Effect of Wind Yaw Angle on Flutter Performance of a Truss Deck Suspension Bridge with Various Aerodynamic Measures

*Le-Dong Zhu\(^1\), Zhen-Shan Guo\(^2\), Xiao Tan\(^3\)

\(^1\) State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
\(^1,2\) Key Laboratory of Wind Resistance Technology of Bridges (Shanghai) of Ministry of Transport, Tongji University, Shanghai 200092, China
\(^3\) Lin Tung-Yen & Li Guo-Hao Consultants LTD. Shanghai, Shanghai 200437, China

\(^1\) Ledong@tongji.edu.cn

ABSTRACT

To improve the flutter performance of a suspension bridge with a 1088m-span truss-stiffened deck, various aerodynamic measures, such as the central gap, the upper and lower central stabilizing barriers and the aerodynamic wings, etc., were investigated at first via wind tunnel test of sectional model under the normal wind condition. The yaw wind effect on the flutter performance of the bridge with or without the above aerodynamic measures was then examined via a series of wind tunnel tests of oblique sectional model. It was found that in the most cases, the lowest flutter critical wind speed occurred when the incident wind deviated from the normal direction by a small yaw angle about 5\(^\circ\)-10\(^\circ\). However, the normal wind was still most dangerous to the bridge in some other cases, such as that with the measures of double-layer wings mounted in the truss and at the inclination angle of 3\(^\circ\).

1. INTRODUCTION

Investigations on flutter performances of long-span bridges focus on the special case of normal wind conventionally (Scanlan & Gade 1977, Scanlan 1978, Agar 1989, Namini 1992, Jain et al. 1996, Katsuchi 1999, Ge & Tanaka 2000, Ding et al. 2002), because the wind normal to the bridge span is generally regarded to be most dangerous to bridges. However, it was already found that this kind of cognition about the dangerous wind direction was not always true. Aware of that strong winds often attack bridges in a yawed direction deviating from the normal of the bridge span, Zhu et al. (2001, 2002) investigated the yaw wind effects on the flutter critical wind speed of the Tsing Ma suspension bridge in Hong Kong, which has a truss-stiffened deck of bluff box-shape with a small width-to-height ratio of only 5.37 and one central vent slot on
each of its upper and lower layers (see Fig.1). It was found that the lowest flutter critical wind speeds occurred at a yaw angle of 5° for the inclination angles of 3° and 5° whilst that for the inclination angle of 0° happened in the normal wind case.

To understand the flutter performances of flat bridge decks under skew wind, Zhu et al. (2006, 2008) further investigated the yaw wind effects on the flutter critical wind speeds of three typical bridges in China via a series of wind tunnel test of oblique sectional models. The 1st one was the 3rd Nanjing Bridge over Yangtze River in Jiangsu Province, a cable-stayed bridge with a main span of 648m and a flat closed single-box cross section of deck (see Fig.2). The 2nd one was the Hongguang Bridge over Liu River in Guangxi Zhuangzu Autonomous Region, a suspension bridge with a single span of 380m and a flat π-shape open thin-wall cross section of deck (see Fig.3). The 3rd one was the 2nd Chongqing Bridge over Yangtze River, a cable-stayed bridge with a main span of 444m and a flat twin side-girder cross section of deck (see Fig.4). The test results show that the critical wind speed of skew wind flutter varies in an undulate manner with yaw angle. The variation pattern varies significantly with the change of wind inclination angles. The lowest flutter critical wind speed often occurs in skew wind case with a certain yaw angle between 5° and 20°. For the wind inclination angles between −3° and 3°, the drop of critical wind speed due to the yaw wind effect may reach a notable percentage of 5% for the flat closed open single-box deck, 10% for the flat π-shape open thin-wall deck and 15% for the flat twin side-girder deck, respectively.
As it is well known that the truss-stiffened deck has been frequently used in cable-supported bridges, for examples, the Verrazano-Narrows suspension bridge (1298m), the Golden Gate suspension bridge (1280m), the Mackinac suspension bridge (1158m), the Tacoma Narrows suspension bridges (eastbound and eastbound, 853m) in USA; and the Akashi-Kaikyo suspension bridge (1911m), the Minami Bisan-Seto suspension bridge (1100m), the Kita Bisan-Seto suspension bridge (990m), the Higashi Kobe cable-stayed Bridge (485m), the Yokohama Bay cable-stayed bridge (460m) in Japan, etc. Because of the large vertical stiffness and the convenience to erection of bridges, the adoption of truss-stiffened deck has also become more and more prevalent in Chinese long-span bridges with the rapid development of the high-speed railway and the deep exploitation of the mountain regions in the west China. For instances, it was used in the Aizhai suspension bridge (1146m), the Balinghe suspension bridge (1088m), the Yichang Yangtze suspension bridge (960m), Xiling Yangtze suspension bridge (900m), the Siduhe suspension bridge (900m), the Beipanjiang suspension Bridge (636m), the Minpu cable-stayed bridge (708m), the Tianxingzhou cable-stayed bridge (504m, railway), etc. It is then concerned how about the flutter performances of truss-stiffened deck bridges under skew (yawed and inclined) wind. As an example to answer this concern, the yaw wind effects on the flutter performances of Balinghe Bridge with and without various aerodynamic measures, like the central slot, the upper and lower central stabilizing barriers and the aerodynamic wings, etc., were studied via wind tunnel tests of sectional model, and are to be discussed in this paper.
2. **BRIEF DESCRIPTION OF BALINGHE BRIDGE**

