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Aerodynamic Flutter Control for Typical Girder Sections of Long-Span Cable-Supported Bridges

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Abstract. Aerodynamic flutter control for long-span cable-supported bridges was investigated based on three basic girder sections, i.e. streamlined box girder section, box girder section with cantilevered slabs and two-isolated-girder section. Totally four kinds of aerodynamic flutter control measures (adding fairings, central-slotting, adding central stabilizers and adjusting the position of inspection rail) were included in this research. Their flutter control effects on different basic girder sections were evaluated by sectional model or aeroelastic model wind tunnel tests. It is found that all basic girder sections can get aerodynamically more stabled with appropriate aerodynamic flutter control measures, while the control effects are influenced by the details of control measures and girder section configurations. The control effects of the combinations of these four kinds of aerodynamic flutter control measures, such as central-slotting plus central-stabilizer, were also investigated through sectional model wind tunnel tests, summarized and compared to the flutter control effect of single measure respectively.

Keywords: Aerodynamic instability; flutter control; cable-supported bridge; fairing, central-slotting; central stabilizer.

1. Introduction

With the rapid increase of bridge span length, bridge structures are becoming more flexible and more vulnerable to wind-induced vibrations, and one of the most challenging problems encountered is flutter instability, since it will lead to structural collapse. When a long-span cable-supported bridge is predicted to have its intrinsic limit in the aspect of flutter instability, it is necessary to adopt some countermeasures to improve aerodynamic performance to meet with the appropriate wind resistance requirements.

As far as flutter control is concerned, many countermeasures were proposed and investigated both theoretically and experimentally in the long history of researches and practices in aerodynamic instability (Richardson 1981, Fung 1993, Walshe, *et al*. 1997, Larsen, *et al*. 1998, Matsumoto, *et al*. 1999, Sato, *et al*. 2000, Tokoro, *et al*. 2001, Simiu, *et al*. 2006). Theoretical and experimental investigations reported in the literature support the conclusion that the application of central slotting and central stabilizer in box girder section can improve the flutter performance of long-span cable-supported bridges very effectively. However, there are other popular girder sections in the design of

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cable-supported bridges besides box girder section, especially the main span of the bridge is not very large. And sometimes dramatic changes to the original girder section like central-slotting is not acceptable, can relatively small adjustment to the aerodynamic configuration of girder section be effective to improve aerodynamic performance to meet with the requirements?

In this paper, four kinds of aerodynamic flutter control measures, i.e. adding fairings, central-slotting, adding central stabilizers and adjusting the position of inspection rail, were investigated through wind tunnel tests, based on three kinds of popular girder sections for long-span cable-supported bridges, i.e. streamlined box girder section, box girder section with cantilevered slabs and two-isolated-girder section. The flutter control effects of the combinations of these control measures were also investigated and compared to the control effect of single measure respectively.

2. Basic Sections

Three basic girder sections, widely used in the design of cable-supported bridges, were selected in the current investigation, which are shown in Fig. 1. Section A is a streamlined box girder section which is popularly adopted in long-span suspension bridges and cable-stayed bridges, such as the Great Belt East Bridge, Runyang Bridge, Sutong Bridge etc. While Section B, a box girder section with cantilevered slabs, and Section C, a two-isolated-girder section, are used in cable-stayed bridges of relatively small span compared to Section A, such as Eastsea Bridge, Nanpu Bridge, Yangpu Bridge etc. Based on these three representative sections, four kinds of aerodynamic flutter control measures, i.e. adding fairings, central-slotting, adding central stabilizers and adjusting the position of inspection rail, were investigated through wind tunnel tests.

