A hybrid method of generating realistic full scale time series of wind loads from large-scale wind tunnel studies: Application to solar arrays

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1 INTRODUCTION

The demand for accurate wind loads on relatively smaller structures such as solar arrays has highlighted the issue of properly considering the approach flow full turbulence spectrum when conduction atmospheric boundary layer wind tunnel testing or CFD simulations. In the wind tunnel, the necessary detail in typical solar arrays requires that these structures be modeled at large scales, so the appropriate lower frequencies of the turbulence spectrum cannot be modeled. The authors have previously advocated the technique of high frequency spectrum matching, in which the spectrum is matched above the quasi-steady (QS) frequency cutoff [1]. Below this cutoff, the effects of the missing energy are captured with quasi-steady theory, that is they are assumed to have the same effect as an increase in mean wind speed of modest duration.

A method for creating low-frequency compensated wind loading time series was developed on this basis [2]. In this QS compensation method, the low frequency turbulence is essentially ***added*** to the wind load time series. Above the QS threshold, it is assumed that the loading is accurately captured by the testing, and no energy is added.

Such realistic time series are used by the structural engineer (SE) as time-dependent inputs to finite element models of solar structures. This process allows the SE to accurately characterize companion loads (e.g. maximum uplift at the time of maximum torque) and peak loads on various component.

Perhaps more importantly, the time series approach also allows the SE to simultaneously examine dynamic effects from all mode shapes on any particular structural component. Interior rows of typical ground mount solar arrays also exhibit buffeting response due to periodic vortex shedding from the upwind rows of panels. Self-excitation of the first windward row in the array is also observed. Large-scale wind tunnel tests are able to capture this vortex shedding phenomena, being exhibited as a hump in the spectrum of loads [3]. The extent and severity of this dynamic response depends on several parameters including the tilt angle, row-to-row spacing, low-edge ground clearance as well as the location of the affected row from the edge of the array, as detailed in a companion paper [4].

An accurate time series is therefore very valuable. The absence of low frequency turbulence in the wind tunnel data creates raw time series that are unrealistically steady. This can be compensated for using high frequency spectrum matching during the testing (to ensure that short intervals are realistic) and QS compensation (to ensure that loads rise and falls appropriately over longer intervals). However, this method does not properly capture the energy transfer from low frequencies to high frequencies (across the QS threshold) via vortex shedding. This effect is akin to **scaling** the wind tunnel time series in both time step and magnitude.

This paper proposes a method for analytically accounting for both effects of the missing low frequency turbulent energy. This method can be alluded to as a “hybrid method”, since it uses a combination of analytical estimates and (large-scale) wind tunnel measurements to re-construct synthetic time series of wind loads on structures that resemble full scale measurements. The hybrid method empirically accounts for the energy transfer between the compensated low frequency turbulence scales to scales at which vortex shedding exists.

The proposed method has been verified by testing a geometrically identical model of an isolated heliostat at a smaller scale (1:250) at which the full spectrum can be modeled in the wind tunnel, and repeating the test at a larger scale (1:50) at which the full turbulence spectrum cannot be modeled.

Wind tunnel tests are being designed to quantify this transfer of energy by varying the mean speed in the tunnel for simulating the effect of this missing low frequency turbulence. This, in turn, is expected to establish the empirical parameters needed for fitting the appropriate admittance functions to allow energy transfer in the frequency band associated with vortex shedding.

2 THEORETICAL AND EXPERIMENTAL BACKGROUND

Force balance tests were performed on a geometrically similar model of an isolated solar panel in the wind tunnel at two different scales; 1:50 and 1:250. A profile similar to exposure C (open-country roughness, as per ASCE 7-10 [5]) was used to model the boundary layer in the tunnel [see Figure 1 (a) and (b)]. Further details pertaining to physical modelling, including boundary layer set-up specifications and the instrumentation used will be presented in the full paper.

Figure 2(a) and (b) presents the normalized longitudinal turbulence spectrum of velocity at 10 m height (in full scale) modelled in the tunnel at scales 1:50 and 1:250 respectively. Additionally plotted is the fitted Von Kàrmàn spectrum based on the estimated integral length scale and turbulence intensity measured in the tunnel in comparison to the ESDU [6] predicted target spectrum in full scale.

