Three-dimensional Panel Configurations to Reduce Wind Load and Increase Convection Cooling of Photovoltaic Surface on Solar Tracking Systems

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ABSTRACT

The efficiency of tracking mechanisms in photovoltaic power systems is limited by wind loads on their solar panels. By overlapping layers of non-overlapping panels a new structure withstanding 10% higher wind speeds without additional wind load can be created to replace present day side by side panel arrangements.

The new structure's double-layer subclass is examined to explain the associated wind loads and scope for higher efficiencies than those so far found.

The new structure has characteristically large vents able to passively cool and mitigate heat related photovoltaic efficiency losses typically peaking above 10% for high performance solar cells in summer and 0.23%/F° in general.

Early design for demand choices are identified relevant to the new structure's uptake in power systems.

Keywords: solar energy, efficiency, photovoltaic, wind, design for demand

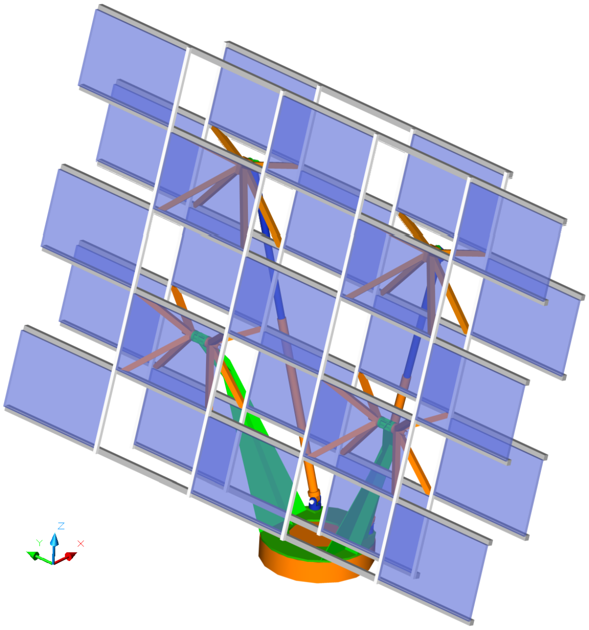

Figure 1: Panels in layers elevation 15° to horizon.

1 3D LAYER STRUCTURE

Double-layer orthogonal-offset panel (DLOOP) arrays are newly investigated flat panel structures shown by analysis and test to have lower maximum drag than side by side panel arrangements of equivalent frontal area. The new structures are unique in having overlapping layers of non-overlapping panels.

As an example an 8×8 *chessboard* DLOOP array has an upper-layer of thirty-two panels in black square positions directly above a layer of thirty-two panels in white square positions. DLOOP arrays are to be assembled and turned as an ensemble, just as today's side by side panels are, attached to a solar tracking mechanism. The chessboard's orthogonal offset, between panels of overlapping layers, results in zero overlap between individual panels – this is necessary for solar applications to prevent shading because sunlight arrives predominantly in a direct line and is only marginally diffuse. Figures 1 and 2 illustrate a 5×5 DLOOP tracking system.

A solar tracking mechanism doesn't come without cost but in return it: delivers up to 40% more power from its high performance panels than otherwise; has total photovoltaic area 6–7 × less than the most economically friendly substitutes in fixed installations for the same diurnal energy out; and spreads energy production more evenly throughout the day which better serves user needs and output electronics budgets.

2 PARAMETER SPACE

The DLOOP array's structure offers a large parameter space of layer distance, panel count, panel and envelope shape, array-to-ground height, array elevation angle range and wind azimuth angles to consider or select from. Even additional layers are possible.

DLOOP arrays are required to work with minimal shade, so an early design preference is for two axis, azimuth and elevation, designs that can point close to the horizon and be deployed identically to any latitude.

Having an equal and odd number of panels in both senses across the DLOOP array's envelope allows diagonal structural members or wire harnesses to run between its layers from envelope corner to corner without casting shadow on lower layer photovoltaics; that is when the central panel is on the upper layer, and noting

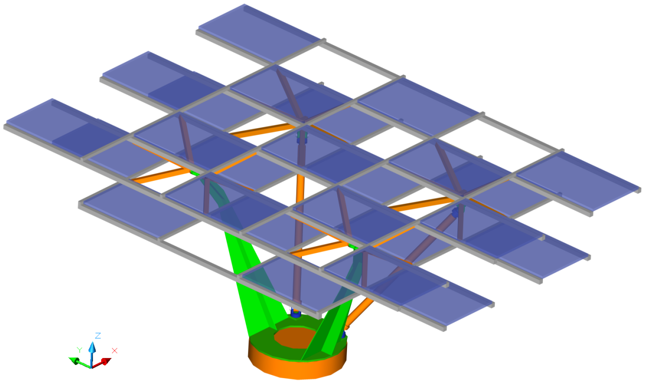

Figure 2: Panels in layers elevation 90° to horizon.

individual panels have finite corner areas which are inactive due to frame width and constituent cell diameters. This advantageous feature, coupled with limited commercial high performance panel size ranges, makes the 5×5 and 7×7 arrays early panel count favourites.

