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Data-Enabled Design and Optimization (DEDOpt): Tall steel building frameworks

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ABSTRACT

Recent increases in computational resources and speed have opened the door to the possibility of integrating informational databases into the design process of civil structures. The aim of this paper is twofold. Firstly, efficient time/frequency domain procedures for the estimation of local and global load effects are presented with focus on the use of proper orthogonal decomposition of the spectral and covariance matrices. Secondly, a procedure is presented that fully automates the design procedure through the rigorous discrete member size optimization of the structural system subject to multiple performance constraints on both the local and global load effects.

1. Introduction

The possibility of using databases of simultaneously recorded aerodynamic pressure measurements characterizing the external pressure field acting on the surface of rigid building models represents one of the two main methods for estimating wind loads acting on tall buildings, the other being the High Frequency Base Balance (HFBB) that measures the dynamic base reactions of rigid building models [1,2]. While both methods have their advantages and disadvantages, it is generally accepted that the first method, termed Synchronous Multi-Pressure Sensing System (SMPSS) method, yields the most complete information concerning the dynamic wind loads acting on the building surface. Traditionally the HFBB was the tool of choice due to a reduced amount of data that needs to be stored during wind tunnel tests, compared to the SMPSS technique, and due to the close relation of the base moments to the fundamental generalized forces of the structure allowing the direct utilization of the measured aerodynamic loads in the dynamic response estimation of the building [3–5]. This led to the development of a number of analysis schemes that attempt to generalize the HFBB technique therefore allowing its application to building systems that exhibit for example coupled and non-linear fundamental mode shapes through the definition of appropriate correction coefficients [6–9]. Together with the HFBB approach for estimating the aerodynamics of tall buildings based on a significantly reduced quantity of experimental data, procedures were developed for the expedient dynamic analysis based on a truncated modal analysis [3,10]. These procedures were based in the frequency domain for the simple reason that this again reduced the computational burden. Together with modal truncation a number of other approximations were introduced that took advantage of the particular dynamic response characteristics of traditional tall buildings, for example the neglect of the cross spectral densities of the fundamental generalized forces due to their relative insignificance in the response of tall buildings with uncoupled modes. Over the years these methods have been refined and generalized and now represent an extremely efficient and well vetted baseline for approximately estimating the dynamic performance of wind excited tall buildings [4,5]. Further refinements have also been reported since then [11, e.g.].

Over the past decade or so there has been an explosion in the availability of computational resources and speed. This has opened the door to the possibility of using large data sets of detailed aerodynamic and climatological information in the design of tall buildings and in general civil infrastructure. Concerning tall buildings, methods have been developed that use large data sets of HFBB measurements [12], as well as SMPSS measurements [13–16] during their wind resistant design. These last have been commonly coupled with dynamic response estimation techniques set in the time domain with the possible conviction that frequency domain approaches are not suited for accurately estimating the dynamic response of tall buildings [14,16]. This misconception most probably has its roots in associating frequency domain analysis with the traditional approximate methods that normally go hand in hand with the HFBB technique for the aerodynamic characterization [4,5]. However, when dealing with multicorrelated stationary random process/fields, such as pressure fluctuations on structures

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exhibiting linear dynamic behavior, the frequency domain is not only dual to the time domain, but it also offers a number of possible data compression/reduction schemes that could significantly enhance the attractiveness of data-driven design and optimization procedures.

In particular the possibility of applying a covariance/spectral Proper Orthogonal Decomposition (POD) framework, based on the work described in [17–24], to the covariance matrix and full cross power spectral density (XPSD) matrix of the SMPSS estimated floor load vector would seem particularly interesting. This would not only provide physically meaningful insight into the loading process, but, more importantly, it is recognized that in recombining the decomposed spectral floor load structure only a small number of eigenmodes corresponding to eigenvalues with larger magnitudes are dominant allowing significant mode truncation of the loading process to be performed. This would result in considerably higher computational efficiency in comparison to time domain procedures without any undue loss of accuracy or phase information (provided by the cross spectra of the recomposed spectral structure). Having said this, investigation into exactly how many loading modes are necessary for accurately describing both local (i.e. demand to capacity ratios) and global (inter-story drift ratios) load effects is necessary, as there has been some indication that for local responses a considerable number of loading modes must be kept [21,22].

Alongside the efficient dynamic response estimation and successive combination with data sets of directional wind climate information yielding responses with specified Mean Recurrence Intervals (MRIs), the possibility of performing discrete section size optimization is of particular interest to any data-enabled design setting as this would eliminate the traditionally iterative trial-and-error procedure that can become particularly cumbersome during a data-intensive analysis scheme. Discrete section size cost optimization of tall buildings has been the focus of numerous research projects over the years [25–28]. However, these methods are not directly applicable to a data-enabled design setting where probabilistic peak responses with specified MRIs, that rigorously account for wind directionality, need to satisfy specified performance targets. Indeed, traditional optimization schemes, including those recently proposed [27,28], are based on the concept of defining a limited number of idealized Equivalent Static Wind Loads (ESWLs) derived from a carefully but arbitrarily chosen critical load effect (usually base moments or top floor displacements). MRIs are then inferred to these ESWLs through appropriate scaling to non-directional wind climates. In order to optimize the cost of a structural system analyzed in a data-enabled environment, optimization procedures capable of handling large numbers of inequality constraints on implicit probabilistic response functions must be defined.

