DuraMAT
Durable Module Materials Consortium

A simulation and optimization framework for managing wind-driven loading on PV systems

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Motivation

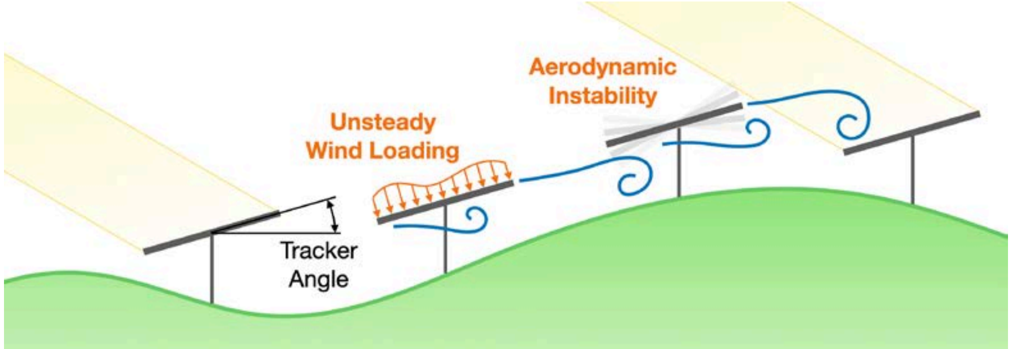
Wind loads are an important design consideration for solar tracking PV arrays:

- Higher wind speeds can initiate unsteady aerodynamic instabilities (galloping) which can **initialize cracks** and/or **destroy sections of the array.**
- Moderate wind loads create unsteady, reversing that lead to the **worsening of existing cell cracks** over time.

1. E. Wesoff, "Trackers in wind and the terror of torsional galloping", PV Magazine, Jan 2020
2. T. Sylvia, "Trackers vs. the elements, part one: tackling uneven terrain", PV Magazine, May 2022

Motivation

Complicating factors:
- Varying wind speeds/conditions
- Terrain and array geometry
- Non-universal stow strategies



Goal: Understanding the **fluid-structure interaction (FSI)** driving this instability can *improve high-wind stow strategies* and *inform stabilizing layout and hardware design*.

Approach: PVade Framework

PV Aerodynamic Design Engineering (PVade)

- Python package the makes extensive use of the open-source finite element package FEniCSx[3]
- Focus on enabling both laptop and HPC-level simulations
- Input files and command line interface for user input
- **Meshing and solution algorithm handled without significant user involvement**

```
domain:
  x_min: -20
  x_max: 100
  y_min: -30
  y_max: 30
  l_char: 4
pv_array:
  stream_rows: 3
  stream_spacing: 7.0
  span_rows: 3
  span_spacing: 12.0
  elevation: 1.5
  panel_chord: 2.0
  panel_span: 7.0
  panel_thickness: 0.04
  tracker_angle: 0
```

Example input file, array options easily accessible

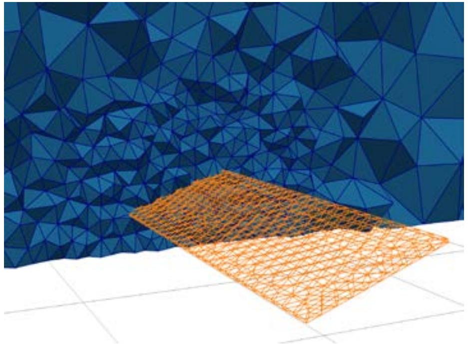
3. Wells, G. N., Ballarin, F., Baratta, I. A., Dean, J. P., Dokken, J. S., Hale, J. S., Habera, M., Richardson, C. N., Scroggs, M. W., & Sime, N. (2021). DOLFINx: Next generation FEniCS problem solving environment. https://github.com/FEniCS/dolfinx

Approach: Fluid & Structure Solution

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

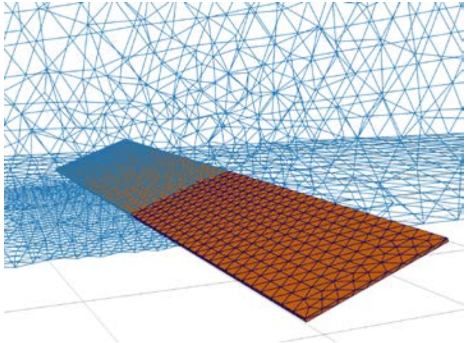
$$\rho\left(\frac{d\boldsymbol{u}}{dt} + (\boldsymbol{u} - \hat{\boldsymbol{u}}) \cdot \nabla\boldsymbol{u}\right) = \mu\nabla^2\boldsymbol{u} - \nabla P$$

