DuraMAT

Durable Module Materials Consortium

Simulating wind-driven loading on PV systems

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DuraMAT Webinar

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U.S. DEPARTMENT OF ENERGY | NREL | Sandia National Laboratories | BERKELEY LAB

Motivation

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

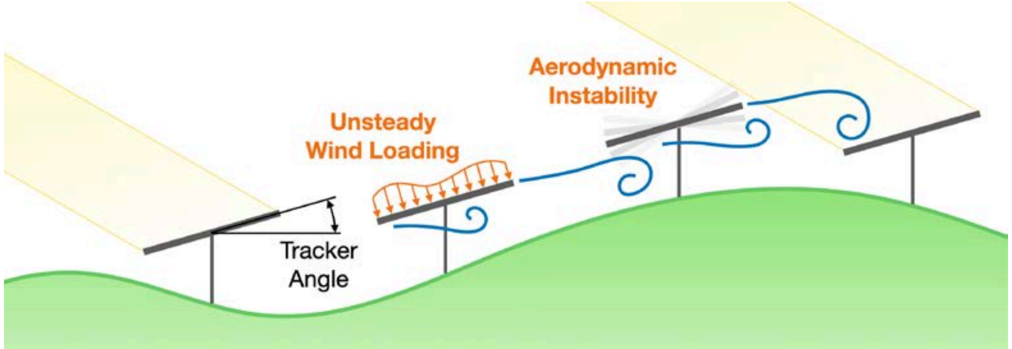
- Higher wind speeds can initiate unsteady aerodynamic instabilities (galloping) which can **initialize cracks** and/or **destroy sections of the array.**
- Moderate wind loads create unsteady, reversing that lead to the **worsening of existing cell cracks** over time.

