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Frequency domain assessment of the extreme responses of transmission tower under moving downburst

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SUMMARY:
Localized severe wind such as downbursts are responsible for structural failures of the transmission line. They are always characterized by small size, high intensity and sudden change. This paper aims to develop a theoretical framework for dynamic response analysis of transmission towers under downbursts in frequency domain. First, based on the theoretical model of time-varying mean wind and non-stationary fluctuating wind, the expressions of wind load on transmission tower by the moving downburst in time domain and frequency domain are given separately. Second, based on the random vibration theory, the frequency domain solution of non-stationary fluctuating wind-induced response of trans-mission towers is derived. Then, through the extreme value theory, the extreme value probability distribution of the dynamic response under non-stationary downburst wind load is proposed The simplified solution for peak factor is presented using equivalent stationary extreme value distribution. The accuracy of the proposed theoretical method was verified using finite element transient analysis results. It is found that the proposed theoretical framework can accurately assess the extreme value responses of transmission towers under non-stationary moving downbursts.

Keywords: Transmission tower, Extreme value probability distribution, Downburst

1. INTRODUCTION

Transmission lines are exposed to strong typhoons, downbursts, tornadoes, and thunderstorms, of which downbursts cause severe damages to transmission lines (Chay et al., 2006). Therefore, research on the wind-induced vibration characteristics of transmission tower line system under downburst is critically important.

Savory et al. (2001) used tornado and microburst-induced wind loading as the operational load, and then used numerical simulations to model a lattice tower close to the actual structure. Shehata and EI Damatty (2007) derived the time history of downburst wind data based on a validated computational fluid dynamics model. Darwish et al. (2010) and Aboshosha et al. (2016) analyzed the downburst wind-induced vibration response of a multi-span transmission tower system using dynamic finite element analysis. Elawady et al. (2018) carried out aero-elastic tests on a multi-span transmission line subjected to downburst wind.

Based on the theory of wind-induced vibration response analysis, the frequency domain calculation method of non-stationary fluctuating wind vibration response of transmission tower is derived through random vibration theory. Then based on the extreme value theory, a simplified calculation method of equivalent stationary extreme value distribution and peak factor is proposed. Finally, the accuracy of the frequency domain theory method is verified by comparing the statistical results of the finite element transient dynamic analysis with random samples.

2. ANALYSIS FRAMEWORK

2.1. Frequency domain analysis

Based on the theory of non-stationary random vibration, the evolutionary power spectrum $S_{q_1}(\omega,t)$ of the first-order modal wind-induced vibration displacement response can be derived as follows (Lutes and Sarkani, 2004):

$$S_{q_1}(\omega,t)=\varphi_1^T|I_1^*(t,i\omega)\bar{S}_F(\omega)I_1(t,i\omega)|\varphi_1 \tag{1}$$

where $I_1(t,\omega)$ can be expressed as

$$I_1(t,i\omega)=\int_0^t h_1(t-\tau)\boldsymbol{G}(\tau,\omega)e^{-i\omega\tau}\mathrm{d}\tau \tag{2}$$

In the present paper, the non-stationary modulation function $\boldsymbol{G}(t,\omega)$ is the modulation function, expressed as $\boldsymbol{G}(t,\omega)=a(10,t)\boldsymbol{a}(t)$. Thus, the variance of the first-order modal displacement response $\sigma_{q1}^2(t)$ can be obtained as:

$$\sigma_{q1}^2(t)=\int_{-\infty}^{\infty}S_{q_1}(\omega,t)\mathrm{d}\omega \tag{3}$$

When time-varying mean loads on the tower are approximated to be synchronously, which means $\boldsymbol{G}(t,\omega)$ can be taken as $\boldsymbol{G}(t,\omega)=a(10,t)^2$ in Eq. (2), the approximate synchronous solution of $\sigma_{q1}^2(t)$ can be denoted by $\sigma_{q1a}^2(t)$.
Furthermore, the non-stationary fluctuation wind loads are approximated to be a slow-varying process. In Eq. (2), $G(t,\omega)$ can be separated from the integral. The approximate synchronous and slow-varying solution of $\sigma_{q1}^2(t)$ can be denoted by $\sigma_{q1b}^2(t)$.

