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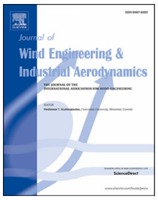

Flutter and galloping of cable-supported bridges with porous wind barriers

Andrija Buljac[a,*], Hrvoje Kozmar[a], Stanislav Pospíšil[b,c], Michael Macháček[b]

[a] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb, Croatia
[b] Institute of Theoretical and Applied Mechanics, Prosecká 76, 19000 Prague, Czech Republic
[c] Faculty of Civil Engineering, VŠB-Technical University of Ostrava, 17. listopadu 15/2172, 70833, Ostrava, Poruba, Czech Republic

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ABSTRACT

Wind-tunnel experiments are carried out to analyze the influence of wind-barrier porosity and height on aerodynamic and aeroelastic characteristics of wide long-span cable-supported bridges. The experiments are carried out on sectional models of the Golden Gate Bridge (USA), Kao-Pin Hsi Bridge (Taiwan), and Great Belt Bridge (Denmark). The bridge-deck section models are equipped with the wind-barrier models at the windward (leading) edge of the studied sections. The experimental results indicate that the effects of wind barriers on galloping sensitivity of studied bridge decks are rather negligible, while bridge decks become quite prone to flutter for wind barriers placed at their windward edge. These trends are more exhibited for more-solid wind barriers. The effects of increasing wind-barrier height are not unambiguous, as they are simultaneously influenced by the aerodynamic shape of bridge decks as well.

1. Introduction

Strong cross-winds on bridges and viaducts cause dynamic instabilities of vehicles and trains. Due to these adverse wind effects, vehicles may overturn, collide with each other or with structural elements. Hence, during extreme wind events, viaducts and bridges are often closed to traffic.

To protect vehicles from cross winds, roadway wind barriers are commonly designed, e.g. Kozmar et al. (2009, 2012a), Chu et al. (2013), Chen et al. (2015), as vehicles are particularly vulnerable to cross-wind effects on viaducts and bridges, e.g. Argentini et al. (2011), Dorigatti et al. (2012), Kozmar et al. (2012b, 2015), Zhou and Chen (2015).

The major properties of wind barriers that determine their sheltering efficiency for vehicles are porosity and height. Flow characteristics on bridges equipped with wind barriers are predominantly influenced by the bleed flow through the wind-barrier cavities, separated shear layer and the reversed flow downwind of the barrier, e.g. Telenta et al. (2014).

Chen et al. (2015) indicate that larger porosity of wind barriers is unfavorable for dynamic stability of vehicles on bridges, as the obtained velocity reduction may not be sufficient in case the wind-barrier cavities are too large. Sheltering efficiency of wind barriers is strongly affected by the wind-barrier height, Chu et al. (2013). An optimal wind-barrier design with respect to wind perpendicular to bridges is considered the one with 30% porosity and 5 m height, e.g. Kozmar et al. (2014).

While the protective effects of wind barriers for vehicles are fairly known, their influence on aerodynamic forces and dynamic stability of bridges is quite unknown. Only some recent studies consider aerodynamic forces for bridges with wind barriers, Guo et al. (2015). The effects of bird-protection barriers on aerodynamic and aeroelastic behavior of high-speed train bridges are reported in Ogueta-Gutierrez et al. (2014).

Apart from wind barriers, other structural elements of bridges and viaducts, e.g. railings, crash barriers, central slotting, prove to influence aerodynamic forces and moments of bridges as well, e.g. Raggett (2007), Diana et al. (2013), Xu et al. (2014a).

Design of bridge-deck cross sections may influence their aeroelastic behavior as well, Xu et al. (2014b), while bluff cross sections are commonly more susceptible to flutter, e.g. Nikitas et al. (2011). Vehicles can significantly alter the dynamic stability of bridge decks, e.g., Han et al. (2014, 2015), Pospíšil et al. (2016).

