August 27-31, 2023
FLORENCE - ITALY
ICWE 16
16th International
Conference on
Wind Engineering

Solar tracker case study on the importance of high frequency spectrum matching for large scale models

E. Gavanski [1], D. Banks [2], Y.J. Fewless [3], A.F. Akon [4], T.K. Guha [5]

[1]CPP Wind Engineering, Fort Collins, Colorado, USA, egavanski@cppwind.com
[2]CPP Wind Engineering, Fort Collins, Colorado, USA, dbanks@cppwind.com
[3]CPP Wind Engineering, Fort Collins, Colorado, USA, yfewless@cppwind.com
[4]CPP Wind Engineering, Fort Collins, Colorado, USA, fakon@cppwind.com
[5]NEXTracker, San Francisco, California, USA, tguha@nextracker.com

SUMMARY:
When detailed pressure measurements are required on small structures such as single axis solar trackers, large-scale models (in the range of 1/20 to 1/50) are often used. There is not a consensus on how best to model the approach flow or convert wind load coefficients from such testing for use at full scale. Comparison among full-scale measurement and wind tunnel measurements under conventional turbulence intensity matching flow and high frequency spectrum matching flow on single-axis tracker model is performed in order to present the effect of flow simulation and pressure normalization on the wind pressure coefficients.

Keywords: Wind tunnel, Turbulence, Solar tracker

1. INSTRUCTION

When large-scale models are tested in an atmospheric boundary layer wind tunnel, the simulated flow in the tunnel also needs to contain relatively large turbulence for replicating the appropriate aerodynamics around them. Since the physical size of the wind tunnel is limited, the turbulence length scale which can be passively created in the typical wind tunnel is limited to 0.5-1.0 m. This is usually large compared to the size of the tested models but can be much too small compared to the target turbulence length scale, which is often over 100 m. Where the mismatch in the turbulence energy spectrum is significant, it is uncertain whether the wind pressure data obtained under such flow simulations are adequate for the further analysis and design.

This problem has been receiving attentions and been examined since 1970s. Among several researchers, Tieleman conducted extensive research on this issue (e.g., Tieleman et al., 1978). According to Tieleman, simultaneous simulation of mean velocity profile, $\bar{u}$, turbulence intensity, $I_u(=\sigma_u/\bar{u})$, and turbulence integral scale, L_x, is difficult to achieve. However, a good agreement between model and full-scale roof pressure coefficients is possible if L_x is as large as the largest model dimension and is not less than 20% of the full-scale target value (Tieleman et al., 1998). Additionally, Stathopoulos and Surry (1983) mentioned the possibility of a small relaxation of L_x up to a factor of 2. These findings have been cited in subsequent research papers to justify the veracity of flow simulation and measured C_p with large-scale models.

Other researchers have suggested not only the conditions of the flow simulation but also the correction methods on the obtained C_p. Basically, such studies suggest that high frequency (small scale) turbulence, which affects suctions on building surfaces, needs to be correctly simulated in wind tunnel flow simulations and that a correction on the obtained C_p data should be applied in order to consider the effect of missing low frequency (large-scale) turbulence in the tunnel. This is called Partial Turbulence Simulations (PTS) according to ASCE49-21(2021). The suggested data correction methods on the obtained C_p are different depending on the studies but mainly for static analysis. For example, Banks et al. (2015) corrected wind load time series by adding the low frequency turbulence below Quasi-Steady (QS) cut-off frequency to the measured wind load time series analytically in the frequency domain using transfer function. Here, 'QS cut-off frequency' is meant to be the frequency above which QS theory is not expected to work, e.g., the wind pressure spectrum does not follow the velocity spectrum.

Although several studies on PTS have been published, its use is not widespread. Instead, these large models are tested with the same process as much smaller models where the full spectrum is present. The reason for this might be partially because its necessity has not been clearly presented and hence its benefit/importance is not well recognized, or because the simplicity of PTS is not apparent. Therefore, the purpose of this study is to present the effect of improperly scaled turbulence in the flow on the measured C_p by comparing wind tunnel results and full-scale measurement, and to describe a simple method of implementing PTS. It is anticipated that this will promote the use of PTS for the accurate measurement of C_p, further enabling a safer design of structures.