Located in the south-west part of Guizhou Province in China, Balinghe Bridge is a long-span suspension bridge with a 1088m-span truss-stiffened deck (see Fig.5 to Fig.7), crossing the Balinghe deep gorge at a 368m level (about 2/3 depth) above the gorge bottom. The altitudes are 956.000m and 1160.516m for the pillar top and bottom of Guanling Tower, 965.000m and 1153.988m for the pillar top and bottom of Zhenning Tower, and 1048.341 for the deck top at the mid-span. Therefore, the altitudes of the whole bridge are between 956.000m and 1160.516m. The gorge of Balinghe (see Fig.5) goes approximately from north to south. It is about 560 deep at the bridge site and is about 2.0 to 2.5km wide at its top. The altitude of the gorge bottom is about 680m at the bridge site.

![Fig.5 Balinghe Bridge over the deep gorge of Baling River](image)

![Fig.6 General layout of Balinghe Bridge (unit: m)](image)
The stiffening truss girder is comprised of two vertical main trusses, a series of transverse trusses, one top horizontal brace system and one bottom horizontal brace system. The vertical main truss is composed of an upper chord, a lower chord, a series of vertical and batter webs (see Fig.7b). The central distance between the two main trusses is 28.0m, and the central distance between the upper and lower chords of the main truss is 10.0m. The overall height of the stiffening truss girder is 10.7m and its overall width is 20.7m. The length of a standard truss segment is 10.8m. Closed square-box cross-sections are used for the upper and lower chords, the batter webs of the main trusses, whilst a H-shape cross-section is used for the most of the vertical webs. As shown in Fig.7a, each transverse truss is comprised of a pair of upper and lower transverse beams, a pair of vertical webs, a pair of inboard oblique webs and a pair of outboard oblique webs. The outboard webs of the transverse truss have a H-shape cross-section whilst the other members possess closed square-box cross-sections. Both the top and bottom horizontal brace system are of K-shape pattern, and closed square-box cross-sections are chosen for their members.

As shown in Fig.7a, twin separate decks of orthotropic steel plates with a central gap of 0.6m are adopted in this bridge. And the orthotropic decks are comprised of steel plates, longitudinal U-shape and plate-shape stiffening ribs, transverse beams, and longitudinal inverse T-shape beams which are connected to the upper transverse beams of the transverse trusses using pull-press-resistant basin-type rubber bearers. The overall height of the single orthotropic deck is 1.38m and its width 12.90m.

The natural frequencies of the first vertical and torsional symmetric modes obtained via the finite element analysis with ANSYS are 0.1545Hz and 0.2780Hz, respectively. The torsional-vertical frequency ratio is thus about 1.8. The corresponding equivalent mass \( m_{eq} \) and equivalent mass moment of inertia \( I_{meq} \) of the truss-stiffened deck considering the effect of whole bridge 3D vibration are 29.623t/m and 4704.477tm2/m, respectively (Zhu & Xiang 1995).
3. CONFIGURATION AND INSTALLATION OF SECTIONAL MODEL

The wind tunnel tests of spring-suspended sectional model were carried out in TJ-2 Wind Tunnel of the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University, China, for the normal wind case and yaw wind cases with different yaw angles. TJ-2 Wind Tunnel is a boundary layer tunnel of closed-circuit-type. The working section of the tunnel is 3m wide, 2.5m high, and 15m long. The achievable mean wind speed ranges from 0.5m/s to 68.0m/s, adjustable continuously. Both the vertical inclination angle of wind flow deviating from the horizontal plane and the horizontal yaw angle of wind flow deviating from the longitudinal symmetric axis of the wind tunnel are smaller than 0.5°. The turbulent intensity and the spatial non-uniformity of mean wind speed are less than 0.5% and 1%, respectively.

