Study on the Application of HHT in Bridge Health Monitoring

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Abstract: HHT method has been used to decompose the health monitoring data and the EMD signal decomposition to reveal the internal characteristics of bridge monitoring data, so that to get more reliable data of the amplitude and frequency. The amplitude and frequency variation in the monitoring process is calculated so as to judge the health of the bridge. It innovatively applies the segment data to make comparisons, accurately locates the specific data segment with structural damage and provides the simultaneous monitoring scheme while reducing the amount of calculation.

Keywords: A_{\text{inf}}, F_{\text{inf}}, HHT, EMD, Hilbert spectrum.

1. Introduction

With the increasing use of bridges, bridge structure would inevitably have degradation in safety and its functions, due to natural factors like earthquakes, climate and environmental erosion etc, growing traffic volume, man-made accidents and other factors. If it is not maintained or repaired in time, these kinds of degradation would affect traffic safety and shorten service life of bridges, and even lead to sudden destruction or collapse of bridges [1]. Therefore, bridge health monitoring is very important for improving structural safety of bridges. Bridge health monitoring mainly refers to obtain different information manually or automatically, so as to have a comprehensive understanding of bridge structure, systematic analysis of bridge safety, and effective evaluation of bridges. In cases of unusual weather or traffic accidents, early warning signals will be triggered, to provide favorable theoretical basis for daily bridge management [2-4].

Health monitoring of bridge structure is quite complex. Therefore, there are great defects by using traditional health monitoring technology to monitor the health and safety of bridges, such as fuzziness and strong subjectivity. In addition, the process of bridge health monitoring is quite complicated and it is hard to get a better adaptability [5-7]. Thus, an effective technology shall be used for health monitoring of bridge structure. With high adaptability, HHT can solve arbitrary problems effectively and has obvious advantages in bridge health monitoring.

2. Features and Advantages of HHT

The signal analysis is the research and representation of basic property of signal. The time variation of signal is fundamental, for the time is the basis. From the perspective of mathematics, different expressions of signal can be realized through
decomposing the signal in the complete set of function, and there are countless situations. However, the importance of a special expression lies at which expression can be used for better understanding of signal features, for this kind of expression adopts the actually or currently important physical quantity to express its features. Except for time, the most important expression is the frequency [17].

The mathematical method of frequency expression is invented by Fourier. As one of the most great inventions in mathematics and science, the Fourier analysis is also the most common and main method to analyze and process stationary signal. The traditional signal analysis and processing is based on Fourier analysis which has 3 basic hypotheses: linearity, gaussianity, and stationarity; therefore, what Fourier analysis establishes is an ideal model. The Fourier analysis plays a very important role in all fields of science and technology; however, due to the global conversion used, it can’t express time-frequency partial performance of signal, and such property is just the most fundamental and critical property of non-stationary (time-varying) signal, thus the Fourier analysis is not applicable for analyzing the non-stationary signal. Most of natural or artificial signals existing in the real life are non-stationary signal, such as voice signal, mechanical vibration, electrocardiosignal, radar signal and earthquake signal. Therefore, in order to analyze and process non-stationary (time-varying) signal, people carry out popularization and even fundamental revolution for Fourier analysis, propose and develop a series of new signal analysis and processing theory, that is, non-stationary (time-varying) signal analysis and processing [17, 18].

Through research on time-varying signal processing, we can analyze and process various time-varying signals and construct the system model which is closer to life on this basis to be applicable for more application fields and effectively serve for actual engineering practice. Therefore, our research on new time-varying signal processing technology can help to better analyze and process various time-varying signals, promote the development of time-varying signal processing theory, and make such theory widely applied and better serve for various fields of science and technology, thus promoting the development of various fields of science and technology. Currently, the research on time-varying signal processing has become one of the hot points in research on modern signal processing [17-18].

In 1984, Morlet keenly perceived the great development potential of wavelet analysis in signal analysis in research on geophysical signal; he firstly proposed the concept of wavelet transform (WT), and actively promoted its development. Currently, WT has become one of common methods used in nonlinear and non-stationary signal; what’s more, multiple WT-based time-frequency analysis methods appear in succession on this basis, such as wavelet packet decomposition, chirplet transform, and matching pursuit method [17-19].

Over several decades of research and efforts, people have put forward various time-frequency analysis methods; however, almost all of those time-frequency analysis methods take Fourier transform as the ultimate theoretical basis, and it is difficult for those methods including linear transform method based on window function, bilinear time-frequency method, and parametric time-frequency analysis method matched based on signal feature, etc. to make a breakthrough in time-frequency method due to various kinds of insurmountable limitations. Due to existence of those problems, the final result obtained via time-frequency analysis is often difficult to be explained, or has vague physical significance, or can be explained only with the help of large quantity of mathematical reasoning.

HHT (Hilbert-Huang Transform) proposed by American Chinese N. E. Huang et al. in 1998 is a new method of data analysis.

