AREA-AVERAGED CHARACTERISTICS OF WIND LOADS ON ROOF-MOUNTED SOLAR ARRAYS

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ABSTRACT

With the increasing use of solar photovoltaics, wind-induced loads on rooftop solar arrays have become a problem. A series of wind tunnel experiments have been performed to evaluate wind loads on solar panels on flat roofs, mainly focusing on their area-averaged characteristics such as mean and negative peak force coefficients, and peak factors. Solar array models were fabricated with pressure taps installed as densely as possible to identify the area-averaged characteristics. Design parameters of solar arrays including panel position, tilt angle and distance between arrays have been considered. Although values for unfavorable mean and peak differ for different tilt angles, the variation tendencies and peak factors are similar. The results were also compared to Japanese Standard (JIS C 8955) which correctly estimates negative mean module force coefficients but not peak values.

Keywords: Area-averaged force coefficient, Peak factor, Roof-mounted solar array, Wind tunnel experiment

Introduction

Due to the rapidly increasing global use of solar photovoltaics (PV), the third most important renewable energy source after hydro and wind power, the structural performance of such systems under environmental loads is becoming an increasingly important issue. For PV installations built into roofs (either roof-integrated or simply rooftop), wind-induced uplift loads is one of the most critical issues, and may determine the potential needs for mounting the systems. Design of such structures based on insufficient knowledge or simplifications often result in unsafe or uneconomic results.

During past several decades, several wind pressure experiments on rooftop solar arrays have been conducted. One of the first studies on inclined solar panels was made by Radu et al. (1986) and Radu and Axinte (1989), which only presented mean wind forces results due to the restriction of measurement techniques at that period. Recently, experiments on wind loads on solar energy systems can be performed with more sophisticated and cutting edge technology, resulting in not only reliable mean but also peak force values, including Wood et al. (2001), Geurts and Van Bentum (2007), Saha et al. (2011) and Kopp et al. (2012). Although there is a number studies on wind loads on rooftop solar arrays, many of them are contradictive (Stathopoulos et al., 2012) and it is difficult to generalize experimental data from different tests for the improvement of building code provisions. More sophisticated and systematic studies are necessary, especially for area-averaged pressure coefficients that can be used for the data-base improvement and design provisions in future wind loading standards.
The objective of this study is to systematically evaluate wind loads on solar panels mounted on flat roofs, mainly focusing on their area-averaged characteristics such as mean and negative peak force coefficients, and peak factors, which can be used for design provisions in future wind loading standards and codes of practice. Pressure taps on the panels have been installed as densely as possible for area-averaging. Two main design parameters of solar arrays such as tilt angle and distance between arrays were considered. The results are presented in terms of unfavorable negative area-averaged force coefficients on panels as well as local pressure distributions for unfavorable wind directions. Besides, discussions have been made based on comparison between the present work and recommendation values in “Design Guide on Structures for Photovoltaic Array” (JIS C 8955: 2011).

Outline of Wind Tunnel Experiments

Pressure models

A medium-rise building model with a flat roof and dimensions of 25m ($B$) × 25m ($D$) ×20m ($H$) in full scale was used to support the installation of solar panel models on the roof (Fig. 1), with a geometry scale of 1:50. Considering the following investigations on the effects of building geometries on wind loads on panel modules, the building model is composed of several blocks that can be conveniently removed or installed to create varying building geometries (Fig. 2a).
Solar panel models (Fig. 2b) with open substructures included two instrumented with pressure taps (A and B in Fig. 1) and others without pressure taps that served as dummy models in the experiments. Each pressure-tapped panel model was 7m ×2m (14cm ×4cm in model scale), and 112 taps were installed on both upper and lower surfaces (56 taps for each) as shown in Figure 1. The pressure-tapped panel models were supported by an open frame shaped like a triangular prism that could be fixed at different locations on the building model roof, and tilt angles could be varied by changing the supporting frames to give different angles of triangular bases.

