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Ultrasonic Thickness Inspection of Oil Pipeline Based on Marginal Spectrum of Hilbert-Huang Transform

Yimei MAO, Peiwen QUE, Qi ZHANG

Department of Instrument Science and Engineering, Shanghai Jiaotong University; Shanghai, P.R.China

Phone: +86 21 34205295, Fax: +86 21 34205372;

e-mail: ymmao@sjtu.edu.cn, pwque@sjtu.edu.cn, zhangqi2004@sjtu.edu.cn

Abstract

Measurement of pipeline wall thickness is one of the main contents of nondestructive inspection on offshore oil pipeline. A novel approach based on the marginal spectrum of the Hilbert-Huang transform is proposed for ultrasonic echo signal processing. The demodulated ultrasonic echo signal contains the thickness information of pipeline wall, which is an approximately periodic signal. The marginal spectrum is obtained by applying Hilbert-Huang transform to the ultrasonic echo signal. It effectively reveals the information of wall thickness of pipeline. The relation between the main frequency and the wall thickness of pipeline is established to calculate the wall thickness. The validity and the robustness of the proposed method are shown by signals collected by ultrasonic pipeline intelligent gage.

Keywords: marginal spectrum, Hilbert-Huang Transform, ultrasonic thickness inspection, pipeline inspection, ultrasonic signal processing

1. Introduction

It is very important to inspect the pipeline in time, because those offshore oil pipelines are prone to internal corrosion usually by the presence of the water (salty or not), external damage by anchor or others[1]. The ultrasonic nondestructive inspection technique is currently the most common used pipeline inspection method which can detect metal loss and cracks of pipelines accurately[2]. The pipeline corrosion can be judged by the residual value of the pipeline wall thickness which can be estimated by the ultrasonic echo signals acquired and stored for pipeline inspection using ultrasonic in-line inspection device. In order to acquire the value of pipeline wall thickness, the frequency of the pipeline wall thickness must be estimated according to the ultrasonic echo signals firstly. But the classic frequency estimation method, such as Fourier transform, may cause some problems with its low resolution because of acquired ultrasonic echo signal with noise.

Recently, Hilbert-Huang Transform (HHT) which was proposed by N.E. Huang, et al in 1998 is a promising signal processing technique coping with nonlinear and nonstationary time series[3]. In this paper marginal spectrum of HHT is adopted for ultrasonic echo signal processing to obtain the accurate pipeline wall thickness in order to increase the resolution. The Hilbert-Huang transform has two components, one is empirical mode decomposition (EMD) to obtain the intrinsic mode functions (IMF), the other is applying Hilbert transform for IMFs to get marginal spectrum. The marginal spectrum offers a measure of total amplitude (or energy) contribution from each frequency value. It represents the cumulated amplitude over the entire data span in a probabilistic sense. The contribution of the amplitude from each frequency is measured by the marginal spectrum.

In this paper, ultrasonic echo signals are collected by ultrasonic pipeline intelligent gage (pig) from the inside out. Ultrasonic echo signals about pipeline wall thickness are analyzed by HHT to get the frequency value of the pipeline wall thickness according to the marginal spectrum of HHT. The results show that the pipeline wall thickness based on the marginal spectrum has high inspection accuracy, especially for the ultrasonic echo signals with high noises.

2. Marginal Spectrum of the Hilbert-Huang Transform

Hilbert-Huang Transform has proven to be a powerful tool for the analysis of nonlinear and nonstationary signal. It consists of two parts: empirical mode decomposition and Hilbert spectral analysis (HSA).

2.1 Basics of the empirical mode decomposition method

With the empirical mode decomposition method, any complicated data set can be decomposed into a finite and usually small number of intrinsic mode functions. An IMF is defined as a function satisfying the followin g conditions:

(a) In the whole dataset, the number of extrema and the number of zero-crossings must either equal or differ at most by one;

(b) 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 is developed from the simple assumption that any signal consists of different simple intrinsic mode oscillations. The essence of the method is to identify the intrinsic oscillatory modes by their characteristic times scales in the signal and then decompose the signal accordingly. The characteristics time scale is defined by the time lapse between the successive extremes. The EMD algorithm will not be described here due to the limitation of the length of the paper. The readers are referred to [4] for details.