3. Adding Fairings

For aerodynamically very bluff girder section like Section C, which has square edge configurations in both windward and leeward sides, adding fairings can be very effective to improve aerodynamic stability. The revised Section C with fairings added on is shown in Fig. 2. Wind tunnel tests of the aeroelastic model with the original Section C and the revised one were carried out in

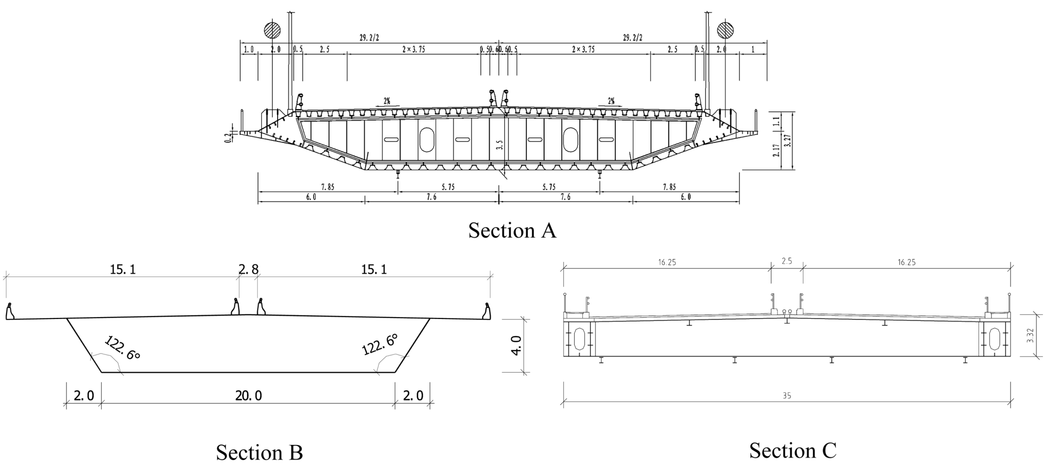


Fig. 1 Three basic girder sections

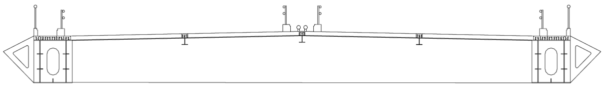


Fig. 2 Section C with fairings

Table 1 U_{cr} of Section C (m/s)

Angle of attack	-3º	0º	+3º
Original section		72.5	
Section with fairings	95.0	>100	95.0

smooth flow at Tongji University's TJ-3 Boundary Layer Wind Tunnel with the working section of the 15 m width, the 2 m height and the 14 m length. The flutter critical speeds U_{cr} for both sections were measured and summarized in Table 1. As the tested results show, adding fairings will make the air flow around the cross section more smoothly, and the flutter critical speed has been increased by at least 31%. In addition, the aerodynamic performances concerning other wind-induced responses, such as vortex-induced vibrations and aerodynamic forces, have also been improved with fairings added on.

4. Central Slot

Contrary to the case of adding fairings, central-slotting tends to decrease the flutter performances of those aerodynamic very bluff girder sections like Section C or rectangular section etc. based on previous investigation carried out by the authors, and with the increasing of slotting width they will become more aerodynamically unstable (Yang, *et al*. 2002, 2006). However, the application of central slotting in the box girder section can improve aerodynamic stability of cable-supported bridges according to theoretical and experimental investigations reported in the literature (Walshe, *et al*. 1997, Richardson 1981, Fung 1993, Miyata 2002). The effect of location and size of the slot on the aerodynamic characteristics was examined through section model wind tunnel tests (Sato, *et al*. 1995), and it was found that the slot at the center increased the flutter onset wind speed and the flutter onset wind speed was increased with the width of the slot (Sato, *et al*. 2000, Sato, *et al*. 2001). The effectiveness of central slot was further confirmed by a full aeroelastic model wind tunnel test based on an assumed super long-span bridge with the main span of 2800m (Sato, *et al*. 2002).The feasibility study of Gibraltar Bridge shows that not only there is a clear trend for the slotted-box section to become increasingly aeroelastically stable for increasing deck vent width but also this increase ratio of critical wind speeds with vent width can be fitted to the Power-law expressions by means of the least squares method (Larsen, *et al*. 1998). While previous investigations carried out by the authors indicate that the relationship between structural aerodynamic stability and vent width is not mono increase even for some kind of box girder section (Yang, *et al*. 2002, 2006).

In the current investigation, the flutter control effect of central-slotting was tested and analyzed based on the simplified section of Section A, which is shown in Fig. 3. According to previous research results, slot width is a key parameter in determining the aerodynamic performance of a slotted box girder section. In order to establish the experimental evidence linking vent width to aerodynamic stability, the ratio of vent width b to the solid box width B was respectively set to b/B = 0, 0.2, 0.4, 0.6, 0.8, and 1.0 in wind tunnel tests.

