Key Engineering Materials Vols. 291-292 (2005) pp. 655-660
online at http://www.scientific.net

Online available since 2005/08/15

Hilbert-Huang Transform and its Application in Gear Faults Diagnosis

H. Li, H. Q. Zheng and L. W. Tang

First Department, Shijiazhuang Mechanical Engineering College, Shijiazhuang 050003, People's Republic of China

Keywords: Gear, Empirical mode decomposition, Faults diagnosis, Hilbert-Huang transform, Signal processing

Abstract. Time-frequency and transient analysis have been widely used in signal processing and faults diagnosis. These methods represent important characteristics of a signal in both time and frequency domain. In this way, essential features of the signal can be viewed and analyzed in order to understand or model the faults characteristics. Historically, Fourier spectral analyses have provided a general approach for monitoring the global energy/frequency distribution. However, an assumption inherent to this method is the stationary and linear of the signal. As a result, Fourier methods are not generally an appropriate approach in the investigation of faults signals with transient components. This work presents the application of a new signal processing technique, empirical mode decomposition and the Hilbert spectrum, in analysis of vibration signals and gear faults diagnosis for a machine tool. The results show that this method may provide not only an increase in the spectral resolution but also reliability for the gear faults diagnosis.

Introduction

Vibration signal analysis has been widely used in the faults detection of rotation machinery. Many methods based on vibration signal analysis have been developed. These methods include power spectrum estimation, cepstrum analysis, synchronous time average and phase demodulation, which have been proved to be effective in gear fault detection. However, these methods are based on the assumption of stationary and linearly of the vibration signal. Therefore, new techniques are needed to analyze vibration for faults detection in gear mechanism. Gear faults by their nature are time localized transient events. To deal with non-stationary and non-linearity signals, time-frequency analysis techniques such as the Short Time Fourier Transform (STFT) [1], Wavelet Transform (WT) [2-6] and Wigner-Ville distribution (WVD) [7-9] are widely used. The STFT [1] uses sliding windows in time to capture the frequency characteristics as functions of time. Therefore, spectrum is generated at discrete time instants. An inherent drawback with the STFT is the limitation between time and frequency resolutions. Furthermore, this method requires large amounts of computation and storage for display. The Wavelet Transform (WT), on the other hand, is similar to the SHFT in that it also provides a time-frequency map of the signal being analyzed. The improvement that the WT makes over the STFT is that it can achieve high frequency resolution with sharper time resolutions. A very appealing feature of the wavelet analysis is that it provides a uniform resolution for all the scales. Limited by the size of the basic wavelet function, the downside of the uniform resolution is uniformly poor resolution. Moreover, an important limitation of the wavelet analysis is its non-adaptive nature. Once the basic wavelet is selected, one will have to use it to analyze all the data. This leads to a subjects assumption on the characteristic of the analyzed signal. As a consequence, only signals feature that correlate well with the shape of the wavelet function have a chance to lead to coefficients of high value. All other feature will be masked or completely ignored. The Wigner-Ville distribution (WVD) is a basic time-frequency representation, which is part of the Cohen class of distribution. Furthermore, it possesses a great number of good properties and is of popular interest for non-stationary signal analysis. The difficulty with this method is the severe cross terms as indicated by the existence of negative power for some frequency ranges.

In this work, we introduce a novel approach for nonlinear, non-stationary data analysis. A application of Hilbert-Huang transform method to fault diagnosis of gear crack is presented. The methodology developed in this paper decomposes the original times series data in intrinsic oscillation modes, using the empirical mode decomposition. Then the Hilbert transform is applied to each intrinsic mode function. Therefore, the time-frequency distribution is obtained. The basic method is introduced in detail. The Hilbert-Huang transform is applied in the research of the faults diagnosis of the gear crack.

This paper has been organized as follows: Section 1, gives a brief introduction of the time-frequency analysis technology. Section 2, gives a brief description of the Hilbert-Huang transformation (HHT). Section 3, presents the method and procedure of the fault diagnosis based on HHT. Section 4, gives the applications of the method based on marginal spectrum and instantaneous energy to faults diagnosis of the gear crack. Section 5, gives the main conclusions of this paper.

