Application of Wavelet Transform To Gearbox Fault Diagnosis

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Abstract

The use of gearboxes is quite common in industry. Typical applications are in large electrical utilities, automotive industries, ships and helicopters. Effective gear diagnostic techniques can improve the operability and availability of the equipment. Many of the tools currently in use for the diagnosis of gearbox faults are based on gear vibration signal. Recently researchers have begun to pay their attention to wavelet transform (WT) to utilize its unique features in machinery diagnostics. This paper considers wavelet transforms to detect the local faults of gear transmission systems. Experimental studies conducted on the gearbox include healthy gear and faulty gear with gradual removal of tooth. The gearbox was operated at constant speed and load. Results show that wavelet transform serves as a good visual inspection tool to determine fault severity.

Introduction

Monitoring the condition of large gearboxes in operating industries has attracted increasing interest in recent years owing to the need for decreasing the downtime on production machinery and for reducing the extent of secondary damage caused by failures. Typically, vibration signals collected from a gearbox have a low signal to noise ratio (SNR), especially when faults occurring in the gearbox start propagating. Vibrations generated by large structural components and noises often mask fault-related vibration signals generated by the smaller gears making it difficult to identify the fault related features (Lai Wuxing *et al.*, 2004). On the other hand, it is known that local faults in gearboxes cause impacts, as a result of which transient excitations may be observed in the vibration and acoustic signals. In the presence of growing local faults, the vibration and acoustic signals from gearboxes have non-stationary characteristics. Such signals can be analyzed by time frequency or time scale (wavelet) methods. Short time Fourier transform (STFT) is a classical time frequency technique and some gear faults can be detected by inspecting the energy distribution of a signal over the time frequency space (Meltzer and Yuye Inanov, 2002; Oelhmann *et al.*, 1992). Recent advances in wavelet transform (WT) have provided a very powerful tool for gear damage diagnosis. In contrast to STFT, WT uses a narrow time window at high frequencies and wide window at low frequencies making it highly suitable for analysis of transient and non-stationary signals. Most of the research works reported in literature, which are based on the time frequency distribution, were conducted when the fault conditions were severe in the gearboxes. Besides, most of these studies have been conducted on a spur gear in which the fault condition easily gets reflected in the Fast Fourier technique (FFT) based spectrum of the vibration signal due to the low contact ratio. However due to the large contact ratio in a helical gear, fault conditions are weaker in the vibration signal. Consequently, it becomes a more difficult task to detect features at a very early stage. This paper considers wavelet transforms to detect the local faults of gear teeth in gear transmission systems. Experimental studies conducted on a gearbox include good gear and gears with gradual removal of tooth surface (along the depth) in various stages. The studies have been conducted at constant speed and load. The results prove the effectiveness of wavelet transforms in fault detection in a gear transmission system and in determining the severity of faults.

The Continuous Wavelet Transform (CWT)

The presence of a crack in one tooth introduces short duration changes in the vibration signal. On the contrary, more distributed faults (e.g. gear mesh faults, geometrical imperfections in the gear train and

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uniform wear) introduce "slow" modification of the signals over the gear train revolution period. For advanced faults, time domain technique may be sufficient to detect the damage, but the early detection of defects requires more sophisticated signal processing methods. The non-stationary nature of the signal suggests the use of time-frequency techniques, which makes it possible to look at the time evolution of the signal's frequency content (Dialpiaz *et al., 2000*). Such methodologies have been reported in literature (Staszewski and Tomlinson, 1997; Baydar and Ball, 2003; Isa Yesilyurt, 2003). Wavelet transforms are localized equivalents of the Fourier transform, which provides a powerful tool for presenting local features of a signal. Fourier transforms move data from the time domain to frequency domain with sines and cosines as the basis functions and give the average characteristics of the signal, whereas wavelet transforms move the data from space to a scale domain with wavelets as the basis function giving the localized features of original signal (Keith Worden, 1997).