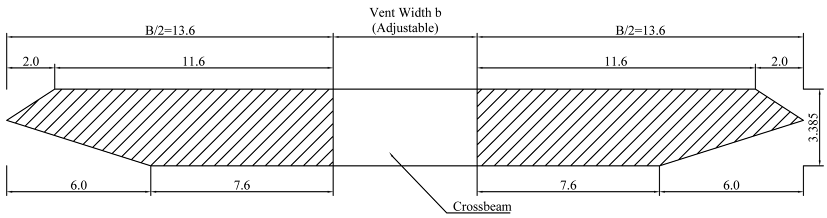


Fig. 3 Simplified Section A (Unit: m)

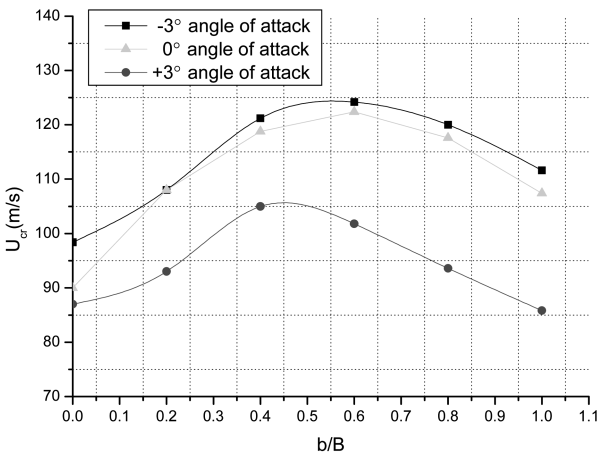


Fig. 4 Flutter critical speeds of central-slotted sections

The spring-supported sectional model wind tunnel testing of the slotted box girders was carried out in smooth flow at Tongji University's TJ-1 Boundary Layer Wind Tunnel with the working section of the 1.8 m width, the 1.8 m height and the 15 m length. The flutter critical speeds of sections with different vent widths and under different wind angles of attack were measured and summarized in Fig. 4.

It can be seen from Fig. 4 that the flutter stabilizing effectiveness of slotted box girders generally depends upon two important characteristics including width of central vent and angle of attack. The results demonstrate a clear fact that the values of critical wind speeds vary with angle of attack for all cases with various widths of central vent: the critical wind speed increases with the relative width of central vent from b/B = 0 to b/B = 0.4 at the +3^o angle of attack, and from b/B = 0 to b/B = 0.6 at the attack angle of 0^o and -3^o, respectively, but decreases with the relative width from b/B = 0.4 to b/B = 1.0 at +3^o and from b/B = 0.6 to b/B = 1.0 at 0^o and -3^o, respectively. This means for each angle of attack, the relationship between flutter performance and vent width is not mono increase, and the evolution trend of flutter critical speed comprises two different regions: the critical wind speed first increases with the relative width of central vent until an optimal point is reached, then decreases.

Since aerodynamic instability takes place whenever a bridge is exposed to wind speeds above the critical value at the attack angle covering from +3^o to -3^o, the dominant factor of aerodynamic stability is the minimum value among three critical wind speeds corresponding to the attack angle of +3^o, 0^o and -3^o. It is interesting to see that all minimum values for certain vent width are at the

+3° angle of attack.

With the application of the experimental results at +3° angle of attack, a Lorentz peak-value function was fitted to the measured critical wind speeds by means of the least squares method. The following empirical expression was obtained for calculating the critical wind speed of slotted box girders shown in Fig. 3.

$$U_{cr}^{Slot} = \eta_{b/B} U_{cr0} = \left(0.91 + \frac{0.12}{0.4 + 4(0.48 - b/B)^2}\right) \kappa f_t \sqrt{\frac{\sqrt{mJ_m}}{\rho B}\left[1 - \left(\frac{f_h}{f_t}\right)^2\right]} \quad (1)$$

where U_{cr0} is critical wind speed defined by Selberg formula (Selberg 1963), m is mass of sectional model in the unit of kg/m, J_m is mass moment of inertia of sectional model in kg-m^2/m, ρ is air density in kg/m^3, B is width of sectional model in m, f_h is the fundamental frequency in vertical bending in Hz, f_t is the fundamental frequency in torsion in Hz, and κ is shape factor of sectional model with $\kappa = 4.0$.