HHT can handle non-linear and non-stationary signals. N. E. Huang et al. deem that any signal is composed of basic signals, i.e., intrinsic mode signal or intrinsic mode function (IMF), and the mutual superposition of IMFs forms composite signals.

Compared with traditional signal or data processing methods, such as Fourier transform, short-time Fourier transform and Wavelet Transform (WT), HHT are featured by the following aspects [11]:

1) HHT can analyze non-linear and non-stationary signals.
2) HHT holds complete self-adaptation.
3) HHT is not restricted by Heisenberg uncertainty principle.
4) The instantaneous frequency of HHT is obtained by derivation.

Based on the above features, with all IMF components obtained by using the HHT method to carry out EMD decomposition for signals, the information about the instantaneous state of the function can be achieved.

The amplitude function is

\[ a(t) = \sqrt{s^2(t) + H^2[s(t)]} \]  (1)

The instantaneous frequency and the instantaneous angular frequency are

\[ \omega(t) = d\phi(t) / dt \]  (2)

and

\[ f(t) = \omega(t) / 2\pi \]  (3)

The frequency of the intrinsic mode function (Fimf) is

\[ Fimf = \left| \frac{1}{T} \int_{0}^{T} f(t) dt \right| \]  (4)
The amplitude of the intrinsic mode function (Aimf) is

\[
Aimf = \frac{1}{T} \int_0^T a(t)dt
\]  

(5)

Use Hilbert spectrum to realize

\[
Aimf = \int_{-\infty}^{\infty} h(\omega)d\omega
\]  

(6)

and

\[
Fimf = \frac{1}{2\pi Aimf} \int_{-\infty}^{\infty} \omega h(\omega)d\omega
\]  

(7)

Hilbert Huang Transform (HHT) is an internationally novel method of digital signal processing, whose data handling capacity remedies the shortages of traditional data processing methods like Fourier transform and wavelet analysis. We can describe the health condition of the structure more accurately and more clearly by applying the HHT method to analyze data about system monitoring.

According to the basic thoughts of HHT, all collected data are composed of basic signals, i.e., the intrinsic mode function (IMF). The mutual superposition of IMFs forms composite signals and the IMF of data signals obtained by the decomposition method of empirical mode is the ‘base’ generated by self-adaption. In accordance with the ‘base’ decomposed and obtained by the HHT method, the original data about the monitoring of the research material can be applied to parameter identification of dynamic property, signal decomposition and reconstruction, damage identification, signal denoising and analysis of long-period tendency, etc.

3. Key Issues in Bridge Monitoring

3.1. Composition of Bridge Health Monitoring System

Bridge health monitoring system is a comprehensive monitoring system integrated with structural monitoring, system identification and structural assessment, including load monitoring, geometric transformation monitoring and structural response monitoring etc. For system composition, bridge health monitoring system can generally be divided into: 1) data acquisition subsystem, including a hardware system for signal acquisition, storage and transmission; 2) data signal processing subsystem, mainly processing various digital signals, such as A/D conversion, digital filtering and noise reduction etc; 3) system identification subsystem, calculating through computer simulation, combining finite element model analysis, and identifying static and dynamic characteristic parameters of bridge structural system; 4) damage identification subsystem, processing acquired data by certain analysis technology, combining with features of bridge structural system, taking various effective means to identify structural damage and completing early damage warning, damage position and damage quantification; 5) bridge structural condition assessment subsystem, combining results of damage identification with expert advices, evaluating the health condition of bridges and proposing structural health maintenance countermeasures; 6) data management subsystem, completing storage, call and management of a large amount of real-time field data. In terms of the development trend of bridge health monitoring, with continuous improvement of relevant technologies, intelligent bridge health monitoring system based on information technology will replace the existing manual inspection and local damage identification [10].

3.2. Data Analysis as the Key Problem in Bridge Health Monitoring

From the perspective of information science, bridge health monitoring is a process of extracting information from data signals by testing and identifying structures. Testing is a detecting method, signals are the description about physical changes and information corresponds to features of structural state taking signals as material carriers. A bridge is able to resist external forces, which is an inherent characteristic of materials. To detect this objective existence, the external forces can be imposed on bridge structural system under study and the accelerated speed time-history signal is obtained containing information to describe inherent frequency and damping ratio of this system. System stiffness can be obtained by further analysis of tested signal, thus the damage and carrying capacity of bridge structure is known.

In the structural health monitoring system, data collected from the field include displacement, strain, accelerated speed and ambient excitation, etc of different measuring points of structure. In case of structure damage in service, the structural performance will change.

