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Kristina Kostadinović Vranešević[1], Ulf Winkelmann[2], Rüdiger Höffer[2], Anina Glumac[3]

WIND TUNNEL STUDY OF WIND-INDUCED LOADING ON AN ISOLATED SOLAR PANEL

Summary: Solar panels (SPs) are designed to withstand wind-induced loading, characterised by varying wind speeds and directions, as well as high turbulence. This paper examines force coefficient statistics—mean, standard deviation, 3-s gust and peak values—on an isolated SP model, using data from an experimental campaign conducted in the atmospheric boundary layer wind tunnel at Ruhr University Bochum. A geometric scale of 1:30 was adopted for the SP model, tested across two terrain roughness profiles, three wind speeds, and various approaching wind directions, at a fixed tilt angle of 30°. Findings indicate that wind profiles with lower turbulence intensity produce lower force coefficients across all wind directions, whereas variations in wind speed show no significant effect. The collected dataset is intended to support the validation of future computational fluid dynamics (CFD) studies.

Keywords: wind loading, wind tunnel testing, solar panel, force coefficient statistics, peak force coefficient

ISPITIVANJE OPTEREĆENJA IZAZVANOG VETROM NA IZOLOVANOM SOLARNOM PANELU U AEROTUNELU

Rezime: Solarni paneli (SP) su projektovani da izdrže opterećenje izazvano vetrom, koje karakterišu različite brzine i pravci vetra, kao i visoka turbulencija. Ovaj rad ispituje statistike koeficijenta sile—srednju vrednost, standardnu devijaciju, 3-sekundni udar i vršne vrednosti—na izolovanom modelu SP, koristeći podatke iz eksperimentalne kampanje sprovedene u aerotunelu atmosferskog graničnog sloja na Univerzitetu Rur u Bohumu. Za model SP je usvojena geometrijska razmera 1:30, testiran pri dva profila hrapavosti terena, tri brzine vetra i pri različitim pravcima vetra, uz fiksni ugao nagiba od 30°. Rezultati pokazuju da profili vetra sa nižom turbulencijom proizvode niže koeficijente sile u svim pravcima vetra, dok varijacije brzine vetra ne pokazuju značajniji efekat. Prikupljena baza podataka namenjena je kao podrška validaciji budućih studija računarske dinamike fluida (CFD).

Ključne reči: opterećenje vetrom, testiranje u aerotunelu, solarni panel, statistike koeficijenta sile, vršni koeficijent sile

[1] University of Belgrade, Faculty of Civil Engineering, kkostadinovic@grf.bg.ac.rs
[2] Ruhr University Bochum, Faculty of Civil and Environmental Engineering
[3] University of Belgrade, Faculty of Civil Engineering

1. INTRODUCTION

The rapid expansion of solar energy highlights the need to understand how environmental factors, especially wind, affect solar panels (SPs). Wind-induced aerodynamic loading poses serious structural risks, particularly in coastal areas where high wind speeds are common. Resulting damage leads to costly repairs and disrupts power production, underscoring the need for improved assessment of wind loads on SPs.

Experimental wind tunnel studies on isolated SP configurations have provided fundamental insight into these loads, free from the array interference effects present in multi-panel installations. Aly and Bitsuamlak [1] established key recommendations on model and wind-profile scaling, showing that smaller geometric scales are prone to significant load errors from ground effects, and that lower incident turbulence increases mean loading while reducing peak values. Stathopoulos et al. [2] further examined the role of tilt angle and wind direction on a row of panels treated as a single unit, identifying oblique wind directions as most critical. The influence of tilt angle over a full range was subsequently explored by Chou et al. [3] and Chung et al. [4] under low-turbulence, uniform-flow conditions representative of offshore exposure, showing that uplift forces stabilise beyond a tilt angle of 60°. More recently, Estephan et al. [5] combined experimental and numerical approaches to predict peak wind loads, following the gust and peak factor definitions established for wind-sensitive structures [6], and showed that code-based coefficients (e.g., ASCE 7-16) are not always conservative for roof-mounted SPs.