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
```

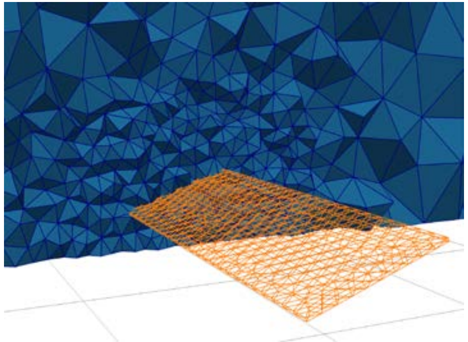
Example input file highlighting the ease of specifying array size and panel dimension

PVade Project

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

Fluid

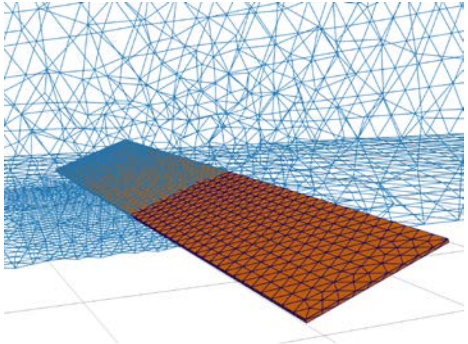


We employ a fractional step method to numerically solve the **arbitrary Lagrangian-Eulerian (ALE) incompressible Navier-Stokes equations**

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

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

Structure



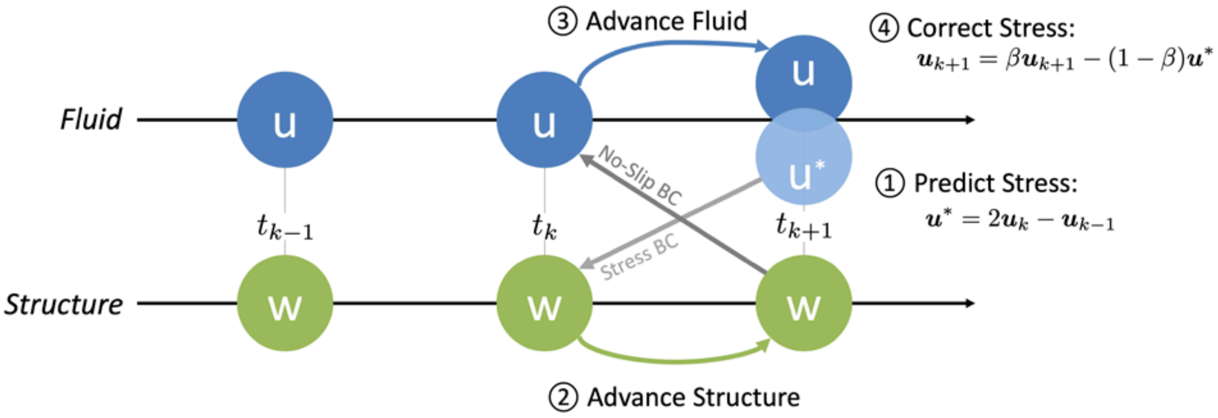
The response of the structure is obtained by solving the **equilibrium equation**

