Flutter Controlling Effect and Mechanism of Central Stabilizer of Liu Jiaxia Bridge

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Abstract. Wind-induced vibration is the constraint of large-span bridge design; search for effective inhibition of wind-induced vibrations of bridge aerodynamic measures is particularly important. Through combination of wind tunnel experiments and theoretical analysis, the effectiveness of the central stabilizing plate on the wind-induced vibration control of Liu Jiaxia bridge and controlling mechanism were analyzed. The main contents are as follows: The original truss bridge section flutter test performance does not meet the requirements of the wind speed, through a variety of control measures flutter selection, the results show that the measures of central stabilizer plate has better inhibition of vibration. Through the wind tunnel test, the measures of central stabilizer plate on the impact of the truss bridge aerodynamic derivatives were researched. Aerodynamic derivatives $A_2$ is reduced with the wind speed increases of good aerodynamic shape of the cross section, the absolute value is large than the original cross-section; By using two-dimensional three degrees of freedom coupling flutter analysis method, the law of development of twisting motion aerodynamic damping and flutter morphology were analysis. The performance of the main beam flutter was improved through increasing torsional movement of pneumatic positive damping $A$, reducing torsional coupling movement implicated generated aerodynamic negative damping term $D$ or enhancing the level of participation in the sport of vertical curve shape of flutter effective vibration control.

1. Introduction

Truss stiffening girders are widely used in suspension bridge because of their large torsional stiffness and high air permeability, and are convenient for construction in area where transportation is difficult. The wind-induced vibration of bridge is the restriction factor of long-span bridge design, so it is particularly important to find effective vibration control measures. The central stabilizing plate are designed to improve the critical flutter wind speed of the bridge such as Runyang Yangtze River Bridge and Akashi Kaikyo Bridge [1, 2].

The Liujiatia Bridge in Gansu Province is suspension bridge, with a main span of 536m. When the bridge is completed, the rise-span ratio is about 1:11, the theoretical sag of the middle span is 48.7 m, the center distance of the main cable is 15.6m, the distance between the main cables in the middle of the span and the bridge deck is 4.0m, and the standard distance of the hangers is 8.0m. Steel truss
stiffening beams, orthotropic slab bridge decks are used, and the center of the chord is 4m. Figure.1 shows the layout of the Liujiaxia Bridge. Figure.2 shows the stiffening girder of the Bridge.

![Figure 1. The layout of the Liujiaxia Bridge.](image1)

Figure 2. The stiffening girder of the Bridge.

![Figure 3. The wind tunnel test model](image3)

Figure 3. The wind tunnel test model

2. Experimental study on flutter control measures

The original section could not meet the requirements of flutter stability, so the influence of the height of upper and lower central stabilizing plates on flutter stability is studied. The test is carried out in the wind tunnel laboratory of Chang'an university. The segment model of the main beam is a rigid model made of a lightweight synthetic material with a geometric scale ratio of 1:40. The length of the model is 2.2m, the width is 0.4m and the beam height is 0.112m. The segment model is suspended in the wind tunnel by 8 springs, and the wind tunnel test model is shown in Figure 3.

The Height h1 of the central stabilizing plate under Liujiaxia Bridge is 1.12m, that is, the ratio of the height of the central stabilizer to the height of the stiffening beam is 0.25 [3]. The overall visual effect shall be considered for the upper stable slab, which shall not be higher than the bridge deck railing. The ratio of the height of the upper stable slab H2 to the height of the crash barrier is about 0.5 (h2=0.8m) and 0.8 (h2=1.28m). The aerodynamic schemes of the central stabilizer and the results of the flutter critical wind speed are summarized in Table 1.

![Table 1. Aerodynamic schemes of the central stabilizer and the flutter critical wind speed](table1)

| Conditions   | Aerodynamic schemes | Flutter critical wind speed (m/s) | Test wind speed (m/s) |
|--------------|---------------------|----------------------------------|-----------------------|
| Original section | ![Schematic diagram](image4) | h1=1.12m | 48.2 43.8 43.8 |
| Condition 1  | ![Schematic diagram](image5) | h1=1.12m | >70.1 46.0 32.9 |
| Condition 2  | ![Schematic diagram](image6) | h1=1.12m, h2=0.8m | >70.1 >70.1 >70.1 48.2 |
| Condition 3  | ![Schematic diagram](image7) | h1=1.12m, h2=1.28m | >70.1 >70.1 >70.1 >70.1 |

53.1
Table 1 shows that the flutter critical wind speed at -3° and 0° attack angles can be significantly increased under working condition 1, and the flutter critical wind speed at 3° attack angle can be reduced. The combined application of upper and lower central stabilizing plates can obviously improve the flutter stability of some wind angles of attack, but the critical flutter velocity can’t meet the requirements for some wind angles of attack. The 5° wind attack angle under condition 2 does not meet the flutter stability requirements; and each wind angle of attack under condition 3 meets the flutter stability requirements.