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



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

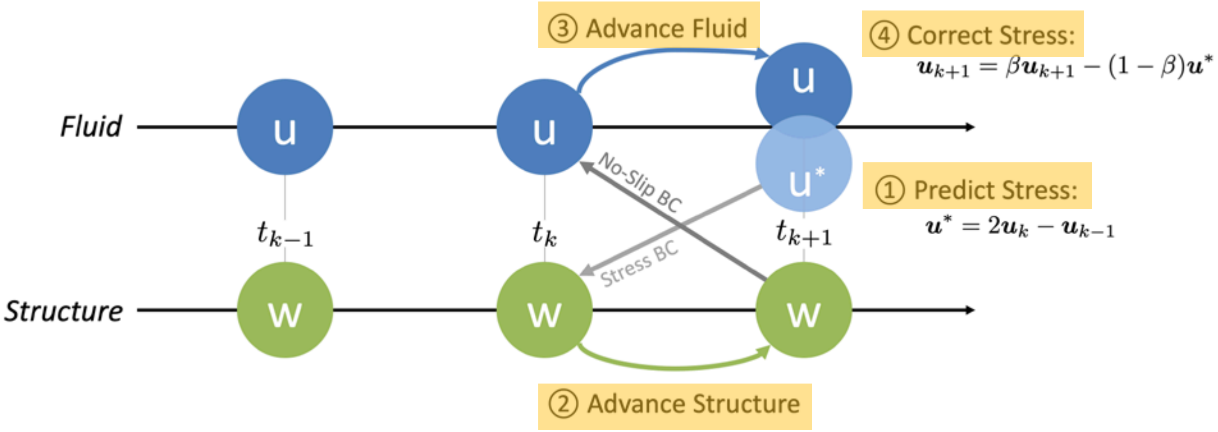
$$\nabla \cdot \boldsymbol{\sigma} + \rho_s\boldsymbol{b} = \rho_s\frac{d^2\boldsymbol{w}}{dt^2}$$



Approach: FSI Coupling

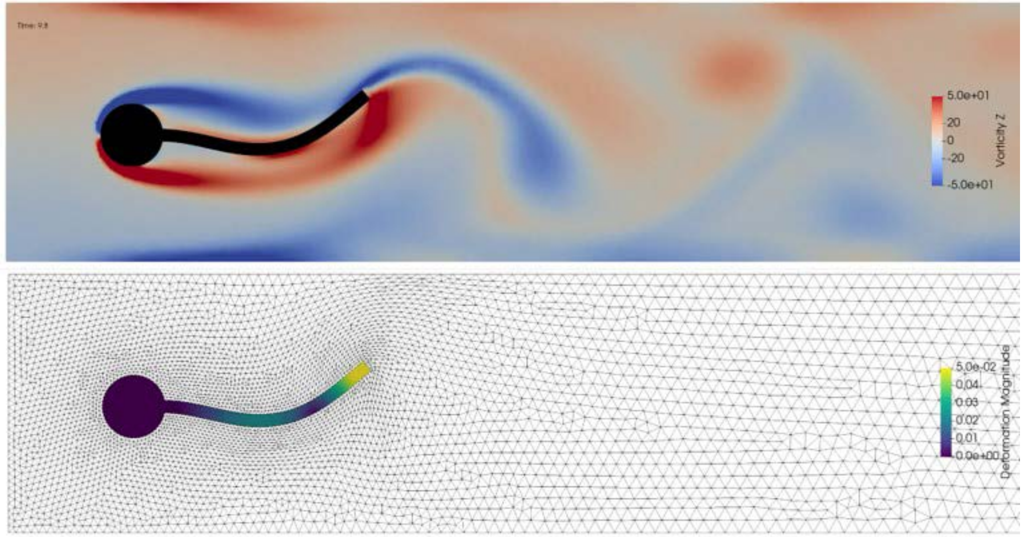
PVade uses a **partitioned FSI** coupling in which fluid and structure are solved separately and coupled through boundary conditions:

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



Approach: Numerical Validation

- To validate our physics and FSI coupling, we chose the **classical 2D flag benchmark problem** outlined by **Turek and Hron**[4]
- PVade shows excellent agreement, <5% error, for all metrics, many <2%



