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Prediction of buffeting loads and responses of a tall building in tornado wind using sectional aerodynamic properties

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SUMMARY:
In the present study, a time-domain method that was developed earlier to predict response of a rectangular tall-building in straight-line wind, is extended to predict the buffeting loads and responses of a circular tall building in non-stationary tornado wind. A time-domain approach is adopted to extend the capability of subsonic wind tunnel facilities to examine the effects of non-stationary winds on the structures. This method uses the governing equations of 2DOF response of a tall building with circular cross-section, that utilizes aerodynamic load parameters obtained from straight-line wind tunnel tests along with wind speed estimates from empirical tornado wind speed profiles based on data measured in the ISU-Tornado Simulator (ISU-TS) to estimate the time history of buffeting loads and responses of the structure. The numerically simulated 2DOF wind-induced response of the slender structure using the proposed method is validated by comparing it with the experimentally obtained responses from a tornado laboratory simulation test of an aeroelastic model of the circular tall building.

Keywords: Non-stationary Winds, Aeroelastic Model, Time-domain method.

1. INTRODUCTION

Modern architecture has drastically changed over the last few decades which has led to an increased construction of tall and slender buildings. With increasing height and slenderness, these structures become prone to dynamic wind loads resulting in large-amplitude vibrations, which significantly affect its structural safety and reliability. In the event of extreme windstorms, especially tornadoes, failure to limit the wind-induced vibration of these structures may even result in catastrophic consequences. The design wind loads for tall buildings and other structures based on straight-line wind events have been studied for a long time. However, the wind profiles associated with extreme wind events such as hurricanes, tornadoes, and microbursts differ from conventional atmospheric boundary-layer-type events.

Wind-velocity field and wind-loads on low-rise buildings in tornadoes have been studied extensively using laboratory tornado simulators but only a few studies exist on tall structures (e.g. Hou and Sarkar, 2020; Alipour et al., 2020). Most studies on characterization of tornado loads on structures have relied on laboratory simulations using tornado simulators, whereas some have used CFD models. Therefore, there is a lack of a general approach to simulate the effects of a translating tornado on tall structures that provides an efficient way to accurately represent the variable nature of the wind loads on these structures. In this paper, an alternate approach is proposed to predict the dynamic effects of tornado winds on a tall building using its aerodynamic properties such as flutter derivatives and buffeting indicial derivative functions extracted from model tests in a subsonic wind tunnel, thereby extending its capability to simulate loading effects of tornado winds on flexible buildings. The results from the proposed method will be validated with data from aeroelastic model tests on the tall building in the ISU-Tornado Simulator.

2. WIND LOADS AND RESPONSE FORMULATION

2.1. Equations of motion

The equations of motion for a 2DOF (along- and across-wind) response of a tall-building can be expressed as (Simiu and Scanlan, 1996),

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

$$m_p\ddot{p}(z,t) + c_p\dot{p}(z,t) + k_p p(z,t) = D_b(z,t) + D_{se}(z,t) \tag{2}$$

where *m*, *c*, *k* are mass, damping and stiffness coefficient per unit height of the structure, respectively. $\ddot{h}(z,t)$, $\dot{h}(z,t)$ and $h(z,t)$; $\ddot{p}(z,t)$, $\dot{p}(z,t)$ and $p(z,t)$ represent acceleration, velocity, and displacement for the structure at height *z* in the across-wind and along-wind direction, respectively. $L_b(z,t)$and $D_b(z,t)$ represent the buffeting load (lift and drag) per unit height of the structure at elevation z, which can be expressed as,

