and $b$ are the dilation and translation parameters, respectively.

The Discrete Wavelet Transform (DWT) is derived from the discretization of CWT $(a,b)$. It is given by [14-18]:

$$DWT(j,k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} s(t) \psi^*\left(\frac{t-2^j k}{2^j}\right) dt$$ (7)

Where, $a$ and $b$ are replaced by $2^j$ and $2^j k$.

The DWT, consists of the introduction of the signal to be analyzed into low-pass and high-pass filters, see Fig.5. At this level, two vectors will be obtained. The vector elements $A_j$ are called approximation coefficients; they correspond to the lowest frequency signal, while the vector elements $D_j$ are called detail coefficients; they are corresponding to the highest of them. The procedure can be repeated with the elements of the vector $A_j$ and successively with each new vector obtained. The decomposition process can be repeated $j$ times, with $j$ the maximum number of levels [14-18].

The principle of The DWT is shown in Fig 6.

Wavelet packet transform (WPT) decomposes not only the approximation coefficients but also the detail coefficients [14-17]. In Fig. 7, an example of a wavelet packet decomposition tree of three levels is illustrated. The sampling rate of the signal

![Fig.6. Procedure of decomposition by DWT.](image-url)
The frequency sub-band at each node of the wavelet packet tree is shown in Fig.7.

Fig.7. Wavelet packet tree

A split on detail coefficients leads to change in basis set and these basis sets are called wavelet packets. Wavelet packets are a collection of functions given by [18]:

\[ \{ 2^{j/2}W_n(2^{-j}t-k), n \in \mathbb{N}, j,k \in \mathbb{Z} \} \quad (8) \]

Above function is generated from the following sequence functions:

\[ W_{2n}(t) = \sqrt{2} \sum h_i W_n(2t-i) \quad (9) \]

\[ W_{2n+1}(t) = \sqrt{2} \sum g_i W_n(2t-i) \quad (10) \]

The original signal, packets (4, 0) coefficients and its spectrums of inner race faults are shown in Fig.8 and Fig.9.

From Fig.8 where a motor speed of 1797 rpm and a motor load of 0 HP are considered, the impact repetition frequency at 162 Hz and its second harmonic at 324 Hz can be clearly recognized. The frequency 162 Hz is very close to calculated Frequencies of Inner Race Fault at 162.2 Hz as listed in table 1. Hence, the fault is identified as Inner Race Fault IRF.

From the Fig 9, where a motor speed of 1730 rpm and a motor load of 3HP are considered, the impact repetition frequency at 156 Hz and its second harmonic at 312 Hz can be clearly recognized. The frequency 156 Hz is very close to calculated Frequencies of Inner Race Fault at 156.13 Hz as listed in table 1. Hence, the fault is identified as Inner Race Fault IRF.
The identification of the bearing faults is possible by using the wavelet packet transform (WPT). The experimental result has been shown that wavelet packet transform (WPT) can effectively diagnose the bearing faults.

IV. CONCLUSION

A bearing-fault detection method based on wavelet packet transform (WPT) is presented in this paper. After this study, the following points are concluded.

1. The temporal analysis allows the tracking of any abnormal change in condition machine. But, the temporal analysis will not provide any information on which component is faulty. This method represents only a strategy of security.

2. The identification of the bearing faults by using spectral analysis is difficult because, it is not suitable for non-stationary signal analysis.

3. The identification of the bearing faults is possible by using the wavelet packet transform (WPT). The experimental result has been shown that wavelet packet transform (WPT) can effectively diagnose the bearing faults.

Our future studies will implement this method on a signal containing other types of faults.