**Upstream Terrain Simulation**

Wind tunnel experiments were carried out in a Boundary Layer Wind Tunnel at Tokyo Polytechnic University, Japan. The test section was 2.2m wide and 1.8m high. Open terrain characteristics were simulated and a velocity scale of 1/3 was adopted. The power law exponent $\alpha$ of mean wind speed was 0.16. The mean wind speed at the height of the building model (400mm above the bottom of the tunnel) was 10m/s and the corresponding turbulence intensity was approximately 20%, as shown in Figure 3a. The measured spectrum of longitudinal turbulence (Fig. 3b) was well agreed compared to the Von Karman spectrum.

![Turbulence intensity profile](image1)

![Mean wind speed profile](image2)

(a) Profile of mean wind speed and turbulence intensity

(b) Spectrum of longitudinal turbulence

**Fig. 3 Simulation of wind flow in wind tunnel**

**Sampling Conditions**

Wind pressures were acquired with a sampling frequency of 1000Hz using a multi-channel simultaneous-scanning pressure measurement system. A sampling period of 36 seconds was adopted for each data record, corresponding to 10 minutes in full scale (Time scale: 3/50). For each test case, wind directions were varied at $10^\circ$ intervals and 10 data records were sampled for each wind direction for the statistical analysis. The measured pressure time histories were digitally low-pass filtered at 300Hz. Numerical compensations were employed to correct the tube effects using the gain and phase-shift characteristics of the measurement system (Irwin et al, 1979).
Variation of Solar Array Design Parameters

Two important parameters need to be considered: panel tilt angle and distance between arrays. The panel tilt angle should be almost the same as the annual optimum angle at which the maximum possible amount of electricity is generated, which differs from region to region. For example, the annual optimum angle for Tokyo is 32° and it increases with increase in latitude. Three tilt angles from 15° to 45° were considered for multi-array cases in this study (see Table 1).

Another parameter, distance between arrays, needs to be considered since solar cells on the panels should not be in the shade. The following basic formula is required (Appelbaum and Bany, 1979):

\[
d \geq \Delta h \times K
\]  

(1)

where \(d\) is distance between arrays; \(\Delta h\) is net panel height and \(K\) is shadow length factor, which also differs from region to region, being 2.3 for Tokyo and increasing with increase in latitude. Three distances corresponding to three different shadow length factors were adopted in this study (see Table 1).

Table 1: Variation of tilt angle and distance between arrays

<table>
<thead>
<tr>
<th>Tilt angle (\beta) (°)</th>
<th>Net panel height (\Delta h) (mm)</th>
<th>Shadow length factor (K)</th>
<th>Distance between arrays (d) (mm)</th>
<th>No. of rows (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>10</td>
<td>2.3</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>2.3</td>
<td>46</td>
<td>5</td>
</tr>
<tr>
<td>45</td>
<td>28</td>
<td>2.3</td>
<td>64</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
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<tr>
<td>15</td>
<td>10</td>
<td>3.6</td>
<td>36</td>
<td>5</td>
</tr>
</tbody>
</table>

Calculations

The local force coefficient at pressure tap \(i\) and time \(t\) \(C_f(i,t)\) (positive downward, see Fig. 2b) can be determined from the local pressure coefficient time histories on upper \(C_{pu}(i,t)\) and lower surfaces \(C_{pl}(i,t)\):

\[
C_f(i,t) = C_{pu}(i,t) - C_{pl}(i,t)
\]  

(2)

If the size of one panel module is considered to be \(0.5m \times 2m\) (1m\(^2\), see Fig. 2a), area-averaged force coefficient \(C_{f,Area,1}\) within this area can be determined by integrating the local force coefficients at four points (there are four taps along the height of the panel):

\[
C_{f,Area,1}(j,t) = \frac{1}{4} \sum_{i=1}^{14} C_f(i,t) \quad (j = 1, 2, \ldots, 14)
\]  

(3)

