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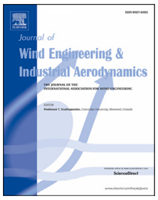

Aerodynamic optimization for flutter performance of steel truss stiffening girder at large angles of attack

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ABSTRACT

The flutter performance of a suspension bridge with truss girder, spanning deep canyon in the dry-hot river valley area where strong wind shows large angle of attack, is analyzed by wind tunnel test. The effects of different horizontal and vertical aerodynamic countermeasures are compared to find effective optimization schemes for improvement of the bridge flutter stability, and a simplified CFD model is further presented to study the corresponding aerodynamic mechanism from the work done by aerodynamic forces perspective. The results show that the combination of central closed deck and vertical stabilizers is favorable to the flutter performance of the suspension bridge. At lower angles of attack, a pair of vortices formed behind the upper and lower stabilizers alternately during the torsional vibration, acts on the downstream bridge deck and produces negative energy which makes the flutter frequency decrease and the critical wind speed increase. On the other hand, at larger angles of attack, the existence of lower stabilizer hinders the movement of the vortex on the same side which becomes the main factor for the occurrence of torsional flutter, and reduces the input energy by aerodynamic forces, which makes the critical wind speed increase with the same flutter frequency.

1. Introduction

Long-span bridges have many aerodynamic and aeroelastic problems as the span increases, and the design has urged special attention to the prevention of flutter occurrence. Flutter that occurs when the critical wind speed is exceeded is a self-induced motion with divergent amplitude leading to the destruction of structure. Aerodynamic optimization is an effective countermeasure for flutter suppression of long-span bridges by changing the cross-sectional shape, controlling the flow pattern and increasing the critical flutter wind speed.

Flutter stability can be realized by various aerodynamic countermeasures, even by a slight change of small parts of the cross-section. Central slotted deck and vertical stabilizer are common and effective aerodynamic countermeasures. For streamlined box section, Sato et al. (2000) showed that the critical flutter wind speed increases with the increase in slot width at the center of the girder. Diana et al. (2006) carried aerodynamic studies of the proposed Messina Strait Bridge with a multiple-box section. Chen et al. (2006) investigated the mechanism of vertical stabilizer for improving aerodynamic stability of an open deck Π-shaped section and a closed box section, and found that vertical stabilizer can increase the amplitude of the heaving motion and decrease that of the rotational motion of the bridge decks. Ge and Xiang (2008) introduced the aerodynamic selection of deck section of Xihoumen Bridge. A single-box section with stabilizer and two slotted deck with different widths can all meet with the flutter stability requirement of 80 m/s. Yang et al. (2015) studied the flutter performance of twin-box bridge decks through experimental investigation and investigated the best slot ratio for flutter stability. Moreover, Wang et al. (2011) showed that a 15° inclined web can restrain the formation of vortex near the tail and improve the aerodynamic stability of long-span bridges. For truss section, Ueda et al. (1990) investigated the effects of vertical stabilizer on the aerodynamic instability for long-span suspension bridge with stiffening truss-girders by wind tunnel test, and concluded that the resulting reseparation from the bottom edge of vertical stabilizer and the air stream blowing through the center grating of the deck lead to the suppression of wind induced oscillation. Miyata and Yamaguchi (1993) described some design considerations of wind effects of the Akashi Kaikyo Bridge to find aerodynamic methods for reducing the flutter instability. This resulted in a median barrier installed at the center of the deck floor, which remarkably raised the critical flutter wind speed. Al-Assaf (2006) discussed the flutter analysis of open-truss stiffened suspension bridges, with an emphasis on the Second Tacoma Narrows Bridge of which the

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aerodynamic characteristics was improved by installing open-grates along bridge deck.

The truss section is widely used in long-span bridges located in mountainous canyon area due to the limited conditions of transportation and construction site. However, there is no consistent understanding about aerodynamic optimization for flutter performance of these suspension bridges, such as whether the central-slotted deck should be adopted or not. Xu (2009) proposed an optimal configuration of deck which is the combination of the central slot and aerodynamic wings to make the 1088 m Baling River Bridge, spanning the Baling River valley, meet with the flutter stability requirement. Wang et al. (2014) showed that the combination of the central slotted deck with a porosity of 50% and the central vertical stabilizer is favorable to the flutter stability of the 538 m Dimu River Bridge. In contrast, the 1176 m Aizhai Bridge, spanning the Dehang valley, meets with the flutter stability requirement by closing the central slot of deck and setting central stabilizers (Chen et al., 2009). The closed deck is also used for the 900 m Sidu River Bridge to improve its flutter stability.

In dry-hot river valley with deep canyon area, in addition to complicated terrain, the circulation in small region caused by the huge temperature difference in vertical and level directions is very obvious, so the local wind environment is very complex where strong wind shows large angle of attack. With the development of highway traffic, increasing number of long span bridges with steel truss stiffening girder are now constructed in the dry-hot river valley with deep canyon area. The aerodynamic stability of these bridges at large angles of attack becomes an increasing concern for the design and construction, calling for further investigations on the flutter performance and the aerodynamic optimization of this type of cross-section.

