Bearing Faults Diagnosis Using Empirical Mode Decomposition

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Abstract- *This paper presents a new method to study the vibration signal through using empirical mode decomposition and Hilbert Transform. This method solves a problem of the time domain analysis to detect the bearing fault types and fault location. First of all, a vibration signal is decomposed into a number of intrinsic mode functions, and then applying Hilbert transform to the intrinsic mode functions to get its envelope spectrum and extract the fault characteristic frequency from the envelope spectrum. We Created Faulty vibration data in mechanical department, the method is used to verify the bearing status that is fault type and fault location. Experimental results show that the new method can diagnose the bearing fault correctly.*

Keywords- Empirical mode decomposition (EMD), Intrinsic Mode Function (IMF), Hilbert spectrum analysis, Bearing fault diagnosis, Fault type and location.

I. INTRODUCTION

Bearing fault is a frequent problem of bearing used in daily practice, which directly affects to the bearing's service life. The bearing's service life may be sometimes up to 20 times different, even if the bearing has the same model and same material in the same working environment, due to the different-different fault types and time. Every mechanical system will usually have the vibration while it performing any operation. The vibration signal can show bearing fault, i.e. when the bearing failure occurs, the vibration signal contains the fault characteristic information. Using a fast and simple vibration signal diagnosis method, the on-line fault monitoring of the bearing is easy to achieve. So this method is widely applied to fault diagnosis of the bearing. The vibration diagnosis technology is generally divided into three processes of vibration signal acquisition, data analysis, and fault identification. The time domain based detection method can be adapted to detect the bearing fault according to the mutants of the vibration signal amplitude, but not directly to identify the fault type and fault location, as the different fault will correspond to the different characteristic frequency. In general, the frequency domain based fault detection method is to generate the vibration signal spectrum, and then find a frequency of the peak value, corresponding to the characteristic frequency, to decide the fault type and fault location. For a typical fault type and fault diagnostic problem, reference proposed a stress wave method using the wavelet analysis for diagnosis of the low-speed rolling bearing. At the same time, a fundamental mechanical model of low-speed rolling bearing is established through a finite element numerical analysis method. The model can be used for further diagnosis of the low-speed rolling bearing fault by using stress wave technique. By extracting the features of motor current signal using wavelet analysis method, a bearing fault of the variable speed motor also can be diagnosed. However, due to wide frequency band of the force caused by fault, the frequency may cover the natural frequencies of the bearing components. This will arouse a high-frequency vibration of the whole bearing system. Therefore, the use of wavelet analysis method may be difficult to obtain the natural frequency of the bearing vibration system directly.

Figure 1: Inner and Outer ring faults of bearing

As the vibration signal contains mainly two components of the intrinsic low and resonant high frequency, it is necessary to remove the low frequency from the vibration signal by using an adaptive function of the band-pass filter. After demodulation of the signal using an envelope detector and removal of the exponential decay components, only the low-frequency signal containing the fault feature information is left. Finally the fault type and the faulty position can be detected according to information of the fault characteristic frequencies accurately. In order to extract an intrinsic frequency included in the fault signal through a resonance demodulation method, the vibration signal band-pass filter is needed. However, in the actual bearing system, the natural frequency of each component is not identical. The natural frequency will be affected by difference of the bearing structure. Obviously, the pre-estimation of bearing system natural frequency is very difficult.

Under this paper, an empirical mode decomposition (EMD) based method is proposed and used to decompose the vibration signal into a number of intrinsic mode functions (Intrinsic Mode Function, referred to as IMF). The intrinsic mode function containing the most oscillating (high frequency) components is also used to obtain its envelope spectrum through Hilbert spectrum analysis. The fault characteristic frequency is extracted from the envelope spectrum. Finally, the proposed method is tested and verified by using a benchmark fault data created in mechanical department. The testing results show the method is correct and effective.

