PROPOSED TECHNIQUE FOR DETERMINING AERODYNAMIC PRESSURES ON RESIDENTIAL HOMES

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ABSTRACT

Wind loads on low-rise buildings in general and residential homes in particular can differ significantly depending upon the laboratory in which they were measured. The differences are due in large part to inadequate simulations of the low-frequency content of atmospheric velocity fluctuations in the laboratory and to the small scale of the models used for the measurements. The imperfect spatial coherence of the low frequency velocity fluctuations results in reductions of the overall wind effects with respect to the case of perfectly coherent flows. For large buildings those reductions are significant. However, for buildings with sufficiently small dimensions (e.g., residential homes) the reductions are relatively small. A technique is proposed for simulating the effect of low-frequency flow fluctuations on such buildings more effectively from the point of view of testing accuracy and repeatability than is currently the case. Experimental results are presented that validate the proposed technique. In addition to

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eliminating a major cause of discrepancies among measurements conducted in different laboratories, the technique allows the use of considerably larger model scales than are possible in conventional testing. The technique is applicable to wind tunnels and large scale open jet facilities, and can help to standardize flow simulations for testing residential homes as well as significantly improving testing accuracy and repeatability. The work reported in this paper is a first step in developing the proposed technique. Additional tests are planned to further refine the technique and test the range of its applicability.

KEY WORDS: Aerodynamics; atmospheric surface layer; building technology; low-rise structures; open jet facilities; residential buildings; wind engineering; wind tunnels.

INTRODUCTION

High winds cause the largest losses due to natural disasters in the U.S. In hurricanes alone annual losses due predominantly to high winds averaged on the order of $10 billion from 1990-1995. Low-rise buildings such as single-family residences and small commercial structures, which constitute over 70 % of the U.S. building stock, account for a majority of these losses. The reduction of the losses requires the development of appropriate design and retrofitting provisions for such buildings, which currently are limited owing to aerodynamic measurement difficulties in the current state of the art. An international round-robin set of wind tunnel tests of low-rise structures conducted at six reputable laboratories produced the result that wind-induced internal forces in structural frames, and pressures at individual taps, can differ from laboratory to laboratory by factors larger than two (Fritz et al., 2008). This variation is a barrier to rational building standards. Owing in part to such differences aerodynamic pressures on low-rise structures specified in the ASCE 7 Standard (ASCE 7-2005) can be smaller by as much as 50 % than pressures measured in the wind testing laboratories or specified in the literature (Surry et al., 2003; StPierre et al., 2005; Ho et al., 2005; Coffman et al., 2009).

Among the reasons for the non-repeatability of conventional tests across laboratories (i.e., for the dependence of test results on the laboratory in which they are conducted) are two facts. First, the low-frequency fluctuations of the oncoming flow turbulence in the atmospheric surface layer are difficult to simulate, and second, the techniques for their production in the laboratories are not standardized. Since those fluctuations contain the bulk of the turbulent energy, they contribute overwhelmingly to the turbulence intensity and the integral turbulence scale.

For large buildings the imperfect spatial coherence of the atmospheric flows results in significant reductions of the overall wind effects with respect to the case of perfectly coherent flows. However, for buildings with sufficiently small dimensions (e.g., residential homes) such reductions are relatively small. It is hypothesized that peak aerodynamic effects experienced by a small building subjected to flows whose velocities have significant low-frequency fluctuations (hereinafter called "*atmospheric boundary layer-type or ABL-type flows*") are not substantially different from the aerodynamic effects induced by flows (hereinafter called "*simplified flows*") for which the low-frequency content is negligible, while the mean velocities are larger than their counterparts in atmospheric boundary layer flows by amounts that make up for the absence of low-frequency fluctuations.

The objective of the proposed technique is, then, to achieve flow simulations aimed to determine aerodynamic pressures on residential homes that are more effective from the point of view of testing accuracy and repeatability than is the case for conventional simulations in most wind testing facilities, including wind tunnels (Cermak, 1995) and large scale open jet facilities (Huang et al., 2009, Masters and Lopez, 2010, Smith et al., 2010). The experimental approach for achieving this goal is the following. No attempt is made to simulate low-frequency components, i.e., components with non-dimensional frequencies $nz/U(z)$ less than say, 0.1 or 0.2, for which it is commonly accepted that inertial subrange assumptions are no longer applicable (n = frequency, z = height above the surface, U = mean wind speed of the turbulent flow averaged over, say, 10 min or 1 hour) (Fichtl and McVehil, 1970). Rather, the mean speed of the laboratory flow is augmented from $U(z)$ to $cU(z)$, where $c > 1$ is determined as shown in the Appendix. Note that the vertical profile of the simulated flow speeds $U(z)$ and $cU(z)$ is the same. This approach amounts in effect to substituting for the low-frequency fluctuations of the flow with mean speed $U(z)$ an incremental speed $(c\text{-}1)U(z)$ constant in time. This incremental speed may be viewed as a conceptual flow fluctuation with vanishing frequency (i.e., with infinite period). The spatial coherence for this conceptual fluctuation is unity.

In addition to eliminating a cause of discrepancies among measurements conducted in different laboratories, the proposed approach allows the use of considerably larger model scales than are possible in conventional testing, since it eliminates restrictions imposed by integral turbulence scales achievable in the laboratory.

Provided that the spatial separations are of the order of, say, 20 m or less, for the low-frequency components of the atmospheric flow fluctuations the spatial coherences are relatively large. This is shown in the Appendix by using the expression for spatial coherence (Vickery, 1970):

$$Coh(r,n) = e^{-f} \tag{1}$$

$$f = \frac{n[C_z^2(z_1 - z_2)^2 + C_y^2(y_1 - y_2)^2]^{1/2}}{\frac{1}{2}\left[U(z_1) + U(z_2)\right]} \tag{2}$$

where n is the frequency of atmospheric flow fluctuations, $U(z)$ is the mean wind speed at height z, y_1, y_2 and z_1, z_2 are horizontal and vertical coordinates of points M_1 and M_2, and the line M_1, M_2 is assumed to be perpendicular to the direction of the mean wind speed. The proposed testing procedure for low-rise buildings is based on the hypothesis that the spatial coherences of interest are indeed sufficiently large.

To test the hypothesis that peak aerodynamic effects experienced by a small building subjected to ABL-type flows are not substantially different from the aerodynamic effects induced by simplified flows, two sets of tests were carried out as follows. One set of tests used a model of the Silsoe building (Murakami and Mochida, 1990; Richards et al., 2001), while the second set used a model of the Texas Tech. University (TTU) test building (Okada and Ha, 1992). Each set of tests was based on two types of flow. The ABL-type flow was simulated by imparting to the fans quasi-periodic rotations induced by a quasi-periodic waveform signal (for details see Huang et al., 2009). The simplified flow contained negligible low-frequency fluctuations (substituting for the low-frequency fluctuations an incremental speed $(c\text{-}1)U(z)$ constant in time), as explained earlier. As is shown subsequently, the pressure measurement results obtained under these two types of flows support the hypothesis on which this paper is based.

