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Three-parameter auto-spectral model of wind pressure for wind-induced response analysis on large-span roofs

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ABSTRACT

The unified wind pressure spectra model with certain precision can simplify the wind-induced response analysis and standardize the design process of the wind resistance. An auto-spectral model of wind pressure was proposed with three parameters which denote the descending slope, the dominant frequency and the peak value of the reduced auto-spectral curve respectively. The values of the model parameters were identified and studied statistically based on 4 types of rigid large-span roof models in which 115 typical wind tunnel pressures were measured. The results show that the distribution patterns of the parameters is in accord with the flow characteristics and can be expressed in the form of zone area, which may indicate the physical meaning of the parameters. The zone values of the parameters were summarized statistically, and the wind pressure spectral model was validated by 1) comparing the spectral curves with relevant studies and 2) comparing the wind-induced responses calculated through the proposed model with the wind tunnel data on 642 cases of large-span grid structures. It concludes that the spectral model can be applied in further exploring the wind load characteristics as well as calculating wind-induced responses in engineering practices.

1. Introduction

The Power Spectral Density (PSD) or auto-spectrum of wind pressure can describe the distribution of the fluctuating energy over a range of frequencies, and they can be estimated from the wind pressure time-series obtained from the wind tunnel tests or field measurements. Xu (1995) and Dalley (1996) compared the wind pressure spectra through the wind tunnel and field measurements on Taxas Tech Building and Silsoe Cube respectively. The results indicated that, despite some local spectral differences on the windward roof, the wind pressure characteristics can be further explored by the auto-spectral data. Kumar (1997) studied wind pressure spectral curves on low-rise buildings in the wind tunnel, and the auto-spectrum was represented by an empirical formula which was used as an input for the digital simulation of wind pressures. Chen (2000) analyzed the spectral characteristics on gable roof houses based on wind tunnel tests, and three typical categories of spectra corresponding to different zones of roof surfaces were summarized, which indicates the spectral analyses can identify potential sources of body-induced turbulence.

In the frequency domain the auto-spectra are the prerequisites to calculate the wind-induced response of structures. Based on the modal force spectrum integrated by the wind pressure spectrum Uematsu et al. (1996) investigated the wind-induced dynamic response and estimated the resonant load on a square long-span roof, and the results were used to formulate the gust loading factor empirically in the Architectural Institute of Japan (AIJ) 1993 wind load code (Tamura et al., 1996). And then Uematsu et al. (1997, 1999) approximated the reduced auto-spectrum of wind load by a power function for the beams of flat roofs in the high frequency range specifically (reduced frequency >0.4). The power fitted "by eye" is about −2 to −3, which provides a simplified procedure to estimate the dynamic resonant wind load on rectangular and circular long-span flat roofs. Pan (2008) fitted the wind pressure spectra with empirical formulas, and then the wind-induced responses were calculated in the frequency domain.

With the development of the database technology, the wind pressure spectra and wind pressure statistics characteristics (such as mean, RMS, skewness and kurtosis) could be collected in the aerodynamic database to evaluate wind loads. Sun (2007) built an aerodynamic database, and the wind pressure spectra were used to reconstruct the wind pressure field. Uematsu and Tsuruishi (2008) used the spectral information to present a computer-assisted wind load evaluation system for the roof cladding design on spherical domes.

In all of the research works mentioned above, the wind pressure auto-spectra were represented by empirical formulas with determined

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Table 1
Some empirical formulas of wind pressure auto-spectral model.

Researcher and reference	Application condition	Expression of wind pressure auto-spectral model
Kumar, 1997 Uematsu and Tsuruishi, 2008	Low-rise buildings/ Spherical domes	$\frac{S_p(f)}{\sigma_p^2} = a_1\exp(-c_1 f) + a_2\exp(-c_2 f)$, a_1, a_2, c_1, c_2 are parameters to be determined.
Tamura et al., 1996 (AIJ, 1993)	Flat roofs	$\frac{f\cdot S_p(f)}{\sigma_p^2} = \frac{F}{\pi\cdot F_m}\left[\frac{\lambda}{(F/F_m+1)^2+\lambda^2} + \frac{\lambda}{(F/F_m-1)^2+\lambda^2}\right]$, $F=f\,H/U_H$; F_m is reduced dominant frequency, recommended as 0.25; λ is band width parameter, recommended as 1.0.
Uematsu et al., 1997, 1999	Flat roofs (square and circular)	$\frac{f\cdot S_p(f)}{\sigma_p^2} = AF^{-\beta}$; $A = 0.11 I_{uH}\ln\left(\frac{D}{H}+0.22\right)+0.01$, $F = f\,H/U_H$ ($F>0.4$). For circular flat roofs, β = 2.7, A is fitted with turbulence intensity I_{uH}, span/height=D/H; For a square flat roof, with different azimuths A=0.012, β=3.0, and A=0.036, β=2.3 are summarized for modal force.
Sun, 2007	Large-span roofs	$\frac{f\cdot S_p(f)}{\sigma_p^2} = \frac{A\cdot F}{(1+B\cdot F^2)^\beta}$; A, B, β are to be determined.
Pan, 2008	Large-span roofs	$\frac{f\cdot S_p(f)}{\sigma_p^2} = \frac{A\cdot F}{C+B\cdot F^{10/3}}$; A, B, C are to be determined.

parameters, which was the auto-spectral model of the wind pressure. Compared with the wind velocity spectral models, which were summarized from large quantities of observed data and acknowledged as basic data for structural wind engineering, there is still a lack of specific summarization study on wind pressure spectral models.

