Influence of Girder Spacing on Vortex-Induced Vibration Performance and Flow Field Characteristics of Double-Layer Box Girder

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Abstract. Through wind tunnel tests and computational fluid dynamics (CFD), the vortex vibration performance and flow field characteristics of double-layer box girder with different girder spacings were studied. The results showed that the double-layer box girder has vortex-induced vibration phenomena at 0° and positive wind angle of attack. Among them, at 0° wind angle of attack, the double-layer box girder's vortex performance gradually became better with increasing girder spacing. Under the wind attack angles of +3° and +5°, the vertical bending vortex vibration performance of the double-layer box girder showed a trend of first optimizing and then worsening with the increase of the girder spacing, and the torsional vortex vibration performance of the double-layer box girder showed a tendency to deteriorate first and then improve with the increase of the girder spacing. The development of vortices caused by the enhancement of the flow separation between the upper surface of the upper girder and the lower surface of the lower girder caused by the aerodynamic interference between the upper and lower girders of the double-layer box girder, and the magnifying effect of the upper girder on the vortex in the wake area of the upper surface of the lower girder were the internal reasons for the influence of the girder spacing on the vortex vibration performance of the double-layer box girder.

1. Introduction

Vortex-induced vibration is due to the flow separation of the air flow after passing through the main girder cross section and the formation of a wide wake in the downstream area, and then the vortices fall off alternately in the vicinity of the structural section. When the frequency of vortex shedding is close to the natural vibration frequency of the structure, the structural cross-wind limiting vibration phenomenon is induced. Although the vortex vibration with self-limiting characteristics will not cause the overall structural dynamic instability, excessive amplitude will affect pedestrian comfort, driving safety and cause fatigue damage of components, affecting the durability of the structure[1][4]. The vortex vibration phenomenon is relatively easy to occur in the normal use state of the bridge. The problem of the vortex induced vibration of the soft long-span bridge must be given sufficient attention by engineering design and scientific researchers.

At present, many scholars at home and abroad have conducted many studies on the vortex vibration performance and the surrounding flow field characteristics of single-layer box girders, and have achieved certain results. Zhu Ledong et al.[5] took the single pylon cable-stayed bridge with a main span
of 310m as the research background, studied the influence of the aerodynamic interference effect on the flutter performance and vortex vibration characteristics of the bridge with separated double-amplitude box girder through a series of segment model wind tunnel tests. Li Chunguang et al. [6] studied the mechanism of the influence of railing foundation on the vortex vibration performance of closed box girder bridges through a wind tunnel vibration and pressure test. Hu Chuanxin et al. [7] took a typical closed box girder cross section as the research object, and carried out vibration and pressure wind tunnel tests and numerical simulation studies on the segment model, and combined with the vortex vibration response, the time-frequency characteristics of surface wind pressure and the flow field characteristics, expatiated the vibration suppression mechanism of the railing handrail damper plate.

At present, as a new type of cross-section, double-section box girders have been gradually applied to extra-large span suspension bridges with high traffic requirements. However, no scholars at home and abroad have studied the double-layer box girders' vortex vibration performance. This study takes double-layer box girder as the research object, through wind tunnel test and numerical simulation software (CFD) to study the effect of girder spacing on double-layer box girder vortex performance and flow field characteristics.

2. Experiment Overview

2.1. Experiment model and bracket

The scale ratio of the double-layer box girder model was 1:50, and the dimensions of each layer of the box girder model were: B=894mm, height H=66mm, and length L=1800mm. Rigid connection between the upper and lower box girders, the net spacing \( \Delta \) of double-layer box girder was set to 0.5h, 0.75h, h, 1.5h, 2h, 2.5h, 3.5h, 4.5h (h is the height of single-layer box girder). The cross-section of the double-layer box girder used in the test was shown in figure 1.

