Study on buffeting performance of double cantilevers of П type beam cable-stayed bridge under oblique wind

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Abstract. Based on the aeroelastic model experiment of a long-span cable-stayed bridge, the vertical and torsional buffeting responses of π beam under different wind deflection angles are studied, and the influence of wind attack angle on buffeting response is further studied. The results show that the vertical and torsional buffeting displacement responses of the main girder increase in quadratic function with the wind speed. Moreover, the maximum value of buffeting response is not at the 0° wind deflection angle, and the position of the most unfavorable buffeting response is different under different attack angles. With the increase of wind deflection angle, the vertical and torsional buffeting displacement response of π type girder generally decreases first and then increases, then decreases and then increases, presenting the phenomenon of "three twists and turns". The increase of wind deflection angle to buffeting response is generally between 10% and 20%, and the maximum can reach 40%. The comparison between the test results and the analysis results shows that the influence of the oblique wind effect and the wind attack angle on the buffeting response must be considered when analyzing the buffeting response of the cable-stayed bridge.

1. Introduction

Buffeting is an important phenomenon of wind-induced vibration, which is mainly caused by the inherent turbulence characteristics of natural wind and the characteristic turbulence generated by the wind flow through the blunt body structure, so it is a random forced vibration [1]. The measured results of some long-span bridges show that the direction of strong wind often deviates from the normal direction of the bridge span with a large deflection angle, and the wind tunnel test results [2-3] also show that the inclined wind is often more unfavorable. However, the buffeting response of normal wind is usually considered in the buffeting design of long-span bridges, and the oblique wind effect is ignored, especially for the common blunt girder section in engineering, the oblique wind effect may be unfavorable. Moreover, the natural wind does not necessarily blow to the bridge deck horizontally, and there may be a wind attack angle. Previous studies on buffeting have paid less attention to the influence of oblique wind and wind attack angle coupling on buffeting response [4].

In this paper, a typical bluff body bridge section, double-sided I-beam section, is selected as the test object. Taking a long-span cable-stayed bridge as an example, through the wind tunnel test of the largest double cantilever aeroelastic model of the cable-stayed bridge, the variation law of buffeting response of the bluff body section cable-stayed bridge under different wind attack angles and wind deflection angles is studied.
2. Aeroelastic model test

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2.1. Model introduction

The main span of the cable-stayed bridge is a three-span, double-tower and double-cable plane steel-concrete composite girder cable-stayed bridge with a main span of 565 m. The main girder section is a duplex steel beam + concrete bridge deck, and the longitudinal is a semi floating system. The stay cables are fan-shaped. The wind tunnel test of the largest double cantilever aeroelastic model of the cable-stayed bridge is carried out in the CA-1 boundary layer wind tunnel of Chang'an University. The geometric scale ratio of the model is 1/145, and the wind speed ratio is 1/12.04. The main beam section is shown in figure 1:

![Figure 1. section size of main beam model (unit: mm).](image)

The main beam of the model consists of a core beam, a jacket and a counterweight. The core beam is a channel cross-section, which is used to simulate the vertical bending stiffness, transverse bending stiffness and free torsion stiffness of the main beam. The outer jacket is used to simulate the geometry of the main girder. The counterweight is used to adjust the mass and inertia moment of the girder model to meet the similar conditions. The same tower model is made up of steel core, coat and counterweight. Among them, the steel mandrel simulates the structural stiffness, the outer shell simulates the shape of the bridge tower, and the counterweight is used to adjust the mass and mass distribution of the model to meet the similar requirements. The assembled model is shown in figure 2.

![Figure 2. aeroelastic model.](image)

2.2. Model parameters

The design values of the main natural frequencies of the real bridge and aeroelastic model are obtained by the finite element program analysis. The first four modes of aeroelastic model are obtained by modal test before the experiment. The natural frequency test results of the model are given in Table 1. In order to facilitate comparison, the corresponding first four modes of real bridge, design value of natural frequency of model, measured value of natural frequency of model and deviation between measured value and design frequency of model are also given in the table. It can be seen from the table that the measured values of each natural frequency of the model are in good agreement with the design values, and each deviation is less than 3.99%. The measured damping ratio of each mode of the model is also listed in the table. It can be seen from the table that the modal damping ratio of the model is between 1.20% and 1.50%. The measured damping ratio of the fourth mode is also close to the required damping value of 1%, which meets the test requirements.
Table 1. Dynamic characteristics of aeroelastic model

| Mode order | Mode description    | Real bridge value (Hz) | Target value (Hz) | Design value (Hz) | Error | Measured damping ratio of the model |
|------------|---------------------|------------------------|-------------------|-------------------|-------|-----------------------------------|
| 1          | Vertical pendulum   | 0.1868                 | 2.2491            | 2.241             | -0.36%| 1.20%                             |
| 2          | Swinging            | 0.2966                 | 3.5711            | 3.440             | -3.67%| 1.40%                             |
| 3          | First stage side bending | 0.4307              | 5.1856            | 4.988             | -3.81%| 1.40%                             |
| 4          | First stage torsion | 0.4680                 | 5.6347            | 5.859             | 3.98% | 1.50%                             |

