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GEARBOX FAULT DETECTION BY MOTOR CURRENT SIGNATURE ANALYSIS

A. R. Mohanty

Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur
Kharagpur, 721 302
INDIA
amohanty@mech.iitkgp.ernet.in

Abstract

In this paper the results of an experimental study on fault detection in a gearbox using motor current signature analysis is presented. Broken teeth and teeth wear have been artificially introduced in the gears as faults. Signal processing techniques like the multiresolution fourier transform (MFT) has been used for feature extraction from the current signals drawn by the induction motor driving the gear box. The present technique is able to detect faults at very low loads on the gearbox, where the modulation index is very low. Such a technique can be used to successfully detect faults in many rotating machines.

1. INTRODUCTION

Vibration monitoring has been a traditional technique used for health monitoring of gearboxes. Staszewski et al. [1]; in a series of articles; have classified defects in gears into three categories, viz. tooth breakage (loss of total or part of tooth), cracked tooth and surface wear. While studying spur gears, they have investigated a severe case of tooth breakage i.e. two teeth broken in spur gears. Aatola & Leskinen [2] have diagnosed three teeth breakage in spur gears with an over-loading of 150%. Byder and Ball [3] have experimented with a 2-stage helical gearbox to find tooth breakage and root crack (with severest root crack of 4mm) by analyzing the vibration signatures using wavelet transform. Along with one tooth, the adjacent tooth was broken to 50-100% in their experiments. Zheng et al. [4] have investigated vibration signatures of an automotive transmission gearbox with the severest breakage of teeth i.e. 5 numbers of teeth are broken with first tooth 0% and last tooth 100% broken. Root crack of gear tooth has also been studied by Wang & McFadden [5], Stander et al. [6] with severest crack of 3mm, Wang [7] with a crack dimension of $2\text{mm} \times 0.1\text{mm} \times 1\text{mm}$, and Dalpiaz et al. [8] with a crack of 20-45% of fracture line. Surface wear has been investigated by Stander et al. [6]. Besides these, diagnosis of spalling and pitting has been discussed by Wang & McFadden [9], and Badaoui et al. [10]. In Ref. [11], these authors have considered one tooth breakage and two consecutive teeth breakage in an automotive transmission helical gearbox. Since, in the present study there were three stages of gears under syncho-meshed condition, and 2-3 numbers of lines of contact in helical gears at each stage, these defects were not severe enough to investigate the vibration or current signatures. Moreover, the gearbox was operated with under-rated load such as 5.625 kW load whereas the rating of the gearbox was as high as 37 kW. Signal processing techniques used in analyzing vibration signals for gearbox fault diagnosis are wavelet transform [1,3-5,8,11], short time fourier transform (STFT) [9], wigner-ville distribution [6], cepstrum analysis [2,8,10], and demodulation [7]. Dalpiaz et al. [8] have compared some of these techniques and opined the wavelet transform as the best technique to enhance fault detection capability in a gearbox.

Literature review of motor current signature analysis can be found from Ref. [11]. These authors [11] have analytically found that any frequency present in the vibration signature is observed to be having sidebands across supply line frequency in the current signature at steady loads. Experiments with a multi-stage gearbox also confirmed this phenomenon. It is also inferred that detecting tooth breakage in a helical gear at an early stage is possible while monitoring current signals, i.e. one tooth breakage in 2nd gear of the helical gearbox is severe than two teeth breakage in the same gear.

Here, the objective is to apply multiresolution fourier transform (MFT) to vibration and current signals for monitoring the health of the multi-stage automotive transmission helical gearbox; described in Ref. [11]. The procedure adopted in the paper is as follows;

1. Three numbers of artificial defects are introduced in the 2nd gear;
2. DWT is applied to the vibration signatures, and a particular DWT level is chosen that contains information of gear mesh frequencies;
3. MFT is applied to this level to distinguish the faults;
4. Steps 2 to 3 are repeated for current signatures, as well.

