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Comprehensive evaluation of aerodynamic performance of twin-box girder bridges with vertical stabilizers

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ABSTRACT

Although vertical central stabilizer (VCS) on long-span cable-supported bridges is one of practical passive aerodynamic countermeasures, the effectiveness of VCS in improving aerodynamic performance is much dependent on the parameters of VCS. Through a series of wind tunnel tests, in present study we investigated the influences of various combinations of six heights and two positions of VCS on three crucial aerodynamic performances (i.e. stationary aerodynamic performance, flutter performance and vortex-induced vibration (VIV) performance) of a twin-box girder suspension bridge. Results show that for the 20% slot width ratio (SWR) bridge, increasing the height of upward VCS (UVCS) has limited contribution to the improvement in stationary aerodynamic performance owing to the increase of drag force coefficient (C_D) and pitching moment coefficient (C_M). In addition, the critical flutter wind velocity initially increases with the height increase of VCS, and then significantly decreases after the height of VCS reaches to a certain threshold. Furthermore, the VIV displacement responses significantly become larger after installing higher UVCS and downward VCS (DVCS) from 0.6 h/H to 1.0 h/H, especially for heaving VIV. Most importantly, the implementation of 0.2 h/H DVCS for the 20% SWR twin-box girder bridge could produce the best aerodynamic performance outcomes after comprehensive evaluation.

1. Introduction

Wind-induced effects (WIE) exhibited by long-span cable-supported bridges can be divided into two categories based on characteristics of bridge structural responses: (1) Amplitude divergence phenomena, namely, aerodynamic stabilization; and (2) Amplitude limited vibration (Miyata et al., 1993; Wang et al., 2013; Larsen and Larose, 2015; Wang et al., 2016). The aerodynamic stabilization, which consists of stationary aerodynamic instability and flutter instability associated with structural security, could lead to the collapse of bridges, and therefore special attention should be paid in the wind-resistance design (Tanaka and Davenport, 1983; Chen and Kareem, 2001a,b; Kareem, 2008). Vortex-induced vibration (VIV) and buffeting, which belong to amplitude limiting vibration, could result in a relatively large-amplitude vibration and discomfort feelings to the passengers on the bridges (Miyata, 2002; Tao et al., 2017). However, VIV usually happens at lower wind speeds and also often occurs during the bridge construction and operation, and so should be emphasis taken into account in bridge design (Zasso et al., 2013; Zhu and Xu. 2014). Therefore, the evaluation of three crucial WIE including stationary aerodynamic performance, flutter performance and VIV performance of long-span bridges are usually conducted in wind tunnel tests, respectively.

If a long-span cable-supported bridge has a problem in fulfill aerodynamic performance requirements under wind loading, the implementation of effective countermeasures becomes necessary. Among various countermeasures, passive aerodynamic measure which is one of the most effective and commonly used countermeasures (Wilde et al., 1999), has been successfully applied in many bridge projects, such as the use of central-slotted in a closed-box girder (Sato et al., 2000) and vertical central stabilizers (VCS) (Chen et al., 2006). However, some passive methods could play negative roles in the attempts to control all the three crucial WIE of bridges. For example, although the central-slotted method is useful for improving the flutter performance of closed-box girders (Yang et al., 2017), it may cause the VIV problem of central-slotted box girders (namely, twin-box girders) (Yang et al., 2016). According to the previous studies on wind tunnel tests (Larsen, 1993; Ge et al., 2009; Diana et al., 2013; Yang et al., 2017), a countermeasure strategy using both VCS and twin-box girders has been proven to be an effective way of

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increasing the critical flutter wind velocity (U_{cr}), decreasing the VIV amplitude and increasing torsional divergence critical wind velocity to some extent for long-span bridges. However, the control effectiveness of the combination scheme of VCS and twin-box girders, which is much dependent on a range of critical parameters (e.g. the height of VCS and slot width ratios (SWR)), has not been fully understood so far, and relevant studies in this area are very limited.

Therefore, through a series of wind tunnel tests, the purpose of this study is to identify the optimal configuration of VCS (i.e. height and position) for a twin-box girder bridge which produces better aerodynamic performance outcomes (i.e. stationary aerodynamic performance, flutter performance and VIV performance). These tests were performed on three groups of 20% SWR twin-box sectional models which have six representative heights of VCS and two positons of VCS since the 20% SWR is chosen based on the design of Xihoumen Suspension Bridge in terms of aerodynamic performance and cost efficiency. Firstly, the force-measurement tests of stationary aerodynamic forces were introduced, and then the stationary aerodynamic force coefficients and torsional divergence critical wind velocities were compared. Secondly, the critical flutter wind velocity (U_{cr}) and corresponding modified Selberg formula, damping ratios and flutter derivatives of twin-box girders with various VCS were compared through the flutter tests, respectively. In addition, the velocity filed and surface pressure distributions from CFD simulations were presented to further understand the flow structure change after installing VCS. Finally, both vertical and torsional VIV responses as well as VIV performance of the bridges were evaluated by two important criteria (e.g. Sperling indicator and Wind-resistance specification of China). The present study could potentially contribute to the aerodynamic performance evaluation and wind-resistance design of long-span bridges.

2. Stationary aerodynamic performance of the combination schemes

2.1. Stationary aerodynamic forces measurements

To systematically investigate the influence of the combined use of VCS and twin-box girders in stationary aerodynamic performance, six representative relative height (h/H) of VCS (i.e. h/H = 0, 0.2, 0.4, 0.6, 0.8 and 1.0, h and H is the height of VCS and girder) were selected for the upward VCS (UVCS) and downward VCS (DVCS) in Fig. 1.