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

Approach: Fluid-Structure Coupling

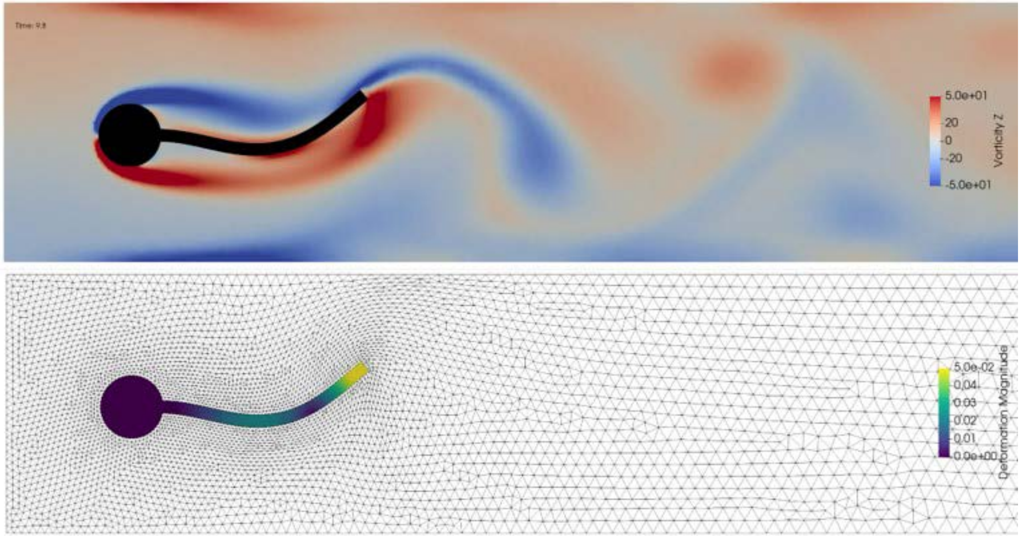
PVade uses a **partitioned FSI** coupling in which fluid and structure are solved separately and coupled through boundary conditions:

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



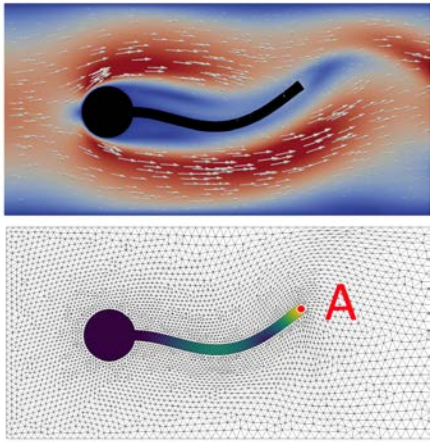
Approach: Numerical Validation

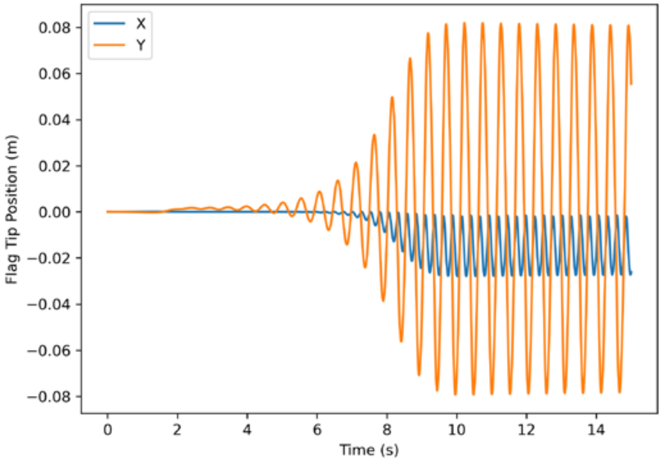
- To validate our physics and FSI coupling, we chose the **classical 2D flag benchmark problem** outlined by **Turek and Hron**[4]
- PVade shows excellent agreement, <5% error, for all metrics, many <2%

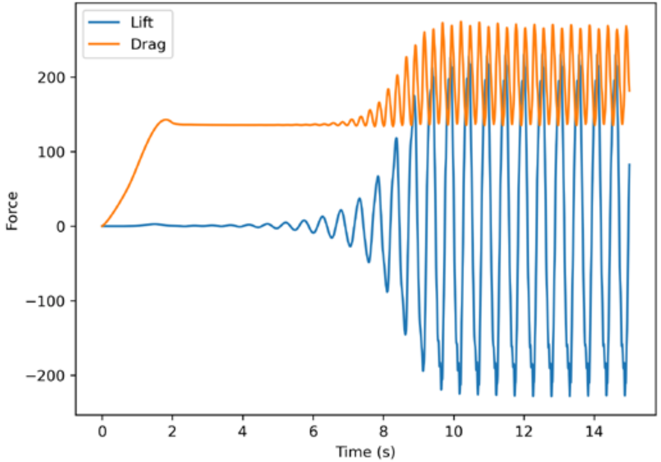