2. THEORY

2.1 Motor Current Signature Analysis

For an ideal operating condition of the induction motor, the current signature is a sinusoidal waveform with supply line frequency of 50 Hz. With the introduction of defects, sidebands of the defect frequencies across the supply line frequency appear in the current spectrum. These defects may be rotor eccentricity and broken rotor bar in the induction motor, or different defect frequencies of rolling element bearings [12], or different rotating or gear mesh frequencies of multi-stage gearbox [11]. In any phase, current drawn by the induction motor (I_s) will reflect the defect frequencies as given in (1) [11], where f_i is the i-th defect frequency with n-number of defect frequencies, f_e is the supply line frequency, A_{sT} and A_{sM} are torque producing and magnetizing components of current respectively, I_0 is the average current drawn by the supply line frequency, and ϕ_0 and ϕ_i are the phase difference for f_e and f_i respectively.

$$\begin{aligned} I_s = {} & I_0 \sin\left(2\pi f_e t + \phi_0\right) + \\ & \sum_{i=1}^{n}\left(\frac{A_{sT_i} + A_{sM_i}}{2}\right)\cos\left(2\pi\left(f_e - f_i\right)t - \phi_i\right) + \\ & \sum_{i=1}^{n}\left(\frac{A_{sT_i} - A_{sM_i}}{2}\right)\cos\left(2\pi\left(f_e + f_i\right)t + \phi_i\right) \end{aligned} \tag{1}$$

For rotor eccentricity and broken rotor bar, the sidebands will depend upon the slip (s) and number of poles (p) of the induction motor with the following expressions [12].

$$f_{ecc} = f_e\left[1 \pm m\left(\frac{1-s}{p/2}\right)\right]; \text{ and} \tag{2}$$

$$f_{brb} = f_e \left[k \left(\frac{1-s}{p/2} \right) \pm s \right] \tag{3}$$

where f_{ecc} and f_{brb} are frequencies due to rotor eccentricity and broken rotor bar, m and k are integers.

2.2 Discrete Wavelet Transform

Discrete Wavelet Transform, also known as multi-resolution analysis, uses orthogonal wavelets such as wavelets of Daubechies series for decomposing the signal into different frequency bandwidth. This is equivalent to passing the signal through a high pass filter and then down-sampling to produce high frequency octaves known as 'Details', and a low pass filter and down-sampling to produce a low frequency signal known as 'Approximate'. The approximate can again be decomposed into another Approximate and Detail. The number of decomposition is known as levels. Reconstruction of the signal from details and last level approximate is governed by the following expression.

$$x = A_J \oplus D_J \oplus D_{J-1} \ldots \oplus D_1 \tag{4}$$

where J is the level of decomposition, A_i and D_i are Approximate and Detail at i-th level respectively. The advantage of DWT is that frequency bandwidth of each level will be devoid of any interference of those from other levels. Moreover, better signal to noise (SNR) can be obtained. A DWT tree showing the levels of decomposition, approximates and details with frequency bandwidth is shown in Fig. 1. An orthogonal wavelet of 'Daubechies 8' is used in this paper.

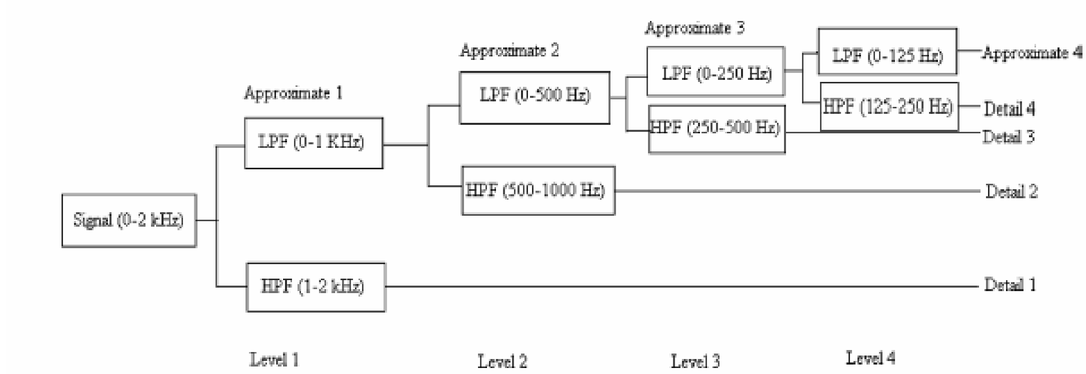


Fig. 1. DWT tree for decomposition of current signals.

2.3 Multiresolution Fourier Transform

MFT combines the characteristics of STFT and WT by convolving a moving window with the signal at a particular scale. The size of the basic analysis window depends upon the scale parameter. Equation (5) is used to evaluate coefficients of MFT [13], where the scaled window is given by Equation (6). If the scale parameter 'a' is reduced, a longer window will result, consequently the temporal resolution is reduced and frequency resolution is improved. Increasing the value of 'a' will result in improving the temporal resolution.

$$\hat{x}(t,f,a)=\int_{-\infty}^{\infty} w_a(t-\tau)\,x(\tau)\,e^{-i2\pi f\tau}d\tau \tag{5}$$

$$w_a(t)=\sqrt{a}\,w(ta) \tag{6}$$

Where $\hat{x}(t,f,a)$ refers to MFT coefficients, *w(t)* and $w_a(t)$ are the mother and scaled window respectively. If a single window is applied to the whole time-record, then MFT will be equivalent to FFT of that scaled signal, and if the window is moved through out the time-record with some overlapping, then MFT will be equivalent to STFT of the scaled signal.

