Application of Hilbert-Huang Transform in Ultrasonic Echo Signal Processing of Composites

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Abstract: The ultrasonic nondestructive testing signals of carbon fiber reinforced composites have the characteristics of non-stationary and low signal-to-noise ratio, and Hilbert-Huang transform has unique advantages in feature extraction of such signals. This paper introduces the basic idea and method of Hilbert-Huang transform, which decomposes ultrasonic echo signals into several intrinsic mode functions, highlights the local characteristics of signals, and then obtains Hilbert spectrogram, marginal spectrum and instantaneous energy spectrum, so as to reveal the process of simultaneous changes of signal energy in time domain and frequency domain.

1. Introduction
When ultrasonic wave is used for nondestructive testing of carbon fiber reinforced composites, defect information will be indicated by the amplitude, frequency or phase of the received ultrasonic echo signal. However, the inhomogeneity and anisotropy of the composites and the complexity of interaction between ultrasonic wave and microstructure of the material result in the non-stationarity of the signals.

A more intuitive method of analysis for non-stationary signals such as ultrasonic echo signals of composites is to use base quantities with locality and basic functions. Instantaneous frequency is a base quantity with locality that easily comes to mind and the concept has long been proposed. A more intuitive definition of instantaneous frequency recognizes it as the derivative of analyzing signal phase, but previously this definition would result in some errors, hence the time-frequency analysis method and theory based on instantaneous frequency has not really been established and developed.

After studying the concept of instantaneous frequency in depth, Huang Norden E and others founded a new method of Hilbert-Huang Transform (HHT). This method creatively puts forward a new concept of Intrinsic Mode Functions (IMF) and steps for decomposing arbitrary signals into intrinsic mode functions—Empirical Mode Decomposition (EMD), which gives a reasonable definition, physical meaning and solution to instantaneous frequency. A new time-frequency analysis method system, which takes instantaneous frequency as the base quantity of signal alternation and intrinsic mode function as the basic time domain signal, is preliminarily established [1-7]. This method system has fundamentally got rid of the constraints of Fourier transform theory, and has already shown some unique advantages in practical application.

Hilbert-Huang transform consists of empirical mode decomposition method and Hilbert transform. Its core is empirical mode decomposition, which decomposes complex signals into several intrinsic mode functions, and then Hilbert transform is performed on intrinsic mode functions to obtain the instantaneous frequency and amplitude of each intrinsic mode function changing with time. Finally, the three-dimensional spectrum distribution of amplitude-frequency-time is obtained [8].
2. Intrinsic Mode Function and Empirical Mode Decomposition

2.1 Intrinsic Mode Function
Reference [1] points out that the limiting conditions that make the instantaneous frequency meaningful are: the function is symmetrical, the local mean value is zero, and the number of zero crossings and is equal to the number of extreme values. Based on this idea, Huang Norden E and others proposed the concept of intrinsic mode function.

The intrinsic mode function must satisfy the following two conditions:

- In the whole data length range, the number of extreme values and the number of zero crossings must be equal or differ by at most one.
- At arbitrary data point, the average value of the envelopes determined by both local maximum and local minimum must be zero.

It is called intrinsic mode function because it represents the intrinsic fluctuation mode of data. According to such definition, IMF is not limited to narrowband signals, can be amplitude modulation, frequency modulation or non-stationary. For each fluctuation period of the intrinsic mode function defined by zero crossing point, there is only one fluctuation mode and no other complex riding wave. Signals that are only amplitude modulated or frequency modulated can also become intrinsic mode functions.

A typical intrinsic mode function is shown in figure 1, and as can be seen from the waveform, this function satisfies the above two conditions.

![Figure1. A typical intrinsic mode function.](image)

2.2 Empirical Mode Decomposition
The process of empirical mode decomposition is as follows: first, the original data is decomposed into the sum of the first IMF and the mean value changing with time; then, the mean value is considered as new data and is decomposed into the second IMF and the new mean value. This decomposition process continues until the last IMF is obtained. The mean value of the last IMF is a constant or trend term. The mean value is obtained by fitting the upper and lower envelopes of the data with cubic spline function, and then determining the average value of the upper and lower envelopes as the mean value.

In order to ensure the accuracy while determining the mean value, multiple iterations are needed until the given criterion is satisfied. EMD should also have a criterion for stopping. Such criterion can be one of the following: stop when the amplitude of the last component or the remaining component becomes smaller than the predetermined value, or when the remaining component becomes a monotone function, and so an IMF cannot be decomposed from it. The selection of this criteria should also be moderate. If the criteria are too strict, then the last few IMFs obtained by decomposition will be meaningless and time-consuming; if the criteria are too loose, useful signal components may be lost.

3. HHT Analysis of Ultrasonic Echo Signal
There are two ways to analyze ultrasonic signals by using Hilbert-Huang transform.
• Intrinsic Mode Function is analyzed in time domain after empirical mode decomposition. Because IMF represents intrinsic fluctuation pattern, analyzing decomposed intrinsic mode function can obtain abundant fluctuation information of signals.

