Research on the Influence of Water Horse on the Vortex Induced Resonance Response of Bridges

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Abstract. Vortex-induced resonance is the most common wind-induced vibration phenomenon in bridge structures. On May 5, 2020, the vortex-induced resonance phenomenon occurred on Humen Bridge. The reason is that the water horses continuously installed along the side guardrails of the bridge changed the steel box. The aerodynamic shape of the beam causes the wind-induced vortex-induced resonance phenomenon in the bridge due to the incoming wind. Therefore, it is necessary to study the influence of the water horse on the vortex-induced resonance performance of the bridge structure. In this paper, with the Xiamen Haicang Bridge as the background, a vortex-vibration wind tunnel test of a segment model with a scale ratio of 1:25 is carried out. The main girder segment model is used to arrange water at the windward side railings of the bridge when the wind attack angle is 0°. The effect of water horses on the railings on the windward and leeward side and the water horses on the railings on both sides on the bridge vortex induced resonance.

Keywords: Wind tunnel test · Segment model · Bridge structure · Water horse · Vortex induced resonance

1 Introduction

Vortex-induced resonance is a wind-induced vibration phenomenon that is very likely to occur in long-span bridges at low wind speeds [1]. It is a self-excited limiting vibration. It is caused by airflow passing through the surface of the main beam. Caused by vortices that fall off regularly at a certain time interval. In a certain range of wind speed, when the frequency of the vortex shedding is close to a certain natural frequency of the bridge, the bridge will produce vortex vibration. At the same time, the bridge vibration will give feedback to the shedding vortex, making a certain wind speed.The frequency of vortex shedding in the interval is locked around the natural frequency of the bridge and does not change with the change of wind speed [1].

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Vortex-induced resonance has occurred in many bridges at home and abroad, such as the Xihoumen Bridge in China, the Humen Bridge in China, the Tokyo Bay Passage Bridge in Japan, and the Kossock Cable-stayed Bridge in the United Kingdom etc. Therefore, in order to ensure the aerodynamic stability of the bridge structure, the study of vortex vibration is essential when the bridge is designed for wind resistance. At present, the research on vortex vibration phenomenon is difficult to use analytical methods. Therefore, the use of wind tunnel test technology is the most widely used method in the study of bridge vortex vibration phenomenon, and the segment model wind tunnel test is one of the most conventional test methods [2].

In order to study the vortex vibration performance of long-span bridges more accurately, the wind tunnel test of the segment model with large scale ratio is more and more adopted. When Larose et al. conducted a wind tunnel test of a segment model of the Stonecutter Bridge with a large scale ratio, they found that the Reynolds number has a direct effect on the vortex detachment characteristics when the bridge reaches the vortex lock interval [3]. Sun Yanguo, Liao Haili, etc. conducted wind tunnel tests on a segment model of a long-span suspension bridge with a scale ratio of 1:20 to study the vortex vibration experiment of the segment model, and analyzed the damping and wind attack. The different influences of other factors such as angle on the vortex vibration response of the bridge [4]; Li Yongle, Hou Guangyang etc.took a long-span highway suspension bridge as an example, produced a section model of the main girder with a scale ratio of 1:45 and performed the vortex vibration wind The tunnel test is used to study and analyze the influence of bridge railings, deflectors, different inspection lane positions and wind attack angles on the vortex-induced resonance response of the main girder. At the same time, aerodynamic control measures to improve the vortex vibration of the main girder are also proposed [5].

On May 5, 2020, the deck of the suspension bridge of the Humen Bridge in Guangdong experienced large vibrations, which aroused strong attention from the academic community. According to the discussion results of the experts, the main reason for the vibration of the Humen Bridge this time was that the water horses were continuously installed along the side guardrails of the bridge, which changed the aerodynamic shape of the steel box girder. The phenomenon of vortex induced resonance. Therefore, this paper uses the Xiamen Haicang Bridge as the research background, and uses a 1:25 scaled segment model to conduct wind tunnel tests to study the response of the water horse on the bridge deck to the vortex induced resonance of a long-span bridge.

