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Dynamic Deformation Monitoring for Long-Span Bridges under Construction and EMD De-noising Method

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Abstract: Construction progress of long-span bridge is complicated and the quality control is strict. Any disadvantage during construction may potentially affect the internal forces and deck alignments after it is open to traffic. To exactly evaluate the periodic alignments, internal forces and safety, geometrical and physical monitoring are needed during construction. This study aims at the requirement of dynamic geometric monitoring during Sutong Bridge construction, and introduces the realization and observing schemes of the self-developed GPS real-time dynamic geometrical deformation monitoring system. Affected by wind load and construction circumstance, GPS (global positioning system) monitoring signal contains a variety of noise. And the useful signal can be extracted from the signal after de-noising the noises. A de-noising method based on EMD (empirical mode decomposition) model is introduced here to process the bridge dynamic monitoring data, and with the wavelet threshold de-noising method are compared. The result shows that the EMD method has good adaptability, is free from the choice of wavelet bases and the number of decomposition layer. The method is an effective de-noising method for dynamic deformation monitoring to large-span bridges.

Key words: Long-span bridge, construction period, dynamic deformation monitoring, empirical mode decomposition, de-noising.

1. Introduction

Construction progress of long-span bridge is complicated. Structures as pylon towers and the bridge deck are prone to displacement under the load such as diurnal temperature, strong wind gusts, tidal current, which affect the designed carrying capacity of the bridge. In order to evaluate the safety and health of bridge regularly, structural engineers require precise, reliable instruments for monitoring rotations, displacements and vibrations of large bridge structures, as well as effective and appropriate analytical methods that allow extracting this useful information from observing data. In the past, monitoring the displacement and dynamic parameters of engineering structures have traditionally relied on measurements made by accelerometers, displacement sensors, total stations and other methods during long-span bridge construction. However, these conventional measurements have many limitations and can not meet the requirement of consecutive, real-time and dynamic monitoring of large bridges. With the real-time, high-accuracy, high sampling frequency and other advantages, modern measurement technology such as GPS-RTK (global positioning system-real time kinematic) has been successfully used to measure dynamic deformation of engineering structure such as long-span bridges and high-rise buildings by many scholars [1-3]. For example, the "real-time kinematic global positioning system on-line monitoring system", which was set up on Humen Bridge that spans 888 m in China, can monitor bridge deck movement and vibration of pylon towers [4]. Another long-term structural health monitoring system was designed and implemented by the Research Center of Structural Health Monitoring and Control of Harbin Institute of

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Technology to monitor loads and response of the bridge [5]. The sampling frequency of GPS receiver can reach to 10 times per second, while the location precision in horizontal and vertical directions can approach 5~10 mm.

However, affected by wind load and construction circumstance, the signal of GPS contains all kinds of noises, which performs non-stationary, non-linear characteristics. For analyzing the signals of GPS, a preprocessing should be done first to filter signals and extract useful information. EMD (empirical mode decomposition), which conducts signal decomposition based on its time scale characteristics without setting any basis functions before, is an adaptive partial frequency signal analysis method proposed by Huang et al in 1998 [6]. At present, the method has been successfully applied to the data analysis fields such as surveying, earthquake, mechanical vibration and so on [6-8].

Aiming at the actual situation of the pylon tower and bridge deck monitoring during Sutong Bridge construction, this paper introduces the application of the GPS real-time dynamic deformation monitoring system and an approach for de-noising based on EMD. This method is used to process the GPS-derived structural response data from the south tower of Sutong Bridge. Comparing with the wavelet de-noising results, the EMD method removes high-frequency component with an adaptively determined window length. The result shows that the dynamic monitoring system has a high accuracy and high sampling frequency while the EMD method has good adaptability, which can extract the essential deformation features of the bridges.

