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Vibration Signature Analysis Of A Chipped Spur Gear Tooth

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Abstract - Signal processing is a widely applied tool for condition monitoring of rotating machinery. These techniques are thus utilized extensively to process experimental signals. However, hypothesis about data and computational efforts often restrict the application of some techniques. The empirical mode decomposition (EMD) and Hilbert spectrum allows to overcome these limitations. This paper applies this method to vibration signal analysis for localised gear fault diagnosis. Considering that the gear fault vibration signal generate both the amplitude and frequency demodulated signals, the EMD could exactly decompose these demodulated signals into a number of intrinsic mode functions (IMFs), each of which can be amplitude-demodulated or frequency-demodulated component, the frequency families could be separated effectively from the gear vibration signal by applying EMD to the gear vibration signal. Furthermore, when fault occurs in gears, the energy of the gear vibration signal would change correspondingly, whilst the local Hilbert energy spectrum can exactly provide the energy distribution of the signal in certain frequency range with the change of the time and frequency. Thus, the fault information of the gear vibration signal can be extracted effectively from the local Hilbert energy spectrum.

Keywords: Gear fault, missing tooth, EMD, IMF, Hilbert energy spectrum.

I. INTRODUCTION

Gearbox is used widely as one of critical mechanical components in industry. Its condition monitoring and fault diagnosis has been the subject of intensive investigation. Many metrics based separately on time analysis and frequency analysis are currently used on vibration data to detect faults from gearboxes [1]. Although these methods have been shown to find faults, traditional methods such as time synchronous average (TSA) and cepstrum analysis were developed for use only on stationary data [2-3]. A signal has weak stationarity when its mean and variance are constant, and strong stationary when all its moments are constant. Many types of gear damage produce localized changes in the signal so that the signal is no longer stationary on the timescale of the gear tooth meshing. The signal near meshing with a defective tooth may vary considerably from the rest of the signal. If the situation is critical, it is important to determine the severity so that corrective actions can be taken.

In standard Fourier analysis, a signal is decomposed into individual frequencies. Unfortunately, there is no way to determine when each of those frequencies has occurred. However, there are signal processing methods that give local information about both time and frequency. These methods localize signal features in both time and frequency; therefore, these methods have the potential to be more sensitive to early changes in the signal due to impending faults. Many time-frequency (TF) methods such as Wigner-Ville distribution (WVD), Wavelet transform (WT) and Short Time Fourier transform (STFT) are developed for the detection of fault in gears [4-7]. There have been many other recent developments in time-frequency techniques to accurately diagnose the local faults in transmission system [8-9]. However, these traditional time–frequency techniques have their own limitations [10].

To improve the technology, a new method that decomposes a signal using the so-called empirical mode decomposition (EMD) into a finite sum of components known as intrinsic mode functions (IMF) was developed by Huang et al. [11]. It then applies the Hilbert transform to the IMFs to obtain a time–frequency representation called the Hilbert spectrum. A breakthrough of this method as opposed to the traditional time-frequency analysis technique is that it does not use pre-specified basis functions or filters but instead decomposes a signal by direct extraction of the local energy associated with the intrinsic time scales of the signal itself. It is therefore highly adaptive and consequently can well depict the time–frequency characteristics of a signal. This method is now known as the Hilbert–Huang transform (HHT) in the literature. Since EMD is suitable for processing nonlinear and non-stationary signals, it has attracted attention from researchers in the field of fault diagnosis of rotating machinery as well [12].

In the present work, the EMD along with Hilbert energy spectrum is used for detection of a missing tooth in a gear mechanisms. In Section 2, the EMD algorithm is explained. Section 3 describes the experimental rig used. Section 4 presents the fault identification strategy. The paper main conclusions are outlined in Section 5.

II. EMPIRICAL MODE DECOMPOSITION ALGORITHM

The EMD method was motivated by computation of instantaneous frequency defined in terms of Hilbert transform. For a real-valued signal $x(t)$, the Hilbert transform is defined by the principal value (PV) integral [13]

$$\frac{1}{\pi} PV \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (1)$$

This leads to the definition of an analytic signal,

$$z(t) = x(t) + iy(t) = a(t)e^{i\theta(t)} \qquad (2)$$

where,

$$a(t) = [x^2(t) + y^2(t)]^{1/2}, \theta(t) = \arctan\frac{y(t)}{x(t)} \qquad (3)$$

The instantaneous frequency is then defined by

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \qquad (4)$$

In the above process, both the amplitude and instantaneous frequency are function of time. One would therefore hope to construct a time–frequency representation based on Hilbert transform. Huang et al. [11], showed that for a function to have physically meaningful instantaneous frequency, it should satisfy the following conditions:

(1) the number of the extrema and the number of the zero crossings are equal or differ at most by one, and

(2) at any point, the mean value of the envelopes defined by the local extrema is zero.