2 Engineering Background

The research in this paper is based on the Xiamen Haicang Bridge. The Xiamen Haicang Bridge is a three-span continuous full-floating steel box girder suspension bridge connecting Xiamen's main island and Xiamen's Haicang District. The span is 230 m + 648 m + 230 m, which is a large-span flexible bridge structure. Due to the geographical environment and wind load, the wind-induced vibration response of the bridge is very obvious, and it causes structural fatigue damage. In order to ensure the safety of the structure of the bridge against wind, the wind tunnel test of the Haixifeng Engineering Research Center of Xiamen University of Technology was carried out to study the vortex induced resonance of the bridge, and the effect of water horses on the vortex vibration response of the bridge was extended to different positions on the bridge deck. The standard cross section of the bridge stiffener is shown in Fig. 1.

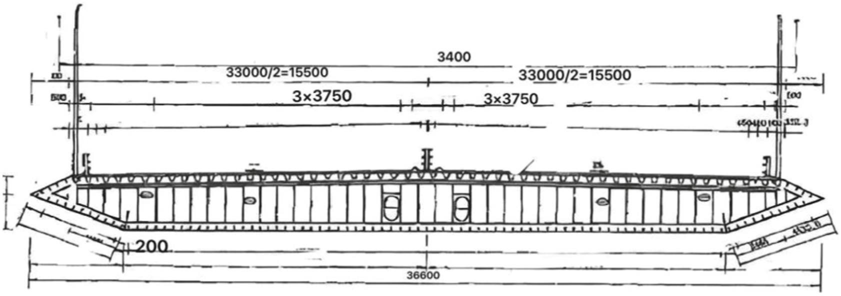

Fig. 1. Standard cross section view of stiffening beam

3 Overview of Wind Tunnel Test

The vortex-induced resonance wind tunnel test of the 1:25 main girder segment model of the Haicang Bridge was carried out in the Wind Tunnel Laboratory of the Haixifeng Engineering Research Center of Xiamen University of Technology, as shown in Fig. 2. This segment model A total of 4 test conditions were studied in wind tunnel tests, including bare bridge status, water horses at the windward side railings, water horses at the leeward side railings, and water horses at both side rails. The water horses are also in accordance with actual engineering. The size used is made according to the scale ratio of 1:25, and its size is: 4 m × 0.032 m, and the test conditions involved are all completed in a uniform flow field at a wind attack angle of 0°.

Fig. 2. Segment model wind tunnel test

3.1 Segment Model Design

The geometric scale ratio of the main girder segment model used for the vortex wind tunnel test is $\lambda_L = 1{:}25$. In order to reduce the influence of the three-dimensional flow at the end of the segment model, the length of the main girder model is taken as L = 4 m and the main girder width B = 1.28 m, the model height is H = 0.12 m, and the model aspect ratio is about 3.125. Use ANSYS software to establish the structural model of the Haicang Bridge, and perform dynamic response analysis to obtain the structural dynamic characteristic parameters, so that the correspondence between the main parameters of the real bridge and the main parameters of the segment model can be determined (Table 1). In order to make the segment model's own structure have good rigidity performance, the main girder segment model is composed of high-strength steel frame and light wood cladding to fully ensure the similarity of geometric shapes. The railings on the main girder are made of acrylic panels in proportion to the fineness. The shape and air permeability of the railing are simulated.

Table 1. Design parameter table of segment model

Parameter	Symbol	Unit	Design value
Length of main beam	L	m	4
Width	B	m	1.28
Heigth	H	m	0.12
Equivalent mass	m_{eq}	kg/m	229
Mass moment of inertia	I_{meq}	kg·m^2/m	49.33
Verticalfundamental frequency	f_h	Hz	1.625
Torsion fundamental frequency	f_t	Hz	3.629
Torsion frequency ratio	ε	/	2.233
Vertical bending wind speed ratio	m_h	/	2.5
Torsional wind speed ratio	m_t	/	3.3

3.2 Allowable Value of Vortex Induced Resonance Amplitude

According to the "Code for Wind Resistance Design of Highway Bridges" [6], the allowable amplitude values of vertical vortex-induced resonance and torsional vortex-induced resonance when the existing bridge of Xiamen Haicang Bridge is completed are:

$$[h_a] = 0.04/f_v = 0.2384\,\text{m}$$
$$[\theta_a] = 4.56/Bf_v = 0.2890^\circ$$

4 Analysis of Test Results

1. Figures 3 and 4 are the vertical displacement amplitude-wind speed curve and the torsional displacement amplitude-wind speed curve of the main beam segment model at 0° wind attack angle.

