INFLUENCE OF VEHICLES ON BRIDGE FLUTTER AND GALLOPING

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ABSTRACT

The paper describes the modifications of bridge aeroelastic behaviour due to stationary vehicles on the deck. Aerodynamic force coefficients, as well as aeroelastic flutter derivatives, obtained by the free-vibration technique, are analyzed for the Kao-Pin Hsi Bridge in Taiwan. When considering static response, vehicles are observed to change aerodynamic coefficients of the bridge, especially in case of torsional coefficient. When considering one degree of freedom motion of the bridge-deck section, empty bridge without the vehicles proved to be more prone to torsional flutter than bridge with various arrangements of the vehicles. For two degrees of freedom system, non-moving vehicles are observed to have an adverse effect on the bridge stability. This is particularly exhibited in the experiment with the vehicles placed in the leeward traffic lanes of the bridge. At last, galloping sensitivity is not much influenced by the presence of vehicles.

KEYWORDS: VEHICLE-WIND BRIDGE SYSTEM, AEROELASTIC DERIVATIVES

Introduction

Flutter is a type of dynamic instability, which may cause the bridges to collapse. The bridge sensitivity to flutter is commonly analyzed using flutter derivatives (FDs), the frequency dependent coefficients of self-excited forces, which are considered to be the indicators of aeroelastic stability of bridges, see Scanlan and Tomko (1971). Aerodynamic and aeroelastic behavior of empty cable-supported bridges is expected to alter in case some additional structures, like roadway barriers, designed to protect vehicles from cross-wind effects, are placed on the bridge deck, e.g., Kozmar *et al.* (2012a) and Kozmar *et al.* (2014), as vehicles proved to be particularly vulnerable on viaducts and bridges, see, e.g., Kozmar *et al.* (2012b), The work by Xu *et al.* (2014) reported that crash barriers, vehicles, and central slotting increased the drag force, while the effects on the lift force and pitch moment were relatively minor. The importance of simultaneous wind-traffic modeling is emphasized by Li *et al.* (2015), where an analytical model for dynamics of wind-vehicle-bridge systems was presented in the time domain. Wu *et al.* (2014) indicated that modified bridge cross-section due to presence of vehicles can considerably affect aeroelastic properties of slender long-span bridges. Han *et al.* (2014) used the forced-vibration method, while their results indicated an influence of spacing density of vehicles on FDs of the bridge.

The present work deals with an influence of stationary vehicles on bridge aerodynamics and aeroelasticity. This situation can represent a traffic jam in metropolitan areas, when a bridge is full of densely spaced non-moving vehicles and simultaneously exposed to the strong wind. The wind-tunnel experiments are carried out on the bridge-section model of the cable-supported Kao-Pin Hsi Bridge in Taipei, Taiwan. The bridge is asymmetric with one pylon shaped as an inverted-Y with the height of 183.5 m. The deck of the main span is made of steel and the deck of the side spans uses prestressed concrete. The back span is 180 m long and the main span is 330 m long, see Wang (2009) for construction details. Aerodynamic force and moment coefficients are determined for various wind incidence angles and various configurations of non-moving vehicles on the bridge, while FDs are determined to evaluate bridge susceptibility to wind-induced vibrations. The obtained data is compared with results for the streamlined flat plate, which is supposed to be insensitive to the flutter.

Experiments

The bridge-deck is a 1:100 scaled-down section model with the length L=560 mm and auxiliary details like pedestrian rails and collision walls. The details and dimensions (in millimeters) of the bridge deck section and the vehicles are shown in Fig. 1.