2. Theoretical Model

2.1 EMD Method

The main idea of EMD method is that any complex signals consist of number of mutually-different, simple and non-sinusoidal function signal components. These basic signals are called IMF (intrinsic mode function), and any IMF between each other are independent. An IMF is a function that satisfies two conditions: (1) In the whole data set, the number of extremes and the number of zero crossings must either equal or differ at most by one; (2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The flowchart of EMD model is shown in Fig. 1.

The method is a relatively new signal processing technique. Given a signal $y(t)$, the effective algorithm of EMD can be summarized as follows:

(1) identify all extremes of $y(t)$;

(2) interpolate between minima (resp. maxima), ending up with some "envelope" $e_{\max}(t)$ and $e_{\min}(t)$;

(3) compute the average $m(t) = (e_{\max}(t) + e_{\min}(t))/2$;

(4) extract the detail $h_1(t) = y(t) - m(t)$;

(5) iterate on the residual $m(t)$.

In practice, the above procedure has to be refined by a sifting process which amounts to first iterating Steps 1~4 upon the detail signal $h_1(t)$, until this latter can be considered as zero-mean according to some stopping criterion. Once this is achieved, the detail is considered as the effective IMF, the corresponding residual is computed and Step 5 applies. For a given signal $y(t)$, EMD ends up with a representation of the form:

$$y(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{1}$$

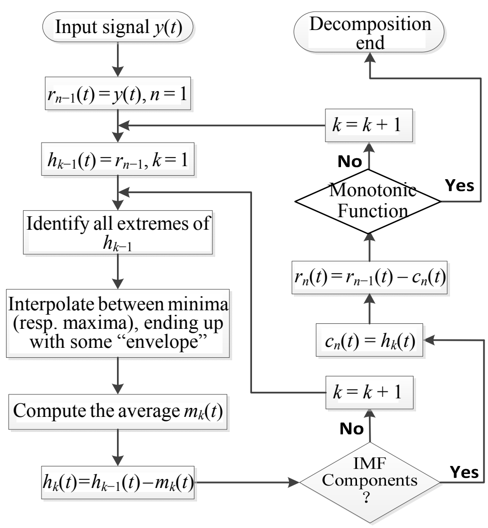

Fig. 1 Flowchart of EMD method.

As the decomposition is based on the direct extraction of the energy associated with various intrinsic timescales of signals, mode mixing during the sifting process would be possible. EMD makes it possible to address the no stationary, nonlinear multipath issues [9].

2.2 Wavelet Method

Wavelet transform decomposes a signal into a set of basic functions. These basic functions are called wavelets. Wavelets are obtained from a single prototype wavelet-call mother wavelet by dilations and shifting:

$$W_t(a,b) = \langle f, \psi_{ab} \rangle = |a|^{\frac{1}{2}} \int_R \overline{\psi(\frac{t-b}{a})} f(t)dt \qquad (2)$$

where:

$\psi(t)$ is the mother wavelet;

$f(t)$ is the decomposed signal;

a is the scaling parameter;

b is the shifting parameter.

The flowchart of wavelet decomposition model is shown in Fig. 2.

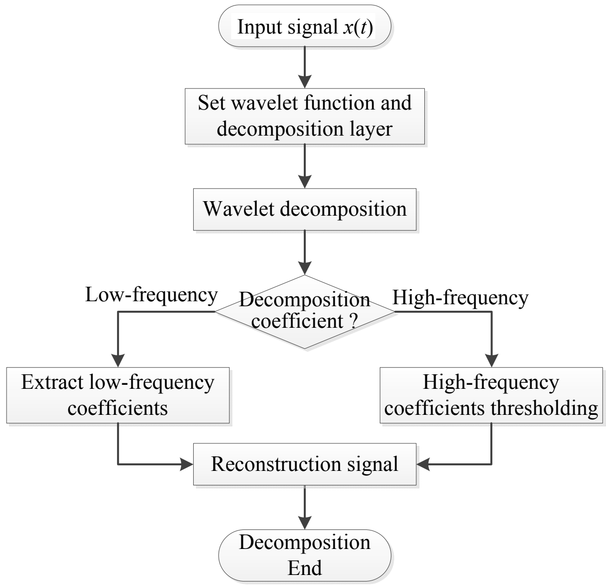

Fig. 2 Flowchart of wavelet decomposition method.

