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# Experimental Investigation and Field Validation of Wind-Induced Dynamic Effects on Rooftop Photovoltaic Systems

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## ABSTRACT

As the world is transitioning to renewable energy sources, the use of photovoltaic (PV) arrays has become increasingly popular over the past few years. Currently, the U.S. is home to more than 2 million rooftop PV installations on commercial and residential buildings, and the installed solar capacity is expected to increase by twenty-fold by 2030. Despite their wide usage, rooftop PV arrays are vulnerable to damage under strong winds. Such damage conditions could be aggravated should the peak wind loads acting on the supporting structures (including dynamic components) be underestimated. This study consists of investigating the wind-induced dynamic effects on rooftop PV arrays based on experimental tests and analytical analyses validated by field measurements. Field measurements were conducted on the rooftop PV array of the Hogue Technology Center at Central Washington University. In addition, experimental tests were carried out at the NSF-NHERI Wall of Wind Experimental Facility at Florida International University on a full-scale PV array model subjected to simulated Atmospheric Boundary Layer flows to measure the wind loading on the PV array including dynamic effects.

## 1. Introduction

The use of photovoltaic (PV) arrays as a source of renewable energy has become widely applied across the U.S. over the past few years. Currently, the U.S. is home to more than 2 million rooftop PV installations on commercial and residential buildings, and a twenty-fold increase in the installed solar capacity is expected by 2030 (*Solar Energy Industries Association*, 2019). Installed on the rooftop of low-rise buildings, PV panels are susceptible to damage during extreme wind events such as hurricanes and thunderstorms. Such damage conditions could be aggravated should the peak wind loads acting on the supporting structures (including dynamic components) be underestimated.

A limited number of full-scale field studies have been undertaken to calibrate wind tunnel results (Andolsek, 2013; Baskaran et al., 2018; Harris, 2013; Plas, 2015). Recently, in-situ measurements have been conducted on a rooftop PV array located at the Hogue Technology Center (HTC) at the Central Washington University (CWU) in Ellensburg, Washington (Bender et al., 2018; Braun et al., 2021; Reed et al., 2016). Besides in-situ measurements, numerous experimental studies using large- and small-scale models have been undertaken in Boundary Layer Wind Tunnels (BLWTs) to investigate wind effects on rooftop PV panels (Banks, 2013; Browne et al., 2013; Kopp, 2013; Stathopoulos et al., 2014). Large-scale wind tunnel testing of low-rise buildings and their appurtenances provides the advantage of a more accurate modeling of the structural details and a better Reynolds number (Re) similarity with the prototype, as compared to small-scale testing. However, owing to the limited sizes of typical

BLWTs, large model scales render the low-frequency turbulence eddies largely unaccounted for in the simulation. To overcome this limitation, a Partial Turbulence Simulation (PTS) approach (Mooneghi et al., 2016; Moravej, 2018) has been previously developed at the NSF NHERI Wall of Wind (WOW) Experimental Facility (EF) (Chowdhury et al., 2017, 2018) at Florida International University (FIU). The method consists of a post-test analysis to analytically incorporate the effects of the missing portion of low-frequency turbulence in the peak pressure coefficients, based on the quasi-steady aerodynamic theory. However, the partial turbulence simulation methods found in the literature apply only to rigid components and do not consider the dynamic resonant effects on dynamically-sensitive structures, such as PV panels. Dynamic effects have been investigated by previous studies on full- and large-scale rooftop PV panels (Moravej et al., 2015; Naeiji, 2017). The studies showed that significant wind-induced vibrations may occur in PV systems with natural frequencies as high as 14 Hz. Miller and Zimmerman (1979) used pressure measurements to determine force coefficients on ground-mounted solar arrays and analyzed the dynamic response of the structure. SEAOC PV2 (2017) identified the need that solar array design shall consider vortex shedding and consequent dynamic resonant effects. Browne et al. (2020) presented a method for determining the design wind loads for multi-row ground-mounted solar arrays, including both static and dynamic wind load coefficients, based on small-scale wind tunnel tests. These studies highlighted the limitations of applying the ASCE 7 criterion for dynamically sensitive structures having a fundamental natural frequency ≤ 1 Hz. This criterion was originally derived with whole buildings in mind and may well be misleading should it be applied to smaller structures (e.g., solar panels).

