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Application of Hilbert-Huang signal processing to ultrasonic non-destructive testing of oil pipelines*

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Abstract: In this paper, a detection technique for locating and determining the extent of defects and cracks in oil pipelines based on Hilbert-Huang time-frequency analysis is proposed. The ultrasonic signals reflected from defect-free pipelines and from pipelines with defects were processed using Hilbert-Huang transform, a recently developed signal processing technique based on direct extraction of the energy associated with the intrinsic time scales in the signal. Experimental results showed that the proposed method is feasible and can accurately and efficiently determine the location and size of defects in pipelines.

Key words: Time-frequency analysis, Hilbert-Huang transform, Empirical mode decomposition (EMD)
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INTRODUCTION

Ensuring the integrity and safe operation of oil pipelines network is critical for ensuring the transportation of one of the most important forms of energy. An inspection vehicle, called intelligent pig, which employs ultrasonic non-destructive testing technique is often used to inspect oil transmission pipelines (Okamoto *et al*., 1999; Reher *et al*., 2002). The ultrasonic detection principle involves the fundamental concept that a propagating wave will be reflected and/or partly transmitted when it encounters a defect or boundary. From the speed of the propagating wave at selected locations, the presence of a defect and its location can be deduced. Therefore, precise detection and identification of defects in pipeline requires an appropriate method for analyzing the signal. Many methods proposed for analyzing ultrasonic signals mainly apply analyses of frequency or time domain, but the non-stationary nature of ultrasonic signals, as with many real-world signals, makes those analyses unsatisfactory since their frequency components change with time (Yamani *et al*., 1997). Recently, many time-frequency analysis methods, e.g. short-time Fourier transform, Gabor transform or Wigner-Ville distribution as well as the wavelet-based approaches have been developed to analyze ultrasonic NDT (Nondestructive Testing) signals (Abbate *et al*., 1995; Malik and Saniie, 1996; Qidwai *et al*., 1999; Legendre *et al*., 2001; Michalodimitrakis and Laopoulos, 2001). Among available time-frequency analysis methods, wavelet transform may be the best one and so, has been widely used for ultrasonic signal analysis (Bettayeb *et al*., 2004) although wavelet transform still has some inevitable deficiencies. For ultrasonic pipeline inspection, the frequency of ultrasonic signals for analysis is often rather high, and according to the Shannon sampling theory, high sampling speed is needed, and sequentially, large size samples are needed for detecting the defect. Thus, it is expected that a desired time-frequency analysis method should not require too much computation time. Computing of wavelet transform is somewhat time consuming and is not suitable for voluminous data. Additionally, due to the

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limitations of the Heisenberg-Gabor inequality, wavelet transform cannot achieve fine resolutions in both time and frequency domain simultaneously.

In this paper, we use a new time-frequency analysis method, called Hilbert-Huang transform (HHT), first introduced by Huang *et al*.(1998). The key to this signal processing technique is a process called empirical mode decomposition (EMD) by which complicated signals can be adaptively decomposed into a set of monocomponent signals, defined as intrinsic mode functions (IMF). The different components sum up to the signal itself exactly to be within the round-off error of the computer, and using Hilbert transform on those obtained components, we can get the full energy-frequency-time distribution of the signal, designated as the Hilbert-Huang spectrum. It has good computation efficiency and does not involve the concept of time resolution and frequency resolution.

This paper first gives a brief description of the empirical mode decomposition, of the Hilbert transform on the extracted intrinsic modes. Then, the Hilbert-Huang method was successfully applied to the spectrum analysis of ultrasonic defect signals. Finally, the experimental results are analyzed and the main conclusions of this paper are presented.

BRIEF OVERVIEW OF HILBERT-HUANG TRANSFORM

Empirical mode decomposition

Hilbert transform was first developed to process non-stationary narrow-band signals. In almost all practical applications, the signal to be treated is not monocomponent but is multicomponent, and it prevents the important concept of the instantaneous frequency from being extensively applied. To make the instantaneous frequency applicable, Huang *et al*. (1998) presented a signal decomposition method, referred to as empirical mode decomposition, which can decompose a signal into some individual, monocomponent signals, defined as intrinsic mode function to which the instantaneous frequency can be applied. The EMD preprocessor-based Hilbert transform is named Hilbert-Huang transform.