There is total 14 area-averaged force coefficients with the area of 1m\(^2\) and the most unfavorable value was picked up as the results discussed below. Also, area-averaged force coefficients can be determined for different effective areas from one module (\(C_{f,Area,1}\) for 1m\(^2\)) to 14-modules (\(C_{f,Area,14}\) for 14m\(^2\)).
Peak local pressure and area-averaged force coefficients were determined using “Cook–Mayne method” [Cook and Mayne (1979)], using a moving average time of \( \tau = 0.03 \) s in full scale. (The moving average time is relatively small since the effect area for each tap is small as a result of densely spaced pressure taps on the panel model). In the peak estimation for each wind direction for each test case, peak values of 10 data records were used to perform the Lieblein Best Linear Unbiased Estimators (BLUE) formulation. The resultant mode and dispersion of the FT1 distribution were used to estimate the peak values for the above pressure or force coefficients.

Peak factors, which were calculated corresponding to area-averaged force coefficients with different area values, can be determined using Equation (4):

\[
g = \left| \frac{C_{f,\text{Area, min}} - C_{f,\text{Area, mean}}}{C_{f,\text{Area, max}}} \right|
\]  

(4)

**Design force coefficients for solar modules in JIS C 8955**

**Mean Force Coefficient**

This guide provides mean design force coefficients \( C_f \) (net pressure coefficients). For the uplift values, they can be estimated as follows:

\[
C_f = \begin{cases} 
0.95 & (0^\circ \leq \beta < 15^\circ) \\
0.71 + 0.016\beta & (15^\circ \leq \beta < 45^\circ)
\end{cases}
\]  

(5)

where \( \beta \) is the tilt angle (°) as used above.

**Peak Force Coefficient**

Besides mean design force coefficients, the guide considered a “Gust Effect Factor” \( G_f \) for the design velocity pressure in calculating design wind loads. Although the \( G_f \) term is specified for wind velocity pressure, a combination of the terms \( C_f \) and \( G_f \), that is \( (G_f \cdot C_f) \) can be regarded as the peak module force coefficients for comparison. It has to be explained that the \( G_f \) term is related to the terrain category and the height of the building. For comparing to present results, a corresponding value of 2.4 is used.

**Effect of Panel Tilt Angle**

**Mean Force Coefficient**

Fig. 5 shows the variation of largest negative mean area-averaged force coefficient with increase in effective area (from 1m\(^2\) for one module with four taps on one surface to 14m\(^2\) for 14 modules with 56 taps). The largest negative mean area-averaged force coefficients were chosen for all wind directions and all modules. Both results for two neighboring panels (Panels A and B, see Fig. 1) were presented with different tilt angle of solar panels.

The results show that values for Panel A are larger than those for Panel B, especially when effective area is small, which indicates the shielding effect for Panel B. The values both Panel A and B decrease with increase in tilt angle. It is therefore concluded that the larger the tilt angle, the higher the uplift wind loads on the solar panels. Meanwhile, the area-averaged force coefficients decrease with increase in effective area and the decreasing tendency for Panel A is more significant than that for Panel B.

Comparisons to JIS C 8955 (Dashed lines in Fig. 5) indicates the Standard values correctly estimates the values for the panels at the first row with small effective areas and become conservative when the panel locates in other rows and the effective areas increase.
Since the values on Panel A are generally larger than those on Panel B, mean pressure distributions (Fig. 6) on Panel A when the largest values occurred are presented. For mean pressure values, the most unfavorable wind direction is near 310°. With the cornering wind of 310°, both high negative pressures on the corners of the upper surfaces of the panel and high positive (causing uplift) pressures on the lower surfaces increase with increase in tilt angle, which result in increase in negative mean forces. On one side, the increasing negative pressures on the upper surfaces indicate that the panel-generated vortices become stronger for larger tilt angles since the locations of the panels with the three tilt angles are the same and the effect of building-generated conical vortices can be regarded as similar for these three cases. On the other side, the increasing positive pressures on the lower surfaces demonstrate that the phenomenon of pressure equalization becomes weakened with larger tilt angles. For example, there is a region (on the last three units) with the mean local force (net pressure) near 0 with the tilt angle 15° in Fig. 6a and this does not occur for tilt angles of 30° and 45°.