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. And the residue shall not contain any kind of oscillation and should be a constant or a data trend.

2.2 The Hilbert-Huang transform and marginal spectrum

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

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

where P is the Cauchy principal value. Coupling $x(t)$ and $y(t)$, an analytic signal $z(t)$ can be produced by

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

where

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

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

Here, $a(t)$ 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:

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

EMD is a necessary pre-processing of the data before the Hilbert transform is applied. It reduces the data into a collection of IMFs and each IMF, which represents a simple oscillatory mode, is a counterpart to a simple harmonic function, but is much more general.

Having obtained the IMF components, one will have no difficulty in applying the Hilbert transform to each IMF component, and in computing the instantaneous frequency according to the Eqs. (4), (5) and (6). After performing the Hilbert transform on each IMF component, the original signal can be expressed in the following form:

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

Eq. (7) enables us to represent the amplitude and instantaneous frequency as functions of time in a three-dimensional plot. The frequency-time distribution of the amplitude is designated as the Hilbert spectrum $H(\omega, t)$.

With the Hilbert spectrum defined, we can also define the marginal spectrum $h(\omega)$ as

$$h(\omega) = \int_0^T H(\omega, t) dt . \tag{8}$$

The marginal spectrum offers a measure of the total amplitude (or energy) contribution from each frequency value. This spectrum represents the accumulated amplitude over the entire data span in a probabilistic sense.

3. Method of wall thickness measurement

The ultrasonic echo signals used in this paper are collected by a ultrasonic pipeline intelligent gage. The smart pig runs through a single 325 mm pipeline buried underground. The pipeline is made of continuous welded, carbon steel sections. The smart pig utilizes ultrasonic sensors to measure the wall thickness. The sensor sends out an ultrasonic pulse signal, which is bounced off and through the pipe wall. The echo from the wall is time measured by perpendicular incidence to determine the size and extent of the internal and external defects. All the ultrasound data gathered during the inspection are digitized and stored in a mass storage unit within the pig modules. Figure 1 shows one sample of the demodulated ultrasonic echo signals.

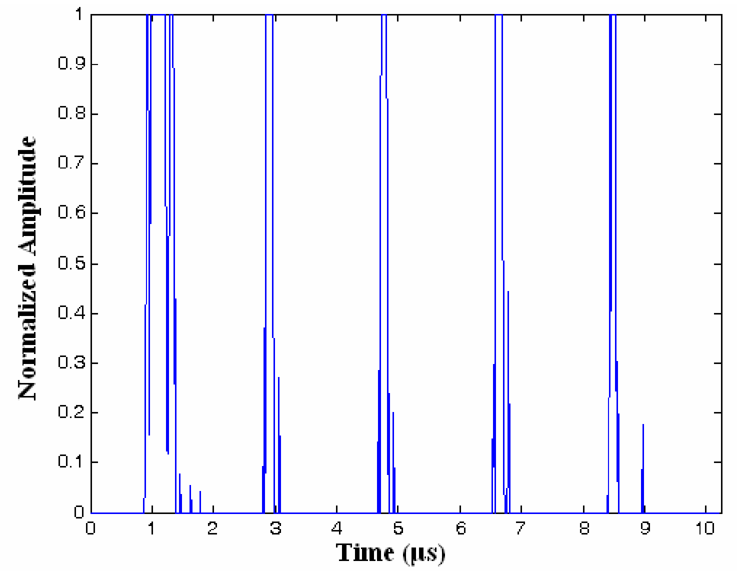

Figure 1. Ultrasonic echo signal from pipeline wall

It is easy to see that the demodulated ultrasonic echo signal contains the thickness information of pipeline wall, which is an approximately periodic signal. The wall thickness can be estimated accurately to a great extent according to the period of the signal. To get the period of the signal, Hilbert-Huang transform is adopted.