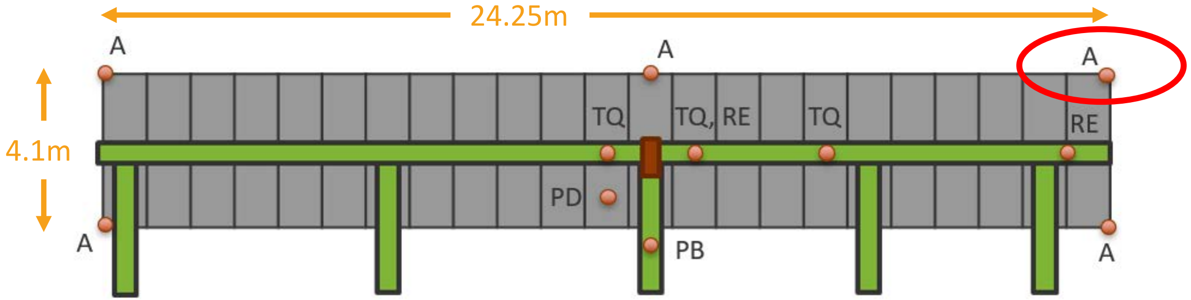
4. S. Turek and J. Hron, "Proposal for Numerical Benchmarking of Fluid–Structure Interaction Between an Elastic Object and Laminar Incompressible Flow," in Fluid-Structure Interaction: Modelling, Simulation, Optimisation, 2007, doi.org/10.1007/3-540-34596-5_15

Progress and Outcomes: Single Row Validation

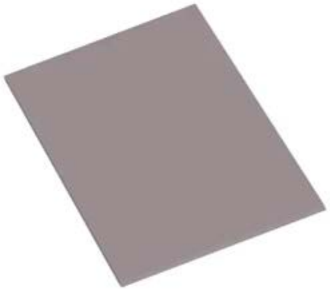
To validate PVade on a more realistic problem, we rely on measurements from the **DuraMAT 1 Solar-Tracking Array project**.

