Stress and noises of steel box girders in Sutong Bridge

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Abstract: Sutong Bridge is a cable-stayed bridge with a main span of 1 088 m. 370 high-precision stress monitoring measured data show that in the process of hoisting the steel box girders, the stress of the main girders is in the fluctuant and complex state and many meteorological factors, such as sunshine radiation, temperature and wind, have important influence on the change of stress of the steel box girders. According to the real-time weather data, the stress data after the process of wavelet denoising from representative measuring points in different weather conditions is picked to establish the stress response brought by meteorological factors with Layered Separation method, thereby basically eliminating the influence of meteorological factors on the stress of main girders, so that accurate and reliable stress data can be got for steel box girders adjustment and cable-tensioned construction control.

Key words: Sutong Bridge; cable-stayed bridge; steel box girder; wavelet denoising; meteorological factor; Layered Separation method

1 Introduction

Sutong Bridge, which is the largest cable-stayed bridge with a main span of 1 088 m, has double pylons and double cable-planes. Streamlined orthotropic steel box girder is adopted by main beam. The beam width of bridge deck is 35. 4 m, the beam height of centre line is 4 m, and the length of standard beam is 16 m. The cantilever assemblage method, of which the maximum length of single cantilever reaches to 540. 8 m, is adopted by the steel box girder erection and as mechanical characteristics are complicated, stress monitoring is developed in the hoisting processing of steel box girder. The monitoring work only focuses on the 23 standard beams of the main beam. For the 22 beams of them, the stress measured points are laid as Fig. 1. In order to tracking monitor the stress of the main beam in the construction and provide basis for construction control, 370 high-precision stress monitoring points are laid. All test components use model 4000 arc weldable strain gauges of Geokon Incorporated that can be used to measure the stress (or strain) and temperature of different points at the same time and realize the real-time online measuring in the construction. The starting time of steel box girder stress monitoring is the March 28, 2007 and the on-line monitoring continues to the traffic operation.

From the measured data, it can be seen that in the hoisting construction process, the stress and its distribution of the large cantilever beam are not only related to dead weight and alignment, but also interfered by sunshine radiation, temperature change, wind and other unsure factors. So the time history curve of stress of the steel box girder fluctuates at different degrees. In order to provide expediently applied stress data for construction control and feedback analysis, it is necessary to remove the stress response caused by environmental factors and unsure factors from measured stress data by using signal-noise separation technology.

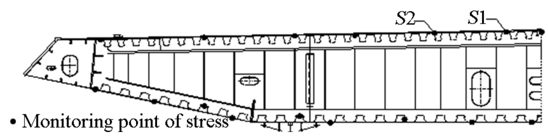

Fig. 1 Stress measuring points layout of standard cross section of half of steel box girder

Wavelet analysis, a time-frequency domain analysis, has the characteristics of multi-resolution analysis [1,2]. Making use of the different resolutions in various positions of the time-frequency plane, waveform characteristics are effectively got. So, signal-noise separation to the measured data by using wavelet transform has good applicability. However, in the denoising process for measured data, abrupt stress caused by construction load would affect the de-noising level, so, firstly, stress increment caused by construction load should be removed, making the stress data only reflect the impact of environmental factors and unsure

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factors; secondly, combined with the measured meteorological data, Layered Separation method is used to basically separate the stress response caused by different meteorological factors; thirdly, the time history curve of stress change is drew after resuming the stress increment caused by construction load. It provides more accurate stress data for steel box girders adjustment and cable-tensioned construction control.

2 Wavelet transform and application

The wavelet transform gives the wavelet structure of signals in different time and scales. Because the actual observation signals $f(t)$ are discrete signals, the successive wavelet must be discrete too. Therefore, the scale factor a and the displacement parameters τ in the wavelet basis function $\psi_{a,\tau}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{(t-\tau)}{a}\right)$ are taken the value on some discrete points. Supposed that $a = a_0^m, a_0 > 0, m \in Z$, the corresponding wavelet function is $a_0^{-j/2}\psi[a_0^{-j}(t-\tau)], j = 0,1,2,...$. But after taking the value of the uniform discrete displacement parameters τ, the wavelet function should be altered as:

$$a_0^{-j/2}\psi\left[a_0^{-j}\left(t - ka_0^j\tau_0\right)\right] = a_0^{-j/2}\psi\left[a_0^{-j}t - k\tau_0\right],$$

it is defined as:

$$\psi_{a_0^j, k\tau_0}(t) \tag{1}$$

The discrete wavelet transform is defined as:

$$WT_f\left(a_0^j, k\tau_0\right) = \int_{-\infty}^{\infty} f(t)\overline{\psi}_{a_0^j,k\tau_0}(t)\,dt$$

$$j = 0,1,2,...,k \in Z \tag{2}$$

Where, a_0 is taken the value of two.