![Diagram](image)

Fig. 8 Schematic diagram for the configuration of oblique sectional model

The model was made at a length scale of 1/60 using steel and ABS plastic plates. The width and height of the truss model were 0.478m and 0.178m, and the model height of the orthotropic deck plate is 0.023m. To fulfill the wind tunnel tests under various yaw wind conditions, oblique sectional models with different shapes were adopted in this study. The plane configuration of the oblique model is shown as Fig.8. Each oblique model is comprised of 5 parts: one rectangular middle segment with the length of \( L_c = 2.172 \) m; two trapezoidal end parts with the average length of \( (L-L_c)/2 = 0.286 \) m for each, where \( L = 2.744 \) m is the total axial length of the oblique model; and two transverse suspended arms through the two end parts, respectively. The function of the two trapezoidal end parts is to adjust the shapes of the oblique model ends to ensure that the two ends of the oblique sectional model are always parallel to the mean wind during the test. Therefore, different end parts, which are replaceable, should be employed in the tests for different yaw angles of wind (\( \beta \)). However, the lengths of the middle part (\( L_c \)) and the whole model (\( L \)) remain unchanged during the test for all yaw angles of wind. In the normal wind case (i.e., \( \beta = 0^\circ \)), the two end parts...
become rectangular. Moreover, the length-to-width ratio ($L/B$) of the oblique sectional model should be as large as possible to reduce the influence of 3D flows existing around the model ends on the test results. It is generally suggested that $L/B$ should not less than 5, and is equal to 5.74 in this study.

In the test, the oblique sectional model was suspended in the wind tunnel with 8 helical springs from the 4 steel arc tracks mounted on the ceiling and floor, as shown in Fig.9. The two suspended arms were kept horizontal for all the inclination angles and yaw angles of wind. To prevent the model from any significant lateral (or along-wind) static and dynamic displacement, it was restrained with four long tight wires with small springs in along-wind direction.

![Fig.9 Sectional model suspended in the TJ-2 wind tunnel](image)

![Fig.10 Sectional model suspended in the TJ-2 wind tunnel](image)
The inclination angle ($\alpha$) and the yaw angle ($\beta$) of wind in this study are defined, respectively, as the angle between the mean wind and the horizontal plane, and the angle between the mean wind and vertical plane normal to the bridge span. Thus, the anticipated yaw angle can be easily attained via fitting the 8 helical springs at proper locations on the tracks, whilst the desired inclination angle can be achieved via rotating the deck model around the central axis through the centers of the two suspended arms, as shown in Fig.10. However, it should be noticed that the inclination angle attained in this way is the “model inclination angle ($\alpha_m$), which is slightly different from the defined inclination angle of wind when the yaw angle is not zero. The relation between the two kinds of inclination angle is as follows:

$$\alpha = \alpha_m \cos \beta$$ (1)

3. FLUTTER PERFORMANCES UNDER NORMAL WIND CONDITION

The flutter performances of the bridge were tested at first under the normal wind at three inclination angles of $+3^\circ$, $0^\circ$ and $-3^\circ$, and the effects of the central gap (CG) between the twin orthotropic deck plates, the upper and lower central stabilizing barriers (UCSB and LCSB) and the aerodynamic wings (AW), on the flutter critical wind speed of the truss suspension bridge were investigated. The detail results are as follows.

![Fig.11 Schematic diagram of central gap and upper and lower stabilizing barriers](image)

3.1. Effect of Central Gap on Flutter Performance

The definition of the central gap width ($D$) is shown in Fig. 11. In all, five kinds of the central gap width ($D$) were tested to investigate the gap influence on the bridge flutter critical wind speed. The tested gap widths of model ($D_m$) are 0mm, 5mm, 10mm, 15mm
and 20mm, and the corresponding ratios of $D/b$ (or $D_m/b_m$) are about 0.0%, 2.3%, 4.7%, 7.0% and 9.3%, respectively, where $b_m=215\text{mm}$ is the model width of the single orthotropic deck, corresponding to the prototype value ($b$) of 12.90m. $D_m=10\text{mm}$ is corresponding to the prototype one ($D$) of 600mm, which is finally adopted in the real bridge.

Fig. 12 Effect of central gap on flutter

Fig. 12a and Fig.12b show, respectively, the variation curves of the flutter critical wind speed of the bridge with central gap ($U_{cr}^{CG}$) vs. the gap ratio ($D/b$) and the variation curves of the increase ratio of flutter critical wind speed due to gap ($\eta_{CG}$) with $D/b$, where, $\eta_{CG}$ is defined as follows:

$$
\eta_{CG} = \left[ \frac{U_{cr}^{CG}(D/b) - U_{cr}^{0.0}}{U_{cr}^{0.0}} \right] / U_{cr}^{0.0}
$$

(2)

Where, $U_{cr}^{0.0}$ is the flutter critical wind speed of the truss suspension bridge without any gap (i.e., $D/b=0.0\%$) and any other aerodynamic control measures.

