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A stochastic model for examining along-wind loading uncertainty and intervention costs due to wind-induced damage on tall buildings

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ABSTRACT

This study describes some recent results of a numerical study on the wind-induced response of a tall building, contaminated by along-wind loading uncertainty. The study also proposes the use of "intervention costs" in the form of a dimensionless random variable, which nonlinearly depends on the dynamic response of the structure, for the examination of the structural performance during high-wind events.

The CAARC building is employed as the benchmark structure. Three nonlinear reduced-order models are used to describe the dynamic response. In these models various hypotheses are introduced to systematically and efficiently simulate both loading uncertainty and cost variability. The generalized models are formulated in terms of stochastic differential equations and are approximately solved by equivalent stochastic linearization. In the case of loading uncertainty analysis, the joint probability density function of the roof-top lateral dynamic displacements in the two primary bending planes of the building is determined as a function of the mean wind speed and the standard deviation of a parametric error term. Dependence of the cross-correlation among the two response components on the input standard deviation of the parametric error term is observed. In the case of the intervention cost analysis, it is noted that the main contributing factor to the distribution of the intervention cost random variable is the mean wind speed.

The combination of wind loading uncertainty and projected intervention costs on the dynamic response of the structure is the first step towards the implementation of alternative but rational analysis methods for performance-based wind engineering, applied to tall buildings.

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1. Introduction

Simulation methods for estimating the wind-induced response of tall buildings have been proposed mainly to study the dynamic response or accelerations. Various formulations can be employed for analyzing the performance of the structure (e.g., [1–3]). In recent years more and more interests have emerged in the structural engineering community to investigate the structural performance of tall structures, accounting for various sources of uncertainty in the wind loading. For example, a risk-based framework, in which the lateral loads along with their uncertainty are indirectly derived from the results of a wind tunnel test (high-frequency force balance; HFFB) and directly utilized in the estimation of the full-scale response, has been applied to study the wind-induced response of tall buildings [4–6]. In the HFFB method the aerodynamic forces, measured in the wind tunnel at the base of a rigid model, are used to simulate the full-scale generalized modal forces and to predict the structural response. Nevertheless, the HFFB method possesses some inherent limitations in the presence of three-dimensional structural modes or when torsional effects are of relevance, which can be partially alleviated by appropriate post-processing of the data (linearization of mode shapes, non-planar modes, etc. [7–9]). Since limitations of the HFFB method can be an issue in wind engineering practice, the Database-Assisted Design (DAD) method for high-rise buildings has been introduced (e.g., [10–13]). This method, which employs a large set of pressure measurements on a wind-tunnel rigid model of the structure exposed to a boundary layer flow, overcomes some of the limitations of the HFFB; in fact, it can be used to investigate structural reliability and performance of the structural members [10]. Also, by combining the philosophy of the HFFB and DAD methods, an original wind tunnel method for tall buildings has been recently examined [14]. This method [14] relies on wind tunnel experimentation and utilizes an aeroelastic model of the building to simultaneously measure both wind pressures and aeroelastic response.