- A: Accelerometer
- PB: Pier bending
- PD: Panel displacement
- TQ: Torque tube

Photo and illustration credit: Scott Dana and Chris Ivanov

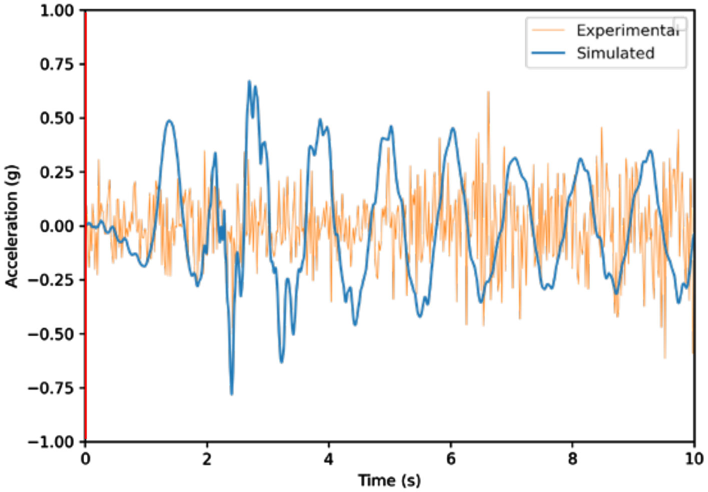


Progress and Outcomes: Single Row Comparison

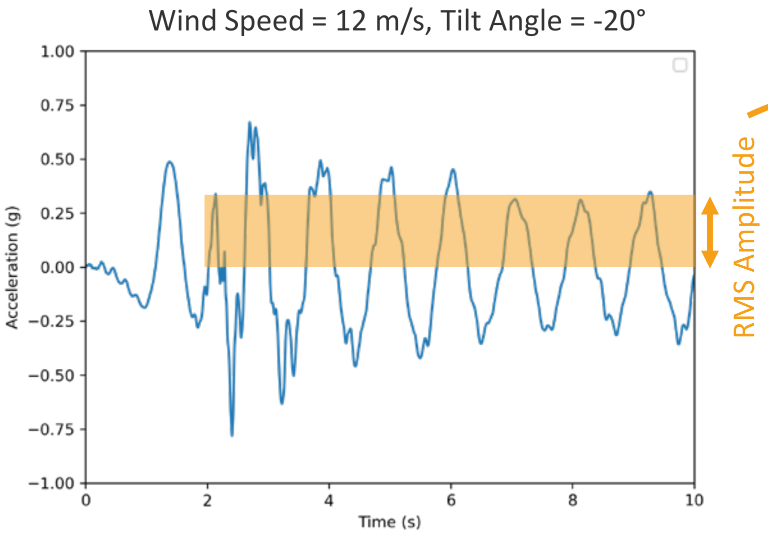


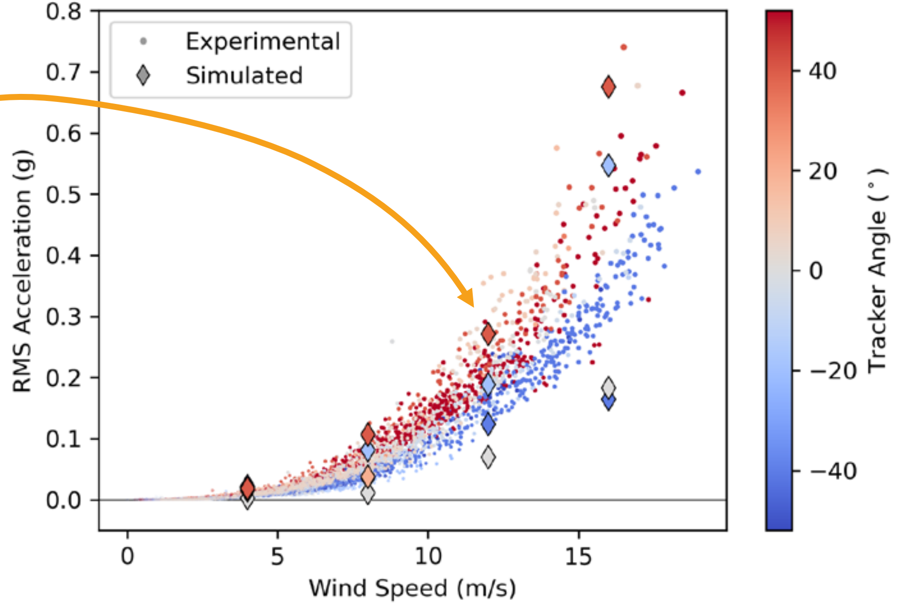
Acceleration measured at NE corner

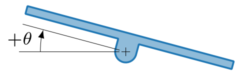
Wind Speed = 12 m/s, Tilt Angle = -20°

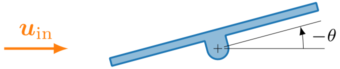


Progress and Outcomes: Acceleration Magnitudes





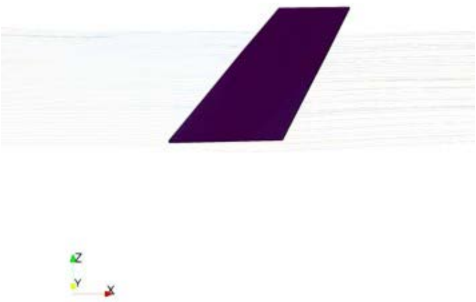




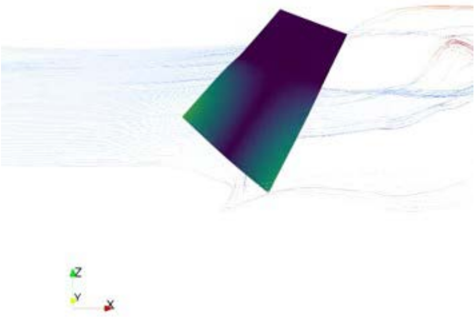
Progress and Outcomes: Effect of Tilt Angle

Both the experimental data and simulations agree:
larger accelerations are associated with positive tilt angles