4. S. Turek and J. Hron, "Proposal for Numerical Benchmarking of Fluid–Structure Interaction Between an Elastic Object and Laminar Incompressible Flow," in Fluid-Structure Interaction: Modelling, Simulation, Optimisation, 2007, doi.org/10.1007/3-540-34596-5_15

Approach: Numerical Validation







	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

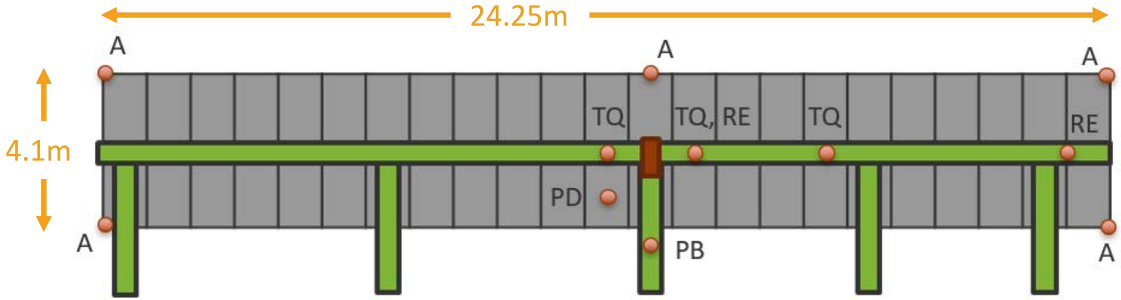
Single Row Validation

Progress and Outcomes: Single Row Validation

Photo and illustration credit: Scott Dana and Chris Ivanov

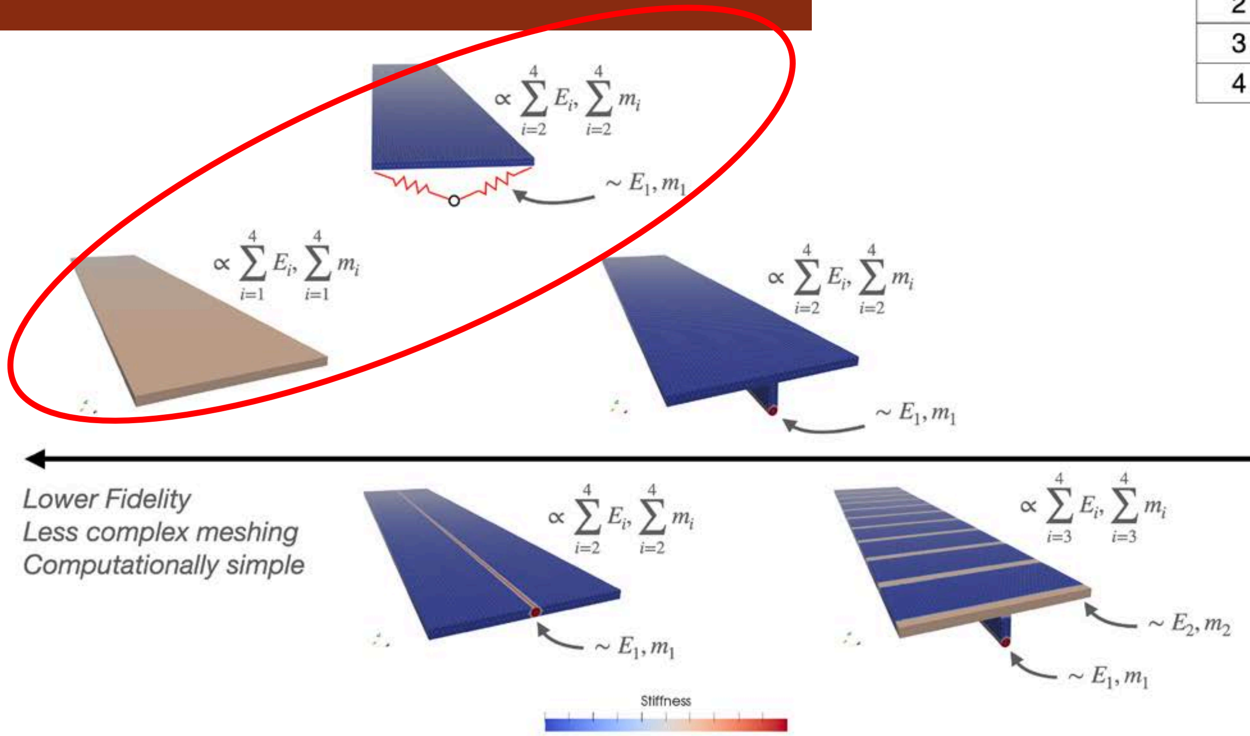
To validate PVade on a more realistic problem, we rely on measurements from the **DuraMAT 1 Solar-Tracking Array project**.

