

Buffeting response of solar photovoltaic panels from full-scale informed wind fields

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Summary

Field measurements at the Nevada Solar One (NSO) site revealed that near-surface turbulence deviates from classical surface-layer spectral models and exhibits pronounced non-Gaussian velocity fluctuations (Wan et al., 2025). This study evaluates their influence on the buffeting response of solar photovoltaic (PV) trackers using stochastic wind fields generated from site-specific spectra, with non-Gaussianity introduced via a moment-based Hermite transformation. Time-domain simulations with quasi-steady aerodynamics and zero tilt angle show that the site-specific spectrum increases the Free end torsional displacement response standard deviation by approximately 15%, while non-Gaussian fluctuations primarily affect extreme responses. These results suggest that near-surface PV designs may require modified turbulence models for accurate load prediction.

Keywords: *Buffeting load, Solar photovoltaic, dynamic response, non-Gaussian*

1 INTRODUCTION

Modern and future solar photovoltaic (PV) systems mounted on trackers are increasingly lightweight (Buchroithner et al., 2025), making them more susceptible to dynamic wind loading. Single-axis trackers are flexible, low-mass structures with limited stiffness and damping and are therefore highly sensitive to turbulent inflow. Buffeting loads on slender structures such as towers, bridges, and PV arrays are traditionally modelled assuming Gaussian, stationary wind fluctuations using mean wind speed, one-point velocity spectra, and coherence functions within the classical atmospheric surface layer (ASL) framework. Current standards rely on turbulence models developed in the 1960s–1980s (Kaimal et al., 1972; Simiu & Scanlan, 1996), predating large-scale ground-mounted PV systems. These arrays operate below 5 m above ground, within the eddy surface layer (ESL) (Hunt & Morrison, 2000), where ground blockage strongly alters turbulence, leading to statistics that can differ substantially from ASL-based predictions.

Analysis of sonic anemometer data from a two-year field campaign at the Nevada Solar One (NSO) power plant (Wan et al., 2025) revealed significant departures from Gaussian velocity fluctuations and a power spectral density characteristic of the eddy surface layer, including deviations from the classical Kaimal model. Such non-Gaussian turbulence can induce stronger extreme structural responses than those predicted by Gaussian-based buffeting formulations, motivating a reassessment of traditional turbulence models for near-surface PV installations. To date, few studies have incorporated site-specific near-surface turbulence measurements or non-Gaussian effects into wind-loading assessments of solar PV systems. Accordingly, this study re-evaluates classical models using full-scale near-surface measurements and computes the buffeting response of solar PV trackers driven by turbulence-informed wind-field simulations.

This study computes the buffeting response of a 34 m single-axis solar tracker (Taylor et al., 2024) using time-domain simulations with quasi-steady aerodynamic coefficients. The tracker elevation is approximately 2.3 m above ground. The objectives are to (i) quantify changes in the predicted response when the power spectral density model of Wan et al. (2025) replaces the classical Kaimal spectrum (Kaimal et al., 1972), and (ii) assess the influence of the non-Gaussian

turbulence characteristics reported by Wan et al. (2025) on the structural response. The paper is organized as follows: section 2 describes the wind datasets and structural model; section 3 details the wind-field simulation procedure and response metrics; and section 4 evaluates the impact of non-Gaussian effects and flattened NSO turbulence spectra on the predicted buffeting loads.

2 BACKGROUND

Buffeting loads are turbulence-induced aerodynamic forces that drive fatigue and long-term degradation of solar PV arrays. Underestimation shortens structural lifespan and increases the levelised cost of energy (LCOE), while overestimation results in overly conservative designs, unnecessary capital expenditure, and similarly higher LCOE. For single-axis trackers, the buffeting response is dominated by torsional dynamics and can be modelled analogously to line-like structures such as long-span bridges. Required structural inputs include the free span length, mass moment of inertia per unit length ($I_\theta = 112 \text{ kg, m}^2/\text{m}$), torsional mode shapes idealised as those of a clamped beam, and a torsional damping ratio of $\zeta_t \approx 0.05$.