The continuous wavelet transform $W_x(t,a)$ of signal x(t) is defined as convolution integral of x(t) with the dilated version of the mother wavelet function w(t):

$$W_x(t,a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(\tau).w\left(\frac{t-\tau}{a}\right) d\tau \qquad (1)$$

where $a = f/f_o$ is the scale parameter. The frequency f_0 is the lowest frequency of interest, i.e. $f_0 = 1/T$. In the present study complex Morlet wavelet is used and is defined as

$$w(t) = \exp\left\{-\frac{1}{2}\frac{t^2}{b^2}\right\}\exp\{i\omega_c t\} \qquad (2)$$

Here 6b = $5.336/f_c$ is the 'effective support' of the wavelet and $\omega_c = 2\pi f_c$ is the circular frequency. When the signal x(t) is periodic, equation (1) becomes a circular convolution and the CWT is better calculated in the frequency domain according to the equation

$$w_x(t,a) = \frac{1}{\sqrt{a}} F^{-1}[X(w)aW(a\omega)] \qquad (3)$$

with X(ω) and aW (aω) being the Fourier transform of the time synchronous signal x(t) and dilated wavelet W(t/a), respectively. The operator F^{-1}[.] denotes inverse Fourier transformation.

Experimental Investigation

Figure 1 shows the experimental set up. It consists of a 5 HP two stage helical gearbox driven by a 5.5 HP 3-phase induction motor running at 1200 rpm. The mechanical output of the gearbox is used to drive a D.C generator and the power output of the generator is dissipated in a resistor bank, which provides torque load to the generator and gearbox. This arrangement does not lead to any additional vibration in the test rig. The motor, gearbox and generator are mounted on stiffened I-beams, which are anchored to a massive concrete block. A piezo-electric accelerometer B&K 4332 is stud-mounted to measure the vertical vibration signals generated on the bearing housing. An eddy current probe was used to get time synchronous data. Meshing gear frequencies have been calculated to be 320 Hz and its multiples. Different data sets were collected when the helical gear train was working at 0%, 10%, 20%, 40%, 60%, 80% and 100% tooth removal conditions [Wilson *et al.*, 2001, and Baydar and Ball, 2003]. A total of 30 data sets was collected for each operating condition. The signals were truncated to 3 kHz using a low pass filter and sampled at 8 kHz. The accelerometer outputs were conditioned using B&K 2626 charge amplifier. The sampled signals were then processed using MATLAB.