It can be seen from Fig.12 that for all the three inclination angles of $+3^\circ$, $0^\circ$, and $-3^\circ$, the critical wind speed has a relaxed increasing tendency with the increase of the gap width. In the case of the $+3^\circ$ inclination angle, with the increase of the gap width, the critical wind speed increases slowly at first and decreases slowly when $D/b$ is less than 5%. Afterwards, the critical wind speed increases at a relatively high rate, and reach a maximal value at a $D/b$ value of about 7.5% by an increment of about 24%. In the case of the $0^\circ$ inclination angle, the increasing rate of the critical wind speed with the gap width is larger than that in the case of $+3^\circ$ inclination angle, and the critical wind speed attains a maximal value at $D/b\approx7.5\%$ by a significant increment of about 83%. In the case of the $-3^\circ$ inclination angle, the critical wind speed remains the increasing tendency within the considered range of $D/b$, and the increase ratio $\eta_{CG}$ reaches to about 56% at the maximal $D/b$ of 9.3%.
It can also be found from Fig.12 that the inclination angle of +3° is most unfavorable
to the bridge flutter in all five considered cases of gap width. Obviously, the truss
suspension bridge will have a very low flutter critical wind speed of only 52.1 m/s if the
there is no gap on the bridge deck. However, the flutter performance of the bridge can
be improved notably by setting a proper central gap between the twin decks. The
lowest critical wind speed occurred at +3° inclination angle can be raised to about
63.7 m/s by setting a 0.9 m-wide central gap, and to about 56.0 m/s by setting a 0.6 m-
wide central gap.

Nevertheless, the final determination of the gap width often depends on many other
design factors besides the aerodynamic consideration, for example, the limitation of the
whole width of the truss girder due to the economic reason, which was one of the
important reasons why the central gap, finally adopted for the Balinghe bridge, was only
0.6 m wide (D/b=4.7%).

The flutter checking wind speed of the bridge is 48 m/s, which was roughly
determined by the design engineers based on the historical wind data recorded at a
few observatory stations of surrounding counties. However, the local terrain of the
Balinghe deep gorge is very complex as mentioned before, and the wind data observed
in situ of the bridge is very lack, therefore, the above flutter checking wind speed has
some uncertainties. In this connection, to have enough redundancy of the wind-
resistant safety, an additional proper aerodynamic measure is needed to promote the
flutter critical wind speed of the bridge in conjunction with the measure of 0.6 m-wide
central gap. And the truss-stiffened deck with a 0.6 m-wide central gap is to be regarded
as a basic configuration of truss-stiffened deck, i.e., every of the aerodynamic
measures discussed below is added on the basic deck configuration, in other words, is
combined with the control measure of 0.6 m-wide central gap.

3.2. Effect of Upper Central Stabilizing Barrier on Flutter Performance

As shown in Fig.11, h is the whole height of the upper central stabilizing barrier
(UCSB) above the upper surface of the upper transverse beam of the transverse truss,
while \( h_1 \) represents the UCSB height above the upper surface orthotropic deck. In all,
five kinds of the UCSB heights were tested to investigate the influence of UCSB on the
bridge flutter critical wind speed, i.e., \( h_m = 30.4 \text{mm}, 34.5 \text{mm}, 38.5 \text{mm}, 42.6 \text{mm} \) and
46.6 mm, or \( h_{1m} = 7.5 \text{mm}, 11.6 \text{mm}, 15.6 \text{mm}, 19.7 \text{mm} \) and 23.7 mm. Therefore, \( h_1/T = h_{1m}/T_m \approx 33\%, 51\%, 68\%, 86\% \) and 103\%, where, \( T=1.38 \text{m} \) and \( T_m=23 \text{mm} \), are the
prototype and model values of the overall height of the orthotropic deck. The top of the
UCSB reaches to the central level of the inboard crash-barrier when \( h_1/T = 33\% \), and
exceeds the inboard crash-barrier top at the half height of the inboard crash-barrier.
Where, the height of the inboard crash-barrier is 0.936 m for the prototype and 15.6 m
for the model.