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

$$D_b(z,t) = \frac{1}{2}\rho U^2(z,t)D_c\left[\frac{2C_D}{U(z,t)}\int_0^s u(z,\sigma)\phi_D'(s-\sigma)\mathrm{d}\sigma + \frac{\frac{\mathrm{d}C_D}{\mathrm{d}\alpha}-C_L}{U(z,t)}\int_0^s v(\sigma)\phi_D'(s-\sigma)\mathrm{d}\sigma\right] \tag{4}$$

where C_L, C_D are mean lift and drag coefficients, respectively; $C_L' = \frac{dC_L}{d\alpha}, C_D' = \frac{dC_D}{d\alpha}$, α is angle of attack; $U(z,t)$ is the resultant horizontal velocity of the tornado at elevation *z* and at time *t*; $s = U(z,t)t/D\_c$ is non-dimensional time; $D_c = \sqrt{A}$ is an equivalent diameter of the cross-section, where $A = \pi D^2/4$ is the area of the cross-section of the circular section with diameter *D*; *u* (*z*, *t*) and *v* (*z*, *t*) are longitudinal and transverse wind-turbulence fluctuations; $\phi'(s)$ are buffeting indicial derivative functions, which can be expressed in the following form:

$$\phi'(s) = A_1e^{-A_2s} + A_3e^{-A_4s} \tag{5}$$

where A_1 to A_4 are constants that are extracted by analyzing the buffeting loads in the frequency domain. $L_{se}(z,t)$ and $D_{se}(z,t)$ are the self-excited loads per unit height of the structure in across- and along-wind direction, respectively, after neglecting aeroelastic stiffness and the coupled aeroelastic damping terms, which are expressed as,

$$L_{se} = \frac{1}{2}\rho U^2(z,t)D_c[\frac{KH_1^*}{U(z,t)}\dot{h}(z,t)] \tag{6}$$

$$D_{se} = \frac{1}{2}\rho U^2(z,t) D_c [\frac{K P_1^*}{U(z,t)} \dot{p}(z,t)] \quad (7)$$

where H_1^* and P_1^* are flutter derivatives that influence the aerodynamic damping and expressed as $H_1^* = -(C_D + C_L')/K$ and $P_1^* = -2C_D/K$ in quasi-steady form, K is non-dimensional frequency. Once the aerodynamic loads are obtained, the SDOF generalized equation of motion can be solved to obtain the responses, following the procedure adopted in Hou and Sarkar (2021).

2.2. Analytical tornado load estimation

The wind-speed profiles of the tangential wind speed for a stationary tornado with core radius of r_c and a Swirl Ratio (S_c) of 0.25 were derived from the empirical equations proposed in Alipour et al. (2020) based on the multiple data sets obtained from ISU-Tornado Simulator by Sarkar and his team (Sarkar, 2019). The tangential wind-speed profiles were calculated by dividing r in three zones: (1) $0 \leq r < r_c$ (2) $r_c \leq r \leq 1.2\, r_c$ (3) $1.2\, r_c \leq r \leq 4.5\, r_c$. As deriving a universal form of the radial wind speed profile is an involved task due to its continuous change with distances r and z, the radial wind speeds in this study at a given location (r, z) are obtained by dividing the model building's total height H =12z_c (0.6 m) into four zones: (a) $z<=1.4z_c$, (b) $1.4\, z_c \leq z \leq 4.25\, z_c$ (c) $4.25\, z_c \leq z \leq 7\, z_c$, (d) $z>7z_c$, where z_c (=0.05m here) is the height at which absolute maximum (largest) tangential wind speed occurs (Razavi and Sarkar 2018a,b). Once the radial and tangential wind speeds are obtained, the resultant horizontal velocity $U(z,t)$ can be obtained by calculating the vector summation of the translation velocity of the tornado U_T (= 0.5 ms^{-1} here) and $U_H(z,t) = \sqrt{U_r^2(z,t) + U_\theta^2(z,t)}$ where U_r and U_θ are the radial and tangential velocity components at a given elevation z and time t which depends on the radial location of the tornado from the structure. The wind fluctuations in the along and across wind directions of the upstream wind are calculated using a constantly evolving spectra for a translating tornado that is modeled as Kaimal spectra, at a given radial location of the tornado from the structure assuming a quasi-steady approach as in (Hou and Sarkar, 2021).

