Fourier and Wavelet Transform Features for Whirl Tower Diagnostics*

Scott Fornero[1], N. Kehtarnavaz[2], M. Swaminadham[3], and Don A. Phillips[4]**
[1,2] Department of Electrical Engineering
[3] Department of Engineering Technology and Industrial Distribution
[4] Department of Industrial Engineering
Texas A&M University
College Station, TX 77843-3128, U.S.A.

ABSTRACT

This paper describes the application of signal processing methods to extract key features for detection and prediction of faults in rotating mechanical components of a whirl tower test facility. Procedures will be described for processing the vibration signals from critical components of the whirl tower using the Fourier transform and the wavelet transform. The wavelet transform provides localization of signals in both time and frequency, revealing data that is averaged out in the Fourier analysis. The features extraction processes described are based on specific knowledge of the whirl tower equipment. The real-time analysis discussed will allow for scheduling of inspection, repair, or replacement of failed and degraded components with minimal impact on production.

1. Introduction

To date, only a few helicopter manufacturing companies have whirl tower facilities to spin and test new and/or refurbished rotor blades for structural integrity and dynamic balancing. Whirl tower, a spin test facility, is a production unit and its safe and reliable operation are important for the manufacturer. When used for defense purposes, the system availability will often affect national security. Therefore, the availability of such test systems has to be ensured by electronic monitoring devices and advanced signal analysis, and interpretation schemes. This paper describes how digital signal processing methods will detect and diagnose the condition of selected mechanical components of a large helicopter rotor blade test facility.

Signal processing can reduce complex data to feature vectors that can be used to classify the signals. Frequency analysis has been routinely used to diagnose the condition of mechanical components [3]. The frequency spectrum generated by applying the Fourier transform

$$F(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt \tag{1}$$

to time series data provides valuable information about the health of rotating mechanical equipment including gears and bearings. In order to observe time variant characteristics of a gear meshing vibration signal, Staszewski and Tomelson have proposed use of the wavelet transform [6].

$$W_{\Psi} f(b,a) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\Psi^{*}\left(\frac{t-b}{a}\right)dt \tag{2}$$

where $\Psi(t)$ is the wavelet function, a is the scaling factor, and b is the translation factor. The wavelet transform uses the scaling and translation factors to localize data in both frequency and time while the Fourier transform averages out time variant signals [1]. Knowledge of a system under study will facilitate the choice of appropriate features to be extracted by both techniques and this paper illustrates such feature selection.

2. Whirl Tower Equipment

The whirl tower described here has overall dimensions of 50 feet diameter and 40 feet height. This three-bladed system whirls one master and two test helicopter rotor blades, each 20 to 25 feet in length and 250-270 lb. in weight. The drive system consists of a 150 hp start-up motor, a 3000 hp/1800 rpm drive motor, a magnetic clutch to engage and disengage the combined-bevel and spiral gear drive, and a high torque-brake system to stop whirling of the rotor. The operator controls the input speed of the gear drive is controlled by the user through the magnetic clutch. An input of 1536 rpm is necessary to obtain the required operational output speed of 242 rpm