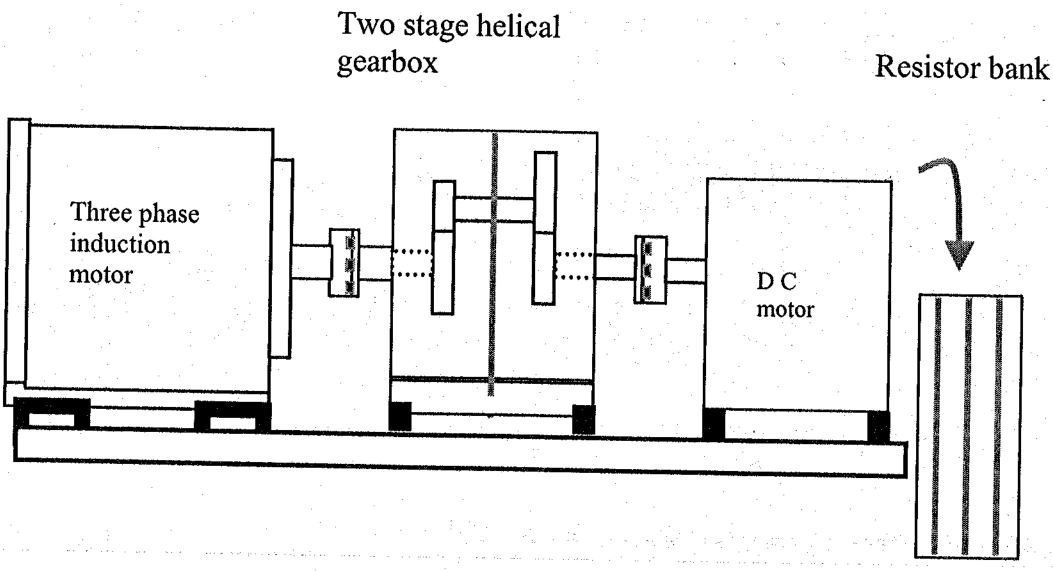

Figure 1. Experimental setup of two stage helical gearbox

Results and Discussion

A pair of healthy gears was installed in the test rig and the vibration data were collected and processed. The frequency range analyzed was 0-1600 Hz and this includes the important gear meshing harmonics in the experimental data. Typical time synchronous averaged vibration signals and spectra for healthy gears are shown in Figures (2a) and (2b) and those for gears with 20% and 100% tooth removal are shown in Figures (3a), (3b) and (4a) and (4b) respectively. Representative wavelet plots of magnitude and phase for healthy gear and gears with 20% and 100% fault are shown in Figures 5, 6 and 7 respectively. In order to appreciate this influence quantitatively, the wavelet coefficients have been plotted in Figures 8 to 10. Figure 8 shows the wavelet coefficients at the first gear mesh frequency (320 Hz) over one full rotation for different degrees of fault (0 to 100%). One can see distinct peaks around 180° correlating with the presence of fault at that location. Similar data are shown in Figures 9 and 10 for the second and third gear mesh frequencies. These figures also indicate the presence of fault around 180° as a function of increase in wavelet coefficients. The influence of faults on wavelet coefficients for different angular positions of the gear is shown in Figure 11. Figures 12-14 show variations in wavelet coefficients with various severity of fault at 180^0, 120^0, and 240^0 respectively. Comparing this with Figures 2b, 3b and 4b, one can conclude that wavelet coefficients are more sensitive to gear faults than spectral peaks at corresponding gear mesh frequencies.