5. Central Stabilizer

Theoretical and experimental investigations reported in the literature (Matsumoto, *et al*. 1999, Matsumoto 2002, Tokoro, *et al*. 2001) support the conclusion that the application of vertical stabilizers in the cross section center can improve aerodynamic stability of cable-supported bridges, for example, Akashi Kaikyo Bridge (Ueda 1988), and Runyang Bridge (Xiang and Ge 2003). Further studies show that not only vertical stabilizers (central barriers) but also horizontal stabilizers (guide vanes) are effective to enhance critical flutter speed of suspension bridges (Ueda 1998). The investigation on aerodynamic and structural countermeasures for cable-stayed bridges with 2-edge I-shaped girder section indicated that the blocked central guard fence (a kind of central stabilizer) makes the flutter performance better in this kind of girder section (Murakami, *et al*. 2002). However, can central stabilizer be effective for all three basic girder sections? And what is the relationship between flutter performance and stabilizer height? These are questions the authors tried to answer in the current investigation.

Section A

For Section A, three stabilizer patterns were selected in the current study including a central stabilizer on the top of the box cross section called Stabilizer A, a stabilizer below the bottom namely Stabilizer B, and two stabilizers both on the top and below the bottom, Stabilizer A+B, shown in Fig. 5. In each pattern, the ratio of the stabilizer height h to the box depth H was

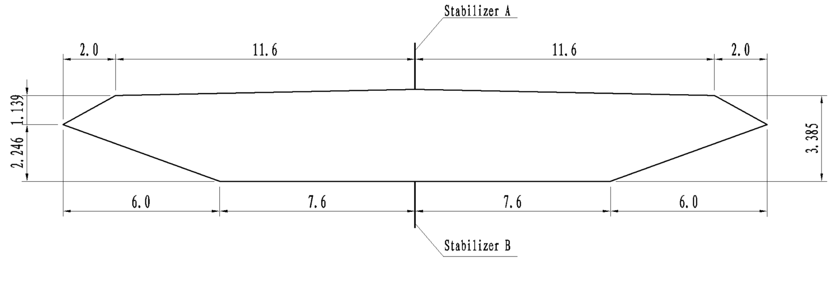


Fig. 5 Simplified Section A with central stabilizers (Unit: m)

respectively set to h/H = 0, 0.2, 0.4, 0.6 and 0.8.

The spring-supported sectional model wind tunnel testing of three central stabilizer patterns A, B and A+B was carried out in smooth flow at Tongji University's TJ-1 Boundary Layer Wind Tunnel. The most important wind tunnel test result links the flutter critical wind speed U_{cr} of the box cross section to the height of central stabilizer for the cases at the attack angles of +3°, 0° and -3° and is summarized in Table 2.

It can be seen from Table 2 that the stabilizing effectiveness of central stabilizer generally depends upon three important characteristics including stabilizer patterns, height of stabilizer and angle of attack. First of all, the values of critical wind speeds vary with angle of attack for all cases. Since aerodynamic instability takes place whenever a bridge is exposed to wind speeds above the critical value at the attack angles covering from +3° to -3°, the dominant factor of aerodynamic stability is the minimum value among three critical wind speeds corresponding to the +3°, 0° and -3° angle of attack for the certain stabilizer pattern with the certain height of stabilizer. The minimum critical wind speeds, therefore, are extracted for three certain stabilizer patterns with five heights of stabilizer and described in Fig. 6.