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



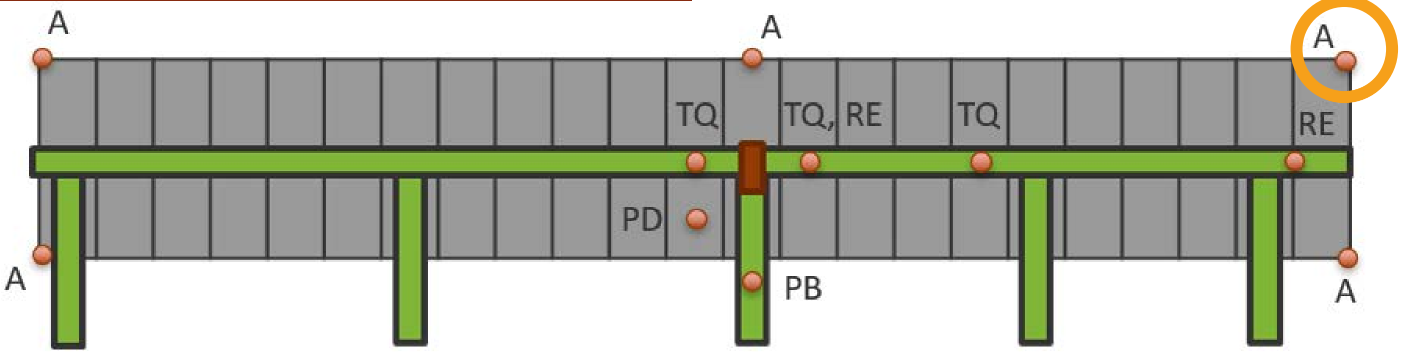
Progress and Outcomes: Single Row Setup

ID	Component
1	Torque tube
2	Rails, purlins
3	Frame
4	Module

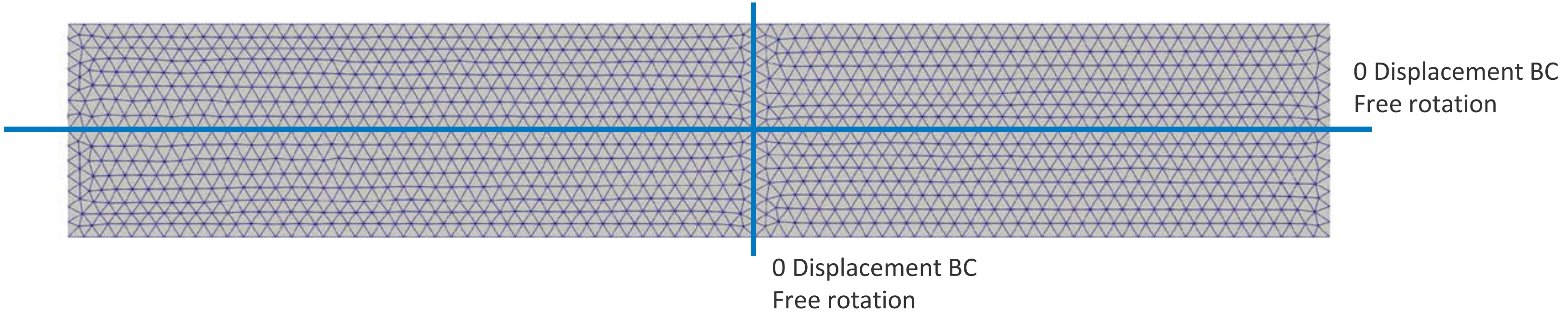


Progress and Outcomes: Single Row Setup

