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Flutter suppression of a suspension bridge sectional model by the feedback controlled twin-winglet system

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ABSTRACT

Active controlled twin-winglet system is one of the aerodynamic affiliated facilities, which can increase the flutter stability of a suspension bridge. Though much attention has been paid on this method in recent years, most of the studies only focus on theoretical analysis, and few research groups have conduct experiments to validate their control effects. In this paper, we successfully realize the control progress of the twin-winglet system on a bridge sectional model in the wind tunnel, where feedback control tests are carried out to examine a previously proposed theoretical framework. According to the framework, control parameters are determined at the flutter critical wind speed with laminar incoming flow assumption. To check effectiveness and robustness of these theoretical assumptions, we conduct a series of wind tunnel tests under various actual wind speed in both laminar and turbulent inflows. With the efforts above, theoretical basis and application effect of the theoretical framework are verified in a relatively systematical way.

1. Introduction

Driven by the rapid development of economy and technology, bridge construction has entered a new era of crossing wider sea straits and linking islands. As a bridge type, having strongest spanning ability, suspension bridges have been widely constructed to satisfy the need of development. The 1650 m span Xihoumen Bridge in China keeps the span record in the world (Ge and Xiang, 2011) as the longest box-girder bridge, and the Akashi Kaikyo Bridge, with a truss-girder, sets the bridge span record up to 1991m (Makoto, 2004; Miyata, 2013). Since long-span bridges are particularly vulnerable to wind effects owing to their inherently low structural stiffness and damping. Planned super projects, like the Messina Strait Bridge with a central span of 3300 m (Brown, 1996; Matsumoto et al., 2007), require much more attention on the wind-induced response to guarantee the safety of the structure.

Aerodynamic flutter is the most dangerous wind-induced response for long-span suspension bridges. It is manifested as divergent oscillation of the bridge deck. It occurs and leads to the collapse of the whole structure when wind speed exceeds one threshold point, namely the flutter critical speed. The iconic Tacoma Narrows Bridge disaster (Billah and Scanlan, 1991) preluded extensive researches on the suppression of the bridge flutter, and subsequent studies have revealed the essence of the aerodynamic flutter as one type of the dynamic instabilities (Simiu and Scanlan, 1986). Since cross-sea bridges are frequently exposed to strong wind, flutter control has become the key point in their construction. For suspension bridges with a main span of several kilometers, alternative approaches have been studied. As aerodynamic flutter is a dynamic process, most of the flutter control approaches can be classified into three categories, according to their contributions in the kinetic equation. One of the approach is to modify the structural form to adjust stiffness and mass, like introducing auxiliary-cable or eccentric mass distribution. Another effective approach is to install additive energy dissipating equipment to increase the apparent damping, such as using tuned-mass-damper (TMD) or active-mass-damper (AMD). Finally, employing aerodynamic approaches to change the external force is the most common way. For instance, changing the shape of the bridge deck or installing movable aerodynamic facilities (Kwon et al., 2000). Detailed introductions and comments on the recent researches of these three

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categories could be found in the authors' previous articles (Guo, 2013; Li et al., 2015), and only experimental studies relative to the movable aerodynamic facilities are briefly discussed below.

According to the forms of the movable aerodynamic facilities, they can be classified into movable flaps and winglets, which are demonstrated in Fig. 1 respectively. Researchers mainly focus on theoretical analysis on their flutter control capacity, however few research groups have conduct experiments to validate their control effects. As for movable flaps, Kobayashi et al. (1998) and Gouder et al. (2015). realized the control process of the deck-flap system both in theory and wind tunnel tests. The involved aerodynamic model was based on the Theodorsen's circulatory function for thin airfoils (Theodorsen, 1935), which was extended to a modified version of the wing-aileron-tab configuration (Theodorsen and Garrick, 1942). Since it is apparently not appropriate to using Theodorsen's function to estimate the aerodynamic forces of bridge deck, Hansen and Thoft-Christensen, 2001 examined the control effect of the active flaps in a bluff deck-like model with artificially selected feedback gain. In addition, Boberg et al. (2015) examined the aerodynamic parameters with a similar model and verified their effectiveness in a series of phase-shift control processes. Considering the better robustness of passive control, Wilde et al. (1999) and Starossek and Aslan, 2008 combined the flaps with a pendulum and a TMD system, respectively. Comparative cases in their studies highlighted the contribution of the flaps instead of the driving facility. As for movable winglets (Ostenfeld and Larsen, 1992; Ostenfeld, 1996), corresponding wind tunnel tests are even more scarce. Kobayashi and Nagaoka (1992) were the first to realize the active winglets control in wind tunnel tests. In their studies, the twin-winglet system was active controlled according to the motion of the bridge deck. The flutter critical speed was increased by a factor of two. While the control effect was highlighted, it is a pity that the feedback control gain was artificially selected instead of results from control theory analyses. To clarify the control mechanism and interference effects in the deck-winglet system, Guo (2013) conducted a series of preliminary studies with a pair of non-feedback controlled winglets. The results revealed the nature of the deck motion under winglet control as forced vibration, and made it easier to build a theoretical feedback control framework, which was established later by Li et al. (2015).