Despite this progress, two aspects remain insufficiently addressed. First, while the sensitivity of wind loading to incident turbulence and terrain roughness has been noted, systematic comparisons across distinct wind profiles remain limited. Second, the influence of Reynolds number—often acknowledged but rarely quantified—has received limited attention, particularly regarding its effect on the higher-order statistics of the aerodynamic force coefficients, as opposed to mean values alone. Where Reynolds number sensitivity has been examined for isolated SPs, it has typically been limited to a single tilt angle and wind direction [7], leaving its interaction with terrain roughness and multi-directional loading unexplored.

This paper addresses these gaps through a wind tunnel investigation of an isolated SP model under two distinct incident wind profiles, with the RAU8 profile further tested at three rotational wind speeds to isolate Reynolds number effects. Force coefficients are analysed in terms of their mean, standard deviation, 3-s gust, and peak values, providing a more complete statistical picture of the wind loading response than mean-value comparisons alone. The study forms part of the experimental campaign carried out at the atmospheric boundary layer (ABL) wind tunnel of Ruhr University Bochum, Germany, under a Short-Term Scientific Mission (STSM) of the MODENERLADS COST Action CA20109.

The paper is organised as follows. Section 2 describes the experimental setup, including the SP model, wind tunnel setup and wind profiles. Section 3 presents the methodology for evaluating pressure and force coefficients and related statistics. Resulting wind loading under varying Reynolds numbers and wind profiles is shown in Section 4. Section 5 concludes with a summary of findings and their implications for wind load assessment of isolated SPs.

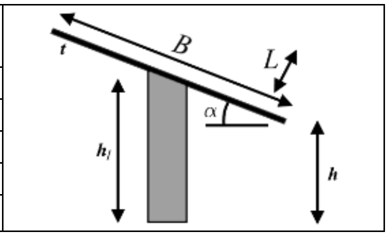
2. EXPERIMENTAL SETUP

The experimental campaign was conducted in the ABL wind tunnel at Ruhr University Bochum, Germany, as part of the STSM within the MODENERLADS COST Action CA20109. The campaign included tests on both an isolated SP and a panel array; however, this paper presents results for the isolated SP only. This section outlines the experimental setup, providing details of the SP model (Subsection 2.1), the wind tunnel setup (Subsection 2.2), and the characteristics of the incident wind profiles (Subsection 2.3).

2.1. MODEL OF THE SOLAR PANEL

The SP geometry is adapted from Aly and Bitsuamlak [1], using a geometric scale of 1:30 for the panel model and 1:300 for the incident boundary layer profile, a configuration previously shown to yield reliable pressure distributions [1]. Geometric characteristics of the model are provided in Table 1 in both full-scale and model-scale, with graphical representation in Figure 1. The model was fabricated via 3D printing and equipped with 48 pressure taps (25 on the front face and 23 on the rear); the distribution pattern is given in Figure 1(a). The assumption of a rigid model is adopted, as the investigation isolates wind-induced surface pressures on the SP rather than structural aeroelasticity. The 3D-printed model was designed with sufficient thickness and structural rigidity to prevent wind-induced deflections.

Table 1: Dimensions of the SP in full and model scale

	Full-scale 1:1	**Model scale 1:30**	
B [mm]	1 500	50	
L [mm]	10 000	333	
h_1 [mm]	1 200	40	
t [mm]	150	5	
α [°]	20°, 30°, 40°	20°, 30°, 40°	

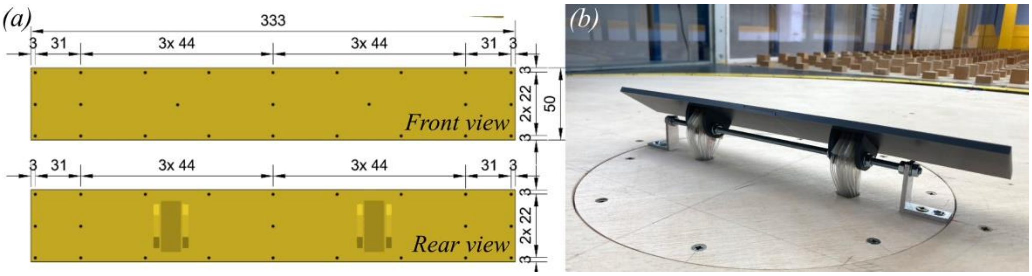


Figure 1: SP model: (a) Location of pressure taps on the front and rear faces; (b)Model mounted in the ABL wind tunnel at Ruhr University, Bochum, Germany

