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Torsional stiffness degradation and aerostatic divergence of suspension bridge decks

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ABSTRACT

The mechanism of aerostatic torsional divergence (ATD) of long-span suspension bridges is investigated. A theoretical analysis on the basis of a generalized model is presented, showing that the vertical motion of a bridge deck is crucial to the torsional stiffness of the whole suspended system, and that the vertical motion of either cable with a magnitude beyond a certain threshold could result in a sudden degradation of the torsional stiffness of the system. This vertical motion-induced degradation of stiffness is recognized as the main reason for the ATD. Long-span suspension bridges are susceptible to such a type of divergence, especially when they are immersed in turbulent wind fields. The divergences that occur in turbulent wind fields differ significantly from those in smooth wind fields, and the difference is well explained by the generalized model that the loosening of any one cable could result in the vanishing of the part of stiffness provided by the whole cable system. The mechanism revealed in this paper leads to a definition of the critical wind speed of the ATD in a turbulent flow; that is, the one resulting in a vertical motion so large as to loosen either cable to a stressless state. Numerical results from the nonlinear finite-element (FE) analysis of the Xihoumen suspension bridge, in conjunction with observations from wind tunnel tests on an aero-elastic full bridge model, are in support of the viewpoint presented in this study.

1. Introduction

The definition of the aerodynamic torsional divergence (ATD) dates back to early years of aeronautic engineering. A classical concept of the ATD, based on linearized aerodynamic coefficients, involves a critical flow speed beyond which an unlimited growth in structural rotation occurs (Bisplinghoff and Ashiley, 1962). However, an unlimited growth in deformation is unrealistic, and hence it is more reasonable to define the critical divergence wind speed as one at which the twist of an airfoil increases rapidly to the point of failure (Dowell et al., 2004). Although concerns were generally centered on the critical wind speeds, some attentions were also paid to the post-critical stress/strain state for predicting structure reliability (Dimentberg, 1999).

As for bridge decks, Simiu and Scanlan (1996) presented a simple, linear method to evaluate the critical wind speeds of ATD, as

$$U_{cr}=\sqrt{\frac{2K_\alpha}{\rho B^2 C_{M0}^{'}}},\tag{1}$$

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where K_α is the structural torsional stiffness, ρ the density of the air, B the reference width of the bridge deck, and C'_{M0} the derivative of the coefficient of pitching moment with respect to the wind angle of attack. As far as a suspension bridge is concerned, the method of Eq. (1) has the deficiencies of not only ignoring all nonlinear and non-uniform features of the wind loads exerted along the bridge deck but also misleading one to believe that the crucial reason for the divergence is just a strong enough wind field instead of a combination of the wind effects with the degradation of the structural stiffness itself, as will be shown in this study.

In order to take into consideration the nonlinearities, Boonyapinyo et al. (1994) developed a static finite-displacement method and analyzed the coupled buckling of a long-span cable-stayed bridge. Later, Cheng et al. (2002, 2003) studied the aerostatic instability of a long-span cable-supported bridge, where geometric nonlinearities as well as the non-uniform wind angles of attack distributed along the deck were taken into account. Boonyapinyo et al. (2006) considered three types of nonlinearities, including geometric, material, and deformation-dependent wind loads.

ATD of a bridge deck is, in essence, a wind-induced instability involving a dynamic process; methodologies employed in most of the literatures related to the ATD, however, are confined in the static, step-by-step iterative FE analyses. Given a wind velocity, this method provides the static response of the concerned structure by solving an incremental equilibrium equation

$$[K(\delta)]\{\Delta\delta\} = \{\Delta P(\delta)\}, \tag{2}$$

where $[K\{\delta\}]$ is the tangent stiffness matrix of the structure; $\{\Delta\delta\}$ is the displacement increment vector; and $\{\Delta P(\delta)\}$ is the vector of nodal-force increments induced by the wind load nonlinearity and structural deformations. The solving of Eq. (2) should be repeated every time the wind velocity is renewed, up to a value leading to aerostatic instability.

Recently, Arena and Lacarbonara (2012) set up a nonlinear analytical model in terms of tensor denotations and investigated the aerostatic torsional divergence, and outcomes in this literature indicate that an increment of the upward loads can lead to pronounced softening of the cable system.

A wind field in nature is always turbulent, and bridge structures in general respond stochastically as a consequence of the turbulence inherent in the oncoming flow and the signature turbulence caused by the structure itself. Nevertheless, in what manners the aerodynamic responses could influence the ATD remains unknown. Recently, authors of this paper investigated in time domain the effects of turbulence on the ATD of bridge decks (Zhang et al., 2010). The results indicate that the ATD in turbulent flows shows a pattern of stochastic and intermittent instability, and that the turbulence plays a role in decreasing substantially the aerostatic stability. However, the mechanism regarding this effect needs further investigations.

For most suspension bridges with medium span lengths, the critical wind speeds of ATD are generally higher than those of flutter instability. As the span length increases, however, it is possible for the ATD to arise before the flutter, as indicated in recent wind tunnel tests on the aeroelastic model of Xihoumen suspension bridge, which boasts a super long span of 1650 m. Some novel and informative phenomena observed in regard to the ATD of Xihoumen suspension bridge are sketched as follows: (i) ATD of the deck was observed in all tested wind angles of attack, including -3°, 0°, and $+3^\circ$. The critical wind speeds corresponding to these angles of attack are, when transferred to the full-scale bridge, 115 m/s, 105 m/s, and 95 m/s, respectively. (ii) The critical wind speeds of ATD observed in wind tunnel are much lower than those calculated by the static nonlinear FE analyses. (iii) The deck rotations in divergence are always oriented in a nose-up direction. As a matter of fact, even though the nose-down directed mean rotation was observed in the case of -3° wind angle of attack, the final divergence was oriented still in the nose-up direction.

In view of these motivations, the objective of this study is, specific to long-span suspension bridges, investigating the motion-induced effects on the system stiffness and the mechanism of the ATD of suspension bridges immersed in turbulent flows.

2. Geometric characteristics of a cable in suspension

The intention of this section is not providing an extensive discussion of the general features but deriving for the supposed situation some specific characteristics indispensible to the subsequent discussions. For most super-long-span suspension bridges, geometric configurations of the main cables can be approximated as quadratic simply for the reason that the uniformly distributed dead load (weight of the deck) is much greater than that of the cables. As shown in Fig. 1, if one fixes the origin of the coordinate system at the central point O, the equation of the cable configuration is then given by

$$y(x) = f - \frac{4f}{l^2}x^2, \tag{3}$$

where l is the cable span and f the cable sag.

Making use of Eq. (3), the length of the cable can be integrated as

$$S(f) = 2\int_0^{l/2} \sqrt{1 + (dy/dx)^2}dx = \frac{1}{2}\sqrt{16f^2 + l^2} + \frac{l^2}{8f}\ln\left(\frac{4f}{l} + \frac{1}{l}\sqrt{16f^2 + l^2}\right), \tag{4}$$

where S is the total length of the cable, function of the sag f.

As a result, the length increment ΔS of a single cable due to a sag increment Δf can be easily obtained from Eq. (4), as $\Delta S = S(f) - S(f_0)$.