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Effects of attachments on aerodynamic characteristics and vortex-induced vibration of twin-box girder

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ABSTRACT

An experimental investigation was carried out on the effects of attachments on the aerodynamic characteristics and vortex-induced vibration (VIV) of a twin-box girder. In the study, the flow pattern, pressure distribution, vortex shedding frequency, and VIV of five models, namely Model A (twin-box girder without attachments), Model B (twin-box girder with handrails and crash barriers), Model C (twin-box girder with handrails, crash barriers, and wind barriers), Model D (twin-box girder with maintenance rails), and Model E (twin-box girder with full ancillaries), are compared with a bare deck in detail. The results demonstrate that, owing to the large leading flow separation induced by the attachments, the flow characteristics and VIVs of the twin-box girder with attachments differ considerably from the bare twin-box girder. Because of the large porous ratio, the handrails and crash barriers exert relatively weak influences on the surface pressure distribution. However, the leading wind barrier and maintenance rail generate large flow separation at the leading edges, resulting in larger pressure fluctuations, a wider wake, and larger scale vortex with lower shedding frequency than that of the bare deck. Furthermore, owing to the large leading flow separation, the vertical VIV induced by the motion-induced vortex in the gap is suppressed. However, a torsional VIV is generated by the large-scale alternately shedding vortex in the wake of the downstream box girder.

1. Introduction

For flow passing over a bluff body, the boundary layer state is a crucial factor in the flow dynamics surrounding the body. Therefore, any disturbance to the boundary layer will have a significant effect on the flow characteristics around the bluff body. For long-span bridges, to maintain driving safety and for daily maintenance, attachments are required on the bridge deck surfaces, such as crash barriers located at both sides of lanes, handrails on the maintenance road, maintenance rails on the lower surface, and wind barriers. Because these attachments are very close to the bridge deck surface, the bridge deck boundary layer is severely disturbed, resulting in significant effects on the aerodynamic characteristics of the bridge deck. The handrails and crash barriers are usually installed at both sides of lanes for driving safety, and owing to their location on the leading edges, the disturbance to aerodynamic characteristics is significant. Bruno and Mancini (2002) numerically investigated the effects of deck equipment (median dividers and edge safety barriers) on the aerodynamic characteristics of a Normandy cable-stayed bridge and the Great Belt suspension bridge. The authors concluded that such equipment increases

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the overall degree of bluffness of the section, resulting in increased drag force and decreased mean lift force. These effects are more prominent in streamlined bridge decks. Xu et al. (2014) found that the drag force of a streamlined closed-box section is influenced mostly by the crash barriers, while the effects on the lift and torsional moment may be negligible for small attack angles. Haque et al. (2016) compared the aerodynamic responses of perforated and solid handrails on the bridge deck by using unsteady RANS simulation with the k-ω-SST turbulence model. The authors found that a perforated handrail produces less aerodynamic responses than a solid one, which can be attributed to the flow moving on the top deck surface and causing the top deck vortex to disappear, resulting in a reduction in the total wake size and thereby improving the aerodynamic behavior. Nagao et al. (1997) studied the effects of a handrail on the leading separating shear flow and vortex-induced vibration (VIV) of a box-girder deck with $B/D = 5.77$ (B is the deck width and D is the deck depth) at a 3 degree attack angle. The authors found that the size and position of the horizontal bar of the handrail had a significant effect on the separated shear flow and torsional VIV, according to the intensity and forms of interaction between the first separated flow from the bridge deck and secondary separated flow from the handrail. Guan et al. (2014) experimentally investigated the VIV response of an inverted trapezoidal box with a cantilever arm beam with and without crash barriers, and the results demonstrate that distinguished vertical VIVs occur for the box girder with crash barriers, while no VIVs are observed for that without crash barriers. The fluctuating pressure distribution indicates that the vortices shed from the downstream section with crash barriers provide a larger contribution to the vertical VIV. Zhu et al. (2015) investigated the optimization of the VIV of a flat steel-box girder at a large attack angle. The results indicate that the railing type can significantly affect the vertical and torsional VIV; however, the crash barriers exert less influence. Furthermore, the maintenance rail on the leeward side is a key factor in the generation of VIV.

