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Revisiting moment-based characterization for wind pressures

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ABSTRACT

The estimation of peak wind pressures is important in the reliability- and performance-based design for low-rise buildings. Typically, Davenport's formula is widely used to determine the peak factor if the pressure approximately follows Gaussian distribution. Recently, the moment-based Hermite polynomial model (HPM) is becoming popular to estimate the peak factor when the non-Gaussianity of wind pressure exists. However, their performances deserve further study based on the appropriate wind tunnel data. In this study, Davenport's formula and moment-based HPM are reviewed. The peak value of wind pressure is determined using very long time histories of wind pressure data to evaluate the performance of moment-based HPM and Davenport's formula. Results suggest that moment-based HPM should be adopted in the peak value estimation for wind pressures when the skewness and kurtosis of a process are sufficient to capture its non-Gaussian properties. Results also show that Davenport's formula may cause noticeable errors in the peak factor estimation for the wind pressure data close to Gaussian process while HPM provides a robust estimation for these data.

1. Introduction

The low-rise building roof is very vulnerable to strong winds, thus the characterization of wind pressures on the roof top is an important issue in the reliability- and performance-based design for low-rise buildings. In most design codes and specifications, the mean value of the peak wind pressure during the duration T is determined from the peak factor, which is defined as

$$g = (\mu_{x_p} - \mu_x)/\sigma_x \quad (1)$$

where μ_{x_p} represents the mean of peak values for wind pressure coefficient $X(t)$, and μ_x and σ_x are the mean and standard deviation (STD) of $X(t)$, respectively. Note that the peak value selected from each segment is the instantaneous maximal value from the raw data, and not averaged for a short duration, such as 3 s in full scale. When the wind pressure approximately follows the Gaussian distribution, the well-known Davenport's formula can be used to determine the peak factor. However, significant portions of wind pressures on the roof top may exhibit non-Gaussianity and it has been shown that the application of Davenport's formula to non-Gaussian data can lead to unconservative peak factor estimates (e.g., Balderrama et al., 2012).

Based on whether kurtosis is larger than 3, the non-Gaussian process is classified as "hardening" (kurtosis <3) and "softening" (kurtosis >3) cases (Winterstein, 1988). "Hardening" wind pressure processes may have bimodal distributions (Ding and Chen, 2014), and skewness and kurtosis may not be effective to characterize these non-Gaussian features. The peak factor of the "hardening" wind pressure process is usually less than that of a Gaussian process and the application of Davenport's formula is conservative in the cladding design. Therefore the "softening" wind pressure is the focus hereafter. For "softening" processes, the peak factor can be calculated by moment-based Hermite polynomial model (HPM) through closed-form formula. Based on skewness and kurtosis, Kareem and Zhao (1994), Chen and Huang (2009) and Kwon and Kareem (2011) derived the closed-form formula, while Huang et al. (2013) obtained it from the probability function of local peaks of wind pressures, which was fitted by Weibull distribution. If the peak wind pressure follows Gumbel distribution, the peak factor is associated with the peak wind pressure at 57% fractile. Note that fractile values presented in this study are referring to the distribution of the peak pressure and the peak value is selected from the pressure time history of duration T where T could be 10-min or 1 h. Due to the conservativeness and simplicity, Holmes and Cochran (2003) recommended the use of Gumbel distribution.

78% fractile of the peak pressure coefficient is suggested for defining design wind loading in codes and standards to consider the randomness of both wind speed and pressure coefficient (e.g., Cook, 1990; Chen and Huang, 2010). Focusing on 78% fractile peak

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pressure coefficient for non-Gaussian roof pressure data, Peng et al. (2014) demonstrated moment-based HPM has the satisfactory performance based on the closed-form approximate solution to HPM coefficients by Yang et al. (2013). Although both of Davenport's formula and moment-based HPM have been studied previously (e.g., Balderrama et al., 2012; Peng et al., 2014; Huang et al., 2015), there is a need to systematically scrutinize their performance in estimating the peak factor and peak value using very long wind pressure data.

In this study, Davenport's formula and moment-based HPM are reviewed, and some new insights are presented. Using very long wind pressure data collected by the University of Western Ontario (UWO), the peak values of wind pressures are quantified empirically. Then the ability of moment-based HPM and Davenport's formula to estimate the peak factor and peak value is evaluated in detail. Finally, concluding remarks will be given.

2. Davenport's formula

For the standard Gaussian process *U(t)*, the cumulative distribution function (CDF) of the peak value during the time period T is given as follows

$$F_{U_p}(u_p)=\exp\left[-v_0T\exp\left(-\frac{u_p^2}{2}\right)\right] \tag{2}$$

and the corresponding probability density function (PDF) is given by

$$f_{U_p}(u_p)=v_0Tu_p\exp\left[-v_0T\exp\left(-\frac{u_p^2}{2}\right)-\frac{u_p^2}{2}\right] \tag{3}$$

where U_p is the peak value of the process $U(t)$ during T and u_p are specific values of U_p, and v_0 is the mean upcrossing rate across zero. The upcrossing rate v_0 can be computed by

$$v_0=\sqrt{\int_0^\infty f^2S_U(f)df}\Big/\sqrt{\int_0^\infty S_U(f)df} \tag{4}$$

where f is the frequency and $S_U(f)$ is the power spectral density (PSD) of $U(t)$.