Ultrasonic echo signal is typical nonstationary signal, which can be accurately decomposed by empirical mode decomposition. Then by Hilbert transform, we can obtain Hilbert spectrum and marginal spectrum of the ultrasonic echo signal. Figure 2 shows the marginal spectrum of the ultrasonic echo signal. It can be clearly seen that the energy mainly concentrates on lower frequency domain. It is easy to see that the signal energy is mainly concentrated on the main frequency. On the other hand, one has no difficult in seeing the main frequency is precisely the reciprocal of signal period. Figure 3 shows the main frequency of the ultrasonic echo signal. It is easy to see from the right figure that the main frequency concentrates on about 0.226, which is the reciprocal of the signal period.

From the above analysis, it is concluded that the marginal spectrum effectively reveals the information of wall thickness of pipeline. Therefore, the relation between the main frequency and the wall thickness of pipeline is established.

$$d = v / 2f \, , \tag{9}$$

where d is the wall thickness of pipeline, v is the sound velocity in the steel pipeline and f is the main frequency obtained from the marginal spectrum of HHT.

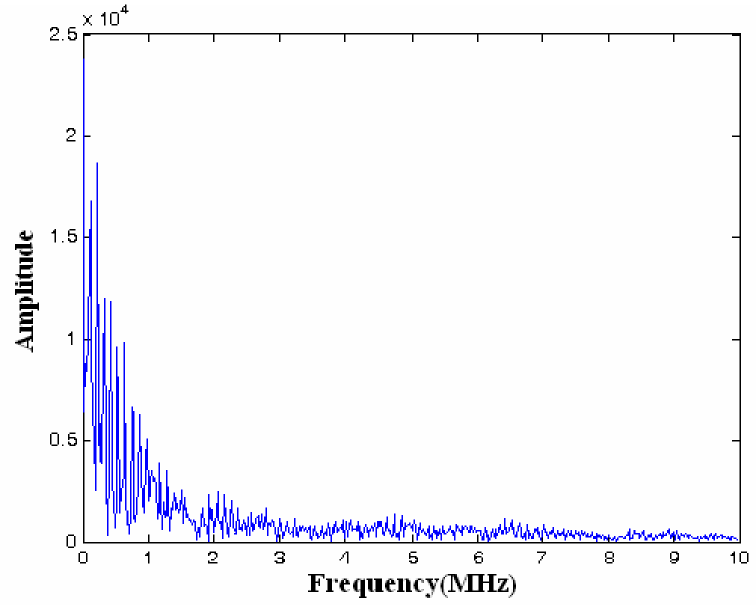

Figure 2. Marginal spectrum of the ultrasonic signal in Figure 1

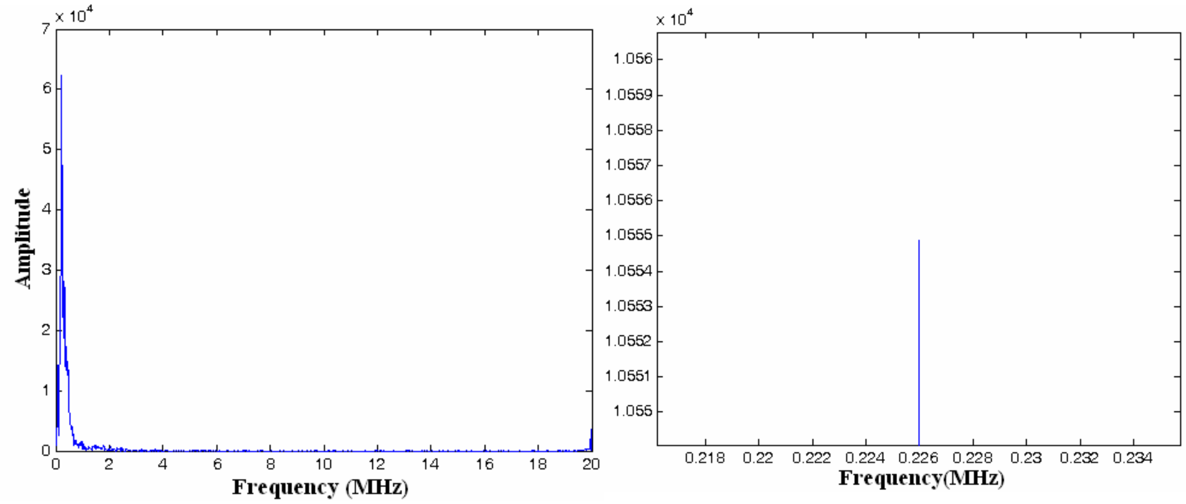

Figure 3. Main frequency of the ultrasonic signal in Figure1