2.2. The extreme value probability distribution

2.2.1. Equivalent stationary extreme value distribution based on Poisson assumption

Considering that the wind-induced vibration response $Y(t)$ is a uniformly modulated stochastic process, it is known that the probability distribution $P_{Y_m}(\hat{y})$ of the maximum value of the stochastic response $Y(t)$ is

$$P_{Y_m}(\hat{y})=\exp[-N^+(\hat{y},T)] \tag{9}$$

At this point the expectation $N_P^+(\hat{y},T)$ of the zero-mean stochastic process $Y(t)$ extremum crossing $\hat{y}$ can be expressed as:

$$N_P^+(\hat{y},T)=v_{y0}^+\int_0^T\exp\left(-\frac{\hat{y}^2}{2\sigma_Y^2(t)}\right)\mathrm{d}t \tag{10}$$

where $v_{y0}^+=\frac{1}{2\pi}\frac{\sigma_{\dot{Y}}(t)}{\sigma_Y(t)}$ is the average zero-crossing rate. When the extreme values of the downburst-induced response are assumed to follow a Gumbel distribution, referring to the expression for $N^+(\hat{y},T)$ for a stationary process, the equivalent approximation N_{eq}^+ of the exact equation Eq. (10) can be given as:

$$N_{\mathrm{eq}}^{+}(y,T) = v_{y0}^{+} T_{\mathrm{eq}} \exp\left(-\frac{\hat{y}^2}{2\sigma_{\mathrm{eq}}^2}\right) \tag{12}$$

where the variance σ_{eq}^2 and the time T_{eq} of the equivalent stationary process can be obtained by an iterative process.

2.2.2. Equivalent stationary extreme value distribution based on Vanmarcke assumption

In case the stochastic response $Y(t)$ yields the Vanmarcke process, the expectation $N_V^{+}(\hat{y},T)$ of the zero-mean stochastic process $Y(t)$ extremum crossing $\hat{y}$ can be expressed as:

$$N_V^{+}(\hat{y},T) = \frac{1}{2\pi}\frac{\sigma_{\dot{Y}}(t)}{\sigma_Y(t)}\int_0^T \frac{1-\exp\left[-\sqrt{\frac{\pi}{2}}q_Y\frac{\hat{y}}{\sigma_Y(t)}\right]}{\exp\left(\frac{1}{2}\frac{\hat{y}^2}{\sigma_Y{}^2(t)}\right)-1}\mathrm{d}t \tag{13}$$

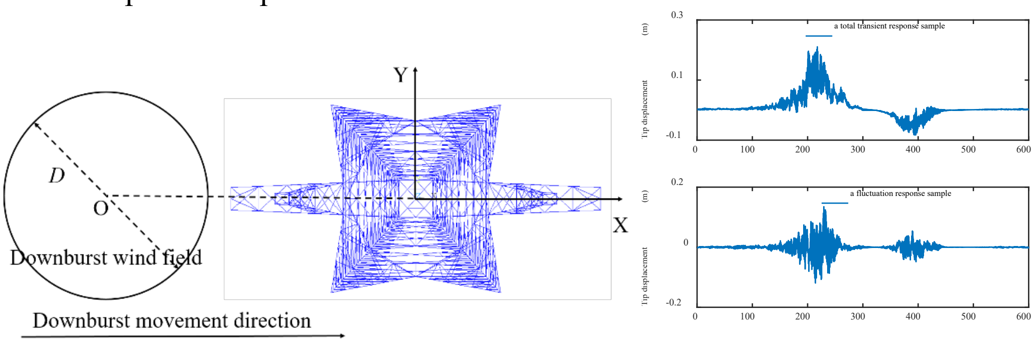
The equivalent approximation N_{eq}^{+} for the exact equation Eq. (13) under the Vanmarcke assumption can be written as:

