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Experimental study on aerodynamic derivatives of a bridge cross-section under different traffic flows

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ABSTRACT

The presence of traffic on a bridge deck has an important primary impact on the bridge cross-section's aerodynamic configuration, which may affect the static force coefficients and the aerodynamic derivatives that will in turn influence the self-excited forces acting on the bridge. Compared to the investigations of the traffic effect on the static force coefficients, its effect on the aerodynamic derivatives is rather rarely studied. In the present study, the forced vibration device is adopted in the wind tunnel to test a scaled bridge section model with vehicle models distributed on the bridge deck considering three simulated traffic flows. The influence of vehicles of different traffic flows under different wind attack angles on the aerodynamic derivatives of the bridge with the reduced wind velocity are investigated based on the experimental results. The measured results show that the influence of vehicles on the aerodynamic derivatives of the bridge cannot be ignored. The impacts of vehicles under different traffic flows on the aerodynamic derivatives are different for different aerodynamic derivatives. The effect of vehicles on the aerodynamic is different for different wind attack angles and different for different traffic flow conditions at a certain attack angle.

1. Introduction

With the economic development and traffic volume growth, more long-span bridges in the coastal and canyon areas are subjected to high winds and stochastic traffic flows, resulting in a high risk of fatigue failure of bridges. Thus, it is important to investigate the dynamic responses of long-span bridges under loads of vehicles and wind. However, the impacts of vehicles were ignored in most existent research on the aerodynamic responses, such as buffeting responses of bridges (Davenport, 1962; Holmes, 1975; Scanlan, 1978; Xiang et al., 1995; Jain et al., 1996; Xu et al., 1998; Ding and Lee, 2000; Chen et al., 2000, 2009; Ding et al., 2002). For example, the models of vehicles in the computational model and the interference of vehicles in the testing of aerodynamic parameters of bridges were not considered because it was believed that the traffic would be closed under strong wind or the effect of vehicles was small and could be ignored. The traffic will not be closed under some strong wind even it is over the limit speed actually, considering the economy consequence and impact of the closed bridge on the transportation. Therefore, traffic vehicles and strong wind effects may appear in long-span bridges at the same time. In addition, the interactions between vehicles and bridges can affect the dynamic responses of bridges considerably and cannot be ignored, which was indicated in many previous studies (Xu and Guo, 2003; Cai and Chen, 2004; Li et al., 2005).

Compared to the investigations on the coupled dynamic analysis of road vehicles and long-span bridge systems, studies on the impacts of vehicles on the aerodynamic parameters of bridges are rare. Li et al. (2004, 2013) developed a special device, called the Cross Slot System, to measure the aerodynamic characteristics of the rail vehicle-bridge system, taking the aerodynamic interaction between the rail vehicle and the bridge into account. Han et al. (2011, 2013) investigated the static force coefficients of the bridge with one vehicle or three vehicles by using CFD method and by carrying out a series of wind tunnel tests. However, the corresponding data for the aerodynamic derivatives, especially for under different traffic flows where many vehicles are arranged in different ways, is sparse.

The aerodynamic derivatives were proposed by Scanlan and Tomko (1971) to characterize the self-excited forces acting on a bridge depending on the configuration of the bridge cross section, which were usually identified from wind tunnel experiments (Sarkar et al. 1994; Iwamoto and Fujino, 1995; Diana et al., 2004; Chen et al., 2005; Niu et al., 2007). The aerodynamic derivatives were not only adopted to the analysis of flutter stability but also to

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the buffeting analysis of long-span bridges considering the effect of the aerodynamic stiffness and aerodynamic damping. In traditional buffeting analysis, traffic was typically ignored in wind tunnel tests to identify the aerodynamic derivatives. However, if the traffic is realistically considered, the aerodynamic configuration of the bridge cross section will be modified constantly due to the moving traffic flow. Therefore, it becomes crucial to investigate the effect of traffic on the aerodynamic derivatives in predicting the response of long-span bridges induced by wind turbulence and traffic.

In general, there are two methods to investigate the aerodynamic derivatives of bridges, the free vibration method (Sarkar et al., 1994; Iwamoto and Fujino, 1995) and the forced vibration method (Diana et al., 2004; Chen et al., 2005). (Chen et al., 2005; Niu et al., 2007, 2011) developed a forced vibration system to obtain the flutter derivatives of bridge decks, and identified the flutter derivatives in both the frequency and time domains. This paper adopts the forced vibration device to carry out a series of wind tunnel tests to examine the aerodynamic derivatives of a bridge in the wind tunnel and investigates the impact of vehicles under different traffic flows on the aerodynamic derivatives.

The wind tunnel experiments are outlined in Section 2, which illustrates the bridge deck and vehicle geometries, the forced vibration device, the instrumentations, simulations of different traffic flows, test conditions, and testing procedure. Section 3 describes the identification procedure of the eight aerodynamic derivatives using the forced vibration method. For verifying the validity of the identification method and the reliability of the program, a numerical simulation is carried out in Section 4. Section 5 reports and examines the aerodynamic derivatives of the bridge corresponding to a variety of test configurations. Moreover, the values, percentage of the variation and the variations of the aerodynamic derivatives under different traffic flows were compared and investigated. Finally, some conclusions are drawn in Section 6. It is found that the effects of vehicles on some aerodynamic derivatives are significant and cannot be ignored.