Wind Speed = 16 m/s,
Tilt Angle = -20°



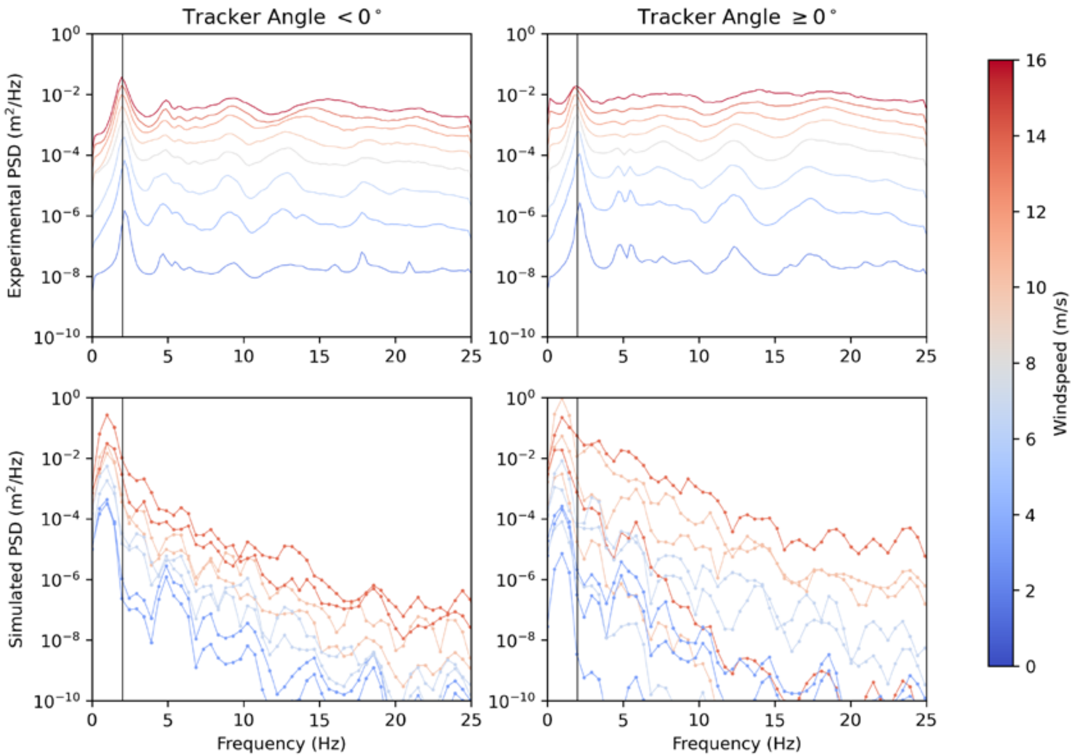
Wind Speed = 16 m/s,
Tilt Angle = 0°



Wind Speed = 16 m/s,
Tilt Angle = 20°

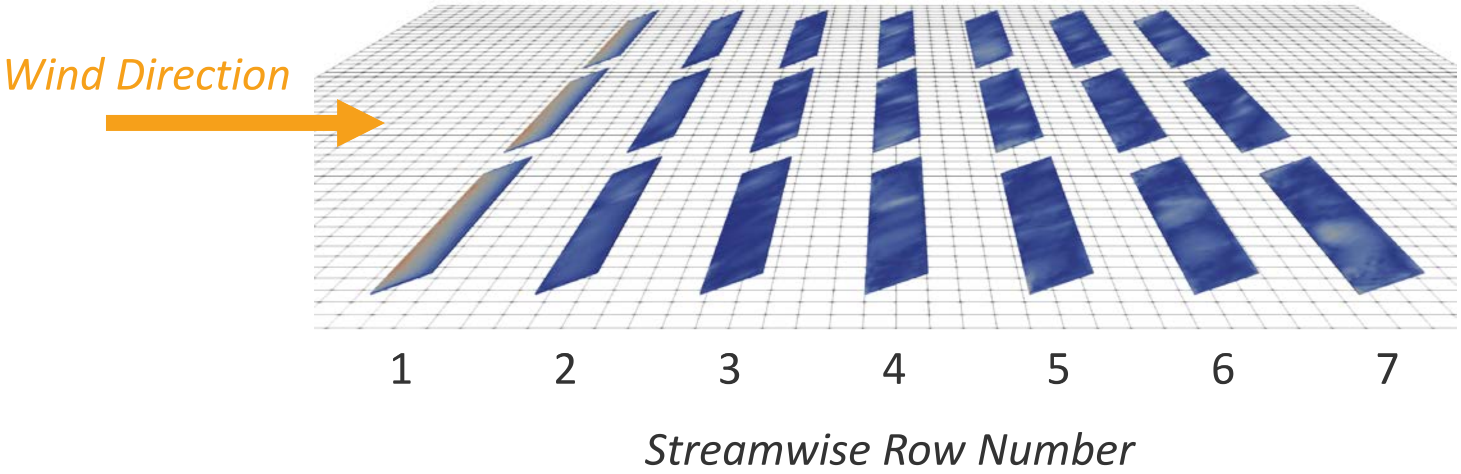
Progress and Outcomes: Frequency Response

- Both the experimental and simulated **power spectral density (PSD)** exhibit a **peak at ~2 Hz**.
- Significantly less high-frequency content in simulated results.



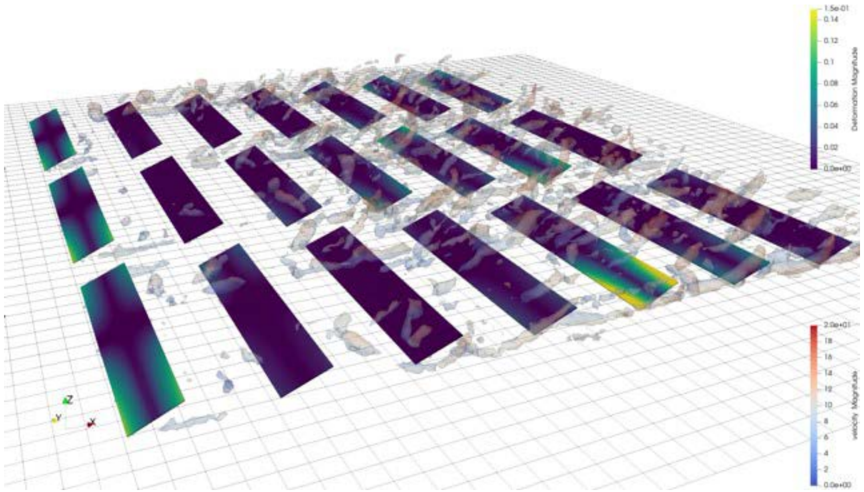
Progress and Outcomes: Multi-Row Effects

Using our calibrated single-row definitions, we carry out multi-row studies to determine how the FSI-to-tracking-angle relationship **propagates and stabilizes/destabilizes an array**.