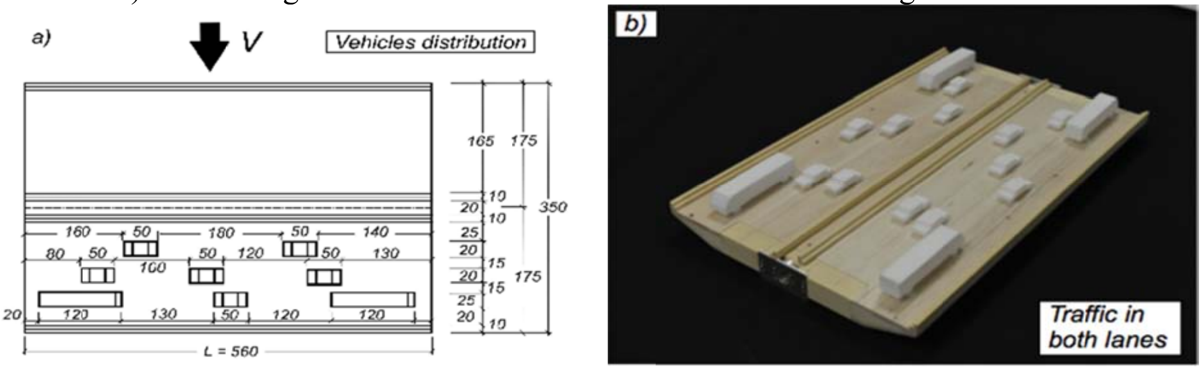

Figure 1: Bridge-section model dimensions and arrangement of vehicles on the bridge-section model.

Two types of vehicles are considered; smaller one representing passenger cars with the average height of 1.5 m and a larger one representing trucks with the height of 2.8 m. Vehicle models are manufactured in the identical (1:100) geometrical scale as the bridge-deck section model. They were made from polystyrene to reduce their weight and consequently their influence on the system mass and mass moment of inertia is negligible. Hence, vehicles are placed on the bridge-deck section in different configurations (C) respectively; C1-model without vehicles, C2-vehicles placed in the leeward traffic lanes only, C3-vehicles placed in the windward traffic lanes only, and C4-vehicles placed in both traffic lanes. An empty bridge-section model is also tested as a reference case. Wind-tunnel experiments were carried out in the closed-circuit climatic boundary layer wind tunnel of the Centre of Excellence Telč, Czech Republic.

Results

The FDs for single-degree-of-freedom (SDOF) are shown at Fig. 2. The A_2^* derivative is particularly important in analysis of the torsional SDOF flutter. Positive values of this derivative indicate a loss of the bridge-deck stability in torsional motion. The results reported in Fig. 2 show that the bridge-deck section without vehicles is the most susceptible to torsional flutter, as the A_2^* becomes positive at the lowest reduced wind velocity in comparison with other configurations. Moreover, the configuration with the vehicles placed in the leeward traffic lanes has similar trend for A_2^*. It can be observed from the positive sign of A_2^* values that all studied configurations exhibit negative aerodynamic damping at certain reduced wind velocity, which is not favorable to overall bridge-deck oscillations. Similar results among all studied configurations for A_3^* derivative (not shown here) indicate also that vehicles do not significantly alter generalized oscillation frequency of the wind-vehicle-bridge system. Derivative H_1^* describes aerodynamic heave damping. The negative values of it suggest that the investigated bridge-deck section is not prone to the heave instability, since the aerodynamic damping increases with increasing wind speed. This trend in the H_1^* is observed for all studied configurations. Similar results are obtained for example by Brownjohn *et al.* (2001). The difference in H_1^* among the tested configurations is small and all studied configurations can be considered as stable with respect to the SDOF heave motion.