2. Wind tunnel experiments

2.1. Bridge deck and vehicle geometries

The bridge section model scaled from a real bridge is made with wood, in which the aluminum strips are used to increase the stiffness of the model. The pedestrian guard rails and collision walls are made with plastic sheets. The scale is 1:60 and the length of the model is 1.50 m. Two vehicle types, a sedan and a small bus, are considered and made with cystosepiments to reduce the weight. The widths of the sedan and the small bus are 2.88 cm and 3.67 cm, respectively. The details and dimensions of the bridge deck section and the vehicles are given in Fig. 1(a)–(c).

2.2. Experimental set-up and instrumentations

A forced vibration device, as illustrated in Fig. 2, is adopted to investigate the aeroelastic force acting on the bridge cross-section in the HD-2 wind tunnel at Hunan University, China, which is a low-speed, one-circuit medium-sized boundary layer wind tunnel with two parallel test sections. The device includes two parts, one is located in the wind tunnel and the other one is outside it. The fairing was used to mantle the one in the wind tunnel to minimize its disturbance to the flow field of the wind tunnel. Each part includes a mechanical driving system, as shown in Fig. 3. Three servo motors and numerical servo drivers are adopted to control the section model to make a pure harmonic motion at each degree-of-freedom (DOF) in the vertical, lateral and torsional directions, respectively. Photoelectrical encoders and the inductance near-switches are used to control the motion accurately. 1-DOF, coupled 2-DOF and 3-DOF harmonic oscillations of the tested model can be realized in the wind tunnel. Furthermore, the frequency, amplitude of each DOF, and the phase shift among the three DOFs are adjustable according to the test target. To reduce the vibration interference between different DOFs, 1-DOF harmonic oscillation of the tested model is simulated in this paper. Table 1 gives the vibration parameters of the tested model and sampling parameters.

Two five-component force balances are used at the two ends of the section model to measure the total aerodynamic force acting on the model, as shown in Fig. 4. To reduce the mechanical interference, the balances are fixed on the model so that the forced vibration device drives the balances to move together with the model, as shown in Fig. 5. The vibration displacements of the model are measured using two laser displacement meters that are arranged under the model symmetrically along the bridge axis. The distance between them is 278 mm, as shown in Fig. 6. The vertical and torsional displacements can be calculated from the displacements measured by the laser displacement meter as follows:

$$h = -\frac{h_1 + h_2}{2 \times 1000}\,(m) \tag{1}$$

$$\alpha = \frac{h_1 - h_2}{278}\,(rad) \tag{2}$$

2.3. Simulated traffic flow and testing cases

The transportation research board in the United State classifies the level of service (LOS) from A to F (A—free flow; B—reasonable free flow; C—stable flow; D—approaching unstable flow; E—unstable flow; F—forced or breakdown flow) based on the range of traffic occupancy in the highway capacity manual (AASHTO, 2007; Chen and Wu, 2011). Three occupancies (q) are considered in the present study: (1) “free flow”, $q=0.07$ corresponding to level B (9 vehicles/km/lane), (2) “moderate flow”, $q=0.15$ corresponding to level D (20 vehicles/km/lane) and (3) “busy flow”, $q=0.24$ corresponding to level F (32 vehicles/km/lane). The proportions of the vehicles in category 1 (sedan) and 2 (small bus) among all vehicles are assumed to be 0.7 and 0.3, respectively. There are totally 8 lanes in the two traffic directions and the simulated traffic flows are shown in Fig. 7.

Four testing cases are studied to investigate the impacts of vehicles under different traffic flow conditions on the aerodynamic derivatives. For each testing case, three wind attack angles of -3°, 0°, and $+3^\circ$ are investigated and the experimental configurations examined in the current work are outlined in Table 2.

3. Identifications of aerodynamic derivatives using forced vibration method in time domain

Self-excited lift force L and pitching moment M per unit length are defined as (Scanlan and Tomko, 1971)

$$L = \rho U^2 B[K_h H_1^*(\dot{h}/U) + K_\alpha H_2^*(B\dot{\alpha}/U) + K_\alpha^2 H_3^* \alpha + K_h^2 H_4^*(h/B)] \tag{3a}$$

$$M = \rho U^2 B^2[K_h A_1^*(\dot{h}/U) + K_\alpha A_2^*(B\dot{\alpha}/U) + K_\alpha^2 A_3^* \alpha + K_h^2 A_4^*(h/B)] \tag{3b}$$

in which h is the vertical or heaving displacement; α is the torsional or pitching displacement; $\dot{h}$ is the vertical or heaving velocity; $\dot{\alpha}$ is the torsional or pitching velocity; ρ is the air density; U is the mean wind velocity; B is the bridge deck width; $K_i = \omega_i B/U$ ($i = h,\ \alpha$) is the reduced circular frequency; ω_h and ω_α are the circular frequencies of the heaving and pitching motions,