II. EMPIRICAL MODE DECOMPOSITION AND HILBERT TRANSFORM METHOD

A. Empirical Mode Decomposition

The empirical mode decomposition method was invented by Norden E. Huang in year 1998 in the United States of America Aerospace Bureau (NASA). Using the EMD technique, the signal can be decomposed into the different intrinsic mode functions (IMFs), IMF usually carries the most oscillating (high frequency) components. The method does need prior test. In theory, it can apply to any form of the signal. It has an obvious advantage in the treatment of non-steady and non-linear signals with a high ratio of the signal to noise. The method can be used for smoothing of the signal containing noise.

In the EMD, different simple intrinsic modes of oscillation represent the original signal. IMF represents simple oscillatory mode as counterpart to harmonics. In dataset, IMF is defined as

1. The number of local extrema and the number of its Zero-crossings must either be equal or differ at most by one.
2. At any time, the mean value of the upper envelope (determined by the local maxima) and the lower envelope (determined by the local minima) must be zero

As the most signal does not belong to the intrinsic mode functions, it needs to decompose the signal into a number of different intrinsic mode functions using the empirical mode decomposition (EMD). The specific calculation steps are shown as follows:

Assuming the original signal is *y(t)*,

Step (1) to identify all of the local maximum and minimum values of the *y(t)*, using the cubic spline interpolation method; to draw the upper envelope curve by connecting with each local maximum value and lower envelope line by linking each local minimum value.

Step (2) to calculate the average value of upper and lower envelope curves; it is average envelope $x_a(t)$

Step (3) to calculate $y_1(t)$= the original signal *y(t)* – the average envelope $x_a(t)$

Step (4) to decide if $y_1(t)$ is an intrinsic mode function. If it is true, then the $y_1(t)$ is the first intrinsic mode function $I_1(t)$ of the *y(t)*, $y_1(t)=I_1(t)$; if not, then returns to Step 1, and sets $y_1(t)$ as the original signal.

Repeat Steps 1~4, to get $y_2(t)$, $y_2(t)=$ $y_1(t)$ - $x_{a1}(t)$, here the $x_{a1}(t)$ is the mean envelope of $y_1(t)$. this procedure is repeated many times until an intrinsic mode function is found. Assuming it is repeated ***k** times*, the k_{th} intrinsic mode function is given in equation (1).

$$y_k(t)=I_1(t) \qquad (1)$$

Where the $y_k(t)$ = $t_{k-1}(t)$ - $x_{ak}(t)$; the $x_{ak}(t)$ is the average envelope of $y_k(t)$. The $I_1(t)$ is the first intrinsic mode function of the *y(t)*.

Step (5) to calculate residual signal $r_1(t)$, it is shown in equation (2).

$$r_1(t)=y(t)-I_1(t) \qquad (2)$$

Step (6) to set the *r1(t)* as the original signal and repeat Step1~5 to get the second residual signal $r_2(t)$ in equation (3).

$$r_2(t) = r_1(t) - I_2(t) \qquad (3)$$

Step (7) repeat Steps 1 to 6 until the final residual signal is a monotone function. If a total of repeating times is *n* and the last remaining signal $r_n(t)$ is a monotonic function, it cannot be decomposed further, as shown in equation (4).

$$r_n(t) = r_{n-1}(t) - I_n(t) \qquad (4)$$

Up to now, the whole empirical mode decomposition process is complete. The original signal *y(t)* is decomposed into *n* intrinsic mode functions and one residual $r_n(t)$, as shown in equation (5).

