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Low-Tilt Torsional Instability of Single-Axis Solar Trackers

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SUMMARY:
Single-axis trackers (SATs) are lightweight flexible structures, susceptible to aeroelastic torsional instability. This has been identified as the underlying cause of several site failures at wind speeds significantly lower than the design speed. CPP have performed aeroelastic wind tunnel tests for dozens of tracker designs. The torsional divergence equation is found to appropriately describe the stiffness-driven instability at low tilts, as there is low sensitivity to moderate (below 30%-of-critical) torsional damping or to frequency changes due to inertia. This divergence does not usually break the tracker immediately, so the motion is typically cyclical. Sample timeseries of angular motion from aeroelastic wind tunnel testing are presented to illustrate the explosive motion of this cyclical torsional divergence. The quasi-steady torsional divergence equation has been calibrated to predict critical wind speed using aeroelastic wind tunnel tests at low tilts. This allows a discussion of key system parameters defining the low-tilt critical wind speed and provides a tool for SAT designers to optimize the tracker from an instability perspective.

Keywords: Solar tracker, instability, torsional divergence

1. BACKGROUND

The increased power generation potential of single-axis trackers (SATs), in comparison to fixed-tilt structures, have made them a popular utility-scale mounting choice within the rapidly growing solar industry. The conventional SAT configuration consists of panels mounted onto a north-south orientated central torque tube, with multiple bearing posts along the span, as shown in Fig. 1. One or more drives provide torque and rotate the trackers from east to west throughout the day. These trackers are often stowed in a flat (0° tilt) stow position during high wind events, minimizing lateral loads, removing the need for accurate prediction of storm wind direction, and maximising power generation in stow.

A significant number of SAT failures in the field have been attributed to torsional instability (Valentino et al., 2022) which has been described by various terms, including torsional galloping (Rohr et al., 2015) and single-degree of freedom flutter (SDOF) (Martinez-Garcia et al., 2021). This paper will make the case that, at low tilts, the instability mechanism is better described as cyclical torsional divergence. The critical wind speed at which quasi-steady torsional divergence is expected, U_{cr}, is often provided as a balance of the wind-induced moment and torsional stiffness of the structure (Bisplinghoff, 1996):

$$\frac{1}{2}\rho U_{cr}^2 L^2 S \frac{\partial C_m}{\partial \theta} = k_\theta \tag{1}$$

where the applied moment increases with the velocity pressure ($\frac{1}{2}\rho U^2$), the moment arm (chord length, L) and the area (the product of span, S, and chord). The divergence condition is met if the wind-induced moment increases at a greater rate ($\partial C_m/\partial\theta$) than the elastic resistance, k_θ, of the tracker as it twists to a larger tilt, θ. A key assumption of Eq. (1) is that the moment coefficient is quasi-steady; it is purely a function of the tilt of the tracker, and not of the tracker motion.

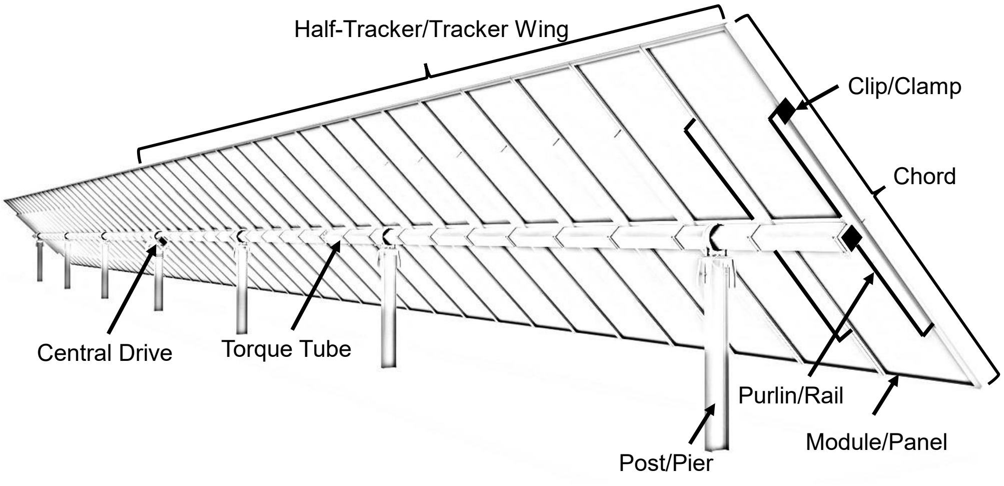

Figure 1. Conventional single-drive SAT schematic with typical components outlined

This study uses wind tunnel test data for several tracker designs to test this assumption, ultimately providing a modified empirical equation to predict U_{cr} near 0° (±3°) tilt, hereafter referred to as low-tilt instability. Additional instability mechanisms, that can transition to cyclical torsional divergence, define U_{cr} at moderate and high tilts and are not discussed in this paper.