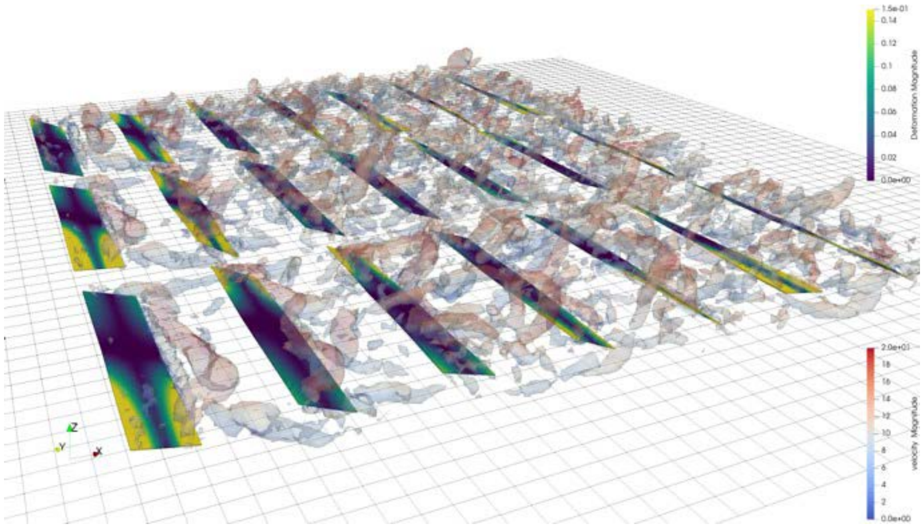


Progress and Outcomes: Multi-Row Effects

As was seen in the single row case, **negative tilt angles experience less acceleration** due to generating a less turbulent flow state