The most efficient calculation method is Rapid Wavelet Arithmetic (also known as the tower algorithm)[3] proposed by S. Mallat, which is developed in 1988. According to the arithmetic, signal $f(t)$ is multiresolution decomposed in different scales and the mixed signals composed of various frequencies are decomposed into the sub-signals in different frequency periods. So, the arithmetic has the ability to process the signals according to the frequency.

The wavelet denoising[4] is that setting the threshold value, discrete wavelet transform of signals, calculating all the wavelet coefficients, eliminating the ones considered noise-related, and getting the useful signals by inverse transform of wavelet transforms. The keys of the threshould setting are threshould choice and mode. On the threshould choice, wavelet coefficients of all the scales can choose not only the same threshold, but also the different ones. On threshold modes, there are mainly two kinds: soft threshold and hard threshold[5,6].

Hard threshold method: it can be expressed as:

$$\hat{d}_{j,k} = \begin{cases} d_{j,k} & |d_{j,k}| \geqslant \lambda \\ 0 & |d_{j,k}| < \lambda \end{cases} \tag{3}$$

Soft threshold method: it can be expressed as:

$$\hat{d}_{j,k} = \begin{cases} \operatorname{sign}(d_{j,k})\cdot\left(|d_{j,k}| - \lambda\right) & |d_{j,k}| \geqslant \lambda \\ 0 & |d_{j,k}| < \lambda \end{cases} \tag{4}$$

Where, $d_{j,k}$ is the wavelet coefficient of signal including noises after wavelet transform, $\hat{d}_{j,k}$ is the estimated value of wavelet coefficients of signals having been processed with threshold function and λ is threshold value.

Hard-threshold function only retains the absolute values of the wavelet coefficients that are greater than threshold λ and the reserved wavelet coefficients are similar to the original ones. While for soft-threshold function, in the formula, the absolute values of wavelet coefficients which are less than threshold λ would be covered for zero, and the absolute values of the ones which are greater than threshold λ would be contracted with λ. Generally speaking, soft threshold method has a more smoothing and filtering effect than hard threshold method.

3 Application of Layered Separation method based on wavelet de-noising

3.1 The advancement of Layered Separation method

From the measured data, it reflects that stress response of the main beam of Sutong Bridge is very complicated. The stress response caused by the meteorological factors such as sunshine radiation, temperature change and wind and the on-site construction environment is piled up, which leads that the main beam stress in different conditions can't be properly given. So, some methods and strategies should be adopted to separate the influence of these interference factors on measured stress. It is regrettable that there isn't any mature method to determine the influence degree. Therefore, measured data are separated by level-division and time-division by combining the conditions and meteorological data. In view of the Layered Separation method based on wavelet de-noising algorithm proposed by this article, practices and steps are as follows:

1) Remove the stress increment caused by construction load of steel box girder. That means, removing the stress increment caused in the process of steel box girders hoisted, firstly tensioned and the crane of bridge deck moved forward from the measured data to make the measured data only reflect the influence of environmental factors.

2) Combine the meteorological measured data and analyze the influence degree of different meteorological factors. Based on these, the time periods of data pro-

cessing are divided, and the types of time periods are cloudy days, strong wind, strong solar radiation, and great temperature changes.

3) By using wavelet threshold de-noising method, layered processing is done to separate the influence of different interference factors on main beam stress.

4) Resume the stress increment caused by construction load which is removed. The time history curve of stress change including little noise of the steel box girder in the construction process is got.

3.2 The application of Layered Separation method

The monitoring content of steel box girders includes the stress of the upper plate, the bottom plate, u-rib slab and welding lines. The data are taken from the measured result of points *S*1 and *S*2 (Fig. 1) on the upper plate of beam No. 23 of the northern main span from 0:00 on May 10, 2007 to 3:00 on May 18, 2007. The time history curve of stress change measured in above period is shown as Fig. 2 (*S*1 and *S*2 in the figure represent the corresponding stress of them respectively). Meanwhile, in order to analyze the stress changes in this period, times of different construction links are given in Table 1.