Fig. 13a and Fig.13b show, respectively, the variation curves of the flutter critical
wind speed of the bridge with the UCSB \( (U_{cr}^{USB}) \) vs. the height ratio \( (h_1/T) \) and the
variation curves of the increase ratio of flutter critical wind speed \( (\eta_{USB}) \) due to the
UCSB vs. \( h_1/T \), where, \( \eta_{USB} \) is defined as follows:

\[
\eta_{USB} = \left[ U_{cr}^{USB} \left( h_1/T \right) - U_{cr}^{4.7} \right] / U_{cr}^{4.7}
\]

(3)
Where, $U_{cr}^{4.7}$ is the flutter critical wind speed of the truss suspension bridge with a 0.6m-wide central gap (i.e., $D/b=4.7\%$), but without any other aerodynamic control measures.

It can be found from Fig. 13 that, for all the three inclination angles of $+3^\circ$, $0^\circ$ and $-3^\circ$, the critical wind speed increases with the increase of the UCSB height on the whole, but meanwhile, at an undulating manner. The general increasing rates in the case of the $+3^\circ$ and $0^\circ$ inclination angles are close and significant whilst that in the case of the $-3^\circ$ inclination angle is relatively small. Nevertheless, the inclination angle of $+3^\circ$ is also most unfavorable to the bridge flutter in all considered cases of the UCSB height.

In case of the $+3^\circ$ inclination angle, the UCSB with $h_1/T \leq 33\%$ is ineffective, even negative to improving the flutter performance. However, by increasing $h_1/T$ to 51\% (about 75\% of the inboard crash-barrier height), the flutter critical wind speed can be raised from 56.0m/s to 89.4m/s, i.e. $\eta_{USB} = 60\%$. If $h_1/T$ is further increased to 68\%, the flutter critical wind speed drops slightly to 85.4m/s on the contrary, i.e., $\eta_{USB} = 52.5\%$. The maximal increase ratio of flutter critical wind speed $\eta_{USB}$ is about 95\% when $h_1/T$ reaches to about 93\%. In this case, although the flutter critical wind speed can be promoted to about 109m/s, the UCSB protrudes above the deck surface by about 1.24m, which may significantly increase the horizontal drag force. Therefore, a proper and acceptable UCSB should be as low as possible under the precondition of meeting the requirement for the flutter performance. In this connection, the UCSB with $h_1/T$ of 51\% will be taken into account in the following research on wind yaw angle effect.

3.3. Effect of Lower Central Stabilizing Barrier on Flutter Performance

As shown in Fig.11, $h_2$ represents the height of the lower central stabilizing barrier (LCSB) beneath the upper surface of the upper transverse beam of the transverse truss. In all, five kinds of the LCSB heights were tested to investigate the influence of LCSB on the bridge flutter critical wind speed, i.e., $h_2m = 17.8\text{mm}$, $26.7\text{mm}$, $35.6\text{mm}$, $44.5\text{mm}$ and $53.4\text{mm}$. Therefore, $h_2/H = h_{2m}/H_m \approx 10\%$, 15\%, 20\%, 25\% and 30\%, where,
$H=10.7m$ and $H_m=17.8mm$, are the prototype and model values of the overall heights of the truss girder. The prototype heights of LCSB are between 1.07m and 3.20m.

Fig. 14 Effect of the Lower central stabilizing barrier on flutter (gap width $D=0.6m$)

Fig. 14a and Fig.14b show, respectively, the variation curves of the flutter critical wind speed of the bridge with the LCSB ($U_{cr}^{LSB}$) vs. the height ratio ($h_2/H$) and the variation curves of the increase ratio of flutter critical wind speed ($\eta_{LSB}$) due to the LCSB vs. $h_2/H$, where, $\eta_{LSB}$ is defined as follows:

$$\eta_{LSB} = \left[ U_{cr}^{LSB} \left( \frac{h_2}{H} \right) - U_{cr}^{4.7} \right] / U_{cr}^{4.7} \tag{4}$$

From Fig.14, it can be found again that the inclination angle of $+3^\circ$ is most dangerous to the bridge flutter in all considered cases of the LCSB height. Furthermore, the effect of the LCSB on the flutter performance is clearly negative in the cases of $-3^\circ$ and $0^\circ$ inclination angles. In the case of $+3^\circ$ inclination angle, the LCSB has notable positive effect only when the height ratio ($h_2/H$) is in the close vicinity of 25%. $\eta_{LSB}$ reaches its maximal value of 22.3% when $h_2/H=25\%$. In this case the maximal flutter critical wind speed is about 68.5m/s, and the height of LCSB ($h_2$) is 2.67m.