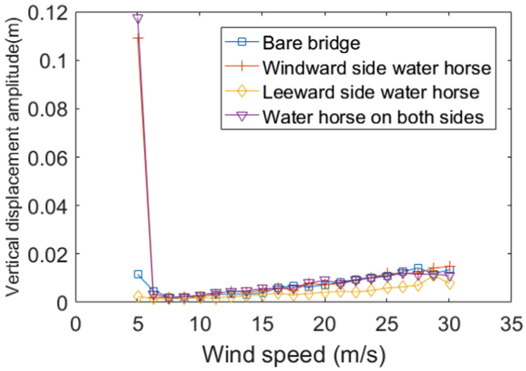

Fig. 3. Vertical displacement amplitude-wind speed

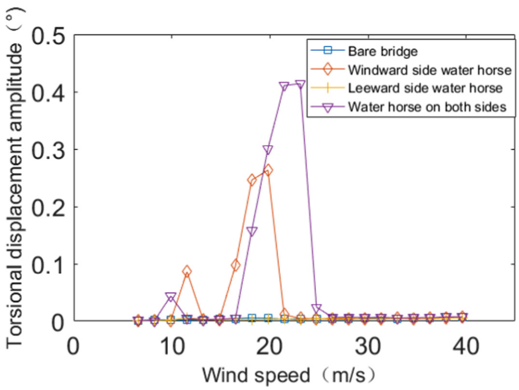

Fig. 4. Torsional displacement amplitude-wind speed

Figure 5 is the vertical vibration time history diagram corresponding to the four working conditions when the wind speed is 5 m/s. Figures 6 to 8 are the bare bridge and the windward side railing at the wind speed 5 m/s with the water horses and the two side railings. Vertical vortex frequency corresponding to water horse. It can be seen from Figs. 3 and 5 that when the wind speed is 5 m/s, the bare bridge, the water horses at the windward side railings, and the water horses at the railings on both sides all have vertical vortex-induced resonance, and the amplitude is 0.01153 m respectively, 0.109 m, 0.1176 m, the frequency when the vibration occurs and the vertical fundamental frequency of this wind speed are both 0.1625 Hz (as shown in Fig. 7–9), and the amplitude of the vertical vortex-induced resonance displacement of the main beam is less than "The allowable value of the "Code for Design of Wind Resistance of Highway Bridges", while the bridge structure does not have vertical vortex-induced resonance when the water horse is arranged on the leeward side.