The 5 m high wind barrier with 30% porosity, suggested by Kozmar et al. (2014) with respect to the protection of vehicles on bridges from cross-winds, proved to deteriorate dynamic stability of bridge decks, Buljac et al. (2017). However, in practice, wind barriers are manufactured with various porosities and heights, depending on specific wind characteristics for a certain geographic location and respective terrain characteristics. At this moment, it is not completely known whether and to what extent the aerodynamic and aeroelastic characteristics of

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* Corresponding author.
E-mail address: abuljac@fsb.hr (A. Buljac).

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cable-supported bridges alter due to wind-barrier porosity and height.

The present study focuses on effects of the wind-barrier porosity and height on aerodynamic characteristics of three typical wide long-span cable-supported bridge decks and their sensitivity to self-excited vibrations. Wind-barrier models with different porosities and heights are placed at the windward (leading) edge of the bridge-deck section models, as strong cross winds that may destabilize or overturn vehicles on bridges predominantly blow from one direction only, and wind barriers are commonly placed at the windward bridge-deck edge with respect to the dominant wind direction. Aerodynamic drag and lift force, as well as the pitch moment coefficients, are determined in a boundary layer wind tunnel for various flow incidence angles, and the susceptibility of the studied bridge-deck sections to galloping and flutter is analyzed.

2. Analysis of self-excited vibrations

2.1. Aerodynamic loads and galloping instability

The aerodynamic coefficients are determined for flow incidence angles from -10° to $+10^\circ$ with an increment of 1° using the following equations:

$$C_D(\alpha) = \frac{2F_D(\alpha)}{\rho v_\infty^2 HL}, \quad C_L(\alpha) = \frac{2F_L(\alpha)}{\rho v_\infty^2 BL}, \quad C_M(\alpha) = \frac{2M(\alpha)}{\rho v_\infty^2 B^2 L}, \tag{1}$$

where F_D and F_L are aerodynamic drag and lift forces, respectively, M is aerodynamic pitch moment. C_D, C_L and C_M are aerodynamic drag force, lift force and pitch moment coefficients, respectively. v_∞ is average flow velocity in undisturbed freestream flow, α is flow incidence angle, ρ is air density, B is bridge-deck width, L is bridge-deck length.

$$L_s(t) = \frac{1}{2}\rho v_\infty^2 BL\left[KH_1^*(K)\frac{\dot{h}(t)}{v_\infty} + KH_2^*(K)\frac{B\dot{\alpha}(t)}{v_\infty} + K^2H_3^*(K)\alpha(t) + K^2H_4^*(K)\frac{h(t)}{B}\right],$$
$$M_s(t) = \frac{1}{2}\rho v_\infty^2 B^2L\left[KA_1^*(K)\frac{\dot{h}(t)}{v_\infty} + KA_2^*(K)\frac{B\dot{\alpha}(t)}{v_\infty} + K^2A_3^*(K)\alpha(t) + K^2A_4^*(K)\frac{h(t)}{B}\right]. \tag{5}$$

Galloping is a wind-induced dynamic instability characterized by large amplitudes of oscillations in direction normal to the main wind flow. This low-frequency instability may occur on structural elements with bluff cross-sections, e.g. Ruscheweyh et al. (1996), Carassale et al. (2013), Mannini et al. (2014), Nguyen et al. (2015).

The galloping sensitivity of bridge-deck sections is analyzed based on measured aerodynamic lift and drag forces and the pitch moment, Den Hartog (1934), Simiu and Scanlan (1996). The necessary criterion for galloping to occur, e.g. Xu (2013):

$$\frac{\partial C_L}{\partial \alpha} + C_D < 0. \tag{2}$$

2.2. Flutter instability

Flutter is the most aggressive self-excited dynamic instability of long-span cable-supported bridges. It is commonly studied using flutter derivatives (FDs), which are contributors to the generalized stiffness and damping matrices of the system, e.g. Chowdhury and Sarkar (2004). FDs are considered as indicators of the bridge dynamic stability. Original method for extracting dimensionless FDs is proposed by Scanlan and Tomko (1971).

