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A cyberbased Data-Enabled Design framework for high-rise buildings driven by synchronously measured surface pressures

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ABSTRACT

This study presents a new Data-Enabled Design Model for high-rise buildings driven by pressure datasets, DEDM-HRP, which seamlessly combines synchronous pressure measurement databases with a rigorous computational framework to offer convenient estimation of wind load effects on high-rise buildings for their preliminary design. To respond to the need for practical applications, DEDM-HRP employs a web-based on-the-fly framework designed with user-friendly/intuitive web interfaces for the assessment of wind-induced responses as well as equivalent static wind loads in the three principal response directions, for any incident wind angle of interest, with minimum added complications or requirements of knowledge of comprehensive background theories for its use.

1. Introduction

Globally, high-rise buildings are becoming an ever more desirable venue for both businesses as well as residences. This has brought about trends toward structures with increasing heights, complex profiles and lighter more slender construction, all of which has increased their sensitivity to the action of wind. Although most international wind standards offer provisions for calculating wind load effects on tall buildings, they generally rely on simplified methodologies and formats. Indeed, most standards primarily focus on the estimation of alongwind load effects through the adoption of a quasi-steady gust loading factor approach (e.g., [1–6]). The codes and standards that do consider response directions other than alongwind, i.e. the acrosswind and torsional directions, generally do so in a limited and empirical manner (e.g., [7–9]). Due to this limitation, wind tunnel experiments are generally necessary for appropriately estimating the response of wind excited structures. For tall buildings, the two most important experimental techniques to this end are the high frequency base balance (HFBB) approach (e.g., [10–13]) and the synchronous pressure measurement (SPM) approach (e.g., [14,15]). The HFBB technique consists in measuring the base forces/moments on rigid models in wind tunnel tests and therefore, after appropriate scaling, allows to conveniently quantify the fundamental generalized wind forces acting on tall buildings that exhibit uncoupled linear fundamental translational mode shapes and constant first torsional mode shape. To account for non-ideal fundamental mode shapes, corrections are in general required that can either be based on empirical relationships/analytical formulations (e.g., [13,16–21]) or, more recently, on probabilistic models [22,23] to be included in appropriate reliability frameworks (e.g. [24,25]), that allow the propagation of the inevitable uncertainties generated by non-ideal fundamental modes [26] to the response. The SPM technique, on the other hand, is based on synchronously measuring the pressure field in wind tunnel tests on rigid building models equipped with a number of pressure taps distributed over the model's surface [27,28]. The advantage of this method compared to the HFBB is the possibility of directly assessing the local and global aerodynamic loads acting on the structure. This allows for the direct estimation of any number of coupled and non-linear generalized forces (e.g., [29,30]). The only drawback of this approach compared to the HFBB technique is the considerably larger amount of data associated with the measurements and the higher costs of the experimental setup.