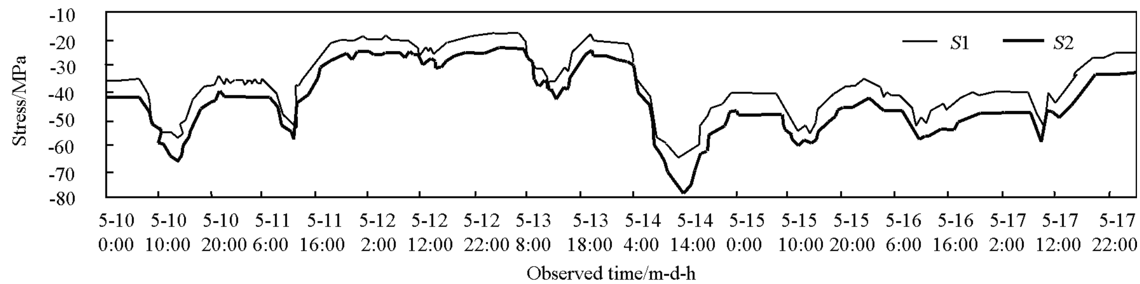

Fig. 2 The time history curve of stress change of the upper plate of steel box girder

Table 1 Main condition schedule in analyzing period

Beam	Hoisting	Welding	Tentioned 1	The crane moved forward	Tentioned 2
NJ31	12:00 - 15:00 the 11th	8:00 the 12th - 19:00 the 13th	19:00 the13th - 9:00 the 14th	13:00 - 15:30 the15th	1:00 - 3:00 the 16th
NJ32	10:30 - 13:30 the 17th	8:00 the 18th - 18:00 the 19th	19:00 the19th - 9:00 the 20th	7:30 - 10:00 the 20th	20:00 - 22:30 the 20th

Combined with the Table 1, the Fig. 2 shows that stress changes of steel box girder hoisting and firstly tensioned are big and regular, while the stress response caused in the process of welding, the crane of bridge deck moved forward and secondary tensioned is not obvious. That is because construction position is far from the observed beam, the influence of little load on main beam stress is small, and stress changes can't be directly distinguished as the environmental factors are mixed. In order to separate the influence of environmental factors on stress, the stress increment caused in the construction load such as hoisting steel box girders, firstly tensioned and the crane of bridge deck moved forward is removed respectively. The result is as Fig. 3. In the figure, *S*1 and *S*2 are the stress of monitoring point, (the unit of stress is MPa), T_e is the environmental temperature for the bridge deck, (the unit is ℃), and V_x is the wind speed across the bridge deck, (the unit is m/s).

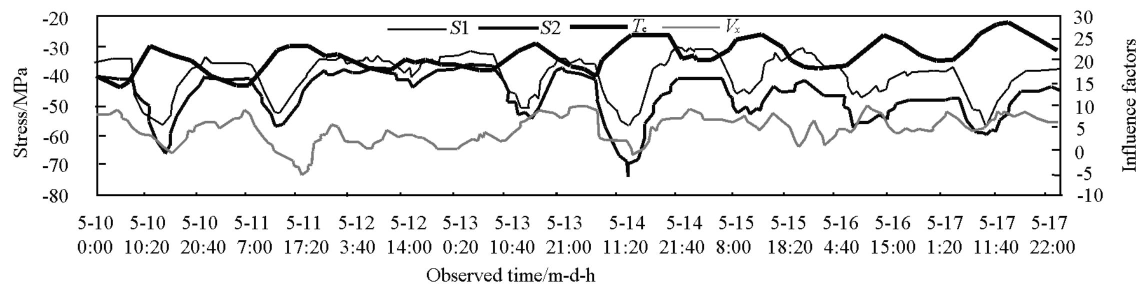

Fig. 3 Corresponding relation among stress, wind and environment temperature

The time history curve of stress change in Fig. 3 mainly reflects the correlation among environmental temperature, wind and stress changes of measuring points. It can be seen that the main beam stress has obvious fluctuation and is negative related to environmental temperature changes. But the relationship between wind and stress changes is not obvious, which has brought to the analysis difficulty. Therefore, the data measured in the days having small changes in temperature (such as cloudy) are considered. The data that don't conclude the stress response caused by sunshine radiation basically are considered to mainly reflect the impact of wind speed on stress. According to this rule, observed results of the measured points *S*1and *S*2 from 13:20 on June 13, 2007 to 9:20 on June 14, 2007 are chosen. (Fig. 4.) (During this period, the environmental temperature change is only 1.3 ℃, but the maximum wind speed across bridge deck reaches to 7.04 m/s and the total wind speed is 10.09 m/s). The figure shows that in these meteorological conditions, the stress changes of points *S*1 and *S*2 are 1.4 MPa and 1.3 MPa respectively. Using above method, the stress changes of the different wind speed can be got, the relationship between wind speed and the stress can be established and finally the stress response of wind speed on steel box girders can be rudely eliminated. Based on this, the temperature effect can be separated.