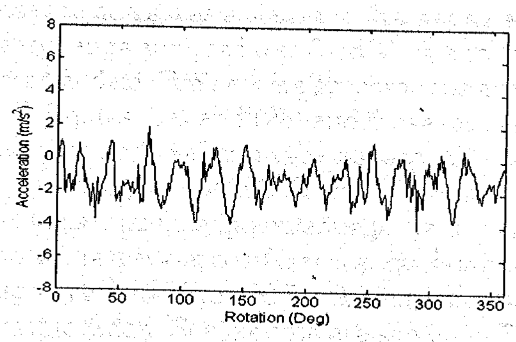

Figure 2. (a) Time synchronous average - healthy gear

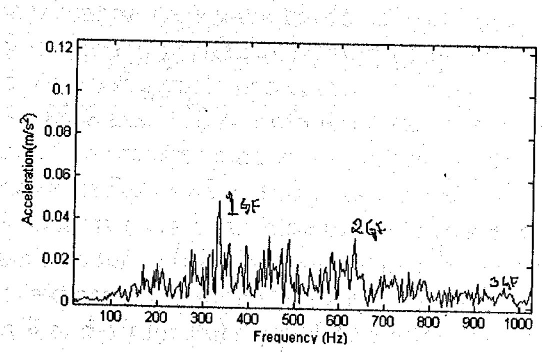

Figure 2. (b) Spectrum - healthy gear

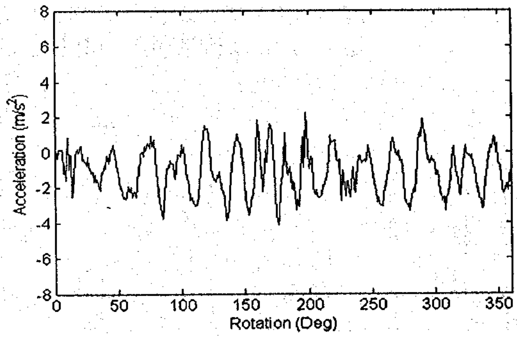

Figure 3. (a) Time synchronous average - 20% tooth removal

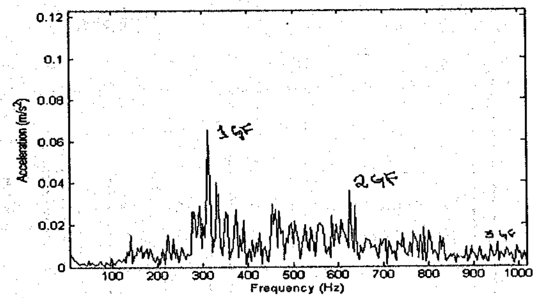

Figure 3. (b) Spectrum - 20% tooth removal

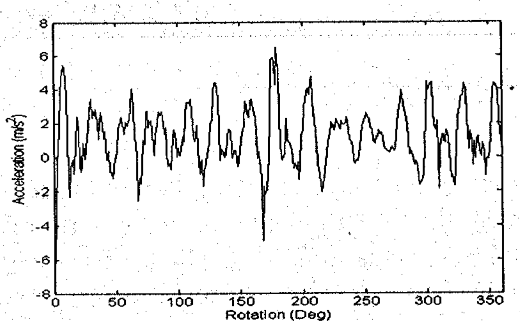

Figure 4. (a) Time synchronous average - 100 % tooth removal

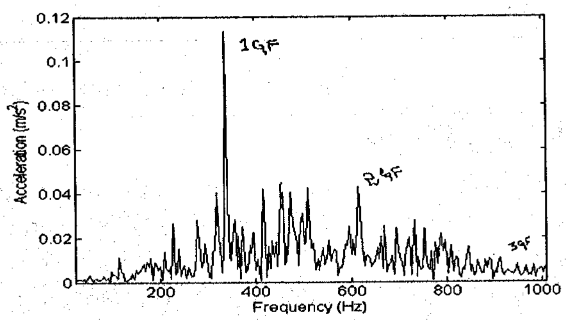

Figure 4 (b) Spectrum - 100% tooth removal

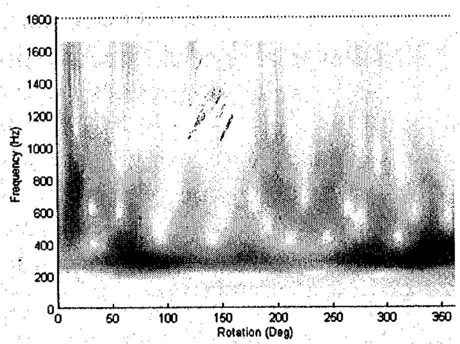

Figure 5. (a) Wavelet magnitude -healthy gear

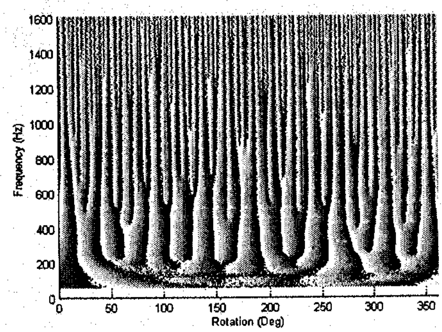

Figure 5. (b) Wavelet phase -healthy gear

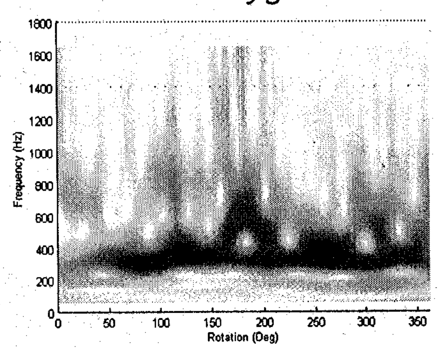

Figure 6. (a) Wavelet magnitude - 20% tooth removal