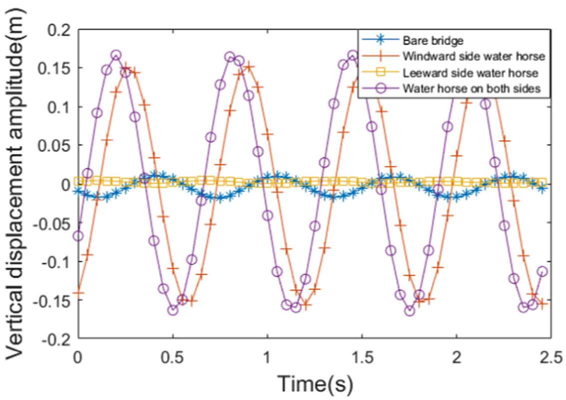

Fig. 5. 5 m/s vertical vibration time history chart

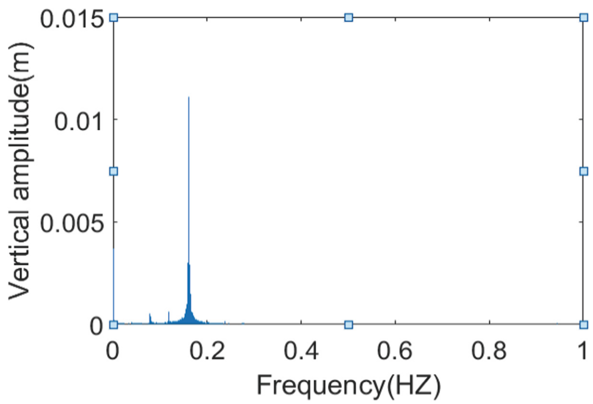

Fig. 6. 5 m/s vertical vortex frequency of bare bridge

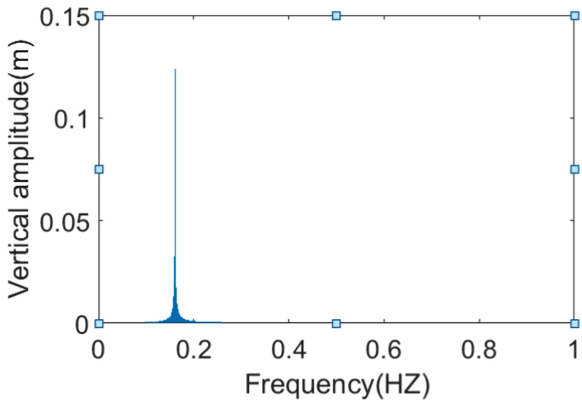

Fig. 7. Vertical vortex frequency of windward side

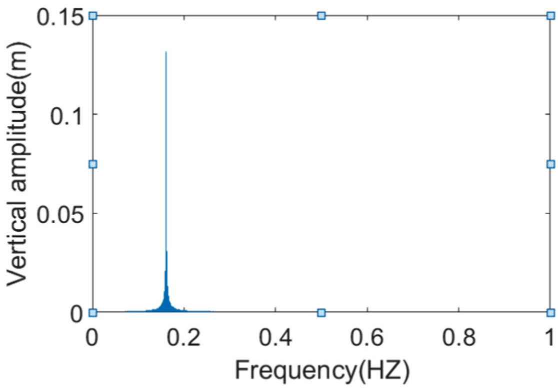

Fig. 8. Vertical vortex frequency of leeward

2. When the water horse is arranged at the railing on the windward side of the main beam segment model, Fig. 9 and Fig. 10 are the torsional vibration time-history diagram and torsional vortex vibration frequency corresponding to the main beam when the wind speed is 8.75 m/s, as shown in Fig. 4, It can be seen that the torsional vortex induced resonance occurs in the wind speed range of 7.5 m/s–10 m/s, with an amplitude of 0.1066°, and its vibration frequency is consistent with the torsional fundamental frequency at this wind speed, which is 0.4799 Hz (Fig. 10) Shown). Figure 11 and Fig. 12 are the torsional vibration time-history diagram and torsional vortex frequency corresponding to the main beam when the wind speed is 15 m/s. It can be seen from Fig. 4 that torsion occurs in the wind speed range of 11.25 m/s–16.25 m/s For vortex-induced resonance, the wind speed with the largest amplitude of 6 m/s is selected for analysis. Its amplitude is 0.3362°, which is greater than the allowable value of the specification. The vibration frequency and the torsional fundamental frequency at this wind speed are both 0.4799 Hz (as shown in Fig. 12).