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Nomenclature

$\mathbf{A}$	state matrix corresponding to the strictly linear portion of the drift function $\mathbf{a}(\mathbf{W})$
$\widetilde{\mathbf{A}}$	linearized state matrix, stochastic linearization, Eq. (24)
$\mathbf{a}(\mathbf{W})$	nonlinear drift functions of the stochastic models without intervention costs in general form, Eq. (15)
$\mathbf{a}_1(\mathbf{W})$, $\mathbf{a}_2(\mathbf{W})$	nonlinear drift function of "Type-1" and "Type-2" stochastic models without intervention costs in Eq. (18) and Eq. (20)
$\mathbf{a}_{NL}(\mathbf{W})$	strictly nonlinear portion of the function $\mathbf{a}(\mathbf{W})$
$\mathbf{a}_{\Gamma}(\mathbf{W})$	nonlinear drift function of "Type-3" stochastic model with intervention costs in Eq. (23)
$B(s)$	scalar Wiener process of unit-variance increments
C_D	static drag coefficient per unit height
$C_{\widehat{DL}}$	force coefficient, $C_{\widehat{DL}} = (C_D + \mathrm{d}C_L/\mathrm{d}\alpha)$
C_L	static "lift" coefficient (transverse) per unit height
$C_{\widehat{LD}}$	force coefficient, $C_{\widehat{LD}} = (C_L - \mathrm{d}C_D/\mathrm{d}\alpha)$
$c_{z,u}$, $c_{z,v}$	coherence decay coefficients of wind turbulence
D_x, D_y	building dimensions (floor plan)
$\mathbf{d}$	diffusion vectors of the stochastic models without intervention costs in general form, Eq. (15)
$\mathbf{d}_1$, $\mathbf{d}_2$	diffusion vectors of the "Type-1" and "Type-2" stochastic models without intervention costs
$\mathbf{d}_{\Gamma}$	diffusion vector of the stochastic model with intervention costs
det(.)	determinant operator
$F_x(z,t)$	along-wind dynamic load per unit of length z
$F_y(z,t)$	across-wind dynamic load per unit of length z
G_{1u}, G_{2u}	parameters of the auto-regressive model for $\hat{u}_{0.6h}$ in Eq. (12)
G_{1v}, G_{2v}	parameters of the auto-regressive model for $\hat{v}_{0.6h}$ in Eq. (13)
h	building height
I_u, I_v	turbulence intensities of fluctuating wind components u and v
$\widetilde{\mathbf{K}}$	covariance matrix of the approximate solution by stochastic linearization, Eq. (26)
K_{1x}	reduced frequency of mode "1x"
K_{1y}	reduced frequency of mode "1y"
k	integer index designating the generic step of the recursive procedure for stochastic linearization, Eq. (27)
M_{1x}, M_{1y}	generalized masses of modes "1x" and "1y"
$m(z)$	mass of the building per unit height
$\tilde{n}$	number of states (dimension) of the stochastic model
n, n_{1x}, n_{1y}	generic frequency (Hertz) and frequencies of modes "1x" and "1y"
$p(\mathbf{w})$	joint probability density function of the state vector $\mathbf{W}$
Q_{1x}, Q_{1y}	generalized wind loads of modes "1x" and "1y"
s	dimensionless time, $s = tU_h/D_x$
t	time
$U(z)$	mean wind speed at height z
U_h	reference mean wind speed at roof top
$u(z,t)$	horizontal turbulence, along-wind component
$\hat{u}(z,s)$	dimensionless horizontal turbulence, along-wind, with $\hat{u} = u/U_h$
$\hat{u}_{0.6h}$	reference dimensionless along-wind turbulence component at $z = 0.6h$
$v(z,t)$	horizontal turbulence, across-wind component
$\hat{v}(z,s)$	dimensionless horizontal turbulence, across-wind, with $\hat{v} = v/U_h$
$\hat{v}_{0.6h}$	reference dimensionless across-wind turbulence component at $z = 0.6h$
$x(z,t)$	along-wind horizontal dynamic displacement
$y(z,t)$	across-wind horizontal dynamic displacement
$\mathbf{W}$	random state vector of "Type-1" and "Type-2" models without intervention costs in Eqs. (14) and (15)
$\mathbf{W}_{\Gamma}$	random state vector of the model with intervention costs in Eqs. (16) and (17)
$\widetilde{\mathbf{W}}$	approximate state vector, corresponding either to $\mathbf{W}$ or $\mathbf{W}_{\Gamma}$, by stochastic linearization
$\mathbf{w}$	value of random state vectors $\mathbf{W}$ or $\mathbf{W}_{\Gamma}$ in the real domain
z	generic coordinate along the vertical axis of the building (floor)
α	angle of attack of the wind (reference static angle $\alpha_0 = 0$)
Γ	intervention-cost function in Eq. (21)
$\Delta_{NL}^{(\Gamma)}(s)$	compound variable used in Eq. (23)
$\Delta_{U(z)}$	function describing the mean-wind velocity profile
ε_u	shape parameter of parametric random error spectrum (Eq. (19))
ζ_{1x}, ζ_{1y}	modal damping ratios of modes "1x" and "1y"
$H_{1x,1x}$, $H_{1x,1y}$	modal coupling terms in Eqs. (3) and (4)
$H_{1y,1y}$, $H_{1y,1x}$	modal coupling terms in Eqs. (5) and (6)
$\Lambda_{1x,u}$	modal correlation length, 1x-mode generalized loading, as in Eq. (7)
$\Lambda_{1y,u}$, $\Lambda_{1y,v}$	modal correlation lengths, 1y-mode generalized loading, as in Eq. (8)
λ_u	zero-mean random perturbation to $\Lambda_{1x,u}$
$\xi_{1x}(t)$, $\xi_{1y}(t)$	dimensionless generalized coordinates of modes "1x" and "1y"
$\xi'_{1x}, \xi'_{1y}, \xi''_{1x}, \xi''_{1y}$	first and second derivatives of ξ_{1x} and ξ_{1y} with respect to s, with $(\,)' = \mathrm{d}(\,)/\mathrm{d}s$
ρ	air density
$\rho(\xi_{1x}, \Gamma)$	correlation coefficient between variables ξ_{1x} and Γ
$\sigma_{\lambda u}$	standard deviation of random λ_u
τ	minimum exceedance threshold in Eq. (21)
Φ_{1x}, Φ_{1y}	dimensionless mode shapes of the bending modes (planes "z–x" and "z–y")
$\mathbf{\Psi}^{(E)}$	matrix of elements $\Psi_{i,j}^{(E)} = E\left[a_{NL,i}(\widetilde{\mathbf{Z}})\widetilde{Z}_j\right]$ in Eq. (26), with recursive notation $\mathbf{\Psi}_k^{(E)}$

The information is later used to estimate the building response at full scale with a focus on structural serviceability limit states.

In line with the above-described emerging techniques for the analysis of wind loading and response on vertical structures, the author has proposed the use of stochastic models and semi-analytical solutions to investigate the wind-induced stationary response of tall buildings. These are reduced-order and state-space models, in which the quasi-steady approach is employed to describe the lateral wind loads. The lateral wind loads are partially-correlated due to wind turbulence but are transformed to an equivalent fully-correlated load acting over a limited portion of the lateral building surface. This step is necessary to limit the number of random variables and the dimension of the system to a realistically manageable value.

The reduction of the wind load model is based on the concept of modal correlation length. The correlation length depends on the building height, mode by mode; this quantity has been utilized for many decades in wind engineering [15,16] to quantify wind loads on vertical structures. Nevertheless, this hypothesis usually introduces a simplification in the modeling of the wind loading. It is therefore important to investigate the effects of this modeling simplification, in particular the "along-wind loading error", on the

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