Davenport (1962) established the relationship between wind pressure auto-spectra and wind velocity auto-spectra with the aerodynamic admittance functions χ^2, but it was found that the aerodynamic admittance functions could be derived only under simple conditions such as small scale areas (Davenport, 1962; Lawson, 1980). Kawai (1983) summarized the admittance functions on a square prism, and Geurts (1996) measured the wind pressure of a full-scale building and found that the admittance function cannot be fitted using formula similar to Kawai (1983), which means that the model (Kawai, 1983) cannot be used for large-span buildings.

Many of the researchers (Kumar, 1997; Tamura et al., 1996; Uematsu et al., 1997, 1999; Sun, 2007; Pan, 2008; Uematsu and Tsuruishi, 2008) tried to fit the wind pressure auto-spectra data with empirical formulas (shown in Table 1). It is worth mentioning that the last 2 formulas (Sun, 2007 and Pan, 2008) came from the generic model, i.e. the universal model of wind velocity auto-spectra described by Olesen et al. (1984) and Tieleman (1995) in Eq. (1), where different subsets of the parameters have been suggested (in Sun, 2007, C =1, α=2 and γ=1; in Pan, 2008, α=10/3, β=1 and γ=1).

$$\frac{f\cdot S_u(f)}{\sigma_u^2} = \frac{A\cdot F^\gamma}{(C+B\cdot F^\alpha)^\beta}; \quad F = f\cdot L/U. \tag{1}$$

Li et al. (2012) studied the effects of the parameters in Eq. (1) (shown in Fig. 1). It can be seen that coefficient parameters, A, B and C are related to the location of the auto-spectral curves, and index parameters, α, β and γ, are related to the shape of the curve. However, due to lack of comparison studies, the auto-spectra fitted

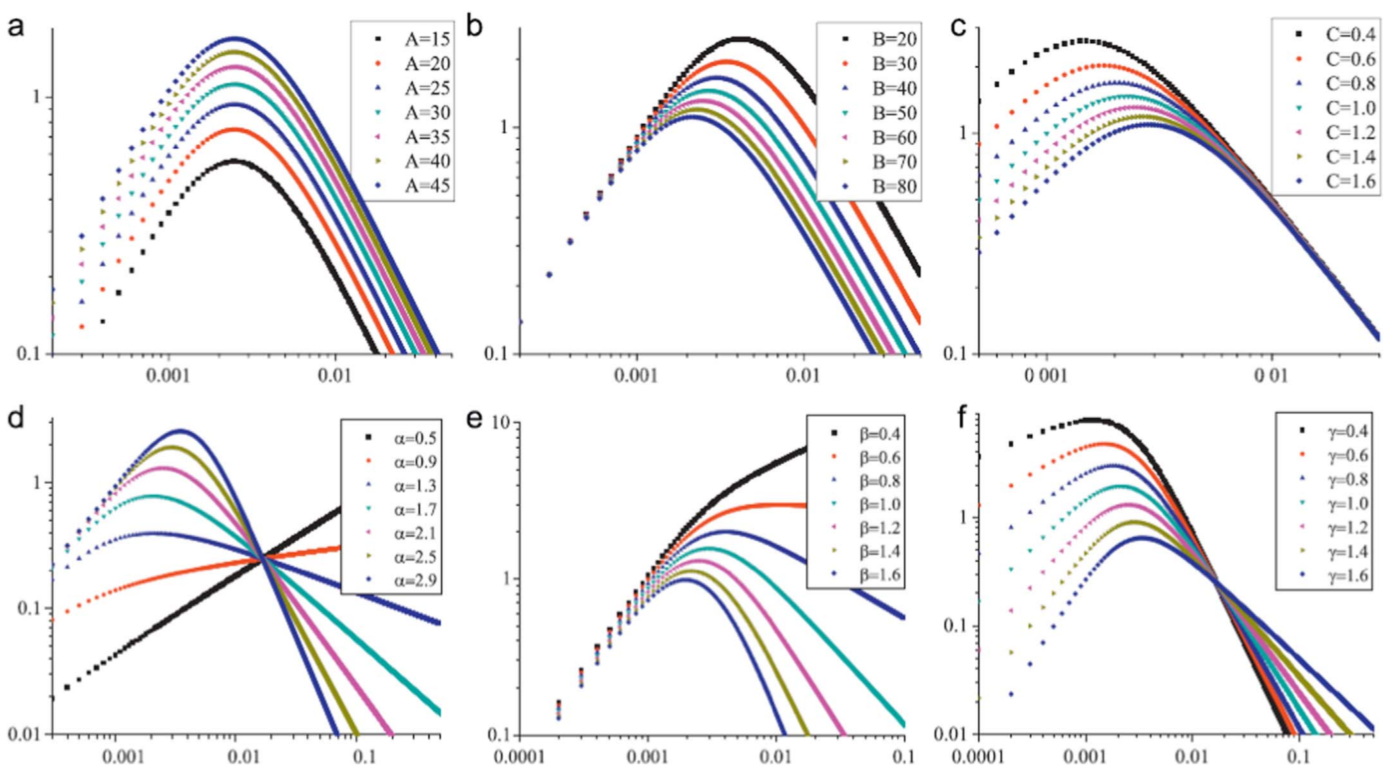

Fig. 1. Parametric influence on auto-spectral curves (Li et al., 2012) (where the abscissa is F =60f; the ordinate is the reduced auto-spectra S, see Section 3).