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A quasi-steady model to account for the effects of upstream turbulence characteristics on pressure fluctuations on a low-rise building

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A B S T R A C T

The effects of upstream turbulence on roof pressure fluctuations of a low-rise building are investigated via the quasi-steady (QS) vector model. Atmospheric boundary layer (ABL) turbulence, with intensities ranging from 13% to 27% and integral length scales from 6 to 13 times the building height, is simulated in a boundary layer wind tunnel. The model building surface pressures are measured synchronously with the velocity at a point one building height above the leading edge. The QS model is found to accurately explain the effects of the ABL turbulence with scales larger than about 5 building heights. Furthermore, a QS model established in one terrain can explain the pressure fluctuations in the other terrains based on the fact that the model functions are similar over the range of observed upstream terrain conditions. This finding is important to the Partial Turbulence Simulation approach since there may be a range of turbulence intensity – integral scale combinations which can yield the same aerodynamic behavior, allowing more flexibility for choosing the model length scales. However, further work is required for modelling the effects of small-scale turbulence on the peak pressures and in defining appropriate bounds when the precise turbulence simulation can be relaxed.

1. Introduction

The fluctuating component of roof surface pressures on low-rise buildings induced by strong wind has been a focus for wind engineering researchers due to its importance for design and understanding failures in post-event damage surveys. Because turbulence in the Atmospheric Boundary Layer (ABL) flow governs the roof surface pressure fluctuations, understanding the effects of turbulence provide engineers with insights for assessing risk levels.

In order to study the fundamental effects of turbulent flow on the wind load while removing other complexities (e.g., mean shear in the flow or geometry complexity), many experiments have been conducted on two-dimensional (2D) bluff bodies placed in an uniform stream. For an upstream smooth flow passing a 2D rectangular bluff body, a laminar shear layer is formed by the flow separation at the leading edge. Due to small-scale disturbances, the laminar shear layer rolls up into discrete Kevin-Helmholtz (KH) vortices (e.g., Brown and Roshko, 1974). These KH vortices can pair, forming larger vortices, breaking into random turbulent eddies, and ultimately impinging the roof surface or shedding downstream (e.g., Kiya and Sasaki, 1983). Gartshore (1973) was the first to identify that it was the turbulence on the stagnation streamline that caused the separated shear layer to be modified by accelerating the process associated with the KH instability. It is the presence of the small-scale turbulence which controls the separated-reattaching flow and the resulting aerodynamic loads (e.g., Hillier and Cherry, 1981; Bearman and Morel, 1983). Lander et al. (2016) also confirmed Gartshore's finding with a turbulence intensity, I_u, of 6.5% and an integral scale, $L_{ux}/H = 0.33$, where H was the across-flow dimension of their square cylinder.

It is well established that the peak and fluctuating wind loads depend to a great extent on both the intensity and scale of the ABL turbulence (e.g., Tieleman, 2003). Relatively large integral length scales are usually encountered in the ABL, e.g., $L_{ux}/H \approx 30$ for the TTU-WERFL building (Levitan and Mehta, 1992b), with a turbulence intensity typically greater than 15% at the roof height of low-rise buildings. This causes challenges for precise matching of these scales in scale-model boundary layer wind tunnel studies (e.g., Tieleman, 2003) since the ideal approach in wind tunnel modelling is to match both the intensity and length scale. The dimensions of typical wind tunnels limit this for low-rise buildings where relatively large model scales are required. For example, wind tunnel studies of roof-mounted solar arrays require the model scales of about 1/20 (e.g., Stenabaugh et al., 2015). At a scale of 1/20, the wind tunnel needs to reproduce an integral length scale of 6 m in order to match a

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Nomenclature

a_{1k}, b_{1k}	k-th order Fourier coefficients associated with $Cp_{\text{inst}}(\theta, \overline{\beta})$
a_{2k}, b_{2k}	k-th order Fourier coefficients associated with $B(\theta)$
B	Gradient of the instantaneous function, i.e., $\partial Cp_{\text{inst}}/\partial \beta'$
Cp	Pressure coefficient
Cp_{inst}	Instantaneous function associated with the quasi-steady model
G	Frequency response of the moving average process
H	Height of the low-rise building
I_u	Turbulence intensity of streamwise velocity component
L_{ux}	Integral length scale of streamwise velocity component
n	Frequency
n_s	Sampling rate
N_1, N_2	Maximum order in the Fourier functions
p	Pressure
p_∞	Ambient static pressure
S_{CpM}, S_{CpQS}	The spectral density of measured and QS-predicted pressures respectively
$S_{\text{CpQS, CpM}}$	The cross-spectral density between the QS-predicted and measured pressures
S_{uu}, S_{vv}, S_{ww}	Spectral density of the three velocity components
t	Time.
Δt	Time step increment, i.e., $\Delta t = 1/n_s$
u	Stream-wise velocity component with direction parallel to x-coordinate
$\mathbf{u}$	Velocity vector, $\mathbf{u} = u\mathbf{i} + v\mathbf{j} + w\mathbf{k}$
$\mathbf{u}_s$	Smoothed velocity time series obtained from moving average technique
$\mathbf{u}_{\text{m}}$	Velocity measured at point m
u_H	Upstream stream-wise velocity at roof height
u_{ref}	Reference velocity
w	Vertical velocity component with direction parallel to z-coordinate
x	x-coordinate of the space
$\mathbf{x}$	Space vector, $\mathbf{x} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$
z	Vertical coordinate of the space
z_o	Roughness length
β	Elevation angle of velocity
θ	Azimuth angle of velocity
ρ	Density of air
$\langle a \rangle$, $\overline{a}$	Estimated or (time) averaged value of a
a'	Temporal fluctuation of a, i.e., $a' = a - \overline{a}$
$f(a)$	Probability density function of a
$\min(a)$	Minimum value of a
$\max(a)$	Maximum value of a
$\text{Re}(a)$	Real part of a
$\text{rms}(a)$	Root mean square of a, i.e., $\text{rms}(a) = \sqrt{\overline{a'^2}}$