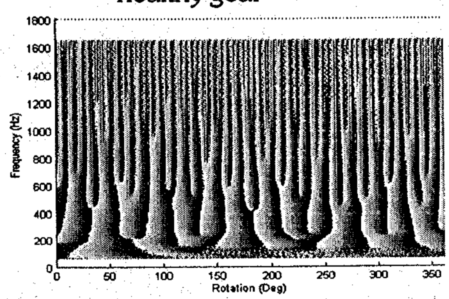

Figure 6. (b) Wavelet phase - 20% tooth removal

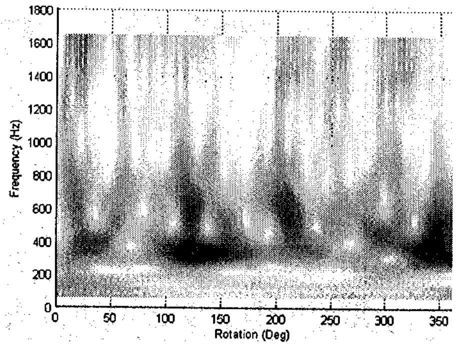

Figure 7. (a) Wavelet magnitude -100% tooth removal

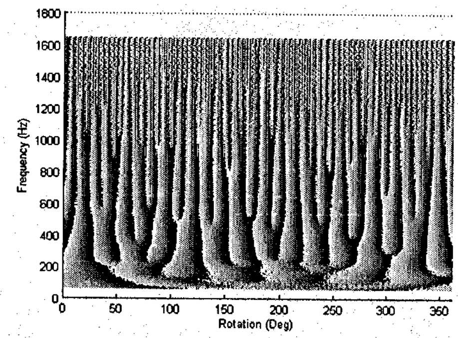

Figure 7. (b) Wavelet phase - 100% tooth removal

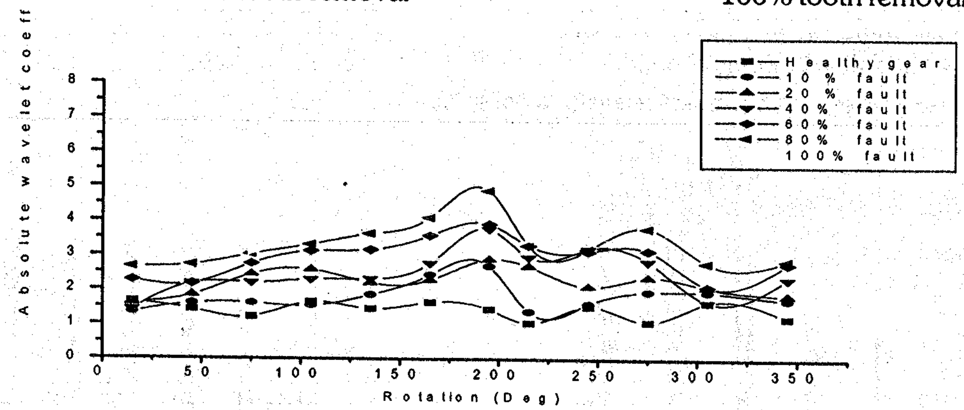

Figure 8. Magnitude of wavelet coefficients at first mesh frequency

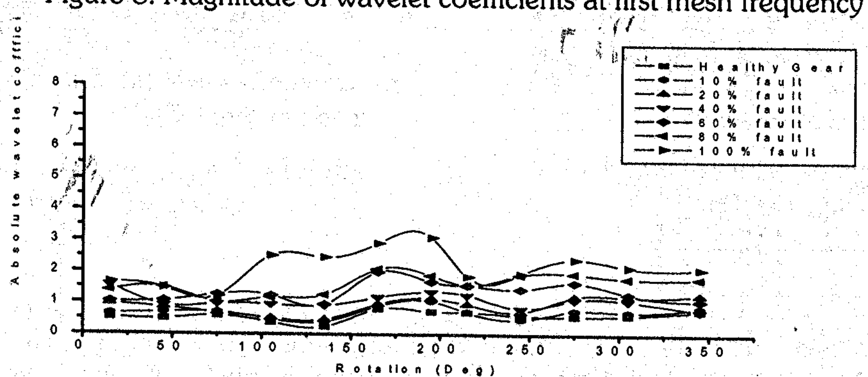

Figure 9. Magnitude of wavelet coefficients at second mesh frequency

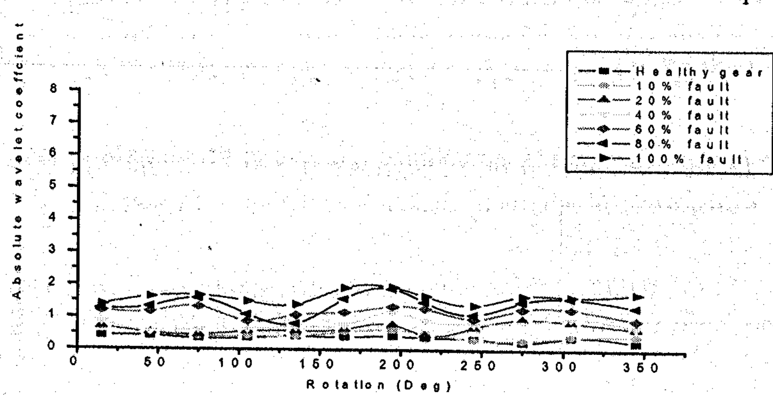

Figure 10. Magnitude of wavelet coefficients at third mesh frequency

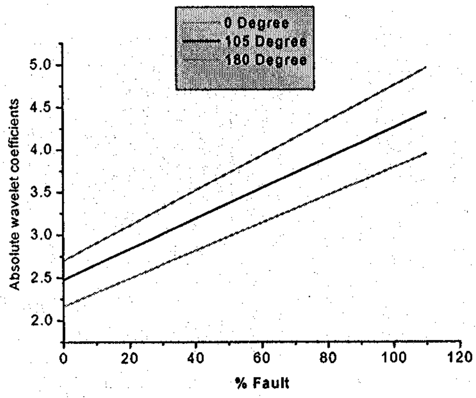

Figure 11. Effect of faults on wavelet coefficients for different angular positions of gear

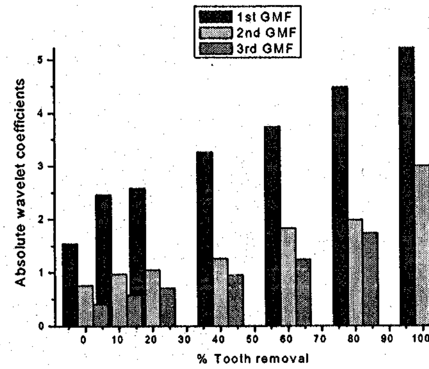

Figure 12. Average values of wavelet coefficients vs. fault at 180^0