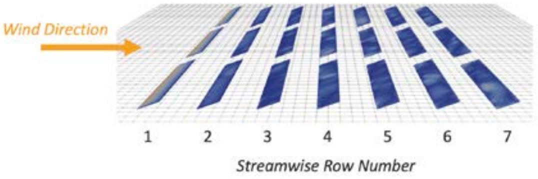


Wind Speed = 12 m/s,
Tilt Angle = -20°

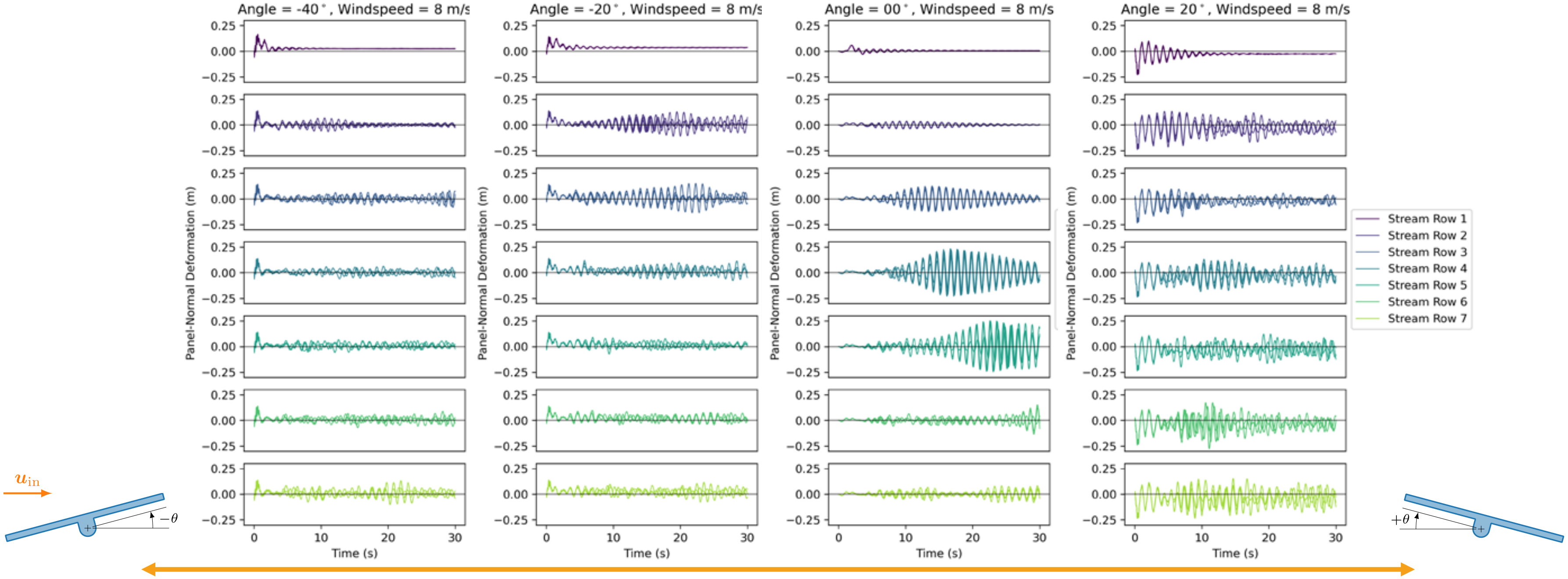


Wind Speed = 12 m/s,
Tilt Angle = 20°

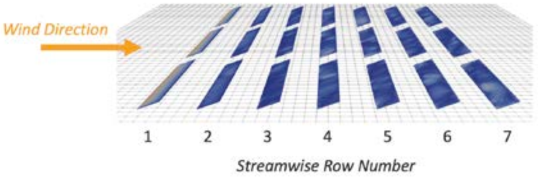
Progress and Outcomes: Multi-Row Deformation at 8 m/s



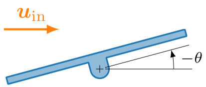
Negative tilt angles experience less deformation

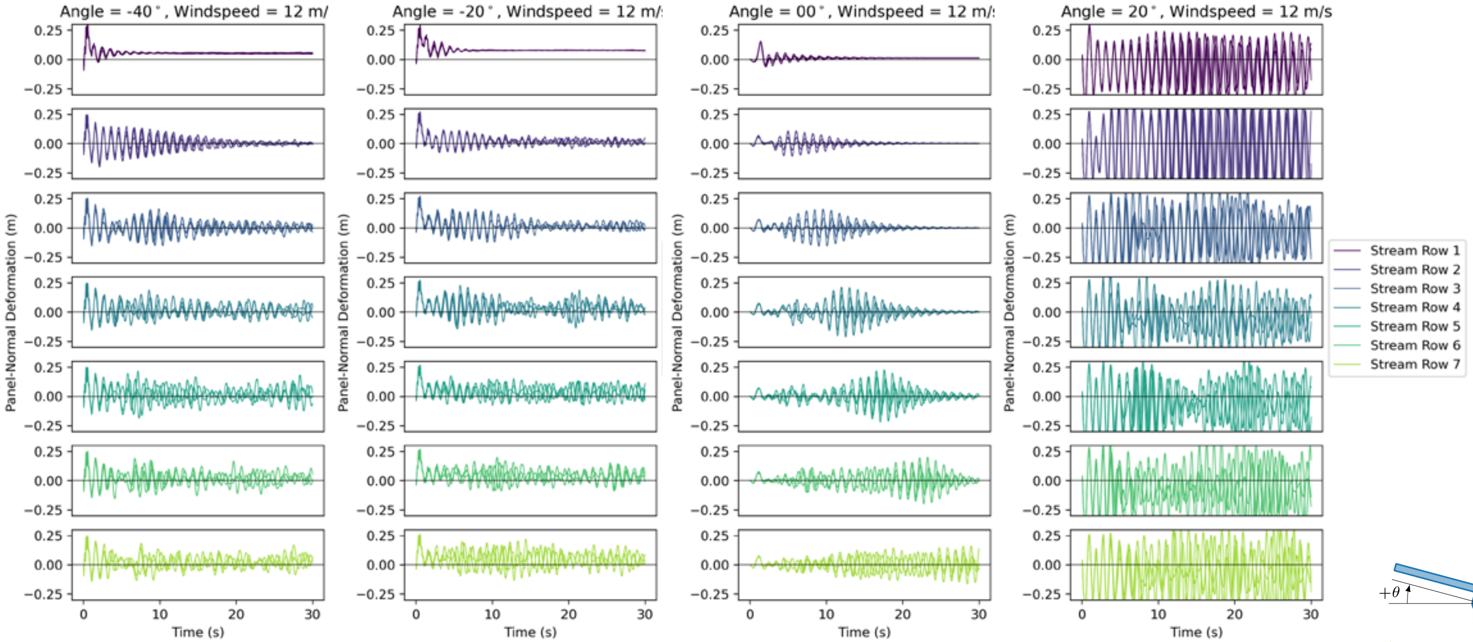


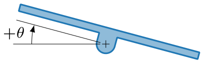
Progress and Outcomes: Multi-Row Deformation at 12 m/s



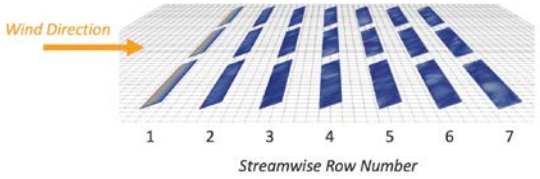
Smaller tilt angles are less predictable