Wind tunnel testing is a key experimental method for the evaluation of wind effects on rooftop PV panels of low-rise buildings and formulation of provisions in wind design standards. However, new standards on rooftop PV systems, such as ASCE 7 (ASCE, 2022), are limited to simple geometries and orientations (Bender et al., 2018) and do not consider dynamic amplification effects for smaller structures (Browne et al., 2020; Moravej et al., 2015). Recently, a new provision has been added in ASCE 7-22 to provide design wind loads for ground-mounted PV panels while considering dynamic effects. For rooftop PV arrays, there is still a need for the incorporation of peak dynamic wind loads or dynamic amplification factors that can be used in conjunction with the existing peak design pressure coefficients in standards. This paper provides a full-scale experimental investigation coupled with analytical analysis and validated based on field measurements. The analytical analysis consisted of the use of the recently developed advanced PTS method that takes into account the inflow turbulence and dynamic effects on rooftop PV arrays. This research’s findings can be used to inform wind load provisions in standards which will ultimately help in the design and retrofit of more resilient dynamically-sensitive building appurtenances.

## 2. Methodology

### *2.1 Field measurements on a rooftop PV array*

Field measurements have been conducted on a rooftop PV array located on the three-story HTC building of CWU. The enhanced field measurements help calibrate the full-scale testing of a selected PV array at the NHERI WOW EF at FIU. A top-corner segment of the PV array was selected to monitor the wind-induced pressures and accelerations. The selected panels, measuring 0.9 × 1.6 m (2.9 × 5.2 ft) each, coincide with the predominant North-West wind direction and are expected to exhibit dynamic behavior. The characteristics of the near-building ABL flow were measured using an R.M. Young ultrasonic anemometer Model 85000 (wind speed accuracy: ±0.1m/s; wind direction accuracy: ±2°) mounted on the Northern corner of the roof at 22 m (72 ft) above ground (i.e., 12 m above the roof height). This anemometer, referred to as “Anemometer 1” or “Rooftop Anemometer” in Figure 1, was mounted at a sufficient height above the roof surface so that its measurements are not affected by the building-generated turbulence. On the other hand, the near-array flow may be disturbed due to possible vortex shedding, separation, and reattachment over the roof surface. These phenomena are characterized by higher energy in the power spectrum of wind velocity fluctuations compared to that of near-building flows at frequencies close to the PV array's natural frequency. For this reason, the characteristics of the near-array flow were measured using an R.M. Young ultrasonic anemometer Model 86000 (wind speed accuracy: ±0.1m/s; wind direction accuracy: ±2°). This anemometer, referred to as "Anemometer 2" in Fig. 3.1 or "Panel Anemometer", was mounted on the northern side of the panels at mid-height of the top instrumented array [i.e., 12.5 m (41 ft) above ground]. Differential pressure transducers (Setra Model 267) and triaxial accelerometers (Dytran Model 3263A3) were installed at the bottom surface of the array to measure the aerodynamic net pressures and dynamic properties of the panels, respectively. To avoid perforating the panels and affecting their dynamic properties, one end of the pressure transducer was flush with the top surface of an aluminum plate installed between the adjacent panels, while the other end was flush with the bottom surface.