The system considered is a 34 m single-axis tracker comprising a slender beam-like structure rotating about a central torque tube (fig. 1). Its aerodynamic behaviour is governed primarily by the static tilt angle and structural stiffness, with additional influences from height-to-chord ratio and damping (Taylor et al., 2024). Along-wind and vertical velocity fluctuations induce torsional moments about the rotation axis, and the resulting rotation angle constitutes the primary response variable in the buffeting analysis.

3 METHODS

The mean wind speed at the 2.3 m torque-tube height is obtained from a neutral logarithmic profile using a roughness length of 0.03 m, a displacement height of 0.8 m, and an arbitrarily selected reference wind speed of 20 m/s, from which the friction velocity is derived. All turbulence inputs follow Wan et al. (2025), except that only the Davenport decay coefficient for vertical separations was measurable; the lateral decay coefficient is therefore prescribed arbitrarily. The solar PV array is modelled as by Taylor et al. (2024) with a configuration where $\theta_s = 0^\circ$.

Following Wan et al. (2025), the power spectral densities of the along-wind and vertical veloc-

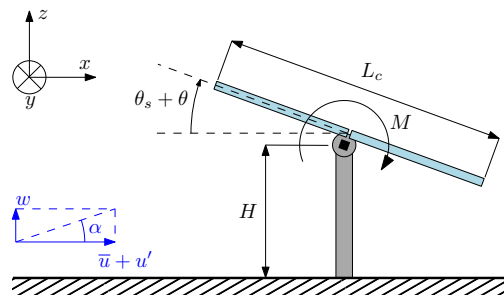


Figure 1: Sketch of the solar tracker (side view) with θ being the structural rotation angle from the dynamic response, θ_s is the tilt angle, α is the angle of attack, M the torsional moment and u and w are the along-wind and vertical velocity components, respectively. The sketch is inspired by Taylor et al. (2024)

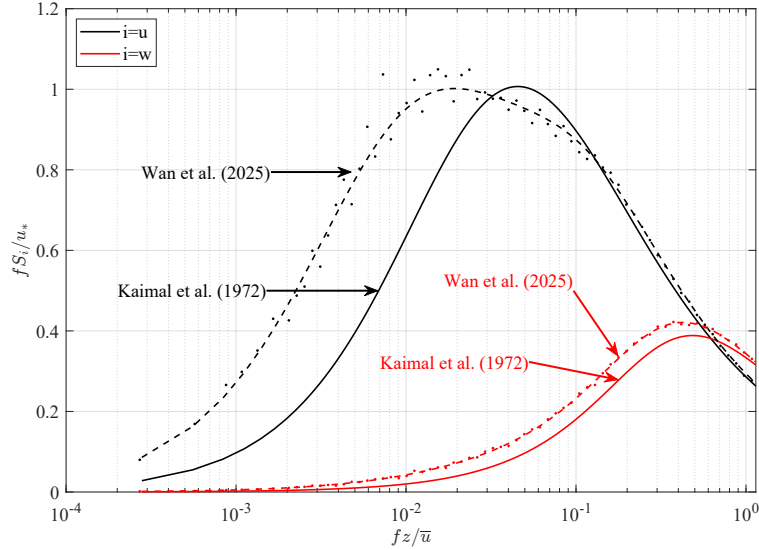


Figure 2: Simulated (markers) and target (solid lines) power spectral densities (PSD) of the along-wind u and vertical w velocity components, compared with the Kaimal model (Kaimal et al., 1972).

ity fluctuations are modelled as

$$\frac{f S_i}{u_*^2} = \frac{a^i 1 f_r}{(1 + a^i 2 f_r)^{5/3}} + \frac{a^i 3 f_r}{1 + a^i 4 f_r^{5/3}}, \quad (1)$$

$$a_3^u = -a_1^u a_4^u (a^u 2)^{-5/3} + 0.3, a_4^u, \quad (2)$$

$$a_3^w = -a_1^w a_4^w (a^w 2)^{-5/3} + 0.4, a_4^w, \quad (3)$$

where $i = u, w$. This formulation reproduces the flattened spectral peak observed in near-surface ESL measurements while preserving inertial-subrange isotropy; the normalised spectra therefore converge asymptotically to the Kaimal and Simiu–Scanlan models at high frequencies. The turbulent velocity field is generated using a spectral-representation method. Non-Gaussian fluctuations are subsequently introduced using the moment-based Hermite transformation of Denoël (2005), which transforms an initially Gaussian field to match prescribed skewness and kurtosis appropriate for slightly non-Gaussian wind fields.