Based on the minimum values of critical wind speed shown in Fig. 6, both Stabilizers A and B can improve aerodynamic stability at the certain height of stabilizers for cable-supported bridges with box girders. Similar to the case of central-slotting, the relationship between flutter performance

Table 2 U_{cr} of simplified Section A with central stabilizers (m/s)

h/H	Stabilizer A			Stabilizer B			Stabilizer A+B		
	+3°	0°	-3°	+3°	0°	-3°	+3°	0°	-3°
0	87.0	90.0	98.4	87.0	90.0	98.4	87.0	90.0	96.4
0.2	91.2	115.2	109.8	90.0	110.4	111.6	72.0	108.6	127.2
0.4	96.0	118.8	102.0	82.8	102.0	112.8	106.2	102.0	87.0
0.6	111.0	105.0	96.0	72.0	99.0	110.4	108.6	91.8	<87.0
0.8	121.2	94.8	91.2	55.8	91.2	95.4	<87.0	<87.0	<87.0

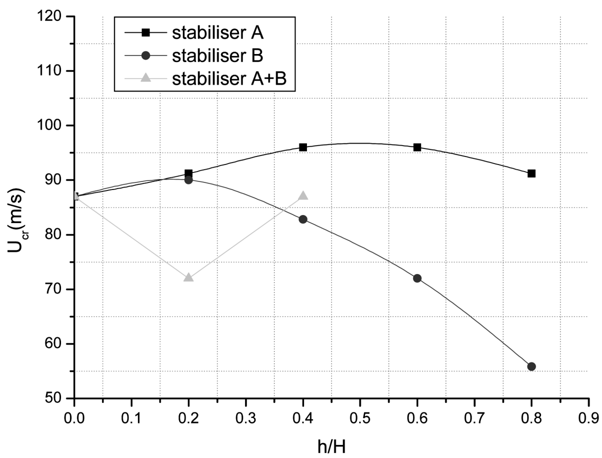


Fig. 6 Minimum values of critical wind speed

and stabilizer height is not mono increase, and the evolution trend of flutter critical speed also comprises two different regions: the critical wind speed first increases with the relative height of central stabilizer until an optimal point is reached, then decreases. In particular, the critical wind speed increases with the relative stabilizer height from h/H = 0 to h/H = 0.6 with the peak increased ratio of 11.3% for Stabilizer A and from h/H = 0 to h/H = 0.2 with the peak increased ratio of 4.1% for Stabilizer B, respectively, but decreases with the relative height from h/H = 0.6 to h/H = 0.8 for Stabilizer A and from h/H = 0.2 to h/H = 0.8 for Stabilizer B, respectively. Stabilizer A+B, however, makes it impossible to increase critical wind speed at any relative height of stabilizer.

Since Stabilizer A has the best flutter control effect, a Lorentz peak-value function was fitted to the measured critical wind speeds of simplified Section A with Stabilizer A by means of the least squares method. The following empirical expression was obtained for calculating the critical wind speed of box girders with Stabilizer A shown in Fig. 5.

$$U_{cr}^{Sta} = \eta_{h/H} U_{cr0} = \left(0.92 + \frac{0.136}{0.7 + 4(0.5 - h/H)^2}\right) \kappa f_t \sqrt{\frac{\sqrt{mJ_m}}{\rho B}\left[1 - \left(\frac{f_h}{f_t}\right)^2\right]} \tag{2}$$

where U_{cr0} is critical wind speed defined by Selberg formula (Selberg 1963), m is mass of sectional model in the unit of kg/m, J_m is mass moment of inertia of sectional model in kg-m^2/m, ρ is air density in kg/m^3, B is width of sectional model in m, f_h is the fundamental frequency in vertical bending in Hz, f_t is the fundamental frequency in torsion in Hz, and κ is shape factor of sectional model with $\kappa = 4.0$.

<u>Section B</u>

For Section B, central stabilizer was installed on the bridge deck as shown in Fig. 7. Three different heights of central stabilizer were selected to investigate the controlling effect of this aerodynamic flutter control measure on such a basic section, which are 0.8 m, 1.0 m and 1.2 m respectively, or 20%, 25% and 30% of the girder depth respectively.

