Natural characteristics of long span bridge under initial load: a case study of Minpu bridge

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Abstract. Natural frequencies and modes of bridges are very important for wind-resistant design, seismic design and damage test. Natural characteristics of existing bridge in design stage cannot consider the initial complex stress conditions. Actually, the bridge bears the complex initial load (Gravity load, Vehicle load, etc.) in the operation stage, which will cause a certain initial deflection, especially for long span bridges. So, the natural characteristics of bridge get changed. According to the design data of Minpu bridge, the three-dimensional finite element model of Minpu bridge is established by using frame element system based on SAP2000. Result shows that the first and second natural frequencies of the Minpu bridge in design stage are 0.12 Hz and 0.33 Hz respectively. Natural characteristics of Minpu bridge in the operation state are tested by using the microtremor measurement, and the first and second natural frequencies and modes of it are obtained. Result shows that the first natural frequency is 0.39 Hz. The second natural frequency is not uniform, which is within 2.34 ~ 3.70 Hz. The results reflect that the first and second natural frequencies of the Minpu bridge in operation stage increased greatly, which show that the initial loading state will have a great impact on the natural characteristics of long span bridges.

1. Introduction

The damage of bridge under the effect of wind or earthquake frequently occurs, which have close relation with its natural characteristics. Tacoma Strait bridge was built in 1940, four months later, large distortion occurred and it finally collapsed under the effect of the gale with a speed of 69 km/h, resulting in a direct economic loss of $8 million[1]. From April 26 to May 18, 2020, the Yingwuzhou Yangtze River bridge in Wuhan, Humen bridge in Guangdong, and Xihoumen sea crossing bridge in Zhoushan, Zhejiang Province suddenly occurred large vibration. The direct cause of the large vibration of these bridges is vortex-induced vibration[2]. In the 1995 Kobe earthquake in Japan, the studs on the side span piers of a double-layer cable-stayed bridge with a main span of 485 m fell off, causing the bridge to collapse. The Akashi Kaikyo bridge with a span of 1900 m was under construction at that time. Under the action of the earthquake, the anchorage platforms on both sides produced a horizontal displacement of 1.4 m, and the main tower also produced a horizontal displacement of 1.3 m[3].

In the seismic design of the structure, the natural frequency of the beam should different from the seismic wave, so as to avoid the resonance effect[4]. The influence of internal damping force should be considered in the wind resistance analysis, the natural vibration period and mode of the structure should be considered in the vibration control analysis, and the vibration modes test should be used in
the damage test of the bridge[5]. Therefore, the analysis of structural natural characteristics is of great significance to ensure the safe and stable operation of long-span bridges. In recent decades, people have proposed many methods to identify the natural mode of structure, including peak extraction method, frequency domain decomposition method, time-frequency domain method, time domain method, random decrement technique. The peak extraction method is based on the characteristic that the frequency response of the structure will have a peak at the natural frequency. According to the appearance of the peak, the natural frequency of the structure is estimated, and then the vibration mode and damping parameters are determined[6]. The frequency domain decomposition method is based on the peak extraction method and uses the principle of singular value decomposition to decompose the frequency spectrum of the system into multiple groups of frequency domains corresponding to different modes, so as to increase the identification accuracy[7]. The time-frequency domain method can directly identify the mode of the system through time-frequency transformation of the response signal[8]. Time domain analysis method uses the autoregressive model according to the relationship between the response and the system to extract the natural characteristics of the system[9]. This method is suitable for mode analysis without knowing the input parameters of the system. The random decrement method is based on the principle of sample average to eliminate the random uncertainties in the response, so as to obtain the vibration response under the initial excitation. In the mode analysis of bridge, the field test method is widely used. The frequency response function of the structure can be obtained by processing the original signal. Then, the mode parameters of the structure, such as natural frequency and natural mode, can be obtained.

Firstly, according to the design data of Minpu bridge, the three-dimensional finite element model of the bridge is established based on SAP2000 finite element analysis software, and the natural modes of the bridge without considering the initial loading state are obtained. Secondly, by using microtremor measurement, the microtremor test of 17 measuring points along the whole length of Minpu bridge is carried out at the same time. Then, the relatively stable waveforms of each measuring point are selected to calculate natural frequencies of each measuring point based on FFT. By adding position information and connecting the amplitudes corresponding to the first and second natural frequencies of each measuring point, the first and second mode shapes of the bridge are acquired. Finally, the measured results are compared with the numerical simulation results, and the effect of initial complex loading state on the natural characteristics of the bridge is clarified.

