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Response analysis of lattice tower based on a modified hybrid model of thunderstorm downburst

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ABSTRACT

The failure of transmission line towers around the world can to the largest extent be attributed to the thunderstorm downburst. Currently, the existing downburst model and the response analysis of lattice tower under downburst wind are still yet to be improved. In this paper, a modified hybrid model is proposed firstly. Subsequently, the response analyses of an actual collapsed lattice tower under the generated downburst wind and boundary layer wind are performed based on non-linear finite element method. Results show that the modified model is more reasonable to explain the failure of the structure under the downburst wind. Furthermore, compare to the response under the stationary wind in the boundary layer, the nonstationary response admits smaller peak factor and gust response factor (GRF). The reason mainly attributed to the fact that the extreme response had insufficient time duration to develop.

1. INTRODUCTION

The extreme wind events such as thunderstorm downbursts and tornados are responsible for the failure of power transmission towers around the world (Hawes and Dempsey 1993; Dempsey and White 1996). The flow field generated by such an event is significantly different from the traditional atmospheric boundary layer (Fujita 1990; Letchford et al. 2001). It is well known that the extensive research about the boundary layer wind effects on structures have formed the basis for current wind loading codes and standards. However, the understanding of the characteristics of those transient nonstationary wind effects on structures has yet to be improved.

Currently, field measurements, numerical and physical simulations have been used to investigate the characteristics of the downburst. Concerning field measurements, such as the severe microburst that occurred at Andrews Air Force Base (AFB) in 1983 and the thunderstorm downburst, which is the outflow of a real-flank downdraft (RFD)

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near Reese Technology Center, Lubbock, Texas, were reported (Fujita 1985; Gast and Schroeder 2003). However, it is always difficult to capture the downburst in the field due to its small spatiotemporal scales and random occurrences. Therefore, the numerical and physical simulations of downburst have received great attention (Wood et al. 2001; Letchford and Chay 2002). Based on those studies, Salory et al. (2001) conducted the response analysis of the lattice tower structure to the downburst wind in which the smaller-scale wind turbulence is neglected. Chen and Letchford (2004) analyzed dynamic response of a cantilevered structure based on the proposed deterministic-stochastic hybrid model of downbursts. However, its time-varying mean is obtained from the empirical model and its fluctuation is simplified to an amplitude-modulated nonstationary process. Chen (2008) developed a frequency domain framework for quantifying tall building response under the nonstationary wind. Huang et al. (2013) presented a time domain response analysis framework of the tall building using multiple wind speed samples generated from the RFD record. However, the structural responses caused by RFD downburst may be lower than those by the design wind speed based on the codes. This may not explain that the majority of the failures of the transmission towers are caused by thunderstorm downbursts. Hence, it is necessary to establish a reasonable downburst which has destructive effects.

In this paper, a modified hybrid model is proposed firstly. In this model, the derived time-varying mean and the estimated evolutionary power spectra density (EPSD) of RFD sample at height of 10 m are modulated by the maximum mean wind speed in the vertical profile of the Andrews AFB downburst to generate a larger downburst wind. Subsequently, the simulated downburst samples based on the modified model are used to calculate the nonlinear response of an actual collapsed transmission tower. The time-varying mean, root-mean-square value, gust response factor (GRF) and peak factor are determined from the multiple response time histories. Furthermore, those results will be compared with those under the boundary layer winds.

2. MODIFIED HYBRID MODEL

Generally, the wind speed of a downburst can be expressed as the summation of a time-varying mean and a fluctuation, which is given as follows:

$$U(z,t) = \bar{U}(z,t) + u(z,t) \tag{1}$$

where $U(z,t)$ is the wind speed at height z; $\bar{U}(z,t)$ is the time-varying mean; $u(z,t)$ is the fluctuating component.