3.4. Effect of Double-layer Aerodynamic Wings on Flutter Performance

Fig.15 shows the combined aerodynamic control measure of the double-layer aerodynamic wings and a 0.6m-wide central gap. The double-layer aerodynamic wings are supported by the posts of the lower maintenance paths. Each of the wings is of elliptic shape with the long axis of 1.4m and a short axis of 0.15m. The vertical central distance between the two wings is 1.3m, and the vertical distance between the upper wing center and the upper surface of the upper transverse chord of the transverse truss is 5.2m. The horizontal distance between the wing center and the vertical symmetric axis of the truss girder is 12.1m.
The tested flutter critical wind speeds of the prototype bridge with this combined aerodynamic control measures are 56.3 m/s, 109.2 m/s and 121.4 m/s, respectively, for the inclination angles of +3°, 0° and -3°. By comparing with the critical wind speeds of the bridge with only 0.6 m-wide central gap, which are 56.0 m/s, 87.5 m/s and 122.6 m/s, respectively, it can be seen that the double-layer aerodynamic wings can significantly raise the flutter critical wind speed by about 24.8% for the case of the 0° inclination angle, but exert very small influence on the flutter critical wind speed for the cases of the +3° and -3° inclination angles.

Fig. 15 Schematic diagram of double-layer aerodynamic wings and central gap

4. FLUTTER PERFORMANCES UNDER YAW WIND CONDITION

The yaw wind effect on the flutter performance of Balinghe Bridge with various aerodynamic measures was investigated via a series of wind tunnel tests of oblique sectional model. The truss-stiffened deck with a 0.6 m-wide central gap as shown in Fig. 7a was also selected at first as a basic configuration of truss-stiffened deck (TSD) in the investigation of yaw wind effect. Other aerodynamic measures, including the sealed central gap (SCG), the upper central stabilizing barriers (UCSB) with different heights, the lower central stabilizing barriers (LCSB) with different heights, and the double-layer aerodynamic wings (DLAW) were then added on the basic structural configuration in the test. In the following context, however, only the UCSB height of \( h_1/T = 51\% \) and the LCSB height of \( h_2/H = 25\% \) will be considered for discussions on the test results of the central stabilizing barrier (CSB) cases, because of the limitation of the space.
4.1. Yaw Wind Effect on the flutter performance of the basic configuration

As mentioned above, the basic configuration of truss-stiffened deck has twin orthotropic decks with a 0.6m-wide central gap (see Fig.7a). Fig.16a shows the variation curves of the flutter critical wind speed of the basic deck configuration \( U_{cr}^{CG}(\beta) \) vs. the yaw wind angle, while Fig.16b shows the variation curves of increase ratio of the flutter critical wind speed of the basic deck configuration \( \gamma_{CG}(\beta) \) vs. the yaw wind angle, where, \( \gamma_{CG}(\beta) \) is defined as follows:

\[
\gamma_{CG}(\beta) = \left[ U_{cr}^{CG}(\beta) - U_{cr}^{CG}(0^\circ) \right] / U_{cr}^{CG}(0^\circ)
\]  

(5)

Where, \( U_{cr}^{CG}(0^\circ) \) is the flutter critical wind speed of the bridge with the basic deck configuration (i.e., with a 0.6m-wide central gap, and \( D/b=4.7\% \)) under the normal wind.

From Fig.16, one can find that the +3° inclination angle is always most unfavorable to the bridge flutter of the basic configuration for all the yaw wind angles from 0° to 15°, and the flutter critical wind speed reaches a minimal value of 50.6m/s at a yaw angle of about 5°, which is about 9.5\% lower than that under the normal wind condition.

For the 0° inclination angle, the flutter critical wind speed increases with the yaw angle rising from 0° to 15°, and the lowest one is 87.5m/s, occurring in the normal wind cases (i.e. \( \beta=0^\circ \)).

For the -3° inclination angle, the flutter critical wind speed increases with the yaw angle rising from 0° to about 9°, and drops then with the further increase of yaw angle up to 15°. Thus, the lowest one occurs at the 15° yaw angle and is 103.6m/s, 15.5\% lower than that in the normal wind case.
4.2. Yaw Wind Effect on the flutter performance of the SCG configuration

In this “Sealed Central Gap” configuration of truss-stiffened deck, the 0.6m-wide central gap is sealed completely. Fig.17a shows the variation curves of the flutter critical wind speed of the SCG configuration \( U_{cr}^{SCG}(\beta) \) vs. the yaw wind angle, while Fig.17b shows the variation curves of increase ratio of the flutter critical wind speed of the SCG configuration \( \gamma_{SCG}(\beta) \) vs. the yaw wind angle, where, \( \gamma_{SCG}(\beta) \) is defined as follows:

\[
\gamma_{SCG}(\beta) = \left[ \frac{U_{cr}^{SCG}(\beta) - U_{cr}^{SCG}(0^\circ)}{U_{cr}^{SCG}(0^\circ)} \right]
\]

Where, \( U_{cr}^{SCG}(0^\circ) \) is the flutter critical wind speed of the bridge with the SCG configuration under the normal wind.