The conventional MFT uses non-orthogonal window for which it becomes equivalent to CWT, thus the two limitations; such as redundant coefficients and large computation time; arise. Therefore, in this paper, a corrected MFT is used for classifying the gear defects. Rather than using the same window for scaling the signal, DWT with 'Db8' wavelet is used to scale the signal. Then a hanning window with 256 number of data points and 50% overlap is applied to the scaled signal to find the MFT coefficients. In Ref. [11], MFT with constant window (equivalent FFT analysis) has been referred as combined DWT and FFT analysis.

3. EXPERIMENTAL SETUP

The same experimental set-up used in Ref. [11] is used in the present study. An automotive transmission gearbox is chosen in the experiment because of three reasons. First, a number gears (2nd, 3rd and 4th) are under synchro-meshed condition, thus making the diagnosis process very intensive. Second, a large contact ratio in helical gears gives rise to 2-3 numbers of lines of contact, thus removal of one or two teeth in any one gear will not affect the performance. Third, simultaneous presence of no load and full load makes monitoring process difficult. For example, at 2nd gear operation, power flows from 4th gear to 2nd gear, but the 3rd gear rotates freely as illustrated in Fig. 2. Moreover, the gearbox is operated with a maximum load is 5.625 kW whereas the rating of the gearbox is of the order of 37 kW. The rotating shaft frequencies such as input shaft frequency (f_1), lay shaft frequency (f_2) and output shaft frequency (f_3) are of the order of 49 Hz, 30 Hz and 20 Hz. Gear mesh frequencies (GMFs) in 2nd, 3rd and 4th gears in the gearbox are of the order of 630 Hz, 780 Hz and 930 Hz respectively. Types of artificial defects introduced in the gearbox are given in Table 1. 8192 number of data points were acquired at a sampling frequency of 4.096 kHz. Only one case of steady load conditions i.e. 5.625 kW and 2nd gear operation is discussed in this paper. The analysis procedure comprises of DWT with an orthogonal wavelet of 'db8', and the corrected MFT (STFT for a particular level).

Table 1. Numbers of artificial defects introduced in gears

Sl.No.	Gear	Type of defect	Notation
1	-	No defect	d0
2	2nd gear (main)	1 tooth broken	d1
3	2nd gear (main)	2 teeth broken	d2
4	2nd gear (lay shaft)	2 teeth broken	d3

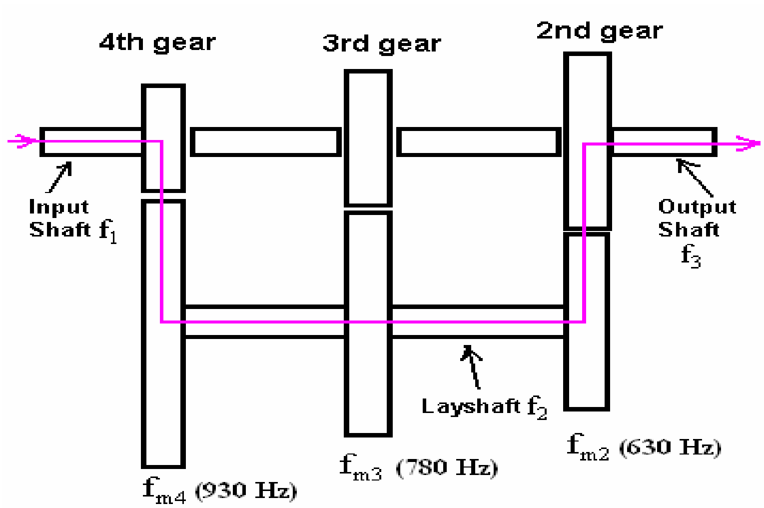


Fig. 2. Gearbox details showing various frequencies and power transmission during 2nd gear operation.

