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Robust and reliable optimization of wind-excited cable-stayed masts

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ABSTRACT

Deterministic optimization methods have been widely used in the design of structures in order to reduce costs and improve the structural performance. However, it is well known that uncertainties related to design, construction and loading can lead to suboptimal performance of the system, especially for wind sensitive slender structures that show a behavior highly dependent on dynamic properties and loading. For these reasons, optimization methods under uncertainties have gained an increasing importance as they are powerful tools for providing robust, reliable and cost-effective designs. Two are the main objectives of the paper: the first is to propose an optimization framework for cable-stayed masts, subjected to wind load, taking into account the uncertainties on the characteristics of the structure and on the wind excitation. The procedure provides both reliability and robustness and can tackle all the peculiarity of wind exposed slender structures, like geometric non-linearity, uncertainty in the loads definition, uncertainty in cable prestress and dynamics. The second goal is to compare robust and reliable solutions and highlight the differences in terms of performance and safety levels.

1. Introduction

In order to rationalize design costs of structures, characterized by an elevated number of degrees of freedom, there is the need of using optimization methods. The traditional approach to optimization considers deterministic models and parameters and accounts for uncertainties in a simplified manner, for example through the introduction of appropriate safety factors (Melchers, 1987). This can lead to non-economical solutions and cannot provide a quantitative estimation of the risk associated with the randomness of the parameters (Beck and de Santana Gomes, 2012). For this reason, optimization under uncertainties has recently gained an increasing importance in many engineering fields, like aerospace, aeronautics, products manufacturing and structural and infrastructural engineering (Tsompanakis et al., 2008; Yao et al., 2011). According to literature reviews (Park et al., 2006; Beyer and Sendhoff, 2007; Shuëller and Jensen, 2008; Bucher, 2009; Valdebenito and Shuëller, 2010), structural optimization under uncertainties is performed according to two different approach categories. The first approach, reliability-based design optimization (RBDO), is concerned with the solution of an optimization problem, where safety is ensured with a prescribed probability (Papadrakakis and Lagaros, 2002; Youn and Choi, 2004; Agarwal, 2004; Karadeniz et al., 2009). The second one, robust design optimization (RDO), looks for designs that provide satisfactory performance of the system and are relatively insensitive with respect to uncertain parameters changes (Zang et al., 2005; Bucher, 2009; Bhattacharjya and Chakraborty, 2011; Chakraborty et al., 2012). Robust design optimization problems incorporating probability inequality constraints are also referred to as reliability-based robust design optimization problems (RBRDO) (Lee et al., 2008; Paiva et al., 2014).

Reliability-based (performance-based) approaches are adopted frequently for large structures and infrastructures in which a prescribed level of safety must be guaranteed. Conversely, robust optimal design approaches are often adopted for mechanical and construction components that require large adaptability. Reliability is related to the probability of avoiding limit states crossing, while robustness is oriented to reduce the variability of structural performance caused by parameters variation. In this perspective, reliability and robustness are two competing objectives as the former is pursued through an improvement of the structural performance while the latter is sought through a reduction of the performance scatter.

Large effort was made by researchers to optimize wind sensitive structures. At first, deterministic optimization methods were proposed for wind-exposed flexible structures in which the random nature of wind action was considered through equivalent static loads (Negm and Malawi, 2000; Jasim and Galeb, 2002; Heydari et al., 1974; Belevičius et al., 2013). More accurate stochastic definitions of wind load was adopted in Chan and Chui (2006), Venanzi and Materazzi (2007), Chan et al. (2010), Huang

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et al. (2010), and Xie (2014). More recently researchers proposed optimization methods for wind-excited structures considering uncertainty in structural parameters and wind load definition (Spence and Gioffré, 2011; Venanzi and Materazzi, 2013; Beck et al., 2014; Spence and Kareem, 2014; Huang et al., 2015; Venanzi, 2015). Among wind sensitive structures, guyed towers present specific design problems (Bao and Zhang, 2011; Støttrup-Andersen, 2014; Nielsen, 2014; Meshmesha et al., 2006; Shehata and Damatty, 2007) like the modeling of the non-linear cable behavior (Desai and Punde, 2001), the influence of cable prestress on the dynamic response (Yang et al., 2013), and the problem of icing that makes uncertain the definition of both dead and wind loads (Makkonen et al., 2014). For these reasons, the optimal design of guyed towers cannot disregard the uncertainties in the definition of wind load and the dynamic characteristics of the structure.

The first aim of the present paper is to present an optimization framework providing both reliability and robustness. A solution strategy based on an enhanced Monte Carlo sampling method, an evolutionary algorithm, inverse probabilistic constraints and artificial generation of wind load time histories is proposed. The procedure is particularly appropriate for slender structures, like cable stayed masts and chimneys, as it can tackle all the peculiarities of wind sensitive flexible structures, like geometric nonlinearity, uncertainty in load definition, uncertainty in modal characteristics and cable prestress dynamics. The second goal is to compare robust and reliable solutions and highlight the differences in terms of structural performance for different values of the parameters characterizing the definition of the objective function and the constraints.