The spring-supported sectional model wind tunnel tests were also conducted in TJ-1 BLWT, and the flutter critical speeds U_{cr} were measured and summarized in Table 3. According to the tested results, central stabilizers with all three different heights can improve the flutter performance of Section B, and the 1.2 m high central stabilizer has the best flutter control effect, which increases

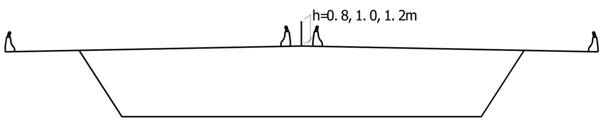


Fig. 7 Section B with central stabilizer

Table 3 U_{cr} of Section B (m/s)

Angle of attack	−3°	0°	+3°
Original section	>176	145.0	81.4
0.8 m central stabilizer	>176	151.8	85.8
1.0 m central stabilizer	>176	151.8	85.8
1.2 m central stabilizer	>176	154.0	90.2

the flutter onset speed by approximately 11%. It also can be seen that the flutter performance of girder Section B gets improved with the increase of stabilizer height from h/H = 0 to h/H = 0.3.

Section C

For Section C, central stabilizer was installed under the bridge deck and with the same height as the girder depth as shown in Fig. 8. Aeroelastic model tests are carried out to verify the flutter control effectiveness of the installation of central stabilizer in TJ-3 BLWT. The measured flutter critical speeds are shown in Table 4. Although the flutter controlling effectiveness of the central stabilizer on Section C is not as remarkable as that of the application of fairings, it still increases the flutter performance by 13.8%.

6. Local Adjustment

Sometimes we are put into a difficult situation when the flutter performance of a bridge structure should be improved while dramatic changes to the original girder section like central-slotting is not acceptable. All we can do is to make some local adjustment to the aerodynamic configuration of the original girder section, and a very prominent measure is to adjust the position of inspection rails.

Central-slotted Section A

For central-slotted Section A with vent width of 6 m as shown in Fig. 9, the different positions of the inspection rail under investigation are shown in Table 5. Flutter critical speeds of these six sections were measured in spring-supported sectional model wind tunnel tests conducted in TJ-1 BLWT and also summarized in Table 5.

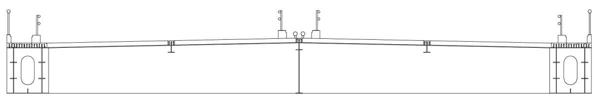


Fig. 8 Section C with central stabilizer

Table 4. U_{cr} of Section C (m/s)

Angle of attack	–3°	0°	+3°
Original section		72.5	
Section with fairings	87.5	82.5	>100

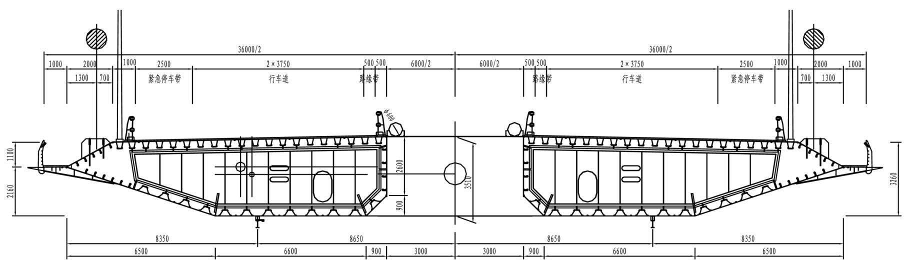


Fig. 9 Central-slotted Section A with 6 m central vent (Unit: m)

Table 5 U_{cr} of sections with different positions of inspection rail

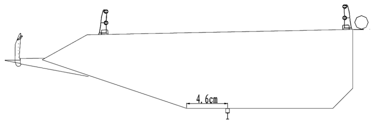
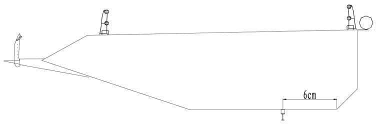
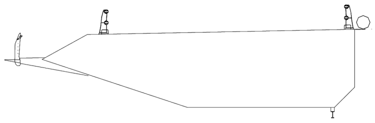
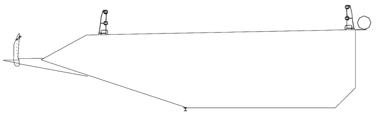
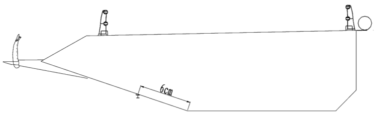
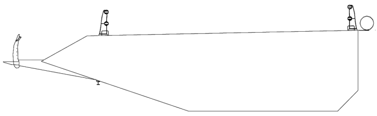
Case No.	Girder section with inspection rail	U_{cr} (m/s)	Improved ratio (%)
1		76.2	0.0
2		77.1	+ 1.2
3		77.3	+ 1.4
4		79.0	+ 3.7
5		76.9	+ 0.9
6		76.6	+ 0.5