DESCRIPTION OF TESTS

The experiments were carried out by utilizing the 12-fan small-scale Wall of Wind (WoW) (Fu et al., 2010, Gan Chowdhury et al., 2010), an open jet test facility at Florida International University (Figure 1). Two specimens were built as follows:

(1) 8.9 x 8.9 x 8.9 cm (3.5 x 3.5 x 3.5 in) Silsoe cube (length scale being 1:67.5),

(2) 17.5 x 26.0 x 7.7 cm (6.89 x 10.24 x 3.03 in) TTU building (length scale being 1:52).

High frequency cobra probes were used for wind speed measurements and set at 625 Hz sampling rate. A 64 channels pressure transducer was used at a 100 Hz sampling rate. For specimens (1) and (2), all the pressure taps were distributed over the external surface, covering the windward, roof, leeward, and side walls as shown in Figure 2. Pressures were measured for wind angles of attack of 0 ˚ and 45 ˚.

Two types of wind flows were generated to simulate the wind stream without and with low frequency turbulence. To simulate the wind flow without low frequency turbulence components, a flat waveform signal was input into the WoW controller. To simulate the wind flow with low frequency components, a quasi-periodic waveform signal was input into the WoW controller, based on the spectrum of the longitudinal velocity fluctuations for real hurricanes (Yu et al., 2008). The waveform generation details are described in Huang et al. (2009). Figure 3 presents the input waveforms for generating the airflows without and with low-frequency turbulence. The peak of the input signal for the quasi-periodically driven fans (generating ABL-type flows) was equal to the constant input signal for the uniformly driven fans (generating simplified flows). Simplified estimation of increased mean wind speed $c'U(z)$ was estimated by using Step 4, variant (b), of the Appendix. To ensure stability and repeatability of the peak pressure values, all the tests were carried out for duration of 5 min. For the TTU model this duration corresponds at full scale to 90 min, as shown by Eqs. 3 and 4:

$$\frac{T_p U_p}{L_p} = \frac{T_m U_m}{L_m} \tag{3}$$

$$T_p = \left(\frac{L_p}{L_m}\right)\left(\frac{U_m}{U_p}\right)T_m = (52)\left(\frac{16.9(m/s)}{50(m/s)}\right)\times 5(\text{min}) = 87.9\,\text{min} \tag{4}$$

where *T, U,* and *L* are the time, mean wind speed, and characteristic length, respectively, and the subscript *p* and *m* refer to the prototype and the model, respectively. The length scale of 1:52 was based on the scale of the TTU model and the full-scale wind speed is considered as 50 m/s. For the Silsoe model the 5 min. duration corresponded to about 2 hrs at full-scale.

To simulate atmospheric boundary layer (ABL) wind profiles, a passive device was used to generate the vertical profile of wind flows (Gan Chowdhury et al., 2010). This device consisted mainly of a set of planks. The inclination of each plank was adjusted by trial and error to ensure that the mean speeds of the air flow match reasonably well the mean flow in typical open terrain (power law exponential $\overline{\alpha}$ = 1/6 pertaining to mean flow, see Figure 4).

The turbulence intensity at 89 mm (3.5 in) above ground (corresponding to the roof height of the Silsoe model) was approximately 6 % for the flat flow and 26 % for the quasi-periodic flow. Mean wind speeds were 24.8 m/s and 16.9 m/s for the flat and quasi-periodic flows, respectively, which ensured that the flow with negligible low-frequency content had a mean velocity equal to the sum, in the flow with significant low-frequency content, of (a) the mean velocity, and (b) the peak fluctuating velocity induced by the low-frequency fluctuations. The optimum distance between the exit of the WoW and the windward wall surface of the test models was 22.0 cm (8.6 in). Figure 5 shows the wind velocity time histories of the flows without and with low-frequency components. Figure 6 shows the dimensional spectra for both flows. For comparison purposes the figure also shows the spectrum proposed by Yu et al. (2008) for hurricane wind data in open terrain exposure, obtained within the framework of the Florida Coastal Monitoring Program (Masters, 2004) [mean wind speed of 16.9 m/s, turbulence intensity of 26 %, and parameter β = 6.0 (Table 2.3.1, Simiu and Scanlan, 1996)].

Because of the limitations of the small scale WoW fan's performance, it was possible to obtain spectra covering only the dimensional interval n = 0.03 Hz to n = 10 Hz, that is, the non-dimensional interval up to f = 0.06. The turbulence intensities achieved in the experiments increased from 6 % in the absence of low-frequency fan rotations to 26 % when quasiperiodic fan rotations were activated. The results of the experiments presented in the paper show that the the effect of increments in the mean speeds (i.e., the effect of incremental "zero frequency" fluctuations) was a reasonable substitute for the effect of low-frequency fluctuations, not only on the aerodynamics of the windward face of the structure, but also on the aerodynamics of the structure as a whole. Quantitative experimental information (a) corresponding to other non-dimensional frequency intervals and (b) on the sizes of the windward face for which the assumption of perfect coherence of the oncoming low-frequency fluctuations is not excessively conservative, will require large-scale WoW testing used in conjunction with analytical calculations in which the parameters of the flow coherence are based on measurements of the large-scale turbulent flow.

Results

Typical time histories of roof pressures are shown in Figure 7. The observed peaks can exhibit wide variability from one realization to another due to their random nature. To remove the uncertainties inherent in the randomness of the peaks, probabilistic analyses were performed using the procedure developed by Sadek and Simiu (2002) (www.nist.gov/wind) for obtaining statistics of pressure peaks from observed pressure time histories. Because estimates obtained by this procedure are based on the entire information contained in the time series, they are more stable than estimates based on observed peaks and provide a clearer and more meaningful basis for the comparisons. The comparisons were in all cases based on the 95th percentile of the estimated distributions of the peaks.

Figure 8 shows the ratio (R) of the 95th percentile estimates of peak pressures measured for the Silsoe model under flow with no low-frequency content to peak pressures measured with low frequency content. The experiments were repeated 5 times. As the results show, the ratios are typically close to unity. In a few cases they are higher than unity by approximately 20 %, and lower than unity by approximately 17 %.

Table 1 lists means and standard deviations of the ratio R obtained for five repeated tests on the Silsoe model for two wind azimuths (0 ˚ and 45 ˚). Taps were chosen to represent windward wall, roof, leeward wall, top corner, and side walls. Results show that the mean value of the ratio R for the five trials is also close to one.

Figure 9 shows peak pressure ratios for TTU model. The largest ratio R at the roof is about 20 % higher than unity. Table 2 lists mean and standard deviation of the ratio R obtained for five repeated tests with the TTU model for two wind azimuths (0 ˚ and 45 ˚). Arbitrary taps were chosen to represent windward, roof, leeward, top corner, and side wall. Results show that the mean value of the ratio, R, for the five trials is close to one. The standard deviations of the results are in all cases small. This establishes the repeatability of the tests performed in accordance with the procedure proposed in this paper.