If $\xi=v_0T\exp\left(-\frac{u_p^2}{2}\right)$ is introduced, then $u_p=\sqrt{2\ln(v_0T)-2\ln\xi}$. Based on Taylor's theorem, u_p is expressed as

$$u_p=\beta-\frac{\ln\xi}{\beta}-\frac{\ln^2\xi}{2\beta^3}+\cdots \tag{5}$$

where $\beta=\sqrt{2\ln(v_0T)}$. The mean and standard deviation (STD) of the peak value can be derived as

$$\mu_{u_p}=\int_0^\infty u_pdF_{U_p}(u_p)=\int_0^\infty u_p\exp(-\xi)d\xi \tag{6}$$

$$\sigma_{u_p}=\sqrt{\int_0^\infty (u_p-\mu_{u_p})^2dF_{U_p}(u_p)}=\sqrt{\int_0^\infty (u_p-\mu_{u_p})^2\exp(-\xi)d\xi} \tag{7}$$

Neglecting the terms of order β^{-3} and substituting Eq. (5) to Eqs. (6) and (7) respectively, the mean and STD of the peak value can be determined by (Davenport, 1964)

$$\mu_{u_p}=\beta+\frac{\gamma}{\beta} \tag{8}$$

$$\sigma_{u_p}=\frac{\pi}{\sqrt{6}\beta} \tag{9}$$

where $\gamma\approx0.5772$ is Euler's constant. It is well known that $g=\mu_{u_p}$ is Davenport's peak factor for the standard Gaussian process.

In addition, the peak factor and STD of the peak value can also be conveniently derived from the perspective of Gumbel distribution because the peak value distribution of $U(t)$ approximately follows Gumbel distribution. The CDF of the peak value during the time period T can be approximately expressed as

$$F_{U_p}(u_p)=\exp\{-\exp[-\alpha_{u_p}(u_p-\widehat{u}_p)]\} \tag{10}$$

and the corresponding PDF is given by

$$f_{U_p}(u_p)=\alpha_{u_p}\exp\{-\exp[-\alpha_{u_p}(u_p-\widehat{u}_p)]-\alpha_{u_p}(u_p-\widehat{u}_p)\} \tag{11}$$

where the dispersion $1/\alpha_{u_p}$ is a measure of "spread" and the mode $\widehat{u}_p$ is the value with maximum likelihood.

Based on the assumption that the CDF defined by Eq. (2) and its derivative are equal to those associated with Eq. (10) at the mode $u_p=\widehat{u}_p$, the following simultaneous equations can be obtained

$$v_0T\exp\left(-\frac{\widehat{u}_p^2}{2}\right)=1;\quad v_0T\widehat{u}_p\exp\left(-\frac{\widehat{u}_p^2}{2}\right)=\alpha_{u_p} \tag{12}$$

Hence

$$\widehat{u}_p=\sqrt{2\ln(v_0T)}=\beta;\quad \alpha_{u_p}=\beta \tag{13}$$

and the mean and STD of the peak value are given by

$$\mu_{u_p}=\widehat{u}_p+\frac{\gamma}{\alpha_{u_p}}=\beta+\frac{\gamma}{\beta} \tag{14}$$

$$\sigma_{u_p}=\frac{\pi}{\sqrt{6}\alpha_{u_p}}=\frac{\pi}{\sqrt{6}\beta} \tag{15}$$

Furthermore, according to Eq. (2), the q fractile value of the peak value of $U(t)$ can be determined as

$$u_{p,q}=\sqrt{2\ln\frac{v_0T}{\ln(1/q)}} \tag{16}$$

Because the peak value of $U(t)$ approximately follows Gumbel distribution, the peak factor can be readily estimated by substituting $q=57\%$ to Eq. (16). Also other q fractile values can be obtained, such as 78% and 86% fractiles.

3. Moment-based HPM

As mentioned previously, $X(t)$ represents wind pressure coefficient process. Accordingly, the standardized process is expressed by $\tilde{X}(t)=[X(t)-\mu_x]/\sigma_x$. For the "softening" case, the following third order HPM is used to relate the standard Gaussian process $U(t)$ and the standardized non-Gaussian process $\tilde{X}(t)$ (Winterstein, 1988):

$$\tilde{x}=H(u)=\kappa[H_1(u)+h_3H_2(u)+h_4H_3(u)] \tag{17}$$

where $\kappa=1/\sqrt{1+2h_3^2+6h_4^2}$ is a scaling factor to ensure that $\tilde{X}(t)$ has unit variance; h_3 and h_4 are parameters which control the shape of the distribution of $\tilde{X}(t)$; the ith Hermite polynomial function is defined as

$$H_i(u)=(-1)^i\exp\left(\frac{u^2}{2}\right)\frac{d^i}{du^i}\left[\exp\left(-\frac{u^2}{2}\right)\right] \tag{18}$$

More specifically, $H_1(u)=u$, $H_2(u)=u^2-1$ and $H_3(u)=u^3-3u$.

The parameters can be obtained through numerical solution of the nonlinear equations derived by Tognarelli et al. (1997) and Gurley (1997), or by Ditlevsen et al. (1996). The derivation and equivalence for both sets of equations can be found in Appendix A, where the equivalence between them is also illustrated. To improve the computational efficiency, several closed-form approximate formulas have been proposed to estimate the parameters, including Winterstein (1988), Winterstein and Kashef (2000) and Yang et al. (2013). The approximate solution by Yang et al. (2013) has been shown to perform well for mildly and strongly non-Gaussian wind pressure. In this study, the nonlinear