Aerodynamic Divergence of a Super-long Span Cable-stayed Bridge under Very Strong Wind

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ABSTRACT: Wind tunnel test of aeroelastic full model of Sutong Bridge is introduced, and special aerodynamic instability style was observed. The aeroelastic full model is regarded as a non-normal vibration system, and the vibration characteristics are investigated and analyzed. Complex modal analysis is carried out using SSA (Stochastic Search Algorithm) and SSI (Stochastic Subspace Identification). The results of both methods are agreed well. The torsional mode participates largely in vertical and lateral vibration, while the vertical and lateral modes have a little participation in the other two modes respectively.

KEYWORDS: Sutong Bridge; Aeroelastic model; Aerodynamic instability; Complex modal analysis; Power spectra analysis; Modal coupling

1 INTRODUCTION

Sutong Bridge lies in the southeast of Jiangsu Province in China, connecting Suzhou and Nantong City, with main span of 1088m, it will be the longest cable-stayed bridge in the world after its completion. The wind loads, aerodynamic stabilities, nonlinear vibrations of cables and vortex shedding possibility on the pylons and the steel deck had been proved to be the dominant factors for bridge design. Detailed wind-resistant performance researches had been carried out by the state key laboratory for disaster reduction in civil engineering at Tongji University (Chen, 2004).

Firstly, the wind tunnel test of aeroelastic full model of Sutong Bridge briefly introduced. Then the aeroelastic full model is regarded as a non-normal vibration system, and the vibration characteristics are investigated and analyzed. Moreover, the power spectra of displacements at high wind speed are studied. Furthermore, complex modal analysis is carried out. Finally, major conclusions are summarized and prospects are proposed.

2 FULL BRIDGE AEROELASTIC MODEL TEST

A special phenomenon of the aeroelastic full model was observed in wind tunnel testing. When wind speed attains certain value, Sutong Bridge aeroelastic model approaches to the critical state of aerodynamic instability. The deck and cables vibrate in lateral and vertical directions with large amplitude simultaneously in ellipse shape, accompanied with torsional oscillation. Figure 1 shows the aeroelastic model photo in wind tunnel at Tongji University.

Figure. 1 Full Aeroelastic model of Sutong Bridge
3 DECK MOTION TRACE AND CHARACTERISTICS ANALYSIS

The traces of torsional center of the deck at the cross section of the middle span, of the quarter span and middle side span are shown in Figures 2-3 (Xu, 2006). The coordinates origin are the location of torsional center at zero wind speed. At the critical instability state, some characteristics can be observed from Figure 2, which may be summarized as follows:

1) The movement at middle section has the same phase with that at quarter section, which reveals that the main span moves symmetrically. The movement at main span has the anti phase with that at side span. It can be seen that the main span is lifted and banked by the static wind load, while the side span was pressed and anti-banked.

2) When the vertical displacement of middle span increases, the lateral displacement decreases, and the movement of deck is in windward direction. When the vertical displacement arrives at its maximum value, the lateral displacement also arrives at its minimum value. This state is the most close to the equilibrium position at zero wind speed for lateral displacement. In another word, the middle span moves up in windward direction and moves down in leeward direction, which is the same for the side spans.

3) The motion trace of the deck is an approximate ellipse shape, not a strict ellipse, which depends on vertical and lateral frequencies, amplitude and phases.

![Figure 2: Motion trace of Sutong Bridge within a quasi period](image1)

![Figure 3: Motion trace of Sutong Bridge](image2)

Figure 2. Motion trace of Sutong Bridge within a quasi period

Figure 3. Motion trace of Sutong Bridge

Figure 4 shows the location of the deck at some time with the trace of torsion center, windward and leeward sides. The lowest section in the figure indicates the location of the deck at zero wind speed. Both displacements and torsion angles are exaggerated for intuitive and convenient analysis purpose. It can be found from the phenomena of testing and acquired signal, that the deck is raised with positive attack angle. Moreover, the deck is close to windward, and the amplitude is bigger.

![Figure 4: Sketch map of deck locations at different time](image3)

![Figure 5: Power spectra of displacements at middle section](image4)

Figure 4. Sketch map of deck locations at different time

Figure 5. Power spectra of displacements at middle section
4 INTERPRETATION OF THE AERODYNAMIC INSTABILITY

The description and interpretation of the aerodynamic instability can be made from Figures 2-3 and the video shot. With the increase of wind speed, the wind loads acting on the deck and the cables increases. The vertical displacement, lateral displacement and added attack angle increase, while the supporting stiffness of cables decreases and the vertical frequency falls down. When wind speed approaches to the critical wind speed, the 1st symmetrical vertical frequency decreases rapidly. Self-excited displacements of deck and cables under the periodical self-excited force go to a balanced state with the equilibrium of the energy of input and output. Figure 5 shows the power spectra of middle cross section displacements at higher wind speed approach to the critical state.