4. RESULTS AND DISCUSSIONS

4.1 Multiresolution Fourier Transform (MFT) of Vibration signatures

Vibration signals are decomposed into four levels using Discrete Wavelet Transform (DWT). The details at level 2 of the decomposed signal corresponds to 500-1000 Hz bandwidth, which contains information of all gear mesh frequencies (GMFs). MFT coefficients are found for this scaled signal for all load and defective conditions using a moving hanning window. Figure 3 illustrates MFT at 5.625 kW load and all defect conditions. Tooth breakage will lead to impact once in a rotation and hence the energy levels of the sidebands of the rotating shaft frequencies across gear mesh frequencies will increase. MFT maps these energy levels of sidebands around a particular GMF, indicating an overall energy contained in that GMF. The energy levels possessed by the sidebands of rotating shaft frequencies across 2nd GMF (f_{m2}) go on increasing with increase in severity of defect in 2nd gear [11]. In Figure 3a, i.e. for defect-free condition, 2nd GMF possess negligible energy in comparison to that of 4th GMF (f_{m4}). The reason can be attributed to the fact that 4th GMF, which is coupled to the induction motor, is the main energy carrier. But for d1 defective condition, i.e. one tooth breakage in 2nd gear, the 2nd GMF will have higher energy levels in its sidebands of rotating shaft frequencies. Hence the energy level around the 2nd GMF increases, as illustrated in Figure 3b. Even for d2 and d3 defective cases (illustrated in Figure 3c and Figure 3d), the energy possessed around 2nd GMF is much larger than that in 4th GMF. This phenomenon gives rise to a definite trend in the energy level possessed by 2nd and 4th GMF, which is helpful in classifying the type of defect introduced.

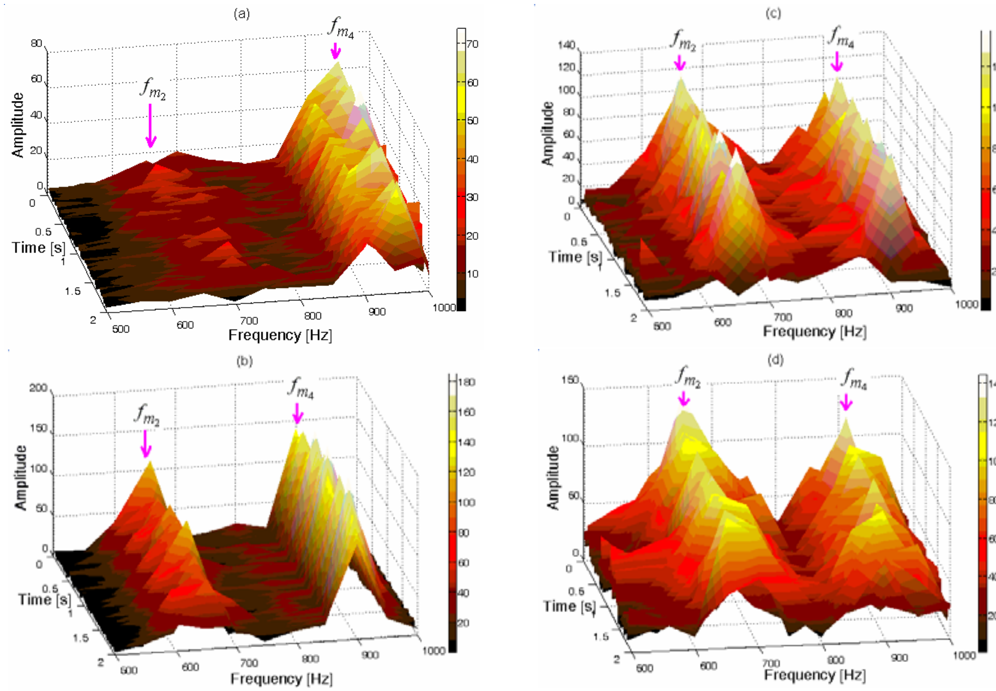
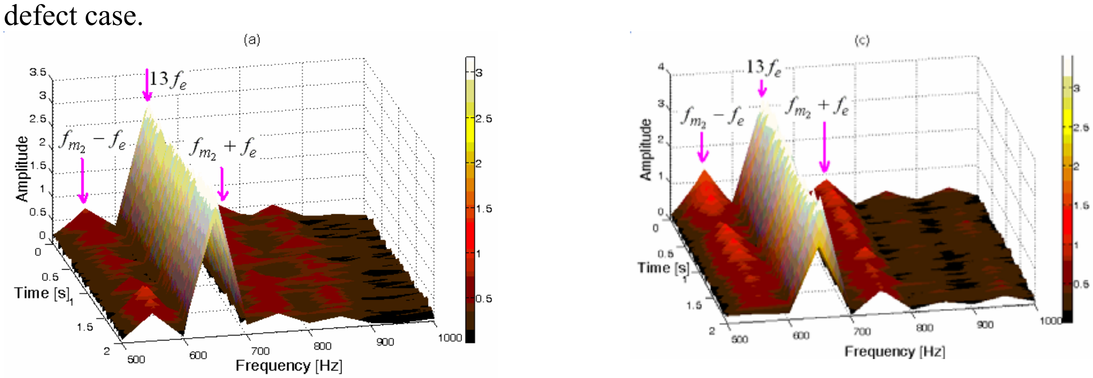


Figure 3. Multiresolution Fourier Transform (MFT) of vibration signatures at 'details 2' level; for 5.625 kW load and following defective conditions, a) d0; b) d1; c) d2; and d) d3.