2. CONVENTIONAL FLOW SIMULATION WITH LARGE MODELS

As mentioned in the introduction, since the maximum size of turbulence created in the tunnel is limited, it is common to see that power spectrum at low frequency (large turbulence) is insufficient in comparison with the one for full scale. In order to match I_u profile, which is a common practice, under this situation, it is necessary to increase the spectrum at high frequency (small turbulence) given that area under the curve of spectrum plot is σ_u^2 (Figure 1, left). This is usually achieved by making the upstream roughness elements to be exaggerated. However, since it is possible that having too much high frequency turbulence can change the mean C_p pattern on structures (Richards et al., 2007), aiming to match I_u profiles is not necessarily the ideal solution.

In terms of the effect of high frequency turbulence, small-scale turbulence controls whether the separated shear layers remain separated or become attached, which changes the magnitudes of mean and fluctuating surface pressure coefficients on the sides and rear faces of a prism (Tieleman and Akins, 1996, etc). Melbourne (1979) expressed the content of the small-scale turbulence as S in the following equation, and this has to be large enough so that the fluctuating wind pressure becomes independent of S.

$$S = [nS_u(n)/\sigma_u^2]\ (\sigma_u/\bar{u})^2 \times 10^6 \text{ evaluated at } n=\bar{u}/L_B \qquad (1)$$

where L_B is the characteristic dimension of the target structure. This has been studied by many researchers and Irwin (2008) presented its importance by comparing full-scale data and wind tunnel data obtained under the flow where the high frequency portion of spectrum was matched with full scale.

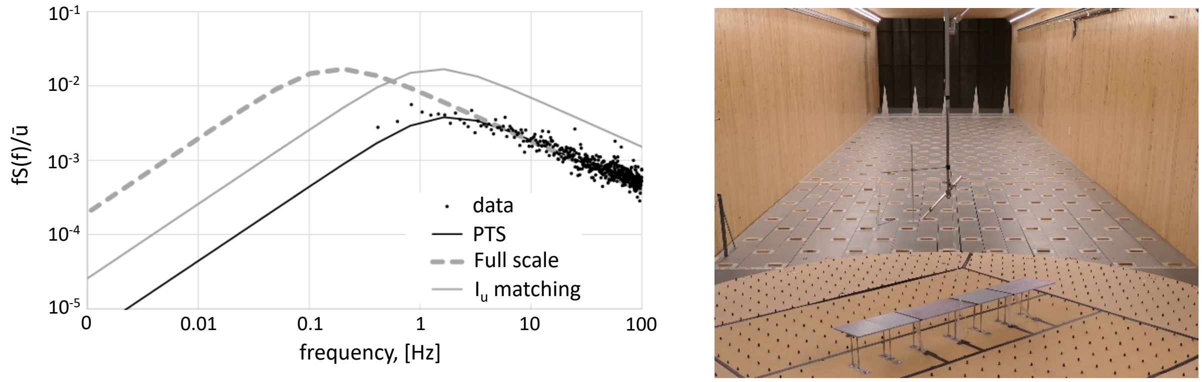

Figure 1. (left) Wind velocity spectrum; (right) Arrangement of approach flow of HFSM method

3. PARTIAL TURBULENCE SIMULATION

In Section 2, the insufficient spectra at low-frequency in the flow with large-scale model has been mentioned. There are several suggested methods to address this missing energy.

On way to address this is to turn the tunnel speed up and down and rotate the model simultaneously in a very slow and random manner in order to physically simulate low frequency turbulence. This is tedious procedure and hence, is not a preferred solution.

Researchers at Florida International University (FIU) (Mooneghi et al., 2016; Moravej and Irwin, 2019; Estephan et al., 2022, etc) have suggested a post-test analysis using the assumptions of quasi-steady theory and including the contribution of low frequency turbulence on wind loads by assuming the probability distribution of the load.

The method Richards et al. (2007) has suggested is the simplest and will be called Richards' method hereafter. They describe that such fluctuations are effectively low-frequency fluctuations in the mean wind speed and direction and the results of full-scale coherence analysis suggest that the flow field is responding to these fluctuations in a quasi-steady manner. Furthermore, such low-frequency fluctuations do not alter the character of the flow significantly. Hence, normalizing peak C_p by a gust speed instead of mean speed makes the resulting design gust pressure coefficient (e.g. GC_p in ASCE 7 or c_{pe} in Eurocode) less sensitive to the level of low frequency fluctuations.

Following Richard's method, Banks (2011) discussed the threshold of high frequency range for spectrum matching to be above the QS cut-off frequency and that 3 seconds, which is the duration for design wind speeds in many jurisdictions, satisfies this as well as the condition of S in Eq. (1) for solar trackers.