In this paper, the flutter performance of a suspension bridge with a center span of 1100 m, spanning deep canyon in the dry-hot river valley area, is analyzed. At first, the reliability of the wind tunnel test results at large angles of attack is discussed using CFD simulations. Subsequently, a series of horizontal and vertical aerodynamic countermeasures are selected and their effects on the critical flutter wind speed of the bridge are compared by wind tunnel test to find effective optimization schemes. Finally, a simplified CFD model is presented to study the corresponding aerodynamic mechanism from the work done by aerodynamic forces perspective.

2. Wind tunnel test

2.1. Engineering backgrounds

A suspension bridge with steel truss stiffening girder and a center span of 1100 m located in the dry-hot river valley with deep canyon area is selected to carry out wind tunnel tests, as shown in Fig. 1. The width of steel truss stiffening girder is 27 m, and the height is 8.2 m, as shown in Fig. 2. The steel truss stiffening girder is suspended by hangers at intervals of 10 m. The bridge deck is made up of longitudinal steel I-beams and concrete slabs.

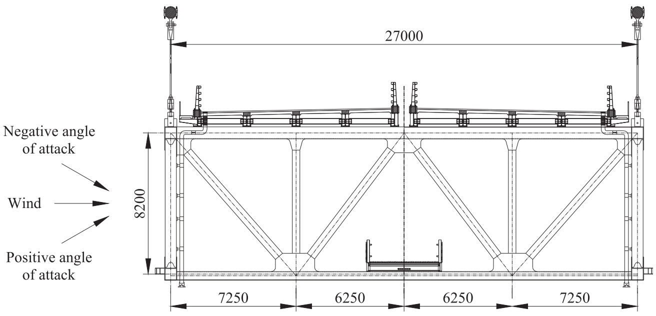

Fig. 2. Outline of the steel truss stiffening girder (unit: mm).

The distance of the bridge deck to the normal water lever is larger than 200 m, and the mountain peaks with high altitude near the bridge site are covered with snow all the year round. The wind characteristics over the site are analyzed by field measurement, wind tunnel test and CFD simulation, as shown in Fig. 3. The design standard wind speed of girder V_d is 32.6 m/s, and the corresponding flutter checking wind speed is expressed as $[V_{\rm cr}] = 1.2 \cdot \mu_f \cdot V_d$, where $\mu_f = 1.31$ is the correction coefficient of fluctuating wind velocity according to the bridge span and the terrain roughness. Due to the complicated terrain and the special climate, the mean angle of attack of inflow at the height of bridge deck reaches to -4.46°, so the angles of attack ranging from -7° to 7° are selected in flutter analysis.

2.2. Experimental model for flutter analysis

The wind tunnel tests are conducted in the second test section of XNJD-1 wind tunnel. The scale of 1/43.6 sectional model with a length of 2.1 m for the suspension bridge is designed, as shown in Fig. 4. The mass of the model is 17.3 kg per meter, and the mass moment of inertia is 0.916 kg m^2 per meter. A finite element model is established using ANSYS software to analyze the dynamic characteristics of the suspension bridge, and some natural frequencies of modes for girder are shown in Table 1. In the wind tunnel test, the vertical and torsional frequencies of flutter test system are 1.82 Hz and 3.87 Hz, respectively. The wind speed ratio between reality and test is 3.66. The damping ratios of flutter test system in vertical and torsional directions are 0.45% and 0.13%, respectively.

2.3. Reliability of test results

In the wind tunnel test, the sectional model for flutter analysis is hanged by eight springs installed at the exterior of the tunnel, and different angles of attack are realized by keeping the direction of inflow unchanged while rotating the sectional model. As the spring system is fixed, the difference between the testing vibration direction and the actual vibration direction becomes apparent gradually with the increase in angle of attack, and cannot be neglected when the angle of attack is large, as shown in Fig. 5.

To analyze the effects of the difference of vibration direction on test

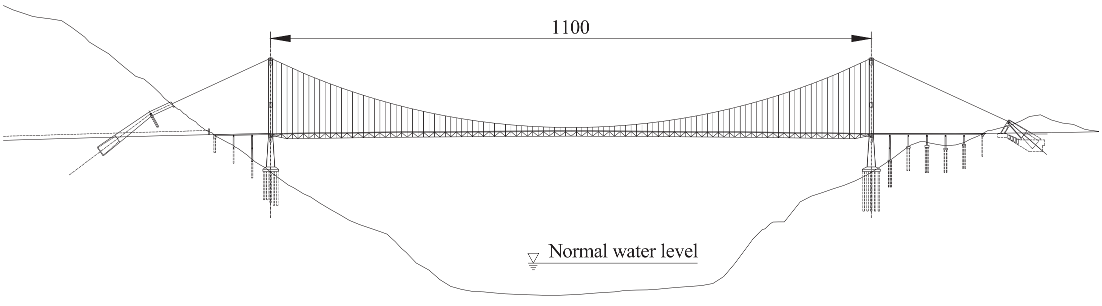

Fig. 1. Elevation of the suspension bridge (unit: m).