![Figure 1. Geometric parameters of double-layer box girder model (unit: mm)](image)

In the study, an internal support system was used to suspend the model in the low-speed test section of the wind tunnel. The double-layer box girder segment model was elastically suspended by 8 springs, which provide vertical and torsional stiffness. The model and the boom were connected by a flange, which can easily adjust the wind angle of attack. Figure 2 is a model of a double-layer box girder suspended in a wind tunnel.
2.2. Study conditions
In order to study the effect of girder spacing on the vortex vibration characteristics of double-layer box girders, the net spacing of the upper and lower girders was adjusted to 0.5h, 0.75h, h, 1.5h, 2h, 2.5h, 3.5h at 0 °, 4.5h (where h is the height of the single-layer box girder), and separately conducted wind tunnel vibration test. In addition, several typical girder spacings (0.5h, 1.5h, 2.5h, 3.5h, 4.5h) were tested at ±3° and ±5° wind attack angles.

3. The effect of girder spacing on the lock interval of amplitude and wind speed
Figures 3 to 5 were the curves of the vortex vibration amplitude of the double-layer box girder with the wind speed when the wind attack angle α was 0°, +3° and +5° respectively. In order to facilitate the comparison, the test results of single-layer box girder were added under each wind angle of attack for comparative analysis. At -3° and -5° wind attack angles, no vertical bending and torsional vortex vibrations occurred. Due to space limitations, the curve of the vortex amplitude of the double-layer box girder under negative wind angle of attack with wind speed is no longer listed.
Through the above study results, it can be found that:

(1) At 0° wind angle of attack, the single-layer box girder exhibited no vortex vibration; for the double-layer box girder, vertical bending and torsional vortex vibration have occurred within the girder spacing $\Delta$ of 0.5h ~ h. From the curve of the vortex amplitude with the wind speed, it was found that with the increase of the girder spacing, the vortex performance of the double-layer box girder gradually became better, the maximum amplitude of the vortex gradually decreases, and the vortex lock interval also gradually shortens.

(2) At a $+3^\circ$ wind attack angle, both single-layer girders and double-layer girders with various girder spacing had different degrees of vertical bending and torsional vortex vibration. As for the vertical bending vortex vibration, the maximum amplitude of the vertical bending vortex vibration of the double-layer box girder decreased first and then increased with the increase of the girder spacing. When the girder spacing $\Delta$ was 3.5h, the vortex vibration amplitude dropped to the minimum, was 0.3mm, and the corresponding wind speed was 3.4m/s, and the maximum vertical bending vortex amplitude of single-
layer girders was between double-layer girders with girder spacing of 0.5h and 1.5h. For torsional vortex vibration, the torsional vortex amplitude of single-layer girders was higher than that of double-layer girders at all girder spacing. As the girder spacing increases, the maximum torsional vortex amplitude of the double-layer box girder tends to increase first and then decrease. When the girder spacing was 1.5h, the torsional vortex amplitude reaches the maximum, was 0.21°, and the corresponding wind speed was 10.2m/s.

(3) Under the +5° wind attack angle, the single and double girders also exhibited vertical bending and torsional vortex vibration to varying degrees. For vertical bending vortex vibration, with the increase of girder spacing, the vertical bending vortex vibration amplitude of the double-layer box girder showed a trend of decreasing first and then increasing, and it decreased to a minimum of 0.67mm when the girder spacing Δ was 3.5h. The maximum amplitude of vertical bending vortex vibration of single-layer box girder was between double-layer box girder with girder spacing Δ of 1.5h and 2.5h. For torsional vortex vibration, the maximum amplitude of the torsional vortex vibration of single-layer box girders was greater than that of double-layer girders with different girder spacing. As the girder spacing increased, the maximum amplitude of the torsional vortex vibration of the double-layer box girder exhibited an "S" shape that increases first, then decreases and then increases, and reached a maximum of 0.23° when the girder spacing was 1.5h, the corresponding wind speed was 10.2m/s.