Conclusions

The question arises whether it is desirable to use for the testing of residential homes and other low-rise buildings or portions thereof flows that attempt to simulate low-frequency fluctuations. The drawbacks of tests in such flows are the following. First, they induce errors in the estimation of the pressures. These errors tend to be significantly larger than those inherent in the use of flows with no low-frequency fluctuations and affect adversely the repeatability of the tests. To achieve better agreement of results across different laboratories, a standard flow simulation protocol for low-rise buildings would have to be used. Such a protocol would be applied to wind tunnels and large scale open jet facilities in an effort to standardize flow simulations for residential homes and improve testing accuracy and repeatability.

Second, the simulation of low-frequency turbulent fluctuations imposes severe constraints on the geometric model scale, which unavoidably entail additional errors in the estimation of aerodynamic effects. To within limitations associated with blockage these constraints are eliminated for flows with no low-frequency fluctuations.

The results of the tests presented in this paper support the hypothesis that flows with no low-frequency content that simulate correctly the mean wind profile in the atmospheric boundary layer are adequate for the simulation of pressures induced by atmospheric flows on low-rise buildings with dimensions comparable to those of individual homes. The errors inherent in such flows are far smaller than those that can occur in conventional wind tunnel tests. The proposed technique allows the use of larger test models allowing the modeling of architectural details, Reynolds number improvements enhancing aerodynamic accuracy, and higher spatial resolution of pressure measurements. The work reported in this paper is viewed as a first step in developing the proposed technique. Additional tests are planned to further refine the technique and test the range of its applicability.

Appendix. Determination of factor *c*

This Appendix proposes an answer to the question: how large should the increment of the mean velocity be in order to provide a correct approximate substitute for the missing low-frequency fluctuations?

Consider the simple case of the total wind force acting on the windward face of a rectangular building acted upon by wind normal to that face. For this case it is possible to calculate approximately that force both for flow nominally conforming to the conventional ABL model, and for flow conforming to the simplified model described earlier. The study also proposes an answer to the following question: what is the definition of "low-frequency fluctuations?" The answers based on the present study are intended to provide guidance required for aerodynamic testing of small buildings in simplified flows.

The wind speed $U(y, z, t)$ is assumed to vary with time t, width y, and height z, and consists of the mean wind speed $U(z)$ and the wind speed longitudinal fluctuations about the mean, $u(y, z, t)$. The velocity $U(y, z, t)$ is assumed to be normal to the wider face of the building.

The objective is to create a simplified flow such that the peak total aerodynamic force F_{peak} it induces on the windward face of a building is approximately equal to the peak force induced by the ABL-type. The calculations entail the following steps:

Step 1: Estimation of peak force F_{peak} induced by the ABL flow on the windward building face:

The calculation of the peak total aerodynamic force F_{peak} is performed here under the following assumptions:

1. The spectral density of the longitudinal flow fluctuations u is described by the expression for the modified Kaimal spectrum:

$$\frac{n\,S_u(z,n)}{u_*^{\,2}} = \frac{200f}{(1+50f)^{5/3}} \tag{A1}$$

where f is the reduced frequency defined as $nz/U(z)$ and u_* is the friction velocity (Simiu and Scanlan, 1996, p. 59). This expression is valid for frequencies $0 < f \le f_c$ in which it is reasonable to assume a cut-off frequency $f_c = 10$ (i.e., $S_u(z, n) = 0$ for $f > f_c$). If appropriate, different expressions for the spectrum may be employed.

2. The expression for the spatial coherence of the longitudinal wind velocity fluctuations u is given by Eqs. 1 and 2.

3. The longitudinal flow fluctuations and the flow-induced forces on the windward wall are approximately Gaussian.

Using these assumptions, the total wind-induced peak force F_{peak} on the windward wall can be expressed as the sum of the mean force and the peak force due to all fluctuations:

$$F_{peak} \approx F_U + \kappa_{Fp}\sigma_{Fp} \tag{A2}$$

where

$$F_U = \int_0^h \int_0^b \tfrac{1}{2}\rho C_p U^2(z)\,dy\,dz \tag{A3}$$

b is the width of the building, h is the height, ρ is the air density, $C_p = P(z) \big/ \left[\frac{1}{2}\rho U^2(z)\right] \approx 0.8$ is the mean pressure coefficient where $P(z)$ is the mean pressure at height z, K_{Fp} is the peak factor, and σ_{Fp} is the r.m.s. of the fluctuating force F'.

The peak factor for a flow with a duration of T seconds is approximately (Davenport 1964)

$$\kappa_{Fp} \approx \sqrt{2\ln(\nu_{Fp}T)} + \frac{0.577}{\sqrt{2\ln(\nu_{Fp}T)}}$$
$$\text{where} \quad \nu_{Fp} = \left[\frac{\int_0^{n_c} n^2 S_{Fp} dn}{\int_0^{n_c} S_{Fp} dn}\right]^{1/2} \tag{A4}$$

where ν_{Fp} is the expected frequency for the peak force, and n_c is the dimensional cut-off frequency corresponding to f_c, S_{Fp} is the spectral density of the fluctuating force F_p on the windward wall. The r.m.s. of the fluctuating force F_p is obtained by integration as follows:

$$\sigma_{Fp} = \left[\begin{array}{c}\int_0^{n_c}\int_0^h\int_0^h\int_0^b\int_0^b \rho^2 C_p{}^2 U(z_1)U(z_2)\, S_u{}^{1/2}(z_1,n)\, S_u{}^{1/2}(z_2,n)\times \\ \text{Coh}(y_1,y_2,z_1,z_2,n)\, dy_1\, dy_2\, dz_1\, dz_2 dn\end{array}\right]^{1/2} \tag{A5}$$

This completes the calculation of the peak force F_{peak} induced by the ABL flow.

Step 2: Estimation of peak force F_{peak1} induced by the simplified flow.

The estimation process is similar to Step 1 except that:

1. The spectral density of the longitudinal velocity fluctuations u in the simplified flow is

$$S_u(z,n) = 0 \qquad \text{for } 0 < f \le f_{low}$$

$$\frac{n\,S_u(z,n)}{u_*^{\,2}} = \frac{200f}{(1+50f)^{5/3}} \qquad \text{for } f_{low} < f \le f_c \tag{A6}$$

where f_{low} can be selected near the lower limit of the interval within which the Kolmogorov inertial subrange hypothesis holds in the ABL wind, and f_c = 10 as explained earlier. Recall that the reduced frequency f is based on mean wind speed $U(z)$.

The simplified flow has no (or weak) low-frequency fluctuations (area *A* in Fig. A1) (see Eq. A6), and has an increased mean speed cU which is required so that the peak force generated by the ABL flow (with speed *U* and spectral content denoted by *A* and *B* in Fig. A1) be the same as the peak force generated by the simplified flow (with speed cU and spectral content denoted by *B*). Note that wind-induced pressures on buildings are affected by high-frequency fluctuations, which should be simulated in the simplified flow.

The calculation of the peak force F_{peak1} (= F_{cU}) due to the simplified flow is similar to the calculation of the force F_{peak} in Step 1.