$$y(t) = \sum_{k=1}^{n} I_k(t) + r_n(t) \quad (5)$$

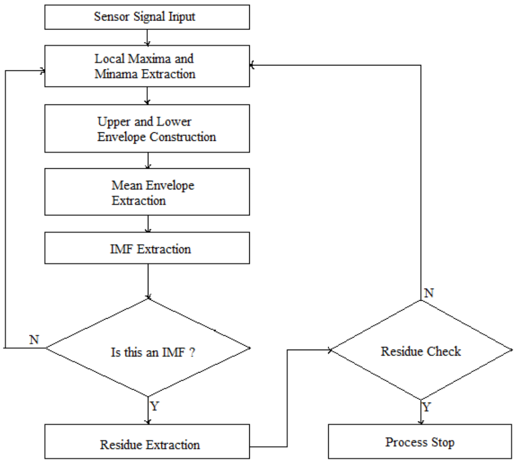

Figure 2: The flowchart of the decomposition process of EMD

B. Hilbert Frequency Spectrum Analysis

Based on analysis of the intrinsic mode function envelope using the empirical mode decomposition method, each intrinsic mode function envelope spectrum is obtained. Thus, the fault characteristic frequency can be derived. The specific steps are as follows:

Step (1) To have been decomposed into intrinsic mode function of the Hilbert transform in equation (6).

$$H[I_n(t)] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{I_n(\tau)}{t-\tau}\, d\tau \quad (6)$$

Where $H[I_n(t)]$ is the Hilbert transform at n intrinsic mode function $I_n(t)$.

Step (2) To find the envelope function through creating analytic function.

An analytic function $C_n(t)$ of the intrinsic mode function $I_n(t)$ is defined as equation (7)

$$C_n(t) = I_n(t) + jH[I_n(t)] \quad (7)$$

The envelope function *bn(t)* of *Cn(t)* is given in equation(8)

$$b_n(t) = \sqrt{I_n^{\,2}(t) + H^2[C_n(t)]} \quad (8)$$

Step (3) to calculate the envelope spectrum.

The envelope spectrum $B_n(f)$ can be obtained through FFT (Fast Fourier Transform) of the envelope function $b_n(t)$. Fault Characteristic frequency can be extracted from envelope spectrum easily.

III. TESTING RESULTS AND ANALYSIS

As In the test, the benchmark data is created in the mechanical department. the faulted bearing was reinstalled into the test motor and vibration data was recorded for motor loads of 0 to 3 HP. The test ring consists of 2 HP three-phase AC motor, Accelerometer sensors, and the electronic control devices. The motor shaft is supported by a testing shaft bearing. The testing bearing is implanted a single local fault at outer ring through electrical discharge machining (EDM) technology. The fault area has the diameters in 7mil (1mil=0.001inches). The testing bearing is a type of 1207 EKTN9 SKF self-aligning double row ball bearing. The vibration signal is measured by an acceleration sensor with a sampling frequency of 40KHz. DEWEsoft7 is used to import data in Matlab because recorded data cannot open in Matlab directly.

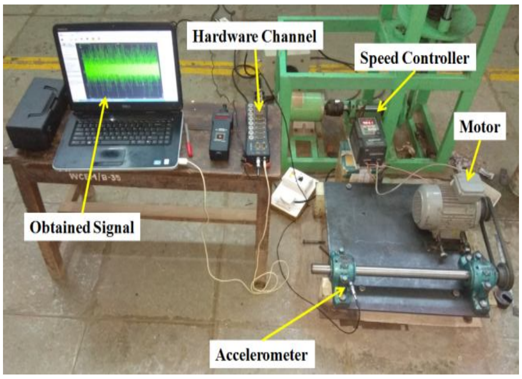

Figure 3: Setup for creating vibration data(Mechanical Department WCE,Sangli)

A. Empirical Mode Decomposition Experiments

For a bearing outer ring fault at the terminal of driving shaft bearing, the testing results of the vibration signal waveform are shown in Figure 3. In Figure 3, the X-axis is a sampling point and the Y-axis is a magnitude of the vibration signal acceleration. The original vibration signal is decomposed under a condition of a faulty point with a diameter of 7mil, load 0.0W and rotating speed 1695rpm.

Figure 4 shows four IMF of the vibration signal through the EMD.

