Evaluation of Stress Using Ultrasonic Technique Based on Hilbert-Huang Transform

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Abstract. Pressures vessel are widely used in the modern industry. It is important to measure pressure of vessels. It has been proved that the change of ultrasonic velocity can be used to detect the stress of the material, and the velocity change can be obtained by estimating the time delay of two ultrasonic pulses. In this paper, the Rayleigh wave is selected as the ultrasonic pulse. Because the Rayleigh wave usually contains noise which deteriorates the estimation precision of the time delay, a signal processing method has to be used. Compared with the continuous wavelet transform, the correlative time estimation method based on the Hilbert-Huang Transform is presented in order to calculate the transit time difference. The experiments results show that this method can improve the accuracy of the time estimation.

1. Introduction

Pressure vessels are popular used in the modern industry. It is very important to measure the pressure in vessels for ensuring vessels working properly. Lin [1,2]develops a novel method to measure the pressure noninvasively based on the Rayleigh wave. This method establishes the relationship between the transit time difference and the vessel pressure. Therefore, it is critical to estimate the time difference of two ultrasonic pulses.

To improve the time estimation precision and capability of anti-interference, many methods have been put forward, such as the delay line method, Sing-around method, pulse-echo-overlap-method. But there are some restrictions: complex apparatus; hard to automatic check, etc. With the development of the electronic technology, the digital signals of ultrasonic, whose frequency is above $10^6$ Hz, can be obtained with fast a A/D acquisition card. Based on this technology, the digital signal processing Cross-Correlation Function (CCF) was presented to estimate the time delay. Unfortunately, due to the pulse high attenuation and distortion, the waveforms of two measured ultrasonic pulses had large difference. As a matter of fact, the time delay results estimated based on CCF often have large errors and the repeat errors are high.

As a result, a signal processing method should be used. The wavelet transform is one of the effective signal processing methods. In recent years another method named Hilbert-Huang Transform (HHT) [3] is becoming more and more popular. In this paper, those two methods were compared and the HHT was chose. The HHT technique works through performing empirical mode decomposition (EMD) on the signal; and then the signal will be decomposed into a set of intrinsic mode function (IMF). Some of the IMF contain the most of noise, and others represent actual signal components. Utilizing those IMFs and the CCF method, we can get the time delay accurately.
2. Brief Introduce of Hilbert-huang Transform

For an arbitrary time series, \( x(t) \), we can always have its Hilbert Transform, \( y(t) \), as following:

\[
y(t) = \frac{P}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau
\]

where \( P \) indicates the Cauchy principal value. Coupling \( x(t) \) and \( y(t) \), an analytical signal, \( z(t) \), can be given:

\[
z(t) = x(t) + iy(t) = a(t)e^{i\phi(t)}/2)
\]

where

\[
a(t) = \left[ x^2(t) + y^2(t) \right]^{1/2}, \quad \phi(t) = \arctan(y(t)/x(t)).
\]

Instantaneous frequency \( \omega(t) \) can be defined as the time derivative of instantaneous phase \( \phi(t) \):

\[
\omega(t) = \frac{d\phi(t)}{dt}
\]

EMD can decompose a signal into some individual, nearly monocomponent signals named intrinsic mode function (IMF) [4]. The Hilbert transform is utilized to each IMF, and then compute the amplitude and instantaneous frequency according to Eq. (3) and Eq. (4). After performing the Hilbert transform on each IMF component, the signal can be expressed as:

\[
x(t) = \sum_{j=1}^{n} a_j(t) \exp(i\int \omega_j(t) dt)
\]

where \( a_j(t) \) is the instantaneous amplitude, and \( \omega_j(t) \) is the instantaneous frequency.

The frequency-time distribution of the amplitude is designated as the Hilbert-Huang spectrum, \( H(\omega, t) \). The time integral of Hilbert-Huang spectrum is the Hilbert marginal spectrum \( h(\omega) \):

\[
h(\omega) = \int_0^T H(\omega, t) dt
\]

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. Consequently, the frequency in the marginal spectrum indicates the likelihood that there exists an oscillation with such a frequency.