In summary, previous studies on active flaps (Kobayashi and Nagaoka (1992); Hansen and Thoft-Christensen, 2001; Boberg et al., 2015; Gouder et al., 2015; Bakis et al., 2016) and active twin-winglet systems (Ostenfeld, 1996; Wilde and Fujino, 1998; Nissen et al., 2004; Guo, 2013) have highlighted the advantages of active aerodynamic control, including high flutter control efficiency and potential ability in multi-target control. But experimental studies on these facilities are rare indeed. It is because of the difficulties in introducing mechanical transmission devices and feedback control channel into traditional wind tunnel tests. To obtain an efficient feedback control law, an analytical description of the controlled system should be firstly established. Because the stabilizing mechanism of the twin-winglet system is relatively simpler than flaps, it is a typical study object as a beginning.

For the above reasons, experimental studies of the feedback controlled twin-winglet system are proposed in this paper. Firstly, experimental design of the extended deck sectional model is given (Sec. 2), where the mechanical devices and data communicating channel are emphasized. Then, feedback control parameters are obtained based on a previously proposed theoretical framework (Sec. 3.1). Followed it, the control processes are realized in the wind tunnel with different incoming flow conditions and actual wind speeds. The correctness, effectiveness and robustness of the theoretical framework are verified, by applying different control weights (Sec. 3.2 and Sec. 3.3). Finally, concluding remarks are given in Sec. 4, to give several suggestions to the future researches and applications.

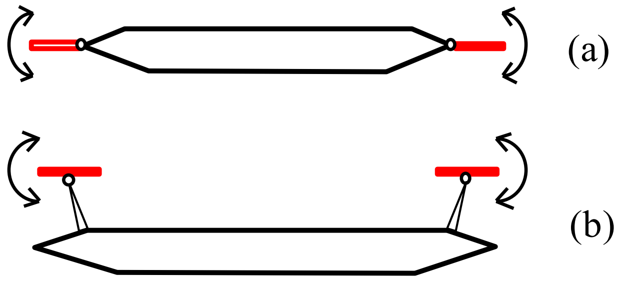

Fig. 1. Flutter suppressing methods with movable aerodynamic facilities (a) flaps (b) winglets.

2. Experimental set-up

As a standard tool to investigate a bridge's aero-elastic flutter stability, an extended sectional model with the twin-winglet system is shown in Fig. 2. A streamlined box girder is designed according to the aerodynamic outline of the Runyang Yangtze River Bridge (1490 m of main span) in China, and a pair of winglets is installed symmetrically above the upper flange of the deck. They can rotate independently along the hinges, and the rotation axis is parallel to the deck axis. A pair of servo motors is installed inside the box girder, manipulating the winglets' rotations by link bars, and thus their influence on the wind field is minimized. As for the dimensions, the experimental model follows a non-interference assumption, which is used in most theoretical models (Wilde and Fujino, 1998; Arco1 and Aparicio, 1999; Nissen et al., 2004; Guo, 2013). The distance between the deck and the winglets is artificially set as three times of the deck height, to treat the total aerodynamic force as a superposition of the independent force acted on the winglet and the deck. With this set-up, we attempt to minimize the influence of the interference, to fully take advantage of the aerodynamic forces on the winglets. The width of the winglets and the distance between them are respectively set to 0.1 and 1.3 times of the deck width. This is because numerical investigations of the control mechanism in the authors' prior papers (Li, 2017) have revealed that the total torque, generated by the anti-phase moving winglets, is the key contribution in the flutter stabilization process. This setting can amplify the stabilizing effect.

The experiments are carried out in the TJ-2 boundary layer wind tunnel in Tongji University. The height, width and length of its test section are 2.5 m, 3 m and 15 m, respectively. The wind speed can be adjusted from 1 m/s to 67 m/s, with an interval of 0.1 m/s. The overall configuration of the test in the wind tunnel is demonstrated in Fig. 3. The deck-winglet system is placed between two parallel walls to ensure the two-dimensional characteristics of the incoming wind flow. The model is anchored to a suspension system, where eight springs are used to simulate the heave and pitch stiffness of the bridge and a pair of drag wires is used to restrict the deck in the horizontal degree of freedom. Meanwhile, four laser sensors are installed on the walls to monitor the deck's heaving and pitching, with a sampling frequency of 200 Hz. The final assembled deck-winglet system in the wind tunnel is demonstrated in Fig. 4.

Active control tests in this paper are realized in a feedback control form, which means dynamic adjustment of the winglets with real-time deck monitoring. To calculate the control parameters, brief

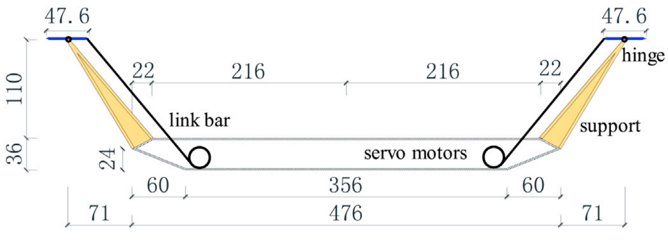

Fig. 2. Configuration of the bridge sectional model with a pair of twin-winglet.