![Graphs showing critical wind speed and increase ratio](image)

Fig.17 Yaw wind effect on flutter performance of the bridge with the SCG configuration

From Fig.17, it can be found that the +3° inclination angle is also most unfavorable to the bridge flutter of the SCG configuration for all the yaw wind angles from 0° to 15°, and the variation pattern of the flutter critical wind speed with yaw angle is similar to that of the CG configuration. For the +3° inclination angle, the flutter critical wind speed reaches a minimal value of 42.8m/s at a yaw angle of about 5°, which is about 5.5% lower than that under the normal wind condition.

For the 0° inclination angle, the lowest flutter critical wind speed is 51.4m/s and occurs in the normal wind cases.

For the -3° inclination angle, the variation of flutter critical wind speed is insignificant within the yaw angle range between 0° and 10°, and the lowest one occurs at the 15° yaw angle and is 73.8m/s, 2.5% lower than that in the normal wind case. Furthermore, it can also be seen that the flutter critical wind speeds of the SCG configuration are evidently lower than those of the CG configuration.
4.3. Yaw Wind Effect on the flutter performance of the UCSB configuration

In this UCSB configuration of truss-stiffened deck, the "Upper Central Stabilizing Barrier" with $h_1=51\% T=0.70m$ was adopted in conjunction with the 0.6m-wide central gap. Fig.18a shows the variation curves of the flutter critical wind speed of the UCSB configuration ($U_{cr}^{USB}(\beta)$) vs. the yaw wind angle, while Fig.18b shows the variation curves of increase ratio of the flutter critical wind speed of the UCSB configuration ($\gamma_{USB}(\beta)$) vs. the yaw wind angle, where, $\gamma_{USB}(\beta)$ is defined as follows:

$$\gamma_{USB} = \frac{U_{cr}^{USB}(\beta) - U_{cr}^{USB}(0^\circ)}{U_{cr}^{USB}(0^\circ)}$$ (7)

Where, $U_{cr}^{USB}(0^\circ)$ is the flutter critical wind speed of the bridge with the UCSB configuration under the normal wind.

![Graph](image)

Fig.18a shows that the $+3^\circ$ inclination angle is also most unfavorable to the bridge flutter of the UCSB configuration for all the yaw wind angles from $0^\circ$ to $15^\circ$, and the corresponding flutter critical wind speed attained a minimal value of 81.1m/s at a yaw angle of about $5^\circ$, which is about 9.3% lower than that under the normal wind condition.

For the $0^\circ$ inclination angle, the flutter critical wind speed rises at first with the increasing yaw angle, and attained a maximal value at the yaw angle of $5^\circ$, then drops. The lowest flutter critical wind speed occurs at the yaw angle of $15^\circ$, and is 107.7m/s, 15.4% lower than that in the normal wind case.

For the $-3^\circ$ inclination angle, the flutter critical wind speed enhances at first until the yaw angle reaches to $10^\circ$, and descend afterwards. A maximal value at the yaw angle of $5^\circ$, then drops. The lowest flutter critical wind speed occurs in the normal wind case, however, the critical wind speed at the yaw angle of $15^\circ$ is very close to that in the normal wind case.
4.4. Yaw Wind Effect on the flutter performance of the LCSB configuration

In this LCSB configuration of truss-stiffened deck, the “Lower Central Stabilizing Barrier” with $h_2=25\%H=2.67m$ was adopted in conjunction with the 0.6m-wide central gap. Fig.19a shows the variation curves of the flutter critical wind speed of the LCSB configuration ($U_{cr}^{LSB}(\beta)$) vs. the yaw wind angle, while Fig.19b shows the variation curves of increase ratio of the flutter critical wind speed of the LCSB configuration ($\gamma_{LSB}(\beta)$) vs. the yaw wind angle, where, $\gamma_{LSB}(\beta)$ is defined as follows:

$$
\gamma_{LSB} = \left[ U_{cr}^{LSB}(\beta) - U_{cr}^{LSB}(0^\circ) \right] / U_{cr}^{LSB}(0^\circ)
$$

(8)

Where, $U_{cr}^{LSB}(0^\circ)$ is the flutter critical wind speed of the bridge with the LCSB configuration under the normal wind.

![Graphs showing critical wind speed and increase ratio vs. yaw angle](image)

Fig.19a shows that the $+3^\circ$ inclination angle is still most unfavorable to the bridge flutter of the LCSB configuration for all the yaw wind angles from 0° to 15°, and the corresponding flutter critical wind speed attained a minimal value of 81.1m/s at a yaw angle of about 7°, which is about 22% lower than that under the normal wind condition.