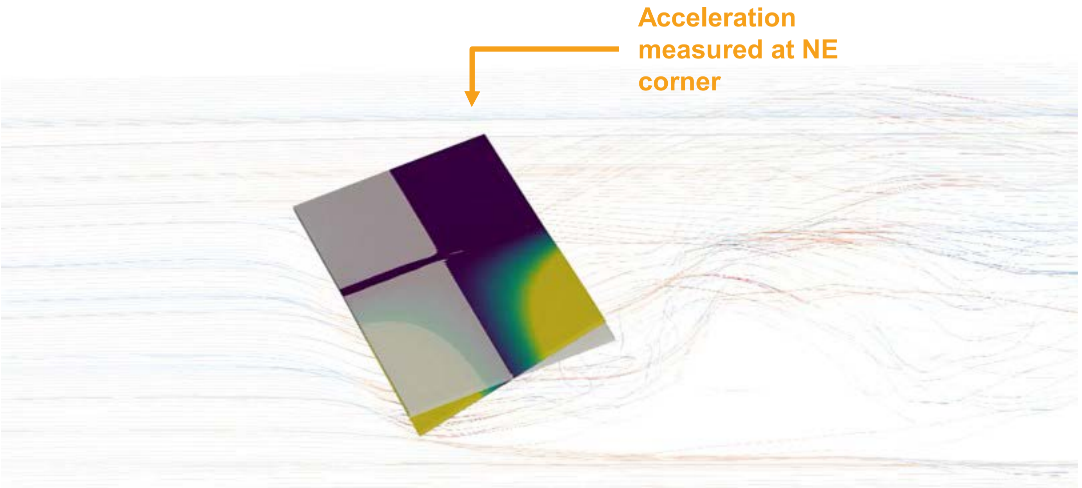
Experimental

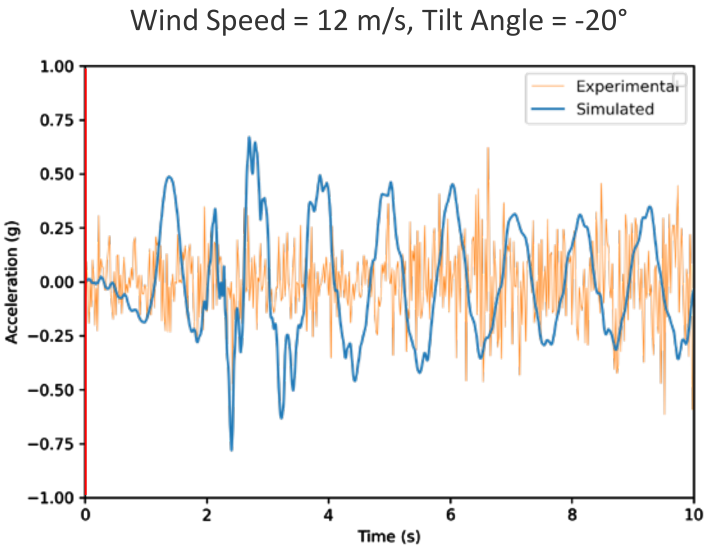


Modeled

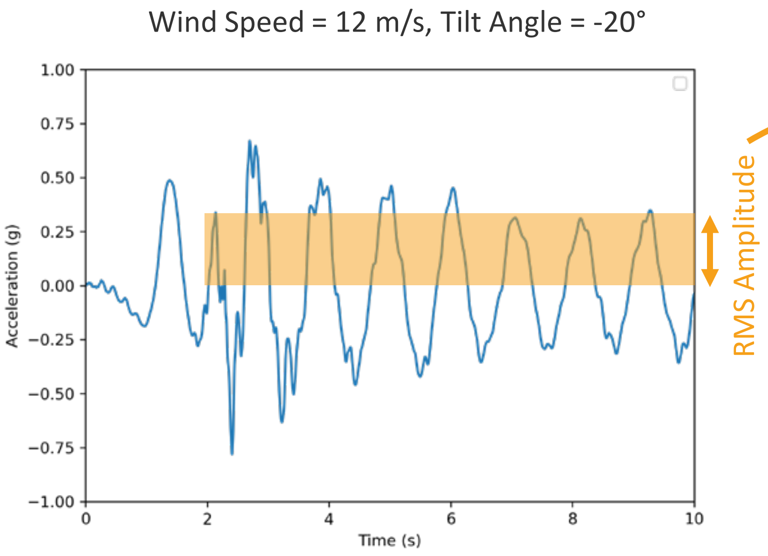


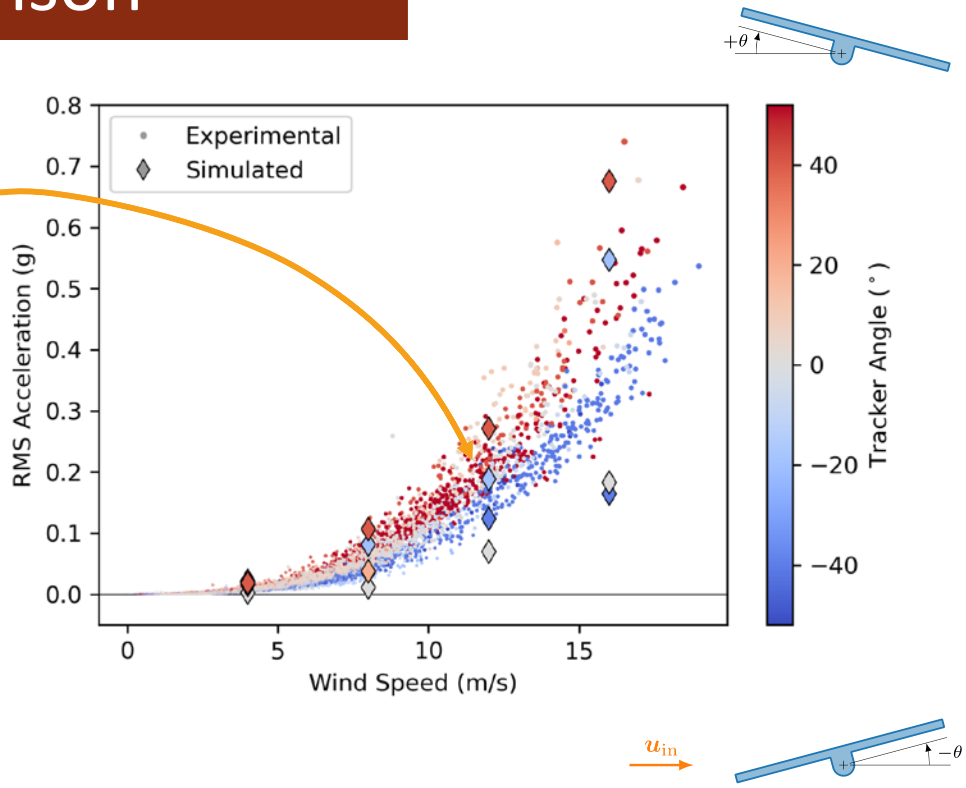
Progress and Outcomes: Time Series Comparison





Progress and Outcomes: Statistical Comparison



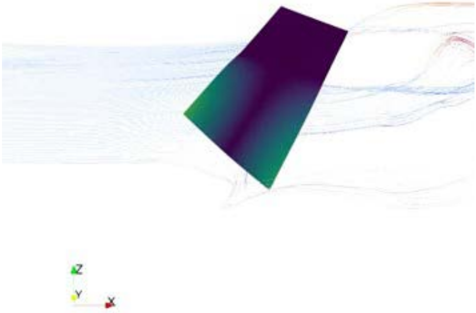


Progress and Outcomes: Effect of Tilt Angle

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

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

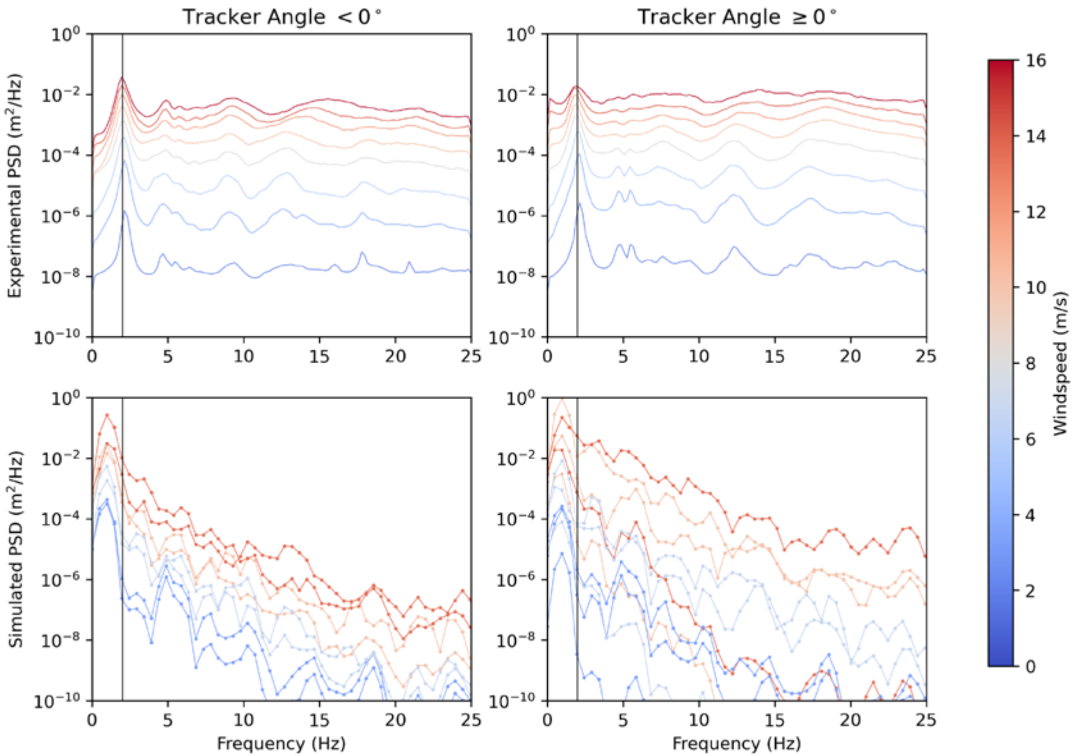
Wind Speed = 16 m/s,
Tilt Angle = 0°



Wind Speed = 16 m/s,
