

Article

Investigation of the Effects of Vortex Isolation Plates with Different Opening Ratios and Sizes on Vortex-Induced Vibration

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Featured Application: The study can further guide the application of vortex isolation plates in wind-induced vibration of twin-box girders.

Abstract: Twin-box girders are a good option for long-span cable-bearing bridges due to their excellent stability. Nonetheless, the girder's slots may generate vortex-induced vibrations (VIVs). Fortunately, appropriate aerodynamic measures can effectively suppress the VIVs in twin-box girders while reducing costs. To examine the effects of vortex isolation plates with varying aperture diameters and opening ratios on the VIVs, a segment model wind tunnel test was conducted. The results demonstrated that a reduction in the opening ratio improved the performance under heaving VIVs, but there was no discernible trend under torsional vibrations. It was also discovered that the opening size significantly influences the length of the lock-in region of torsional vibrations. Furthermore, heaving VIVs have a substantial correlation with both of the girder's boxes, while torsional vibrations are mostly connected with the downstream section.

Keywords: VIV; vortex isolation plate; wind pressure; twin-box girder; wind tunnel test

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1. Introduction

Wind-induced vibrations (WIVs) are a crucial aspect to consider in bridge construction and are one of the focuses of bridge engineers [1–3]. To avoid WIVs, a plethora of section types and vibration suppression measures have been proposed and extensively studied by researchers and industry professionals alike [4–6]. One of these researches, the twin-box girder, has become an option in long-span bridge construction due to its good stability under flutter. However, twin-box girders are susceptible to VIVs in windy conditions due to their complex section design. Continuous and frequent VIVs can significantly reduce bridge components' service lives and compromise the safety of the entire bridge structure. As a result, the cause of VIVs in twin-box girders and their subsequent control have become prominent research areas, leading to the creation of vibration suppression measures in twin-box girders.

The VIV phenomenon in twin-box girders is commonly attributed to the influence of vortex shedding in the slot and the formation of wake vortices. Particle image display technology was used to discover that the vortices generated in the slot may contribute to large-amplitude VIVs [7]. This finding aligns with those of other researchers [8,9]. A study was conducted by Laima et al. [10] involving an analysis of the vortex distribution and surface pressure around a section using wind tunnel tests and numerical simulations. These researchers also explored various methods to suppress vibrations, including the use of closed railings. In a study by Kwok et al. [11] on the influence of the slotting width in twin-box girders, it was found that the surface pressure distribution is significantly affected by the slotting width. de Miranda et al. [12] conducted a study on the slot width of twin-box girders using RANS and LES approaches. They found that a change in the

slot spacing between the upper and lower girders can affect the interactions, subsequently affecting the aerodynamic force. Yang et al. [13] conducted a study on slot spacing and found that unslotted sections have a better VIV performance compared to slotted sections. Jeong et al. [14] used numerical simulations to show that a twin-box girder with a large angle of attack (AOA) would have large-scale vortex shedding in the downstream section. Liu et al. [15] found that the presence of a central slot enhances the overall vortex-induced force in an analysis of the aerodynamic evolution process. Additionally, by analyzing the field-measured data gathered in a wind tunnel test at Xihoumen Bridge, it was found that the vortex shedding in the slot and of the downstream box girder surface is closely related to VIVs [16,17]. According to current research, a close correlation exists between the VIVs in twin-box girders and the central slot. Based on this, Cheng et al. [18] conducted a wind tunnel test using a central stabilizing plate to study the performance of twin-box girders under VIVs. The results of this study indicated that the size and placement of the central stabilizing plate had a significant impact on vibration suppression. The research conducted by Ma et al. [19] focused on a wide twin-box girder, identifying a vortex isolation net as an effective means of mitigating VIVs. Additionally, Li et al. [20] utilized delayed detached eddy simulations to study the function of the central grid, concluding that the central grid was beneficial for suppressing VIVs in twin-box girders. Furthermore, some scholars have implemented aerodynamic measures at various positions in twin-box girders to try to mitigate the effects of VIVs, which have proven to be effective. For example, an investigation of the Hong Kong–Zhuhai–Macao river/sea direct ship channel bridge revealed that a guide plate set on the web can effectively suppress VIVs [21]. Similarly, Wang et al. [22] examined Jiashao Bridge and found that a windshield plate in the bridge deck and a guide plate set at the bottom of the section can also suppress VIVs in twin-box girders. Ouyang et al. [23] identified that heaving VIVs can be suppressed by introducing a cover plate to form a streamlined wind fairing with the sidewalk. In conclusion, extensive research conducted on VIVs in twin-box girders has yielded significant results and valuable recommendations for engineers. However, the VIV and vibration-suppression mechanisms remain unclear. Therefore, a more comprehensive investigation into the influence of aerodynamics on twin-box girders is necessary.

In this paper, a deep analysis focusing on twin-box girders is performed, and the impact of a vortex isolation plate on the performance under VIVs at different AOAs is examined. Additionally, the internal characteristics of the VIV lock-in region are explored based on vortex isolation plates with different opening ratios, providing valuable recommendations and guidance for engineers.

