DuraMAT
Durable Module Materials Consortium

Accelerating a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035.

NREL/PO-2C00-89033

# Predicting Instability and the Effect of Wind Loading on Single-Axis Trackers

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Multi-Scale, Multi-Physics Model

**Awarded FY22 Core Modelling Call**

**Period of Performance: FY23-FY24**
**Funding: $800K**

## Contributing to DuraMAT Consortium Goals

We are developing computational tools and case studies to reduce the destructive effects of wind loading on PV panels and in turn minimize degradation effects that can worsen cell cracking and reduce performance over the lifetime of the module. We will identify the exact mechanism(s) by which wind loading leads to the deterioration of modules (e.g., vortex shedding, array layout) to inform design and operation guidelines to reduce degradation and avoid the most damaging phenomena associated with wind loading in PV arrays.

## Project Overview

As PV modules continue to trend toward larger, thinner, and more flexible forms they grow more susceptible to damage from dynamic wind loading. As a result, understanding the impact of wind on PV systems, particularly when mounted on solar-tracking hardware, and identifying robust, stable array layouts and stow strategies is becoming increasingly important for the PV community. We are developing **PVade (PV Aerodynamic Design Engineering)**[1], an open-source, fluid-structure interaction (FSI) software to predict **unsteady PV loading and dynamic instability due to wind**. This software will enable researchers to test hardware, layout, and tracker control changes, leading to enhanced stability, optimized stow strategies, and a reduction in wind-driven damage.

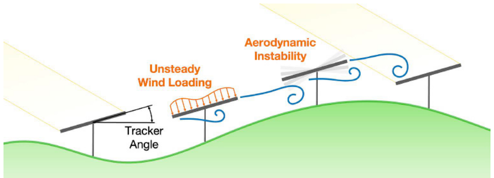



**Figure 1**: Wind loading combined with terrain and buffeting from upstream wakes can lead to fluttering and instability of panels, particularly when mounted on compliant, solar-tracking hardware.

## Verification

### Problem Definition

To verify the convergence and scaling of our fluid, structure, and FSI coupling algorithm, we chose the **classical 2D flag benchmark problem** outlined by Turek and Hron[6]. They define a channel flow problem in which fluid interacts with a structure defined by a rigid cylinder (flagpole) and an attached flexible beam (flag), where a strong oscillatory flapping emerges over time. We present the results of this FSI benchmark below.

### Results

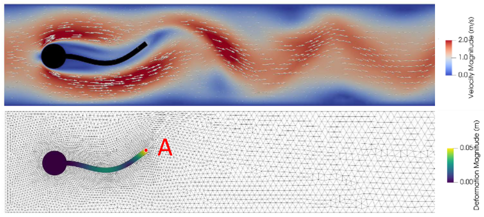



**Figure 3**: (top) a snapshot of the fluid responding to and driving the actively-flapping flag colored by velocity, arrows indicate flow direction, (bottom) the deformation in the structure and the adaptation induced in the surrounding fluid mesh.

| | $w_x$ of A ($\times 10^{-3}$) | $w_y$ of A ($\times 10^{-3}$) | Lift | Drag |
|---|---|---|---|---|
| PVade | -14.78 ± 13.23 | 1.28 ± 80.62 | 204.81 ± 69.60 | 1.78 ± 232.1 |
| Turek and Hron | -14.58 ± 12.44 | 1.23 ± 80.6 | 208.83 ± 73.75 | 0.88 ± 234.2 |
| Error (%) | 1.3 ± 6.4 | 4.5 ± 0.0 | -1.9 ± -5.6 | 102.3 ± -0.9 |

**Table 1**: The x- and y-displacement of the flag tip, A, and the integrated lift and drag along the flag and flagpole, reported as **average ± amplitude** and measured after steady-state oscillations begin.

## Outcome and Impact

We have released an open-source FSI tool for PV systems, PVade. The fundamental **fluid, structure, and coupled FSI solves have been verified** individually and in aggregate using canonical problems from FSI literature. We have begun the process of validating our models using experimental data, and although results are preliminary, we show reasonably good qualitative and quantitative agreement to a real single-axis tracking system. PVade is already being used to support studies with **two industry partners enabled via voucher programs** including applications with novel agrivoltaics hardware and floating installations.

## Methodology

PVade is scalable from desktop to high-performance computing hardware with no modification. It makes extensive use of the DOLFINx and Gmsh packages[2,3] and enables easy PV-system problem definitions via yaml input files.