It is evident from Figure 2(a) that the low frequency part of the measured spectrum, below an assumed quasi-steady cut-off of 3 second (in full scale), is grossly under-represented at 1:50 scale tests while a reasonably good match along the entire spectrum is exhibited at a scale of 1:250 in Figure 2(b). This implies that the peak loads measured in the tunnel at scales 1:50 or larger will be much smaller than in full scale and hence may lead to un-conservative design estimates, if not adequately compensated.

Figure 1. Boundary layer wind tunnel tests at scales (a) 1:50 and (b) 1:250

This compensation was accomplished by estimating the transfer function, $|H(f)|$, between the measured (or fitted) and the target velocity spectrum as a means for establishing the relationship between the two spectra on a per-frequency (f) basis. Mathematically this can be written as

$$|H(f)|^2 = \frac{S_{u(f)|_{Target}}}{S_{u(f)|_{Measured}}} \quad (1)$$

where, $S_{u(f)|_{Target}}$ is the target Von Kàrmàn longitudinal spectrum at full scale and $S_{u(f)|_{Measured}}$ is the spectrum of velocity measured in the tunnel. The transfer function obtained using Equation (1) is used to compensate the spectrum of loads (such as pressures) measured in the tunnel at large scales. In other words,

$$S_{Cp(f)|_{Target}} = |H(f)|^2 S_{Cp(f)|_{Measured}} \quad (2)$$

where, $S_{Cp(f)|_{Target}}$ is the target load (here C_p is the pressure coefficient) spectrum obtained by proportionately compensating the measured load spectrum $S_{Cp(f)|_{Measured}}$ using the frequency dependent transfer function. A time series of the compensated loads can thereafter be obtained using Inverse Fourier Transform (IFFT) as

$$C_p(t_k)|_{Target} = \frac{1}{N}\sum_{n=1}^{N} S_{Cp(f_n)|_{Target}} e^{-2\pi ikn/N} \quad (3)$$

where $C_p(t_k)|_{Target}$ is the compensated load (such as pressure) time series at time t_k.

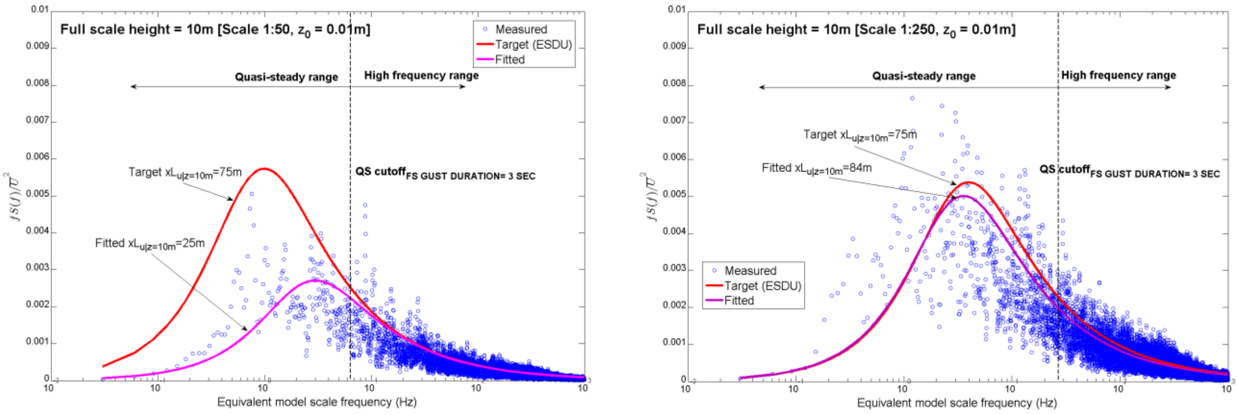

Figure 2. Spectrum of longitudinal turbulence modelled in the tunnel at 10 m height at scale (a) 1:50 and (b) 1:250

3 SAMPLE RESULTS AND DISCUSSION

An application of the "hybrid method" used to compensate the spectrum and time series of the moment at the base of the heliostat post (My), obtained from 1:50 scale wind tunnel tests, is shown in Figure 3. The panel tilt in this case is 15 degrees. The higher peak loads in the compensated time series in visually apparent in the Figure 3 (b), that when applied to time series based analysis of structures will justifiably produce larger responses compared to the un-compensated case.