full-scale value of 120 m. This is generally not achievable in typical boundary layer wind tunnels that have been designed for testing high-rise buildings at much smaller scales ranging from 1/500 to 1/300. Driven by this type of limitation, research has also been conducted to study the consequences of scale relaxations (e.g., Surry, 1982; Stathopoulos and Surry, 1983).

Because of these challenges with wind tunnel simulations, Irwin (2008) argued that this issue may be resolved if the wind load problem can be separated into two parts: determining the effects of (i) the small scales of turbulence and (ii) the large scales. Building on Irwin's work, Asghari Mooneghi et al. (2016) proposed to use of the ‘Partial Turbulence Simulation’ method for wind tunnel studies. In this approach, the aerodynamic effects due to small-length-scale turbulence are modeled directly in the wind tunnel, while the “missing” turbulence energy associated with the large scales are accounted for analytically using quasi-steady theory.

The theoretical concept behind the approach of Asghari Mooneghi et al. (2016) is that the quasi-steady (QS) model works well in explaining the effects of large-scale turbulence. In fact, researchers have shown that QS models overestimate the pressure fluctuations in the high frequency range, indicating there is an ‘attenuation’ of the effects of small-scale turbulence between the incident flow and that in the separated shear layer (e.g., Letchford et al., 1993). More specifically, Wu and Kopp (2016) observed a better correlation between QS-predicted and measured pressure over the low-frequency, large-scale, fluctuations by analyzing the coherence functions between measured and predicted roof surface pressures.

Because turbulence is three-dimensional, the pressure fluctuations on building surfaces are known to be influenced by the transverse (e.g., Tieleman et al., 1996) and vertical (e.g., Wu et al., 2001) velocity components, in addition to the streamwise component. For example, wind azimuth angle changes due to large-scale turbulence can sway the axis of the conical vortices (e.g., Banks and Meroney, 2001; Wu et al., 2001), influencing the location and magnitude of the maximum instantaneous suctions on the roof. Upwardly-directed wind can also alter the axis and intensity of the vortices generated at separation points, which can enhance the suction on the building surface (Wu et al., 2001). By applying the recent development with the QS ‘vector’ models that account for wind azimuth angle (e.g., Letchford et al., 1993; Richards et al., 1996; Banks and Meroney, 2001) or both wind azimuth and elevation angles (e.g., Letchford and Marwood, 1997; Sharma and Richards, 1999; Richards and Hoxey, 2004, 2012; Wu and Kopp, 2016), the effects of large-scale fluctuations of transverse and vertical velocity fluctuations may be accounted for.

One aspect which has not been investigated to date is whether the terrain effects for varied turbulence levels and scales can be more generally accounted for by a quasi-steady model. The primary assumption of Partial Turbulence Simulation is that it is only the small-scale turbulence that must be matched precisely. However, it would be useful if one could adjust model-scale results to other terrain scenarios. The objective for this paper is to examine this issue. The impact of this would be a somewhat more general hypothesis than that proposed by Irwin (2008) and Asghari Mooneghi et al. (2016) who require matching of the modeled and full-scale spectra for the small scales and then correct only for the missing large-scales. To meet this objective, measured wind tunnel data on the roof of a low-rise building in a range of terrain conditions are used. Roof height turbulence intensities ranging from 13% to 27% and integral length scales ranging from 6 to 13 times of building height are examined for mean wind azimuth directions over one quadrant (i.e., 0° to 90°).

The layout of this paper is as follows. The QS vector model established in Wu and Kopp (2016) is reviewed in Section 2. Wind tunnel experiments involving simultaneous measurements of velocity and roof surface pressure are described in Section 3. Section 4 presents the results regarding the prediction performance of the QS model, while Section 5 discusses the implications of the findings. Finally, conclusions are offered.

2. Review of the quasi-steady model

The quasi-steady (QS) vector model described by Wu and Kopp (2016) is briefly reviewed in this section. Basically, the model postulates a functional form in order to link the instantaneous building surface pressures, p, to the instantaneous velocity vector, $\mathbf{u}_{\text{m}}$, measured at a nearby point, m, i.e.,