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Effects of wind fairing angle on aerodynamic characteristics and dynamic responses of a streamlined trapezoidal box girder

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ABSTRACT

Streamlined trapezoidal box girders (STBGs) are widely used for long-span bridges. However, systematical researches regarding the effects of wind fairing angle (β) on the aerodynamic characteristics and the dynamic responses of STBG are still lacking. Herein, such influences are systematically investigated via CFD simulation and the results have been validated through experimental works. The STBG with different wind fairing angles are simulated while the mean aerodynamic coefficients, pressure distributions, and velocity profiles of lanes have been analyzed. Then, the deck performances in terms of vortex-induced vibration (VIV) are evaluated and the associated mechanisms have been studied. The results show that fairing angle has much greater effect on the upper surface than the lower surface. The STBG with smaller wind fairing angle has better aerodynamic performance, but the wind velocity near the surface is relatively larger, which is associated with the vortex at the forepart of the upper surface. The tail of the upper surface supplies a significant amount of energy to VIV, but the source of vortices at the tail is the forepart vortices. Thus, the formation of vortex with remarkable strength at the forepart of the upper surface should be prevented to improve the dynamic behavior of the STBG.

1. Introduction

With the rapid development of economy and society, demands for long-span bridges are also increasing dramatically, more and more long-span cable-stayed and suspension bridges are being built or planned to be built. Studies have demonstrated that the problems caused by the wind are becoming ever more prominent with the increase of bridge span. Streamlined trapezoidal box girder (STBG) is an effective sectional form to enhance the aerodynamic stability of long-span bridges, and with better economical and better construction convenience compared with truss girders (Larsen and Wall, 2012; Ito et al., 2014; He et al., 2017). However, STBGs may suffer from vortex-induced vibration (VIV) at low wind speed. This phenomenon was observed on Storebelt Bridge (Larsen et al., 2000), *Trans*-Tokyo Bay Crossing Bridge (Fujino and Yoshida, 2002), Xihoumen Bridge (Li et al., 2011; Laima et al., 2013), Xiangshan Harbor bridge (Zhu et al., 2013, 2015; Chen et al., 2018) and so on. Larsen emphasized that, for more economical design of long-span bridges, an aerodynamically superior trapezoidal girder without any appendages is required (Larsen and Wall, 2012).

For STBG (Fig. 1), wind fairing (β) is a major factor in the definition of its aerodynamic. Recently, the effects of wind fairings on the aerodynamic performance of the stationary bridge decks have been investigated by some researchers. Sarwar et al. (2008) utilized numerical simulation method to explore the aerodynamic characteristics of a box girder with wind fairing angle of 51°, and found that the impact of wind fairing is nearly identical to increase the width of the bridge deck. Ito et al. (2014) studied the coherence characteristics of lift forces for box girder with an equilateral triangle wind fairing. The results showed that the flow separates obviously from the leading edge for the rectangular section, and the triangle wind fairing could weaken the separation of flow. Haque et al. (2016) used numerical simulation method to explore the effects of different top plate slopes and bottom plate slopes on aerodynamic characteristics of a rectangle girder with wind fairing. It was indicated that the drag and lift values decrease with the decrease of plate slopes, and that the tail flow separation and the leading-edge cavity at the bottom are sensitive to edge fairing shape. He et al. (2017) investigated the influences of aspect ratio, wind fairing angle and fairing nose position on aerodynamic behaviors of a streamlined flat box girder. They found that these parameters affect the aerodynamic performance significantly when the angle of attack is larger than 4°. On the other hand, the larger fairing angle is favorable to the wind resistance

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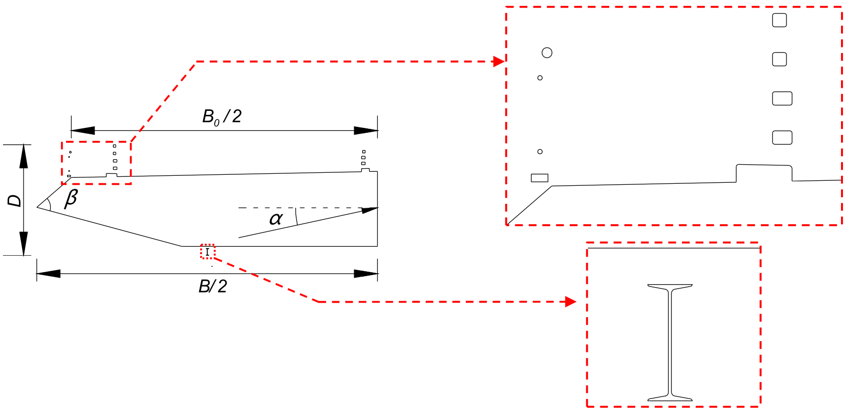

Fig. 1. Schematic view of STBG.

stability of the box girder. Furthermore, the effects of wind fairing angles on the dynamic behaviors also have been studied as follows. Sukamta et al. (2008) discussed the effects of a fairing on the flutter performance of a twin-box girder. Wang et al. (2011) investigated the influence of aerodynamic configuration on flutter and VIV of a streamlined box girder. It is demonstrated that a box girder with the angle between the bottom slab and inclined web of 15° has better flutter stability. Larsen and Wall (2012) compared the VIV performance of a box girder with three kinds of angle between the bottom slab and inclined web of 26.6°, 19.7° and 14.7°, and also indicated that the angle of 14.7° has better VIV stability. Zhou et al. (2015) adopted both wind tunnel test and numerical simulation to investigate the effect of three kinds of wind fairings, including trapezoidal wind fairing and airfoil wind fairings, on VIV stability. They found that all the three different wind fairings could reduce VIV to varying degrees.