$$N_{\mathrm{eq}}^{+}(y,T) = v_{y0}^{+} T_{\mathrm{eq}} \sqrt{\frac{\pi}{2}}\frac{q_{\mathrm{eq}}\hat{y}}{\sigma_{\mathrm{eq}}} \exp\left(-\frac{\hat{y}^2}{2\sigma_{\mathrm{eq}}^2}\right) \tag{14}$$

where q_{eq} is the equivalent bandwidth factor, and then the variance σ_{eq}^2, the time T_{eq} and the bandwidth factor q_{eq} of the equivalent stationary process can be expressed respectively by an iterative process.

3. CASE ANALYSIS

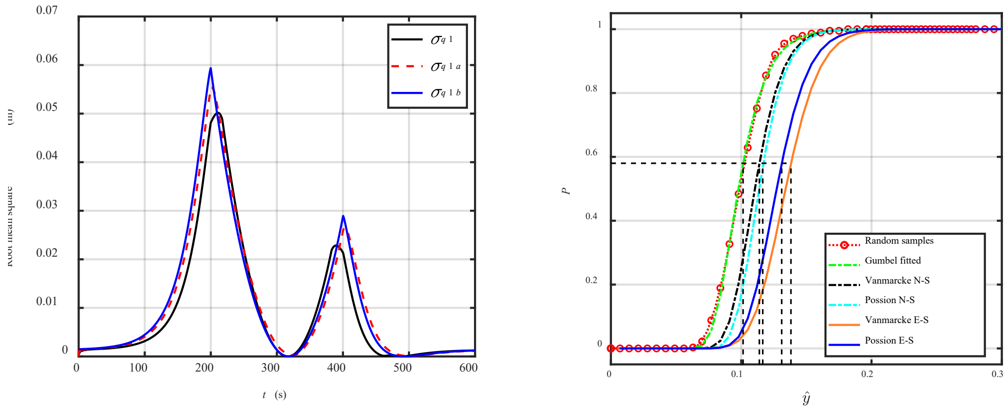
In this paper, a ultra-high voltage direct current transmission (UHV DC) tower is used for a case study. The tower is 60.2m high and the nominal height is 55m. The transmission tower is divided into several tower segments along the height. Fig. 1a shows the downburst on the transmission tower and Fig. 1b shows the time-history of a total transient response sample and a fluctuation response sample.



(a) (b)

Figure 1. Schematic diagram of the effect of downburst on transmission towers (a) and time history of different response samples responding to tip displacement (b)

When the moving wind speed is 8m/s, the frequency domain analytical solution of σ_{q1}^2, σ_{q1a}^2 and σ_{q1b}^2 by Eq.(3) are compared in Fig. 2a. The extreme value responses of the random 1000 samples are analysed to verify the analytical framework. The cumulative distribution, as well as their exception values of the samples are compared with the results obtained from the analytical methods in Fig. 2b. The results show that the expectation value of the extreme response by the non-stationary method (N-S) is about 10% larger than the results by random samples analysis, and is more precise than the results by the equivalent stationary method (E-S). There is no evident difference between the results of Vanmarcke and Passion assumption.



(a) (b)

Figure 2. Comparison of approximate values of time-varying root mean square (a) and extreme value cumulative distribution curves (b).

4. CONCLUSIONS

A frequency domain theoretical framework for assessment of the extreme value responses of transmission tower under non-stationary moving downburst wind load is proposed and verified. The approximate stationary equivalent peak factor expression is presented. The following conclusions can be obtained:

(1) The transient dynamic analysis results of 100 random samples verifies the accuracy of the proposed frequency domain method for non-stationary RMS and the extreme responses.

(2) The non-stationary downburst wind load can be regarded as a slow-varying process, which not only simplifies the calculation process of the frequency domain solution, but maintains sufficient accuracy.

(3) The extreme values of the non-stationary moving-downburst-induced response can be described by the Gumbel distribution. The peak factor by the proposed stationary equivalent extreme value distribution is concise and applicable for engineering application.

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