2.2. WIND TUNNEL SETUP

The open circuit wind tunnel, with test section dimensions of 9.3 × 1.8 × 1.6 m (length-width-height), was used in the experimental campaign. The incident wind profile (i.e., the profile at the middle of the turning table in the domain without the SP model) was developed by applying the traditional spire-roughness technique. Two setups of turbulence elements in the precursor domain were considered:

- **RAU6:** Test section without roughness field (only barrier+spires as shown in Fig.2(a)), aiming to mimic wind profile for terrain Category 0 by Eurocode [8]: open sea/coastal areas and
- **RAU8:** Fully equipped wind tunnel (barrier+spires+roughness field as shown in Fig.2(b)), representing Category II (low vegetation with isolated obstacles).

Velocity measurements of the incident wind profile at seven heights were performed using a hot-wire probe, providing the streamwise and vertical components of the velocity vector (a zoomed-in view of the hot-wires is given in Fig. 2(d)). Three rotational speeds at the inlet were considered for RAU8: 625 rot/min, 1000 rot/min and 1400 rot/min, resulting in mean velocities at 10 m height in full scale (U_{10}) of 12 m/s, 19 m/s and 26 m/s, respectively. RAU6 was tested only at 1000 rot/min, serving as a single-speed terrain-category comparison case rather than as part of the Reynolds number sensitivity study, which applies to RAU8 only.

Pressure data were collected at the upper and lower surfaces of the SP model (Fig. 1(a)) using piezoresistive pressure sensors; the apparatus is shown in Fig. 2(c). Nine approach wind directions (β) were analysed: 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. The sampling frequency for both velocity and pressure measurements was 1000 Hz and the sampling time was equal to 10 hours in the equivalent full scale (EFS).

Figure 2:(a) Configuration RAU6 in ABL wind tunnel at Ruhr University Bochum; (b) Configuration RAU8 in ABL wind tunnel at Ruhr University Bochum; (c) Apparatus for pressure measurements; (d) Hot-wire probe for velocity measurements

2.3. INCIDENT WIND PROFILE

Figure 3 shows the resulting incident wind profiles, presenting mean speed normalised with the velocity at model height (U_{ref}) and turbulence intensity. While Fig. 3(a) provides a comparison of the measured data for RAU6 and RAU8 with target Eurocode profiles [8], Fig. 3(b) analyses the impact of different rotational speeds in the RAU8 configuration.

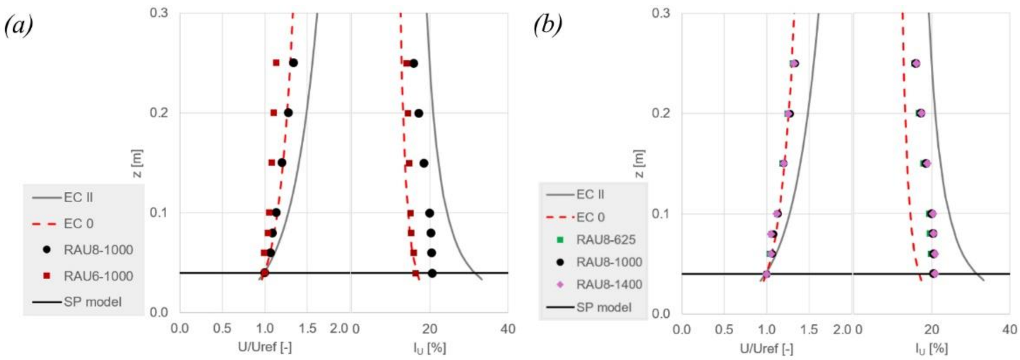


Figure 3: Incident wind profiles of normalise mean wind velocity (U/U_{ref}) and turbulence intensity (I_U) at the centre of the turning table from wind tunnel, compared with target profiles for Eurocode terrain Categories 0 and II: (a) RAU6 vs. RAU8 at rotational speed of 1000 rot/min and (b) RAU8 at three rotational speeds, 625 rot/min, 1000 rot/min and 1400 rot/min

