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Optimization of uncertain and dynamic high-rise structures for occupant comfort: An adaptive kriging approach

Seymour M.J. Spence

Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109, USA

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ABSTRACT

Performance requirements concerning serviceability often govern the design of high-rise structures. While various methods have been proposed for obtaining optimal systems that meet serviceability constraints set on the performance of non-structural components, e.g. the cladding system, methods are still lacking for optimizing under constraints aimed at ensuring occupant comfort. This is especially true for systems whose performance is assessed within modern performance-based design frameworks that consider a full range of uncertainties, including wind loads modeled as stochastic processes. This paper is focused on the development of a novel optimization framework for overcoming these limitations. The method is based on constructing an adaptive kriging metamodel of the probabilistic performance metric of interest in the low-dimensional modal space of the system. By then relating this space to the design variables, an approach is defined that can handle a wide class of occupant comfort metrics within high-dimensional spaces of design variables and uncertain parameters.

1. Introduction

The design of high-rise structures is often governed by wind-induced limit states on serviceability performance that aim to ensure the integrity of the interior and exterior finishes, i.e. cladding system, as well as the comfort of the building's occupants. This last can also be a critical limit state in the case of low-rise buildings equipped with base isolation devices [1–4]. Indeed, these devices have the effect of decreasing the fundamental vibration frequencies of the structure, therefore increasing sensitivity to wind induced vibrations. While limit states associated with the interior and exterior finishes are often in terms of interstory drift, occupant comfort is in general related to the acceleration response of the system [5–7]. Various measures of acceleration have been considered as indicators of possible occupant discomfort including peak values, standard deviations, and rate of acceleration change (i.e. jerk) [8–10]. Once a measure of acceleration has been identified, the problem becomes the need to limit this measure during the design process.

A common approach to this end is to add auxiliary damping devices to the structural system [11]. In alternative, a number of studies have proposed methods that directly optimize the structural system in order to meet the acceleration targets [12–15]. These approaches are centered on the observation that the acceleration response of a typical wind-excited high-rise building can be effectively reduced by increasing the system's fundamental natural frequencies [12]. In this respect, methods have been developed for deterministic systems subject to constraints on both standard deviation and peak accelerations [12,13]. Methods have also been developed that allow for the treatment of system uncertainties using traditional reliability models [14,15]. However, approaches that allow for the optimization of uncertain high-rise structures subject to wind loads modeled as general stochastic processes have yet to be developed. Such models would allow for the optimization of high-rise systems whose performance is described in terms of recently proposed simulation-based probabilistic performance-based design (PBD) frameworks (e.g. [7,16–20]). They would also circumvent the limitations and complexities involved in describing combinations of peak wind effects, e.g. resultant accelerations, through upcrossing rates based on the Rice formula and its variants [21,22].

A major challenge to the development of such a framework is the need of methods that can treat high-dimensional (order of thousands) uncertain spaces—necessary for the modeling of the stochastic processes—together with high-dimensional design spaces (order of hundreds), which typically characterize the design of high-rise systems. Indeed, while a number of robust simulation-based optimization strategies exist that can handle constraints on accelerations over high-dimensional uncertain spaces (e.g. [23–28]), these methods are generally limited to low-dimensional design spaces, i.e. a dozen or so free design parameters [29]. For example, methods based on building local or global metamodels in the space of the design variables are limited by the need to directly explore, globally or locally, the design space during the construction of the metamodel. This fast becomes computationally prohibitive as the number of free parameters increases. A similar curse of dimensionality will in general affect methods based on local

E-mail address: smjs@umich.edu.