2. Introduction to Experiments

2.1. Test Equipment and Parameters

Tests were carried out in the CA-01 atmospheric boundary layer wind tunnel at Chang'an University, with a work section size of 15 m × 3 m × 2.5 m. The test model was designed based on an actual project, where the geometric scale ratio is 1:70. The length of the model is 1.80 m, the width is 0.72 m, and the height is 0.057 m. The heaving and torsional frequencies are 3.42 Hz and 8.30 Hz, respectively, and the remaining test parameters are shown in Table 1.

Table 1. Motion parameter.

Parameter	Symbol	Unit	Real Bridge Value	Scale Ratio	Test Value	Error (%)
Width	B	m	50.4	1/70	0.72	-
Height	H	m	4	1/70	0.057	-
Length	L	m	-	-	1.80	-
Mass per unit length	m	kg/m	37,000	1/70 ²	7.72	−2.2
Mass moment of inertia per unit	J _m	kg·m ² /m	8,490,000	1/70 ⁴	0.34	2.9
Heaving frequency	f _b	Hz	0.1432	—	3.42	1.2

Table 1. Cont.

Parameter	Symbol	Unit	Real Bridge Value	Scale Ratio	Test Value	Error (%)
Torsional frequency	f_t	Hz	0.6295	—	8.30	−1.7
Heaving damping	ξ_b	%	—	—	0.3	-
Torsional damping	ξ_t	%	—	—	0.21	-

The model was suspended from the inner support using eight springs during the testing phase. The model skeleton was composed of aluminum alloy to ensure adequate stiffness and strength at high wind velocities. To minimize the impact of the end effect, the model's aspect ratio was set to 2.5 and a binary end plate was placed at the end of the model, as illustrated in Figure 1. Three Panasonic laser displacement meters were employed to monitor and collect the model's heaving and torsional motion. These signals were recorded at a sampling frequency of 200 Hz for a duration of 40 s. Additionally, the pressure characteristics of the section were monitored using an MPS4164 scanner from Scanivalves (Liberty Lake, WA, USA). The signals were sampled at a frequency of 850 Hz for 40 s. The model was divided into ten distinct regions based on its shape to capture pressure variations. To guarantee accuracy, 78 pressure taps were used to continually monitor the sectional surface pressure. Figure 2 clearly illustrates the model's layout and zones.

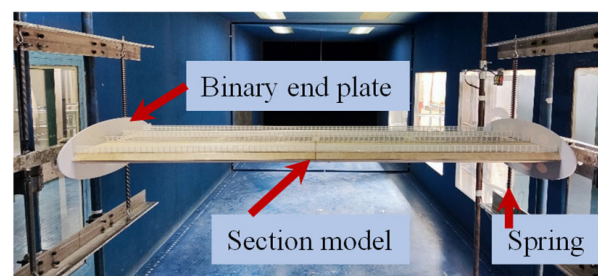


Figure 1. Section model in the wind tunnel.

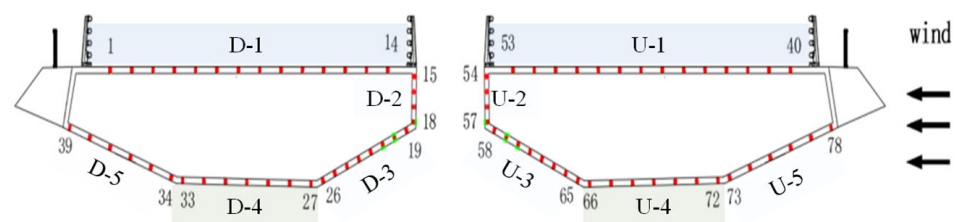


Figure 2. Layout of pressure taps and zones.

2.2. Test Cases

In the combined vibration–pressure measurement experiments, two-type vortex isolation plates with different openings were purposefully set up, and five varying opening ratios were used for each plate. The experiment included a total of 32 combinations. The opening ratio was calculated using Equation (1). An AOA of 0° was used initially for each set of opening ratios, while an AOA of -3° was used last. Details of the test cases can be found in Table 2.