Considering mean velocity profiles, good agreement between the measured profiles of mean wind speed and terrain Category 0 by Eurocode [8] is achieved. However, a clear difference in the velocity gradient between the RAU6 and RAU8 profiles is evident, with a steeper gradient in the RAU6 configuration due to the absence of the roughness field. Mean velocity profiles show no sensitivity to different rotational speeds in the RAU8 configuration, confirming Reynolds independence for this setup. Regarding turbulence intensity, results for the RAU6 configuration align closely with those for terrain Category 0 by Eurocode [8], while results for the RAU8 configuration fall between Categories 0 and II. Again, results are consistent across the different rotational speeds. Overall, RAU6 can be considered a good representative of terrain Category 0, while the RAU8 configuration falls between Categories 0 and II by Eurocode [8] for the adopted geometric scale of 1:30.

3. METHODOLOGY

In order to examine wind loading on the SP model, pressure and force coefficients with related statistics are calculated. Two pressure coefficients are defined: the pressure coefficient at the measurement point, C_p, calculated by Eq. (1), and the net pressure coefficient, $C_{p,net}$, given by the difference between the pressure coefficients on the upper and lower sides of the SP (Eq. (2)). The force coefficient C_f for the entire SP is obtained by integrating the net coefficients over the surface, as shown in Eq. (3). Figure 4 shows the pattern of the associated areas overlapped with the distribution of the mean pressure coefficient on the upper and lower surfaces of the SP model for configuration RAU8, at a rotational speed of 1000 rot/min and a tilt angle of 30°.

$$C_p = \frac{p(t)}{\frac{1}{2}\rho U^2} \tag{1}$$

$$C_{p,net}(t) = C_{p,upper}(t) - C_{p,lower}(t) \tag{2}$$

$$C_f(t) = \frac{\sum_{i=1}^{n} C_{p,net,i}(t) A_i}{\sum_{i=1}^{n} A_i} \tag{3}$$

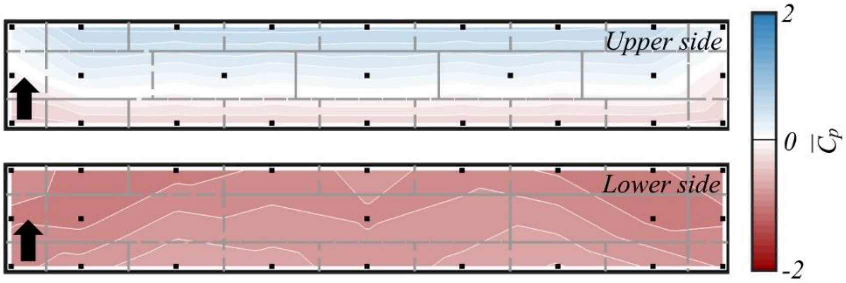


Figure 4: Surface distribution of mean pressure coefficient for RAU8 configuration at rotational speed of 1000 rot/min and tilt angle of 30º with the pattern of associated areas (A_i) for force coefficient calculations

The related statistics consist of the mean and standard deviation of the pressure and force coefficients, as well as peak values. For evaluating peaks, a time window of 10 minutes in EFS is taken as the representative event duration, and two approaches are analysed:

- 3-s gust value: following [1], the 3-s peak values of loads may be obtained from Eqs. (1)-(3) by replacing U with U_3, the 3-s mean wind speed. By dividing the time history of the force coefficient into a number of windows, each of 3-s duration in full-scale time and containing n samples, a relatively large number of 3-s observed peak values is obtained. The mean value of these peak values provides a robust estimate of the 3-s peak value.

- Traditional "epochal" approach, described in [6]: a Gumbel distribution is applied to the series of peak values, each collected as the maximal coefficient value within the analysed time window representing one epoch. 15 epochs are taken to form the distribution, and values with a probability of non-exceedance of 80% are reported.

Both approaches are applied consistently across all tested configurations.

4. RESULTS

Data analysis is streamlined in two directions. The first is a comparison of the force coefficients across the two configurations, RAU6 and RAU8, presented in Subsection 4.1, with the goal of isolating the influence of terrain roughness on wind loading. The second direction of the analysis is aimed at quantifying the influence of Reynolds number by comparing results from different rotational speeds in the RAU8 configuration, given in Subsection 4.2. All results are presented in terms of the force coefficient statistics reported in Section 3. Since the total pressure signal duration of 10 h in EFS provides a solid basis for the uncertainty quantification of peak values, the uncertainty range at a 95% confidence level is reported.