2.3. Wind field simulation

According to the analysis of the wind environment at the bridge site, in the CA-1 atmospheric boundary layer wind tunnel of Chang'an University, A-type landform turbulence wind field with a scale of 1:145 is simulated by using the steeple and the rough element. The layout of the simulated wind field is shown in figure 3. The target value of wind speed profile index $\alpha$ at the bridge site is 0.12, and the gradient wind height is 300 m [5]. The wind speed profile index of the simulated wind field obtained from the test data fitting is 0.12, and the fitting average wind profile is consistent with the target profile, as shown in figure 4. The downwind turbulence of the simulated wind field is shown in figure 5.

2.4. Test conditions

In this study, the wind deflection angle is defined as the horizontal angle between the average wind direction of the incoming flow and the normal direction of the bridge span, i.e. 0° wind deflection angle means that the incoming flow is orthogonal to the bridge span direction. In order to study the effect of wind deflection angle on the buffeting response of the main beam in double cantilever state, the aeroelastic model is fixed on the $\beta$ rotary table mechanism in the CA-1 wind tunnel, and the required wind deflection angle is achieved by rotating the rotary table. Zhu [2] found that the maximum value of buffeting response may occur in the range of 0° - 15° wind deflection angle, so seven cases of wind deflection angle of 0°, 2°, 5°, 7°, 10°, 12° and 15° were considered in the test process, and three wind attack angles of +3°, 0°, and -3° were considered simultaneously. The test wind speed range is 1.0 ~ 6.5 m/s, corresponding to the wind speed at the height of the actual bridge girder is 12.04 ~ 78.26 m/s.

3. Wind tunnel test results and analysis

3.1. Effect of wind speed on buffeting response of main girder
In this section, the vertical, horizontal and torsional buffeting responses of the main girder under the condition of maximum double cantilevers are discussed. Because the variation of mid span and side span cantilever end is similar, and the lateral displacement is smaller than the vertical and torsional displacement, then the vertical and torsional buffeting test results of mid span cantilever end are mainly discussed. Figure 6 and figure 7 show the vertical and torsional buffeting response curve of the main beam with wind speed under +3°, 0° and -3° attack angles respectively. The horizontal axis is the wind speed of the real bridge, and the vertical axis is the buffeting displacement response of the real bridge.

3.1.1. **Vertical buffeting response of main girder**

It can be seen from figure 6 that the vertical buffeting response of π type girder increases as a quadratic function with the wind speed. The variation of vertical buffeting response with wind speed also shows the same rule under different wind deflection angles. figure 6 (a) - (c) are the curves of vertical buffeting response of π type girder with wind speed under +3°, 0° and -3° attack angles respectively. It can be seen that buffeting response increases with wind speed in quadratic function under different attack angles, but the specific curve forms of different attack angles are different. It is found that the vertical buffeting displacement of -3° angle of attack is significantly less than that of +3° and 0° angle of attack. In addition, the vertical buffeting displacement of the main beam at +3° attack angle is greater than that at other wind deflections at 10° wind deflections; at 0° attack angle, the vertical buffeting displacement of the main beam at 10° wind deflections at low wind speeds is greater than that at other wind deflections, and at 7° wind deflections at high wind speeds is greater than that at other wind deflections; at -3° attack angle, the vertical buffeting displacement of the main beam at 10° wind deflections is greater than that at other wind deflections.
3.1.2. Torsional buffeting response of main girder

![Graphs showing torsional buffeting response](image)

It can be seen from figure 7 that the torsional buffeting response of π type girder increases as a quadratic function with the wind speed. The variation of torsional buffeting response with wind speed under different wind deflection angles is similar, and the response values are quite different. Figure 7 (a) - (c) is the curve of π type girder torsional buffeting response with wind speed under different wind attack angles. It can be seen that the buffeting displacement response under different wind attack angles has the same change rule with wind speed, and they all grow as quadratic function. It is found that the torsional buffeting displacement of +3° angle of attack is larger than that of -3° angle of attack. In addition, the torsional buffeting displacement of the main beam at +3° angle of attack is greater than that at other wind deflections at 7° angle of attack; at 0° angle of attack, the torsional buffeting displacement of the main beam at 7° angle of attack is greater than that at other wind deflections; at -3° angle of attack, the torsional buffeting displacement of the main beam at 7° angle of attack is greater than that at other wind deflections.

