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Flutter characteristics of twin-box girder bridges with vertical central stabilizers

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ABSTRACT

It has been well known that Vertical Central Stabilizers (VCS) have the potential of improving flutter performance of long-span bridges. However, the fundamental flutter mechanisms of VCS are still not fully understood so far. In this study, a series of wind-tunnel tests involving the combination of six representative heights and four types of VCS were conducted to fundamentally investigate the influence of VCS on flutter performance of twin-box girders with various Slot Width Ratios (SWRs). Experimental results show that the flutter instability of 20% SWR is significantly sensitive to the height change of VCS, whereas the VCS have little effect on the flutter performance for 80% and 100% SWR. In addition, the results from Two-Dimensional Three Degree of freedom (2D-3DOF) flutter analysis demonstrates that aerodynamic damping Part A with reference of flutter derivative A_2^* makes the greatest contribution to the flutter instability for a 0.8 h/H VCS, while the role of Part D with reference of $A_1^*H_3^*$ becomes critical for a short VCS (i.e. the ratio of h/H is less than 0.2). Besides, the results of Computational Fluid Dynamics simulation indicate that the geometry of VCS could potentially influence the transforming vortices' structures and pressure distribution under the central slotting. Finally, the modified Selberg formula presented in this study has the capability of predicting the critical flutter speeds of twin-box girders with various SWRs and VCS.

1. Introduction

Twin-box girders with a center gap between two girders has been proven to be one of the effective aerodynamic countermeasures for improving the aerodynamic performance of long-span cable-supported bridges, and so its implementation becomes increasingly popular for long-span, or even super long-span bridges [1–3], e.g., Xihoumen Bridge with the main span of 1650 m (China) and Gwangyang Bridge with the main span of 1545 m (Korea). Nevertheless, twin-box girders with various Slot Width Ratios (SWRs, for example, the 20% SWR refers to $D/Bs = 0.2$, where D is slot width and Bs is the width of two decks) may exhibit different flutter performance [4,5]. Although the maximum growth rate of Critical Flutter Wind Speed (U_{cr}) could reach more than 20% after slotting for twin-box girders, the aerodynamic stability of the bridges becomes uncertain when the length of the growing span of the bridge is over certain limit [4,6]. Therefore, the implementation of practicable aerodynamic countermeasures (e.g. Vertical Central Stabilizers (VCS)) becomes necessary for further enhancing the flutter performance of super long-span bridges.

VCS could play an important role in the airflow separation and have been applied in many long-span bridges with different geometrical shapes to improve flutter performance. For example, the Akashi Kaikyo Bridge (the length of the longest span is 1991 m) with a 2.15 m height VCS installed in the centerline of the truss-type stiffening girder [7] and the Runyang Yangtze River Bridge (the length of the longest span is 1490 m, China) with a 0.65 m height VCS on the top of the closed box girder [8]. Based on the numerical simulation, VCS have been verified to be an effective aerodynamic measure to improve the flutter performance of long-span bridges either with an open cross section or with a streamlined box cross section [9]. The results from wind tunnel tests also confirm that both the VCS on the top of two-isolated-girder section and box girders with cantilevered slabs could increase the U_{cr} by approximately 11% [10]. Moreover, the flutter performance of twin-box girders could be significantly improved when installing a reasonable scheme of VCS [11–13].

Over the last decades, a lot of research work has been carried out to investigate the control effectiveness of VCS on the flutter performance of long-span bridges with box girders. It has been

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found that the flutter control effect of VCS is closely related to the height and location of VCS. The flutter performance of box girders will decrease if the height of VCS exceeds a critical limit [10]. The installation of central stabilizer on the top of a box girder (Type A) appears to be one of the best ways of stabilizing box girders aerodynamically, while the optimal height of VCS depends on the types of VCS (three types of stabilizers were studied in present study: Type A-only one VCS installed on the top of deck; Type B - only one VCS installed on the bottom of deck; Type AB – one VCS installed on the top of deck, while another one installed below the bottom of deck) [8]. Flutter performance of a multi-box girder section gradually improves with the increase of the height of VCS on the top of girder section, whereas the U_{cr} decreases when the height of VCS is greater than 0.5 h/H [14]. As for the twin-box girders, Type C has the best flutter-controlling effect for a twin-box girder among three basic types of Type A, B and C (i.e. Type C – installing VCS under the central slotting), and the combination schemes of VCS (Type A + B and Type C + B) are more effective with the about 15% growth rate of U_{cr} [10]. However, the control effect of VCS with various positions and configurations flutter performance for twin-box girder bridges with various SWR is still not well understood. Therefore, further research work on identifying the optimal height and location of VCS for twin-box girder bridges with various SWR is required.