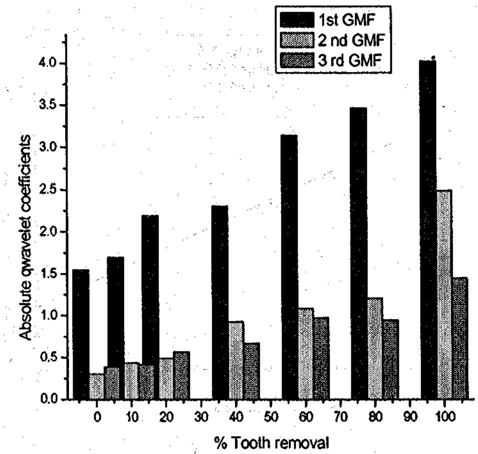

Figure 13. Average values of wavelet coefficients at 120^0

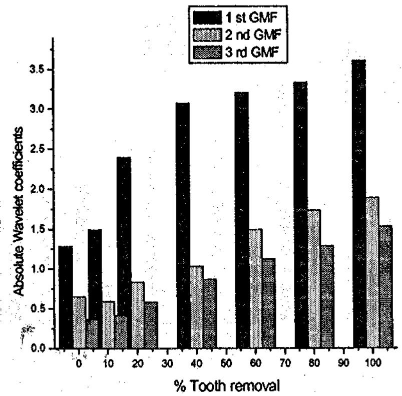

Figure 14. Average values of wavelet coefficients at 240^0

Conclusions

This study shows that the continuous wavelet transform technique is a promising tool for the detection of developing faults in gears. This technique reveals transient vibration signals for defect conditions varying from 10% tooth fault to one complete tooth removal. Phase maps are a little difficult to interpret, but when used in conjunction with amplitude maps provide details of growing faults at mesh frequency zones. On the other hand fault quantification using absolute wavelet coefficients of magnitude wavelet maps provides better representation of fault growth.

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