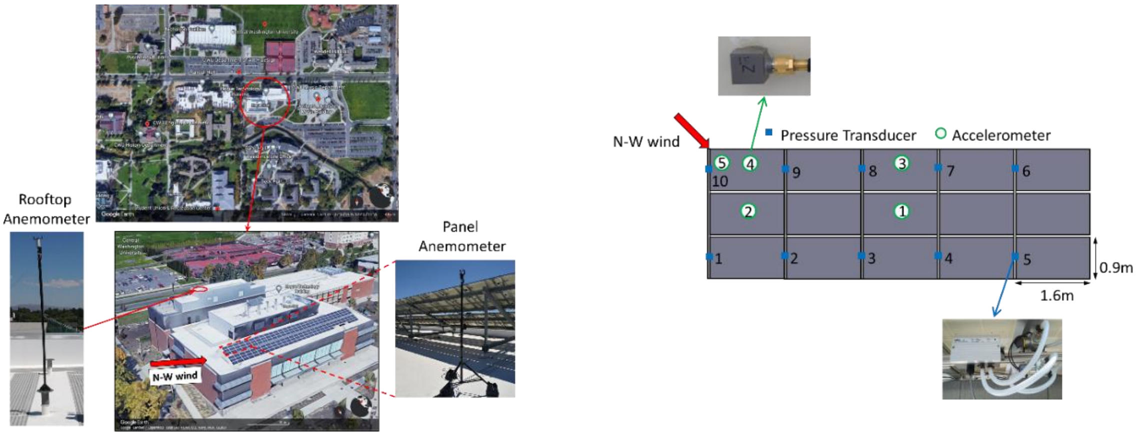


Figure 1. HTC roof and instrumentation layout

## 2.2 Wind tunnel tests of a full-scale PV array model

An essential first step of this study was to design a full-scale PV array model for wind tunnel testing at the WOW EF such that its dynamic properties are similar to those of the field CWU array. For this purpose, a modal analysis was performed using Finite Element Modeling Software SAP2000 to identify the natural frequencies of the first three modes of vibration of the model and full arrays, as described in Estephan et al. (2022). The obtained dynamic properties from the modal analysis were in good agreement with the results of the in-situ hammer test on the full CWU array. Given the size limitations imposed by the WOW test section, testing both the HTC roof section and PV array at full scale was not possible. Therefore, to take advantage of full-scale system-level testing, a ground-based section model with similar dynamic properties and subjected to accurately simulated wind flows can be considered representative of the full rooftop PV array in situ. The 12-fan NHERI WOW EF is a full- and large-scale testing facility capable of generating wind speeds and turbulence characteristics similar to those recorded in Category 5 hurricanes (Chowdhury et al., 2017, 2018). Impact hammer and wind loading tests were performed at the WOW EF on the full-scale PV array model which consists of a 3×5 array of PV panels and a chord length $L_c$ of 3 m (9.8 ft). Figure 2 shows the PV array model mounted on the turntable along with the instrumentation layout. Pressure taps were installed at various locations on the panels' top and bottom surfaces, including those available on the CWU array, to measure the wind-induced net pressures on the panels. Moreover, multi-axial accelerometers and load cells were used to identify the dynamic properties of the PV array and capture the reaction forces acting on the supports, respectively. Suburban terrain wind flows with similar turbulence parameters to those recorded at the CWU site were simulated at WOW. Hammer tests were first performed on the PV array in the absence of wind. The model was then subjected to wind speeds ranging between 7 m/s and 30 m/s at the array's mean height of 1.5 m (5 ft) and wind directions ranging between 180° and 360°. Peak pressure and force coefficients were estimated for a one-hour full-scale storm duration based on Extreme Value Analysis Type I with a 78% probability of non-exceedance. The advanced PTS method (Estephan et al., 2022) was used to analytically compensate the wind loading for both the low-frequency turbulence deficit and dynamic effects in the post-test analysis.

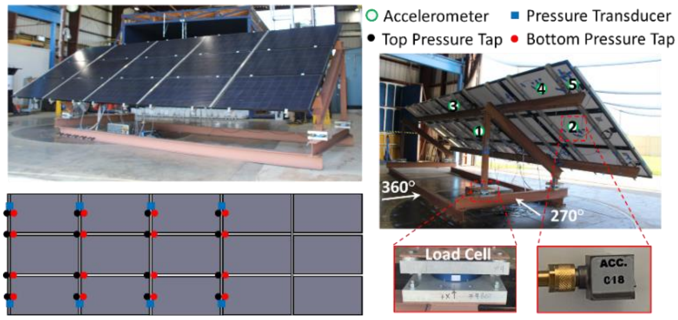
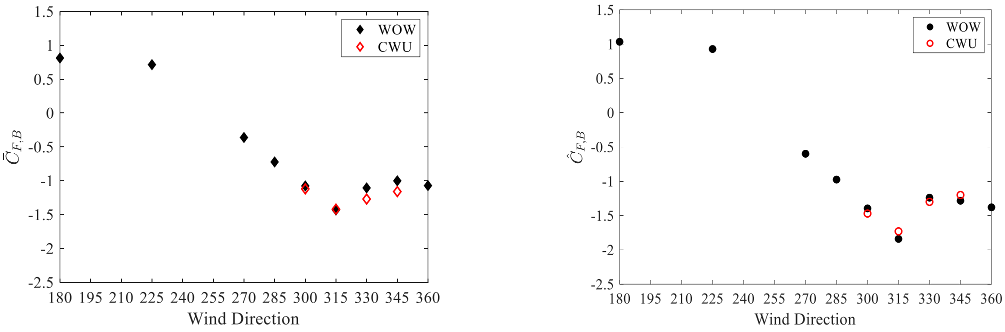