A great number of experiments have been conducted to verify the conclusion. The results show that the pipeline wall thickness based on the marginal spectrum has high inspection accuracy, even for the ultrasonic echo signals with high noises. Moreover, it measures pipeline wall thickness to an accuracy of ±0.2mm. The main frequency can be calculated correctly by means of adding white noise. A great number of experiments also show that the proposed method is valid even for the ultrasonic echo signal from defect which periodicity is very weak. Figure 4 is the ultrasonic echo signal from an internal defect. The wall thickness can be calculated correctly from its marginal spectrum of HHT as shown in Figure 5.

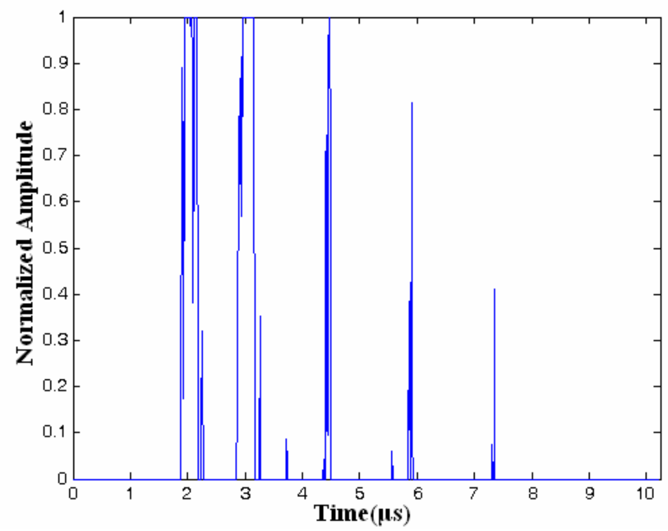

Figure 4. Ultrasonic echo signal from pipeline wall with internal defect

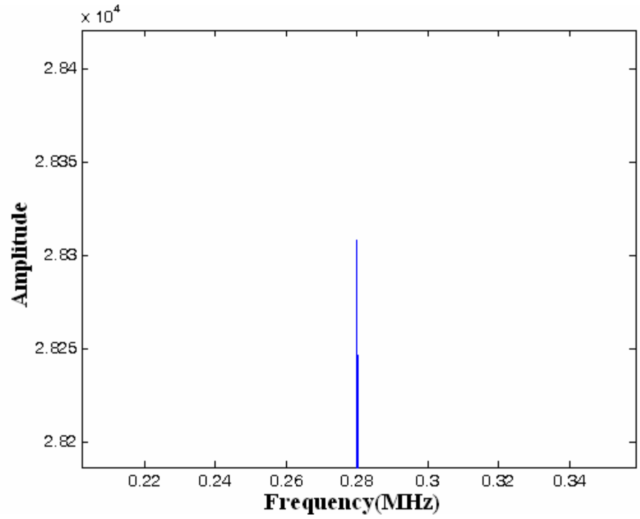

Figure 5. Main frequency of the ultrasonic signal in Figure 4

4. Conclusion

The demodulated ultrasonic echo signal contains the thickness information of pipeline wall, which is an approximately periodic signal. Hilbert-Huang Transform is an adaptive powerful method to analyze nonlinear and nonstationary time series. In this paper, a novel method based on the marginal spectrum of HHT is presented to analyze the ultrasonic echo signal. Firstly marginal spectrum is obtained by applying EMD and Hilbert transform to the ultrasonic echo signal. It provides higher resolution and energy concentration in frequency plane. The marginal spectrum effectively reveals the information of wall thickness. Thus, the relation between the main frequency and the wall thickness of pipeline is established. The examples indicate that the proposed method is simple, powerful and effective. It provides higher resolution and energy concentration in frequency plane.

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