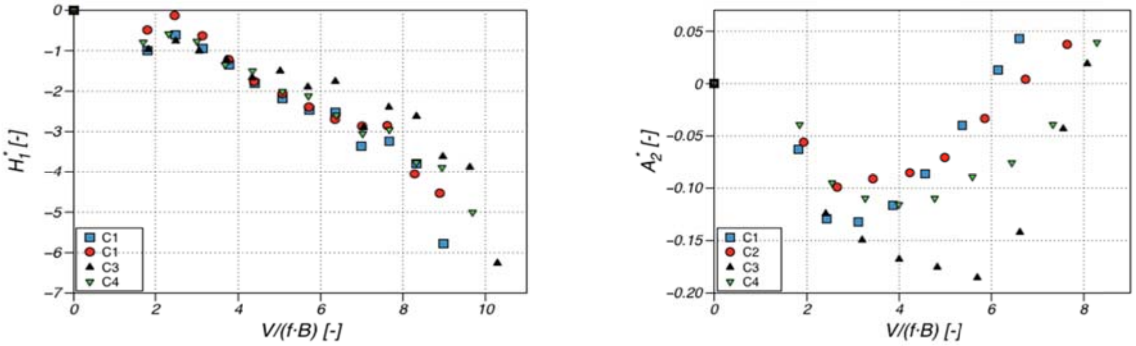

Figure 2: Flutter SDOF derivatives H*1 and A*2

The results for coupled motion are shown in Fig 3 in terms of double-degree-of-freedom (DDOF) FDs. Because the instability onset depends on the heave-to-pitch frequency ratio, see Král *et al.* (2014), two sets of the results were experimented, i.e., a) heave-to-pitch frequency ratio r=2.9/3.7; b) heave-to-pitch frequency ratio r=2.9/2.9. We compared the FDs with the theoretical results on the flat plate by Theodorsen (1935). It can be observed from trends in the H_1^* derivative that vehicles on the bridge influence the bridge stability. For the frequency ratio r=2.9/3.7 and configuration with the vehicles placed in the leeward traffic lanes, the H_1^* values become positive at the reduced velocity V/(fB)≈5, thus the bridge-deck becomes unstable, while for other configurations it remains negative throughout the entire range of investigated reduced wind velocities. At V/(fB)≈6, the configuration with vehicles in the windward traffic lanes exhibits a shift in the trend of the H_1^* derivative that is to be further analyzed in more detail in the future.

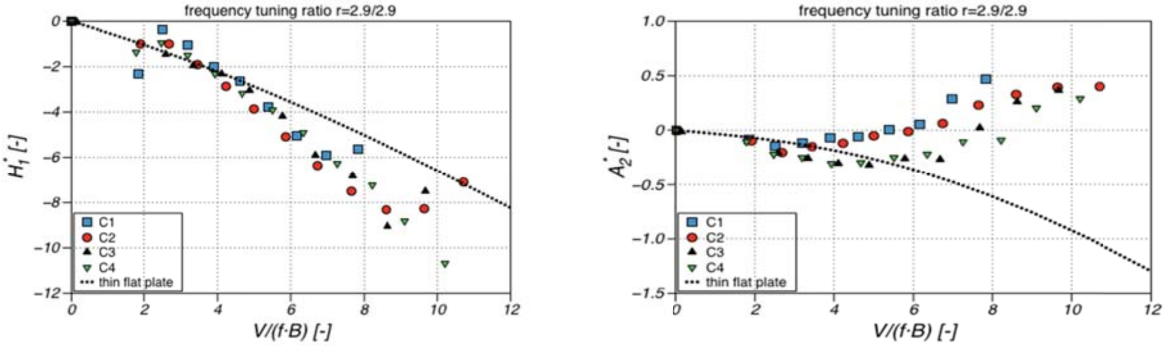

Figure 3: Flutter DDOF derivatives H*1 and A*2

Generally, the presence of the stationary (non-moving) vehicles can have a destabilizing effect on the bridge with respect to motion-induced vibration, which can be observed mainly from the trends in the H_1^*, derivative. Bridge-deck configuration without the vehicles yields similar trend like the theoretical value calculated according to the thin plate theory, see Caracoglia and Jones (2013). The A_2^* derivative becomes positive at lowest reduced wind velocity around 5 in the configuration without vehicles and with vehicles in the leeward traffic lanes. Hence, this configuration proves to be the most susceptible to torsional instability. This is also the case for torsional SDOF system.

Results

Dimensionless aerodynamic (not presented in this abstract) and aeroelastic coefficients were analyzed for the Kao-Pin-Hsi Bridge in Taiwan. For negative wind incidence angles, the absolute values of lift force coefficient were smaller in configuration with vehicles in all traffic lanes in comparison with an empty bridge. The same was also observed for the configurations with vehicles on one bridge side (windward or leeward) only. All studied configurations satisfy the Glauert-den Hartog criterion throughout the whole interval of studied wind incidence angles indicating that vehicles on the bridge do not considerably influence galloping sensitivity of the bridge. The flutter derivatives were determined by employing the free-vibration technique for the single and double degree-of-freedom system. This procedure includes initial disturbance of the bridge-deck section and the measurements of the free-decay oscillations. Heave and pitch motions were analyzed both separately as a one degree of freedom system and simultaneously, as a two degrees of freedom system. The results related to the pitch one degree-of-freedom motion indicate that this bridge deck was the most sensitive to torsional flutter in configurations without vehicles. When the heave motion and one degree-of-freedom was considered, all studied configurations proved to be dynamically stable. Aerodynamic damping increased with increasing wind velocity, while no turning (positive to negative) point was observed. For a two degree-of-freedom system, stationary (non-moving) vehicles are observed to have an adverse effect on bridge-deck dynamic stability. This is particularly exhibited in the experiment with the vehicles placed in the leeward traffic lanes of the bridge.

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