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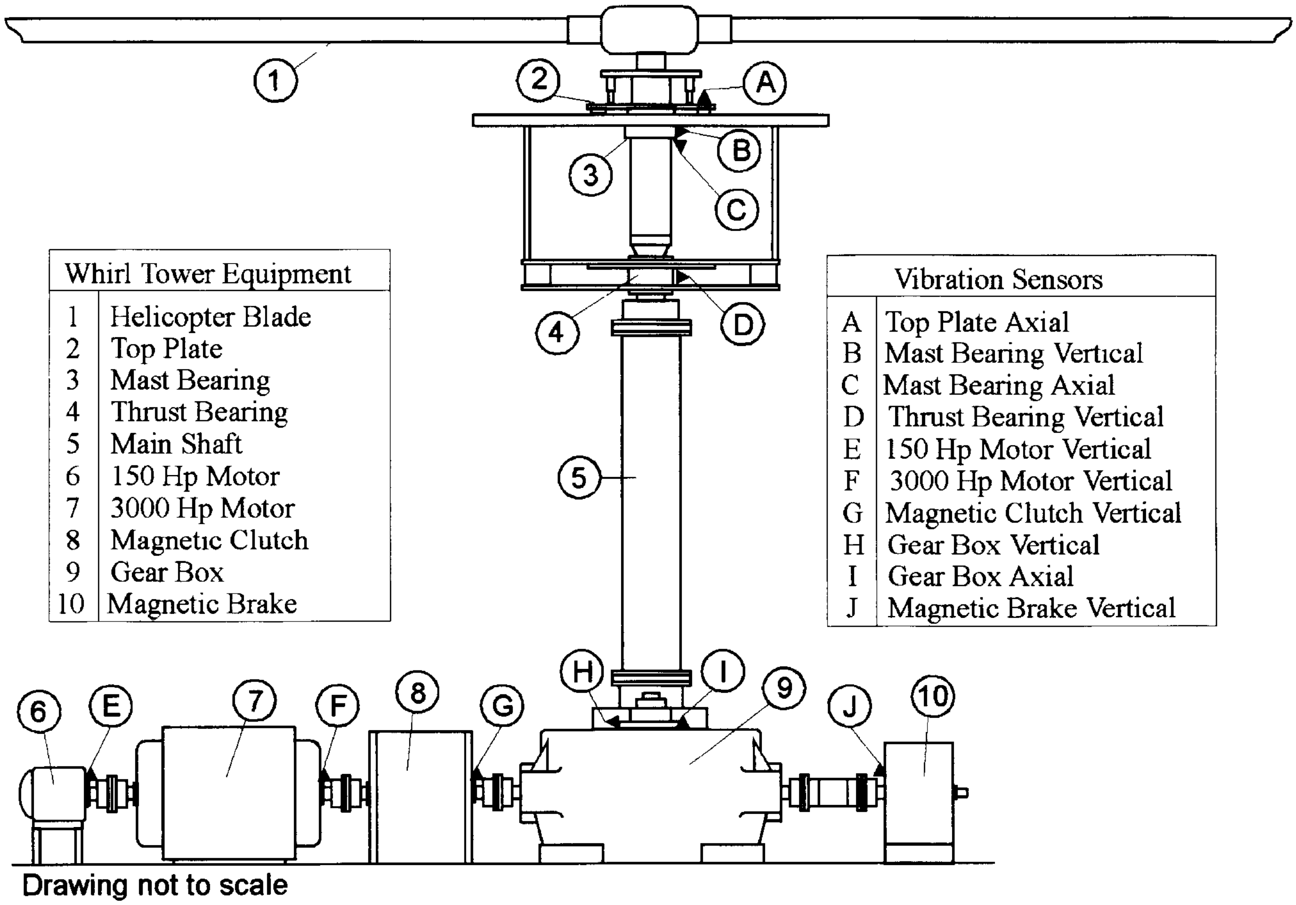
** Corresponding author, fornero@ee.tamu.edu

Figure 1. Whirl Tower Equipment and Vibration Sensors



for the main shaft. Fig. 1 shows the schematic of the whirl tower and its drive components.

3. Test Procedure, Conditions and Instrumentation

The whirl tower in this study whirls two refurbished helicopter rotor blades for dynamic balance. The static and dynamic balance state of the two test blades is compared with the master blade supplied by the original equipment manufacturer. The blades are mounted on rotor head with pitch control device, spun up to the design speed of 242 rpm, and maintained at 0° pitch angle of the blade, simulating hovering of the helicopter. For maintenance purposes, vibrations, temperature, pressure, and other essential data are recorded for 0° pitch and the blades are trim balanced. While the blades are spinning, their pitch angle is changed to 7°, and later to 12°. The 12° pitch angle condition of the blades simulates the full-speed, full-load flight condition of the helicopter and this operating condition applies significantly heavy loads on the rotor shaft, bearings, gears, and the drive motor. Therefor, vibration data must be analyzed separately for each pitch condition. Vibration data synchronized with the tachometer reading on the rotor shaft are collected from the velocity and accelerometer pickups. These pick-ups are mounted in specific directions on selected critical components of the test facility to capture their significant motion. Fig. 1 also shows the transducer locations and directions of the measurements.

The vibration signals as well as the tachometer signal and collective pitch signal are connected to a computer through a National Instruments multi-function data acquisition card. The simultaneous collection of all channels of data occurs at 4096 Hz per channel. Since the main shaft is rotating at 4 Hz, 1024 samples are collected per channel for each rotation of the main shaft. Once data collection and analysis is completed, the results are sent to the network server for further analysis and/or data storage.