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approximations constructed from the gradients of the performance functions. Indeed, these last are generally implicit functions of the design variables that require a probabilistic analysis for their evaluation. As the number of free parameters grows, so does the computational effort necessary for the evaluation of the gradients. To avoid the estimation of the gradients, genetic/evolutionary algorithms have recently been used in optimization of structures subject to general stochastic wind excitation [30]. However, these methods become computationally challenging in the case of large-scale finite element models as genetic/evolutionary algorithms generally require thousands of evaluations of the performance functions for convergence. This is especially true in the case of high-dimensional design spaces [31]. In fairness, it should be observed that these limitations are, broadly speaking, a consequence of the generality of the above outlined methods. Indeed, many are designed to handle general objective/constraint functions as well as nonlinearity in the system responses.

This paper is focused on the development of a novel optimization strategy that can overcome these limitations in the specific case of uncertain high-rise structures subject to stochastic wind loads.

2. Occupant comfort in high-rise buildings

2.1. Assessment of occupant comfort

The assessment of occupant comfort performance of a high-rise structure generally requires that a measure of the acceleration response, $\hat{a}$, be estimated and compared to a target value, $\tilde{a}$, for a windstorm of mean recurrence interval (MRI) y. If $\hat{a}$ is treated as a random variable, i.e. uncertainties are considered in the system parameters and wind excitation, the preceding statement implies that a designer must ensure that the following inequality is true:

$$P_{\text{exc}|y}(\tilde{a}) = P(\widehat{A} > \tilde{a}|y) \leqslant \widetilde{P}_{\text{exc}|y} \tag{1}$$

where $P_{\text{exc}|y}(\tilde{a})$ is the probability that the acceleration response $\hat{a}$ exceeds the target value $\tilde{a}$ conditional on an event of MRI y, while $\widetilde{P}_{\text{exc}|y}$ is the acceptable conditional exceedance probability that must be chosen by the designer, or more in general, the stakeholder. In writing Eq. (1), it should be observed that $\hat{a}$ is intended here as a general measure of acceleration response that can depend on complex phenomena related to the sensitivity of the human body to vibrations at different frequencies. Indeed, many international standards define $\tilde{a}$ as a function of the frequency response of the building (e.g. [32]), while recent studies have also discussed the use of total frequency weighted accelerations [4]. The assessment of occupant comfort performance within this setting therefore requires the estimation of the following probabilistic integral:

$$P_{\text{exc}|y}(\tilde{a}) = 1 - F_{\widehat{A}|y}(\tilde{a}) = 1 - \int_{D(\mathbf{u})} f_{\mathbf{u}|h}(\mathbf{u}|y)d\mathbf{u} \tag{2}$$

where $F_{\widehat{A}|y}$ is the conditional distribution function of $\widehat{A}$, $\mathbf{u}$ is a vector of random parameters modeling the uncertainties in the system parameters (e.g. damping, natural frequencies, etc.) as well as the external wind excitation, $f_{\mathbf{u}|y}$ is the conditional joint probability density function of $\mathbf{u}$, while $D(\mathbf{u})$ is the domain in which $\widehat{A} \leqslant \tilde{a}$. If the stochastic nature of the external wind excitation is explicitly modeled (as in this work), then the probabilistic integral of Eq. (2) will be high-dimensional and therefore generally require estimation using robust simulation methods such as Monte Carlo or Subset Simulation.

Instead of writing the performance requirement of Eq. (1) in terms of probabilities, it is often convenient to write it in terms of the acceleration quantile with conditional exceedance probability $\widetilde{P}_{\text{exc}|y}$. Under these circumstances, the performance requirement of Eq. (1) takes the form:

$$\hat{a}(P_{\text{exc}|y}) \leqslant \tilde{a} \tag{3}$$

where $\hat{a}(P_{\text{exc}|y})$ is the acceleration quantile that can be estimated as:

$$\hat{a}(P_{\text{exc}|y}) = F^{-1}_{\widehat{A}|y}(1 - P_{\text{exc}|y}) \tag{4}$$

where $F^{-1}_{\widehat{A}|y}$ is the inverse conditional distribution function of $\widehat{A}$. The two formulations of the performance requirement are equivalent. From the standpoint of optimization, the formulation of Eq. (3) can be preferable, as constraints written in terms of quantiles instead of probabilities often provide superior convergence behavior [33].