4.1. TERRAIN CATEGORIES 0 AND II

Results for the two configurations, RAU6 and RAU8, at a rotational speed of 1000 rot/min and a tilt angle of 30°, are presented in Fig. 5. It can be noticed that, for all approaching wind angles, mean values of the force coefficient are almost equal. However, differences emerge in the higher-order statistics. The standard deviation of C_f is higher for RAU8 than for RAU6, consistently across wind directions. This is attributed to the higher turbulence intensity in the RAU8 configuration, which produces a higher level of oscillation in C_f compared to the smoother incident wind profile in RAU6. This effect carries over to the peak values as well: the range between the maximum and minimum peak values is larger for RAU8, and the individual extreme values are also higher than those obtained for RAU6. The uncertainty range is likewise slightly larger for RAU8.

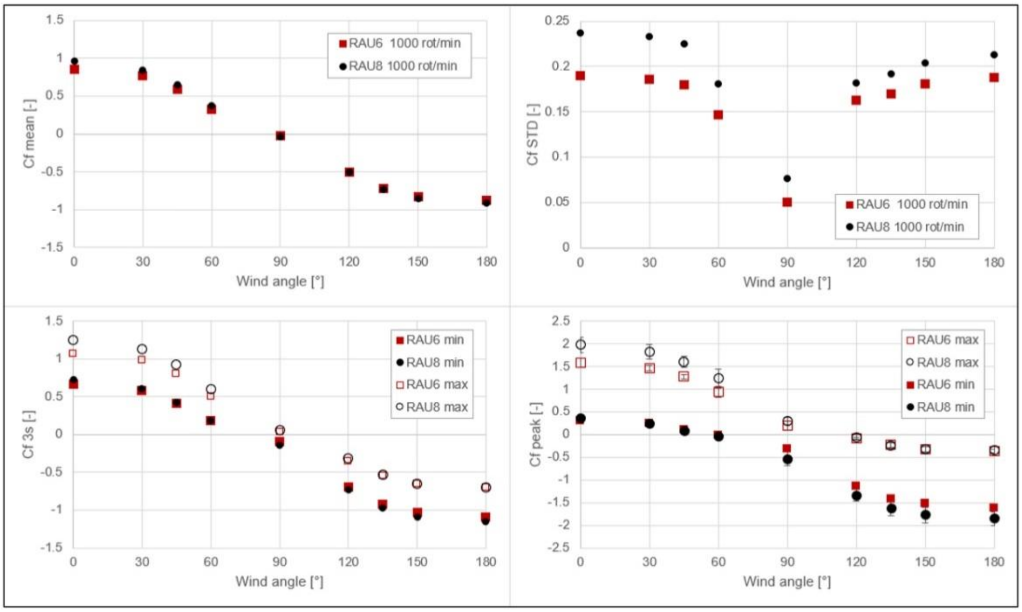


Figure 5: Influence of terrain roughness on force coefficient statistics (mean, standard deviation, 3-s gust and peak values) for isolated SP at tilt angle of 30°, rotational speed of 1000 rot/min, for two configurations: RAU6 and RAU8

Considering that the Eurocode [8] wind loading guidelines are formulated with respect to terrain Category II, and that RAU8 is the configuration more representative of this category, RAU8 produces higher force coefficient statistics (mean, standard deviation, gust and peak values) than RAU6. This suggests that applying Eurocode Category II-based provisions to open-terrain and coastal sites—conditions more favourable for solar farm siting and represented here by RAU6—is conservative, since the predicted loads remain on the safe side relative to the lower loads expected under such terrain conditions.

4.2. IMPACT OF REYNOLDS NUMBER ON FORCE COEFFICIENT STATISTICS

The influence of Reynolds number on the force coefficient statistics is examined by comparing results from the three rotational speeds tested in the RAU8 configuration — 625, 1000 and 1400 rot/min — as presented in Fig. 6.