4. Digital Signal Processing Methods - Fourier Transform (FT) and Wavelet Transform (WT)

The spectral components from FFT indicate the mechanical condition of gears and bearings in the system[3][4]. The interpretation of vibration signals becomes easier if we have knowledge of shaft speeds, gear tooth numbers, bearing roller numbers and geometry, etc. The specifics for the gear box are provided to demonstrate this point. The teeth on the first and second stage bevel gear sets are 35/54 and 23/95, respectively. These geometric characteristics will show up as distinct Fourier spectral components. The fundamental meshing frequency for the vertical shaft - drive gear is given by :

$$f_m = Tf_r, \quad (3)$$

where T is the number of teeth(95) and f_r is the rotational frequency (4.03 Hz). This yields a meshing frequency of 383.2 Hz. The meshing frequency for the first stage reduction gear set is calculated as 899.6 Hz. The spectrum in Fig. 2 clearly indicates these frequencies as peaks with several sidebands. If the gears develop local defects, then the defects will produce amplitude and phase modulation of vibration as:

$$y(t) = \sum_{n=0}^{N} x_n (1 + a_n(t)) \cos[2\pi n f_m t + \Phi_n + b_n(t)] \quad (4)$$

Where a_n and b_n are the amplitude and phase modulating functions respectively with a_n producing sidebands of spacing $f_m \pm n f_r$ and b_n producing symmetry about the mesh frequency. Increases in magnitudes of harmonics and sidebands indicate deterioration of mechanical condition [5]. The energy within specified bands of frequency (bands are denoted by dashed lines in Fig 2) are calculated as features of the signal using the following equation

$$E_{band} = \sum_{i \in band} |F(\omega_i)|^2 \quad (5)$$

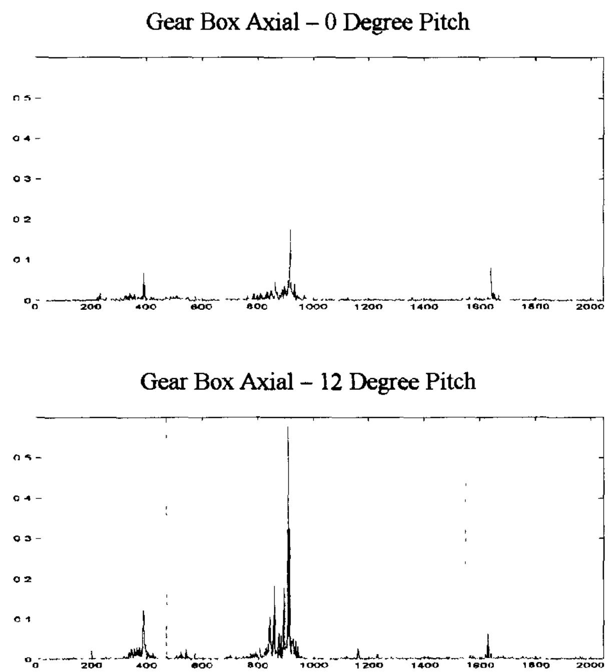
Narrower bands are used near key points of the spectrum (harmonics, sidebands, etc.). Wider bands can be used in other areas of the spectrum to monitor frequencies that are less likely to have much change in energy. For the gear box, primary frequencies include the two gear meshing frequencies and the sidebands of these frequencies.

The Morlet wavelet is used in the continuous wavelet transform of equation (2) to obtain additional features [6].

$$\Psi(t) = e^{j\omega_o t} e^{-(|t|^2)/2} \quad (6)$$

$$\Psi(\omega) = e^{[-(a\omega - \omega_o)^2]} \quad (7)$$

Figure 2. - Frequency Spectrum



From equation (7) it can be seen that the maximum value for ψ occurs when $a\omega = \omega_o$. The following equation describes the relationship in the wavelet transform between the scaling factor, a, and a frequency of interest, f_x [2]:

