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On the aerostatic divergence of suspension bridges: A cable-length-based criterion for the stiffness degradation

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ABSTRACT

Motions of a suspension bridge immersed in turbulent wind flows, including both mean and stochastic, can under certain conditions lead to the degradation of the structure's torsional stiffness and ensuing aerodynamic torsional divergence (ATD). It is the incompressibility of the main cables that determines their effectiveness as supporting members be limited in a tension state, and dropping out of either one cable from a tension state could result in the vanish of the torsional stiffness contributed by the whole cable system. Although the physical conception is quite explicit, evaluation of the critical threshold of ATD of a suspension bridge, when experiencing stochastic aerodynamic responses, can be complicated by the deformations of the towers, the lateral oscillations of the deck and cables, and other high-order modes participating in the vibration. In view of this, a criterion based on the tracking of the length of the main cables is presented in this study. It is shown that, with the numerical example, the advent of ATD, the degradation of the system's stiffness, as well as some striking post-ATD behaviors, can be well explained with the proposed model by tracking the cable lengths.

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1. Introduction

Aerodynamic torsional divergence (ATD) is a phenomenon of wind-induced instability. Thorough canceling of the structural stiffness by aerodynamic negative stiffness is the essence of such an instability, which distinguishes itself from other instabilities driven by negative aerodynamic damping, such as flutter and galloping, etc. The recognition of ATD can date back to early years of the aeronautic engineering, where airfoils, beyond certain critical wind speeds, are prone to be destroyed by a sudden growth in rotation (Bisplinghoff and Ashiley, 1962; Dowell and Clark, 2004). ATD is also an issue that should be dealt seriously with flexible suspension bridges, not only long-span highway bridges but also flexible footbridges as well. Fig. 1 shows the state of a footbridge in China after ATD, which took place recently. For bridge decks, Simiu and Scanlan (1996) presented a two-dimensional, linear method to evaluate the critical wind speeds of ATD, as

$$U_{cr} = \sqrt{2K_\alpha / \left(\rho B^2 C'_{M0}\right)}, \tag{1}$$

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Fig. 1. A footbridge after ATD.

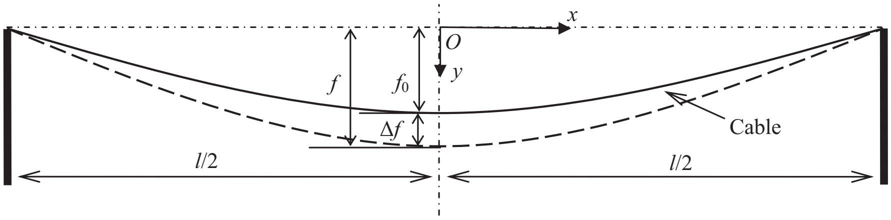

Fig. 2. Schematic diagram of a suspended cable and deflection increment.

where K_α is the structural torsional stiffness, ρ the density of the air, B the reference width of the bridge deck, C'_{M0} the derivative of the coefficient of pitching moment with respect to the wind angle of attack.

Eq. (1) is sufficient in revealing the basic mechanism of ATDs of bridge decks. Lacking of accuracy, however, is much in evidence. In order to take into consideration of nonlinearities, Boonyapinyo et al. (1994; 2006) developed a static finite-displacement method and analyzed the coupled buckling of a long-span cable-stayed bridge. Later, Cheng et al. (2002) employed this method and studied the aerostatic instability of a long-span suspension bridge. Progresses made in these literatures include three-dimensional characteristics of the wind-induced structural deformations, nonlinearities in both geometry and material, as well as nonlinearities in wind loads that are structural deformation dependent. What in common of these literatures is that a static, iterative finite element method is adopted, which should be of course incapable of recognizing the influences of the turbulence and the turbulence induced stochastic oscillations. As is known, wind flows in nature are always turbulent, and flexible bridges exposed in turbulent flows could response significantly in along-wind, cross-wind, and torsional directions. Therefore, the ATD of a flexible bridge could only take place during a course of stochastic, dynamic response instead of a static one.

Arena and Lacarbonara (2012) found that an increment of upward loads can lead to pronounced softening of the cable system of a suspension bridge, and this means an adverse effect to the structural stiffness could be induced by upward motions. Aiming at the effects induced by turbulence, Zhang et al. (2010) investigated the aerostatic stability of a long suspension bridge in time domain, and the results show that the turbulence could decrease the structure's aerostatic stability substantially. However, the mechanism regarding this effect was still not evident. Later, based on observations in wind tunnel, Zhang et al. (2013) revealed the mechanism of the degradation of the torsional stiffness of the cable–deck system. For a super long-span suspension bridge, it is not the bridge deck but the two main cables that contribute most to the system's torsional stiffness (Xiang and Ge, 2003), and the degradation, induced by upward motions, means the loss of the dominant part of stiffness provided by the main cables. Hence, a flexible suspension bridge that has undergone stiffness degradation could be overturned easily by a wind speed much lower than that evaluated with the traditional static, iterative FE method, and this was in accord with the observations from wind tunnel experiments.

The stiffness degradation is dominated by vertical motions of the two main cables. However, the critical quantity of vertical motion can be influenced by other structural deformations. Zhang et al. (2013) estimated the influence of the deformations of the bridge towers, and found it could increase the critical vertical motion as large as more than 40 percent. However, the estimation was specific to the bridge considered, and cannot be generalized to other cases. Moreover, influences of other factors remain unresolved, including those from the lateral oscillations of the bridge deck, lateral oscillations of the main cables, as well as those from high-order structural motions. These issues are the main purpose of this study.

2. Generalized stiffness and stiffness degradation

Referring to Fig. 2, positive deformations of the system are defined as follow: downwards positive for vertical deformation; along-wind positive for lateral deformation; nose-up positive for torsional deformation. The generalized

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