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Numerical simulation of feedback flutter control for a single-box-girder suspension bridge by twin-winglet system

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ABSTRACT

Through numerical simulation investigation, a twin-winglet system is used as an aerodynamic affiliated facility to increase the flutter stability of a box-girder suspension bridge. Its flutter suppression effect can be greatly enhanced when the winglet rotation is feedback-controlled in real-time, depending on the deck motion. Since the control algorithm was previously examined by a self-consistent mathematical model, the control process is realized through computational fluid dynamics simulation in this paper to check the applicability of the device. Moreover, the non-interference assumption used in the control algorithm is analyzed carefully, with several cases of different distance between a deck and winglets. The results verify the effectiveness and robustness of the control algorithm, and also provide a quantitative conclusion about the influence effect, which can be used in the design of a twin-winglet system. In addition, the advantages of this twin-winglet facility are revealed by investigations of the flutter control mechanism.

1. Introduction

As the longest span bridge type, more and more long-span suspension bridges have been constructed to satisfy the need of traffic development. With the ever-growing of span length and structural slenderness of suspension bridges, aerodynamic flutter attracted much attention of bridge engineers after the now iconic Tacoma Narrows bridge disaster (Billah and Scanlan, 1991). It is manifested as divergent oscillation of the bridge deck which occurs and leads to the collapse of the whole structure when wind speed exceeds one certain point, flutter critical speed. Subsequent studies on this phenomenon reveal the essence of aerodynamic flutter as one type of dynamic instability, and successfully avoid the reappearance of such disaster by elaborately selecting structural form and aerodynamic shape of the bridge deck (Simiu and Scanlan, 1986). Up to now, the gradual deepening understanding of flutter helps to refresh the span record of suspension bridges. Akashi Kaikyo Bridge in Japan, having a truss stiffening girder with a central slot and a stabilizer, set the bridge span record up to 1991m (Miyata, 2013; Makoto, 2004), and the 1650 m span Xihoumen Bridge in China keeps the longest span box-girder record in the world (Ge and Xiang, 2011). However, flutter control problem is highlighted again in the construction of longer sea-crossing bridges, like the planned Messina Strait Bridge with a central span of 3300 m (Brown, 1996). The extremely slender structure makes flutter generable at a relatively low wind speed, and thus more effective flutter suppressing methods are required to further improve the aerodynamic stability of suspension bridges (Matsumoto et al., 1995, 2007). In order to find a new solution for this problem, some alternative approaches have been studied and most of them can be classified into three categories: (a) shaping bridge deck; (b) modifying structural form of the bridge; (c) installing mechanical facilities.

As one type of the third category, vibrating aerodynamic facilities (Fig. 1) have been studied in recent years. Passive vibrating flaps (Graham et al., 2011; Phan and Kobayashi, 2011, 2013) and winglets (Wilde et al., 1999; Aparicio and Arco, 1999) are driven by elaborately designed mechanisms and thus to vibrate according to the deck vibration. The most attractive advantage of these vibrating facilities is their independence from external power supply. Unfortunately, it is difficult for such facilities to realize phase difference between the deck vibration and the aerodynamic appendages rotations, which reduce their effectiveness regarding flutter energy consumption in certain circumstances. Analysis

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(a) flaps

(b) winglets

Fig. 1. Suspension bridge decks with rotatable (a) flaps and (b) winglets.

on active vibrating flaps (Kobayashi and Nagaoka, 1992; Hansen and Thoft-Christensen, 2001; Boberg et al., 2015) and active vibrating twin-winglet systems (Wilde and Fujino, 1998; Nissen et al., 2004; Guo, 2013) show advantages in terms of higher flutter control efficiency and their potential ability in multi-target control than passive ones.

To obtain an efficient feedback control law, analytical description of the controlled system should be firstly established. For this reason, the twin-winglet system is a typical study object because of its relatively simple stabilizing mechanism in flutter control. The twin-winglet system is described in Fig. 2. A pair of winglets is installed symmetrically above the upper flange of the deck and can rotate independently along the axes parallel to the deck axis. Supporting bars are set to transmit wind induced forces from the winglets to the deck and also to constrain the winglet motions. With the aerodynamic force produced by the rotatable winglets, the oscillation of the deck can be suppressed and the flutter stability of the bridge can be improved.