3. PRELIMINARY RESULTS AND DISCUSSION

Fig. 1 shows the ISU-Tornado Simulator at Iowa State University (Haan et al., 2008) which was used to generate data for the empirical tornado profiles. The coordinate system with the definitions of angle of attack and aerodynamic force (lift F_L, drag F_D) are also shown in Fig. 1. The mean aerodynamic static load coefficients (C_L, C_D) and their derivatives (C_L', C_D') and the constants (A_1-A_4) for buffeting indicial derivative functions for a circular section were adopted from the reference (Jafari et al., 2019), since the example tall building used here is circular (D=0.127m).

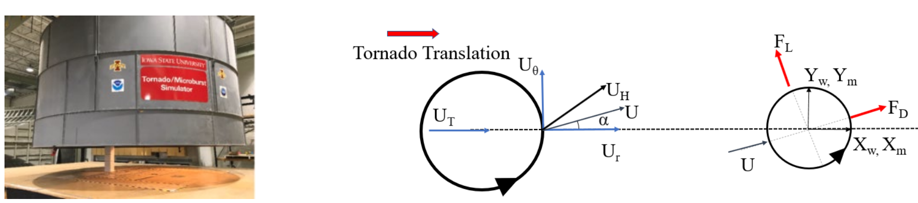

Figure 1. ISU-TS and coordinate system with definition of AOA (Hou and Sarkar, 2021).

The maximum horizontal velocity at building roof height is $U_H(H)$ =11.38 m/s and the turbulence intensities (w.r.t. max. U_H) at the roof height in along- and across-wind directions are I_{uu}=6.3%

and I_{vv}=8.1%, respectively. Mechanical damping and natural frequency of the tall building along both directions are 0.4% and 2 Hz. Fig. 2 shows the generalized aerodynamic loads and responses at the roof height of the tall building (located at r=0), considering the first mode of vibration along each of its two principal directions (X_m, Y_m), with radial location r of the translating tornado from -4r_c to 4r_c. The response time-history in Fig. 2 is non-stationary in nature, with its peak occurring once the tornado has passed the building, which is typical of non-synoptic wind-induced response.

4. SUMMARY

The present study aims to develop an alternate approach for calculating the loads and responses of a tall building with circular cross-section subjected to tornado loading. The horizontal velocity time histories for a translating tornado were simulated using velocity data from the ISU-Tornado Simulator measurements and the aerodynamic load parameters were derived from the regular wind tunnel tests which were then substituted into the governing equations of 2DOF motion to determine the loads and responses of the tall building. Moreover, an aeroelastic model of a circular tall building is tested in the laboratory simulated translating tornado to validate the simulated results in the current study. The significance of this paper is to develop a technique to predict non-synoptic-wind-induced vibration of tall structures that are flexible in time domain using the section model aerodynamic properties from straight-line wind tunnel tests.

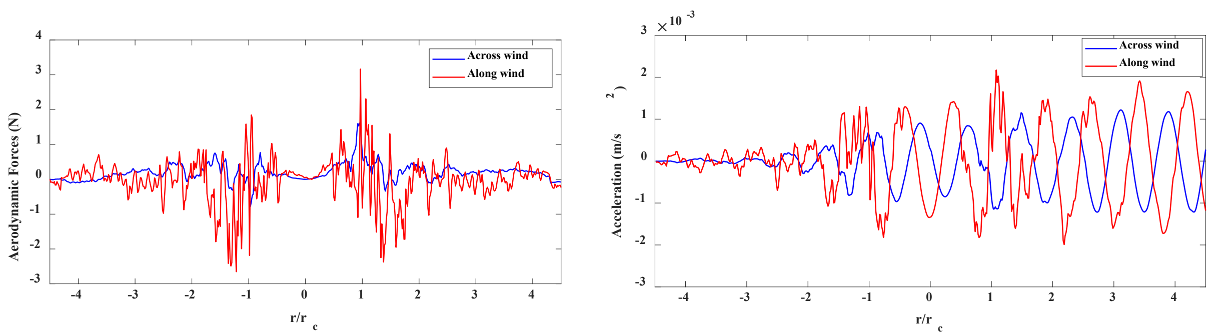

Figure 2. Aerodynamic forces and acceleration responses at the roof height of the tall building.

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