The variation patterns of flutter wind speed with the yaw angle are similar for the 0° and $-3^\circ$ inclination angles. The flutter critical wind speed ascends always with the increasing yaw angle until 15°, namely, the normal wind is most dangerous to the bridge flutter. However, the increasing rate obviously becomes smaller and smaller when the yaw angle approaches 15°. This means that the flutter critical wind speed should attains a maximal value about the yaw angle of 5°.

4.5. Yaw Wind Effect on the flutter performance of the DLAW configuration

In this DLAW configuration of truss-stiffened deck, the “Double-Layer Aerodynamic
Wings" of elliptic shape was adopted in conjunction with the 0.6m-wide central gap. Fig.20a shows the variation curves of the flutter critical wind speed of the DLAW configuration \( U_{cr}^{DAW} (\beta) \) vs. the yaw wind angle, while Fig.19b shows the variation curves of increase ratio of the flutter critical wind speed of the DLAW configuration \( \gamma_{DAW} (\beta) \) vs. the yaw wind angle, where, \( \gamma_{DAW} (\beta) \) is defined as follows:

\[
\gamma_{DAW} = \frac{U_{cr}^{DAW} (\beta) - U_{cr}^{DAW} (0^\circ)}{U_{cr}^{DAW} (0^\circ)} 
\]

(9)

Where, \( U_{cr}^{DAW} (0^\circ) \) is the flutter critical wind speed of the bridge with the DLAW configuration under the normal wind.

Fig.20a shows that the +3° inclination angle is most unfavorable to the bridge flutter of the DLAW configuration in general, and the corresponding flutter critical wind speed always increases with the increasing yaw angle until 15°. The normal wind is therefore most dangerous to the bridge flutter in this case.

For both the 0° and -3° inclination angles, the flutter wind speed experiences a falling stage at first, then a rising stage with the increasing yaw angle. For the 0° inclination angle, the lowest critical wind speed is about 90m/s, about 18% lower than that under the normal wind condition, and happened at a yaw angle between 5° and 6°. For the -3° inclination angle, the lowest one is about 116m/s, and occurs at a yaw angle between 8° and 9°. Nevertheless, the variation of the flutter critical wind speed is slight within the range of yaw angle less than 10°.

CONCLUSIONS

The aerodynamic control measures and the yaw wind effect on the flutter
performance of a suspension bridge with a 1088m-span truss-stiffened deck were investigated via a serious wind tunnel test of sectional model, and have been discussed in this paper. Some major conclusions can be drawn as follows:

(1) +3° is the most unfavorable inclination angle to the flutter performance of the truss-stiffened deck suspension bridge no matter whether the different aerodynamic control measures, such as the central gap with various width, the upper or lower central stabilizing barrier with various heights, and the double-layer elliptic aerodynamic wings, are adopted or not.

(2) In the normal wind case, the proposed control measures of the central gap can raise the lowest critical wind speed by 7%-20%, where, the measure of the 0.6m-wide central gap can improve the flutter critical wind speed by about 7.5%.

(3) In conjunction with the measure of the 0.6m-wide central gap, the proposed control measures of the upper central stabilizing barrier can further raise the lowest critical central wind speed by 50%-90% in the normal wind case. However, the effect of the lower central stabilizing barrier on the flutter critical wind speed is negative in most cases except that it can enhance the critical wind speed by about 22% when $h_2/H=25%$.

(4) Based on the measure of the 0.6m-wide central gap, the proposed double-layer elliptic aerodynamic wings can further increase the flutter critical wind speed significantly by about 24.8% for the case of the 0° inclination angle, but has insignificant effect for the inclination cases of +3° and -3°.

(5) For the most unfavorable inclination angle of +3°, the yaw wind effect can reduce the flutter critical wind speed of the truss-stiffened deck suspension bridge, respectively, by about 5.5% for the case without the any deck gap and other aerodynamic measures, by about 9.5% for the case only with 0.6m-wide central gap, by about 9.3% for the upper central stabilizing barrier with $h_1=51% T=0.70m$ in conjunction with 0.6m-wide central gap, and by about 22% for the case with the lower central stabilizing barrier with $h_2=25% H=2.67m$, in conjunction with 0.6m-wide central gap. The corresponding most unfavorable yaw angles for the above cases are between 5° and 10°.

(6) For the case with the double-layer elliptic aerodynamic wings, the yaw wind effect can decrease the flutter critical wind speed by about 18% and 3% in the inclination angle cases of 0° and -3°, respectively. However, for the most unfavorable inclination angle of +3°, the yaw wind effect raises the critical wind speed, namely, the normal wind is most dangerous to flutter in this cases.

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