The empirical mode decomposition is developed from the simple assumption that any data consist of different simple intrinsic modes of oscillation. The essence of the method is to identify the intrinsic oscillatory modes by their characteristic time scales in the data and then decompose the data accordingly.

By applying the empirical mode decomposition to get the IMFs ($x_j(t)$), an arbitrary signal $x(t)$ can be expressed as

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

where n is the total number of IMFs and $r(t)$ is the residue of the sifting process.

An IMF extracted by EMD represents simple oscillatory mode imbedded in the signal. It is a function that satisfies the following conditions: (1) the number of extremes and the number of zero crossings in the whole data set must be either equal or differ at most by one in the whole dataset, and (2) at any instant in time, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The residue shall not contain any kind of oscillation and should be a constant or a data trend.

Hilbert transform and Hilbert spectrum

Hilbert transform, a well-known signal analysis method, essentially defined as the convolution of signal $x(t)$ with $1/t$ and can emphasize the local properties of $x(t)$, as follows:

$$y(t)=\frac{P}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}\mathrm{d}\tau, \tag{2}$$

where P is the Cauchy principal value. Coupling $x(t)$ and $y(t)$, we can have the to be analyzed signal $z(t)$ of $x(t)$, as

$$z(t)=x(t)+\mathrm{i}y(t)=a(t)\mathrm{e}^{\mathrm{i}\varphi(t)}, \tag{3}$$

where

$$a(t)=\sqrt{[x(t)]^2+[y(t)]^2}, \tag{4}$$

$$\varphi(t)=\arctan\left[\frac{y(t)}{x(t)}\right], \tag{5}$$

$a(t)$ is the instantaneous amplitude of $x(t)$, which can reflect how the energy of $x(t)$ varies with time, and $\varphi(t)$ is the instantaneous phase of $x(t)$.

One important property of the Hilbert transform is that if the signal $x(t)$ is monocomponent, then the time derivative of instantaneous phase $\varphi(t)$ will be the physical meaning of signal $x(t)$'s instantaneous frequency $\omega(t)$ expressed as follows:

$$\omega(t)=\frac{\mathrm{d}\varphi(t)}{\mathrm{d}t}. \tag{6}$$

Having obtained the IMFs, we can apply the Hilbert transform on each IMF, and compute the instantaneous frequency and amplitude according to Eqs.(4), (5) and (6). After performing the Hilbert transform on each IMF component, the signal can be expressed in the following form:

$$x(t)=\sum_{j=1}^{n}a_j(t)\exp\left(\mathrm{i}\int w_j(t)\mathrm{d}t\right). \tag{7}$$

Eq.(7) enables us to represent the amplitude (or the energy), and instantaneous frequency as functions of time in a three-dimensional plot. The frequency-time distribution of the amplitude is designated as the Hilbert-Huang spectrum $H(\omega, t)$. Amplitude squared is more desirable, commonly when we want to represent the energy density, in this case we can plot the energy density versus frequency and time to yield the Hilbert-Huang energy spectrum.

PROPOSED ALOGORITHUM FOR NDT DEFECT DETECTION

To investigate the possibility of application of this method to oil pipelines ultrasonic non-destructive testing, we analyzed a pipe sample with artificial defects. The sample was steel pipe with different depths 1.0 mm wide axial slots. In this investigation, ultrasonic pulse-echo technique was used to find defects or cracks in the pipe. Pulse-echo signals were acquired from the internal pipe walls by a wide-band ultrasonic receiver. A 5 MHz center frequency was selected in this study because at this frequency strong responses from cracks in pipe material have been obtained and attenuation due to the grain structure was apparently not significant. A sample pulse rate of 100 MHz was used for waveforms in this study. The received signal in time domain was converted to that in time-frequency domain by Hilbert-Huang transform. Then, the extracted time-frequency features were used with classification algorithms to distinguish ultrasonic echoes from pipes with and without defects.

To obtain the time-frequency features, EMD decomposition was directly applied to the original signal to generate the intrinsic mode functions and Hilbert transform was applied to these modes.

Regarding a received ultrasonic signal $x(t)$, the IMFs are obtained using the following algorithm (Huang *et al*., 1998):

Step 1: Initialize: $r_0(t)=x(t)$, $i=1$

Step 2: Extract the ith IMF:

(1) Initialize: $h_0(t)=r_i(t)$, $k=1$;

(2) Extract the local maxima and minima of $h_{k-1}(t)$;

(3) Interpolate the local maxima and the local minima by a cubic spline to form upper and lower envelopes of $h_{k-1}(t)$;

(4) Calculate the mean $m_{k-1}(t)$ of the upper and lower envelopes of $h_{k-1}(t)$;

(5) Define: $h_k(t)= h_{k-1}(t)-m_{k-1}(t)$;

(6) If IMF criteria are satisfied, then set $x_i(t)=h_k(t)$ else go to Step 2(2) with $k=k+1$.