3.2. Influence of wind deflection angle on buffeting response of main girder

Based on the discussion in Section 3.1, it can be known that the vertical and torsional buffeting responses of the main girder of the cable-stayed bridge show a quadratic curve growth with the increase of wind speed, and although the response growth curves are similar under different wind deflection angles, the response values are quite different. Therefore, in this section, the influence of different wind deflection angles on the vertical and torsional buffeting responses of π beams will be discussed. Figure 8 and figure 9 show the vertical and torsional buffeting response curve of the main beam with the wind deflection angle under +3°, 0° and -3° attack angles, respectively. The horizontal axis is the wind deflection angle and the vertical axis is the buffeting displacement response of the real bridge.
3.2.1. Influence of wind deflection angle on vertical buffeting response of main girder

Generally speaking, with the increase of wind deflection angle, the vertical buffeting response of the main beam first decreases and then increases, then decreases and then increases, showing a "three twists and turns" phenomenon.

From figure 8(a), it can be seen that when the wind attack angle is +3° and the wind attack angle is 0°, the maximum value of vertical buffeting displacement response appears at 10° wind deflection angle under all wind speeds. When the wind speed of the real bridge is 36.1 m/s, the vertical displacement of 0° wind deflection angle is 0.1977 m, and the vertical displacement of 10° wind deflection angle is 0.2243 m, which is 13.46% larger than that of 0° wind deflection angle.

It can be seen from figure 8(b) that when the wind attack angle is 0°, the maximum value of vertical buffeting displacement response occurs when the wind speed is 12.04 m/s and 18.06 m/s, and when the wind deflection angle is 5°; when the wind speed is 24.0 m/s, the maximum value occurs when the wind deflection angle is 10°; when the other wind speeds, the maximum value of vertical buffeting displacement response also occurs when 7° wind deflection. When the wind speed of the true bridge is 36.1 m/s, the vertical displacement of 0° wind deflection angle is 0.2229 m, and that of 7° wind deflection angle is 0.2484 m, which is 11.44% larger than that of 0° wind deflection angle.

It can be seen from figure 8(c) that when the wind attack angle is -3°, the maximum value of vertical buffeting displacement response also appears in the case of 10° wind deflection angle at each wind speed. When the wind speed of the true bridge is 36.1 m/s, the vertical displacement of 0° wind deflection angle is 0.1510 m, and that of 10° wind deflection angle is 0.1753 m, which is 16.08% larger than that of 0° wind deflection angle.
3.2.2. Influence of wind deflection angle on torsional buffeting response of main girder

![Graph A](image1)

![Graph B](image2)

![Graph C](image3)

Figure 9. Torsional buffeting displacement vs. yaw angle of wind
(a) +3° attack angle (b) 0° attack angle (c) -3° attack angle.

Generally speaking, with the increase of wind deflection angle, the torsional buffeting displacement response of the main beam decreases first, then increases, then decreases and then increases, showing a "three twists and turns" phenomenon.

It can be seen from figure 9(a) that when the wind attack angle is +3°, the maximum value of torsional buffeting displacement response occurs at 7° wind deflection angle at each wind speed. When the wind speed of the real bridge is 36.1 m/s, the vertical displacement of the 0° wind deflection angle is 0.1530°, the vertical displacement of the 7° wind deflection angle is 0.2191°, which is 43.19% larger than that of the 0° wind deflection angle.

It can be seen from figure 9(b) that when the wind attack angle is 0°, the maximum value of vertical buffeting displacement response occurs at 7° wind deflection angle at each wind speed. When the wind speed of the real bridge is 36.1 m/s, the vertical displacement of the 0° wind deflection angle is 0.1753°, the vertical displacement of the 7° wind deflection angle is 0.2085°, which is 18.93% larger than that of the 0° wind deflection angle.

It can be seen from figure 9(c) that when the wind attack angle is -3°, the maximum value of vertical buffeting displacement response also appears in the case of 7° wind deflection angle at each wind speed. When the wind speed of the true bridge is 36.1 m/s, the vertical displacement of the 0° wind deflection angle is 0.1449°, the vertical displacement of the 7° wind deflection angle is 0.1489°, which is 2.75% larger than that of the 0° wind deflection angle.

4. Conclusion

(1) The vertical and torsional buffeting displacement responses of π-type girder cantilever end of the cable-stayed bridge in the state of maximum double cantilevers increase in quadratic function with the wind speed. Moreover, the maximum value of buffeting response is not at 0° wind deflection angle, and the position of the most unfavorable buffeting response is different under different attack angles.
(2) With the increase of wind deflection angle, the vertical and torsional buffeting displacement response of π type girder generally decreases first and then increases, then decreases and then increases, presenting the phenomenon of "three twists and turns".

(3) The most disadvantageous deflection angle of the oblique wind effect is different under different wind attack angles. For vertical displacement, +3° angle of attack, the most unfavorable deflection angle is around 10°. The most disadvantageous deflection angle is around 7° at 0° angle of attack. The most unfavorable deflection angle is around 10° at 3° angle of attack. For torsional displacement, the most unfavorable deflection angle is around 7° at each angle of attack.

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