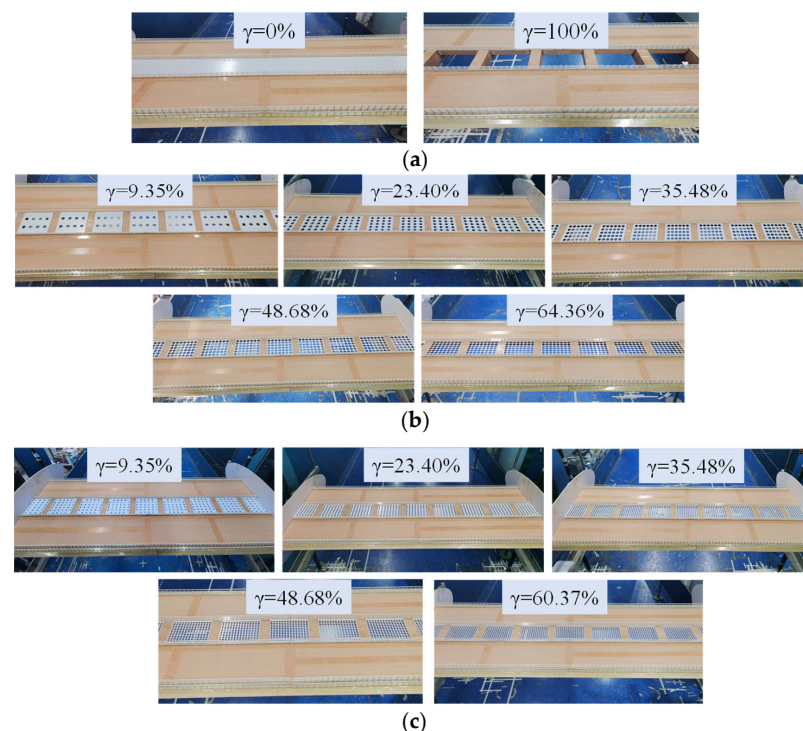
$$\gamma = \frac{A_o}{A_p} \times 100\% \quad (1)$$

where γ denotes the opening ratio; A_p denotes the total area of the entire vortex isolation plate; and A_o denotes the total opening areas of the entire vortex isolation plate.

Table 2. Test cases of different vortex isolation plates in combined vibration–pressure tests.

Cases	Type of Vortex Isolation Plates	Opening Ratio (%)	AOA	Opening Number	Single Opening Area (mm ²)
1	No plate	100%		-	-
2	No opening	0%		0	0
3–5		9.35%		68	
6–8	Plate with	23.40%		170	
9–11	20 mm opening	35.48%	0°	258	314.16
12–14	diameter	48.68%	+3°	354	
15–17		64.36%	−3°	468	
18–20		9.35%		272	
21–23	Plate with	23.40%		680	
24–26	10 mm opening	35.48%		1032	78.54
27–29	diameter	48.68%		1416	
30–32		60.37%		1756	

The vortex isolation plate had a circular opening and a uniform distribution. The seven slots in the middle section of the beam were equipped with vortex isolation plates of the same size, while the two slots near the end also contained vortex isolation plates of the same size. The forms of the vortex isolation plates are shown in Figure 3.

**Figure 3.** Plates with different opening ratios. (a) $\gamma = 0\%$ or 100% , (b) opening diameter $d = 20$ mm, and (c) opening diameter $d = 10$ mm.

3. Vortex-Induced Vibration Performance with Different Vortex Isolation Plates

Figure 4 presents the impact of vortex isolation plates with 10 mm and 20 mm opening sizes on the performance under heaving VIVs in twin-box girders under varying opening ratios. The results show that, with a decrease in the opening ratio, the twin-box girder's performance under VIVs is gradually enhanced. As shown in Figure 4a,b, VIVs occur when the opening ratio is 48.68% at a 0° AOA. Notably, the vibration amplitude of the plate with a 10 mm circular opening is greater than that of the plate with a 20 mm circular opening. At a $+3^\circ$ AOA, both the plates with 10 mm and 20 mm circular openings exhibit similar vibration phenomena. Specifically, at an opening ratio of 23.40%, both plates experience

low-amplitude VIVs at high wind velocities. The effect of the opening ratio on the VIVs at a -3° AOA is similar to that observed at a 0° AOA; however, the amplitude of the former is larger. Notably, the VIV phenomenon occurs at an opening ratio of 35.48%. This suggests that the opening ratio plays a significant role in determining the magnitude of heaving VIVs, particularly when it comes to varying the AOA. As the AOA shifts from positive to negative, the influence of the opening ratio gradually intensifies. Additionally, at the same opening ratio, the performance under VIVs is affected by the opening size of the vortex isolation plate, which can lead to deterioration in the vibration amplitude. This phenomenon emphasizes the importance of carefully considering the opening size when designing a vortex isolation plate.