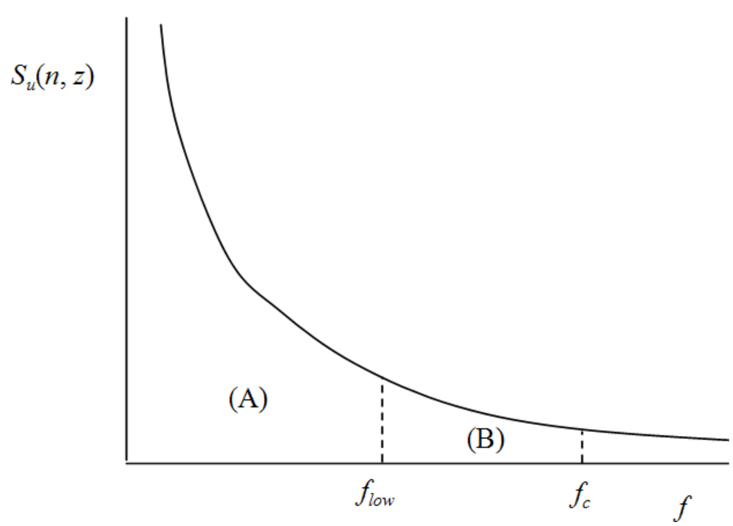

Figure A1. Spectrum of the longitudinal velocity fluctuations.

Step 3: Estimation of the upper limit of low-frequency fluctuations f_{low}.

To generate approximately equivalent peak forces due to the ABL flow (Step 1) and the simplified flow (Step 2), the low-frequency fluctuations must have sufficiently high spatial coherence so that the force they generate can be replaced by the mean force due to the incremental speed ΔU. For small structures, e.g., residential homes, a reasonable approximate estimate of the upper limit of low-frequency fluctuations is f_{low}=0.1 (Yeo, 2010).

Step 4, variant (a): Estimation of increased mean wind speed cU.

Given f_{low}, the increased mean wind speed $cU = U + \Delta U$ can be determined by equating the peak force due to the ABL flow and the peak force due to the simplified flow (i.e., $F_{peak} = F_{peak1}$). The requisite factor c and the corresponding mean wind speed increment ΔU are therefore estimated as follows:

$$F_{cU} = c^2 F_U \tag{A7}$$

$$c = \sqrt{\frac{\kappa_{Fp}\sigma_{Fp} - \kappa_{Fph}\sigma_{Fph}}{F_U} + 1} \tag{A8}$$

$$\Delta U = (c-1)U \tag{A9}$$

where κ_{Fp} is the peak factor and σ_{Fp} is the r.m.s. of the fluctuating force, for the high frequency fluctuations $f_{low} < f \le f_c$.

Step 4, variant (b): Simplified estimation of increased mean wind speed $c'U = U + \Delta U'$.

An alternative estimate of the increased speed, denoted by $c'U$, can be performed by equating the peak wind speed due to the low-frequency fluctuations in the ABL flow and the increment in the mean speed $\Delta U'$ in the simplified flow. The results are then

$$U + \kappa_u \sigma_u = c'U + \kappa_{uh} \sigma_{uh} \quad \text{(A10)}$$

$$c' = \frac{\kappa_u \sigma_u - \kappa_{uh} \sigma_{uh}}{U} + 1 \quad \text{(A11)}$$

$$\Delta U' = \kappa_u \sigma_u - \kappa_{uh} \sigma_{uh} \quad \text{(A12)}$$

where κ_u and σ_u are the peak factor and the r.m.s. of the longitudinally fluctuating wind speed corresponding to all frequency fluctuations $0 < f \leq f_c$, and κ_{uh} and σ_{uh} are their counterparts corresponding to high frequency $f_{low} < f \leq f_c$. The calculated $\Delta U'$ is slightly more conservative (i.e., larger) and less accurate than ΔU calculated in Step 4(a). The larger the building, the less accurate the simplified calculation is.

The software for the numerical implementation of the calculation is provided in Yeo (2010).

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References

American Society of Civil Engineers (ASCE) Standard. *Minimum Design Loads for Buildings and Other Structures*. American Society of Civil Engineers, New York, 2005, ASCE/SEI 7-05.

Cermak, J.E. (1995). "Development of wind tunnels for physical modeling of the atmospheric boundary layer (ABL). A state of the art in wind engineering." *Proceedings of the 9th International Conference on Wind Engineering.* New Age International Publishers Limited, London, U.K., 1995, pp. 1-25.

Coffman, B.F., Main, J.A., Duthinh, D., and Simiu, E (2010). "Wind effects on low-rise buildings: Database-assisted design vs. ASCE 7-05 Standard estimates." *J. Struct. Eng.* (in press).

Endo, M., Bienkiewicz, B., and Ham, H.J. (2006). "Wind-tunnel investigation of point pressure on TTU test building." *Journal of Wind Engineering and Industrial Aerodynamic,* 94, 553-578.

B. Bienkiewicz, M. Endo, and J.A. Main. (2009), "Comparative inter-laboratory study of wind loading on low-rise industrial buildings," *ASCE/SEI Structural Congress*, American Society of Civil Engineers, Austin Texas.

Davenport, A. G. (1964), "Note on the distribution of the largest value of a random function with application to gust loading." Institution of Civil Engineers, London, England, 187-196.

Fichtl, G.H., and McVehil, G.E. (1970), "Longitudinal and lateral spectra of turbulence in the atmospheric boundary layer at the Kennedy Space Center," *J. Appl. Meteor.* 51-63

Fritz, W.P., Bienkiewicz B., Cui B., Flamand O., Ho T. C. E., Kikitsu H., Letchford C.W., and Simiu E. (2008). "International comparison of wind tunnel estimates of wind effects in low-rise buildings: test-related uncertainties," *Journal of Structural Engineering*, 134, 1887-1880.

Fu, T-C., Aly, A.M., Bitsuamlak, G., Gan Chowdhury, A., Simiu, E. (2010). "Flow simulation in 12-fan Wall of Wind testing facility." Proceedings of the 2nd Workshop of the American Association for Wind Engineering (AAWE) (Marco Island, Florida, USA), (CD-ROM).

Gan Chowdhury, A., Aly, A.M., Bitsuamlak, G. (2010). "Full- and large-scale testing to promote wind disaster mitigation." Proceedings of the Fifth U.S.-Japan Workshop on Wind Engineering (Chicago, Illinois, USA), (CD-ROM).

Gan Chowdhury, A., Simiu, E. and Leatherman, S.P. (2009), "Destructive testing under simulated hurricane effects to promote hazard mitigation," *Nat. Hazards Review J. ASCE*, 10(1), 1-10.

Ginger, J. D. and Letchford, C.W. (1999). "Net pressure on a low-rise full-scale building," *J. Wind Eng. Ind. Aerodyn.* 83, 239-250.

Ho, T.C.E., Surry, D., Morrish, D., and Kopp, G.A. (2005). "The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part I. Archiving format and basic aerodynamic data," *J. Wind Eng. Ind. Aerodyn.* 93, 1-30.

Huang, P., Gan Chowdhury, A., Bitsuamlak G., and Liu. R. (2009). "Development of devices and methods for simulation of hurricane winds in a full-scale testing facility," *Wind and Structures*, 12 (2), 151-177.