Although the stationary behaviors and the dynamic performances are investigated in above-mentioned researches respectively, the effect of fairing angle on wind profiles of lanes and sidewalks has not yet been explored, and also there is no systematical analysis that included both the aerodynamic characteristics and the dynamic responses of the STBG. It appears that the analysis of the effects of wind fairings on box girders is not totally comprehensive. Therefore, an analysis of the effects of wind fairings on STBG needs to be carried out for understanding the mechanisms of the aerodynamic characteristics and VIV performance of streamlined box girders with various wind fairing angles.

It is well known that one of the effective measures to determine the aerodynamic characteristics is to visualize the flow field and pressure distribution. To achieve visualization, the most convenient and efficient method is the computational fluid dynamic (CFD). Bruno et al. (2014) and Patruno et al. (2016) investigated the aerodynamic characteristics of a 5:1 rectangle based on both CFD and wind tunnel tests, and such studies highlight that the drag and the Strouhal number of CFD agree well with those of wind tunnel test, but simulation results might be inaccurate to obtain the lift coefficient. Nieto et al. (2015) emphasized that the k-ω-SST model can be applied to identify the VIV prone regions, but this model is inaccurate to predict the flutter for the 4:1 rectangle. Although CFD method may be inaccurate in some situations, acceptable results can be obtained by selecting the appropriate turbulence models, parameters and mesh size, the reliability and accuracy of CFD numerical simulation have been in fact verified by many researchers. Bruno and Mancini (2002) investigated the influences of deck details on the aerodynamic interference behavior in terms of streamlined bridge deck based on CFD method, and they validated the pressure distribution of CFD with experimental results, and finding good agreement. Vairo (2003) employed CFD to simulate the wind loading on long-span bridges, there is a good agreement between CFD results and tested results, for both the aerodynamic coefficients and the flutter derivatives. Ishihara (2006) predicted the flow field around a square prism based on CFD, and also found good agreement between the pressure distributions of CFD and those of wind tunnel tests. Watanabe and Fumoto (2008) adopted CFD to discuss the aerodynamic characteristics of a slotted box deck at various attack angles, the aerodynamic coefficients of simulation agreed well with those of wind tunnel test, and they verified the mechanism of the attack angle and the aerodynamics of bridge deck. Starossek et al. (2009) obtained the flutter derivatives of nine bridge deck sections based on numerical simulation, they proved that simulation results agree well with the experimental results for streamlined sections, and they also found that the CFD method seems less precise for bluff and open bridge sections. Mannini et al. (2010) utilized numerical simulation to obtain the flow field and pressure distribution around a bridge deck, and clarified the efficiency of this method to capture complex Reynolds number effects. Huang and Liao (2011) also used CFD to calculate the flutter derivatives and checked the accuracy of the simulation results by comparing with the experimental results. Šarkić et al. (2012) adopted k-ω-SST turbulence model to simulate the flutter performance of a box girder, and validated the simulation results with tested results. They clarified that CFD is applicable to simulate the dynamic performance of bridge deck. This conclusion was also suggested by Brusiani et al. (2013). They also found that the k-ω-SST turbulence model has the strongest applicability, because of its reduced sensitivity to boundary conditions and its higher accuracy results. Tang et al. (2017) used k-ω-SST turbulence model to calculate the flutter derivatives of a truss girder, and some devices installed in order to optimize the deck performance based on the advantages of visualization of CFD. Chen et al. (2018) calculated the VIV performance of a flat-closed-box girder by using CFD with k-ω-SST turbulence model, and verified the accuracy of the simulations with wind tunnel tests, finding good agreement.

The present paper aims to analyze the effects of wind fairing angle on a streamlined trapezoidal box girder by CFD based on k-ω-SST model. The CFD model and the validation of simulation results will be introduced in Section 2. The aerodynamic characteristics of the STBG with different wind fairing angles will be analyzed in Section 3, including aerodynamic coefficients, mean pressure distributions and mean velocity profiles. Then in Section 4, the comparisons of VIV performances, pressure distributions at VIV process and flow fields for the STBG with different wind fairing angles are presented and analyzed. Finally, conclusions are drawn in Section 5.

2. CFD model

2.1. Implementation of VIV

As merely vertical VIV was observed in corresponding wind tunnel tests (Zhu et al., 2013), only the vertical vortex-induced vibration of this STBG was considered in this study. The vertical motion equation of the STBG can be expressed as follows: