Journal of Wind Engineering & Industrial Aerodynamics 182 (2018) 61–71

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

A time-domain method for predicting wind-induced buffeting response of tall buildings

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1. Introduction

The past few years have seen an increasing number of tall buildings, made possible through advancement of construction technology and adoption of lightweight and high-strength materials, all of which enable such buildings achieve heights that had never been reached before. As buildings become taller they become more vulnerable to wind excitations because of increased flexibility. Large-amplitude vibrations induced by wind loads could lead to occupant discomfort, structural damage, and even catastrophic failure. As a result, a number of methods have been proposed during the past few decades to predict the response of tall buildings under different types of wind loads and they can be broadly classified into frequency-domain methods and time-domain methods.

Wind-induced response analysis of tall buildings is usually performed in the frequency-domain using random vibration theory, in which the response is estimated by the multiplication of load spectra obtained from measurement of fluctuating pressure and the frequency response function (FRF) of the building. Methods to estimate the RMS or peak value of the displacement and acceleration of a tall building, both in across-wind and coupled along-wind and torsional directions, have been developed (Kareem 1982, 1985, 1992). The High Frequency Force Balance (HFFB) technique serves as another efficient way to estimate wind-induced response of a tall building in the preliminary design stage, mainly because of its convenience in approximating the generalized force. Zhou et al. (2002) created an interactive database consisting of high-frequency base balance measurements on tall building models with different cross-sections, in addition, numerous methods have been suggested to make the HFFB method more applicable, such methods can be found in (Kim et al., 2011; Bernardini et al., 2013; Zou et al., 2017). A critical review made by Chen et al. (2014) described the analysis framework of the HFFB method as well as the procedure for mode shape correction. The Gust Loading Factor (GLF) method, used to estimate equivalent static wind load (ESWL), has been adopted as the standard method in many countries to evaluate the extreme response in the along-wind direction of tall buildings since its introduction by Davenport (1967). A comprehensive study was performed by Zhou et al. (2002) with the purpose of assessing differences that exists between various codes and standards. Since the GLF method fails to provide a meaningful assessment of wind loads in the across-wind and torsional direction, whose mean values are typically zero, a number of advanced ESWL modeling examples have been put forth and extensively discussed in the literature (Kasperski, 1992; Holmes, 2002; Repetto and Solari, 2004; Huang and Chen, 2007). In addition to the methodologies mentioned above, the frequency-domain method has been widely adopted to study the response induced by buffeting loads because buffeting loads can be expressed in terms of wind turbulence spectra and aerodynamic admittance function, which could result in significant computational efficiency (Liepmann, 1952). Despite its popularity, the frequency-domain method cannot predict the response for tall buildings continuously in real time because wind loads or wind-induced responses are generally expressed in terms of mean or RMS values. Although Chen (2008) used a frequency-domain method to study along-wind tall building response subject to nonstationary transient winds, the nonlinear and evolutionary characteristics of loads and their interaction with buildings under transient wind conditions make the frequency-domain method impractical to use.

The time-domain method is more suitable than the frequency-domain method for transient response calculation, feedback control design, and fatigue analysis of tall buildings. Time histories of wind loads can be simultaneously simulated at different levels of a tall building, enabling direct assessment of wind-induced response of tall buildings in the time domain (Lam and Li, 2009; Bernardini et al., 2012, 2013). While this approach is widely used for its versatility, independent of geometry or shape of the building, it only works well for fundamental vibration modes. Fatigue analysis can also be carried out in time domain, for example, Kim et al. (2014) calculated the normal stresses on tall buildings by directly inputting the force obtained from pressure measurement on each floor. Chen (2014) presented an analysis framework for

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https://doi.org/10.1016/j.jweia.2018.09.013
Received 30 June 2018; Received in revised form 2 September 2018; Accepted 11 September 2018

investigating the fatigue in the across-wind direction while considering nonlinear aerodynamic damping. In addition, Feng and Chen (2017, 2018) presented an analytical approach that allows for a closed-form solution of wind-induced response of tall buildings with nonlinear restoring force and aerodynamic damping.

With ever-increasing computing power and ever-reducing computer costs, Computational Fluid Dynamics (CFD) has increasingly grown as a popular tool for solving fluid-structure interaction problems. When using CFD method, one of the most challenging issues is the selection of a turbulence model. Several comprehensive studies have been conducted to explore the performances of several commonly used turbulence models, including Large Eddy Simulation (LES), Reynolds Averaged Navier–Stokes Equations (RANS), and Detached Eddy Simulation (DES), in simulating wind loads on and wind flows around a building (Swaddiwudhipong and Khan, 2002; Huang et al., 2007; Liu and Niu, 2016). Braun and Awruch (2009) presented one of the first attempts to investigate aeroelastic characteristics of tall buildings using complex CFD methods, followed by additional research studies pertinent to the calculation of wind-induced response of tall buildings through CFD, as can be found in Huang et al. (2013), Li et al. (2014), and Zhang et al. (2015). However, CFD technique applied to bluff body aerodynamics can be computationally expensive because of the sharp edges of the building where the turbulent flow needs to be treated very carefully and the coupled fluid structure interaction is more difficult to deal with.