2. Case study
As an important transportation channel in Shanghai, Minpu bridge connects Zhejiang S32 expressway and Pudong International Airport. Minpu bridge shown in figure 1 was built in December 2009, with a total length of 3983 m. The length of main part and main span is 1212 m and 708 m respectively. The arrangement of main part is $4 \times 63 \text{ m} + 708 \text{ m} + 4 \times 63 \text{ m} = 1212 \text{ m}$.

The structure of the bridge is a double-layer cable-stayed bridge with double pylons and double cable planes, and the main part is a double plate truss beam structure[10]. There are four side spans on the left and right sides, and the length of each side span is 63 m. The main span of Minpu bridge adopts steel truss beam structure, which is characterized by orthotropic. The side span adopts reinforced concrete composite truss structure, the web members are all supported by steel structure, the upper and lower deck is mainly reinforced concrete, and the steel frame wrapped inside has the function to support deck. The stay cable adopts high strength steel wire to bear the tension. The main tower is H-shaped and reinforced concrete structure. The foundation of main tower pier is steel pipe pile with diameter of 0.9 m. Both the auxiliary pier and the side pier are frame structures. The frame consists of two reinforced concrete columns, and the foundation is bored pile with a diameter of 0.8 m[11]. Minpu bridge has been in good condition since its construction, and there is no obvious damage or deformation.
3. Natural characteristics of Minpu bridge in the design stage
According to the design data of Minpu bridge, the finite element model of Minpu bridge is established with the ratio of 1:1 to acquire its natural characteristics under the design state.

3.1. Three-dimensional finite element model of Minpu bridge
The length and width of the section of Minpu bridge are far less than the span, it can be simplified as a combination of beam elements for finite element analysis. The bridge calculation module of SAP2000 finite element analysis software can be used to establish the three-dimensional finite element model of Minpu bridge. During the modelling process, Minpu bridge is simplified as a beam element system of bridge deck, tower, pier and stay cables. The bridge deck, tower and pier are simulated by frame element. The section is realized by inputting section attributes and assigning frame elements, and the section shape is rectangular. The section size of bridge deck is set as 40 m long and 10 m wide. The section size of bridge tower and pier is 5 m × 5 m. Variable section is used to simulate the part below the bridge deck, and the section width is increased from 5 m to 8 m from top to bottom. The specific sizes of model are shown in Figure 2. The cable is simulated by the equivalent elastic modulus method. It only bears axial tension, without compression. The equivalent elastic modulus method assumes that both ends bear axial load and the material properties are uniform, and the diameter of stay cable is set as 0.5 m. For the whole span of cable stayed bridge, the nonlinear effect of stay cable is very small, so the stay cable is simplified as linear elastic element, and the equivalent elastic modulus method is used in simulation. The prestress of stay cable is input by the temperature drop method, that is, the prestress is simulated by setting a certain temperature for the stay cable. The pylon, the bottom of the pier and both ends of the bridge deck are consolidated. In the finite element analysis of SAP2000, the stay cable is connected with the main tower and girder by rigid connecting rod, that is, the rigid contact condition is simulated by setting continuous bending moment between them.

The main tower, bridge deck and side columns are made of reinforced concrete, and the stay cables are made of prestressed steel strand. The specific material parameters of the model are shown in Table 1. The value mainly come from design data.

| Materials         | Density (kg/m³) | Elastic modulus (GPa) | Poisson ratio |
|-------------------|-----------------|-----------------------|--------------|
| Reinforced concrete | 2600            | 345                   | 0.24         |
| Steel Strand      | 7850            | 200                   | 0.3          |
3.2. Analysis of numerical simulation results
The natural frequency analysis module of SAP2000 is used in the numerical simulation. Result shows that the first natural frequency of Minpu bridge is 0.12 Hz, the second natural frequency is 0.33 Hz, and the other natural frequencies are shown in Table 2.

| Order | Natural frequencies(Hz) |
|-------|-------------------------|
| 1     | 0.12                    |
| 2     | 0.33                    |
| 3     | 0.54                    |
| 4     | 0.57                    |
| 5     | 0.62                    |
| 6     | 0.71                    |
| 7     | 0.74                    |
| 8     | 0.81                    |
| 9     | 0.92                    |

Nine order natural frequencies corresponding to nine order natural modes. The first order and second order natural modes shown in figure 3 and 4. The maximum amplitude of first order mode occurred at the central of bridge and decreased to both ends. The second mode presents a multi peak shape. The value at central is relatively small.