Wavelet transform analyzes the signal by stretching on the scale and shifting on the location of $\psi(t)$ function. As long as an appropriate wavelet function selected, the results of the wavelet transform have good time and frequency locality domain [10].

3. Real-time Dynamic Monitoring System

3.1 Monitoring Program

The Sutong Bridge, a cable-stayed bridge, crosses over the Yangtze River, in China, connecting between Cities of Shuzhou and Nantong. The whole bridge contains six lanes and located in the southeast of Jiangsu Province. It has a main span of 1,088 m and a total length of 8,164 m while the height of main tower is 300.4 m, which is one of the first among worldwide cable-stayed bridges. Affected by the monsoon and typhoon, the annual average wind speed is high, as well as the monsoon and diurnal thermal circle effects are severe. A variety of adverse factors badly cause the pylon towers, the bridge deck and the cables to displace and vibrate considerably, which will affect the monitoring accuracy of the upper construction structure [11]. To ensure the safety of Sutong Bridge during construction and study its external deformation features, a set of automated and all-weather deformation monitoring system has been designed and established by bridge health monitoring system.

Two of the monitoring stations (N0, S0) are mounted on top of the tower and the others are distributed at the same side over the deck along the bridge. According to bridge beam construction process, the number of monitoring points on bridge deck gradually increases. The overall deployment is as following:

(1) When the cantilever beam is installed at the distance 200 m away from the pylon towers, the first pair of monitoring points (N1, S1) is placed and fixed respectively;

(2) When the cantilever beam is installed at the distance 300 m away from the pylon towers, the second pair of monitoring points (N2, S2) is placed and fixed respectively;

(3) With the forward of the cantilever beam, the third pair of GPS monitoring points (N3, S3) is added. The deployment of each monitoring point is shown in Fig. 3.

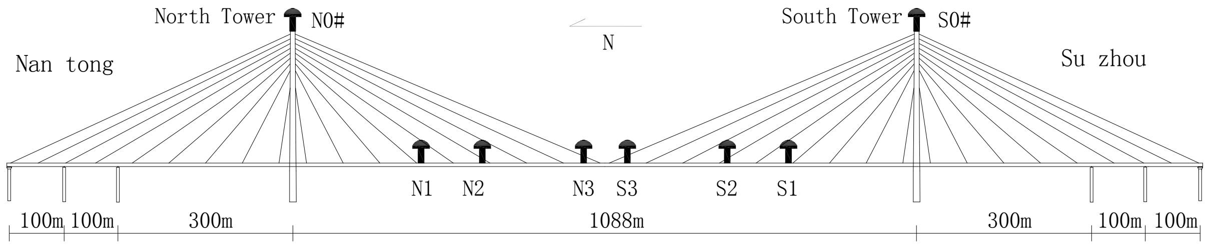

Fig. 3 Deployment of the GPS monitoring points.

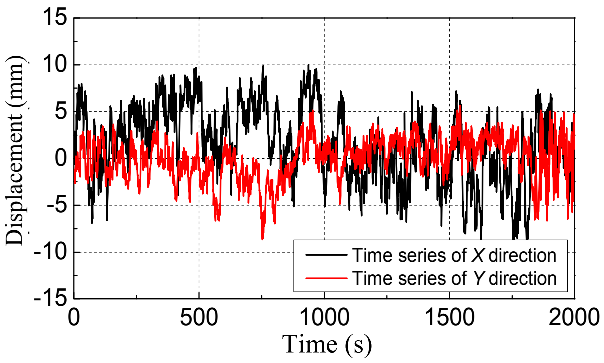

Fig. 4 Time series of X and Y direction.