### Fluid Solver

We employ a fractional step method to numerically solve the **arbitrary Lagrangian-Eulerian (ALE)[4] incompressible Navier-Stokes equations**

$$\rho\left(\frac{d\boldsymbol{u}}{dt} + (\boldsymbol{u} - \hat{\boldsymbol{u}})\cdot\nabla\boldsymbol{u}\right) = \mu\nabla^2\boldsymbol{u} - \nabla P$$

$$\nabla\cdot\boldsymbol{u} = 0$$

### Structure Solver

The response of the structure is obtained by solving the **equilibrium equation**

$$\nabla\cdot\boldsymbol{\sigma} + \rho_s\boldsymbol{b} = \rho_s\frac{d^2\boldsymbol{w}}{dt^2}$$

### FSI Coupling

PVade uses a ***partitioned* FSI** coupling in which fluid and structure are solved separately and coupled through boundary conditions:

- Fluid induces stress on the structure surface
- Structure deforms, moves, and redirects fluid

To avoid a computationally expensive inner-loop iteration to converge these two separate solves, PVade uses a version of a predictor-corrector coupling[5]

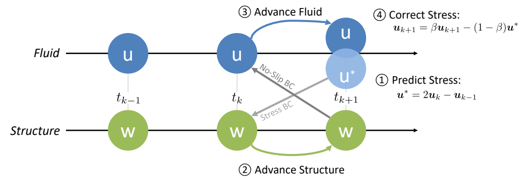


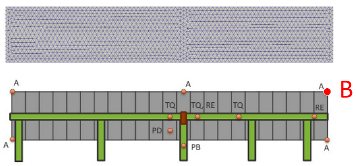

**Figure 2**: PVade's FSI algorithm, to advance from timestep *k* to *k+1*: (1) predict (extrapolate) the hydrodynamic stress using the last two states, (2) advance structure from *k* to *k+1* using this prediction, (3) advance fluid from *k* to *k+1* using the *k+1* structural boundary conditions, and (4) correct the predicted stress with the true stress.

## Case Study

### Definition

To test PVade on a real PV system, we rely on **data from a DuraMAT 1 project** that instrumented a single-axis tracking system at the NREL Flatirons Campus[7].

In our representation (top) we model the entire system with simplified geometry relative to the actual hardware (bottom). The single-axis tracking system is approximated with a rotational degree of freedom along the fictitious torque tube and fixed rotation at the tracker drive.




### Results

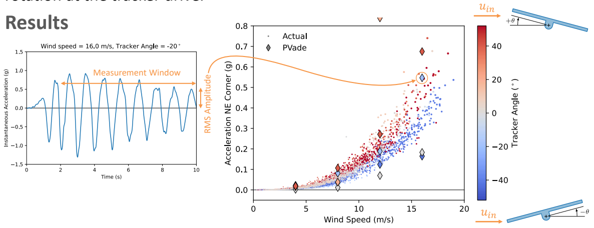



**Figure 4**: (left) The acceleration predicted by PVade at the NE corner, B, as a function of time, (right) the RMS amplitude of PVade's simulated accelerations (◇) overlaid on the amplitude of the *actual* accelerations measured at B when inflow direction was 270±15^o (·); as wind speed increases, acceleration increases exponentially, with positive tracking angles experiencing larger accelerations than their negative tracking angle counterparts.

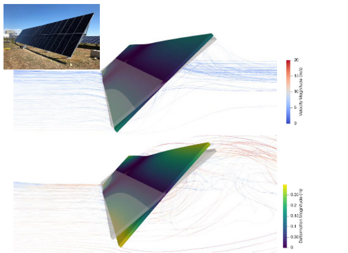


**Figure 5**: Snapshots of deflection cycle start-up for a panel oriented at − 40° in 12m/s (27 mph) wind; streamlines colored by local wind speed, panel by deflection magnitude with undeformed position shown in gray.

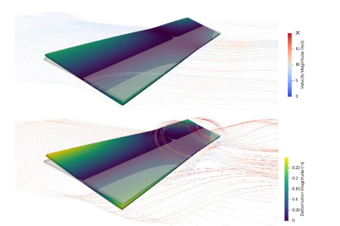


**Figure 6**: Snapshots of deflection cycle start-up for a panel oriented at +20° in 12m/s (27 mph) wind; streamlines colored by local wind speed, panel by deflection magnitude with undeformed position shown in gray.

## Future Work

During the remainder of this project, we will focus on digging deeper into the experimental validation across multiple metrics, implementing higher-fidelity, heterogeneous structural representations, and fine-tuning our material properties. We will also focus on two new features: thermal and heat transfer effects and complex, site-specific terrain.

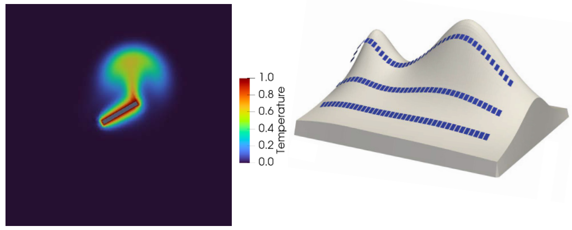



**Figure 7**: Work planned for remainder of project: (left) the addition of thermal effects enables critical buoyancy-driven phenomena and predictions of panel cooling, (right) the interaction of wind, panels, and (extreme) complex terrain will allow us to predict site-specific stow and stability strategies.

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