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Modeling vortex-shedding effects for the stochastic response of tall buildings in non-synoptic winds

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ABSTRACT

This study derives a model for the vortex-induced vibration and the stochastic response of a tall building in strong non-synoptic wind regimes. The vortex-induced stochastic dynamics is obtained by combining turbulent-induced buffeting force, aeroelastic force and vortex-induced force. The governing equations of motion in non-synoptic winds account for the coupled motion with nonlinear aerodynamic damping and non-stationary wind loading. An engineering model, replicating the features of thunderstorm downbursts, is employed to simulate strong non-synoptic winds and non-stationary wind loading. This study also aims to examine the effectiveness of the wavelet-Galerkin (WG) approximation method to numerically solve the vortex-induced stochastic dynamics of a tall building with complex wind loading and coupled equations of motions. In the WG approximation method, the compactly supported Daubechies wavelets are used as orthonormal basis functions for the Galerkin projection, which transforms the time-dependent coupled, nonlinear, non-stationary stochastic dynamic equations into random algebraic equations in the wavelet space. An equivalent single-degree-of-freedom building model and a multi-degree-of-freedom model of the benchmark Commonwealth Advisory Aeronautical Research Council (CAARC) tall building are employed for the formulation and numerical analyses. Preliminary parametric investigations on the vortex-shedding effects and the stochastic dynamics of the two building models in non-synoptic downburst winds are discussed. The proposed WG approximation method proves to be very powerful and promising to approximately solve various cases of stochastic dynamics and the associated equations of motion accounting for vortex shedding effects, complex wind loads, coupling, nonlinearity and non-stationarity.

1. Introduction

1.1. General context and motivation

Tall buildings and slender line-like structures (e.g., tall masts, wind turbines, flexible long-span bridges) are sensitive to wind-induced vibration and complex stochastic response due to the influence of nonlinear, coupled and transient/

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non-stationary aerodynamics and fluid–structure interaction (e.g., Kareem, 2010; Kareem and Wu, 2013). In the relatively low mean wind speed range, crosswind vortex-shedding effects cannot be neglected as they can produce large vibrations in the crosswind direction. At medium-range mean wind velocities, turbulence-induced vibration often results in complex alongwind and crosswind stochastic response due to the coupling between aeroelastic self-excited forces and buffeting forces. The lock-in regime of the vortex shedding is plausible at high speeds for very tall buildings (Chen, 2013), in which nonlinear self-limiting structural vibration is possible due to the combination between nonlinear aerodynamic self-excited load and harmonic vortex shedding load (e.g., Dyrbye and Hansen, 1997). The combination of the random turbulence-induced load and the deterministic vortex-induced load may also possibly trigger stochastic resonance phenomena on slender vertical structures (e.g., Gammaitoni et al., 1998). Moreover, nonlinear effects of the vortex-shedding force could significantly affect the stochastic dynamics of tall buildings either inside or near the lock-in range at higher wind velocities. For example, it is known that a nonlinear damping effect (van-der-Pol type) can influence the stochastic dynamic stability of bluff bodies. The quasi-periodic beating phenomenon is also possible with a limit cycle vibration (e.g., Náprstek and Fischer, 2014); the same phenomenon is therefore plausible in the case of vortex shedding in the proximity of lock-in regime due to the nonlinear terms embedded in the van-der-Pol equation.

The vortex-induced stochastic dynamics of a tall building requires the simulation of aerodynamic terms, such as the turbulent-induced buffeting loads, vortex-shedding force and self-excited force. In addition, coupling, nonlinear and non-stationary aerodynamics can potentially influence the stochastic dynamics of a tall building subjected to strong wind regimes. These particular loading conditions are seldom investigated even though they could be particularly dangerous for tall buildings, especially in the case of strong wind events such as thunderstorm downbursts, which do not satisfy the ordinary hypotheses of synoptic-wind boundary layer and stationary wind loading. An efficient simulation method for the solution of non-stationary stochastic vibration of tall buildings subjected to vortex shedding effects, nonlinear, coupled and transient aerodynamic loading in strong non-synoptic thunderstorm wind regimes is not fully available and still a challenging task.

1.2. Brief overview of vortex-shedding models for vertical structures in synoptic winds

Numerous studies on the vortex-induced vibration of long and flexible structural systems have been carried out in the case of circular and prismatic non-circular cylinder sections (e.g., Landl, 1975; Vickery and Basu, 1983a, 1983b; Goswami et al., 1992, 1993; Matsumoto, 1999). Traditionally, semi-empirical mathematical models have been proposed to replicate the main features of the vortex-induced vibration of line-like structures (e.g., Landl, 1975; Vickery and Basu, 1983a, 1983b, 1983c; Williamson and Govardhan, 2004). Vibration regimes are usually classified as either outside or inside the lock-in range depending on the mean wind speed. In the case of vibration outside the lock-in range, which is common to a large class of vertical structures, the vortex-shedding effects are often modeled as a combination of an aerodynamic self-excited force, either in-phase or out-of-phase with the relative velocity, and a fluid-related (aerodynamic) harmonic vortex shedding force. If the wind speed meets certain conditions and the frequency of vortex shedding is close to the structural frequency, self-sustained lock-in vibration is possible, in which aerodynamic vortex shedding force is negligible and the self-excited nonlinear negative-damping loading effects are predominant. Scanlan (1981) proposed and examined an empirical model to comprehensively describe, in a nonlinear form, the vortex-induced loading inside and outside the lock-in regime; the model is based on a set of physical parameters, which can be obtained from experiments (Ehsan and Scanlan, 1990). In many cases, the nonlinear aerodynamic damping term of the vortex-induced loading outside the lock-in range has been neglected for the sake of simplification (e.g., Wu and Kareem, 2013). Several semi-empirical models have been employed to simulate the effects of vortex shedding on slender structures, which preserve the relevant features of the loading. For time-domain simulations in wind engineering, models by Scanlan (1981), Ehsan and Scanlan (1990) for long-span bridges and by Goswami et al. (1992, 1993) for tall slender chimneys have been proven to be valid and applicable to a wide range of cases. Recent studies on the dynamic response of slender tall buildings (Chen 2013, 2014a) have also indicated the need for carefully re-examining the effects of vortex shedding, by demonstrating the relevance of “lock-in” and nonlinear vortex-induced-vibration for the next generation of super tall structures. Alternative models for vortex shedding response of slender bridges (Larsen. 1995; Wu and Kareem, 2013) and line-like structures (Sun et al., 2014) have been recently examined. It must be noted that the loading parameters of these semi-empirical models are usually determined from the shedding frequency of the von-Kármán vortices outside the lock-in range, while the fundamental structural frequency is applied to estimate the model parameters in the lock-in range. Furthermore, spatial correlation and coherence of the loads is enhanced in the lock-in region. Most mathematical models for the vortex-induced vibration of line-like structures have usually been derived in the frequency domain, making these models adequate in conventional synoptic winds, but they hardly capture nonlinear, unsteady and non-stationary features of the loading in non-synoptic winds.

1.3. Adaptation of current vortex-shedding models to non-synoptic winds

Currently, analysis of the wind-induced stochastic response of slender vertical structures is preferably carried out under the assumptions of linear structural response, simplified modeling of fluid–structure interaction and multivariate stationary wind loading by Fourier analysis (e.g., Kareem. 1985; Piccardo and Solari, 2000; Caracoglia, 2012). The Fourier transformation allows the coupled and nonlinear motion equations to be reduced to an algebraic form. Nevertheless, the solution of