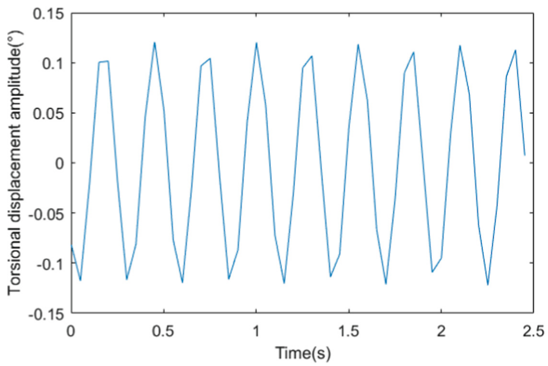

Fig. 9. 8.75 m/s time history diagram of torsional vibration

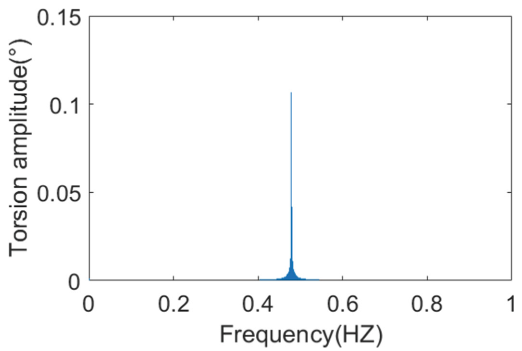

Fig. 10. 8.75 m/s torsional vortex frequency

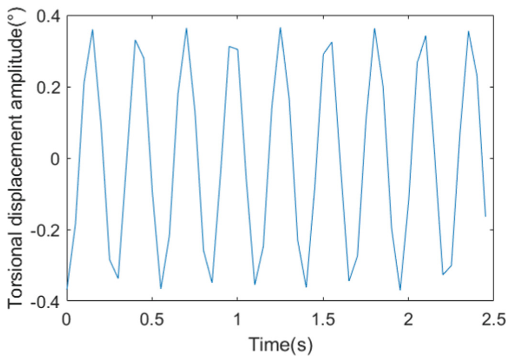

Fig. 11. 15 m/s time history diagram of torsional vibration

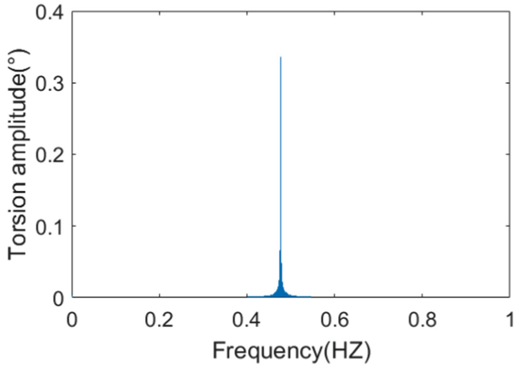

Fig. 12. 15 m/s torsional vortex frequency

3. When water horses are arranged at the railings on both sides of the main girder segment model, Fig. 13 and Fig. 14 are the torsional vibration time-history diagram and torsional vortex vibration frequency corresponding to the main girder when the wind speed is 9.9 m/s. It can be seen that the torsional vortex induced resonance occurs in the wind speed range of 8.25 m/s–11.55 m/s, with an amplitude of 0.0492°, and its vibration frequency is consistent with the vertical fundamental frequency at this wind speed, which is 0.4799 Hz (As shown in Fig. 9). Figure 15 and Fig. 16 are the torsional vibration time-history diagram and torsional vortex vibration frequency corresponding to the main beam when the wind speed is 23.1 m/s. It can be seen from Fig. 4 that it occurs in the wind speed range of 16.5 m/s–24.75 m/s For torsional vortex induced resonance, the wind speed with the largest amplitude of 23.1 m/s is selected for analysis. Its amplitude is 0.5806°, which is much larger than the allowable value of the specification. The vibration frequency and the vertical fundamental frequency at this wind speed are both 0.4799 Hz (as shown in the Fig. 16).

