Fault Diagnosis of Roller Bearings Using the Wavelet Transform

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Abstract: Ball bearings are perhaps the most widely used machine elements and a lot of important and expensive mechanic systems are based on them. Thus, it is necessary to establish a method to detect faults in order to keep the systems running properly. Fault identification of rolling element bearings employing condition monitoring techniques has been the subject of extensive research for the last two decades. Vibration signals of machines provide the dynamic information of the machine condition taking into account the fact that whenever the rolling element encounters a defect, a short duration impulse is generated. These signals are very useful for fault diagnosis. In this paper, the Fast Fourier Transform (FFT) is initially employed for a first comparison between healthy and defective bearings. Then, the main signal analysis is performed using the Wavelet Transform Method (WTM) which proves very effective in problems of this type.

Keywords: Bearings, Vibration, FFT, Wavelet.

1. INTRODUCTION

Impulses are generated due to the motion of rolling elements. It is well established that defects on bearings generate impulses observed as extra frequency components in a Fast Fourier Transform (FFT) generated spectrum. Consequently, these signals cannot be considered as strictly periodic, but rather as cyclo-stationary. Taking these into account, bearing defects are very difficult to detect employing conventional FFT [3]. Therefore, a wavelet based method is considered; it gives more effective results, as wavelet transform (WMT) provides powerful multi-resolution analysis in both time and frequency domains [2].

Ball bearing failures can be caused by several factors, such as incorrect design or installation, acid corrosion, poor lubrication and plastic deformation [4]. Faults as outer race, inner race, ball defect and cage defect, generate frequency components of specific characteristics, depending on the inner diameter, the outer diameter of the bearing, the frequency that the machine and the axis rotates, the number of the balls and the touch angle.

In this study, multiple defects [6-9] are imposed since a ball was hit in a random way. Therefore, a number of extra frequency components are expected to be observed in an FFT produced spectrum. Consequently, a healthy ball bearing is initially used and an electrical motor driven shaft rotates on it. The vibration signals are obtained for a period of 180 s via an accelerometer they are sampled and analyzed both by FFT and WTM. Then, the bearing is uninstalled, a ball is traumatized at random, it reassembled and it is tested employing an identical procedure as before. Then, the results of both analyses are compared. The experiment is repeated many times to ensure the statistical error minimization.

2. WAVELET TRANSFORM

The wavelet transform (WT) [1,5] is a method of converting a function (or signal) into a different form; it either makes certain features of the original signal more amenable to study or enables the original data set to be described more succinctly. A wavelet is a function satisfying certain mathematical criteria. There is a large variety of wavelets to choose from; in this study Mexican hat and Morlet wavelets were used.

The Mexican hat wavelet is described as:

$$\psi(t, b) = \left[1 - \left(\frac{t - b}{\alpha}\right)^2\right] e^{-1/2(t-\frac{b}{\alpha})^2}$$ (2.1)

whereas, the general equation of wavelet transform is:

$$T(\alpha, b) = \frac{1}{\sqrt{\alpha}} \int x(t) \psi^\ast \left(\frac{t-b}{\alpha}\right) dt$$ (2.2)

where:

* denotes complex conjugation

$1/\sqrt{\alpha}$ is set for reasons of energy conservation (i.e. it ensures that the all wavelets, at every scale, have the same energy).

$\alpha$ and $b$ are dilation and location parameters respectively.

In (2.2) the transformed signal $T(\alpha, b)$ is defined on the $a$-$b$ plane, where $\alpha$ and $b$ are used to adjust the frequency and time location of the wavelet in Eq. (2.1); a small $\alpha$ produces a high-frequency (contracted) wavelet, when a high temporal resolution is required, whereas a large $\alpha$ produces a low-
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frequency (dilated) wavelet whenever high frequency resolution is sought for.

For a specific scale, and for a specific \( \alpha \) the wavelet is moving to different locations i.e. to different positions, along the signal. Consequently, the W.T. finds its components related with the signal structures in various scales. In fact increasing \( b \) along the signal we calculate the W.T. using (2.2) for a large number of \( \alpha \). Thus, we find all signal components.

\[
\psi(\frac{t-b}{\alpha}) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0(t-b)/\alpha} e^{-1/2[(t-b)/\alpha]^2}
\]  

(2.3)

In this analysis two different wavelets, one real (Mexican hat) and one complex (Morlet), were chosen to show that results are independent of the wavelet selection. However, the use of these specific wavelets, due to their similarity [8], made the comparison and the conclusions easier and more reliable.

3. EXPERIMENTAL SETUP

The experimental setup (figs 1 and b) consisted of a shaft rotating through two single line ball bearings (type 6302), driven by a variable speed electric motor controlled by an inverter. An accelerometer was connected very close to the bearings and the electrical signals generated by it was digitized and fed to a laptop. Data collection and the subsequent signal processing were performed using Matlab.

4. SIGNAL PROCESSING – RESULTS

The sampling rate was set to 65536 Hz whereas the duration of each sampling was 180 s. FFT was applied in the time series obtained by both health and defective bearings. As it can be seen (fig 3) several extra peaks can be observed in the spectra corresponding to the defective bearings when they are compared to those of the healthy ones. These frequency components are to be identified at the bands around 15.0 kHz and 22.5 kHz. In fact, there are no similar peaks to be identified in the spectra corresponding to the healthy bearings.

![Fig. 1 a) Mexican hat wavelet b) Morlet wavelet](image1)

A simple form of a Morlet wavelet (fig 1.a) is given by:

![Fig. 2a) Experimental setup](image2)

![Fig. 2b) Diagram of the experimental setup](image3)
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This is what makes the selection of the a-parameter employed in the wavelet easy. Then, the continuous wavelet transform focuses on the specific band.

In fact, according to wavelet theory, for a Mexican hat wavelet, the $\alpha$ scale is required to be roughly a quarter of the period $p$ to accentuate possible signal defects. Consequently, for 22500Hz, $\alpha$ must equal $1.11 \times 10^{-5}$. In this work $\alpha$ was set in the range between $10^{-5}$ and $5 \times 10^{-4}$ [1]. Consequently,

$$f = 1/(4\alpha) \quad (4.1)$$

In figures 4a, 4b, 4c and 4d, the vertical axis of the upper plot represents the amplitude of the acceleration in m/s$^2$ and the vertical axis of the lower plot represents the $\alpha$-parameter as described before.

Fig. 4a) Mexican hat CWT for healthy bearing 1

Fig. 4b) Mexican hat CWT for defective bearing 1

Fig. 4c) Mexican hat CWT for healthy bearing 2

Fig. 4d) Mexican hat CWT for defective bearing 2
The horizontal axis in all cases represents the number of the samples. Thus, the time can be found multiplying the individual number with $1.525879 \times 10^{-5}$. For example, the $10^5$ sample is equal to $10^5 \times 1.525879 \times 10^{-5} = 15.255879$ s.

The differences in this spectrum are clear. For the healthy bearings (figs 4a-b) CWT is everywhere zero, contrary to the defective ones (figs 4c-d) where extra frequency components are to be observed in this band.

5. CONCLUSIONS

In this study, a wavelet based method for roller fault diagnosis has been presented.

Wavelet transform offers the possibility to detect specific faults on a roller bearing, such as faults in cage, rolling balls and inner and outer ring. Since the frequency of these is expected to be in a known band, the diagnosis could be done by selecting the proper value for the $\alpha$-parameter which is directly connected with the frequency, as referred above.

The advantage of this method is the safe discrimination between the healthy and the faulty roller bearings using a low cost test procedure cost application.

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