The force (F) on a body in a flow can be approximated by extending Newton's 2^{nd} law empirically to obtain:

$$F = \frac{1}{2}\mathrm{C_d}\rho A u^2 \tag{1}$$

where:

$\mathrm{C_d}$ = body shape's drag coefficient
ρ = fluid (or air) density
A = body shape's area term
u = flow velocity

Equation 1 is useful because many body shapes are found to have constant drag coefficients over significant *Reynolds number* (Re) ranges. The Re captures the essence of a body in a fluid's balance with respect to inertial versus viscous forces: a ratio which reduces to $\rho u\sqrt{A}/\mu$ where μ is dynamic viscosity; and a number unburdened by units – imperial, metric or otherwise.

The high inclination square plate's drag coefficient is the body with the least dependence on Re known: its $\mathrm{C_d} = 1.17$ from Re = 5000 up to the highest sub-sonic levels tested, see [1, Fig.3-26]. Stretching a square into longer and longer rectangles in the limit raises its drag to $\mathrm{C_d} = 1.98$. Note *drag* and *lift* are sometimes used to describe separate components of body wind load force but in this paper – unless otherwise clear – drag and drag force refer to total body wind load force which is the vector sum of its components.

Drag equation 1 works when the incoming flow has a uniform velocity profile, that is, before it is affected by a body's presence. There in uniform flows square panels look superior to rectangular ones for low drag arrays. Surface winds though are part of the *Atmospheric Boundary Layer* (ABL) whose horizontal velocity like typical fluids reduces logarithmically close to walls; or in the case of outdoor winds descends with height to the point of becoming zero on the ground.

Over flat terrain the logarithmic wind velocity profile of the ABL can be written:

$$u_z = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{2}$$

where:

u_z = horizontal flow velocity at height z
u_* = friction velocity, constant for conditions
κ = von Kármán constant
z = vertical height
z_0 = ground roughness, constant for condition

Having a logarithmically lower wind velocity close to ground means that *panel length* to *width* ratios of commercial panels, typically 1.3 to 1.5, may provide reasonable trade-offs between assembly height and panel drag coefficient for DLOOP integrators: to keep wind load particularly associated with height down; and the panel count both ways across the DLOOP array's envelope the same.

With aspect ratio decided nothing evident remains to bring an isolated panel's drag in full frontal winds down further. On the other hand there may be tracking mechanisms (elevation–azimuth types or others) with advantageous features but less stability in winds from behind. The drag coefficient of a hemisphere with its flat side facing a flow is 1.17 like the square panel's; however when the domed side faces the flow it is 0.42, i.e. very much lower. So DLOOP integrators may benefit using domed panel backshells, particularly up high, when rear load stability of their tracking mechanism needs improvement or just to lower its centre of pressure.

2.1 Market factors

Solar energy is unique in having the ability to scale to any need. More than $10,000\times$ the energy arrives by sunlight than via electricity grids and systems are divisible down to a single panel – wind, coal, nuclear and water aren't so accessible energy options for all, and scalability delivers a strong boost to solar panel demand. To keep this market reach the size of a preferred tracking system is household scale, i.e. 250–350 ft^2 of photovoltaics for 20–40 kW hours of electricity per day.

It is unlikely town planers will allow roof top solar tracking systems to become ubiquitous. So another way is needed and one doesn't have to look far. One possibility is to establish sites just outside urban areas where customers can lease an appropriate area with services to connect their tracking system to the grid. This has a liquidity advantage in that, unlike rooftop panels, the investment can be onsold or traded without throwing in a house. Common infrastructure for maintenance, security and monitoring via internet offers more advantages.

3 ANALYSES AND TESTS

Analyses were undertaken using ANSYS v.12.0 CFX software with k-ω Sheer Stress Transport (SST) turbulence model. The SST model has better near wall performance than the industrial workhorse k-ϵ model and equivalent performance elsewhere. Rather than relying on absolute results the analysis is comparative in the sense that a reference plate is always modelled in like conditions to that of the DLOOP arrays in order to obtain a relative performance directly, and also to normalize results when the plate's characteristics in the real world conditions being modelled are known.

The analysis' virtual models sit 2 ft above ground in the ABL with wind speed 60 mph at a height of 16 ft. Their envelopes are square of area 117–356 ft^2 and positioned cleanly (i.e. without support structure) in the worst case orientation for wind loading of tracking mechanisms imaginable, i.e. 15° elevation angle (from horizon to sun), and 180° azimuth angle (wind from rear). Each numeric model comprises 2–3 million elements.