2.1 Time-varying mean

Assume that the time-varying mean can be factorized as the product of a time-invariant vertical profile and a time function as follows

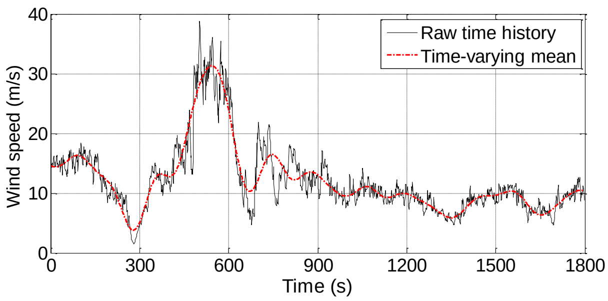
$$\bar{U}(z,t) = U(z) \cdot f(t) \tag{2}$$

where $U(z)$ is the vertical profile of the maximum mean wind speed; $f(t)$ is a time function ranged from 0 to 1. In this study, the Wood model (Wood et al. 2001) is used, which can be expressed as:

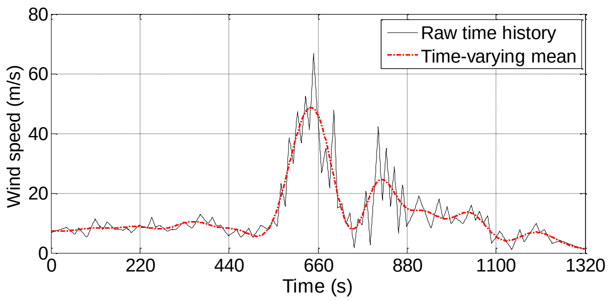
$$U(z) = 1.55\left(\frac{z}{\delta}\right)^{1/6}\left[1 - erf(0.7\frac{z}{\delta})\right] \times U_{\max} \tag{3}$$

where δ is the height where the velocity is equal to half its maximum value; $erf(\cdot)$ is the error function; $U_{\max}$ represents the maximum wind speed in the vertical profile.

In this study, the time histories of RFD at height of 10 m and Andrews AFB are used which are shown in Fig. 1. Their time-varying means and fluctuation components can be derived using the discrete wavelet transform with Daubechies wavelet of order 20 and 6 decomposition level. Level 6 is equivalent to a window size of 64 s, which means the frequency embedded in time-varying mean is lower than 0.008 Hz. The time-varying mean wind speeds of these two samples are also shown in Fig. 1. It can be seen that the maximum time-varying mean wind speed of RFD and Andrews AFB are 31.32 m/s and 48.69 m/s, respectively. As mentioned, the RFD sample may not be available to reflect the destructiveness of the downburst wind. On the other hand, the fluctuating characteristics of the Andrews AFB sample are nearly lost due to its low sampling frequency although the mean wind speed of Andrews AFB sample is larger than that of RFD.



(a) RFD



(b) Andrews AFB

Fig. 1 Time histories and time-varying means of thunderstorm downbursts

The vertical profile of RFD sample is shown in Fig. 2. It can be seen that the maximum wind speed $U_{\max}$ in the vertical profile of RFD sample is 38.12 m/s under the case of $\delta = 400$ m. Similarly, the counterpart of Andrews AFB sample is 66.06 m/s. In this study, the vertical profile of RFD sample is modified by the $U_{\max}$ in the vertical profile of Andrews AFB sample, which is also shown in Fig. 2. It means that the time-invariant vertical profile of RFD is enlarged by a coefficient of 1.733.

In addition, the time function can be obtained from the following equation:

$$f(t) = \frac{U_R(t)}{\max(U_R(t))} \tag{4}$$

where $U_R(t)$ is time-varying mean wind speed of RFD sample. The calculated time function is shown in Fig. 3.

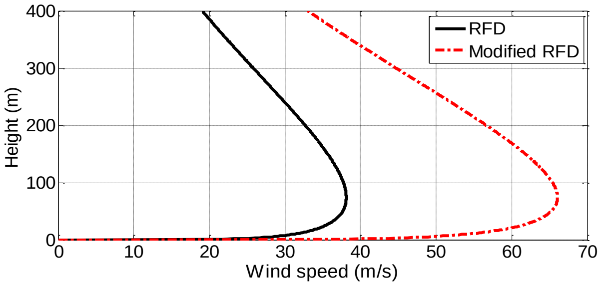


Fig. 2 Time-invariant vertical profile

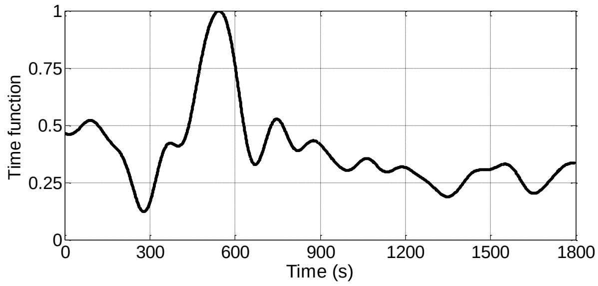


Fig. 3 Time function

2.2 Fluctuation

The fluctuating component of RFD sample is illustrated in Fig. 4. Its EPSD can be estimated using the spectra estimation method proposed by Priestly (1965). Fig. 5 shows the estimated EPSD of fluctuating component of RFD.