For convenience, the power spectra of displacements at three different wind speeds are plotted in the same figure with the peak standardized. It can be found that with the increasing of wind speed, the vertical frequency decreases rapidly with the predominant of vertical frequency. It can also be found from Figures 2-3 that the amplitude of vertical direction is greater than that of lateral direction. The motions of vertical, lateral and torsional direction coupled together into one frequency of vibration at the wind speed of 6.5m/s. The deck and cables moved in ellipse way in both vertical and later directions, which differ from other aeroelastic bridge model with the divergence of torsional vibration.

5 COMPLEX MODAL ANALYSIS

Based on complex mode theory, the vertical, torsional and lateral displacement can be expressed as

\[
\begin{align*}
  h(t) &= h_1(t) + h_2(t) + h_3(t) = A_1 e^{-\alpha_1 t} \cos(\beta_1 t + \theta_1) + A_2 e^{-\alpha_2 t} \cos(\beta_2 t + \theta_2) + A_3 e^{-\alpha_3 t} \cos(\beta_3 t + \theta_3) \\
  \alpha(t) &= \alpha_1(t) + \alpha_2(t) + \alpha_3(t) = A_1 \alpha_1 e^{-\alpha_1 t} \cos(\beta_1 t + \theta_1) + A_2 \alpha_2 e^{-\alpha_2 t} \cos(\beta_2 t + \theta_2) + A_3 \alpha_3 e^{-\alpha_3 t} \cos(\beta_3 t + \theta_3) \\
  p(t) &= p_1(t) + p_2(t) + p_3(t) = A_1 \alpha_1 e^{-\alpha_1 t} \cos(\beta_1 t + \theta_1) + A_2 \alpha_2 e^{-\alpha_2 t} \cos(\beta_2 t + \theta_2) + A_3 \alpha_3 e^{-\alpha_3 t} \cos(\beta_3 t + \theta_3)
\end{align*}
\]

where \( A_i \) is the amplitude of mode; \( \theta_i \) is the phase of mode, with \( i = 1, 2, 3 \) and \( j = 1, 2, 3 \), in which, 1 represents vertical movement, 2 represents torsional movement, and 3 represents lateral movement.

![Figure 6. Amplitude ratios and phase differences of different modes versus wind speed](image-url)
Based on the collected 3-DOF displacement signals, the relative amplitudes, phases, frequencies, and damping ratios are extracted using SSA (Stochastic Search Algorithm) and SSI (Stochastic Subspace Identification) by Xu (Xu, 2006), without constituting the state matrix with extracted flutter derivatives. Obviously, such a technique is equivalent to the common complex modal analysis by Ma (Ma, 2004). The amplitude ratios and phase differences obtained using SSA and SSI are plotted in Figure 6. It can be observed that

1) For amplitude ratio $A_{21}/A_{11}$ and $A_{31}/A_{11}$, it reveals that the torsional component takes a great part in the vertical displacement and the lateral component takes a little.

2) For amplitude ratio $A_{12}/A_{22}$ and $A_{13}/A_{23}$, it reveals that both vertical and torsional frequencies component take a little part in torsional signal and have no obvious tendency with the increasing of wind speed.

3) For amplitude ratio $A_{33}/A_{33}$ and $A_{23}/A_{23}$, it reveals that torsional component takes a great part in lateral signal and vertical component takes a little part.

4) For phase differences $\theta_{21} - \theta_{11}$ and $\theta_{31} - \theta_{11}$, it reveals that the vertical frequency component in torsional signal is anti phase of that in lateral signal.

5) For phase differences $\theta_{12} - \theta_{22}$, it is wandering at 180° stably, $\theta_{12} - \theta_{22}$ fluctuates at 0°. Correspondingly, amplitude ratio $A_{12}/A_{22}$ is more stable than $A_{12}/A_{22}$.

6) For phase differences $\theta_{33} - \theta_{33}$, it ranges a little at lower wind speed, while it increases rapidly at higher wind speed, and decreases a little when the wind speed approach the critical state. Phase difference $\theta_{23} - \theta_{23}$ fluctuates a little around 0°.

To sum up, the following rules can be concluded:

1) The amplitude ratios and phase differences obtained using SSA and SSI agree very well, and the precision and reliability of the two algorithms can be verified mutually;

2) The amplitude ratios and phase differences obtained using 2-DOF mode and 3-DOF mode are in good accordance.

3) The torsional mode takes a great part in vertical and lateral vibration, while the vertical and lateral modes take a little part in the other two modes respectively.

6 CONCLUSIONS AND PROSPECTS

Based on the study of wind performance of Sutong Bridge, some conclusions can be drawn as:

1) The motion trace of the deck is an approximate ellipse shape, not a strict ellipse. The movement at main span has the anti phase with that at side span. The main span is lifted and banked by the static wind load, while the side span was pressed and anti-banked. Both middle span and side spans move up in windward direction and moves down in leeward direction.

2) The amplitude ratios and phase differences obtained using SSA and SSI agree very well, and the precision and reliability of the two algorithms can be verified mutually.

3) The vertical mode has a little participation in lateral and torsional vibration, and the lateral mode has a little participation in vertical and torsional vibration, while the torsional mode participates largely in vertical and lateral vibration.

Comprehensive 3-D flutter analysis of Sutong Bridge attempt to be investigated in another study, considering the function of static wind loads, the participation of cables and the influence of additional attack angle.

7 REFERENCES

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