Such a function is called an IMF. A practical signal is usually not an IMF but using the EMD, the signal can be decomposed into a finite sum of IMFs [11]. Denoted by $x(t)$ the signal to be analysed, the EMD extracts the first IMF by the following sifting process:

1. Find the upper envelope of $x(t)$ as the cubic spline interpolant of its local maxima and the lower envelope as the cubic spline interpolant of its local minima.
2. Compute the envelope mean $m(t)$ as the average of the upper and lower envelopes.
3. Compute $h(t) = x(t) - m(t)$
4. If the sifting result $h(t)$ is an IMF, the programme will be stopped otherwise, treat $h(t)$ as the signal and iterate through steps 1–4. The stopping condition is:

$$\sum_t \frac{[h_{k-1}(t) - h_k(t)]^2}{h_{k-1}^2(t)} < SD \qquad (5)$$

where $h_k(t)$ is the sifting result in the kth iteration, and SD is typically set between 0.2 and 0.3.

The EMD extracts the next IMF by applying the above procedure to the residue $r_1(t) = x(t) - IMF1(t)$, where $IMF1(t)$ denotes the first IMF. This process is repeated until the last residue $r_n(t)$ has at most one local extremum. The above procedure decomposes the original signal as a finite sum of IMFs, $IMF_j(t)$, $j = 1,2,3,..,n$

After performing the Hilbert transform to each IMF component, the original signal can be expressed as the real part (RP) in the following form:

$$x(t) = RP\sum_1^n a_j(t)e^{i\theta(t)}$$

$$= RP\sum_1^n a_j(t)e^{i\int_{-\infty}^{t}\omega_j(\tau)d\tau} \qquad (6)$$

Here we left out the residue $r_n(t)$ on purpose, for it is either a monotonic function or a constant. Eq.6 gives both amplitude and frequency of each component as functions of time. This frequency–time distribution of the amplitude is designated as the Hilbert spectrum $H(\omega,t)$:

$$H(\omega,t) = RP\sum_1^n a_j(t)e^{i\int_{-\infty}^{t}\omega_j(\tau)d\tau} \qquad (7)$$

If $|x(t)|^2$ is regarded as energy density of the vibration signal $x(t)$, then $H^2(\omega,t)$ obtained by performing HHT owns the same physical meaning (namely, energy density). Therefore, we could define $H^2(\omega,t)$ as Hilbert energy spectrum that describes the energy–frequency–time distribution. Leaving out the residue $r_n(t)$, the HHT of $x(t)$ should be energy conservation, namely, the following formula could be obtained:

$$\int_{-\infty}^{+\infty} |x(t)|^2\ dt = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} H^2(\omega,t)d\omega dt \qquad (8)$$

Therefore, we can define instantaneous energy $IE(t)$ as following:

$$IE(t) = \int_{-\infty}^{+\infty} H^2(\omega,t)d\omega \qquad (9)$$

III. EXPERIMENTAL SET-UP AND LABORATORY DATA

Figure 1 shows the experimental setup realized for this study. The test rig consists of two spur gears of EN-353 material with a module of 1.5 mm, pressure angle 20^o, which have 18 and 27 teeth such that 1:2 velocity ratio is achieved. The shafts of the gears are supported by two SKF-6204 ball bearings. The entire system is settled in an oil basin in order to ensure proper lubrication. The gearbox is driven by a motor and the output load is controlled by an alternator of variable capacity. The output power is consumed in electric lamps. The characteristics of the different components of the experimental set up are as follows:

Motor: Three phase type ABB, 1 HP, operates at 220 volts, 1.6A with a current frequency of 50 Hz and rotates at 2840 r.p.m nominal operating rotational speed.

Alternator: Single phase, rotates at 3000 rpm. Under operating voltage of 115 V generates an output current of 36.5 A whereas at 230 V generates 18.3 A.

A variable frequency drive (VFD) from Delta Electronics Inc. was used to control the speed of induction motor. A PCB 608A11 piezoelectric accelerometer was used for measuring vibration signals for its large dynamic range and high mounted resonance frequency with a sensitivity of 10.2 mV (m/s^2).