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Nomenclature

AIJ	Architectural Institute of Japan
ASCE	American Society of Civil Engineering
DED	Data-Enabled Design
DEDM-HRP	Data-Enabled Design Module for High-Rise buildings driven by Pressure datasets
ESWL	Equivalent Static Wind Load
HFBB	High Frequency Base Balance
NALD	NatHaz Aerodynamic Loads Database
SPM	Synchronous Pressure Measurement
TPU	Tokyo Polytechnic University
Δ_{ax}, Δ_{ay}	x and y coordinates of the point on the top floor where the acceleration is to be estimated (Fig. 1)
dr_x, dr_y	x and y distances of the design column, respectively (Fig. 1)
Δ_{dx}, Δ_{dy}	x and y coordinates of the point on the top floor where the displacement is to be estimated
e_{ix}, e_{iy}	x and y components of the eccentricity of the mass center at the ith floor, respectively (Fig. 1)
d_{ix}, d_{iy}	inter-story drift responses in the x and y directions at the ith floor, respectively
a_{px}, a_{py}	acceleration responses in the x and y directions at point p, respectively
N	number of building stories
x, y, θ	response directions (Fig. 1)
$\bar{\mathbf{F}}_s$	mean loading sub-vector in the s direction
$\mathbf{F}_s$	zero mean aerodynamic loading sub-vector in the s direction
$\mathbf{M}, \mathbf{I}$	mass and inertia sub-matrices, respectively
$\mathbf{C}_{sl}, \mathbf{K}_{sl}$	damping and stiffness sub-matrices in the sl direction, respectively
$\mathbf{U}_s, \dot{\mathbf{U}}_s, \ddot{\mathbf{U}}_s$	displacement, velocity, and acceleration response sub-vectors in the s direction, respectively
n	number of modes kept in the model truncation
$m_j, Q_j, \zeta_j, \omega_j, \Phi_{js}$	jth generalized mass, force, damping ratio, circular frequency, mode shape sub-matrix in the s direction, respectively
$q_j, \dot{q}_j, \ddot{q}_j, \sigma_{q_{jr}}$	jth generalized displacement, velocity, and acceleration response, as well as standard deviation of the resonant modal response, respectively
Γ_j	jth modal participation coefficient for R
R	a generic response parameter, e.g., base moments, shears and displacements, etc.
$\mu_R, \sigma_R, \sigma_{\dot{R}}$	mean and standard deviation of the response process R as well as the standard deviation of its derivative, respectively
g, g_b, g_r	peak factor, background peak factor and resonant peak factor, respectively
h_3, h_4, κ	Hermite model coefficients
γ_3, γ_4	skewness and excess kurtosis, respectively
γ	Euler's constant
ν_0	zero crossing rate
T	observation period in seconds
M_b, M_r	background and resonant base moment/torque, respectively
W'_{M_b}, W_{jM_r}	weighting factors with respect to M_b and M_r, respectively
$\mathbf{C}_{\mathbf{F}_s}$	covariance of the aerodynamic loads acting in the s direction
$\mathbf{F}'_{ebs}, \mathbf{F}_{ejrs}$	s direction gust loading envelope and inertial ESWL, respectively
$\mathbf{F}_{eM_bs}, \mathbf{F}_{ejrs}, \mathbf{F}_{eMs}$	s direction background, resonant and total ESWLs, respectively
β	wind direction
U	mean wind speed profile
H	building height
U_H	mean wind speed at the building height H
α	power law exponent of the mean wind velocity profile
B, D	building width and depth, respectively
ρ_A, ρ_B	air and building bulk density
C_D	drag coefficient

The central role played by these experimental procedures during the wind response estimation of structures has led to the establishment of aerodynamic databases of HFBB or SPM measurements for a variety of building geometries. Some examples of such databases are the NatHaz HFBB aerodynamic loads database (NALD) ver. 1.0 [31] for tall buildings, the SPM database of the National Institute for Standards and Technology (NIST) for gable-roofed low-rise buildings [32–36] and the Tokyo Polytechnic University (TPU) database of SPM measurements for low-rise and high-rise buildings [37]. The development of analysis/design procedures driven by these databases has spawned a promising analysis/design methodology, generally termed Data-Enabled Design (DED), which offers convenient fusing of experimental datasets with up-to-date computational analysis/design schemes. Recognizing the usefulness of the DED approach, ASCE 7 has begun to suggest this methodology as a supplemental procedure, e.g. ASCE 7-05 indicates NALD ver. 1.0 for providing guidance at the preliminary design stages of tall buildings, and, more recently, the NIST aerodynamic database has been included in the ASCE 7-10 Commentary. However, such procedures are often difficult to use unless the end-users are familiar with the treatment and management of the numerous wind tunnel datasets that often necessitate the knowledge of comprehensive background theories for correct interpretation. A possible way to address this difficulty is through the introduction of information-/web-based technologies. Indeed, these technologies have begun to emerge as a promising means for solving traditional challenges concerning the user-friendly and efficient interaction with data intensive civil engineering problems such as structural health monitoring (e.g., [38–41]) and construction management (e.g., [42–44]). These approaches are likely to become ever more poignant due to the explosion in network-enabled devices such as desktop/laptop computers, smartphones and tablets, therefore making world-wide-web based technologies/interfaces an important root for facilitating active interaction of geographically dispersed researchers/engineers. Concerning the DED of high-rise buildings, this approach has been explored during the development of the HFBB database-driven analysis/design framework NALD ver. 2.0 [29,45] which is a fully web-based preliminary design tool, publicly available at http://aerodata.ce.nd.edu or https://vortex-winds.org. However, at present, no such on-line on-the-fly analysis/design framework exists for SPM databases. Indeed, while the concept of analysis/design frameworks that use SPM datasets coupled with time domain dynamic response analysis has been proposed in recent years [46–48], these are strictly off-line procedures that require not only the download of the source codes, but also that the user provide, in an appropriate format, the SPM dataset to be used during the response analysis as well as large amounts of information pertaining to the influence coefficients of the numerous design sections of typical tall buildings.