Letchford, C. W. and Chay, M. T. (2002). "Pressure distributions on a cube in a simulated thunderstorm downburst. Part B: moving downburst observations," *J. Wind Eng. Ind. Aerodyn.*, 90, 733-753.

Li Q.S. and Melbourne W.H. (1995). "An experimental investigation of the effects of fee-stream turbulence on streamwise surface pressure in separated and reattaching flows," *J. Wind Eng. Ind. Aerodyn.* 54/55, 313-323.

Okada, H. and Ha, Y.C. (1992), "Comparison of wind tunnel and full-scale pressure measurement tests on the Texas Tech Building", *J. Wind Eng. Ind. Aerodyn.*, 43(1-3), 1601-1612.

Orwig, K.D. and Chroeder J. L. (2007). "Near-surface win characteristics of extreme thunderstorm outflows," *J. Wind Eng. Ind. Aerodyn.*, 95, 565-584.

Masters, F.J. *Measurement, Modeling and Simulation of Ground-Level Tropical Cyclone Winds*. PhD Dissertation, University of Florida, Gainesville, 2004.

Masters, F.J., Lopez, C. (2010). "Progress Update on Wind-Driven Rain Ingress Research at the University of Florida." Proceedings of the 2nd Workshop of the American Association for Wind Engineering (AAWE) (Marco Island, Florida, USA), (CD-ROM).

Murakami, S. and Mochida, A. (1990) “3-D numerical simulation of airflow around a cubic model by means of the k-ε model,” *J. Wind Eng. Ind. Aerodyn.*, 31, pp. 283-303.

National Institute of Standards and Technology (NIST), May (2010), http://www.itl.nist.gov/div898/winds/peakest_files/peakest.htm

Richards, P.J., Hoxey, R.P. and Short, L.J. (2001) “Wind pressures on a 6m cube,” *J. Wind Eng. Ind. Aerodyn.*, 89, 1553-1564.

Sadek, F. and Simiu, E. (2002), “Peak non-Gaussian wind effects for database-assisted low-rise building design,” *J. Eng. Mech.*, 128(5), 530-539.

Smith, J., Liu, Z., Masters, F.J., Reinhold, T. (2010). “Validation of facility configuration and investigation of control systems for the 1:10 scaled Insurance Center for Building Safety Research.” Proceedings of the 2nd Workshop of the American Association for Wind Engineering (AAWE) (Marco Island, Florida, USA), (CD-ROM).

St. Pierre, L.M., Kopp, G.A., Surry, D., and Ho, T.C.E. (2005). “The UWO contribution to the NIST aerodynamic database for wind loads on low buildings: Part II. Comparison of data with wind load provisions,” *J. Wind Eng. Ind. Aerodyn*. 93, 31-59.

Surry, D., Ho, T.C.E., and Kopp, G.A. (2003). “Measuring pressures is easy, isn’t it?” Proceedings, International Conf. on Wind Engineering, Texas Tech University, Lubbock, TX, 2, 2618-2623.

Tieleman, H.W., Surry, D., Mehta, K.C. (1996), “Full/model-scale comparison of surface pressures on the Texas Tech experimental building”, *J. Wind Eng. Ind. Aerodyn*. 61(1–23), 1–23.

Vickery, B. J. (1970). "On the reliability of gust loading factors." the Technical Meeting Concerning Wind Loads on Buildings and Structures, Building Science Series 30, National Bureau of Standards, Washington, DC.

Yeo, D. (2010). "Numerical simulation of along-wind loading on small structures using a simplified wind flow model." NIST Technical Note 1683, National Institute of Standards and Technology, Gaithersburg, MD, (available at publications in www.nist.gov/wind).

Yu, B., Chowdhury A.G., and Masters F.J. (2008). “Hurricane wind power spectra, cospectra, and integral length scales,” *Boundary-Layer Meteorol*, 129, 411-430.

Table 1 Mean and standard deviation of the ratio R obtained for five repeated tests with the Silsoe cube model for two wind azimuths

Azimuth	Ratio	Tap # 5	Tap # 7	Tap # 14	Tap # 49	Tap # 56
0 deg	R_{mean}	1.0092	1.0650	0.9439	1.0166	1.0308
	R_{std}	0.0028	0.0164	0.0257	0.0148	0.0021
45 deg	R_{mean}	0.9796	0.9946	0.9557	0.9854	0.8907
	R_{std}	0.0391	0.0228	0.0160	0.0198	0.0070

Table 2 Mean and standard deviation of the ratio R obtained for five repeated tests with the TTU test model for two wind azimuths

Azimuth	Ratio	Tap # 4	Tap # 8	Tap # 16	Tap # 38	Tap # 60
	R_{mean}	1.0060	1.1528	0.9607	1.2052	0.9786
0 deg	R_{std}	0.0191	0.0338	0.0230	0.0235	0.0107
	R_{mean}	1.0017	0.9773	1.0260	0.8384	1.0320
45 deg	R_{std}	0.0271	0.0218	0.0210	0.0059	0.0117

Figure 1 Small-Scale 12-Fan Wall-of-Wind (WoW)