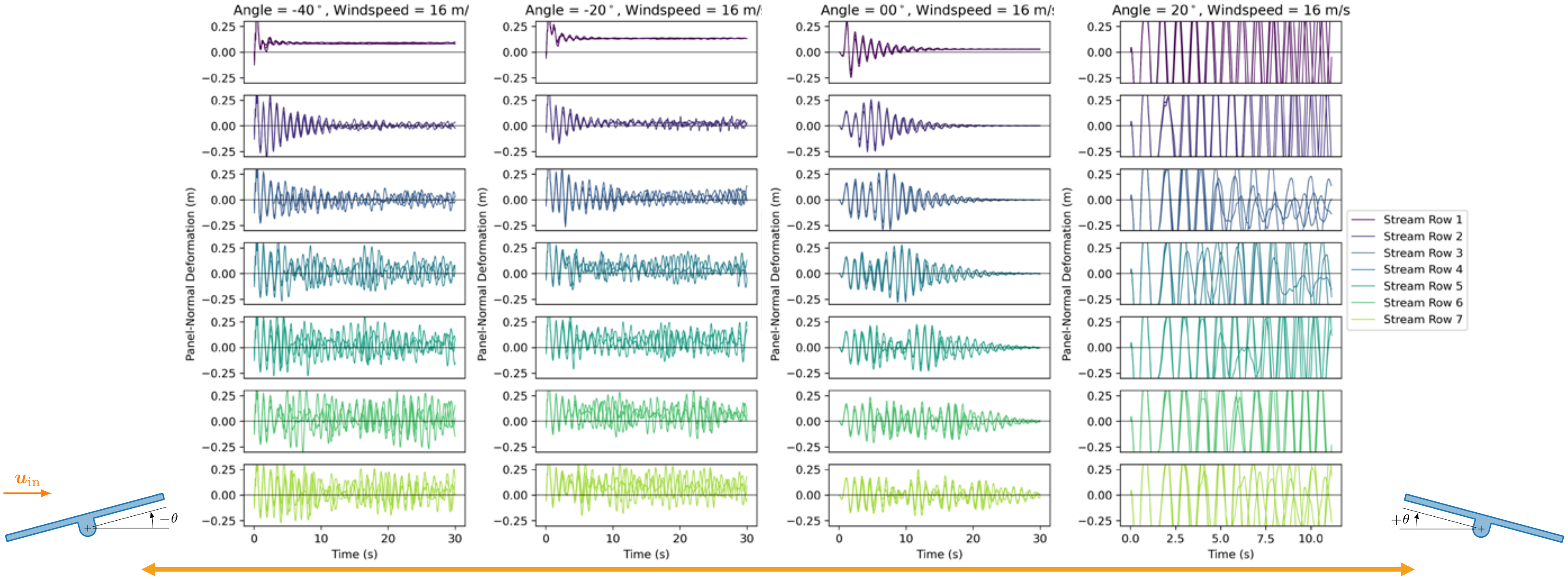




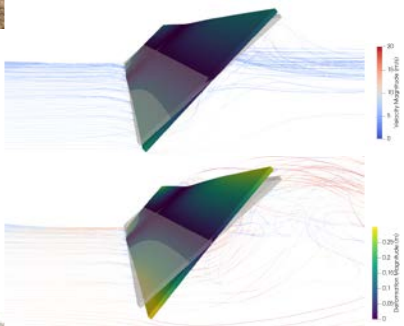
Progress and Outcomes: Multi-Row Deformation at 16 m/s



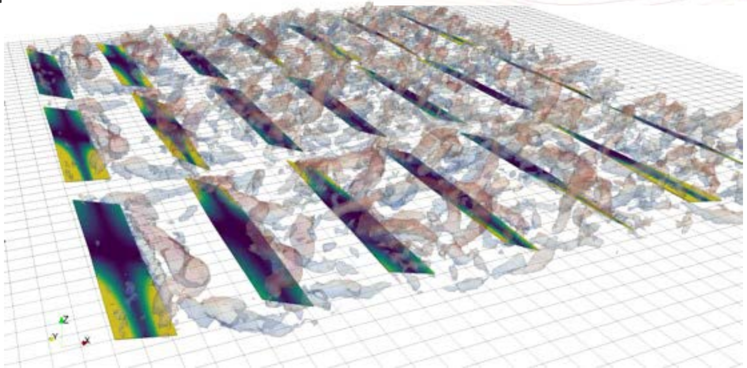
Larger wind speeds generate more deformation



Concluding Remarks



- We have developed an open-source solver to predict the effect of unsteady wind loading on single-axis tracking PV systems.
- ***FY24 At a Glance:***
  - **Verification of FSI algorithm** on canonical problem
  - **Preliminary validation on single-row PV tracking setup**
  - **Multi-row study at different tracking angles**, row spacings, to identify stability regions
  - Find optimal stow strategies for high wind using non-uniform tilt angles
- ***FY25 Goals:***
  - ***Add turbulent inflow option***
  - More detailed structural properties
  - Implement site-specific terrain
  - Temperature driven flow effects



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Thank You

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