Further analysis details are reported in peak professional Australasian wind engineering workshop [2] and fluid mechanics society conference [3] proceedings of 2012.

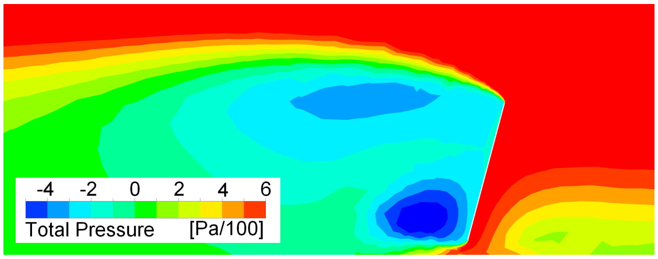

Figure 3: Single plate flow from right ($\text{Re} \approx 13 \times 10^6$).

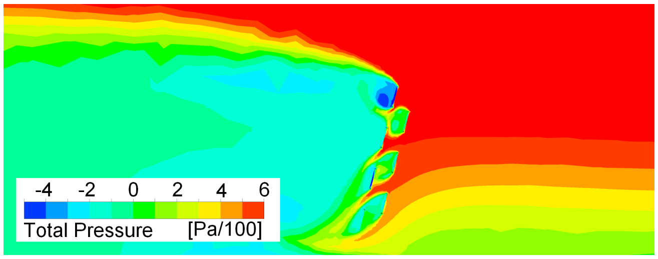

Figure 4: 7×7 array flow from right ($\text{Re} \approx 13 \times 10^6$).

Figures 3 and 4 show aerodynamic pressure from analysis, associated with a virtual slice from top to bottom through the centre of numeric domains, for the large 356 ft^2 reference plate and 7×7 DLOOP array respectively. The figure 4 shows how the DLOOP array works to reduce wind load. The force on panels is their area times the pressure difference across them; e.g. the pressure difference across the plate in figure 3 is, judging by the colors, 800-900 Pa while for the 7×7 array the average pressure difference across its panels is 500–600 Pa. Their *area* × *pressure* difference gives wind force $2\text{–}2\frac{1}{2}$ tons. Having 20–30% less pressure on the same total area, the 7×7 array experiences 20–30% less wind load force. But the figures show more than just numbers, figure 4 shows the 7×7 array builds an intermediate pressure between its front and rear layers which lowers the pressure differentials across both its front and rear layer panels. The reference plate can't do that.

Because of the way they work the distance between DLOOP layers is significant. Figure 5 shows an interpolated analysis drag surface for the 7×7 array, as a percentage of the reference plate's, when Re and *panel-side-length* to *layer-distance* ratio (SDR) are varied. The analysis drag surface slopes down towards the corner having high Re and low SDR. That indicates the 7×7 array works better and better in more and more severe wind conditions, and with layer distances as large as practical. Another important feature of figure 5 to come back to is the drag valley it shows running from SDR = 2 at $\text{Re} = 13 \times 10^6$ to SDR = 1 at $\text{Re} = 7 \times 10^6$.

In figure 6 the same surface as figure 5's is rotated until the Re axis has gone to allow plotting test points having Re's 30 × less. The tests were carried out at the University of Sydney wind tunnel research facility in Australia during 2012 with a reference plate, and 5×5 and 7×7 DLOOP arrays all of composite $\frac{3}{16}$" thick sheet and 20" × 20" frontal area. The tunnel test section is $8 \times 6\frac{1}{2}$ ft^2 and wind speed conditions were 23 mph and 30 mph, the latter being the highest Re condition practical within the facility. The Re difference between analysis and test is not thought critical because: as stated earlier many bodies have constant drag coefficients over extended ranges and flat plates more so than others; and the drag coefficients at the two Re conditions tested were

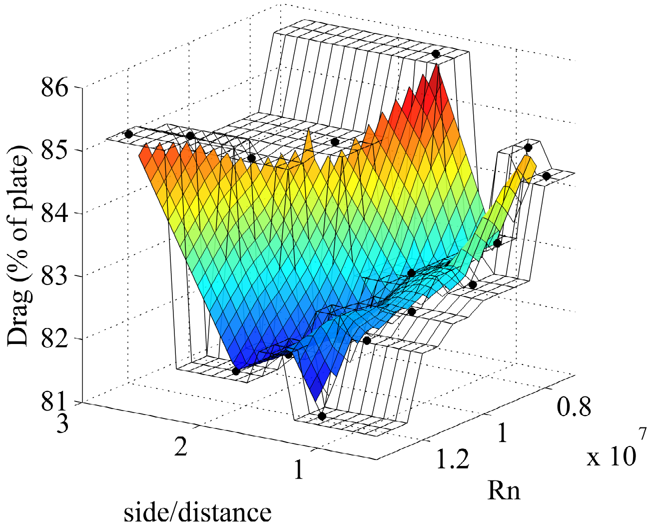

Figure 5: Analysis drag surface for 7×7 Array.

so similar they are plotted in figure 6 as one. More attention needs to be paid to the difference of orientation between analysis and test items: the 15° elevation angle of the analysis isn't in tests and some 0° azimuth angles were tested but not specifically analysed.