Brief description of the Hilbert-Huang transformation [10]

Hilbert-Huang transformation is an emerging novel technique of signal decomposition having many interesting properties. In particular, HHT has been applied to numerous scientific investigations, such as biomedical signals processing [11-13], geophysics [14-15], image processing [16], structural testing [17] and so on. In order to facilitate the reading of this paper we will introduce in detail the Hilbert-Huang transformation, which is a relatively novel technique.

The concept of intrinsic mode function. Huang et al [10] have defined IMFs as a class of functions that satisfy two conditions:

1)In the whole data set, the number of extrema and the number of zero-crossings must be either equal or differ at most by one;

2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Empirical mode decomposition method: the sifting process. The algorithm operates through six steps:

(1) Identification of all the extrema (maxima and minima) of the series $x(t)$.

(2) Generation of the upper and lower envelope via cubic spline interpolation among all the maxima and minima, respectively.

(3) Point by point averaging of the two envelopes to compute a local mean series $m(t)$.

(4) Subtraction of $m(t)$ from the data to obtain a IMF candidate $c(t) = x(t) - m(t)$.

(5) Check the properties of $c(t)$:

- If $c(t)$ is not a IMF (i.e. it does not satisfy the previously defined properties), replace $x(t)$ with $c(t)$ and repeat the procedure from Step 1;
- If $c(t)$ is a IMF, evaluate the residue $r(t) = x(t) - c(t)$.

(6) Repeat the procedure from Steps 1 to 5 by sifting the residual signal. The sifting process ends when the residue $r(t)$ satisfies a predefined stopping criterion.

At the end of the procedure we have a residue $r(t)$ and a collection of n IMFs, named $c_i(t)$ ($i = 1,2,\cdots n$). The $c_i(t)$ is generated being sorted in descending order of frequency and therefore $c_1(t)$ is the one associated with the locally highest frequency. Furthermore the original $x(t)$ can be exactly reconstructed by a linear superposition:

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t), \tag{1}$$

Thus, one achieves a decomposition of the data into n-empirical IMF modes, plus a residue, $r_n(t)$, which can be either the mean trend or a constant.

The Hilbert-Huang transform (HHT) . Having obtained the IMFs using EMD method, one applies the Hilbert transform to each IMF component. Amplitude $a_i(t)$ and phase $\theta_i(t)$ can be expressed as

$$a_i(t) = \sqrt{c_i^2(t) + H^2[c_i(t)]} \quad , \tag{2}$$

$$\theta_i(t) = \arctan\left(\frac{H[c_i(t)]}{c_i(t)}\right) , \tag{3}$$

Therefore, the instantaneous frequency $\omega_i(t)$ can be given by:

$$\omega_i(t) = \frac{\mathrm{d}\theta_i(t)}{\mathrm{d}t} \quad , \tag{4}$$

The time-frequency distribution is designated as the Hilbert-Huang spectrum $H(\omega, t)$:

$$H(\omega, t) = \mathrm{Re}\sum_{i=1}^{n} a_i(t)\exp(j\int \omega_i(t)dt) , \tag{5}$$

where the residue $r_n(t)$ has been left out. Re {.} denotes the real part of a complex quantity.

Eq. (5) enables us to represent the amplitude and the instantaneous frequency, in a three-dimensional plot, in which the amplitude is the height in the time-frequency plane.

With the Hilbert-Huang spectrum defined, the marginal spectrum, $h(\omega)$, can be defined as

$$h(\omega) = \int_0^T H(\omega, t)\mathrm{d}t , \tag{6}$$

where T is the total data length.

The Hilbert spectrum offers a measure of amplitude contribution from each frequency and time, while the marginal spectrum offers a measure of the total amplitude contribution from each frequency.

Therefore, local marginal spectrum of each IMF component is given as

$$h_i(\omega) = \int_0^T H_i(\omega, t)\mathrm{d}t , \tag{7}$$

The local marginal $h_i(\omega)$ spectrum offers a measure of the total amplitude contribution from the frequency that we are interested in.

The instantaneous enery $IE(t)$ is defined as

$$IE(t) = \int_{\omega_1}^{\omega_2} H^2(\omega, t)d\omega , \tag{8}$$

The instantaneous energy $IE(t)$ provides information about the time variation of energy.