In some previous studies (Wilde and Fujino, 1998; Aparicio and Arco, 1999; Guo, 2013; Li et al., 2015), two important assumptions are introduced during the establishment of the analytical description of the twin-winglet system. One is the non-interference assumption and the other is the critical-state assumption. The former indicates that the total force acted on the twin-winglet system can be treated as a superposition of the forces acted on the winglets and the deck, respectively, and the aerodynamic forces on the winglets and the deck in the system are identical to the ones in independent circumstances. The latter assumes that the twin-winglet system is in the critical state of flutter and thus the aerodynamic forces involved obey the flutter derivative description (Scanlan and Tomko, 1971). The control algorithm involved in this paper is also based on these two assumptions and was proposed by the authors based on practical considerations. In our control algorithm, relative winglet rotations are adopted as control target rather than driving forces on them, which makes it possible to be realized and examined in wind tunnel tests and engineering practice. Although the correctness, effectiveness and robustness of the control algorithm were numerically verified in the previous studies (Guo, 2013; Li et al., 2015), some issues still remain to be further considered. Firstly, the disturbance from turbulence components around the deck and the winglets will have an influence on the performance of the control system. Although it was disregarded during the control law derivation because of the difficulties in simulations and its irrelevance to system stability, it should be taken into account in refined analyses. Secondly, the hypothesis of the independence between the forces acting on the deck and the winglets also requires further check even in uniform flow. Previous wind tunnel tests (Wilde et al., 1999) and CFD simulations (Graham et al., 2011) have revealed the fact that the control effect can be influenced by the distance between the winglets and the deck (the “height” in Fig. 2) and so, further research should carefully check the influence degree. Thirdly, final verification of the control algorithm should be accomplished in wind tunnel tests or by Computational Fluid Dynamics (CFD) simulations, instead of a self-consistent mathematical model. Sampling and control should represent the actual situation, and operative limitations should be applied to the winglets based on considerations, e.g. maximum angular acceleration and working angle of the winglets motions. For the above reasons, it is worth studying the control process of the twin-winglet system through CFD simulations and wind tunnel tests. Although wind tunnel test is of great importance in examining the control system, several advantages of CFD simulation make it more appropriate in control mechanism analysis. For example, simultaneously calculating of respective aerodynamic forces on the winglets and the deck, providing abundant flow field information for interference analysis, much more economically than wind tunnel tests, and so on.

The simulation of the control process through CFD tools is one kind of Fluid-Structure Interaction (FSI) problems, in which coupling effect between the structure and the flow around it must be considered: movements of the structure will influence the flow type while the surrounding flow will in turn act on the structure and determine its movements. Although computer technology has developed a lot in the past several decades, computational cost remains a significant barrier to wider adoptions of computational FSI simulation in bridge engineering, mainly because flows around a bridge deck are highly turbulent, unsteady and three dimensional. Therefore, turbulence treatment in the FSI analysis is critical in the coordination between computational cost and accuracy of the solution.

The simplest but the most precise treatment is Direct Numerical Simulation (DNS), which do not introduce any empirical elements in the flow calculation, and thus all scales of turbulence must be resolved using refined meshes and small-time steps (Nomura, 1993; Frandsen, 2004). However, since bridge flutter only occurs at high wind speed, the corresponding Reynolds number ($Re = UB/\nu$, U wind speed, B deck width and ν kinematic viscosity of air) is extremely high. From the author's

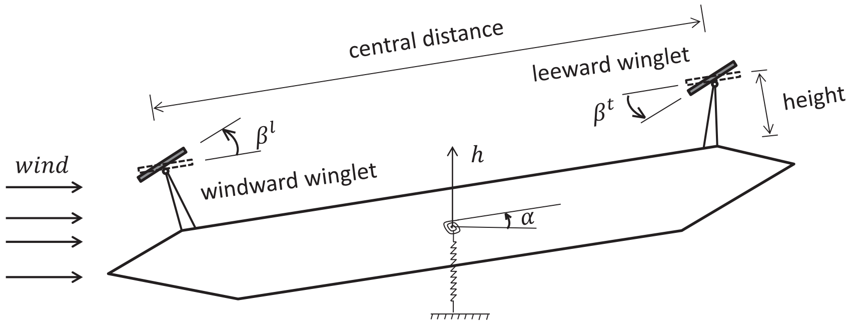

Fig. 2. Cross section of a deck with rotatable winglets.

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