Step 3: Define: $r_i(t)=r_{i-1}(t)-x_i(t)$

Step 4: If $r_i(t)$ still has at least two extremes, then go to Step 2 with $i=i+1$; else the decomposition is completed and $r_i(t)$ is the "residue" of $x(t)$.

Fig.1 shows the received signal from the pipe with a slot which depth of 3.6 mm. As shown in Fig.1, the first peak of this wave denotes the transmitted pulse and its occurrence time can be easily estimated,

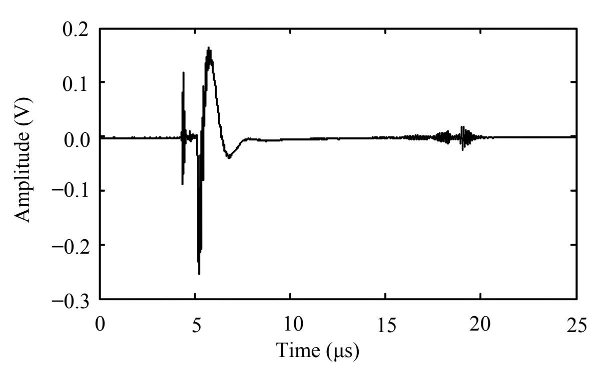

Fig.1 Received signal from pipe with defect

therefore, to judge whether a slot exists or not, the first task is to detect the envelope of the first maxima and separate it from the remaining peaks. Then, with the help of the decomposition algorithm explained above, decompose the remaining signal into the seven IMFs and the residue of this signal in Fig.2. It can be observed that the first IMF component has relatively higher amplitude than the other IMFs. Obviously, the first IMFs contain the main information on defects.

In Fig.3c, we display a contour-plot of the Hilbert-transform $H(\omega, t)$ of the original signal. Obviously, the HHT spectrum has shown the defects and has denoted its occurring time clearly and accurately in the time-frequency domain. The location of the slots can be estimated with the arrival time of the energy peaks (the points of maximum energy) in the Hilbert spectrum corresponding to crack-reflected waves.