Table 6 U_{cr} of sections with different d_I (m/s)

d_I	-3°	0°	3°	minimum
2.6 cm	>87.1	>87.1	87.1	87.1
28cm (S4 Section)	83.9	>87.1	>87.1	83.9
35 cm	>85.5	>87.1	>87.1	>85.5
56 cm	78.4	>87.1	>87.1	78.4
No inspection rail	74.2	>83.9	>87.1	74.2

As the results shown, the effect of adjusting the position of inspection rail on the flutter performance is slightly limited. The maximum improved ratio of the flutter critical speed is 3.7%. However, it does help the flutter performance of this designed section to pass the flutter verification speed of 78.7 m/s. Generally speaking, the flutter performances of those sections with inspection rail under the inclined web are better than the sections with inspection rail under the bottom slab.

In addition to the position of inspection rail, we also adjusted the distance between the top of the inspection rail and the bottom of the inclined web (d_I), and investigated the influence of this kind of adjustment on the structural aerodynamic stability. Flutter critical speeds of these sections were measured in spring-supported sectional model wind tunnel test and are summarized in Table 6.

According to the tested results, the flutter performance of the central-slotted box girder section is varied with the change of the distance between the inspection rail and the inclined web, and there possibly exits an optimum distance which is more or less similar to the optimum vent width of central-slotted box girder section. When the value of distance gets larger than the optimum one, the flutter performance drops down and comes closer to the girder section with no inspection rails added on.

Section B

As shown in Table 3, when at positive angle of attack, the aerodynamic stability of Section B is distinctively low and different from those at negative and zero angle of attack. It can be inferred that adjusting aerodynamic configuration of the windward inclined web and the bottom slab will affect the aerodynamic stability of this girder section dramatically. So flutter control measures concerning different positions of inspection rails were investigated in spring-supported sectional model wind tunnel test. The tested sections are shown in Fig. 10.

Section B1 has inspection rails on the bottom of the inclined web, while Section B2 has inspection rails on the upper side of the inclined web. In Section B3 and Section B4 the inspection rails are on the bottom slab. These four sections all have 1.2 m high central stabilizer on the bridge deck. In Section B5 the position of inspection rails is the same as in Section B1, but has no central stabilizer on the bridge deck. The wind tunnel tested results for these sections are listed in Table 7.

From the tested results we can see that the aerodynamic stabilities of sections with central stabilizer and inspection rails being appropriately positioned have been improved remarkably except

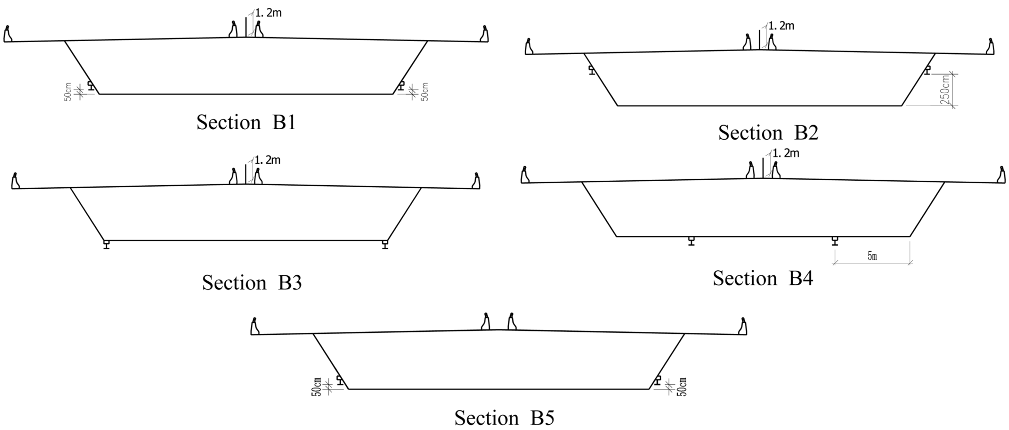


Fig. 10 Section B with different positions of inspection rails

Table 7. U_{cr} of sections with different positions of inspection rails (m/s)