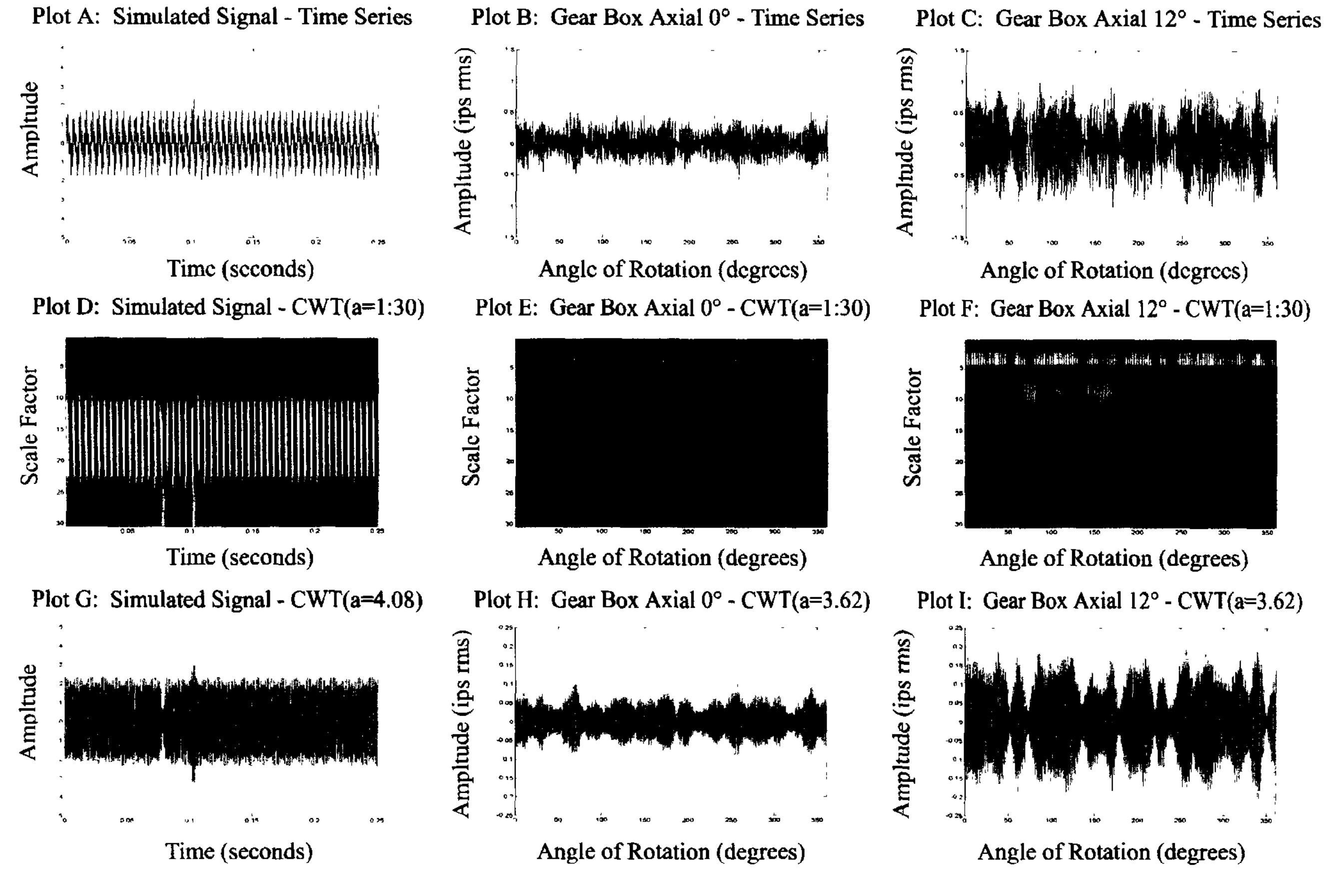
$$a = \frac{\omega_o f_s}{2\pi f_x} \quad (8)$$

where f_s is the sampling frequency, 4096 Hz, and ω_o=5. Therefore, $a f_x$ = 3260 for all a and f_x. The plots in Fig. 3 show some of the useful characteristics of the wavelet transform. Plot A is a computer generated signal combining two sine waves and two delta functions per the following equation:

$$f(t) = \sin(2\pi(800)t) + \sin(2\pi(200)t) + \delta(320) + \delta(420) \quad (9)$$

Plots B & C are time series signals obtained from the vertical transducer of the gear box. Plots D, E, and F are results of the wavelet transform for a from 1 to 30 and b from 1 to 1024. The horizontal bands represent the dominant harmonics of each signal. The vertical bands in Plot D represent the delta functions that occurred at that point in time. Plot F has higher intensity than plot E showing greater intensity of vibration at the same frequencies. Plots G, H, and I are generated by holding a fixed at a value corresponding to the frequencies of interest. The resulting signals are localized in frequency and can be analyzed in time by generating energy bands at

Figure 3 - Time Series and CWT Plots



equally spaced intervals of rotation. The difference between measured and baseline values of these features will increase with the occurence of gear faults[6].

5. Summary

This paper addresses a new industrial application of signal processing. It involves the detection of faults in rotating mechanical equipment of a whirl tower test facility. Features extracted from data collected under working conditions are used to generate baselines for comparison with future data. On a daily basis, feature data will be reported as variance from the baseline. Features that exhibit large variance from baseline will cause alarm signals to be sent to the operators and reports sent to supervisor workstations over the computer network. Feature data will be stored over time to detect trend of increased differences from the baseline. The trend information can be used to determine the necessary maintenance for individual components. Actual data is being collected at this time to verify the procedures for the detection and prediction of faults at the whirl tower facility. The analysis of this data will be included in the final version of this paper.

6. References

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