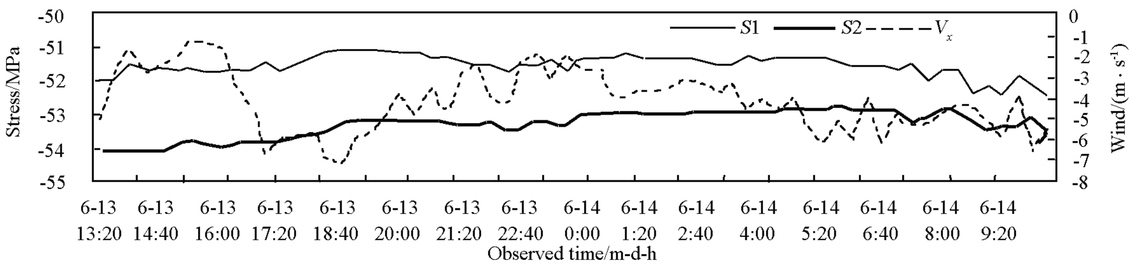

Fig. 4 Corresponding relation between stress changes and wind on cloudy days

In order to analyze the impact of sunshine radiation, the comparison result of the temperature on the upper plate and the bottom plate of steel box girder and the environmental temperature of bridge deck are given in Fig. 5. It should be stated that, because a number of sensors are laid on the upper plate and the bottom plate, the weighted averages for the temperatures of these sensors are processed based on data fusion algorithm[7,8].

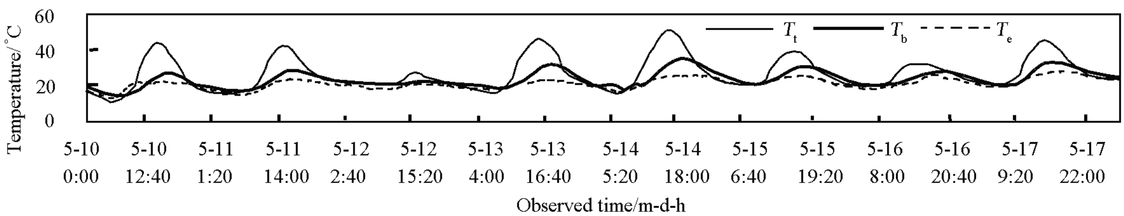

Fig. 5 Corresponding relation between the temperature of steel box girder and environment

Fig. 5 shows that the steel box girders are affected by solar radiation in the day, which makes the beam temperature rising. While, in the night, they are affected by inverse radiation, atmospheric flows and other factors, which makes the beam cool and shows a periodic distribution. As the upper plate of steel box girder is directly affected by sunshine radiation, the temperature is high and rises fast. The temperature difference between the upper plate and the bottom plate of the steel box girder is up to 18.0 ℃ and the large temperature difference on the same section leads to the distinct stress response caused by the steel box girder. In addition, although the bottom plate is not directly affected by sunshine radiation, the average temperature of the bottom plate is higher than the environmental temperature of bridge deck by 4.5 ℃ as the thermal conductivity of the steel box girder is good. The sensitivity of the steel box girder on temperature is also a reason of the very strong stress response. It can be easily seen that in the analysis period, the sunshine radiation on the 14th is the strongest and the daily temperature difference between the upper plate and the bottom plate of the steel box girder is the largest. The result of Fig. 3 show that the intraday stress change is the largest.

When using the Wavelet Threshold method[9] for de-noising, the de-noising effect depends on the selection of wavelet basis and scale. Through numerous comparisons and tries, db4[10] is selected to separate signals and noise. After choosing the wavelet basis function, selection of threshold function and threshold quantization are the keys to eliminate noise. Soft-threshold function is selected here and the threshold value is achieved by empirical formula. Because of the complexity of environmental factors, the influence of different factors can't be separated by only once de-noise. So, according to the analysis of the effects of wind and sunshine radiation, noises caused by wind and other occasional factors are separated by selecting the decomposition scale at three. The result is shown in Fig. 6, where *S1d1* and *S2d1* are the stress of measured points *S1* and *S2* after eliminating the random noises (the unit is MPa). Because the meteorological data show that the maximum wind speed across the bridge deck during this time reaches to 9.1 m/s, the variable quantity of stress is no more than 1.5 MPa. Based on analysis above, scale 6 is used for separating signals and noise at the first step de-noising. The result is in Fig. 6, where *S1d2* and *S2d2* are the stress of measured points *S1* and *S2* after eliminating sunshine radiation (the unit is MPa).

