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Effects of structural nonlinearity and along-span wind coherence on suspension bridge aerodynamics: Some numerical simulation results

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Abstract

The response of suspension bridges to wind excitation is studied by means of numerical simulations with a specifically developed finite element program implementing full structural nonlinearities. A pure time-domain load model, linearized around the average configuration, is considered. The self-excited effects are included through the indicial function formulation, whereas the buffeting is considered according to the quasi-steady model. The response under turbulent wind, both fully and partially correlated, is evaluated through a Monte Carlo approach. A simplified structural model is considered, where only two cross-sections are modeled. This allows a high reduction of the number of degrees of freedom (DoFs) but maintains many characteristics of the true bridge, precluded to the classical 2-DoF sectional-model (e.g. considering more than two modes, including structural nonlinearities, introducing along-span wind coherence). The case studies of a long-span suspension bridge and a light suspension footbridge are analyzed. It is observed that structural nonlinearities deemphasize the presence of a critical flutter wind velocity, as they limit the oscillation amplitudes. On the other hand, fully correlated flow may produce an important underestimation of the structural response.

Keywords: Suspension bridges; Aeroelasticity; Buffeting; Along-span coherence; Nonlinear dynamics; Numerical simulations; Finite elements; Simplified models

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1. Introduction

The suspension bridge scheme seems to be the best solution for long-span bridges, as demonstrated by the recent achievements of Humber Bridge (UK 1981, center span of 1410 m), Great Belt East Bridge (Denmark 1998, 1624 m), Akashi-Kaikyo Bridge (Japan 1998, 1991 m), and by the design for Messina Strait Crossing (Italy, 3300 m). Suspension bridges also demonstrated to be very sensitive to the wind action.

Due to the theoretical complexity arising for bluff cross-sections with irregular geometry, the predominant design tool in wind engineering is the boundary layer tunnel, where intensive experimental campaigns with scaled-down models are performed. Long bridges present, however, scaling problems, as they require a very small scale to fit into wind tunnels. For instance, the testing of an Akashi-Kaikyo Bridge 1:100 model has been carried out in an over 40-m-wide wind tunnel. As well known, it is not also possible, for intrinsic scaling problems, to reproduce the real flow in the wind tunnel. In particular, the along-span correlation of turbulence can be very tricky to simulate.

For these reasons, the most common approach consists in testing cross-sectional models. These models are commonly used for the aerodynamic characterization of the selected deck through aerodynamic coefficients and aeroelastic derivatives. The extension of cross-sectional results to the entire structure, however, is not straightforward. Frequency-domain multi-modal approach [1] offers interesting possibilities but does not allow structural nonlinearities to be taken into account. On the other hand, mixed frequency-time domain simulations usually evaluate aeroelastic derivatives at a single frequency that is often obtained through a trial procedure and is valid only at the critical flutter condition [2]. A different approach in the mixed domain is proposed in [3], where the spectrum is divided in several "bands" and, after solving the equations of motion in the time domain for each band, the superposition effect is applied. This method is confined, however, to linear structures.

The suspension cables have a strong geometrical stiffness only for uniform loads and offer different stiffness characteristics for symmetric and non-symmetric load patterns. Moreover, structural nonlinearities are important for cable-structures as suspension bridges, and the hangers themselves could exhibit nonlinear behavior, as they are unable to sustain compressions (e.g. [4]).

In order to take into account the effects of structural nonlinearities, full time-domain simulations must be performed (e.g. [5,6]). This can be done through indicial function load models (e.g. [7]).

Time-domain simulations offer also other advantages. The overall structural behavior is automatically taken into account, avoiding modal decomposition. Furthermore, the combination of self-excited and buffeting forces is straightforward and the along-span wind coherence can be easily considered (e.g. [8]).

The present work will investigate the effects of structural nonlinearities and along-span coherence through time-domain simulations. The questions are, on one hand, how structural nonlinearities affect the response in the vicinity of the flutter velocity, and, on the other hand, whether the along-span coherence influences in a positive or a negative manner the behavior of suspension bridges.

As the adopted indicial function load model introduces an explicit dependence of the load on the displacement history, it is not possible to use standard structural analysis programs. An "ad hoc" developed finite element (FE) implementation is then provided.