3.2 Monitoring Results

Generally, for the cable-stayed bridges and other large-scale buildings, their natural structure vibration has a lower frequency of 0.1~5 Hz due to their huge mass [12]. According to the Nyquist sampling theorem, if the sampling frequency of the GPS receiver is set to 10 Hz, it will record all vibration signals without distortion. Before using the GPS data for analysis, the raw GPS data, which were received in a WGS84 (world geodetic system 1984) coordinate system, were converted to local three-dimensional coordinates of bridge by coordinate transformation. The conversion processes are as following:

(1) firstly, convert geodetic coordinates (B, L) to the Cartesian coordinates (X, Y);

(2) secondly, project the Cartesian coordinates to a Gaussian plane, obtain Gauss plane coordinates (x, y);

(3) thirdly, convert the Gauss plane coordinates (x, y) to bridge coordinates (x_i, y_i).

The final results obtained by the above process could directly reflect the monitoring point's deformation in bridge longitudinal, lateral and vertical directions.

Collection of time series GPS data was carried out from 2:00 a.m. to 4:00 a.m. local time on May 1, 2007, where the tidal current, temperature and wind have more effects on bridge. This present study selects two monitoring time series, which are intercepted from X and Y direction of monitoring point on the south pylon tower, to filter signals and extract useful information. The two time series are shown in Fig. 4. Then, a comparison was made between the results obtained by using EMD and wavelet de-noising methods, respectively. These filter methods are performed by inserting a subroutine in the Matlab software program as described in the following paragraphs.

As is shown in Fig. 4, the time series contain 2,000 points and the sampling interval is 0.1 s. The precision in horizontal direction is: m_X = ±4.72 mm, m_Y = ±2.26 mm while the observation data have no gross error, which meets the normal accuracy of dynamical measurement. It is difficult to recognize the deformation signal from Fig. 4 since it is overshadowed by the vibration signals, multipath and other errors.

4. Monitoring Data Process and Analysis

4.1 EMD De-noising

The deformation features of the bridge are crucial basis for reflecting its work status, and evaluating the safety and health. Therefore, it is essential to choose an appropriate signal processing method to remove the noise in raw observation data. This paper gives two de-noising methods, in which EMD is an adaptive de-noising method whereas wavelet decomposition eliminates noise according to its characteristics. To begin with, EMD method is employed to decompose raw observation sequence shown in Fig. 4, which obtains a number of IMF and residual. Then, each IMF components was transformed by using FFT (fast Fourier transformation) to distinguish the vibration signals and noise signals. Finally, selecting specific IMF components reconstruct deformation signals.

Decomposed by EMD method, the raw time coordinate series transform to 10 IMF components. Those components and its FFT results are shown in Fig. 5 (the figure shows only six of the ten). From Fig. 5, it is found that cycle of IMF components gradually increases while the frequency gradually decreases until the residual is turned to a monotonic function. Fig. 5 reflects the scale small to large of each signal components in monitoring sequence.

Fig. 5 also shows the FFT results of IMF1~IMF6 components. The statistical and systematic properties of the overall GPS observation series are not fully known, but its spectral distribution is as follows: The structural vibration frequency is between 0.1~0.5 Hz and the multipath effects frequency ranges from 0.005 to 0.1 Hz [13]. Therefore, it can be determined that:

- IMF1 component is high-frequency white noise signal;
- IMF2 component is vibration signal;
- IMF3 component is multipath noise;
- IMF4~IMF10 components are deformation signal of the bridge structure.