The vertical and torsional vibration modes are commonly analyzed when studying dynamic stability of long-span bridges, whereas the lateral vibration mode is commonly considered to have minor influence and it is therefore neglected, e.g. Simiu and Scanlan (1996), Dyrbye and Hansen (1999).

For the two degree-of-freedom (2DOF) bridge-deck dynamic system, the self-excited aerodynamic lift force and the pitch moment are coupled in the vertical and torsional motions. Dynamic response of bridge-deck section considered as a mechanically independent 2DOF system can be described using equations of motion, e.g. Sockel (1994):

$$m\left[\ddot{h}(t) + 2\xi_h\omega_h\dot{h}(t) + \omega_h^2 h(t)\right] = L_s(t) + L_b(t),$$
$$I\left[\ddot{\alpha}(t) + 2\xi_\alpha\omega_\alpha\dot{\alpha}(t) + \omega_\alpha^2\alpha(t)\right] = M_s(t) + M_b(t), \tag{3}$$

where h and α are heave and pitch responses of respective degrees of freedom, ω_h and ω_α are heave and pitch natural circular frequencies, respectively. m is system mass, I is mass of inertia, ξ_h and ξ_α are damping ratios for heave and pitch decay, respectively, L_b is buffeting lift force, M_b is buffeting pitch moment. Aerodynamic self-excited lift force L_s and the pitch moment M_s are functions of the heave and pitch displacements and their respective FDs, Scanlan and Tomko (1971):

$$L_s(t) = \frac{\partial L_s}{\partial h}h + \frac{\partial L_s}{\partial \alpha}\alpha + \frac{\partial L_s}{\partial \dot{h}}\dot{h} + \frac{\partial L_s}{\partial \dot{\alpha}}\dot{\alpha},$$
$$M_s(t) = \frac{\partial M_s}{\partial h}h + \frac{\partial M_s}{\partial \alpha}\alpha + \frac{\partial M_s}{\partial \dot{h}}\dot{h} + \frac{\partial M_s}{\partial \dot{\alpha}}\dot{\alpha}. \tag{4}$$

The indicators of the bridge-deck stability with respect to flutter (FDs), are used to express the gradients of the self-excited lift force L_s and the pitch moment M_s:

H_i^* and A_i^* ($i = 1, 2, 3, 4$) are dimensionless FDs, which are dependent on a dimensionless reduced frequency of motion $K = B\omega/v_\infty$.

The aeroelastic forces and moment contribute to the effective stiffness and damping matrices of the system. The Modified-Unifying-Least-Squares (ULS) identification method is applied to determine the effective stiffness and damping matrices. This procedure is originally developed by Gu et al. (2000) and Chen et al. (2002) and further modified by Bartoli et al. (2009) and Král et al. (2009, 2014). The critical flow velocity for flutter is calculated using the eigenvalues analysis outlined in Xu (2013).

3. Experimental setup for wind-tunnel experiments

3.1. Description of the wind tunnel and bridge-deck section models

Experiments are carried out in the climatic boundary-layer wind tunnel of the Institute of Theoretical and Applied Mechanics in Prague, Czech Republic. The aerodynamic section of this wind tunnel is 1.9 m wide and 1.8 m high rectangular cross-section. The flow is uniform along the wind-tunnel aerodynamic cross section and the turbulence intensity is less than 2%.

The studied bridge-deck sections are: (i) Great Belt Bridge (GBB) with a streamlined cross section, e.g. Bruno and Mancini (2002), (ii) Kao-Pin Hsi Bridge (KPHB) with a quasi-streamlined cross-section with guard walls, which is considered as a semi-bluff section, e.g. Pospíšil et al.