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Wind-load fragility analysis of monopole towers by Layered Stochastic-Approximation-Monte-Carlo method

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ABSTRACT

This paper describes a novel numerical algorithm for the simulation of the along-wind dynamic response of a prototype of slender towers under turbulent winds, using a Layered Stochastic Approximation Monte Carlo algorithm (LSAMC). The proposed algorithm is applied to derive the statistics of the dynamic response in the presence of uncertainties in the structural properties and in the wind loading. Standard "brute force" Monte-Carlo methods are also used for validating the LSAMC results. The proposed methodology efficiently estimates structural fragility curves under extreme wind loads. The methodology enables a significant speedup in the computing time compared to standard Monte Carlo sampling. Furthermore, it is demonstrated that accuracy in the estimation of structural fragility curves is superior to ordinary reliability methods (e.g. "First-order reliability methods" or FORM).

1. Introduction

Comprehensive research activities in the recent past have been undertaken in the area of risk-based assessment of structural integrity with a specific focus on earthquake engineering (performance-based engineering) [1]. In performance-based engineering, the basic idea is to ensure that a structure, for example subjected to various hazard levels (as opposed to the largest predictable event), can achieve a selected performance objective [2]. Performance-based engineering approaches are frequently adopted for large structures and infrastructures, for which a pre-scribed level of safety or a serviceability state level must be guaranteed. The overall concept of performance-based engineering provides an attractive alternative for owners, since it enables cost-effective design, reduces planning in the aftermath of a catastrophic event and avoids expensive repairs of the system consequent to exceedance of a limit state. Structural optimization under uncertainties has recently gained importance in many engineering fields such as aerospace, aeronautics, infrastructural engineering [2,3] and more recently in wind engineering [4,5]. Randomness in the design variables is an important issue for the performance-based engineering approach, also because uncertainty can regard various design variables [6]. In wind engineering spectral-based and peak-estimation methods have been recognized since the early stages of the research activities on high-rise building response (e.g., [7–10]) due to the presence of random turbulence in the structural loading and dynamic vibration. Nevertheless, the concept of performance-based engineering still deserves careful consideration.

Researchers recently proposed several optimization methods for wind-excited structures, considering uncertainty in structural parameters and wind loads [11–13] and uncertainties in the mass distribution [12,14]. Among wind sensitive structures, self-supporting towers present specific design problems, related to the definition of wind load and the dynamic properties of the structure (e.g. monopole towers [15,16], wind turbine towers [17–19]).

Uncertainties can arise from errors in wind tunnel test, modeling simplifications or as a result of unanticipated modifications of some structural characteristics during structural lifetime [6]. Moreover, the problem of icing can introduce uncertainties in the definition of both dead and wind loads [20].

It is generally recognized that flexible structures, such as communication towers or masts utilized for meteorological measurements, are very sensitive to wind effects and to uncertainties related to wind load and structural dynamic characteristics [6,14]. For these reasons, the optimal design of these structures cannot disregard the importance of parameter uncertainties [16] with a focus on structural performance.

Generally, uncertainties can be grouped into two sets of variables (e.g. [6]); the first set includes structural parameters such as mass, stiffness and the size of structural elements; the second set characterizes

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Nomenclature

Abbreviations

BF	"brute force" (Monte-Carlo sampling)
DOF	degree of freedom
FORM	first-order reliability method
LSAMC	layered stochastic approximation Monte-Carlo
SA	stochastic approximation
SGA	stochastic gradient approximation