2.2. Optimization problem

The design of an engineering system generally consists in assigning values to a set of free parameters $\mathbf{x}$ (e.g. the section sizes in structural design) that ensure the satisfaction of a number of performance objectives (e.g. the performance requirements of Eq. (1) or Eq. (3)) while minimizing the overall cost, C, of the system. With respect to the occupant comfort problem of Section 2.1, this design problem can be written in the form of the following optimization problem:

$$\begin{aligned}
&\text{Find} \quad \mathbf{x} = \{x_1, \dots, x_M\}^T \\
&\text{to minimize} \quad C(\mathbf{x}) \\
&\text{s. t.} \quad \hat{a}_j(\mathbf{x}; P_{\text{exc}|y}) \leqslant \tilde{a}_j \quad \text{for} \quad j = 1, \dots, N_c \\
&x_m \in \mathbb{X}_m \quad m = 1, \dots, M
\end{aligned} \tag{5}$$

where $\hat{a}_j$ is the jth acceleration-based occupant comfort performance measure of interest, N_c is the total number of constraints, $\tilde{a}_j$ is the corresponding threshold value, while $\mathbb{X}_m$ is the interval to which the mth component of the design variable vector must belong.

For problems characterized by a large number of design parameters, e.g. the structural design problems of this work, the resolution of the optimization problem outlined above is not straightforward due to the complexity of the constraint functions. Indeed, not only are the constraints implicit in $\mathbf{x}$, therefore significantly hindering gradient evaluation and hence gradient-based optimizers, but they also require a full probabilistic analysis (e.g. a Monte Carlo simulation) for their evaluation, therefore significantly hindering the use of evolutionary-based optimizers, which require repeated evaluation of the system.

To overcome this fundamental difficulty, methods are required for accelerating the evaluation of the constraint functions for any given design, i.e. value of $\mathbf{x}$. In this work, an approach based on adaptive kriging will be introduced that allows for the rapid evaluation not only of the constraint functions, but also of their gradients with respect to $\mathbf{x}$. This will allow the use of efficient gradient-based optimizers therefore enabling rapid resolution of the optimal design problem of Eq. (5).

3. Response and wind load modeling

3.1. Response model

In general, the acceleration response of a structural system can be estimated within a modal framework. This approach entails estimating the structure's first n modal acceleration responses $\ddot{q}_i(t)$ for $i = 1, \dots, n$. These last can be determined by solving the following n independent modal equations, where, without loss of generality, the uncertain modal parameters are decomposed into a deterministic (nominal) component and a random fluctuation:

$$\ddot{q}_i(t) + 2(\xi_i + \delta\xi_i)(\omega_i + \delta\omega_i)\dot{q}_i(t) + (\omega_i + \delta\omega_i)^2 q_i(t) = \frac{(\boldsymbol{\phi}_i + \delta\boldsymbol{\phi}_i)^T \mathbf{f}(t; \overline{V}_y, \alpha)}{(\overline{m}_i + \delta m_i)} \quad i = 1, \dots, n \tag{6}$$

where: q_i and $\dot{q}_i$ are the ith mode's displacement and velocity response; ξ_i, ω_i, m_i, and $\boldsymbol{\phi}_i$ are the nominal values of the ith mode's damping ratio, natural circular frequency, generalized mass and mode shape; $\delta\xi_i$, $\delta\omega_i$, δm_i, and $\delta\boldsymbol{\phi}_i$ are the random fluctuations of the ith modal parameters around their nominal values; $\overline{V}_y$ is the wind speed at top of the building with an MRI of y years; α is the direction of the wind event; while $\mathbf{f}$ is a vector of stochastic wind loads evaluated for α and $\overline{V}_y$. To

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