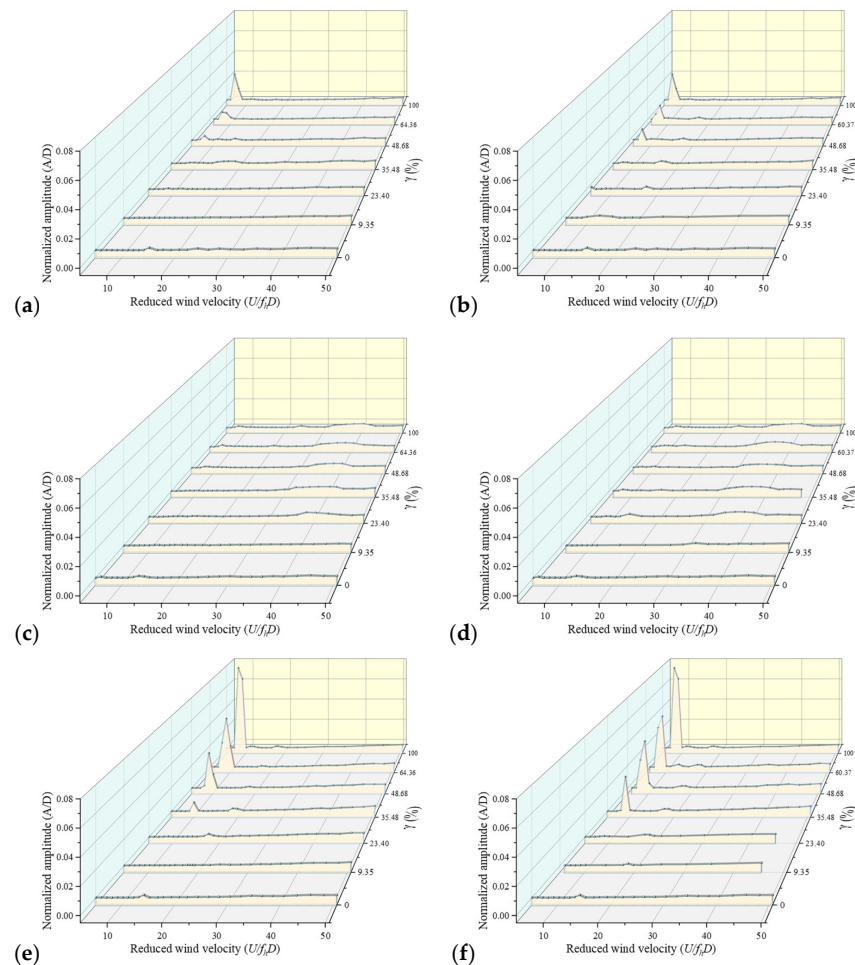


Figure 4. Heaving vortex-induced vibration response of different AOAs using different vortex isolation plates with different opening ratios. (a,b) 0° AOA, (c,d) $+3^\circ$ AOA, and (e,f) -3° AOA; the opening diameter is $d = 20$ mm in (a,c,e), while the opening diameter is $d = 10$ mm in (b,d,f).

Figure 5 illustrates the torsional vibration response at different AOAs for different opening ratios. It appears that the impact of the vortex isolation plate on torsional vibrations is not the same as that on heaving vibrations. At a 0° AOA, at the same opening ratio, the vortex isolation plate with a 10 mm opening size is more likely to exacerbate the torsional VIVs compared to the vortex isolation plate with a 20 mm opening size. When the opening ratio falls between 23.40% and 60.37%, the vortex isolation plate with a 10 mm opening induces torsional VIVs, whereas the vortex isolation plate with a 20 mm opening does not. This observation suggests that the opening size of the vortex isolation plate can significantly impact the performance under torsional VIVs within a certain opening ratio range. At a $+3^\circ$ AOA, the torsional amplitude of the twin-box girder is marginally suppressed as the

opening ratio decreases, and the torsional lock-in region vanishes at an opening ratio of 9.35%. Additionally, when compared to the vortex isolation plate with a 20 mm opening size, the lock-in region of the vortex isolation plate with a 10 mm opening size is slightly expanded. It is noteworthy to mention that the suppression of torsional vibrations at a negative AOA may not be prominent when the opening ratio of the vortex isolation plate exceeds 23.4%. At a -3° AOA, vortex isolation plates with a low opening ratio can still effectively suppress torsional vibrations. With a decrease in the opening ratio, the torsional vibration inhibition effect of the vortex isolation plate with a 20 mm opening size first increases, then decreases, and then increases again. However, the vortex isolation plate with a 10 mm opening size with a low opening ratio amplifies torsional vibrations and its performance is worse under torsional VIVs; specifically, the torsional VIV phenomenon occurs when the opening ratio is 9.35%. The effect of the vortex isolation plate with a 20 mm opening size on torsional vibration inhibition initially increases with a decrease in the opening ratio, then decreases, and finally, it increases again. However, the use of the vortex isolation plate with a 10 mm opening size resulted in torsional vibration amplification. This worsened the performance under torsional VIVs, especially at low opening ratios. Specifically, torsional VIVs were observed at an opening ratio of 9.35%. According to the above phenomenon, it can be concluded that the opening size of the vortex isolation plate has a significant impact on torsional VIVs in twin-box girders. This effect is particularly prominent in vortex isolation plates with the same opening ratio. An inappropriate opening size would worsen the vibration amplitude and the wind velocity of the onset of torsional VIVs.