4. Natural characteristics of Minpu bridge in operation stage
Microtremor measurement are carried out to determine the natural characteristics of Minpu bridge in operation stage.

4.1. Microtremor measurement of Minpu bridge
The test equipment is CV-374 network three component velocity seismograph produced by Tokyo vibration measurement company. The VSE-14C small servo velocity sensor is built in the seismograph, which can receive velocity signals in three directions (2 horizontal component + 1 vertical component). The velocity range of the sensor is ± 0.02 m/s, and the frequency range is 0.1 ~ 100 Hz. In this test, data that observed and collected by microtremor measurement are transformed by FFT method to determine the predominant period and frequency of Minpu bridge.

There are 17 measuring points along the length of Minpu bridge, as shown in the figure 5. The measuring points are symmetric with respect to the central of bridge. The measuring points are placed in a quiet and flat place to eliminate the interference of the surrounding environment, so that the weak vibration signal of the microtremor will not be submerged by the interference signal. The 17 points were observed at the same time. The sampling interval was 0.01 s, the recording time was 15 minutes, each point was recorded 4 times, the total recording length was 60 minutes. In the total 15 minutes of observation data, five groups with duration 60 s and within relatively stable time bands are selected. Then, FFT analysis is carried out on the data, and the Fourier spectrum of three directions is calculated.
Taking the average value of the Fourier spectrum of five groups as the FFT analysis result, the final Fourier spectrum of the measuring point was obtained. 

Figure 5. The layout of measuring points of Minpu bridge (m)

4.2. Analysis of test results

We mainly studied the z direction of Fourier spectrum, because z direction is main vibration direction of bridge and the natural characteristics in different directions have certain similarity. The Fourier spectrum of measuring points in z direction shown in figure 6. Result shows that the first natural frequency of Minpu bridge in z direction is 0.39 Hz. The second natural frequency is not uniform, which is within 2.34 ~ 3.70 Hz. Result reflects that natural frequency of long span bridge in complex operation state increased greatly compared with the simulation result.

Figure 6. The Fourier spectrum of z direction of measuring points

By extracting the spectrum amplitude of each order natural frequency at each measuring point and adding the information of distance between each measuring point and the leftmost pier of Minpu bridge, each natural mode shapes of Minpu bridge can be obtained. The first and second natural mode shapes shown in figure 7. The second natural frequency is in a range, we connect the amplitude that corresponding to the average natural frequency in the range as its second natural mode. Result shows that first and second natural mode obtained by numerical simulation and field test are in good agreement, especially for the first natural mode.

Figure 7. Natural mode of Minpu bridge

5. Results and discussion

(1) The finite element model was established referring to design data of Minpu bridge. Through the numerical simulation, the natural characteristics of Minpu bridge in the design state are obtained. Result shows that the first natural frequency is 0.12 Hz, and the second natural frequency is 0.33 Hz. 

(2) The natural characteristics of Minpu bridge in operation state was tested based on microtremor measurement, and the first and second natural frequencies and natural modes of Minpu bridge were acquired. The first natural frequency of Minpu bridge is 0.39 Hz and the second natural frequency is
within 2.34 ~ 3.70 Hz. The first and second natural mode obtained by numerical simulation and microtremor measurement are in good agreement.

(3) The results show that the first and second natural frequencies of Minpu Bridge increased greatly in operation state under the initial complex stress conditions, especially for second natural frequency. This result reflects that initial loading state will have a great impact on the natural characteristics of long span bridges. Our previous study shows that the reason for the change of its first and second natural frequencies is mainly due to the initial deflection that caused by gravity load, vehicle load, and so on[15]. Actually, due to the weight of the bridge structure, the gravity of the bridge railings, and the load of vehicles, although the stay cables will provide a certain tension, there is still a certain initial deflection on the bridge. The existence of the initial deflection will lead to the change of the stiffness of the bridge, which will lead to the increase of its natural frequency.

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