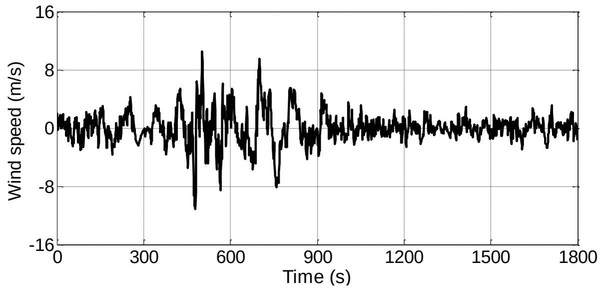


Fig. 4 Fluctuating component of RFD thunderstorm downburst

Once the vertical profile of RFD sample has been enlarged by the $U_{\max}$ in the vertical profile of Andrews AFB sample, the estimated EPSD should be modified. When the mean wind speed is multiplied by 1.733, the frequency and total energy of fluctuation should be multiplied by 1.733 and 3.003 respectively to keep the assumption that the normalized spectrum must remain unchanged. Correspondingly, the time-dependent spectrum should also magnify by 1.733. Fig. 6 illustrates the modified EPSD of the fluctuation of RFD. It can be seen that the frequency and EPSD value are all multiplied by the coefficient of 1.733.

Assume that the auto EPSD of the fluctuation at every height is all identical to the modified EPSD of RFD in this study. In addition, the Davenport coherence function is employed to describe the spatial coherence. It can be expressed as

$$\gamma(z_1, z_2, \omega) = \exp\left[-\frac{\omega}{2\pi}\frac{C_z\left|z_1 - z_2\right|}{0.5\left[U(z_1)+U(z_2)\right]}\right] \tag{5}$$

where ω is circular frequency; $C_z = 8$; $U(z_1)$ and $U(z_2)$ are the wind speed of the time-invariant vertical profile at the height of z_1 and z_2.