Proposed marginal spectrum method and instantaneous energy based on HHT

The procedure of proposed marginal spectrum and instantaneous energy method based on the HHT is given as follows:

1) To decompose the analyzed signal using EMD and to obtain IMFs;

2) To select the interested IMF component $c_i(t)$ according to the objective of fault diagnosis,;

3) To calculate the marginal spectrum $h_i(\omega)$ according to Eq. (7);

4) To compute instantaneous energy of fault signal according to Eq. (8);

5) To analyze the marginal spectrum and instantaneous energy of selected $c_i(t)$ component and to draw a diagnostic conclusion.

Gear faults diagnosis based on marginal spectrum and instantaneous energy

Gears are very popular in industrial application. A broken gear tooth failure may cause fatal accidents, so the recognition of gear tooth cracks is very important for the safety of a machine tool or gearbox. The vibration signals of the gear crack are sampled on a head-box of a machine tool. The motion is produced by an AC motor. Localized defect was seed in the root of the gear of the output shaft by an electric-discharge machine to keep their size and depth under control. The size of the artificial defect was 1mm in depth and the width of the groove was 1.5 mm. The transmission ratio is 36/28, which means that an decrease in rotation speed is achieved.The input speed of the spindle is 1470r/min, that is, the rotating frequency of the output shaft f_r is 19.11Hz. The monitoring and diagnostic system is composed of four accelerometers, amplifiers, B&K 3560 spectrum analyzer and a computer. The sampling span is 6.4 kHz, the sampling frequency is 16384 Hz and the sampling point is 2048.

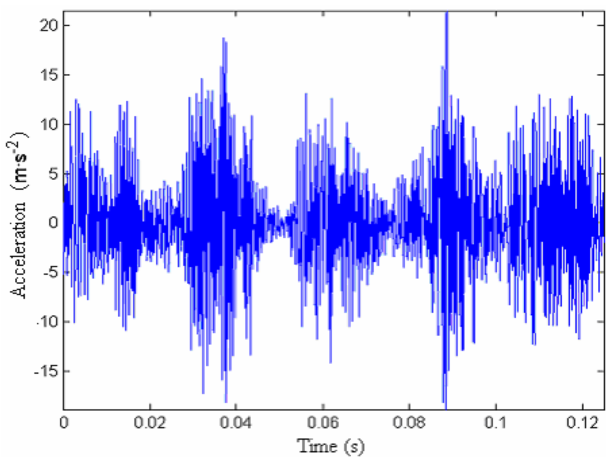

Fig.1 Time-domain vibration signal with gear crack

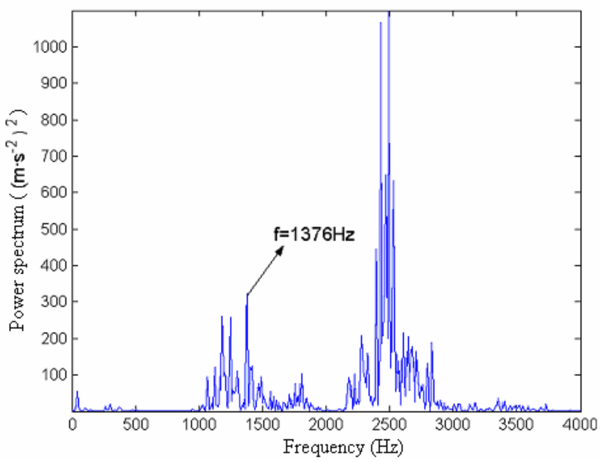

Fig.2 Power spectrum of the vibration signal

The original vibration signal with gear crack is displayed in Fig.1. It is clear that there are periodic impacts in the vibration signal. There are significant fluctuations in the peak amplitude of the signal. However, it is hardly possible to evaluate the gear fault condition only through such time domain vibration signal.

Fig.2 displays the power spectrum of the vibration signal with gear crack. 1376Hz frequency component, which is the second harmonic of the meshing frequency, can be clearly seen in Fig.2. But there is no fault frequency component around 19.11Hz. Therefore, classical Fourier analysis has some limitation such as unable to process non-stationary signals.

To the data of Fig.1, the EMD algorithm is applied. Fig.3 displays the empirical mode decomposition in ten IMFs of the vibration signal in Fig.1. The decomposition identifies ten modes:

$c_1 \sim c_9$ represents the frequency components excited by the crack defects, c_{10} is the residue, respectively. Mode c_1 contains the highest signal frequencies, mode c_2 the next higher frequency band and so on. The transient caused by the crack faults is clearly captured in mode c_1.