Thus, IMF2 component can be considered as structural vibration ingredient; IMF1 and IMF3 components is deemed to be ultra-periodic noise such as multipath effects, which can be excluded from raw

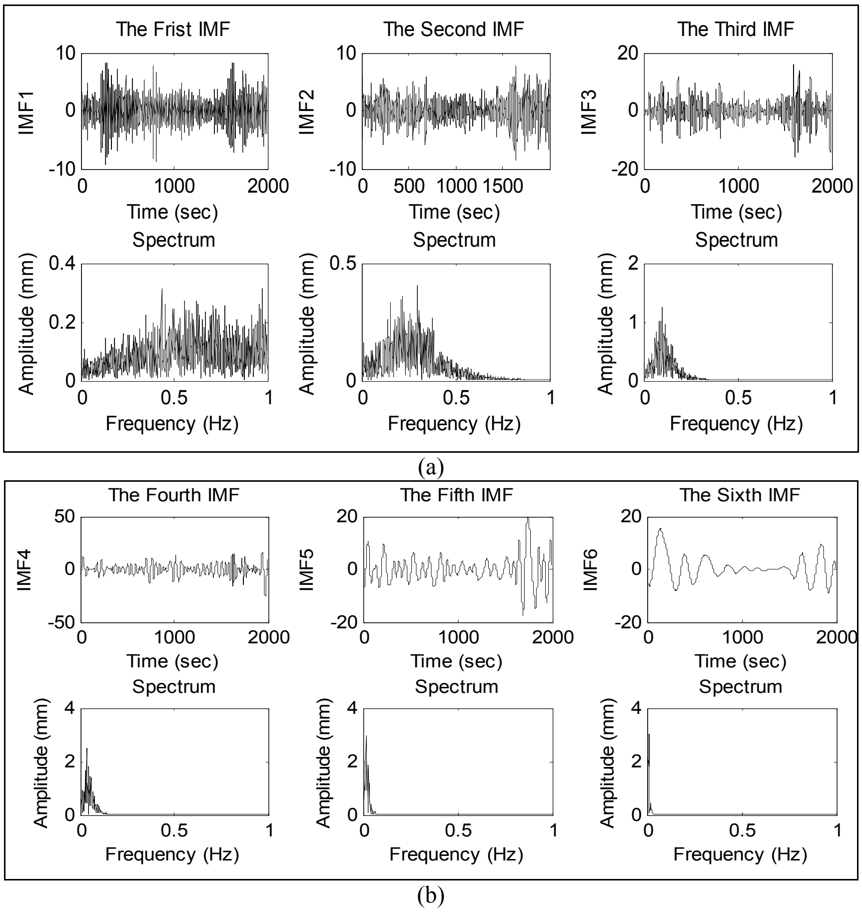

Fig. 5 Each IMF components and the FFT results: (a) IMF1~IMF3 components and the FFT results; (b) IMF4~IMF6 components and the FFT results.

observations sequence; IMF4~IMF10 components can be regarded as structural deformation whose reconstruction to time coordinate series of X-direction is shown in Fig. 6.

4.2 Wavelet De-noising

In order to make a comparison with EMD de-noising result, wavelet decomposition is employed to process the same observation data. Since different wavelet basis has different de-noising ability [9], this paper chooses the usually used db8 and Haar wavelet to implement the 3-layer decomposition and de-noise signals by the default threshold. Time coordinate series reconstructed through the above two wavelets function are shown in Figs. 7 and 8.

For quantitatively analyzing the de-noising ability of the two methods, in the first time we respectively calculate the RMSE (root mean square error) and correlation coefficient R between raw observation series and filtered signal. The results are shown in Table 1, which compares quantitative results calculated by using EMD method and Haar wavelet as well as db8 wavelet.

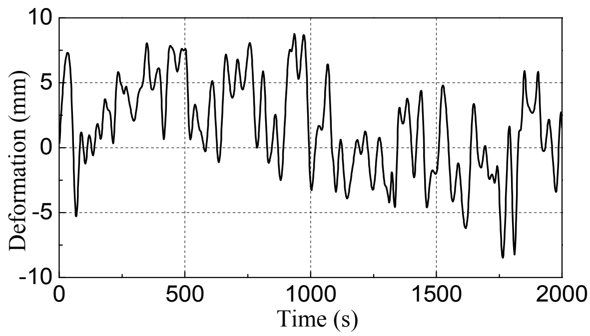

Fig. 6 De-noising result of EMD.