Mean values of C_f are slightly lower at 625 rot/min for wind angles of 0° and 30°, while for all other wind directions the mean values obtained at the three rotational speeds are in close agreement. A similar trend is observed for the standard deviation of C_f, where results across the three speeds are largely consistent, with only minor deviations at the lowest rotational speed.

A more noticeable difference emerges in the maximum peak values, particularly for wind directions between 0° and 60°, where results for 1000 and 1400 rot/min match closely, while values for 625 rot/min are slightly lower. However, even in this range, the largest observed difference remains below 10%.

Overall, these results indicate that reducing the rotational speed—and consequently the Reynolds number—has some effect on the force coefficient statistics, but this effect remains within an acceptable range. This finding is particularly relevant for numerical simulations, where matching Reynolds numbers is often impractical and down-scaled velocities are commonly adopted instead.

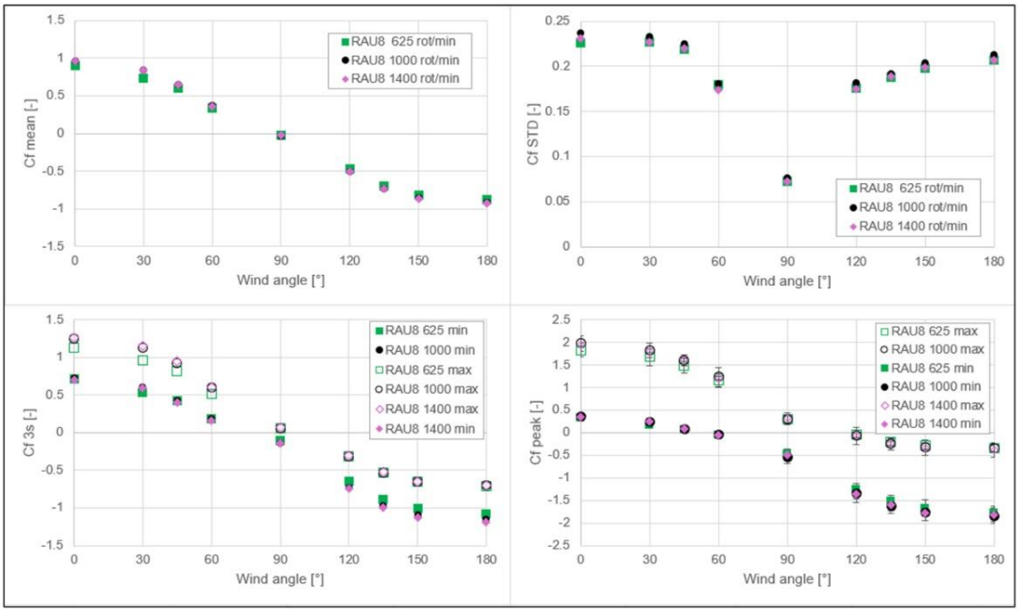


Figure 6: Influence of Reynolds number on force coefficient statistics (mean, standard deviation, 3-s gust and peak values) for isolated SP at tilt angle of 30°, RAU8 configuration, at three rotational speeds: 625, 1000 and 1400 rot/min

5. CONCLUSIONS

This paper presented an experimental investigation of wind-induced loading on an isolated solar panel model, tested in the ABL wind tunnel at Ruhr University Bochum under two incident wind profiles (RAU6 and RAU8) and three rotational wind speeds. Force coefficient statistics—mean, standard deviation, 3-s gust and peak values—were analysed to assess the effects of terrain roughness and Reynolds number on wind loading.

The main conclusions can be summarised as follows:

- A wind profile with lower turbulence intensity (RAU6) produces lower force coefficients on the solar panel across all wind directions compared to a profile with higher turbulence intensity (RAU8). Since RAU8 is the configuration closer to Eurocode terrain Category II, this implies that applying Eurocode provisions for Category II to open-terrain and coastal sites remains on the safe side.
- Peak force coefficients on the solar panel model are not significantly affected by changes in rotational wind speed, and consequently by Reynolds number, with observed differences remaining below 10%. This suggests that wind speed can be reduced in numerical simulations without a major impact on the accuracy of the results.

Future work will focus on further processing of the collected data, including the analysis of tilt-angle effects and panel position within an array. Additionally, the measured coefficients will be benchmarked against relevant code provisions to assess their applicability to solar panel design guidelines.

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