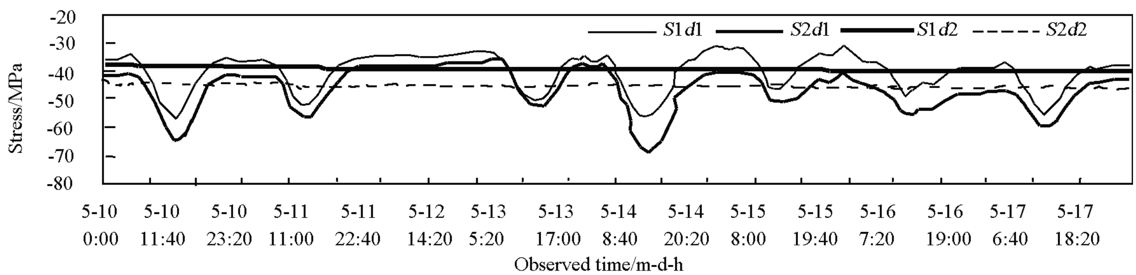

Fig. 6 The stress curve after Layed de-noising

In fact, the influence of temperature on the steel box girder stress is expressed not only on the high-frequency response caused by daily temperature difference, but also on the low-frequency response caused by seasonal temperature difference. In the above-mentioned period, the overall temperature shows an increasing tendency. *S1d2* and *S2d2* in Fig. 6 reflect that the compressive stress of the upper plate of the steel box girder grows slowly with the increased temperature. If the steel box girder erection lasts longer and the temperature changes a lot, similar methods can also be used to separate the impacts.

On this basis, for the time period curve of *S1d2* and *S2d2*, stress increments which are caused by the construction links such as hoisting steel box girders, cable-tensioned and eliminated before are resumed, by which, the time period curve of stress change of the large cantilever beam during hoisting steel box girders, welding, firstly tensioned, the crane of bridge deck moved forward and secondary tensioned is got. The results are shown in Fig. 7, where *S1r* and *S2r* are the stress of measured points *S1* and *S2* after resuming stress increment (the unit is MPa). The outcome is helpful for instructing the cable-tensioned, especially for the construction of cable-tensioned adjustment (secondary tensioned). Under the premise that linear control of the large cantilever beam is basically met, the force of the steel box girder will be more reasonable by adjusting stretching quantity of cable.

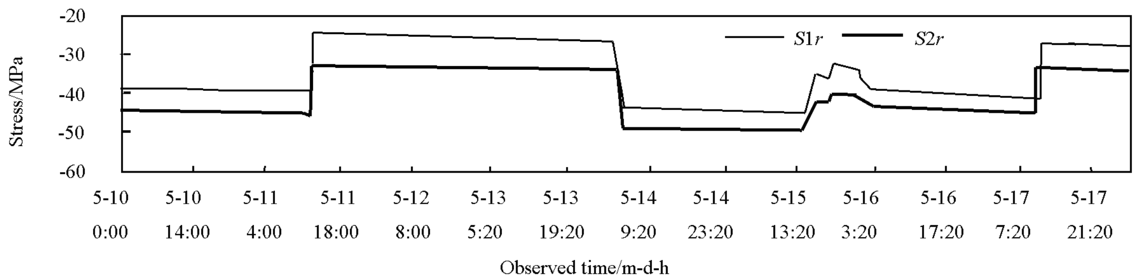

Fig. 7 The time history curve of stress after resuming stress increment caused by construction

3.3 Stress and analysis of steel box girders in Sutong Bridge

Typically, the data of stress analysis on steel box girder are still fetched from the measured point S1 of the Beam No. 23 of the northern main span (the position is in Fig. 1). Fig. 8 is the time history curve of stress change from the hoisting of Beam No. 23 (10:00 on Mar. 29, 2007) to the closure of main span (Jun. 9, 2007). Fig. 9 is the time history curve of stress change after opening to traffic (the time of testing traffic is about May 11, 2008 and the time of formal traffic is Jun. 30, 2008).