• Hilbert transform is performed on the intrinsic mode function group, and then time-frequency domain, frequency domain and time domain analysis are carried out to respectively correspond to the time-frequency amplitude spectrum, marginal spectrum, empirical mode decomposition diagram and instantaneous energy density of signals.

Based on the research of references on HHT theory, the basic method of HHT time frequency analysis of ultrasonic signals can be summarized:

• Observe whether there is interference in ultrasonic signal. If yes, select a filtering method according to characteristics of the interference and filter the interfered signals.

• Empirical mode decomposition is performed on the signals, and the composition characteristics of the signal can be observed from the time domain.

• After Hilbert transform, the decomposed signal is combined into a time-frequency amplitude spectrum, and various characteristics of the signal can be observed in the time-frequency domain.

• The time is integrated through time-frequency amplitude spectrum to get the marginal spectrum, and characteristics of the signal can be observed in the frequency domain.

• The frequency is integrated through time-frequency amplitude spectrum to get the instantaneous energy density of ultrasonic signal, and characteristics of the signal are extracted in the time domain.

From the basic principle of Hilbert transform based on empirical mode decomposition, the algorithm of Hilbert spectrogram can be obtained:

(a) Perform Hilbert transform on each IMF.
(b) Combine the original IMF and Hilbert transformed IMF into a complex sequence signal according to (1).
\[ z_i(t) = c_i(t) + j d_i(t) = a_i(t)e^{j\theta(t)} \] (1)

As in (1), \( d_i(t) \) is the data sequence after Hilbert transform for each intrinsic mode function \( c_i(t) \) obtained by empirical mode decomposition.
(c) Obtain the amplitude and phase at each time point according to (2) and (3).
\[ a_i(t) = \left[ c_i^2(t) + d_i^2(t) \right]^{1/2} \] (2)
\[ \theta_i(t) = \arctan \left[ \frac{d_i(t)}{c_i(t)} \right] \] (3)

(d) Differentiate the phase to time according to (4) to obtain the instantaneous frequency at each time point.
\[ \omega_i(t) = \frac{d\theta_i(t)}{dt} \] (4)

(e) The Hilbert time spectrum is composed according to the instantaneous frequency and amplitude at each time point.
\[ H(\omega, t) = \text{Re} \sum_{i=1}^{N} a_i(t)e^{j\omega_i(t)dt} \] (5)

According to the above method, the ultrasonic echo signal from carbon fiber reinforced composites sample with flat bottom hole defect shown in figure 2 is selected for empirical mode decomposition, and the decomposition result is shown in figure 3. The signal is decomposed into 10 IMF components and one residual component representing the trend, which are arranged in order from top to bottom. Since the residual component is a monotone function with smaller amplitude and has little effect on the analysis of ultrasonic signal, the influence of the residual component can be completely ignored.
Empirical mode decomposition diagram reveals the essence of ultrasonic signal, especially IMF3 has obvious physical significance. The ultrasonic echo components in the original signal are mainly contained in IMF3 and IMF4. Other modes and residual component can be ignored in amplitude relative to IMF3 and IMF4, which are noise, error of numerical calculation and residual component in extracting the modes. It can be seen that empirical mode decomposition has already decomposed the waveforms of different scales of the original signal.

Figure 4 shows the time-frequency amplitude spectrum of intrinsic mode function of the ultrasonic echo signal, which is combined after Hilbert transform, and the X-axis, Y-axis and Z-axis are sampling time, frequency and amplitude respectively. It can be seen from figure 4 that the characteristics of the ultrasonic echo signal such as frequency composition, frequency and signal energy changing dynamically with time can be obtained from the Hilbert time-frequency amplitude spectrum based on empirical mode decomposition.
Figure 4. Hilbert spectrum of ultrasonic echo signal.

Figure 5 shows the marginal spectrum obtained by integrating the Hilbert spectrum of the ultrasonic echo signal on the time axis. It describes the distribution of signal amplitude on the frequency axis, and it can be seen that the instantaneous frequency of maximum amplitude is 1.85MHz. Because the actual frequency of transducer is slightly lower than the design frequency 2MHz and the echo frequency in the composite materials is shifted downward, the marginal spectrum accurately reflects the amplitude-frequency characteristics of the signal.

Figure 5. Marginal spectrum.

Figure 6 shows the instantaneous energy density obtained by integrating the amplitude square of Hilbert spectrum on the frequency axis, which accurately reflects the change of signal energy with time.
4. CONCLUSION

The Hilbert spectrogram obtained by HHT time-frequency analysis directly and truly reflects the non-stationary characteristics of ultrasonic signals. The characteristics and parameters of the ultrasonic echo signal from composites sample with flat bottom hole defect such as frequency composition, frequency and signal energy changing dynamically with time can be obtained from the Hilbert marginal spectrum and instantaneous energy spectrum, and material defect can be accurately located in the thickness direction according to ultrasonic velocity and time difference.

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