**Peak Force Coefficient**

The variation of largest negative peak area-averaged force coefficient with increase in effective area (Fig. 7) shows similar tendency to mean values. However, comparisons to JIS C 8955 (Dashed lines in Fig. 7) show the Standard values fail to estimate the peak force coefficients regardless of the size of effective areas and the location of the panels.

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**Fig. 5** Largest negative mean area-averaged force coefficient for different tilt angles.

**Fig. 6** Mean pressure distribution on Panel A for wind direction 310° for different tilt angles.
Fig. 7 Largest negative peak area-averaged force coefficient for different tilt angles

In Fig. 8, peak local force (net pressure) distributions on Panel A with different tilt angles when the largest values occurred were presented. For peak local force values, the most unfavorable wind direction is around 300°. Similar to the mean results, the largest negative peak local forces on the corner of the panel increases with increase in tilt angle and high peak local force regions (e.g. absolute values larger than 5) continuously increase with increasing tilt angle as well, which can be used to explain the results shown in Fig. 7.

Fig. 8 Negative peak (uplift) local force distributions on Panel A for wind direction 300° for different tile angles.

Fig. 9 Peak Factor for different tilt angles when largest negative peak area-averaged force coefficient occurs
Peak Factor

Fig. 5 depicts peak factor values for different effective areas when the corresponding largest negative peaks occur. Although there is a small discrepancy, peak factors corresponding to largest negative peaks are similar for different tilt angles. It is interesting to notice that the peak factor values do not change although both mean and peak force coefficients decrease with increase in effective area. The values keep almost constant at a value of 6, which are consistent with previous reported values [Kopp et al. (2011)].

Effect of Distance between Solar Arrays

Mean Force Coefficient

Fig. 10 presents the variation of largest negative mean area-averaged force coefficient with increase in effective area with different distances between arrays. For both panels, the values decrease with increase in effective area. Since Panel A is located at same positions for different array distances, the values for Panel A do not vary with change in array distance. However, the values for Panel B increase with increase in array distance.

Mean pressure distributions on Panel B (Fig. 11) were presented with the corresponding most unfavorable wind directions. With increase in array distances, high negative mean pressures on the upper surface of the panel increase, which causes the increase in mean local forces at the panel edge.

![Graph showing variation of largest negative mean area-averaged force coefficient](image)

Fig. 10 Largest negative mean area-averaged force coefficient for different array distances

![Mean pressure distributions on Panel B](image)

Fig. 11. Mean pressure distribution on Panel B with wind direction 300° for different distances between arrays.
**Peak Force Coefficient**

Similar to the mean results, array distance does not change peak area-averaged force coefficients of Panel A at the first row, but increase those of Panel B. The values, which decrease with increase in effective area, exceed the Standard values provided in JIS C 8955, regardless of location of the panel.

In Fig. 8, peak local force (net pressure) distributions on Panel B with different array distances when the largest values occurred were presented, with wind direction around 300°. Similar high negative local forces at the upper corner increase with increase in array distance.

It can therefore be concluded that the recommended values in JIS C 8955 agree well with mean values, but underestimate the peak panel wind loads compared to present results.

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**Fig. 12** Largest negative peak area-averaged force coefficient

**Fig. 13** Negative peak (uplift) local force distributions on Panel B with wind direction 300° for different distances between arrays.

**Fig. 14** Peak Factor When largest negative peak area-averaged force coefficient occurs
Peak Factor

Fig. 14 depicts peak factor values for different effective areas when the corresponding largest negative peaks occur, considering the variation in array distance. Although there is a small decrease with increase in effective area, the values almost remain at a constant value of 6, which is similar to those presented in Fig. 9.

Concluding remarks

Area-averaged characteristics of wind loads on roof-mounted solar arrays, including mean and peak force coefficients and peak factors, were investigated through wind tunnel experiments. Effective area decreases mean and peak force coefficients while it does not affect peak factors. Panel wind loads increase with increase in tilt angle and array distance increase wind loads on panels located in the inner region, but not for those at the array boundary. Present Japanese Standard correctly estimates mean forces with small effective areas but fails for peak values.

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References