As buildings become taller, it can be foreseen that a tall building model could become too large to physically fit in a reasonable-sized boundary-layer wind tunnel, hindering the application of experimental methods that require testing of a full-aeroelastic model. Wind tunnel testing of aeroelastic models of tall buildings is expensive which is going to only increase as buildings become taller. In addition, aeroelastic models have limitations in capturing higher modes of vibration beyond the first dynamic mode. Therefore, to overcome these limitations it is necessary to develop an alternative method for loads and response prediction. In this paper, a time domain method is proposed that is able to predict wind loads and wind-induced response of a tall building continuously in time, and hence overcomes the limitations of the frequency-domain method. The proposed method, as applied to tall buildings, is based on the sectional aerodynamic properties of the building cross section as assessed by section model tests in wind tunnels, combined with numerical simulation technique based on synthetic wind and structural dynamics of the building, much like those used for long-span bridges. This is an alternative method to the one requiring aeroelastic model test and thereby overcomes its limitations. This approach poses some challenges for tall buildings because of the three-dimensional nature of the flow around buildings and variation of wind speed and turbulence with height. The approach simulates time histories of synthetic wind based on known upstream conditions, generates load time histories for the specific building for various heights based on the sectional aerodynamic properties, and solves the governing dynamic equations of motion to determine the building response in time domain.

The paper is organized as follows: Section 2 presents the formulation of wind-induced loads and response. The experimental setup is described in Section 3, and numerical simulation of the response for the selected prototype tall building under straight-line wind conditions and its validation are presented in Section 4. The results of a parametric study to assess the roles of important parameters contributing to the building response such as load correlation, building height, and mode shapes are also presented in this section. Finally, conclusions and related remarks are given in Section 5.

2. Formulation of wind loads and response

2.1. Equation of motion

The equation of motion per unit building height (H) for buffeting response of a tall building in the across-wind direction can be written as:

$$m_h\ddot{h}(z,t)+c_h\dot{h}(z,t)+k_h h(z,t)=L_b(z,t)+L_{se}(z,t). \tag{1}$$

where m_h, c_h, k_h are mass, mechanical damping and mechanical stiffness coefficients per unit height of the building in the across-wind direction (h); $\ddot{h}(z,t)$, $\dot{h}(z,t)$, $h(z,t)$ denote acceleration, velocity and displacement of the building in the across-wind direction at elevation z, respectively; and $L_{se}(z,t)$ is the self-excited (motion-induced) load per unit building height at elevation z in the across-wind direction, as given by Eqn. (2):

$$L_{se}(z,t)=\frac{1}{2}\rho U(z)^2 D_c\left[KH_1^*(K)\frac{\dot{h}(z,t)}{U(z)}+K^2H_4^*(K)\frac{h(z,t)}{D_c}\right]. \tag{2}$$

where ρ is the air density, $U(z)$ is the mean wind velocity at elevation z, D_c is a characteristic building cross-sectional dimension defined by $D_c=\sqrt{BD}$, B = along-wind and D = across-wind cross-sectional dimension for zero AOA ($\alpha=0^\circ$) as defined in Fig. 1, H_1^* and H_4^* are flutter derivatives corresponding to aerodynamic damping and aerodynamic stiffness, respectively, and $K=\omega D_c/U(z)$ is the reduced frequency; and

$L_b(z,t)$ represents buffeting (turbulence-induced) load per unit building height at elevation z in the across-wind direction that can be expressed as

$$L_b(z,t)=\frac{1}{2}\rho U(z)^2 D_c\left[\frac{2C_L}{U(z)}\int_0^s u(\sigma)\phi_u'(s-\sigma)\mathrm{d}\sigma+\frac{\frac{\mathrm{d}C_L}{\mathrm{d}\alpha}+C_D}{U(z)}\int_0^s v(\sigma)\phi_v'(s-\sigma)\mathrm{d}\sigma\right]. \tag{3}$$

where C_L and C_D are mean lift and drag coefficients, respectively; $s=Ut/D_c$ is non-dimensional time; $u(t)$ and $v(t)$ are wind speed fluctuations in along-wind and across-wind direction, respectively; $\phi'_{u,v}(s)$ are the derivatives of buffeting indicial functions or buffeting indicial derivative functions associated with u and v turbulence components, assumed to be same here, that take the following form:

$$\phi'(s)=A_1e^{-A_2s}+A_3e^{-A_4s}. \tag{4}$$

where A_1-A_4 are constants that can be identified by analyzing the fluctuating lift in the frequency domain as follows:

$$S_{L_bL_b}(z,K)=\left(\frac{1}{2}\rho U(z)^2D_c\right)^2\left[(2C_L)^2\frac{S_{uu}(z,K)}{U(z)^2}+\left(C_D+\frac{\mathrm{d}C_L}{\mathrm{d}\alpha}\right)^2\frac{S_{vv}(z,K)}{U(z)^2}\right]\chi^2(K). \tag{5}$$

where $S_{L_bL_b}(z,K)$ is the Power Spectral Density (PSD) of the buffeting load $L_b(z,t)$ while $S_{uu}(z,K)$ and $S_{vv}(z,K)$ are the PSD of the wind speed fluctuations $u(z,t)$ and $v(z,t)$ at elevation z, and $\chi^2(K)$ is the aerodynamic admittance function that can be related the buffeting indicial derivative function whose form is given in Eqn. (4) as follows

$$\chi^2(K)=\left(\frac{A_1K}{A_2^2+K^2}+\frac{A_3K}{A_4^2+K^2}\right)^2+\left(\frac{A_1A_2}{A_2^2+K^2}+\frac{A_3A_4}{A_4^2+K^2}\right)^2. \tag{6}$$

The building displacement, $h(z,t)$, in a specific mode of vibration, i, can be written as

$$h(z,t)=\varphi_i(z)h_i(t). \tag{7}$$

where $\varphi_i(z)$ is the *ith* normalized mode shape of the building and $h_i(t)$ is the *ith* generalized displacement at the tip or roof of the building ($z=H$).

Only the 1st mode of vibration ($i=1$) is considered here for simplicity and comparison with a benchmark wind tunnel study, although participation of higher modes of vibration in estimating the total building