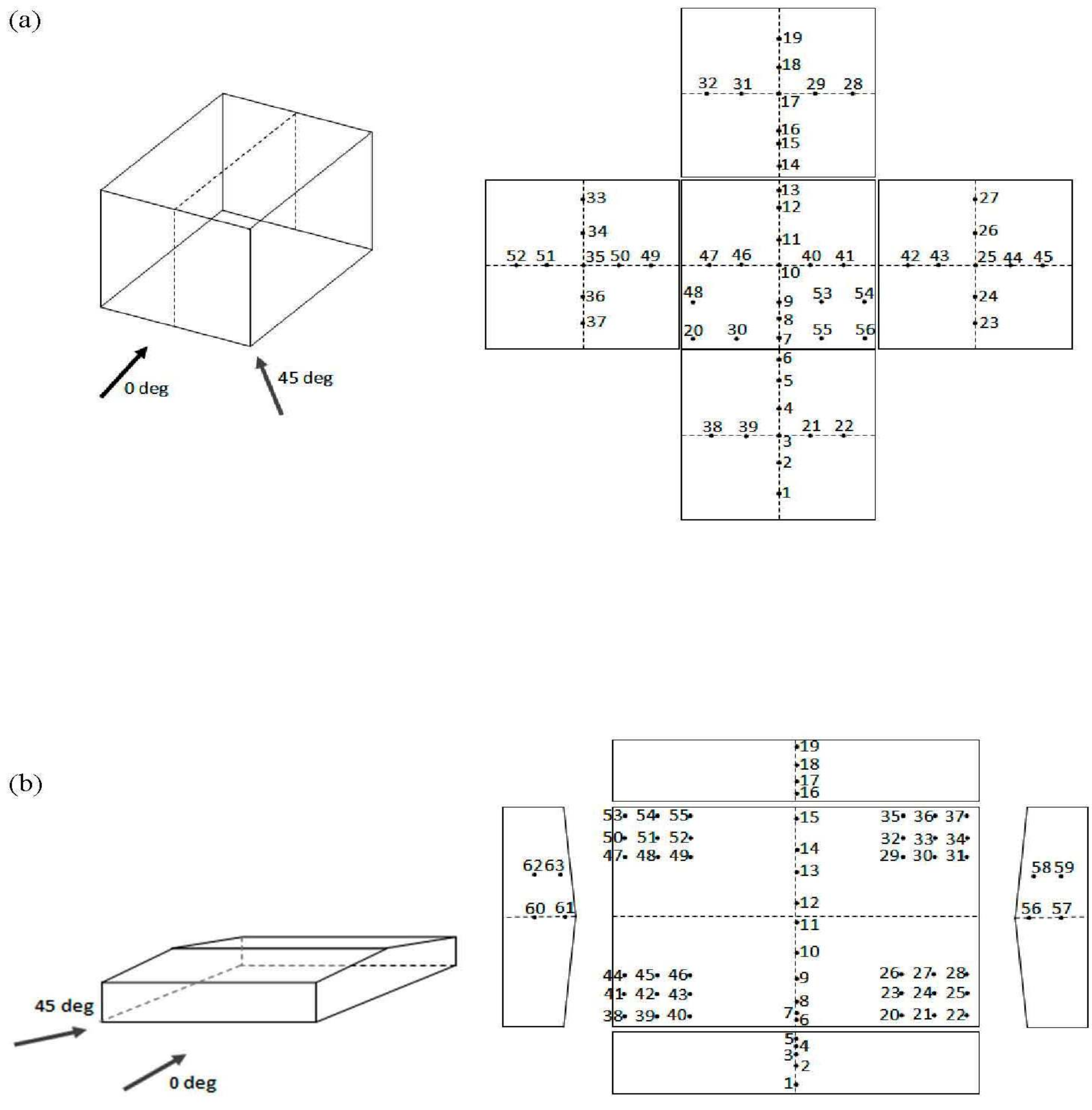

Figure 2 Tap Layout for the Two test Specimens: (a) 8.9 x 8.9 x 8.9 cm Silsoe Cube, and (b) 17.5 x 26.0 x 7.7 cm TTU Building

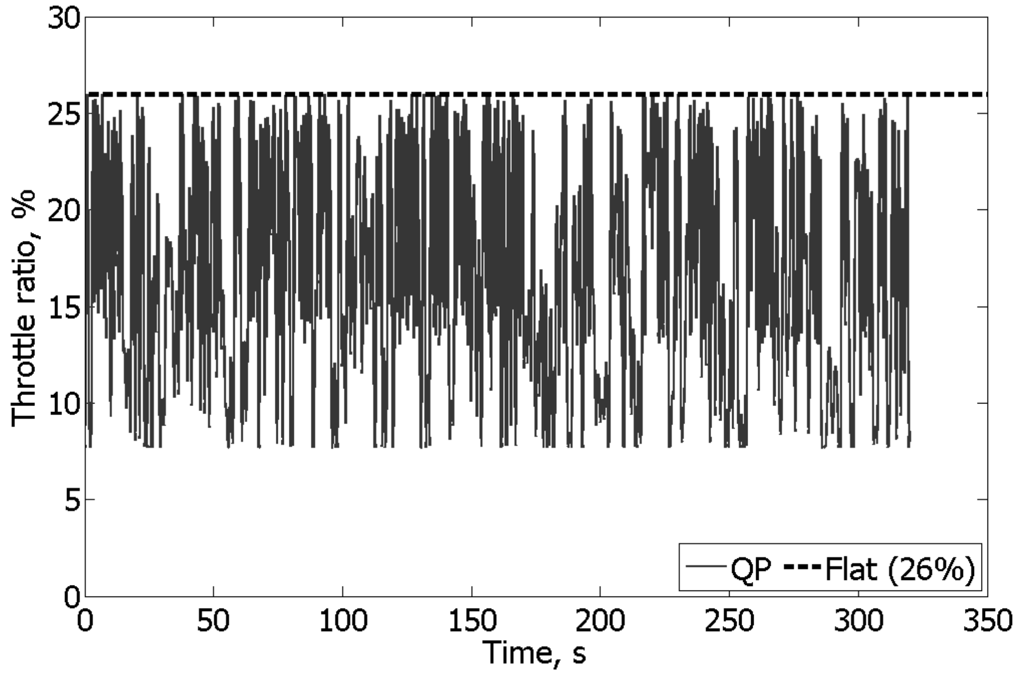

Figure 3 Input Waveforms of Flat Flow (without Low-Frequency Content) and QP Flow (with Low-Frequency Content)