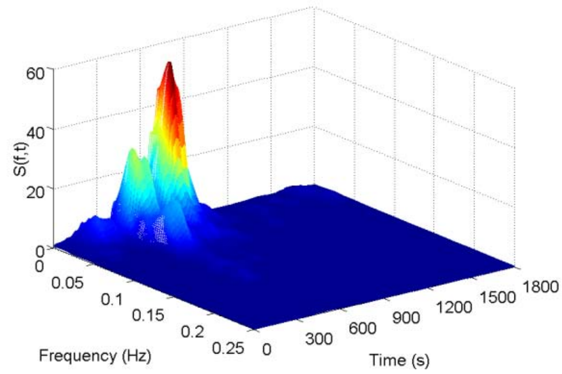


Fig. 5 EPSD of fluctuation

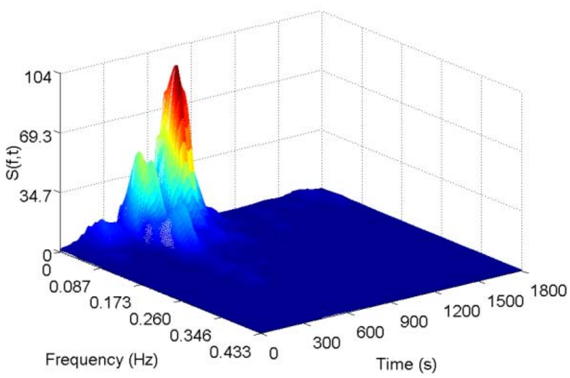


Fig. 6 Modified EPSD of fluctuation

3. LATTICE TOWER RESPONSE ANALYSIS

3.1 Structural model

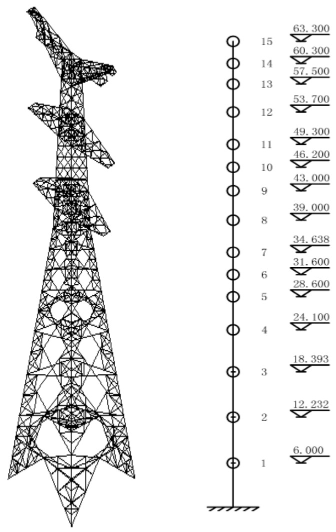


Fig. 7 Whole model and loading point of the tower

To investigate the dynamic response of the lattice tower response under the downburst excitation, a typical power transmission tower is selected. The nominal height and total height of this tower are 39 m and 63.3 m, respectively. Besides, the design wind speed at height of 10 m is 27 m/s. The tower is divided into 15 levels for loading the wind force which are shown in Fig. 7. The first four natural frequencies are 1.744, 1.772, 2.224 and 2.966 Hz, respectively. Correspondingly, their modes of vibration are along-wind vibration, i.e., vibrate perpendicularly to the transmission line, cross-wind vibration, local vibration of tower lag and torsional vibration of the tower.

3.2 Wind field simulation

Based on the section 2.2, the downburst winds can be simulated for the selected heights of tower using the spectral representation method (SRM) (Deodatis 1996a). In the practical simulation, the frequency and the time resolution are 0.0043 Hz and 1s, respectively. The cutoff frequency is 0.866 Hz. Besides, the time period of each sample is 1800 s.

To compare the responses under the downburst wind with those under the boundary layer wind, the boundary layer wind field is also simulated based on the following parameters. The vertical profile can be expressed as

$$U_z/U_{10} = (z/10)^a \tag{6}$$

where U_z represents the mean wind speed at height z; U_{10} is the mean wind speed at height of 10 m which is chose as 27 m/s; $a=0.15$ is roughness index. The Davenport spectrum is chosen which is given by

$$S(\omega) = U_{10}^2 \frac{4kx^2}{\omega/2\pi[1+\mathrm{x}^2]^{4/3}} \tag{7}$$

where $x = 600\omega/\pi U_{10}$; ω is circular frequency; k is the ground roughness coefficient that can be taken as 0.0019 in this study. The coherence function admits the same form of Eq. (5) except that $C_z = 10$.

Similarly, the SRM using FFT algorithm (Deodatis 1996b) is employed to simulate the boundary layer wind. The frequency and time resolution are set to 0.0024 Hz and 0.2 s, respectively. The upper cutoff frequency is 2.5 Hz and the total time period of each sample is 1228 s. The first 360 s are adopted. Fig. 8 shows the simulated downburst and boundary layer wind at the top height of the model.

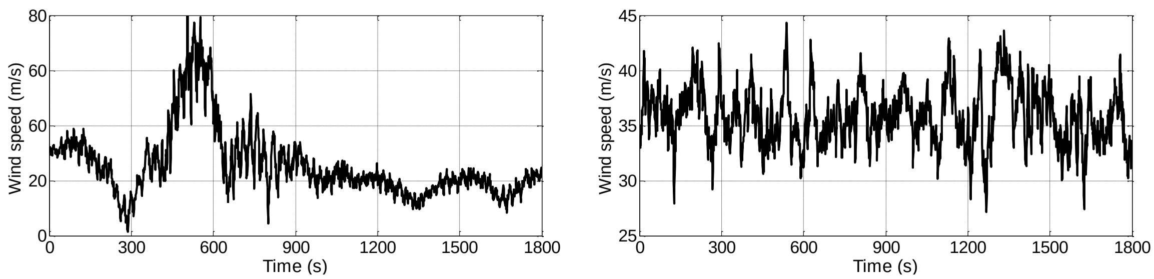


Fig. 8 Simulated samples of downburst and boundary layer wind

3.3 Wind load

The quasi-steady assumption is adopted in current research. The wind force at each loading point of the tower can be calculated by