Fig. 2 shows the force-measured testing of two examples of VCS configuration (i.e. 0.4 h/H UVCS and 0.8 h/H DVCS) in TJ-2 Boundary Layer Wind Tunnel at Tongji University. Two streamlined box section models representing the main girder of Xihoumen Bridge without deck facilities were adopted. Each section is 261.9 mm wide (B_s) and 58.8 mm high (H) with a scale ratio of 1:60. The structural properties of the model sections, such as geometric dimension, mass, fundamental frequencies and damping ratios are given in Table 1. To filter the undesirable model vibrations during testing, a natural frequency which is greater than 25 Hz, was designed for the restrained sectional model. In the force-measurement tests (Table 2), a wind velocity of 10 m/s was adopted with 25 different wind attack angles ranging from -12° to +12° with an increment of 1°.

2.2. Stationary aerodynamic coefficients comparison

Stationary aerodynamic force coefficients of twin-box girders with UVCS and DVCS in the structural axes were measured. Three aerodynamic force coefficients in this study are the drag force coefficient (C_D), lift force coefficient (C_L) and pitching moment coefficient (C_M).

2.2.1. Stationary aerodynamic coefficients of UVCS

Three stationary aerodynamic coefficients of twin-box girders with six heights of UVCS (i.e. h/H = 0 represents the case of without VCS), are described in Fig. 3. It can be seen that the value of C_D is the smallest when the wind attack angle $\alpha = 0°$ and reaches its maximum when $\alpha = \pm 12°$ for most of these cases. Furthermore, the value of C_D generally increases with the increase of the height of UVCS, especially for larger wind attack angles. There is an obvious anti-symmetric change of C_L about $\alpha = 0°$, i.e. the absolute value of C_L gradually increases when α changes from 0° to 12°or from -12° to 0°. Among 6 h/H ratios of UVCS, the absolute value of C_L with 0.2 h/H UVCS is the largest and followed by that without VCS, while the value of C_L is the smallest under both 0.8 h/H UVCS and 1.0 h/H UVCS. Fig. 3c shows that the value of C_M is likely to increase rapidly when α increases from -12° to 12°, and the value of C_M generally decreases with the increase of the height of UVCS.

2.2.2. Stationary aerodynamic coefficients of DVCS

Fig. 4 illustrates three stationary aerodynamic force coefficients of twin-box girders with six heights of DVCS. The symmetric phenomenon about $\alpha = 0°$ is not seen in Fig. 4a, since the value of C_D at positive wind attack angles is significant larger than that at negative angles. In addition, the value of C_D gradually increases when α increases from -12° to 12°. Overall, the value of C_D increases with the increase of the height of DVCS while the value of C_D at $\alpha = 0°$ is the smallest. As shown in Fig. 4b, the absolute value of C_L gradually increases when α increases from -12° to 12°. Both the values of C_L corresponding to the ratios of 0.8 h/H and 1.0 h/H are the largest and this observation is different from that shown in Fig. 3b relating to UVCS. It is interesting that with DVCS, the value of C_L with 0.6 h/H is close to that with 0.4 h/H, while the value of C_L with 0.2 h/H is close to that without VCS. Besides, the value of C_M generally increases with the increase of the height of DVCS when α increase from -12° to 12°, while the direction of C_M shifts from the negative to the positive with the increase of α.

In summary, the value of C_D generally increases when the ratio of h/H increases from 0 to 1, especially for the UVCS. The trends of the change of C_L and C_M with h/H ratio under UVCS are opposite to those under DVCS.

By comparing the stationary aerodynamic force coefficients of twin-box girders with UVCS and DVCS, the CD values of the girder with UVCS under the positive wind attack angles are obvious larger than those with the same height of DVCS, while the CD values of the girder with 1.0 h/H UVCS under the negative wind attack angles are larger than that with DVCS. Meanwhile, the CL values of the girder with DVCS under the

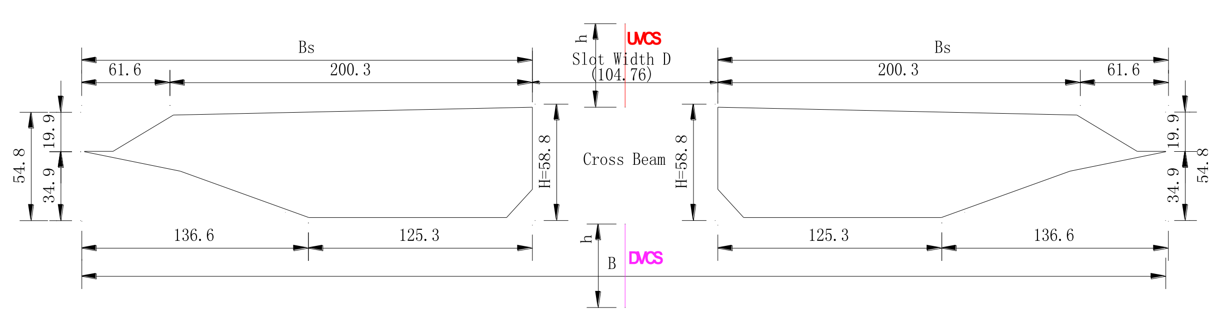

Fig. 1. The cross-section of a twin-box girder bridge deck with VCS (unit: mm).