Figure 2. PV array model and instrumentation layout

## 3. Results and Discussion

The experimentally computed mean and peak aerodynamic force coefficients $\bar{C}_{F,B}$ and $\hat{C}_{F,B}$ are presented in Figure 3 as a function of wind direction. In addition, a comparison was made with the values obtained from the CWU field measurements for wind directions of 300° to 345°. It was observed that the most critical WOW positive $\bar{C}_{F,B}$ and $\hat{C}_{F,B}$ of 0.82 and 1.0, respectively, were observed for 180° which is the direction of the flow acting towards the front side of the array and exerting positive net pressure. For wind directions from 270° to 360°, the WOW $\bar{C}_{F,B}$ and $\hat{C}_{F,B}$ were negative in magnitude with the critical values of -1.4 and -1.85 estimated at the cornering wind direction of 315°. The mean and peak net force coefficients from the WOW experiments were in reasonable agreement with the CWU data for the wind directions of 300° to 345°. Specifically, $\bar{C}_{F,B}$ of -1.4 and $\hat{C}_{F,B}$ of -1.7, calculated from the field measurements for 315° wind direction, agree well with their experimentally-computed counterparts of -1.4 and -1.85, respectively, with less than a 13% difference.



(a) (b)

Figure 3. (a) Mean and (b) peak force coefficients

Wind-induced dynamic effects caused by the panels' vibration under wind action are analytically accounted for in the peak wind load estimation. The dynamic properties of the PV array, such as natural frequency and damping ratio, serve as inputs for the analytical process and can be estimated based on acceleration data using the Random Decrement (RD) technique. Dynamic resonant vibrations were detected in the acceleration spectrum in the form of spectral peaks at the natural frequencies $f_0$ of 11, 14, and 19 Hz. In addition to the natural frequency, another important parameter needed for the estimation of peak dynamic wind loads on the PV array is the total damping ratio $\zeta$, which is the sum of structural and aerodynamic damping. Based on the acceleration time histories recorded during the impact hammer test on the PV array and in the absence of wind, a structural damping ratio $\zeta_{struct}$ of 3.7% was obtained using the RD technique. For the aerodynamic damping $\zeta_{aero}$, which is a function of the tested wind speed, it was observed to range from 0.3% to 1.2% (i.e., $\zeta$ between 4% and 4.9%) when the wind speed was increased from 7.5 m/s to 30 m/s. To quantify the wind-induced dynamic effects on PV arrays, the dynamic amplification factor ($DAF$) is considered. The DAF is the ratio of the peak dynamic net force coefficient $\hat{C}_{F,B+R}$ that includes both the background $B$ and resonant $R$ components to $\hat{C}_{F,B}$ consisting of only the background component. In the current study, $\hat{C}_{F,B+R}$ was calculated based on load cell measurements of the reaction forces acting on the PV array's supports for a range of wind speeds. In addition, $\hat{C}_{F,B+R}$ was estimated in the post-test analytical analysis by compensating the wind loading for both the low-frequency turbulence deficit and dynamic effects. The measured and estimated $DAF$ values are presented in Figure 4 as a function of reduced frequency $f_0 L_c / U_{3s}$ for critical wind direction of 315°, where $U_{3s}$ is the 3-sec gust wind speed at the mean array height. The $DAF$ was shown to increase from 1.15 to 1.3 when $f_0 L_c / U_{3s}$ decreased from 1.9 to 0.5. This is because the turbulent eddies at full scale are moving faster as the wind speed increases causing a shift in the wind turbulence spectrum. This leads to an increase in the dynamic peak net force coefficients with increasing wind speeds.

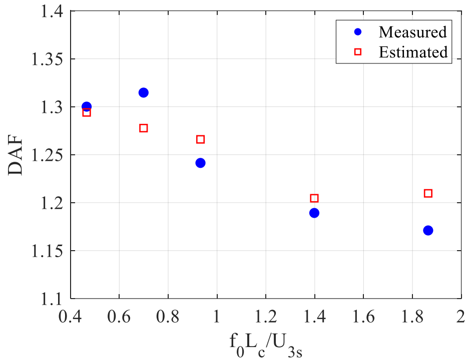


Figure 4. Dynamic Amplification Factor as a function of reduced frequency

## 4. Conclusions

This study investigates the wind-induced dynamic effects on rooftop PV arrays based on experimental tests and analytical analyses validated by field measurements. Field measurements were conducted on the rooftop PV array of the HTC building at CWU. In addition, experimental tests were carried out at the NHERI WOW EF at FIU on a full-scale PV array model subjected to simulated Atmospheric Boundary Layer flows to measure the wind loading on the PV array and its dynamic properties. The post-test analytical analysis was performed on the measured data by using the recently developed advanced PTS method that takes into account the inflow turbulence and dynamic effects on rooftop PV arrays. The experimentally computed wind-induced force coefficients on the PV array as well as the dynamic properties of the latter were in reasonable agreement with the field measurements. Dynamic Amplification Factors were computed as a function of reduced frequency and the dynamic wind loading on the PV array was shown to increase with increasing wind speed.

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