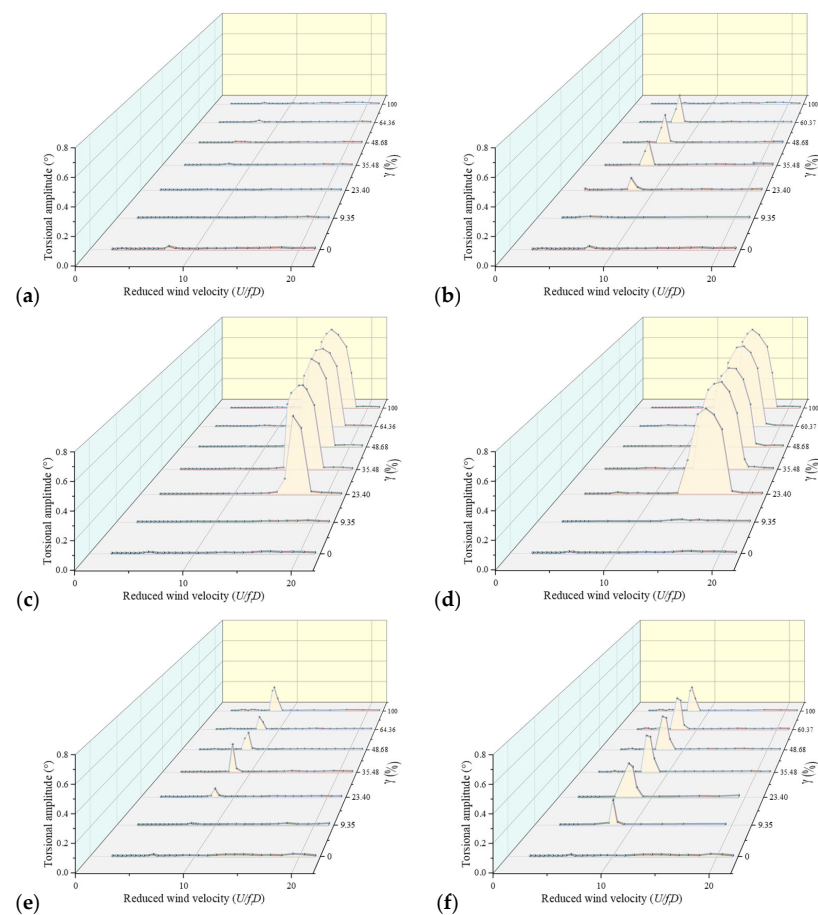


Figure 5. Torsional vortex-induced vibration response at different AOAs using different vortex isolation plates with different opening ratios. (a,b) 0° AOA, (c,d) $+3^\circ$ AOA, and (e,f) -3° AOA; the opening diameter is $d = 20$ mm in (a,c,e), while the opening diameter is $d = 10$ mm in (b,d,f).

4. Wind Pressure Characteristics with Different Vortex Isolation Plates

To gain a better understanding of the vortex behavior around the sections and the vortex isolation plate's impact on VIVs, the wind pressure characteristics around the sections were studied. Combined with those in Section 3, the findings here suggest that sections without a vortex isolation plate exhibit an obvious heave at a -3° AOA and obvious torsional vibrations at a $+3^\circ$ AOA. To further study the differences between the control zones under the two vibration modes, the peak points of heaving and torsional vibrations were recorded. The influence of vortex isolation plates with different opening ratios on the VIVs was also studied. The key points of the VIV response are clearly shown in Figure 6.

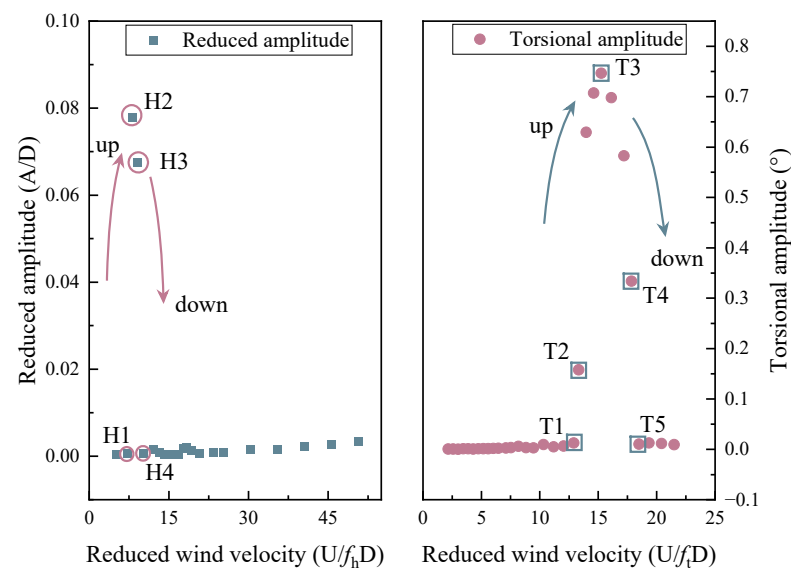


Figure 6. The key points in the lock-in region. H1, H2, H3, and H4 denote the start point, peak point, descend point, and end point in the heaving lock-in region, respectively; T1, T2, T3, T4, and T5 denote the start point, rising point, peak point, descend point, and end point in the torsional lock-in region.

