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Investigation and control of vortex-induced vibration of twin box girders

Shujin Laima [a], Hui Li [a,*], Wenli Chen [a], Fengchen Li [b]

[a] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[b] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150090, China

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ABSTRACT

Stationary and dynamic wind tunnel tests of twin box girders with a space ratio of $L/D=1.70$ have been performed in this study. The vortex-shedding phenomenon under stationary and dynamic conditions and vortex-induced vibration are observed and analyzed. The results indicate that regular vortex shedding occurs only at the trailing edge of the downstream box girder under stationary conditions. Although the strength of the vortex is very weak under stationary conditions, it gives rise to vortex-induced vibrations with a lock-in range of $0.570 \le U_r \le 0.668$ in dynamic testing. The higher harmonics of wind speed around the body is observed and is attributed to nonlinear effects from aerodynamic forces. To further study the flow characteristics around the twin box girder when undergoing vortex-induced vibration, a hybrid method combining experiments with numerical simulations is employed. The pressure distributions, energy transfer between the flow and motion of the body, and evolution of flow patterns over vortex-induced vibration process are analyzed based on the computational results. The results indicate that with an increase in oscillation amplitude, strong vortices form in the gap between the two box girders. These vortices impinge on the windward wall of the downstream box girder and cause the flow to separate and re-attach periodically around the windward corners of the downstream box girder. Based on the analysis of the vortices in the gap, five control measures are used in the wind tunnel test to suppress the vortex-induced vibration of the twin box girders, and the most effective control scheme is obtained.

1. Introduction

With the increase in bridge spans, bridges become more flexible and have little damping capability. Therefore, dramatic oscillation of the bridges when subjected to wind is more frequently observed. A twin-separated box steel girder configuration, i.e., the bridge deck is composed of two parallel longitudinal girders with an open space between them, may help to improve the aerodynamic stability of a long-span bridge. The two parallel girders are connected by transverse cross-beams. Currently, several super-long span bridges have chosen this section configuration, for example, the Xihoumen suspension bridge (main span: 1650 m, China), the Hong Kong Stonecutters cable-stayed bridge (main span: 1018 m, China) and the Gwangyang suspension bridge (main span: 1545 m, Korea). Although it is proven that twin-separated box girders have higher critical flutter speed than single box girders (Ge and Xiang, 2008), the flow

* Corresponding author.
E-mail address: lihui@hit.edu.cn (H. Li).

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characteristics around the bridge deck become more complicated due to the effects of the gap between the two separated box girders.

It is known that when the vortex-shedding frequency is close to the natural frequency of the body, it can cause vortex-induced resonance. Although vortex-induced vibration (VIV) is a kind of limited amplitude vibration and does not directly cause the collapse of a bridge, it can result in large displacements and discomfort to the drivers. In addition, VIVs commonly occur at low wind speeds, so the occurrence probability of VIV is high, resulting in long-term fatigue damage. At present, the VIV phenomena are observed in real bridges (Frandsen, 2000; Fujino and Yoshitaka, 2002; Larsen et al., 2000). Therefore, investigations on VIV of long-span bridges should be conducted. VIV of circular cylinders has been comprehensively studied. Feng (1968) performed some classical experiments of VIVs of circular cylinders in a wind tunnel. These experiments indicated that two amplitude branches existed with a hysteretic between them, and the jump between two branches is associated with a significant jump of phase angle between pressure at 90° and transverse displacement response. Zdravkovich (1982) showed that oscillation amplitudes are correlated with the timing of vortex shedding using flow visualization. In the lower region of the synchronization range, when the amplitude of oscillation reached a maximum, the vortex was shed on the opposite side. However, in the upper region of synchronization, the timing of the vortex shedding changed suddenly such that the vortex was shed on the same side when the amplitude of oscillation reached a maximum. Williamson and Roshko (1988) indicated that the phase jump in Feng's experiment is attributed to the vortex-shedding mode switch between 2S mode and 2P mode. Brika and Laneville (1993) showed that the jump from the upper branch to the lower one is accompanied by an instantaneous change from 2S mode to 2P mode using flow visualization. Research of VIVs of cylinders is abundant, and comprehensive reviews of this issue have been performed (Bearman, 1984; Gabbai and Benaroya, 2005; Sarpkaya, 2004; Williamson and Govardhan, 2004).