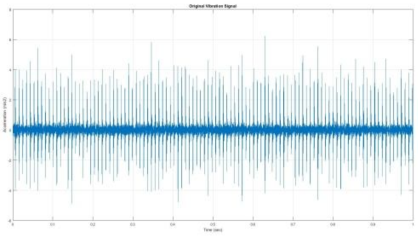

Figure 4: Vibration signal for a fault occurs at the drive shaft terminal of the bearing outer ring

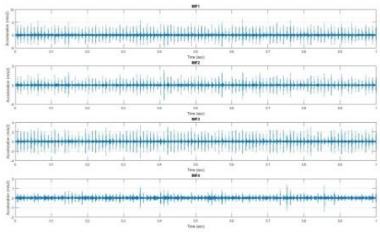

Figure 5: Intrinsic mode functions (IMF1-IMF4) for the bearing outer ring fault

B. Hilbert Transform Experiment Analysis

Figure 8 shows the first 4 order IMF envelope spectrum of the vibration signal for a bearing outer ring fault. It can be seen the IMF1, IMF2 and IMF3 in the peak have the same frequency of 176Hz.

According to bearing pitch diameter *Pd* of 53.289mm, the roller or ball diameter of *Bd* 8.738mm, the number of balls Nb is 15, Revolutions per sec is (1695/60), the contact angle of 8.64 degree, the outer ring fault the speed of 1695rpm using the equations shown in Table 1, the driving shaft bearing characteristic frequency for the outer fault is 177.13Hz. This theoretically calculated frequency is very close to the measured value. The difference is less than 2Hz. This illustrates the method proposed in the paper is correct and effective for diagnosis of bearing inner ring and the outer ring fault. The outer ring fault is more easily detected than inner ring fault as the outer ring fault vibration impact force is greater than the inner ring fault.

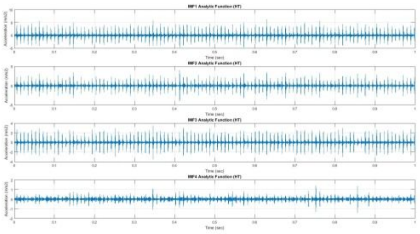

Figure 6: Analytic Function (Hilbert Transform) of each IMF

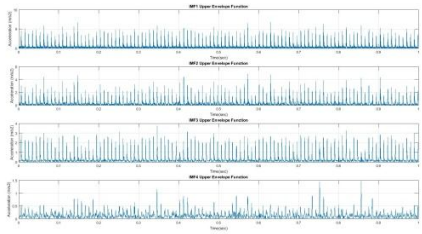

Figure 7: Upper Envelope Function of each IMF

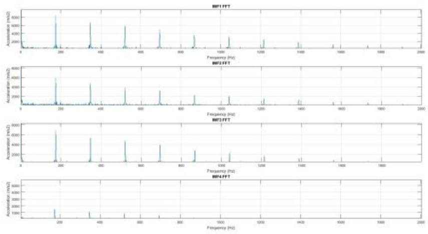

Figure 8: Four intrinsic mode functions for the bearing outer ring fault

Table 1: Fault Characteristics frequency calculation equations

Fault Cause	Fault Characteristic Frequency
Outer Ring injury	f_o =Nb/2 S (1-Bd/Pd cosø)
Inner Ring injury	f_i =Nb/2 S(1+Bd/Pd cosø)
Rolling body injury	f =Pd/2Bd S {1-[(Bd/Pd)^2] [(cosø)^2]}

V. CONCLUSION

Table 2: Fault Characteristics frequency by formula and EMDtechnique

Fault Cause	Using Formula	Using EMD
Outer Ring Fault Frequency	177.13Hz	176Hz

This paper presented empirical mode decomposition and the Hilbert spectrum analysis based method for detection of the bearing fault. The experimental results show that the method is correct and effective to diagnose the bearing outer ring and the inner ring of the fault even if the machine power loading changes during the diagnosis.

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