The structural health monitoring system is to instantly acquire real-time structure test data representing these changes by test instruments, to confirm time and location of structural damage, analyze degree of damage, and thus assess the health condition of bridge structure correctly. Therefore, the advantages and disadvantages of a bridge health monitoring system are mainly determined by the following three factors [8]:

1) Sensitivity and accuracy of sensors as well as performance of data transmission and acquisition devices;
2) Spatial distribution of measuring points, i.e. optimal placement of sensors;
3) Analytical processing of test data.
From current development, hardware facilities for structural health monitoring are increasingly advanced, and high-performance intelligent sensors and signal acquisition devices are increasingly used in engineering. In terms of results of several International Health Monitoring and Damage Identification Conferences, the current sensor technology has reached a high level and the sensor signal acquisition in structural health monitoring system is not a crucial issue [9].

Optimized sensor layout determines the acquisition of overall and local information of a large structure as well as the sensitivity of test data to structural damage changes. How to arrange a limited number of sensors to realize optimal acquisition of structural condition change information is one of the major problems to be solved in large bridge health monitoring. There are currently many research achievements in this field. In analytical processing of test data, identification of structural damage and assessment of overall bridge health condition shall be completed. Therefore, it can be seen that the key of bridge health monitoring is analytical processing of test data. Once health monitoring system is put into operation, the major work is how to acquire information about structural damage condition from test signals. During analytical processing of data, the first step is to carry out signal denoising, to eliminate noise interference in field test signals; then to analyze signals and realize damage classification and identification by signal damage identification algorithm; finally to assess bridge health condition systematically with experts, keep valuable test data as well as and create a profile for bridge health. For signal denoising, signal detection, feature extraction and data compression technologies involved in these three processes, HHT has unique advantages [10].

4. Case Study of Bridge Health Monitoring

The full-year bridge monitoring data is recorded during tied-arch cable replacement construction of tied-arch bridge and long-term monitoring of Wuhan Qingchuan Bridge. Fig. 1 shows a piece of monitoring data.

Calculate values of $F_{imf}$ and $A_{imf}$ by taking initial data as the health structure reference standard. Reference data is selected from the 40001st to the 70000th data of the experiment. Results of EMD decomposition are shown in the Fig. 2, Fig. 3 and Fig. 4:

![Fig. 1. A part of data.](image1)

![Fig. 2. IMFS1-12.](image2)

![Fig. 3. IMF of annual cycle.](image3)

![Fig. 4. Combined comparison between real data and its trend.](image4)
Its Hilbert-Huang spectrum is shown in Fig. 5:

![Hilbert-Huang spectrum](image)

**Fig. 5.** Hilbert-Huang spectrum.

Its marginal spectrum is shown in the Fig. 6:

![Marginal spectrum](image)

**Fig. 6.** Initial marginal spectrum.

Values of $F_{imf}$ and $A_{imf}$ are: 75.6, 0.453.

Compare the end data with data of health structure, with reference data from the 1950001st to the 1960000th data of the experiment.

Similarly, results of EMD decomposition are shown in the Fig. 7, Fig. 8 and Fig. 9:

![EMD decomposition](image)

**Fig. 7.** IMFS1-12.

![IMF of annual cycle](image)

**Fig. 8.** IMF of annual cycle.

![Combined comparison](image)

**Fig. 9.** Combined comparison between real data and its trend.

Its Hilbert-Huang spectrum is shown in Fig. 10:

![Hilbert-Huang spectrum](image)

**Fig. 10.** Hilbert-Huang spectrum.

Its marginal spectrum is shown in Fig. 11:

Values of $F_{imf}$ and $A_{imf}$ are: 81.3, 0.422 m/s$^2$

$$dFimf = \frac{|F_{imf} - F_{imf_0}|}{F_{imf_0}} = 7.5\%,$$  \hspace{1cm} (8)
By defining the health interval of $dA_{imf} = \frac{|A_{imf} - A_{imf_0}|}{A_{imf_0}}$ as $(0, 0.1)$, it can be found by inspection that the end data is just in the interval, i.e., this bridge maintains undamaged in the full-year monitoring data. The same comparison method can also be used in real-time monitoring of bridge health condition. For example, take data of the latest week to calculate values of $F_{imf}$ and $A_{imf}$, and the bridge is in normal condition if these values are in the health interval; while if these values deviate from the health interval, it would warn and find trouble nodes by further data analysis.

$$dA_{imf} = \frac{|A_{imf} - A_{imf_0}|}{A_{imf_0}} = 6.8\%$$

(9)

![Fig. 11. End marginal spectrum.](image)

5. Conclusions

By processing capacity of EMD for non-stationary and nonlinear process data and concepts of $F_{imf}$ and $A_{imf}$, it is able to analyze data obtained in bridge health monitoring very effectively, quantify the health degree of structure by relative values of $dF_{imf}$ and $dA_{imf}$, define boundaries of health degree according to practical experience, and help engineers make valuable judgment in actual structural health monitoring.

HHT has great advantages in processing structure test data. It would have a broad space for development and application values in structural health monitoring system as well as structural damage identification and analysis. However, specific application and project realization of HHT in civil engineering structural health monitoring system shall be further studied.

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