Although the mechanisms of VIVs of circular cylinders are well investigated, there are significant differences in the vortex structures and vortex-induced oscillations between the box girder of a bridge and circular cylinders, which is attributed to different aerodynamic configurations. For the box girder of a bridge, the configuration is more streamlined with a large aspect ratio and wind noses in the windward and leeward regions; therefore, the strength of vortex shedding is much lower than that of a circular cylinder. As many long-span bridges have been constructed, more and more attentions are paid to the VIVs of bridge decks. Diana et al. (2006) investigated the vortex-shedding phenomena of multiple box deck of Messina Strait Bridge and proposed a numerical model to reproduce the vortex shedding forces. Chen et al. (2007) studied the aerodynamic interference between two parallel box-girder bridges. It is concluded that the aerodynamic interference has significant effects on the VIV of two decks. Larsen et al. (2008) investigated the vortex response of a twin box bridge with and without guide vanes. It is observed that the displacement thickness must be at the order of 10% of the guide vane offset in order to allow sufficient flow rate to render the guide vane efficient. They also found that vortices shedding from the upwind box will impinge on the downwind box, resulting in higher fluctuating pressures here than on the upwind box from where the vortices shed. Li and Ge (2008) investigated the effects of size and locations of guide vanes on the response of VIV of a twin-box girder. The results showed that the VIV of a twin-box girder is very sensitively to the size and location of guide vanes. Zhang et al. (2008) studied the VIV of a twin-box girder at low and high Reynolds number. The results indicated that VIV existed in broad range of damping ratio and the amplitude is larger at low Reynolds number. Ge et al. (2011) studied the effects of location of maintenance rail, location of guide vanes, wind barriers, and grid plates installed on the upper and bottom of the gap on VIV of twin-box girders. The results showed that the location of maintenance rail has little influence on the amplitude of VIV. The guide vane installed on the lower surface near the gap, grid plates and wind barriers can effectively suppress the VIV. Although a lot of researches have been conducted, it is still far away to completely understand the mechanism of vortex-induced oscillations of the complex multiple-box girders, in particular the flow characteristics around the multiple-box girders. In addition, the new effective measures to suppress the VIV of the suspension bridge with complex girder shape are also needed to be developed.

The main objective of the study is to investigate the flow characteristics around twin box girders and to gain a deeper understanding of the vortex-induced vibration mechanism of twin box girders. The organization of the paper is as follows: in Section 2, experiments of vortex-induced vibrations of twin box girders are described. The vortex-shedding characteristics of the stationary model, the response to vortex-induced vibrations and vortex-shedding characteristics in lock-in range are discussed. In Section 3, a hybrid method combining experiments with numerical simulations is employed to study the vortex-induced vibration of the twin box girders. The computational mesh and simulation parameters are described, and the validation of the hybrid method is also performed. The pressure distribution, energy transfer and flow pattern evolution throughout the vortex-induced vibration process are discussed. In Section 4, five measures are designed to suppress the vortex-induced vibration of twin box girders, and the reduction of vortex-induced vibration is validated through a wind tunnel test.

2. Experimental investigation of vortex-induced vibrations of twin box girders

2.1. Experiment set-up

The experiments are conducted in a closed circuit wind tunnel, which has a small rectangle test section of 4 m in width, 3 m in height and 25 m in length and a large rectangle test section of 6 m in width, 3.5 m in height and 50 m in length (see Fig. 1). In the small test section, the maximum wind velocity can be 50 m/s, the turbulence intensity of the free stream