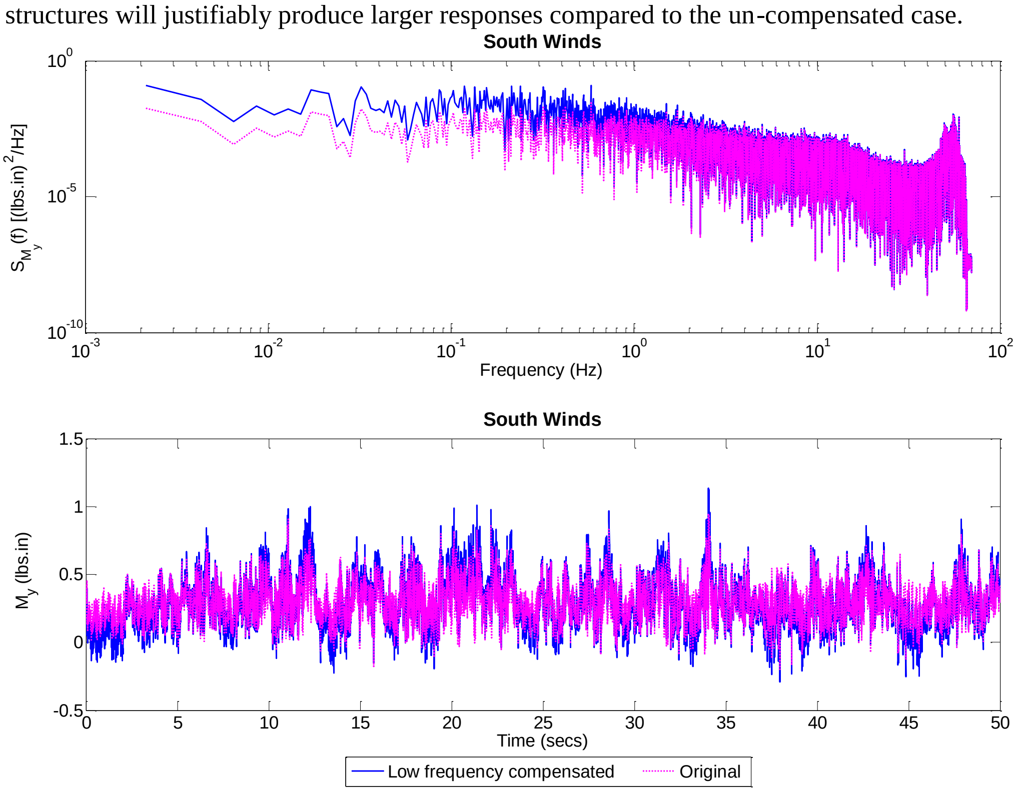

Figure 3. Comparison between the compensated and un-compensated (a) spectrum and (b) time series of load

The compensated load time series obtained using the proposed method is further amenable to conventional extreme value analyses to extract the peak design values that should match the full scale loads or loads obtained from small scale tunnel studies. A comparison between the 10 minute (C_{My}) and 3 second peak (GC_{My}) loads obtained from the small-scale tunnel tests, un-compensated large-scale tunnel tests and low-frequency compensated tests (or hybrid method) are presented in Table 1.

Table 1. Comparison of peak loads from different methods

Scale	**Test/ Method**	**10 min. peak (C_{My})**	**3 sec. peak (GC_{My})**
1:250	Small-scale	0.73	0.43
1:50	Large-scale (un-comp.)	0.64	0.46
1:50	Hybrid	0.71	0.49

The loads obtained using the hybrid method compares well with those obtained from small scale experiments for both the 10 minute and 3 second peaks. However, the large-scale un-compensated test yields a smaller 10 minute peak load due to paucity of slowly varying fluctuations in the spectrum and will lead to un-conservative design estimates.

4 CONCLUSIONS

A hybrid method, based on quasi-steady theory, is proposed for analytically compensating the missing low-frequency turbulent energy in the wind load time series data obtained from large-scale wind tunnel studies. Such realistic time series of wind loads are necessary for accurately analyzing the dynamic and background response of structures subjected to such loads. Additional wind tunnel tests, on arrays of solar panels, are being designed to quantify the effect of this low frequency turbulence on the vortex shedding loads on downwind arrays, being buffeted by the wakes of upwind rows of panels. This, in turn, is expected to establish the empirical parameters needed for fitting the appropriate admittance functions to allow energy transfer in the frequency band associated with vortex shedding from the mean flow (related to slowly varying low frequency turbulence).

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