Figure 7 showcases the pressure characteristics of the original section at different AOAs. The graph clearly shows the heave at -3° AOA and the torsional vibrations at $+3^\circ$ AOA. It appears that the average pressure coefficient of the heave exhibits significant dispersion across various zones in the upstream section. Specifically, there is a clear decreasing trend in the average pressure coefficient in zones U-1 to U-4, while in zone U-5, there is an increasing trend in the average pressure coefficient. In the downstream section, a decreasing trend in the average pressure coefficient is displayed across zones D-1 to D-3. Conversely, zones U-4 to U-5 exhibit an increasing trend in the average pressure coefficient. It appears that there is significant variability in the average pressure coefficient for torsional vibrations in the D-3 to D-4 region. In the upstream section, the average pressure coefficient steadily increases from U-1 to U-4 and then decreases, before rising again in the U-5 region. The average pressure coefficient in the downstream section gradually decreases and then increases from D-1 to D-2, followed by a sudden spike and subsequent drop in D-3. In Figure 7b, the fluctuating pressure coefficient of the heave has a small dispersion, while in the D-2 and D-3 zones, there is a noticeable jump. As for the fluctuating pressure coefficient of torsional vibrations, two platforms are connected by the jump phenomenon between the D-2 and D-3 zones. Based on Figure 7c, the frequency of each pressure tap is close to the natural frequency. However, for heaving, some pressure taps are near the frequency multiplication of the heaving frequency. Additionally, according to Figure 7d, there is a small change in the frequency amplitude of each zone in the heave. It is worth noting that two different changes in the frequency amplitude occur in both the upstream and downstream sections. Specifically, the D-1 zone in the upstream section typically exhibits a rise in frequency, while

in the D-2 zone, the frequency tends to fluctuate sharply. Additionally, in both the D-3 and D-4 zones, the frequency exhibits a sudden increase and then a decrease. Meanwhile, in the oblique web, which is located far from the center, a rising trend is observed in both sections. When torsional vibrations occur at a $+3^\circ$ AOA, the average pressure coefficient, fluctuating pressure coefficient, and frequency amplitude of the lower surface of the downstream section and the middle slot at each pressure tap exhibit clear discontinuities. Additionally, the oblique web on the windward side exhibits a rising trend. When heave occurs at a -3° AOA, the average pressure coefficient both at the downstream upper surface and in the upstream section exhibits notable dispersions. In addition, the fluctuating pressure coefficient shows clear discontinuities near the central slot in the downstream section.

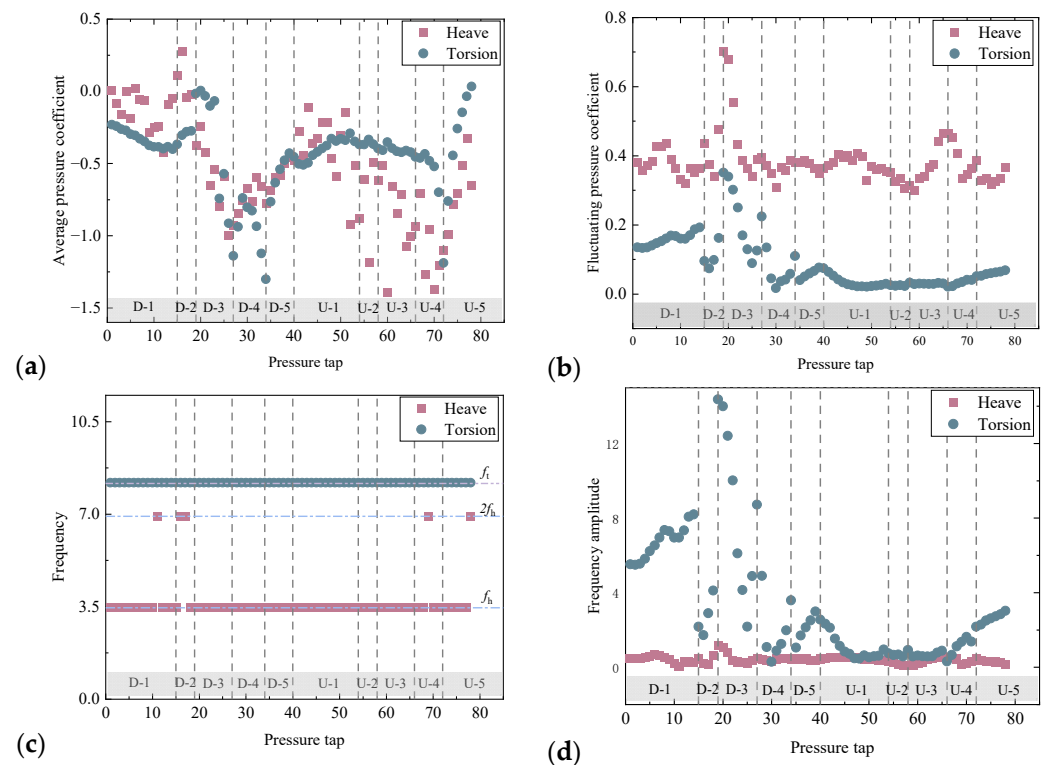


Figure 7. The intrinsic characteristics of the original section. (a) Average pressure coefficient; (b) fluctuating pressure coefficient; (c) frequency; (d) frequency amplitude.