3. Influence of aerodynamic measures of central stabilizer on aerodynamic derivatives

Through the wind tunnel test on the truss model with aerodynamic measures of the central stabilizing plate, the aerodynamic derivatives of flutter data under various working conditions are identified [4, 5]. Figure 4 shows the effect of the central stabilizer on the flutter derivatives.

It can be seen from the figure that at 0° attack angle, the different types of central stabilization plates has little effect on the aerodynamic derivatives $A^r_1$ and $H^r_1$, and the trend of each working condition is the same with little difference in values. The aerodynamic derivative $A^r_2$ of the original truss is consistent with that of the lower central stabilizing plate, which decreases first and then increases slowly with the increase of wind speed, and all $A^r_2$ are negative with the upper stabilizing plate, the absolute value increases with the increase of the height of the upper central stabilizing plate.

The absolute values of the aerodynamic derivatives $A^r_3$, $H^r_2$ and $H^r_3$ of the original truss section are very small. The absolute values of $A^r_3$ and $H^r_2$ increased, and the absolute value of $H^r_3$ is closer to zero with the upper stabilizer plate. With the increase of the height of the upper stabilizing plate, the absolute values of $A^r_3$ and $H^r_2$ decrease and the absolute values of $H^r_3$ increase significantly.

The curves of $A^r_1$ and $H^r_1$ showed the same trend, $A^r_1$ decreased with the increase of wind speed, $A^r_1$ changed from positive to negative at working condition 2, and the other working conditions are negative. $H^r_1$ increased with the increase of wind speed and the height of upper stabilizer plate.
4. Mechanism of the central stabilizer plate

4.1. Aerodynamic damping of system torsional motion

Yang Yongxin’s research \cite{6-8} shows that the flutter divergence of the streamlined and bluff section bridge cross-section, which is driven by the aerodynamic negative damping, is caused by the system torsion, therefore, it is the key to study the flutter control mechanism to deeply analyze the development law of aerodynamic damping of torsional motion. The aerodynamic damping of the system of torsional motion can be expressed in terms of the aerodynamic derivatives as follows:

1. The aerodynamic damping is formed by the aerodynamic lifting torque, which is caused by the torsional velocity can be expressed by $-\frac{1}{2}\cdot\rho B^4/l\cdot A'_i$ (labeled as aerodynamic damping A).

2. The aerodynamic damping is formed by the coupled aerodynamic lifting torque, which is caused by the aerodynamic lift and the vertical velocity generated by torsional velocity, which can be expressed by $-\rho B^4/2m_l\cdot\Omega_{nu}\cdot A'_iH'_i\cos\theta$ (labeled as aerodynamic damping B).

3. The aerodynamic damping is formed by the coupled aerodynamic lifting torque, which is caused by the aerodynamic lift and the vertical displacement generated by torsional velocity, which can be expressed by $\rho B^4/2m_l\cdot\Omega_{nu}\cdot A'_iH'_i\sin\theta$ (labeled as aerodynamic damping C).

4. The aerodynamic damping is formed by the coupled aerodynamic lifting torque, which is caused by the aerodynamic lift and the vertical displacement generated by torsional displacement, which can be expressed by $-\rho B^4/2m_l\cdot\Omega_{nu}\cdot A'_iH'_i\cos\theta$ (labeled as aerodynamic damping D).

5. The aerodynamic damping is formed by the coupled aerodynamic lifting torque, which is caused by the aerodynamic lift and the vertical displacement generated by torsional displacement, which can be expressed by $\rho B^4/2m_l\cdot\Omega_{nu}\cdot A'_iH'_i\sin\theta$ (labeled as aerodynamic damping E).

\[
\Omega_{ij} = \frac{\omega_j}{\sqrt{(\omega_i^2 - \omega_j^2) + 16\xi^2\omega_i^2\omega_j^2}} \quad (i, j = \alpha, h) \tag{1}
\]

\[
\theta_1 = \arctan\left(\frac{2\xi^2\omega_h\omega_d}{\omega_h^2 - \omega_d^2}\right) + \frac{3}{2}\pi \tag{2}
\]

\[
\theta_2 = \arctan\left(\frac{2\xi^2\omega_h\omega_d}{\omega_h^2 - \omega_d^2}\right) \quad (90^\circ < \theta_2 < 180^\circ) \tag{3}
\]
In the above 5 items of aerodynamic damping, aerodynamic damping A is produced by the torsion freedom and aerodynamic damping B,C,D,E are all produced by the coupling effect between the torsional and vertical degrees of freedom.