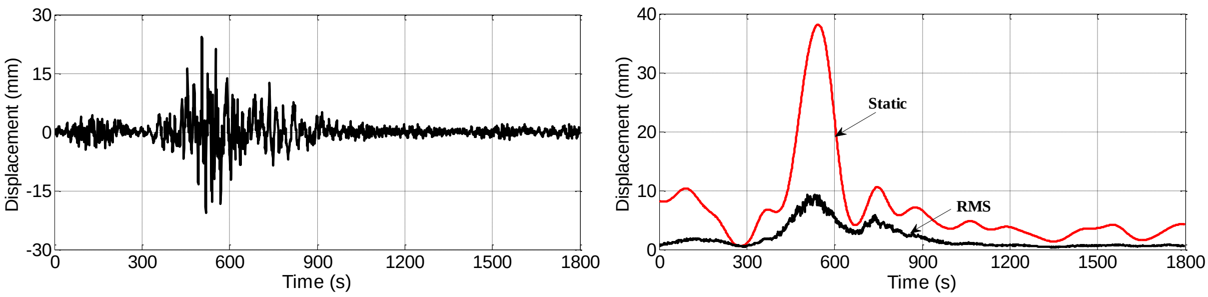
$$F(z_i,t)=0.5C_D\rho U^2(z_i,t)S \tag{8}$$

where $C_D=1.2$ is the drag coefficient used to the whole tower; ρ is the air density which is taken as 1.225 kg/m^3; S is the windward area of the segmental tower at each level.

3.4 Results and discussions

A total of 100 samples of downburst and boundary layer wind are used in this study. The nonlinear time-history analysis is performed by ANSYS software. After obtaining the multiple samples of response time histories, the instantaneous RMS value, the mean extreme values of response can be determined

A top dynamic displacement sample under the downburst winds is shown in Fig. 9(a). It can be seen that its fluctuating trend is almost coincidence with the fluctuating component of RFD. The static and RMS of top displacement are shown in the Fig. 9(b). It can be illustrated that the time lag phenomenon is not very obvious. It might be attributed to the fact that the maximum frequency of the fluctuation is lower than the fundamental frequency of the tower. Therefore, the dynamic amplification effect is not distinct. In addition, a top dynamic displacement sample under the boundary layer wind is shown in Fig. 10.



(a) Top dynamic displacement sample (b) Static and RMS of top displacement

Fig. 9 Top displacement response under the downburst wind

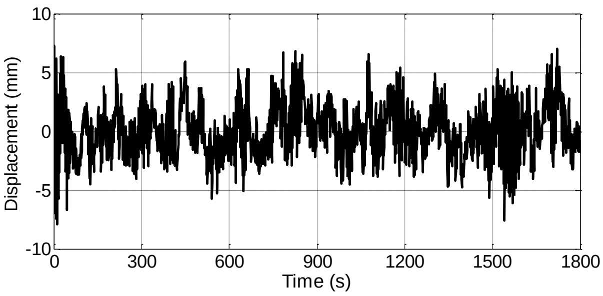


Fig. 10 Top dynamic displacement sample under the boundary layer wind

The GRF and peak factor are defined as

$$GRF = \mu_{r,\max} / R_{static}^{\max} \tag{9}$$

$$g = (\mu_{r,\max} - R_{static}^{\max}) / \sigma_r^{\max} \tag{10}$$

where $\mu_{r,\max}$ is the mean of extreme value of total response including the mean and fluctuating components; $R_{static}^{\max}$ is the maximum static response; $\sigma_r^{\max}$ is the maximum RMS response. The maximum static, maximum RMS, mean extreme, GRF and peak factor of these two wind events are summarized in Tab. 1. It is seen that the mean extreme of the top displacement under the downburst is significantly higher than that of the boundary layer wind. This illustrates that the modified hybrid model is more reasonable to predict the response of the structure under the downburst winds. In addition, the response under the case of downburst wind has smaller peak factor and GRF compare to the stationary wind in the boundary layer. The main reason is that the extreme response had insufficient time duration to develop.

Tab. 1 Comparison of different wind events

	Downburst wind (mm)	Boundary layer wind (mm)
Maximum RMS	9.3	2.5
Maximum Static	38.2	11.3
Mean extreme	56.4	19.3
GRF	1.477	1.704
Peak factor	1.960	3.240

4. CONCLUSIONS

In this study, a modified hybrid model for downburst wind was proposed firstly. Subsequently, the response analyses of an actual lattice tower under the generated downburst wind and boundary layer wind were conducted. Results show that the mean extreme of the top displacement under the downburst is significantly higher than that of boundary layer wind. It illustrates that the modified hybrid model is more reasonable to explain the failure of the structure caused by downburst wind. Compare to the stationary wind in the boundary layer, the nonstationary response admits smaller peak factor and GRF. The reason mainly attributed to the fact that the extreme response had insufficient time duration to develop.

5. ACKNOWLEDGEMENTS

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