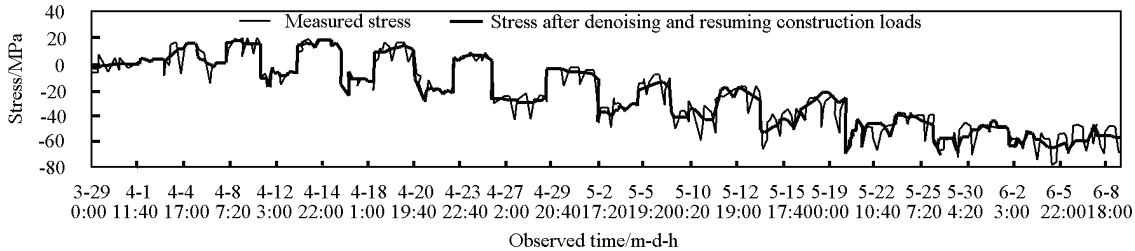

Fig. 8 Contrast diagram of measured stress and processed stress

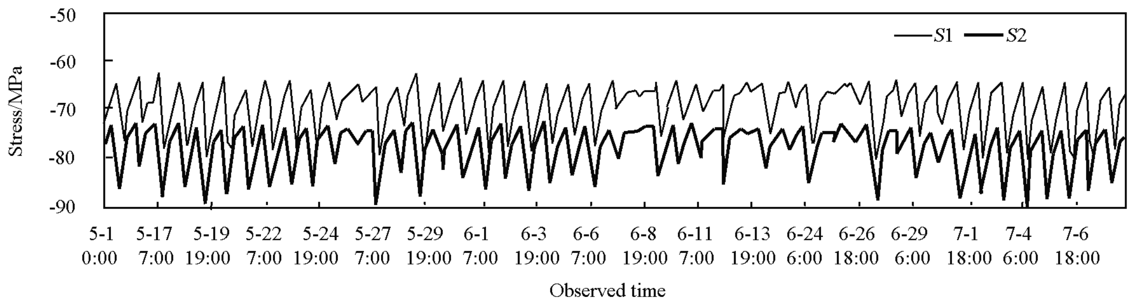

Fig. 9 The measured time history curve of stress before and after opening to traffic

The results in Fig. 8 show that for Beam No. 23, the hoisting of beams from No. 24 to No. 28 makes the upper plate in tension, but with the increasing length of cantilever, the tension tend gradually decreases. Until the hoisting of Beam No. 29, the upper plate of Beam No. 23 is in pressured state, but with the increasing length of cantilever, the pressured tend gradually increases. However, because of the proper construction control, the stress of steel box girder is always in the safety range. Furthermore, as the Sutong Bridge adopts the optimal scheme of temperature natural closure of auxiliary incremental launching. So, before and after the closure of main span, the stress of steel box girder hasn't obvious changes. After completing the bridge, the stress is mainly affected by sunshine radiation (the maxim stress fluctuation in summer reaches to about 26 MPa). And before opening to traffic, the stress changes less.

4 Conclusions

1) The steel box girder of main span of the long-span cable-stayed bridge is erected by using the cantilever assemblage method in Sutong Bridge. The maximum length of single cantilever reaches to 540.8 m, and in the course of erection, the stress level of the main beam is high. Obviously, reasonable adjustment for cable-tensioned can improve the force distribution, so that the security of the steel box girder can be sure. But the measured stress of the steel box girder includes strong noise which disturbs the judgment of the safety trend of stress of the large cantilever beam. In order to provide reliable stress data for feedback analysis and construction control, it is necessary to separate the impact of noise.

2) In the erection process of the steel box girder of main span in Sutong Bridge, the main source of noise caused by meteorological factors is sunshine radiation, while the influence of wind loads on the stress of the large cantilever beam is not obvious. According to the characteristics of the noise, noise is separated from other factors by using Layered Separation method. The noises caused by occasional factors including wind loads are separated firstly, and then the ones caused by sunshine radiation having strong regularity are separated. In order to provide reliable stress data for feedback analysis, noises caused by seasonal temperature

difference, which is a kind of low-frequency noises, are further separated

3) Based on the foundation of wavelet de-noising technology, Layered Separation method is combined with the synchronous meteorological information, which has been done the filter processing. Different with the wavelet de-noising technology, Layered Separation method doesn't directly separate the noise from the measured stress data in accordance with the principle of smoothness and similarity. By this method, stress increment caused in the construction link such as hoisting the steel box girder is eliminated firstly, and then different decomposition scales are selected to separate noise combining the characteristics of noise according to a detailed and accurate timetable for the construction.

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