As implemented at CPP and for the results in this paper, this method uses wind tunnel tests where high frequency turbulence is targeted to match with full scale. The pressure time series measured on the model are divided into a number of segments. The peak pressure and gust speed (measured near the structure) from each segment are obtained. Then, the ratio of each peak from each segment is calculated (this value is shown to be relatively insensitive to the number of segments) and their ensemble average is the peak pressure coefficient. The velocity data is lowpass filtered at a frequency above the QS cutoff. If a 3 second running average can be used, then this output can be directly compared with GC_p in ASCE7-22, for example. This will be called as High Frequency Spectrum Matching (HFSM).

Simulating a wind tunnel flow field that matches with the full scale spectrum for frequencies above 3 seconds is in some ways not as difficult as when attempting to match I_u, given it usually requires modest changes to a profile used at a more typical small scale like 1/300. This is shown in Figure 1 (left) and both spectra correspond surprisingly well. This is partially because of the fact that the target height for larger model is higher than the one for smaller model (for the same full-scale target height), resulting in less turbulence for the larger model. Figure 1 (right) shows the layout of roughness blocks and spires to create the flow of HFSM.

4. METHODOLOGY

In order to examine the effect of HFSM, we will compare C_p data obtained from 1. Full-scale measurement, 2. Conventional wind tunnel tests where matching I_u is focused, and 3. HFSM wind tunnel tests. Pressure measurements on a typical 2 m chord length, single axis tracker will be presented under an approach flow mimicking the flow in the full-scale measurement site. The detail of the methodology as well as the results will be presented in the full paper.

REFERENCES

ASCE49-21. 2021. Wind tunnel testing for buildings and other structures. American Society of Civil Engineers, Reston, Virginia.

Banks, D. 2011. Measuring peak wind loads on solar power assemblies. The 13th Int. Conf. Wind Eng., Amsterdam, Netherlands.

Banks, D., Guha, T.K., and Fewless, Y.J. 2015. A hybrid method of generating realistic full scale time series of wind loads from large-scale wind tunnel studies: Application to solar arrays. 14th Inter. Conf. on Wind Engineering, Porto Alegre, Brazil.

Estephan, J., Chowdhury, A.G., and Irwin, P. 2022. A new experimental-numerical approach to estimate peak wind loads on roof-mounted photovoltaic systems by incorporating inflow turbulence and dynamic effects. Engineering Structures 252, 1-12.

Irwin, P.A. 2008. Bluff body aerodynamics in wind engineering. Journal of Wind Engineering and Industrial Aerodynamics 96, 701-712.

Melbourne, W.H. 1980. Turbulence effects on maximum surface pressures – a mechanism and possibility of reduction. Wind Engineering 1, 541-551.

Mooneghi, M.A., Irwin, P., and Chowdhury, A.G. 2016. Partial turbulence simulation method for predicting peak wind loads on small structures and building appurtenances. Journal of Wind Engineering and Industrial Aerodynamics 157, 47-62.

Moravej, M., and Irwin, P. 2015. A simplified approach for the partial turbulence simulation method of predicting peak wind loads. The 15th Int. Conf. on Wind Engineering, Porto Alegre, Brazil.

Richards, P.J., Hoxey, R.P., Connell, B.D., and Lander, D.P. 2007. Wind tunnel modeling of the Silsoe Cube. Journal of Wind Engineering and Industrial Aerodynamics 95, 1384-1399.

Stathopoulos, T., and Surry, D. 1983. Scale effects in wind tunnel testing of low buildings. Journal of Wind Engineering and Industrial Aerodynamics 13, 313-326.

Tieleman, H.W., Reinhold, T.A., and Marshall, R.D. 1978. On the wind-tunnel simulation of the atmospheric surface layer for the study of the wind loads on low-rise buildings. Journal of Wind Engineering and Industrial Aerodynamics 3, 21-38.

Tieleman, H.W., and Akins, R.W. 1996. The effect of incident turbulence on the surface pressures of surface-mounted prisms. Journal of Fluid Structure 10, 367-393.

Tieleman, H.W., Hajj, M.R., and Reinhold, T.A. 1998. Wind tunnel simulation requirements to assess wind loads on low-rise buildings. Journal of Wind Engineering and Industrial Aerodynamics 74-76, 675-685.