3. Proposed Approach

3.1. Modeling in Theory

For the cylindrical vessel, shown in Figure 1, based on the model of the Rayleigh wave measuring stress and the thin film theory of vessels, the relationship between the transit time difference and the pressure in circumference direction can be deduced:
\[ \Delta t = \left[ \frac{2 - \mu}{2E} - K \right] \frac{R t_0}{\delta} p \]  

where \( E \) denote Young’s modulus, \( \mu \) is Poisson’s ratio of the material, \( K \) is a value relative to the Rayleigh wave acoustoelastic coefficients [5]. \( R \) is the outer radius and \( \delta \) is the thickness of the vessel wall. \( t_0 \) is the transit time of Rayleigh wave in circumferential direction. \( \Delta t \) is transit time difference and \( p \) is the pressure of vessel.

According to Eq. (7), after the transit time difference \( \Delta t \) is determined, the pressure of vessel \( p \) is computed. \( \Delta t \) can be obtained by estimating the time delay of two ultrasonic pulses used the CCF method based on the Hilbert-Huang transform. The fundamental theory of this method has been presented in Figure 2 Two ultrasonic pulses \( x_1(t) \) and \( x_2(t) \) are processed and analyzed through Hilbert-Huang transform, thus two signals \( y_1(t) \) and \( y_2(t) \) are derived. So the CCF method will be applied in order to \( y_1(t) \) and \( y_2(t) \) to obtain the time delay \( \Delta t \).

3.2. Comparison between HHT and wavelet transform

If the distance of two ultrasonic transducers is close, the signal to noise ratio would be high, as shown in Figure 3, in which the distance of two transducers is 80mm. But in this pressure measurement experiment the distance should be long so as to reflect more stress information of the vessel. When the distance is 300mm, the ultrasonic signal is shown in Figure 4. From this figure we can see, the signal to noise ratio is very low. Consequently, a denoising method must be used.

The Signal frequency used in this experiment is 2.5MHz. EMD can decompose the signal into a set of intrinsic mode function. Some of the IMFs contain the most of noise, others represent actual signal components [6]. Figure 5 shows the marginal spectrum of each IMF in order to discriminate useful and disturbed component of the ultrasonic signal. In Figure 5, it is shown that the amplitude integral attain maximum in the frequency 2.5MHz and IMF1, IMF2 have little amplitude integral in frequency 2.5MHz. IMF3~IMF5 include most of amplitude integral in the frequency 2.5MHz. IMF6~IMF8 are mainly the low frequency disturbance. It is concluded that IMF3~IMF5 could be used as the substitute of the whole ultrasonic signal in CCF time estimation.

The wavelet transform has become a well accepted signal processing tool and has been widely used for eliminating noise. Based on many experiments simulated, it is found that the high SNR could be obtained when using the sym8 kernel function. As a result, the sym8 kernel is chose.

A perfect ultrasonic signal is shown in Figure 3. The SNR of this signal is very high. But the original signal shown in Figure 4 has a low SNR. So, the HHT and wavelet transform should be applied to the original signal. The results of the HHT and wavelet transform are shown in Figure 6. From this figure we can see, the result of the HHT is more approximate to perfect ultrasonic signal than the result of the wavelet transform.

Compared the time estimation used HHT with used wavelet transform, results is shown in table 1. Table 1 clearly demonstrates the time delay estimation using HHT is closer to the expected time delay than time delay using wavelet transform. It confirms that the HHT method outperforms the wavelet transform and it can improve the estimation precision of time delay.
Figure 5. Marginal spectrum of IMF1–IMF8.
4. Conclusion
In this study, a novel time-frequency analysis method named HHT has been used to process the ultrasonic signal. EMD is utilized on two original ultrasonic signal pulses and some IMFs will be generated at first. Then a simple but effective IMF selection method is used to select the useful IMFs and eliminate the undesired IMFs. Compared this method with the wavelet transform, it is found that HHT can give better denoising results. Utilized HHT, more precise time difference estimation of two ultrasonic pulses has been obtained. Therefore, the pressure of vessel is measured more accurately. Experiment verifies the effectiveness of this method.

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