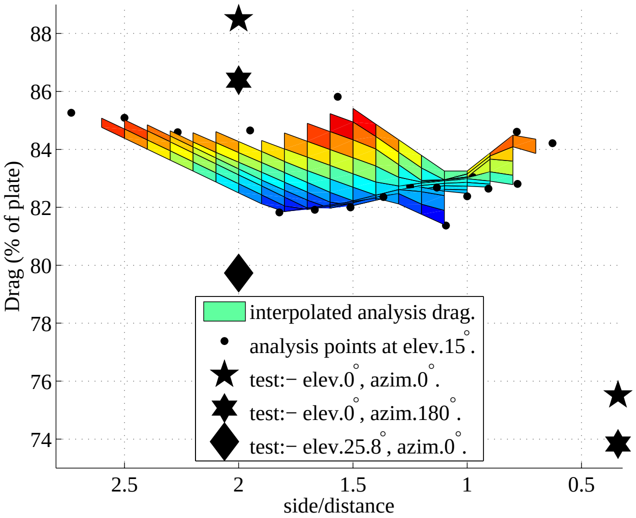

Figure 6: Test points with drag surface for 7×7 Array.

The analysis and test results shown in figure 6 confirm the 7×7 array has significantly less drag than the reference plate in all severe elevation conditions. The tests points show in full frontal winds the drag on the 7×7 array reduced 13% when its SDR was changed from 2 to 0.34, and is in accord with trends observed for this and other arrays in the analysis data set.

Focusing on the figure 6 SDR = 2 data, better and better performance of the 7×7 array relative to the reference plate is shown as elevation angle is increased: at elevation = 0° and azimuth = 180° relative drag = 86% by test; at elevation = 15° and azimuth = 180° relative drag = 83% by analysis; and at elevation = 25.8° and azimuth = 0° relative drag = 79.5% by test again. This contrasts strongly with the drag force (F) on a flat plate which for any angle (ϕ) to the wind given by $-50^\circ < \phi < 50^\circ$ is known not to change in magnitude and be directed *normal* (i.e. perpendicular) to the plate's surface [1, fig.3-29]; e.g. at an angle 15° to the wind the reference plate's force (F) has components $F \cos 15^\circ$ and $F \sin 15^\circ$ in the horizontal and vertical directions respectively. Drag force components of the 7×7 array at elevation $\phi = 15^\circ$ however are $0.83 \times F \cos 15^\circ$ and $0.77 \times F \sin 15^\circ$ in the horizontal and vertical directions respectively, i.e. they may be increased 20% horizontally and 30% vertically before reaching the reference plate's level [2]. That 20% increase in horizontal force could arise from adding 20% more photovoltaic surface to the DLOOP array or, from equation 1, a 10% higher wind speed; either way with the extra charge, the vertical force on the DLOOP array is still 8% lower than on the uncharged reference plate.

Other analysis data relating to 3×3 up to 9×9 DLOOP arrays is reported in references [2] and [3] and is consistent with the trends of the 7×7 array described. As layer-distance drops below the side-length of array constituent panels, which is where practical for solar applications, those DLOOP arrays having the highest panel count came out with the lowest drag.

When comparing drag valleys, the 7×7 arrays' is more pronounced than the 5×5 arrays' and the 9×9 arrays' data is not of adequate resolution to judge. While not minimising drag for the 7×7 array, figure 5 shows a good local minima of 82% relative drag is reached at the short layer distance of 2 ft using big 4 ft by 4 ft panels in 60 mph winds with elevation angle 15°. This is of interest because there is a significant layer distance step for the system to integrate before still lower drags can be seen, and the value of that depends on many system details associated with high inclination dawn (or equally dusk) operations and constraints.

4 CONCLUSIONS

Analysis and test results have been presented to:

- explain the increased efficiency of the DLOOP subclass of new structures, generally described as having overlapping layers of non overlapping panels, for solar tracking systems; and
- show tracking mechanisms adopting 7×7 DLOOP structures can aim to increase photovoltaic carrying capacity by 20% and lighten their foundations by 8% without change to wind specification.

Higher efficiency is expected from 9×9 structures but customization of high performance solar panels is needed to halve their cell counts because catalogue items are all so big 9×9 arrays using them appear too large to.

Other advantages of the new structures are possible and promising from: looking at stress levels and performance of photovoltaic cells cooled by the structure's characteristic venting; and the use of panel backshells to improve balance and stability of tracking mechanisms.

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