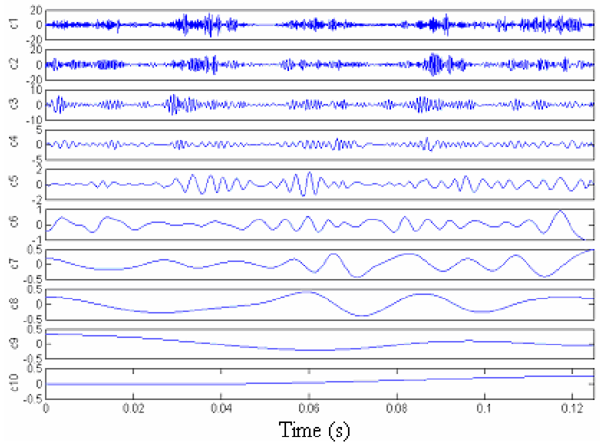

Fig.3 IMFs of the vibration signal shown in Fig.1

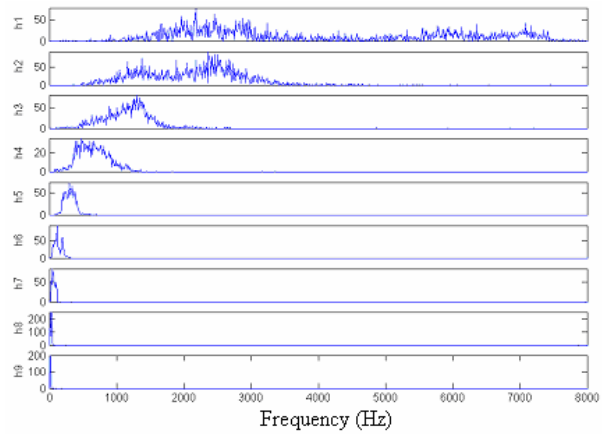

Fig.4 Marginal spectrum of IMFs

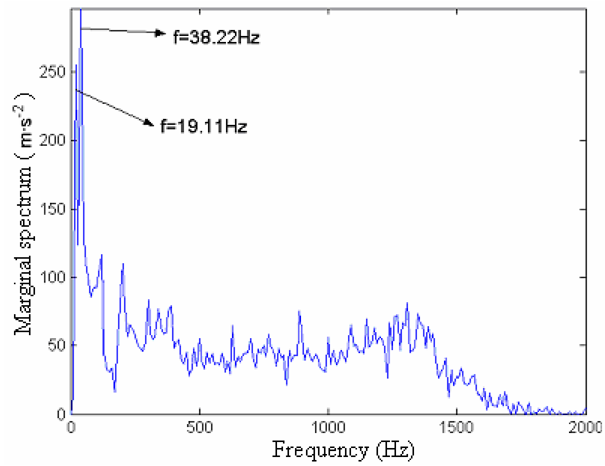

Fig.5 Marginal spectrum of vibration signal

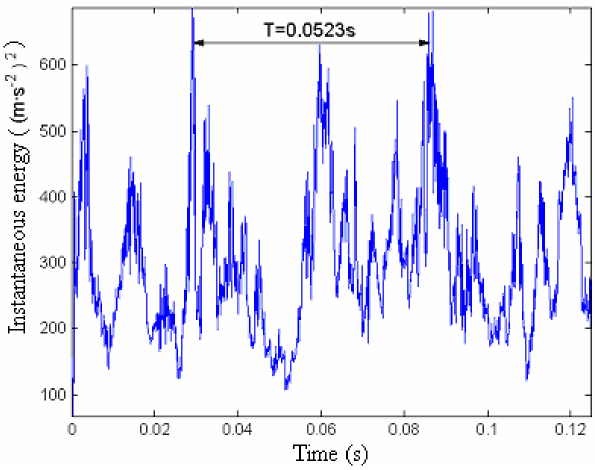

Fig.6 Instantaneous energy of the signal

From Fig.3, it can be easily proven that the EMD decomposes vibration signal very effectively on an adaptive method. The Hilbert-Huang transform can be applied to each IMF $c_i(t)$, resulting in marginal spectrum $h_i(\omega)$. This is shown in Fig.4. The mode c_1 with marginal spectrum centered from 1000 Hz to 8000 Hz and mode c_2 with marginal spectrum centered from 600 Hz to 4000 Hz. Therefore, it is can be concluded that mode c_1 and mode c_2 are the high frequency noise. The mode c_3 with marginal spectrum centered at 1376Hz, which can be obviously associated with the second harmonic of the meshing frequency. Mode c_4, c_5, c_6 and c_7 are associated with the high harmonic of the rotational frequency of the output shaft. The mode c_8 with marginal spectrum centered at 38.22 Hz, which can be obviously associated with the second harmonic of the rotational frequency of the output shaft and mode c_9 with the rotational frequency of the output shaft itself (19.11Hz). Moreover, the amplitude of the marginal spectrum h_8 and h_9 are larger than that of the others. So it can be concluded that the crack faults is occurred in the gear of output shaft. Therefore, it seems that mode c_9 best represents the time scale of the transient caused by gear crack damage. In other words, the IMF mode c_9 is related to gear crack defect of the output shaft. The total marginal spectrum is shown in Fig.5.

The instantaneous energy $IE(t)$ is shown in Fig.6. The presence of crack results in a sudden increase of vibration energy. In Fig.6, the instantaneous energy is relatively high and has the period impulse associated with period of the output shaft revolution.

Conclusions