2. MODEL DESIGN AND EXPERIMENTAL SETUP

Dozens of wind tunnel tests on multi-row aeroelastic tracker arrays have been conducted in CPP's boundary layer wind tunnel facilities. To achieve dynamic similarity between the model and full-scale prototype, the critical parameter is the torsional stiffness of the torque tube, which is a function of the torsional rigidity of the tube and the flexible span length. This controls the deflection of the structure under wind loads, and the consequent changes in the fluid-structure interaction; particularly important at low tilts, where it determines the stiffness-driven cyclical torsional divergence. The scaling, model design, and experimental methodology is outlined in Enshaei et al. 2023, though a brief review will be provided in the full paper.

3. RESULTS

A sample deflection timeseries of a half-tracker with a starting tilt of 0° (flat) is shown in Fig 2. Positive tilt refers to leading edge up. An underlay sinusoid (grey curve) with the natural frequency of the system is included as a reference. Wind speed is gradually increased with time, subjecting the half-tracker to a quasi-static twisting moment. The free end is deflected to approximately +5°, with a portion of the timeseries truncated. As the speed is further increased, the fluctuations grow to smooth sine waves. At each peak, the vortex on the upper surface of the leading edge is shed, and the half-tracker snaps back at the natural frequency. However, the wind-induced moment twists the tracker at a lower twist rate, evidently leading to an overall reduction in frequency of motion compared to the natural frequency of the system. This is a characteristic of the low tilt instability mechanism, further discussed in the full paper. The amplitudes of fluctuations rapidly grow further, reaching waves with peak-to-peak (P2P) motion of 60°. In most tests, the U_{cr} is noted at 30° P2P motion, though this has an insignificant impact on the results due to the explosive nature of cyclical torsional divergence at 0°. This can be readily seen by the wind speed vs P2P plot in Fig. 3. Consequently, we recommend the critical wind speed to be represented as a gust speed.

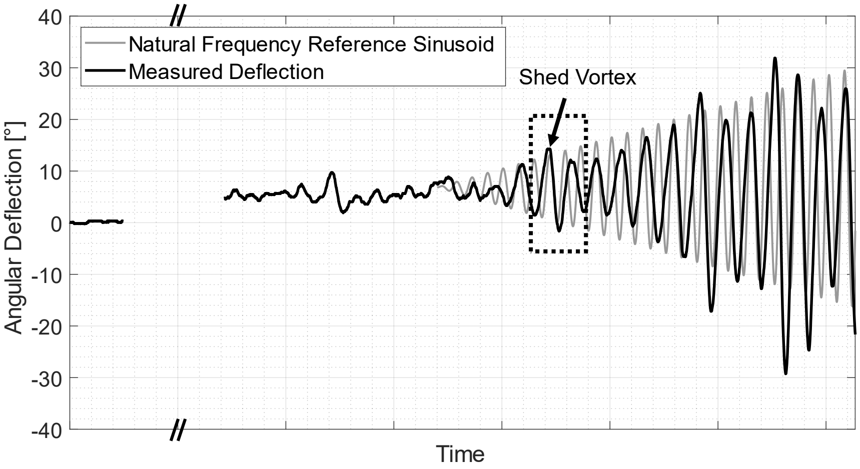

Figure 2. Angular deflection timeseries with increasing wind speed for the first row at a nominal initial tilt of 0° (flat). Growing reference sinusoid at the natural frequency is shown in grey.