Based on the information presented in Figure 8, it is clear that the use of vortex isolation plates with different opening ratios has a significant effect on the heave. Specifically, while the trend in the average pressure coefficient is similar in zones D-1 to D-5 at different opening ratios, there are notable differences in zones U-1 to U-4. Combined with Figure 4e, when the average pressure coefficient fluctuates significantly in the U-1 to U-4 region, the heave of the section disappears. This suggests that changes in the opening ratio can have a significant impact on the pressure distribution in the upstream section, which in turn affects the occurrence of heave. In comparison to other opening ratios, at opening ratios of 48.68% and 64.36%, the fluctuating pressure coefficient exhibits a noticeable jump phenomenon in zones D-2 and D-3, which in turn results in significant heave. During heaving, the frequency at each pressure tap approaches the natural frequency. Conversely, when the section exhibits disorderly vibrations, the frequency at each pressure tap tends to be close to the high-frequency multiplication or near 0. Furthermore, when the frequency amplitude changes significantly in zones D-1 to D-3 and displays a jumping phenomenon in zones D-2 and D-3, a noticeable heave occurs. Based on the above-mentioned observations, we conclude that the heave control zones in the twin box are U-1 to U-4 and D-1 to D-3. This conclusion is based on the fluctuation in the average pressure in the upstream section, the

jump in the fluctuating pressure in the downstream near the slot, the frequency distribution at each pressure tap, and the change in the downstream frequency amplitude.

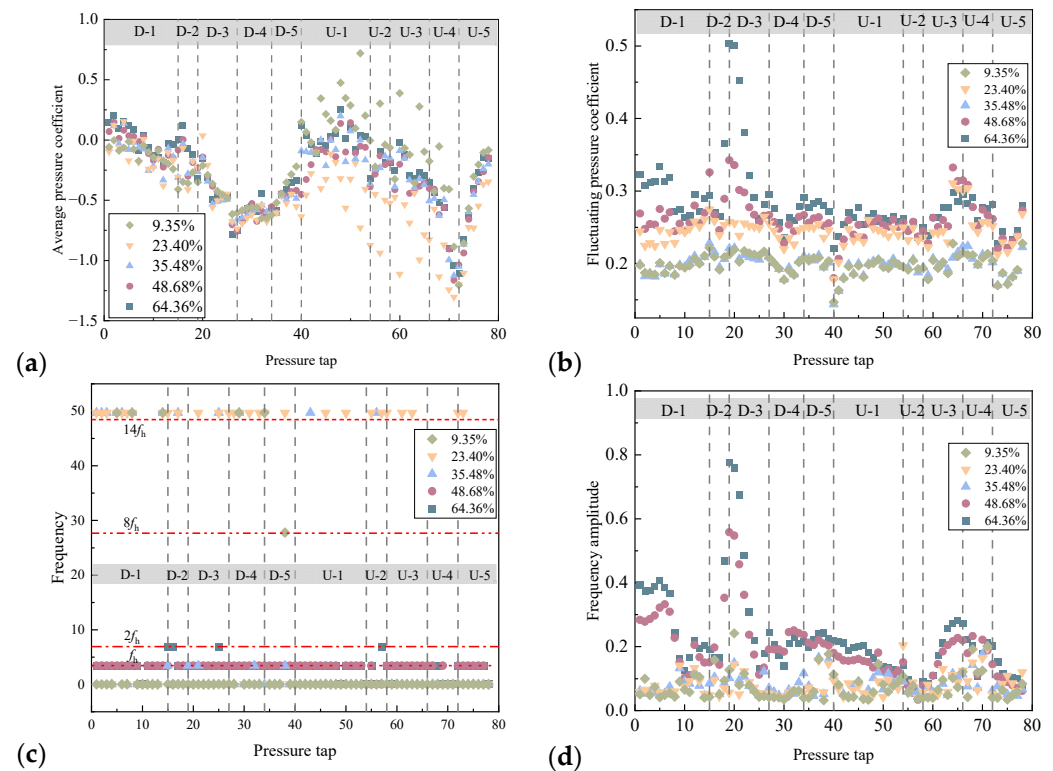


Figure 8. Intrinsic heaving characteristics at different opening ratios. (a) Average pressure coefficient; (b) fluctuating pressure coefficient; (c) frequency; (d) frequency amplitude.

The torsional vibration characteristics at different opening ratios are shown in Figure 9. The average pressure in D-2 to D-5 exhibits irregular variations. Notably, the leading edge of D-2 and D-3 exhibits a step-like change and a sudden drop occurs in the second half of D-3, followed by a “w”-shaped distribution of pressure. Furthermore, there is a sharp decline at the junction of U-4 and U-5, and an increasing trend at U-5, which is similar to that at D-5. This phenomenon suggests that a fixed separation point can significantly affect the surface pressure. Considering Figure 5e, there are two different distribution forms for torsional vibrations and disorder vibrations in the D-1 region. Specifically, in the presence of torsional vibrations, the fluctuating pressure at D-1 increases as the pressure tap is further away from the slot. On the other hand, disorder vibrations generally exhibit a downward trend. There is a clear jump phenomenon present in zones D-2 and D-3, which is similar to the observed heave. We believe that this jump phenomenon may be caused by the periodic impingement of the vortex in the slot at the front of the downstream section. Based on these observations, when the section experiences torsional vibrations at different opening ratios, the pressure taps tend to lock around the torsional natural frequency. However, when the vibrations become disordered, there are multiple different frequencies. Furthermore, the frequency amplitude and fluctuating pressure distributions exhibit a similar trend, with both exhibiting significant spreads and a jump in the downstream section near the slot.