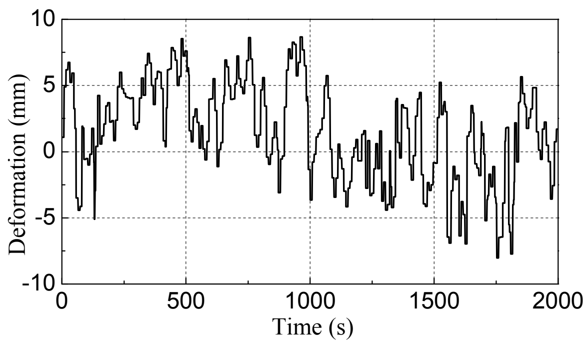

Fig. 7 De-noising result of db8 wavelet.

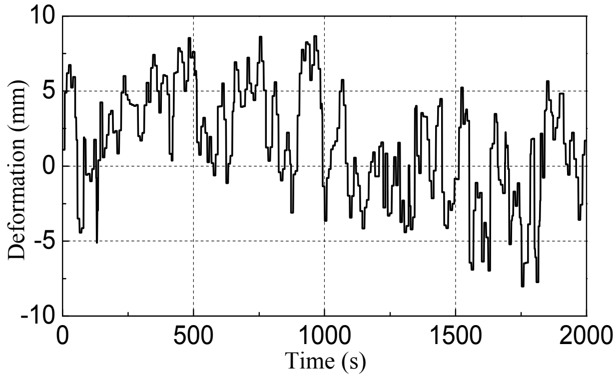

Fig. 8 De-noising result of Haar wavelet.

Table 1 RMSE and *R* of different de-noising method.

De-noising method	Haar wavelet	db8 wavelet	EMD method
RMSE	3.521	3.532	3.025
R	0.908	0.901	0.926

From the comparison among Figs. 6-8, it is indicated that the two methods are able to accurately extract deformation signal from the observation sequence which contains vibration characteristics and random error, where filtered result obtained by using EMD method is smoother than that of wavelet method. On the other hand, as Table 1 demonstrates, the correlation calculated by EMD method is also better than the wavelet filter. In addition, in the wavelet de-noising, selecting different wavelet functions leads to different results. This outcome may be caused by the fact that the more similar between wavelet basis with signal to be analyzed, the better the filtered result is. Compared to it, the EMD method conducts signal decomposition based on its time scale characteristics, which has a strong adaptability and unaffected by wavelet basis selection and decomposition layers.

Besides, the correlation coefficient between the EMD-reconstructed deformation sequences (IMF4~IMF10) and noise sequences (IMF1 and IMF3) is 0.046, and that between with the vibration component (IMF2) is 0.015. Therefore, there are no obvious correlations among the three decomposed components while the reconstructed signal with the raw observation data has strong correlation, which plays an important role in data de-noising and smoothing.

5. Conclusions

The objective of this paper is to verify the feasibility of using GPS technology for measuring displacement and extracting deformation characteristics of the pylon towers during Sutong Bridge construction, and to compare the de-noised result obtained by different filter method. This paper designs and installs a real-time dynamic deformation monitoring system based on GPS carrier phase technology as well as introduces a de-noising method based on EMD. General conclusions from the implementations are as follows:

(1) The real-time dynamic deformation monitoring system can operate in all-weather, which makes it easy to collect precious data of the bridge even under inclement weather;

(2) The sampling frequency of GPS-RTK technology can reach to 10 Hz, while the monitoring precision can approach 5~10 mm;

(3) The EMD method decomposes raw sequence based on the data itself without prior information and not affected by the uncertainty principle and the choice of wavelet function.

The above conclusions indicate that the dynamic deformation monitoring system can provide accurate data for deformation analysis of such large structures as cable-stayed bridge as well as the EMD method has good adaptability and can be used to data processing in surveying fields.

Acknowledgments

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