In order to mitigate the effects of strong cross-winds on vehicles and ensure driving safety, a wind barrier, which is also referred to as a wind shield or wind screen, is an efficient countermeasure for diminishing the wind loads acting on vehicles (Counihan et al., 1974; Bradley and Mulhearn, 1983; Papesch, 1992; Smith and Barker, 1998; Song et al., 2011; Chu et al., 2013). However, owing to the wind barriers usually having a large scale and being located on the leading edge, the influence on the bridge deck aerodynamic performance is considerable. Avila-Sanchez et al. (2016) studied the flow characteristics around the solid wind barriers installed on a railway bridge by using particle image velocimetry. The flow is separated from the upstream solid wind barrier, leading to the formation of a separation bubble in its wake. Furthermore, the downstream wind barrier on the trailing edge restrains the separation bubble on the bridge deck. As the inflow angle increases, the trapped vortex is shifted upward and eventually merges with the vortex in the bridge wake. Moreover, the shear layer produced by the windward fence leads to an increment in the turbulent kinetic energy. Buljac et al. (2017) studied the effects of roadway wind barriers with 30% porosity on the aerodynamic and aeroelastic characteristics of streamlined, semi-bluff, and bluff bridge decks. The results demonstrate that the drag force coefficient increases significantly as the wind barrier is placed on the bridge deck sections, particularly for the streamlined section with an increment of 185%. In terms of the lift force coefficient, the wind barrier alters the trends with the attack angle and its value. Moreover, the influence of the wind barrier on the pitch moment is exhibited particularly for positive wind incidence angles, and the wind barrier reduces the flutter stability of the studied bridge deck sections, especially for the torsional motion and streamlined section. Yang et al. (2016) experimentally investigated the VIV characteristics and countermeasures for twin-box girders with various slot widths. In the study, six representative slot width ratios, ranging from 0 to 1, as well as four countermeasures, including increasing damping, and instating grid plates and guide vanes, are employed. The results demonstrate that the twin-box girder with a width ratio of 0.6 exhibited the strongest heaving VIV, while VIVs were not observed in the twin-box girder with a width ratio of 0. The VIV countermeasure experiments indicate that increasing the damping ratio can reduce the VIV responses, while instating guide vanes may have an adverse effect, and grid plates can successfully suppress heaving VIV. Furthermore, wind barriers can significantly suppress the vertical VIVs of a twin-box girder, but will increase torsional responses.

The maintenance rails on the lower surface also have a considerable influence on the aerodynamic and aeroelastic characteristics of the bridge deck. Xian et al. (2012) investigated the influence of the maintenance rail location on the VIV of a streamlined single-box girder, and concluded that, as the maintenance rail moves away from the leading windward corner, the VIV amplitude decreases. Li et al. (2011) and Sun et al. (2012) also found that the VIV of the stream-like box girder can effectively be suppressed by optimizing the location of maintenance rails. Li et al. (2015) investigated the VIVs of a stream-like box girder with cantilever wale slabs using maintenance rails, and found that moving the maintenance rails toward the center of the lower surface can effectively decrease the VIV amplitude, while implementing guide vanes on the maintenance rails can further suppress the VIV. Wang et al. (2011) studied the effects of attachments and aerodynamic configuration on the flutter and VIV of a streamlined box girder, and found that attachments and aerodynamic configuration can significantly affect wind-induced vibration. The rail of the inspection car at the corner of the box girder bottom plate can intensify VIV, while the VIV amplitude will decrease as the rail moves further away. In terms of aerodynamic configuration, owing to restraining the formation of the vortex near the tail, the critical flutter wind speed of the bridge will increase remarkably, and the VIV will diminish when the horizontal angle of the inclined web of the streamlined box girder is below 16°.

The main objective of this study is to investigate the effects of attachments (such as handrails, crash barriers, wind barriers, and maintenance rails) on the aerodynamic characteristics and VIV of a twin-box girder, which is extensively used in long-span bridges. The remainder of this paper is organized as follows. In Section 2, stationary and dynamic experiments for twin-box girders are described. In Section 3, the results are discussed, including the flow pattern, pressure distribution, vortex shedding frequency, critical gap ratio, and effects on the twin-box girder VIV. Finally, conclusions are summarized.