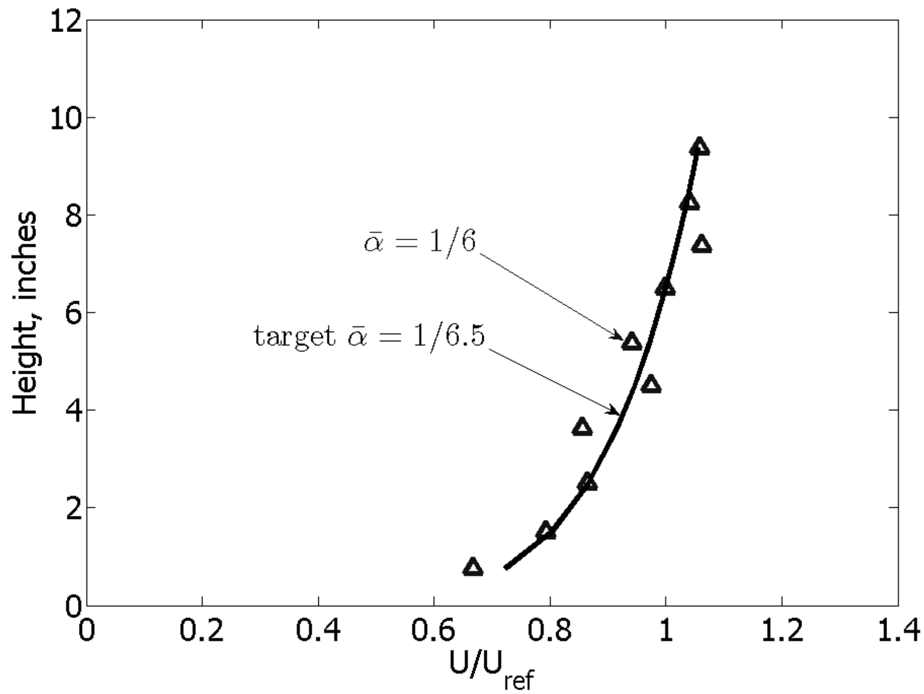

Figure 4 Mean Wind Speed Profile

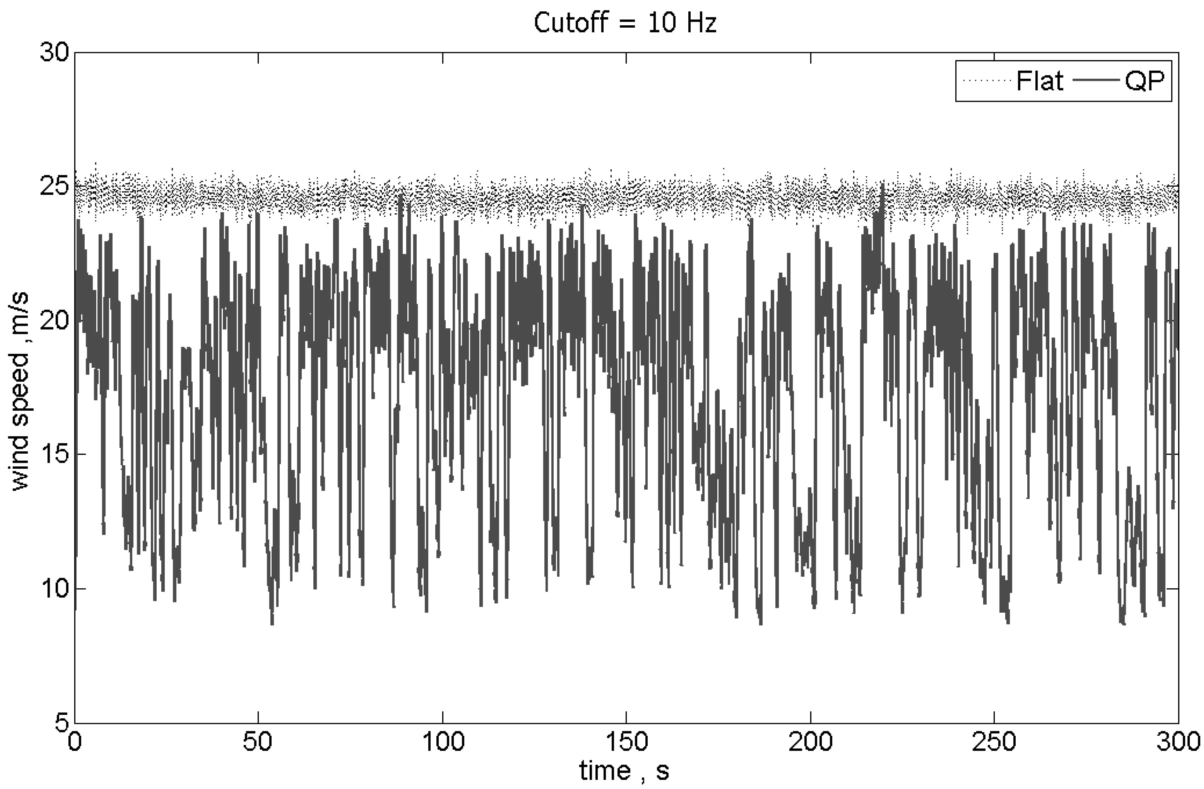

Figure 5 Time History of Flat Flow (without Low-Frequency Content), and QP Flow (with Low-Frequency Content)

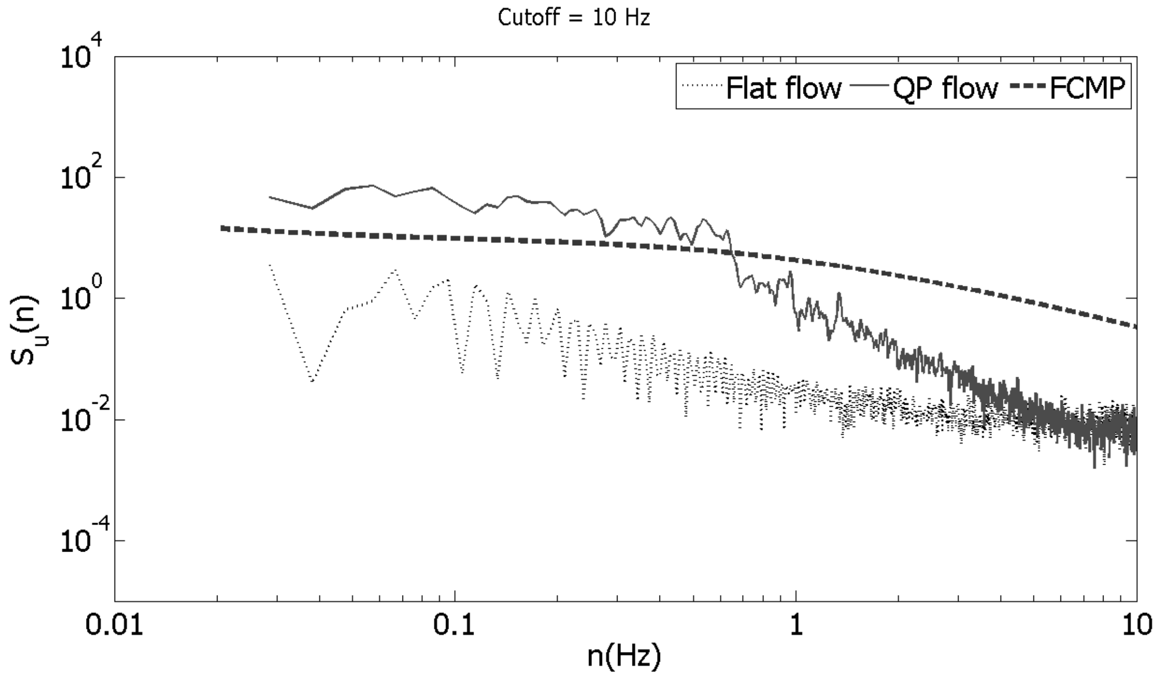

Figure 6 Dimensional Spectra of Longitudinal Wind Flow Fluctuations

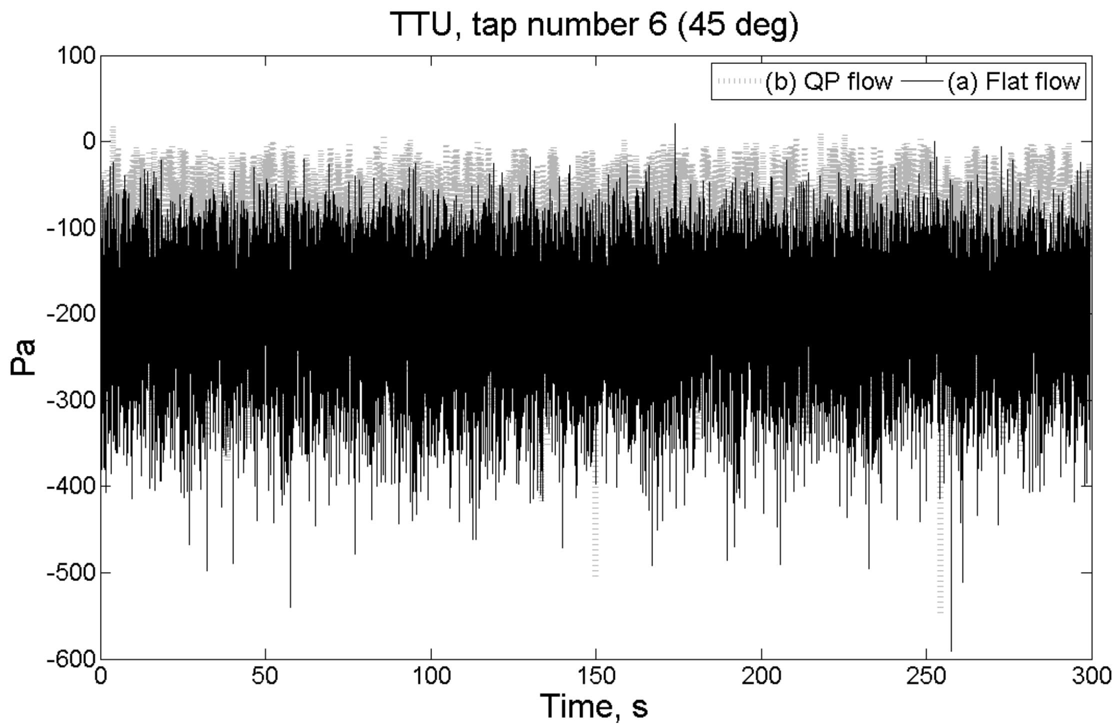

Figure 7 Typical Roof Pressure Time History Data under (a) Flat Wind Flow and (b) Quasi-Periodic Wind Flow