In this paper, a method for gear crack fault diagnosis was presented based on a newly developed signal processing technique named as Hilbert-Huang transform. We have obtained that the original vibration signals of gear crack fault can be decomposed in ten intrinsic modes. Using EMD method, we can recognize the vibration modes that coexist in the system, and to have a better understanding of the nature of the fault information contained in the vibration signal. The experimental result has been shown that marginal spectrum and instantaneous energy can be used as a diagnostic feature for gear crack faults.

Acknowledgement

The authors are grateful to the National Natural Science Foundation of China for supporting this research under grant No. 50375157.

References

[1] L.Cohen: *Time-frequency analysis* (Prentice-Hall, Englewood Cliffs, NJ, 1995).
[2] J.Lin and L. Qu: *Journal of Sound and Vibration*,Vol.234 (2000), No. 1, pp.135-148.
[3] W.J.Staszewski: *Journal of Sound and Vibration*, Vol.211 (2000), No. 3, pp.736-760.
[4] C.James Li and Jun Ma: *NDT&E International*, Vol.30 (1997) No. 3, pp.143-149.
[5] S.Prabhakar, A.R.Mohanty and A.S Sekhar. *Tribology International*, Vol.3 (2002), pp.793-800.
[6] W.J.Wang and P.D.Mcfadden: *Mechanical Systems and Signal Processing,* Vol. 9 (1995), No.5, pp.497-507.
[7] W.J.Staszewski, K. Worden and G.R.Tomlinson: *Mechanical Systems and Signal Processing*, Vol.11(1997), No.5, pp.673-692.
[8] L. Galleani and L. Cohen: *Physics Letters A*, Vol.302 (2002), pp.149-155.
[9] G. Matz and F. Hlawatsch: *Signal Processing,* Vol. 83 (2003), pp.1355-1378.
[10] N .E Huang, Z. Shen and S.R.Long et al : Proceeding of Royal Society London, Series A. Vol. 454 (1998), pp.903～995.
[11] W. Huang, Z. Shen, N. E. Huang and Y.C.Fung: *Proc of the National Academy of Sciences*, USA, Vol. 96(1999), pp.1834～1839.
[12] W. Huang, Z. Shen, N.E. Huang and Y.C.Fung: *Proc of the National Academy of Sciences*, USA, Vol.95(1998), pp.4816～4821.
[13] W. Huang, Z. Shen, N.E.Huang and Y. C. Fung: *Proc of the National Academy of Science*, USA, Vol.95(1998), pp.12766-12771.
[14] N.E.Huang，Z.Shen and S.R.Long: *Annual Review of Fluid Mechanics*, Vol.31(1999), pp.417～457.
[15] M.Datig and T.Schlurmann: *Ocean Engineering*, Vol.31(2004), pp.1783～1834.
[16] J.Nunes, Y.Bouaoune, E.Delechelle, O.Niang and P.Bunel: *Image and Vision Computing*, Vol.21(2003) , pp. 1019-1026.
[17] S.Quek, P.Tua and Q.Wang: *Smart Materials and Structures*, Vol.12 (2003), pp. 447-460.