Symbols and variables

A	projected area of communication devices installed on monopole tower
a_k	gain parameter at step k (Stochastic Approximation)
a	arbitrary constant of the gain parameter (Stochastic Approximation)
C	arbitrary constant of the gain parameter (Stochastic Approximation)
C_D	simulated drag coefficient (stochastic variable)
$C_{D,i}$	*i-the* element of the simulated drag coefficient sequence (stochastic variable)
E	modulus of elasticity of the material (mast cross section)
F_T	structural response fragility
f	natural frequency [Hz]
f_{01}	fundamental-mode natural frequency of the monopole tower [Hz]
g	peak response factor
h	monopole tower height
$H(f)$	normalized mechanical admittance function for point-like structure (Davenport Chain [50])
I	moment of inertia of area of the reference cross section of the tower mast
$M_{\text{base},0}$	overturning moment at the base of the monopole tower, limit-state threshold
m	simulated mass of the tower (lumped mass, stochastic variable)
m_j	j-th element of simulated mass m sequence (stochastic variable)
N	number equally-probable sets (LSAMC approach)
n	number of samples (Monte Carlo sampling)
P	probability of exceedance
$P_{E,AA}$	probability of exceedance found by approximate approach (FORM or LSAMC)
$P_{E,BF}$	probability of exceedance found by Monte-Carlo sampling (BF)
p	generic stochastic variable p (FORM)
S_{uu}	along-wind horizontal turbulence velocity spectrum
t_0	reference duration of the observation for peak estimation
$\overline{U}$	mean wind speed at $z = h$ (tower top)
$\overline{U}_M$	average value of the mean-wind speed corresponding to structural response threshold crossing (MC approach)
$\overline{U}_M^*$	average value of the mean-wind speed corresponding to structural response threshold crossing (LSAMC approach)
V_z	mean wind velocity at $z = h$ (tower top)
X_{peak}	random variable (peak lateral displacement)
$\overline{x}$	mean along-wind displacement at $z = h$ (tower top)
x_0	peak lateral displacement threshold for the predefined limit state at $z = h$ (tower top)
x_{peak}	peak lateral displacement at $z = h$ (tower top)
z	elevation or vertical coordinate along the vertical axis of the tower
δ	arbitrary constant of the gain parameter (Stochastic Approximation)
$\Lambda_{r,CD}$	r-th subset of simulated drag coefficient (stochastic variable)
$\Lambda_{s,m}$	s-th subset of simulated mass (stochastic variable)
$\upsilon_{0,x}^{+}$	arrival rate of up-crossings of the peak value (Davenport Chain [50])
ξ_1	generalized response variable (first lateral mode)
ρ	air density
$\sigma_{\xi 1}$	along-wind RMS response corresponding to generalized response ξ_1
$\Upsilon(\overline{U})$	threshold function Eq. (4) (Stochastic Approximation)
$\Phi_1(z)$	normalized lateral first-mode shape of the tower/mast
$\chi(f)$	aerodynamic admittance function for point-like structure (Davenport Chain [50])

Subscripts and superscripts

k	index of k-th iteration step of SA algorithm (Eq. (5))
r	index of r-th equally probable set of drag coefficient ($\Lambda_{r,CD}$)
s	index of *s-th* equally probable set of mass ($\Lambda_{s,m}$)

the dynamic load acting on the structure such as wind, wind speed, turbulence spectra, tributary or projected areas of the loads and aerodynamic force coefficients.

In the present work, the along-wind response of a generalized model of a monopole tower is employed as a first prototype application. This structure is examined, without any loss of generality, as a point-like structure; a generalized single Degree-Of-Freedom (DOF) model is utilized to simulate the dynamic behavior of the considered monopole tower. Two random variables are selected as representative examples of the two fundamental problems, introduced above and usually associated with the analysis of the structural performance via structural fragility functions (e.g. [21,22]): experimental errors in the aerodynamic wind loads and insufficient knowledge of the structural system. The two selected variables are, respectively, the aerodynamic drag coefficient of the tower elements and the mass of the structure [6,12]. Even though other sources of uncertainty are possible (e.g. structural damping, etc. [23–25]), the two quantities above are employed as illustrative indicators for verification of the proposed method along with the benchmark structural model.

Following recent advances in wind engineering of long-span bridges and tall buildings [22,26,27], performance-based structural analysis is accomplished through construction of fragility functions. These are usually assembled as the probability of exceeding a pre-selected limit-state threshold, conditional on the value of mean wind speed at a reference elevation (e.g. [21,22]). The Monte Carlo approach is conveniently employed for structural analysis and commonly applied for the fragility analysis of wind-sensitive structures (e.g. [21,28]). In the present paper a Layered Stochastic-Approximation-Monte-Carlo (LSAMC) approach, based on implementation of the Stochastic Approximation (SA) is proposed [29,30] to accomplish this task. The LSAMC approach enables the statistical assessment of the wind-induced response in presence of "uncertain scenarios". The LSAMC approach is a viable alternative to a standard Monte Carlo simulation ("brute force method"; e.g. [31]), which requires the generation of a large and statistically meaningful number of realizations of the stochastic problem to determine the response to wind load.

Originally conceived as a tool for statistical computation, the SA has been widely used in electrical engineering, subsequently extended to study the non-linear dynamics of cable networks in cable-stayed bridges [32,33] and the dynamic performance of tall buildings subjected to