Angle of attack	–3°	0°	+3°
Original section	>176	145.0	81.4
Section B1	>176	162.8	94.6
Section B2	>176	151.8	88.0
Section B3	>176	121.0	79.2
Section B4	>176	154.0	90.2
Section B5	>176	154.0	90.2

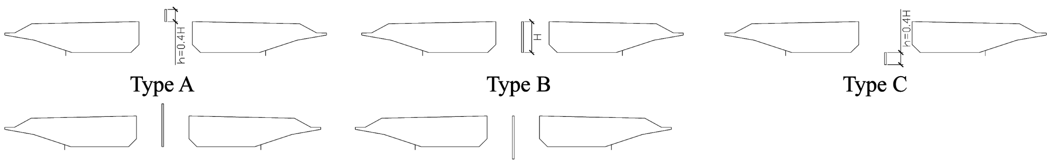


Fig. 11 Five types of central stabilizers installed on central-slotted Section A

Table 8 U_{cr} for central-slotted sections with different setup of central stabilizers (m/s)

Central Stabilizer	-3°	0°	3°	minimum	increased ratio (%)
S4 Section	83.9	>87.1	>87.1	83.9	-
Type A	88.1	>99.0	>99.0	88.1	+ 5.0
Type B	87.7	>99.0	>99.0	87.7	+ 4.5
Type C	90.9	>99.0	>99.0	90.9	+ 8.3
Type A+B	96.5	>99.0	>99.0	96.5	+ 15.0
Type C+B	94.4	>99.0	>99.0	94.4	+ 12.5

Section B3. Section B1 which has 1.2 m central stabilizer and inspection rails at the bottom of the inclined web has the best aerodynamic performance considering flutter instability. For Section B5 which has inspection rails at the same position as Section B1 and no central stabilizer, the aerodynamic stability also has been improved by 11%.

7. Combination Effects

When single measure isn't good enough to fulfill the flutter control task, the combination of two or more flutter control measures may be a good choice. We have already seen the combination effects of central-slotting plus local adjustment (adjustment to inspection rails) and central stabilizer plus local adjustment in previous section of this paper. Furthermore, we tried to investigate the combination effects of central-slotting and central stabilizers. Therefore, a series of wind tunnel tests were conducted to investigate the flutter controlling effects of central stabilizers installed on central-slotted Section A. There are totally five types of central stabilizers investigated in current research as shown in Fig. 11. Type A, Type B and Type C are three basic types of central stabilizers, while Type A+B is the combination of Type A and Type B, Type C+B is the combination of Type C and Type B. The spring-supported sectional model wind tunnel testing results of flutter critical speeds for S4 Section with different types of central stabilizers are listed in Table 8.

The tested results show that all types of central stabilizers can improve aerodynamic stability of central-slotted box girder section. For three basic types of central stabilizers, Type C where the stabilizer is under the central slot has the best flutter-controlling effect. It should also be noted that the combination types of stabilizers (Type A+B and Type C+B) are more effective, which can increase flutter critical speed up to 15%.

8. Conclusions

Aerodynamic flutter control for long-span cable-supported bridges was investigated based on three basic girder sections, i.e. streamlined box girder section, box girder section with cantilevered slabs and two-isolated-girder section. Totally four kinds of aerodynamic flutter control measures (adding fairings, central-slotting, adding central stabilizers and adjust the position of inspection rail) were included in this research. Their flutter control effects on different basic girder sections were evaluated by sectional model or aeroelastic model wind tunnel tests.

Adding fairings is very effective to improve the flutter stability of very bluff girder section like two-isolated-girder section. While the application of central slotting in the box girder section can improve flutter stability of cable-supported bridges effectively, and the relationship between flutter performance and vent width is not mono increase. Central vertical stabilizers can improve the flutter performances of all three basic girder sections. And adjusting the position of inspection rail is very useful to increase the flutter onset speeds of bridge structures without making dramatic changes to the original girder section. Furthermore, the combination of several aerodynamic flutter control measures can get extra improvement on flutter stability if some important parameters are appropriately selected.

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