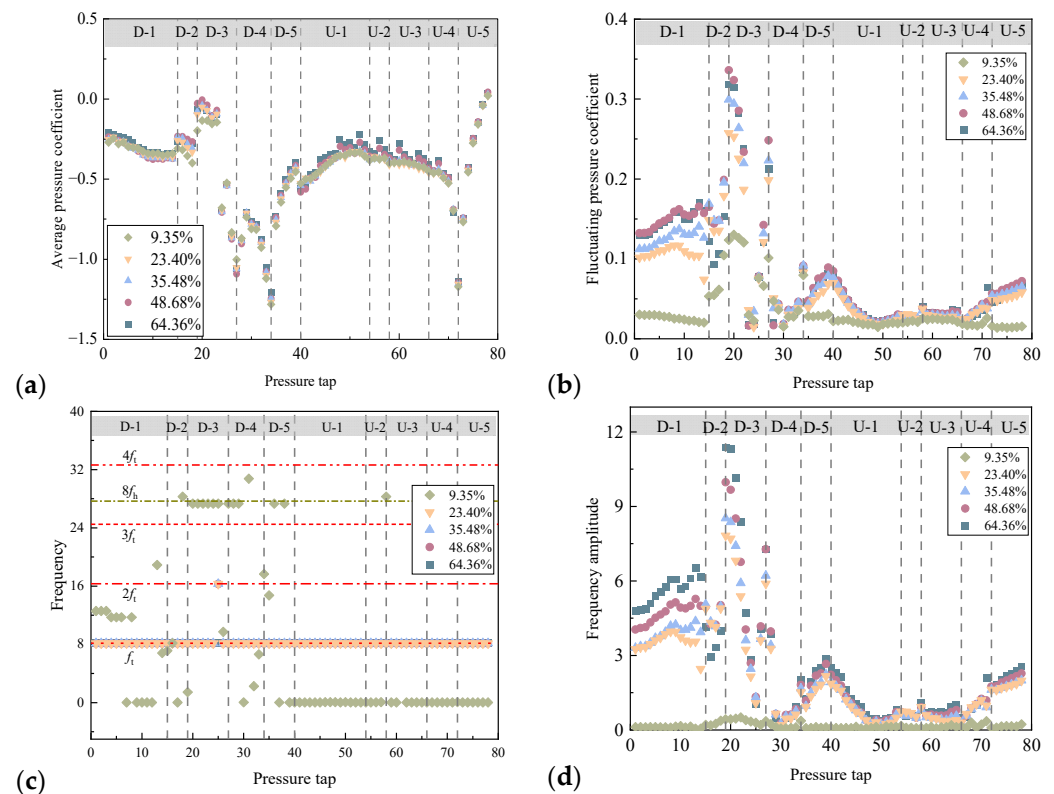


Figure 9. Intrinsic torsional characteristics at different opening ratios. (a) Average pressure coefficient; (b) fluctuating pressure coefficient; (c) frequency; (d) frequency amplitude.

5. Conclusions

In this study, the effects of different opening ratios and opening sizes on torsional vibration and heave were studied via experiments in a 1:70 segment model. Additionally, the effects of different vortex isolation plates on the intrinsic characteristics of VIVs were compared. The main conclusions are as follows:

The effect of the opening ratio of the vortex isolation plate on the heaving performance in a twin-box girder is more significant at a negative AOA than at a positive AOA. Furthermore, a decrease in the opening ratio improves the performance under heaving.

There is little correlation between the performance under torsional VIVs and the vortex isolation plate's opening ratio. However, when the opening ratio is 9.35%, the overall performance under VIVs improves. Additionally, it has been found that a vortex isolation plate with a large opening size can reduce the lock-in region of VIVs to a certain extent.

During torsional vibrations, the pressure taps on the lower surface of the downstream section and near the middle slot exhibit significant discontinuities regarding the average pressure coefficients, fluctuating pressure coefficients, and frequency amplitudes. During heave, the downstream upper surface and the upstream section exhibit a significant spread in the average pressure coefficient. Additionally, noticeable discontinuities in the downstream fluctuating pressure coefficient near the central slot are observed.

The heave in twin-box girders is closely linked to the characteristics of the upstream and downstream sections. On the other hand, torsional VIVs are closely linked to the characteristics of the downstream section.

6. Future Work

The present study has conducted a thorough investigation of the effects of vortex isolation plates with different opening ratios and sizes on vortex-induced vibration using the wind tunnel test, which can help the engineering designer understand the vibration caused by vortex isolation plates and find an effective way to suppress it. It is worth noting

that computational fluid dynamics is a good way to reflect fluid–structure interaction, and it can show the influence of the vortex isolation plate on vortex evolution. Additionally, it can help us further understand the vortex-suppression mechanism. We intend to use three-dimensional numerical simulations to capture motion effects in our later work, which will assist in analyzing the cause of the effects of vortex isolation plates. This further analysis will provide us with valuable insight into the influence of vortex isolation plates.

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