4. Numerical simulation of the flow field characteristics of double-layer box girders with different girder spacing

In order to visually study the flow field characteristics of the single-layer box girder, the CFD software was used to simulate the wind-induced vibration of the box girder, so as to realize the airflow separation, re-adhesion and intuitive capture of vortices, to further analyzed the single-layer box girder vortex vibration mechanism[8][12]. The distribution of flow field around the box girder can be intuitively seen through the pressure cloud diagram and velocity trace diagram around the box girder. Figure 6 was the velocity trace diagram and pressure cloud diagram of double-layer box girder under different girder spacing. Through comparison, it was found that the pressure cloud image of the double-layer box girder is basically consistent with the test results of the wind tunnel pressure test. Therefore, the pressure cloud image and velocity trace of the double-layer box girder obtained by numerical simulation (CFD) can accurately visualize the distribution of the flow field around the double box girder.

According to figure 6, when the girder spacing was 0.5h, because the girder spacing was relatively close, the existence of the lower girder reduced the air flow in the bottom area of the upper girder, which indirectly increased the wind resistance area of the upper girder, resulting in obvious flow separation on the edge of the upper surface’s windward area of the upper girder and a large scale vortex, at last the air flow reattached on the upper surface. For the lower surface of the upper girder, due to the contraction of the inlet in the windward area, the air flow discharged the vortex generated by the flow separation on the diagonal web area of the upper girder. The existence of the upper girder enhanced the flow separation on the diagonal web area of the lower girder, resulting in a larger vortex than that of single-layer girder. Due to the sudden expansion in downstream of the narrow "air path" between the upper and lower girders, there was a vortex in the upper surface downstream of the lower girder and gradually entered the tail vortex area to form a larger vortex. With the increase of girder spacing, the flow separation phenomenon on the upper surface of the upper girder and the lower surface of the lower girder caused by the mutual aerodynamic interference between the two girders was gradually weakened, and the vortex was gradually reduced, besides, the small vortices generated by the upper surface downstream of the lower girder and the phenomenon of enlarging the tail vortex gradually weakened. With the increase of girder spacing, the aerodynamic interference effects between the upper and lower girders gradually disappear.

Through the above analysis, combined with the wind tunnel vibration and pressure test results, the following conclusions can be obtained: The development of vortices caused by the enhancement of the flow separation between the upper surface of the upper girder and the lower surface of the lower girder caused by the aerodynamic interference between the upper and lower girders of the double-layer box girder, and the magnifying effect of the upper girder on the vortex in the wake area of the upper surface.
of the lower girder were the internal reasons for the influence of the girder spacing on the vortex vibration performance of the double-layer box girder.

![Velocity trace diagram (Δ=0.5h)](a)
![Pressure cloud diagram (Δ=0.5h)](b)

![Velocity trace diagram (Δ=2.5h)](c)
![Pressure cloud diagram (Δ=2.5h)](d)

![Velocity trace diagram (Δ=4.5h)](e)
![Pressure cloud diagram (Δ=4.5h)](f)

Figure 6. Pressure cloud diagram and velocity trace diagram of the flow field around the cross-section of the double-layer box girder under different girder spacing

5. Conclusion

This study takes double-layer box girders as the research object, analyzes the influence of girder spacing on the vortex vibration performance and flow field characteristics of double-layer box girders through wind tunnel vibration measurement experiments and computational fluid dynamics (CFD). The main conclusions are as follows:

1. At 0° wind angle of attack, the vortex performance of double-layer box girders gradually became better with increasing girder spacing, which was shown as the amplitude of the vortex vibration is reduced, and the lock interval of the vortex vibration is shortened. It was shown that at 0° wind angle of attack, the aerodynamic interference between the upper and lower girders gradually weakens as the girder spacing increases.

2. At +3° and +5° wind angles of attack, the maximum amplitude of the vertical bending vortex vibration of the double-layer box girder decreased first and then increased with the increase of the girder spacing, and the maximum amplitude of torsional vortex vibration of the double-layer box girder showed a trend of increasing first and then decreasing with the increase of the girder spacing.
(3) The development of vortices caused by the enhancement of the flow separation between the upper surface of the upper girder and the lower surface of the lower girder caused by the aerodynamic interference between the upper and lower girders of the double-layer box girder, and the magnifying effect of the upper girder on the vortex in the wake area of the upper surface of the lower girder were the internal reasons for the influence of the girder spacing on the vortex vibration performance of the double-layer box girder.

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