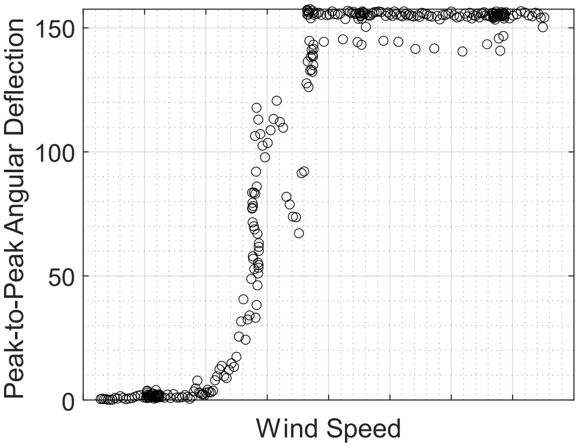

Figure 3. Peak-to-peak angular deflection of the first row vs. wind speed

Rearranging Eq. (1), we have

$$U_{cr} = K * \frac{\sqrt{GJ}}{S} * \frac{1}{L} * \frac{1}{\sqrt{\rho}} \tag{2}$$

where K is an empirical constant, ρ is air density, and GJ is torsional rigidity of the system. In theory, K can be directly calculated from Eq. (1), though we will review some of the challenges in doing so. Eq. (2) has been investigated through comparisons to measured U_{cr} of various tracker designs tested at 0°. All tested designs have a torsional damping level lower than 30%-of-critical. A graph presenting this comparison is shown in Fig. 4, where good agreement between the prediction by Eq. (2) and the measured U_{cr} is observed. System parameters for torsional flutter and galloping such as inertia, frequency, and moderate changes in damping do not impact the results. Some scatter is noted due to array parameters such as, height, row spacing, and perimeter/interior stiffness ratios.

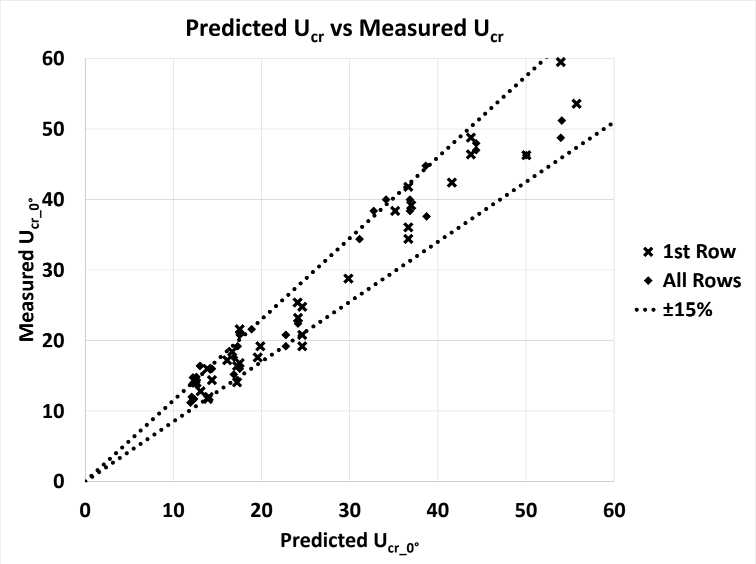

Figure 4. Predicted vs. measured critical wind speeds for various tested trackers at 0°

4. CONCLUSIONS

Aeroelastic testing of scaled models and analysis of the deflection timeseries show that the mechanism driving the low-tilt torsional instability in single-axis trackers is described well by cyclical torsional divergence. The equation for quasi-steady torsional divergence is adapted to predict wind speed causing torsional instability at 0°, U_{cr}. Measured critical wind speeds from dozens of wind tunnel tests are shown to be in good agreement with predicted values.

REFERENCES

Bisplinghoff R.L., Ashley H., Halfman R.L., 1996. Aeroelasticity. Dover Publications, New York, USA.

Enshaei P., Chowdhury J., Sauder H., and Banks, D., 2023. Wind tunnel testing of torsional instability in single-axis solar trackers: summary of methodologies and results. Submitted for Proceedings of 21st Australasian Wind Engineering Society Workshop, 2-3 Feb. 2023. Sydney, Australia.

Rohr, D., Bourke, P.A., and Banks, D., 2015. Torsional instability of single-axis solar tracking systems. Proceedings of 14th International Conference on Wind Engineering, 21-26 Jun. 2015. Porto Alegre, Brazil, 21-26.

Martinez-Garcia E., Blanco-Marigorta E., Gayo, J.P., Navarro-Manso A., 2021. Influence of inertia and aspect ratio on the torsional galloping of single-axis solar trackers. Engineering Structures 243, 112682.

Valentin D., Valero C., Egusquiza M., Presas A., 2022. Failure investigation of a solar tracker due to wind-induced torsional galloping. Engineering Failure Analysis 135, 106-137