Figure 5 shows the aerodynamic damping curve of the original truss section and the measure section of the central stabilizing plate with the wind speed. The aerodynamic damping changes from negative to positive and becomes bigger and bigger with the wind speed increasing. Therefore, the aerodynamic damping A produced by the torsional motion decreases from positive to negative with the increase of wind speed, that is, the aerodynamic damping produced by the torsional motion only becomes positive at the lower wind speed, which plays a role in stabilizing the system, then, as the wind speed increases, it decreases rapidly, which is not conducive to the stability of the system's torsional motion, as shown in Figure 4.

Among the other four aerodynamic damping due to the coupling effect of torsion and vertical degrees of freedom, the aerodynamic damping D is the determining force of the torsional divergence. In other words, the torsional flutter is driven by the negative aerodynamic damping. The driving mechanism of the original truss section is the same as the measure section at 0° and 3° attack angles. The aerodynamic damping A keeps always positive with the increase of wind speed, which plays the role of stabilizing the system.

In Condition 3 with the upper and lower central stabilizing plates, the aerodynamic damping A is formed by the torsional motion, which increases with the increase of wind speed and keeps positive always. The aerodynamic damping D which is formed by the coupling of torsional and vertical degree of freedom is the main reason for the divergence. At 0° wind attack angle of condition 2, the aerodynamic damping A is always positive and increases with the increase of wind speed, which plays a role in stabilizing the system. The coupling aerodynamic damping C is another force to stabilize the bridge with the increase of wind speed. The aerodynamic damping A and aerodynamic damping B prevent the speed of negative aerodynamic damping.
4.2. Flutter modality

Flutter modality [6-8] is also an important factor to study the mechanism of flutter, that is, to understand the degree of torsion and vertical freedom. It can be calculated by using formula (4-5) for a two-degree-of-freedom flutter analysis. Figure 5 shows the flutter modality of the original truss section and the central stabilizing plate section when they reach the flutter critical state.

\[ V_e = \frac{\rho B^2}{m_h} \Omega_{h,a} \sqrt{H_2^2 + H_3^2} \frac{1}{C_o} \quad (4) \]

\[ V_h = \frac{1}{C_h} \left( \frac{\rho B^4}{I} \Omega_{v,a} \sqrt{A_v^2 + A_u^2} \right) \quad (5) \]

In the formula:

\[ C_o = \sqrt{\frac{\rho B^2}{m_h} \Omega_{h,a} \left( H_2^2 + H_3^2 \right)} + 1 \]

\[ C_h = \sqrt{\frac{\rho B^4}{I} \Omega_{v,a} \left( A_v^2 + A_u^2 \right)} \]

From the position of the vector, it can be concluded that the flutter mechanism of each sections is different, that is, the coupling degree and freedom is different. Torsional degree of freedom is the most important factor and the vertical degree of freedom is the lowest when the original truss section reaches the flutter critical state. In Condition 1 with the lower central stabilizing plate, the coupling degree of different freedom is strongest and the flutter critical wind speed is largest at -3° wind attack angle. The degree of participation of vertical freedom is higher with the lower and upper central stabilizing plate, and the critical wind speed of flutter is significantly increased compared with the original truss section at various wind attack angles.
5. Conclusion
The influence of different central stabilizing plates on the truss section of the main girder on the aerodynamic performance is mainly reflected in the change law of the aerodynamic derivatives. The change of aerodynamic derivative $A_2^*$ is more significant than $A_3^*$. After taking effective aerodynamic measures, $A_2^*$ turned from positive to negative, forming aerodynamic damping, which increases the total damping of bridge section, decreases the flutter frequency and increases the flutter critical wind speed.

By using two-dimensional three degrees of freedom coupling flutter analysis method, the law of development of twisting motion aerodynamic damping and flutter modality were analysis. The performance of the main beam flutter was improved through increasing torsional movement of pneumatic positive damping $A$ or reducing torsional coupling movement implicated generated aerodynamic negative damping term $D$.

The mechanism of effective aerodynamic measures is to transfer the flutter form from single-degree-of-freedom torsional vibration to flexural-torsional vibration by increasing the participation degree of vertical bending freedom, the flutter frequency is decreased and the critical wind speed is increased.

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