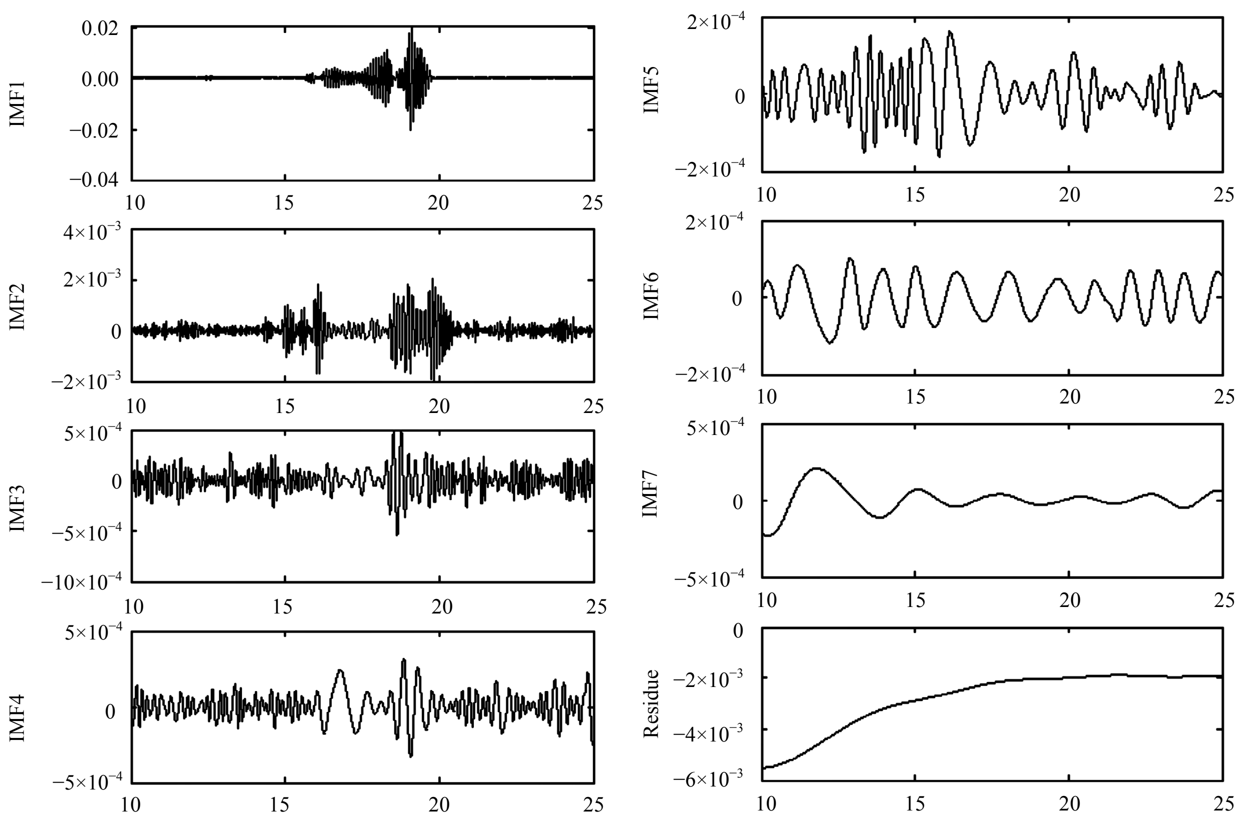

Fig.2 The seven IMFs and the residue of the original signal

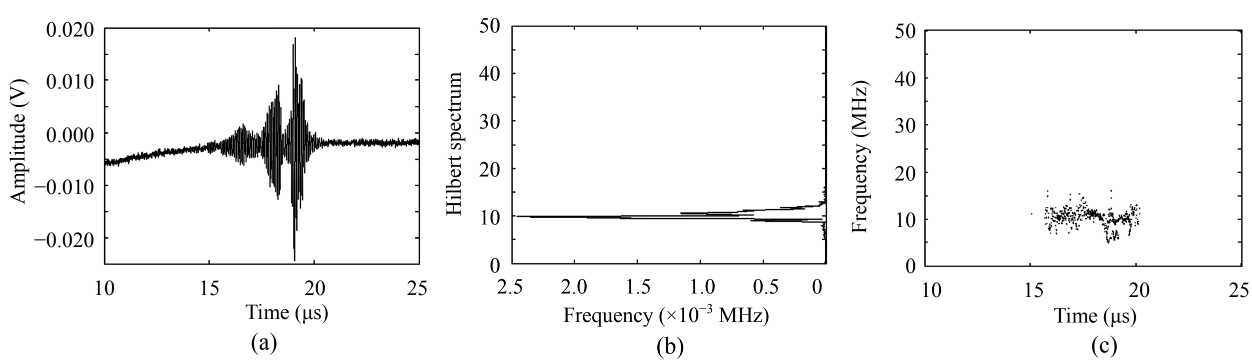

Fig.3 (a) The defect signal; (b) Hilbert spectrum of the defect signal; (c) HHT spectrum of the defect signal

In the Hilbert spectrum of the received signal (Fig.3b), we can see that most of the signal energy along time, accumulates around 10 MHz. There is clearly a peak around 10 MHz, which shows a persistent accumulation of energy in the Hilbert spectrum, around this value.

The preceding results demonstrated the usefulness of Hilbert-Huang transform as a signal processing technique for the analysis of ultrasonic waveforms. The time-frequency features extracted from Hilbert-Huang transform also appear to be effective in classification and require less computation. The results are not presented here because of space limitation.

CONCLUSION

This paper deals with the use of Hilbert-Huang technique to analyze ultrasonic signals. Use of HHT based logarithm for oil pipelines detection and localization has showed the usefulness and effectiveness of the proposed algorithm for these purposes.

The results showed that one of the advantages of HHT is that its most computation consuming step, EMD operation, does not involve the convolution and other time-consuming operations, therefore the HHT can deal with voluminous data on signals. Numerical tests showed that the procedure requires much less computer time than wavelet transform method for ultrasonic signals analysis. Additionally, the Hilbert-Huang spectrum does not involve the concept of frequency and time resolution but that of instantaneous frequency. HHT is a promising tool for analyzing ultrasonic non-destructive testing signals.

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