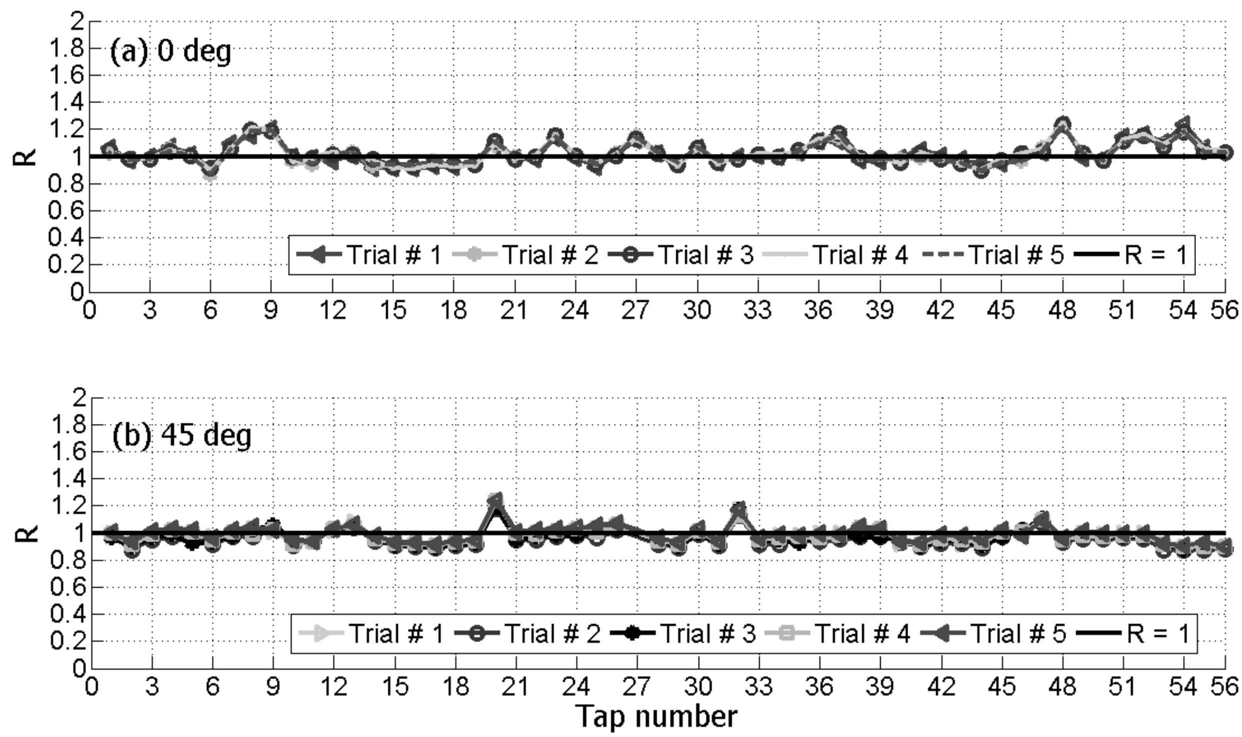

Figure 8 Peak Pressure Ratio of Flat to Quasi-Periodic vs. Tap Number (Silsoe Cube)

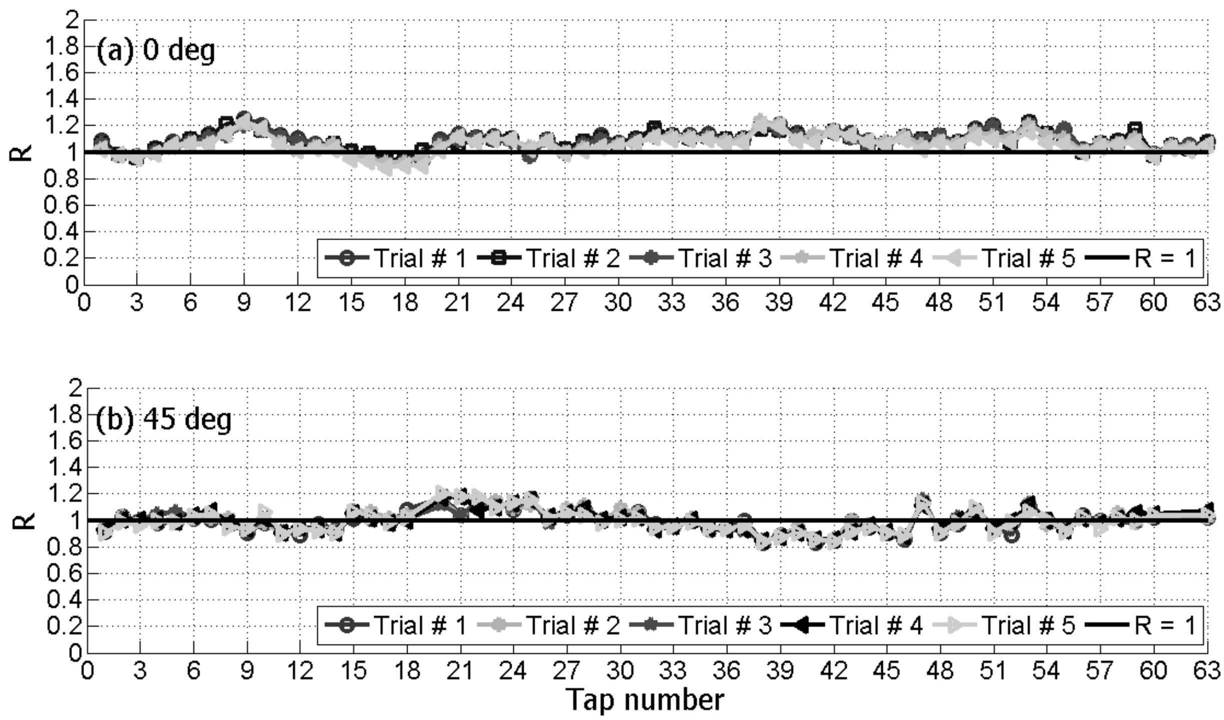

Figure 9 Peak Pressure Ratio of Flat to Quasi-Periodic vs. Tab Number (TTU Model)