Figure 1: Experimental setup

A steel mounting piece is screwed to the gearbox wall to provide mounting for the accelerometer in the direction of the gear line of action. The accelerometer is mounted in this direction to pick up the vibrations along the pressure line only. The vibration signal is collected using a NI-9234 A/D data acquisition board and the acquisition software used was LabView. The gear fault is induced in driven gear by removing a tooth i.e. missing tooth fault (MTF) is generated using wire electrical discharge machine (EDM). The data of healthy gear and faulty gear is collected to determine the altering condition in gearbox at 20 Hz speed and at a constant load of 10Nm. In total, 32768 number of samples were acquired at every stage with a sampling rate of 5120 Hz for a sampling time of 6.4 s. The system was operated for 30 minutes in which 3 vibration recordings are conducted, each one of approximately 5 seconds duration.

IV. FAULT IDENTIFICATION PROCEDURE

Vibration signals resulting from gear systems are non-stationary by their nature. In addition, the presence of damage results in severe system nonlinearity. The gearbox is made to run at a speed of 30 Hz at a constant load of 100W for both the healthy and faulty conditions. Figure 2 and Figure 3 shows the comparison of time domain signal and spectrum obtained of a healthy and faulty gears respectively. The signals of a healthy gears are observed to be more uniform while abrupt change in amplitude defines the faulty gears time signals as can be observed in Figure 2.

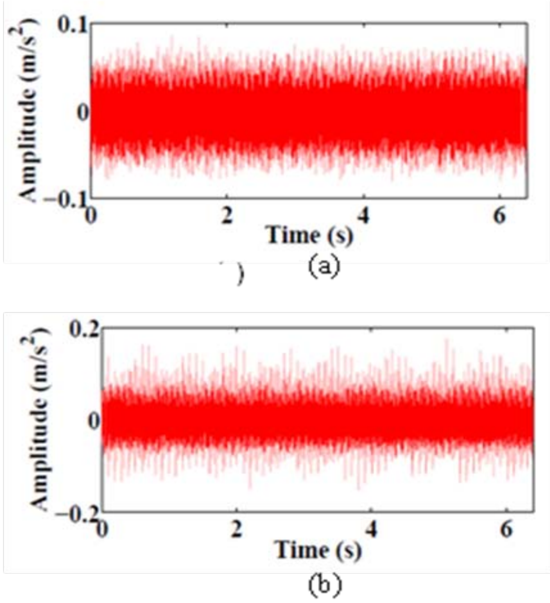


Figure 2: Comparison of time domain signals at 30 Hz and at load 100W of (a) Healthy gearbox; (b) Faulty gearbox

The gear mesh frequency (GMF) of 30 x 18 = 540 Hz is observed in Figure 3 for both conditions. The change in the magnitude of frequency components of spectrum around gearmesh frequency in Figure 3(b) can be attributed to the faulty condition in a gear. However, It is clear that the MTF characteristics cannot be established by either the time domain or spectrum signals.

Thus, EMD method is used to decompose the time domain signal of Figure 2 into intrinsic mode functions (IMF). There are 23 IMFs generated out of which the first five IMF's are shown in Figure 4. The rest of the IMFs have lower energy modes and are thus being neglected. IMF1 contains the highest signal frequencies, mode IMF2 the next higher frequency band and so on.

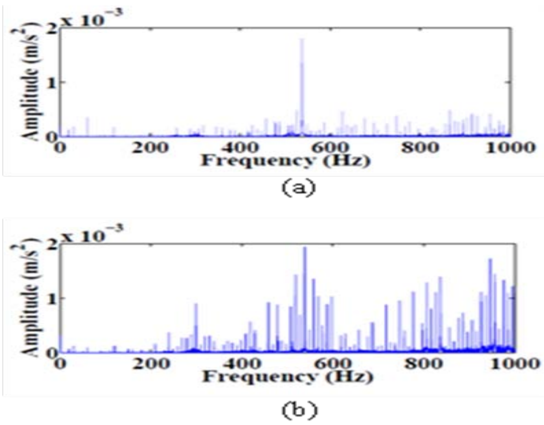


Figure 3: Comparison of frequency spectrum signals at 30Hz and at load 100W of (a) Healthy gearbox; (b) Faulty gearbox

On performing the fast Fourier transform on each IMF, the gear mesh frequency can be very well revealed in IMF4 as seen in Figure 5. The presence of MTF results in a sudden increase of vibration energy in the particular time scales covered by mode IMF3 as shown in Figure 6. This is otherwise blurred by noise and vibration that have high energy content in other IMFs. It is observed in the IMF3 that the average time spacing between the neighbouring impulses is coming out to be T = 0.034 s. It is 30 Hz in frequency, which is close to the rotation frequency of the damaged gear.