4 RESULTS

Figure 2 presents the normalised along-wind and vertical turbulence spectra derived from full-scale, site-informed wind fields, highlighting deviations from the Kaimal model. Figure 3 shows the power spectral density of the solar PV panel torsional displacement response S_{r_θ} , together with the standard deviation and maximum torsional response σ_{r_θ} along the span. While the resonant response is largely insensitive to the turbulence model and to Gaussian versus non-Gaussian assumptions, the quasi-static response exhibits clear differences. Using the site-specific spectrum increases the Free end response standard deviation by approximately 15%, with non-Gaussian fluctuations having limited influence on the standard deviation. However, the maximum response, denoted $\max(r_\theta)$, indicates that non-Gaussian effects are not negligible for extreme-value analysis.

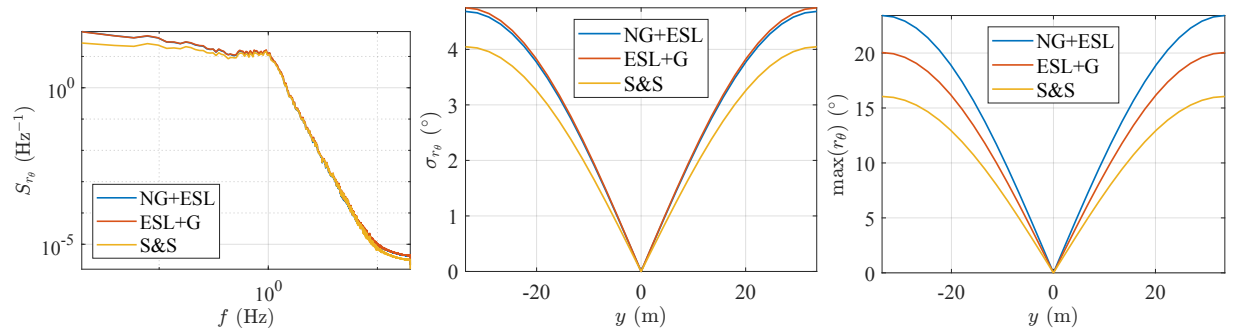


Figure 3: Left: Power spectral density of the solar panel torsional response at the span end (free-end) for a wind speed of 20 m s^{-1} , the Kaimal model (S&S) and the new ESL spectral model with Gaussian (ESL+G) and non-Gaussian (ESL+NG) fluctuations. Middle: Standard deviation of the torsional response along the span for the same models. Right: Maximum torsional response along the span for the same models.

5 CONCLUSIONS

This study investigated the buffeting response of ground-mounted solar PV trackers using full-scale, site-specific turbulence statistics from the Nevada Solar One facility. By combining near-surface spectral models, measured non-Gaussian velocity statistics, and spectral-representation wind-field simulations, the influence of eddy surface layer turbulence on the torsional dynamics of a 34 m single-axis tracker was quantified. Compared to the classical Kaimal model, the site-specific ESL spectrum increased the Free end torsional response standard deviation by approximately 15%, while the resonant response remained largely insensitive to spectral choice and to Gaussian versus non-Gaussian assumptions. In contrast, the maximum torsional response exhibited a clear sensitivity to non-Gaussian turbulence, indicating that higher-order flow moments may be important for extreme-value and fatigue-related assessments of near-surface PV systems. Future work will examine the influence of tracker tilt angle on the buffeting response and assess whether sustained non-Gaussian fluctuations can contribute to the onset of aeroelastic instability in solar PV trackers.

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