This paper proposes a Data-Enabled Design and Optimization (DEDOpt) framework that estimates the dynamic response in the time domain or in the frequency domain. In particular emphasis is placed on the possibility of developing an extremely efficient reduced order frequency domain approach based on the concept of spectral/covariance decomposition. In a second step, large scale discrete optimization procedures are proposed for minimizing the material cost of tall steel frameworks subject to multiple load combinations and performance targets on peak responses with specified MRIs. In particular, peak inter-story drift ratios over critical column lines and peak demand to capacity ratios over all members composing the structural system are limited.

2. Problem statement

Consider a tall building with N floors and M generalized members making up the structural system. Now consider K column lines for which the inter-story drift ratio with specific MRI, y_d, is to be controlled in two orthogonal directions ($s = X, Y$). With the objective of minimizing the weight, W, of the structure in terms of a vector of discrete design variables, $\mathbf{x} = [\mathbf{x}_1, \ldots, \mathbf{x}_M]^T$, while ensuring that specified performance targets are met for the peak inter-story drift and member capacity ratios under L load combinations, also with specified MRI y_b, the following discrete member size optimization problem may be defined:

$$\text{Find} \quad \mathbf{x} = [\mathbf{x}_1, \ldots, \mathbf{x}_M]^T \tag{1}$$

$$\text{to minimize} \quad W(\mathbf{x}) \tag{2}$$

subject to:

$$\begin{gathered}\underbrace{\hat{d}_{cks}(\mu_{d_{cks}}, \sigma_{d_{cks}}, g_{d_{cks}})}_{y_d} - \tilde{d}_{ck}^{y_d} \leqslant 0 \\ (c = 1, \ldots, N) \ (k = 1, \ldots, K) \ (s = X, Y)\end{gathered} \tag{3}$$

$$\begin{gathered}\underbrace{\hat{b}_{il}(\mu_{b_{il}}, \sigma_{b_{il}}, g_{b_{il}})}_{y_b} - \tilde{b}_i^{y_b} \leqslant 0 \\ (i = 1, \ldots, M) \ (l = 1, \ldots, L)\end{gathered} \tag{4}$$

where $\hat{d}_{cks}$ and $\hat{b}_{il}$ are the peak response functions given in terms of their second order response statistics, $\mu_{d_{cks}}$, $\sigma_{d_{cks}}$ and $\mu_{b_{il}}$, $\sigma_{b_{il}}$ respectively, and their peak factors $g_{d_{cks}}$ and $g_{b_{il}}$; $\tilde{d}_{ck}^{y_d}$ and $\tilde{b}_i^{y_b}$ are the performance targets for the inter-story drift and capacity ratios; while $\mathbf{x}_i = \{x_1, x_2 \ldots\}_i^T$ are discrete sets of possible values that may be taken by the components of the design variable vector $\mathbf{x}$ indicating, for instance, how member i must belong to a standard steel profile (e.g. a AISC W30 profile). It should be observed that the problem is outlined in terms of generalized members (i.e. each generalized member, referred to hereafter simply as a member, will in general be composed of a group of members with the same profile).

The focus of this paper is twofold. Firstly, methods are presented for the rapid and accurate estimation of the peak response functions $\hat{d}_{cks}$ and $\hat{b}_{il}$ with specified MRIs y_d and y_b, calculated in a data-enabled design setting by integrating into the analysis procedures large data sets of directional SMPSS measurements characterizing the aerodynamic performance of the structure and climatological information describing the site-specific directional wind hazard intensity. Secondly, a procedure is proposed for rigorously and efficiently solving the large scale discrete optimization problem outlined in Eqs. (1)–(4) for tall steel frameworks designed in satisfaction of the AISC steel specifications.

3. Response estimation

The global behavior of tall buildings can be modeled by an equivalent dynamic system considering each floor to have three degrees of freedom (i.e. x- and y-displacement of the center of mass relative to the ground and θ-rotation about a vertical axis through the center of mass) [3,5]. Under these hypotheses the dynamic equilibrium of an N story building with mass and stiffness eccentricities which can vary from floor to floor is given by:

$$\mathbf{M}\ddot{\mathbf{z}}(t) + \mathbf{C}\dot{\mathbf{z}}(t) + \mathbf{K}\mathbf{z}(t) = \mathbf{f}(t, \mathbf{v}) \tag{5}$$

where $\ddot{\mathbf{z}}(t)$, $\dot{\mathbf{z}}(t)$ and $\mathbf{z}(t)$ are the response vectors, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the $3N \times 3N$ mass, damping and stiffness matrices respectively while $\mathbf{f}(t, \mathbf{v})$ is the $3N \times 1$ vector of the time varying stationary forcing functions acting at the centers of mass of each floor and evaluated for the hazard intensity $\mathbf{v} = \{\bar{V}_H, \alpha\}$ characterized by the mean wind speed $\bar{V}_H$ occurring at the top of the building of height H and the incident wind direction α. The following sections will focus on methods for determining the solution, in terms of a generic response R, to Eq. (5).