The outline of the paper is as follows. After a brief literature review of reliability-based optimization methods and robust optimal design approaches (Sections 2), the proposed framework for RBRDO is presented in Section 3. Section 4 describes in detail the particular case study examined, while the main results obtained from the numerical simulations are presented in Section 5. Finally, some concluding remarks are given in Section 6.

2. Optimization problem considering uncertainties

The mathematical statement of an optimization problem under uncertainties can be written as follows:

$$\begin{aligned} &\text{find} \quad \mathbf{y} \\ &\text{minimizing} \quad F(\mathbf{y},\mathbf{x}) \\ &\text{subject to } G_i(\mathbf{y},\mathbf{x}) \le 0, \quad i = 1, \ldots, I \\ &\quad \mathbf{y}_{min} \le \mathbf{y} \le \mathbf{y}_{max} \end{aligned} \tag{1}$$

where **y** is the vector of the deterministic design variables, F is the objective function, G_i are functions defining the set of I inequality constraints, $\mathbf{y}_{min}$ and $\mathbf{y}_{max}$ are the lower and upper bounds of the design variables. The vector **x** contains random variables representing uncertainties.

In structural engineering problems, the constraint functions G_i are usually limit state functions assuring the structural safety:

$$G_i(\mathbf{y},\mathbf{x}) = \hat{y}_i(\mathbf{y},\mathbf{x}) - LS_i \tag{2}$$

where $\hat{y}_i$ are the peak response functions and LS_i are the limit states thresholds. As the limit state functions depend on uncertain parameters, it is not possible to guarantee that the inequality $G_i(\mathbf{y},\mathbf{x}) \le 0$ in Eq. (1) is always satisfied but it is possible to maintain sufficiently small the probability of failure, obtained by integrating the joint probability density function over the failure domain:

$$P_{f,i}(\mathbf{y}) = \int_{G_i(\mathbf{y},\mathbf{x}) \le 0} f_{\mathbf{x}}(\mathbf{y},\mathbf{x})\, d\mathbf{x} \tag{3}$$

where $P_{f,i}(\mathbf{y})$ is the failure probability associated with the ith failure mode and $f_{\mathbf{x}((\mathbf{y},\mathbf{x})}$ is the joint probability density function of the random variables. Direct integration of Eq. (3) is often impossible and numerical methods are applied to give an approximation of it.

2.1. Reliability-based design optimization

Reliability based design optimization (RBDO) is aimed at obtaining cost-effective designs characterized by a low probability of failure. The targets of lowering costs and increasing reliability are competing between each other, hence the need of setting acceptable reliability thresholds (Smith and Caracoglia, 2011). In designing systems with multiple failure modes, it is important that the solution is sufficiently reliable with respect to each critical failure mode (Wen, 2001). In a RBDO formulation, failure modes are taken into account through constraints on probabilities of failure. The reliability index or the probability of failure can be computed by performing a probabilistic reliability analysis (Nowak and Collins, 2000).

A general RBDO problem can be stated as follows:

$$\begin{aligned} &\text{find} \quad \mathbf{y} \\ &\text{minimizing} \quad F(\mathbf{y},\mathbf{x}) \\ &\text{subject to } P_{f,i}(\mathbf{y},\mathbf{x}) \le P_{f,i}^{acc}, \quad i = 1, \ldots, I \\ &\quad \mathbf{y}_{min} \le \mathbf{y} \le \mathbf{y}_{max} \end{aligned} \tag{4}$$

where $P_{f,i}(\mathbf{y},\mathbf{x})$ is the failure probability associated with the ith failure mode and $P_{f,i}^{acc}$ is the corresponding acceptable value.

Two main approaches can be identified for the approximate evaluation of the convolution integral in Eq. (3): the first approach comprehends approximate reliability techniques like first and second order reliability methods (FORM and SORM) (Enevoldsen and Søresen, 1994; Di Sciuva and Lomario, 2003; Chen et al., 2014) and dimension reduction method (DRM) (Li and Zhang, 2011) and the second approach includes simulation techniques like decoupling approach (Jensen and Catalan, 2007; Spence and Gioffré, 2011) and direct integration with optimization algorithms (Jahani et al., 2014). Early works on analytical evaluations of failure probability introduced the first order second moment reliability index (Hasofer and Lind, 1974). First order refers to the order of the Taylor approximation of the failure function whereas second moment refers to the statistical measure used to describe the stochastic variables. FORM is accurate and efficient method when the limit state equation is linear, whereas SORM is used when the nonlinearity of the limit state equation is significant.

Most RBDO procedures are computationally expensive by nature, as the reliability analysis is nested in the solution of the optimization problem (double-loop method). Moreover, the computational effort associated with RBDO grows exponentially as the number of random variables and the number of critical failure modes increase. To alleviate the high computational cost, researchers have developed sequential RBDO methods (Royset et al., 2001; Zou and Mahadevan, 2006; Cho and Lee, 2011) where a design obtained by performing a deterministic optimization is updated based on the information obtained from the reliability analysis or by using some nonlinear transformations, and the updated design is used as a starting point for the next cycle. Moreover, RBDO requires the repeated evaluation of the structural response for different sets of design variables and uncertain parameters and the evaluation of the structural response may require finite element (FE) analyses. To solve this problem, several