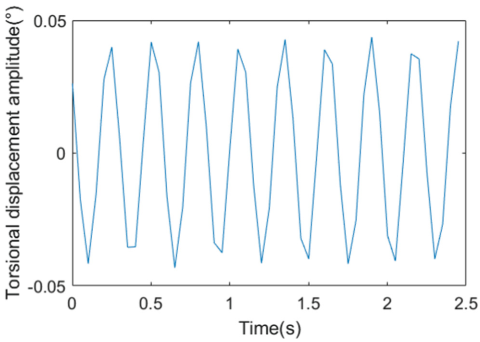

Fig. 13. 9.9 m/s time history diagram of torsional vibration

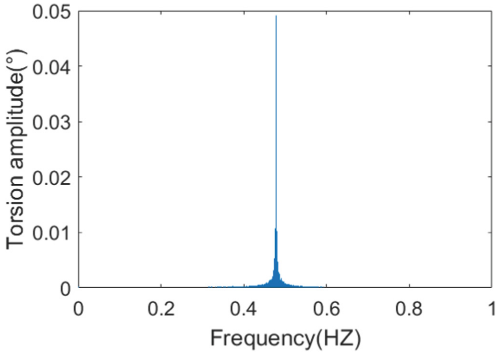

Fig. 14. 9.9 m/s torsional vortex frequency

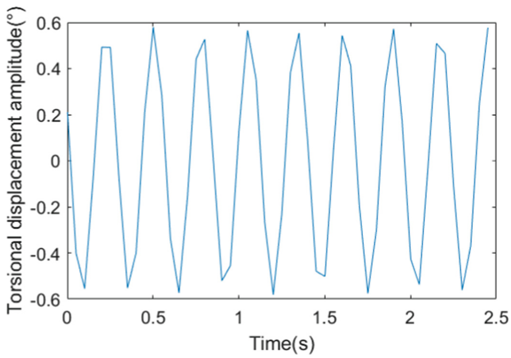

Fig. 15. 23.1 m/s time history diagram of torsional vibration

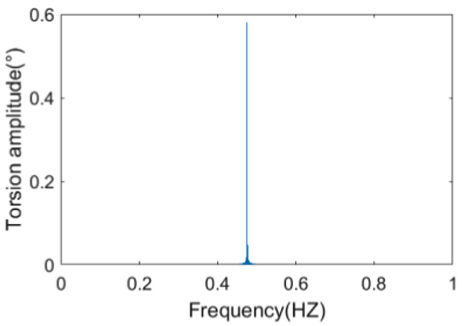

Fig. 16. 23.1 m/s torsional vortex frequency

5 Conclusion

The vortex induced resonance phenomenon of the main girder structure generally occurs in the lower wind speed range, and it is very sensitive to the changes in the aerodynamic shape of the bridge. The water horses arranged on the bridge will change the aerodynamic shape of the bridge structure, making the main girder structure It is no longer the original streamlined section. When subjected to wind load, due to being blocked by the water horse, a larger vortex will be formed. The original bare bridge is very different. When the frequency of the force is close to the natural frequency of the bridge structure, the bridge will have a vortex-induced resonance phenomenon, and the amplitude is very large.

Comparing the wind tunnel test on the influence of the vortex-induced resonance response of the bridge when the water horses are arranged at different positions at a wind attack angle of 0°, the following conclusions can be drawn.

1) When water horses are arranged at the windward side railings of the bridge deck, water horses are arranged at the railings on both sides, and the bare bridge is in the state of the main girder when the wind speed is 5 m/s, vertical vortex induced resonance occurs, and the amplitudes are 0.109 m and 0.1176 m respectively, 0.01153 m are within the allowable value of the specification, and the corresponding vertical vortex frequency and vertical fundamental frequency are consistent with 0.1625 Hz,
2) When the water horse is arranged at the railing on the windward side of the bridge, the main girder has torsional vortex induced resonance, and the vortex vibration lock interval is 7.5 m/s–10 m/s and 11.25 m/s–16.25 m/s, the largest The torsion amplitude is 0.3362°, which is greater than the allowable value in the specification. When the water horses are arranged at the railings on both sides of the bridge deck, the main beam also has torsional vortex induced resonance, and the vortex vibration lock interval is 8.25 m/s–11.55 m/s and 16.5 m/s–24.75 m/s, the maximum torsion The amplitude of 0.5806° is much larger than the allowable value of the specification. It can be concluded that: arranging water horses on the windward side railings and the railings on both sides of the bridge will cause the main beam to produce vertical vortex induced resonance and torsional vortex induced resonance, and the torsional vortex induced resonance is the largest in the two states The amplitude exceeds the allowable value of the specification. At the same time, the vertical vortex-induced resonance amplitude and the torsional vortex-induced resonance amplitude of the water horses arranged at the railings on both sides are larger than the vortex vibration amplitudes of the water horses arranged at the windward side railings.
3) When the water horse is arranged on the leeward side railing of the bridge deck, there is no vortex-induced resonance phenomenon in the main beam. It may be that when the water horse is arranged on the leeward side, the bridge deck does not easily cause aerodynamic flow, resulting in no vortex-induced resonance of the main beam.

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