Most gear diagnosis methods at present are based on variation of vibration signal energy. However, local faults always occur only in certain teeth so that energy variation resulted from faults is small compared with the total energy of the gear vibration signal. So it is difficult to detect the fault by comparing this kind of variation.

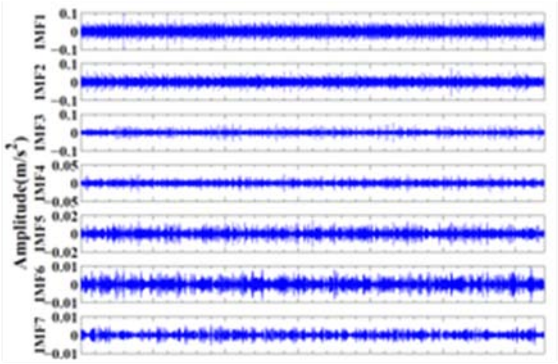


Figure 4: IMF of a faulty gearbox

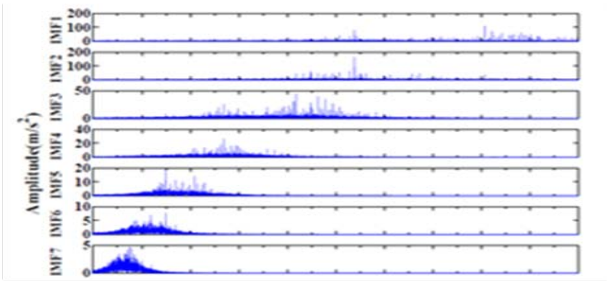
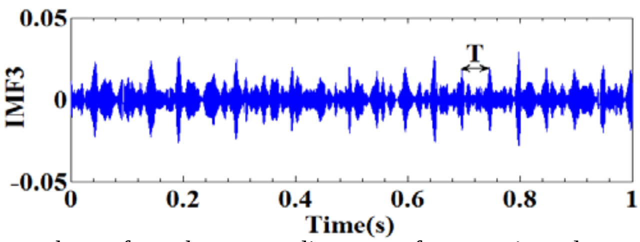


Figure 5: Fast Fourier Transform of the extracted IMF revealing gear mesh frequency

The local Hilbert energy spectrum also known as Instantaneous energy (IE) which is applied to a particular IMF of interest could exactly provide precise energy–frequency–time distribution of signal with the change of time and some frequencies, therefore it is possible to extract MTF characteristic by analyzing signal energy distribution with change of frequency and time.



y e e e d gear

Figure 6: IMF3 vibration signal of a faulty .

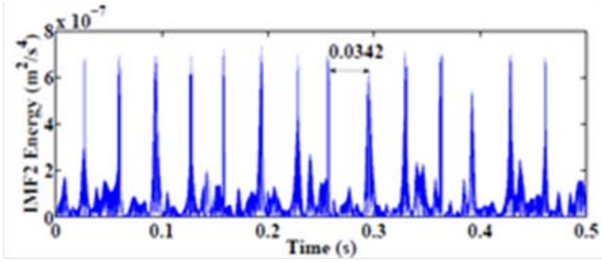


Figure 7: IE of IMF3 vibration signal of faulty gearbox

V. CONCLUSION

In this paper, a method for gear fault identification was presented based on a newly developed joint time-frequency signal processing tool named the empirical mode decomposition. The method is based upon the local characteristic time scale of the signal and could decompose the complicated signal into a number of intrinsic mode functions. Frequency components contained in each IMF not only relates to the sampling frequency, but also changes with the signal itself. It has been shown that defect in the form of a tooth loss is manifested as an increase in the envelope amplitude of one of the intrinsic modes. The selection of the appropriate IMF that encloses the missing tooth information is important. The defect evolution can be monitored by computing the energy of the intrinsic mode that is most sensitive to damage. In the light of the new method, any signal resulting from a nonlinear process can be considered as both amplitude and frequency modulated. Missing tooth vibration signal of gear present obvious periodical characteristic along time axis in instantaneous energy spectrum. Meantime, obvious impulse feature of gear fault vibration signal found in IMFs and instantaneous energy spectrum can be correlated to the gear rotation frequency to know the source and type of the defect.

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