4.2 Multiresolution Fourier Transform (MFT) of Current signatures

In Ref. [11], it is shown that FFT analysis is inadequate to trace the gear mesh frequencies in the current signatures, for which a combined DWT and FFT analysis is applied in order to separate out high frequency noise, and dominant supply line frequency and its harmonics. This combined DWT and FFT technique; which can also be termed as MFT with constant window; is very powerful in monitoring even amplitude of 1 mA current and can trace not only the gear mesh frequencies but also its sidebands of rotating shaft frequencies.

When MFT with a moving hanning window is applied to the details at level 2 of the current signal, the result for 5.625 kW load and all defective conditions is illustrated in Figure 4. It can be observed that 13th harmonics of the supply line frequency, ($13f_e$) is more predominant in the frequency bandwidth of 500-1000 Hz (Details 2) in the case of defect-free gears (Figure 4a), for d1 defective case (Figure 4b), energy is shifted to the left and right hand sidebands of 2nd GMF across supply line frequency (f_{m2}-f_e and f_{m2}+f_e). For d2 defective case (Figure 4c), this energy of the sidebands decreases. Therefore, the same inference drawn in Ref. [11] is obtained in this case also that d1 defect case can be diagnosed very early than d2 defect case.



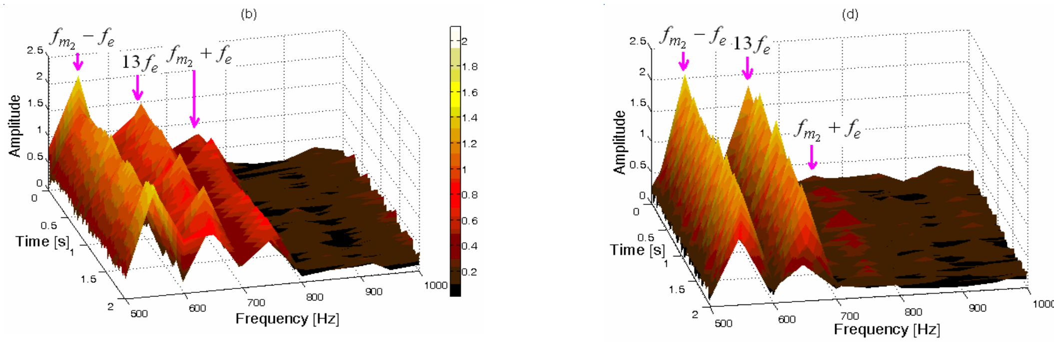


Figure 4. Multiresolution Fourier Transform (MFT) of decomposed current signatures at ‘details 2’ level for 5.625 kW load and following defective conditions, a) d0; b) d1; c) d2; and d) d3.

5. CONCLUSIONS

The paper proposed a new signal processing technique i.e. corrected Multiresolution Fourier Transform for health monitoring of a multi-stage gearbox. Both vibration and current signatures were analyzed in order to detect some artificially introduced defects in the gearbox. The corrected MFT advocated in scaling of the signal using Discrete Wavelet Transform (DWT) with an orthogonal wavelet of ‘db8’, then Short-Time Fourier Transform was applied to the level that contained information about gear mesh frequencies i.e. Details at level 2.

It is inferred that while monitoring vibration signatures, use of MFT will facilitate in classifying the types of defects by tracking the energy level possessed by the defect characteristic frequencies. It is found that for a defect-free gearbox, 4th GMF was dominant whereas with increase in severity of defects in the 2nd gear, 2nd GMF gradually dominates the 4th GMF. In case of current signatures, energy is confined to the 13th harmonics of supply line frequency for a defect-free gearbox. For defective gearbox, energy is smeared into the sidebands of 2nd GMF across supply line frequency. Early detection of defect is also possible as one tooth breakage in 2nd gear has more effect than the two teeth breakage in the same gear. Monitoring of current signatures is found to be very effective when applied along with MFT, and hence can be very useful in remote online health monitoring of a multi-stage gearbox.

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