To further understand the role of VCS in the improvement of flutter performance, the present study mainly focuses on the flutter instability taking into consideration flutter derivatives and the coupling effects of heaving and torsional degree, as well as the effect of flow structures around girders. Matsumoto et al. [15] proposed a new approach in studying the flutter instability of flutter branches. Their results suggested that the controlling flutter derivatives is a way of controlling the flutter mechanism. Chen et al. [16] found that the aerodynamic damping with the reference of flutter derivative A_2^* is the most important stabilizing term among five flutter derivatives, and the use of VCS could produce a higher level of heaving degree participation and greater critical wind speed for a truss-girder section. In addition, many studies have successfully employed the Computational Fluid Dynamics (CFD) technique for simulating the flow structures around oscillating bridge sections with the aim of exploring the flutter mechanism and predicting the critical flutter wind speed [17–23]. CFD simulation results based on Random Vortex Method also showed that the U_{cr} could be increased by using VCS since the strength of the large vortices' structure become weakened and its rhythmic motion is destroyed [9]. CFD simulation results showed that the VCS control the stream around the girder as well as the vortex generation [16]. However, the relevant studies on the flutter mechanism of twin-box girders with VCS are limited and need to be further investigated. In the present study, we aim to investigate the flutter characteristics of twin-box girders with various schemes of SWRs and VCS. Firstly, wind tunnel tests were firstly conducted to demonstrate the influence of bridge geometry in the flutter performance of twin-box girders with six representative height and four types of VCS. The measured U_{cr} corresponding to these schemes of aerodynamic countermeasures, such as different combination of five SWRs and VCS, were analyzed and compared, respectively. Secondly, a Two-Dimensional Three Degree of Freedom (2D-3DOF) flutter analysis method has been adopted to quantify the flutter mechanism with regard to aerodynamic damping and DOF participation level of three types of VCS. Accordingly, the velocity filed and pressure distributions from CFD simulations were used to further understand the aerodynamic behavior of twin-box girder bridges with various VCS. In addition, both the Lorentz function and Sine function were employed to estimate the correction coefficient of the modified Selberg formula, which is of importance for estimating the U_{cr} of twin-box girders with various SWRs and VCS.

2. Flutter performance of twin-box girders with VCS

2.1. Experimental set-up

The measurement of the U_{cr} of twin-box girders with different combination schemes of SWR and VCS is the purpose of this experimental investigation. As shown in Fig. 1(a) and (b), a series of 1:80 simplified section models of twin-box girders without consideration of the deck secondary structures were performed in the TJ-1 Wind Tunnel of Tongji University to accommodate the size of sectional models and testing section. Since the SWR plays an important role in the aerodynamic performance of twin-box girder bridges [4,5], spring-supported rigid sectional models with five representative cases of SWR (i.e. D/B_s = 0.2, 0.4, 0.6, 0.8, and 1.0) were used in the testing to assess the control effectiveness of VCS on the flutter instability in twin-box girders bridges. In addition, to systematically investigate the influence of different heights of VCS on the flutter instability of the bridges, six representative relative height (h/H) of VCS (i.e. h/H = 0, 0.2, 0.4, 0.6, 0.8 and 1.0) were selected for Types A, B, AC and BC (Fig. 1(c) and Table 2). The values of structural parameters used in the testing, such as geometric dimensions, mass characteristics, fundamental frequencies and structural damping, are given in Table 1. It should be mentioned that, the adjustable additional mass on the section models were adopted to make the equivalent mass characteristics consistent in all testing cases.

Table 2 shows a total of 240 test cases under three wind attack angles (i.e. +3°, 0° and −3°), in which Type A and Type B are two basic types which are the first focus of this study. The smaller SWR (i.e. 20% and 40%) are common ratios in the existing twin-box girders bridges and their flutter performance are better than those with larger SWR (i.e. 80% and 100%) [4]. Therefore, two combination types of Type AC (both on the top and under the central slotting) and Type BC (both below the bottom and under the central slotting) are mainly focus on two small SWR (i.e. 20% and 40%). In this study, a naming convention was adopted for all testing cases, for example S02_A02 denotes case Type A with 20% SRW and 0.2 h/H of VCS.

2.2. Effects of VCS on critical flutter speed

The objective of this testing phase was to study the influence of different schemes of VCS on the minimum U_{cr} of twin-box girders with various SWR, since the dominant factor of flutter instability is the minimum value of three U_{cr} corresponding to the attack angles of +3°, 0° and −3°, respectively. The lowest U_{cr} under three wind attack angles and their corresponding growth rates (β) for twin-box girders with six SWR (including the 0% slot ratio) and six h/H of VCS are illustrated in Fig. 2. It is noted that the growth rates β of U_{cr} are calculated by using the equation: $\beta = (U_{cr} - U_{cr0})/U_{cr0} \times 100\%$, where U_{cr0} is the value of U_{cr} without consideration of VCS. It should be noted that the wind attack angle of +3° results in the lowest U_{cr}, and thus represents the most unfavorable condition under wind loading.

2.2.1. Height of central stabilizers

For Type A and Type B, U_{cr} and their β of twin-box girders with 0% SWR were obtained from the study of Ge et al. 2009, which are defined as two cases (i.e. s00_A and s00_B in Fig. 2), respectively. It is interesting that the 0% SWR of Type B has a rapidly decline along with the increase of the h/H of VCS, and thus the Type B has disad-