Tilt Angle = 20°

Progress and Outcomes: Frequency Comparison

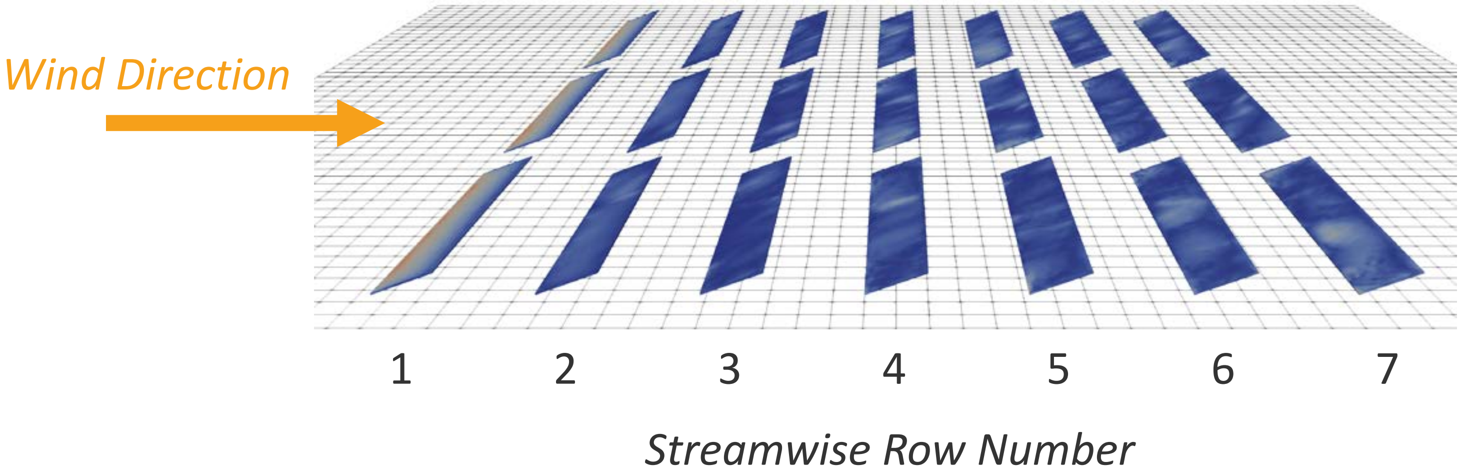
- Both the experimental and simulated **power spectral density (PSD)** exhibit a **peak at ~2 Hz**.
- Significantly less high-frequency content in simulated results.



Multi-Row Effects

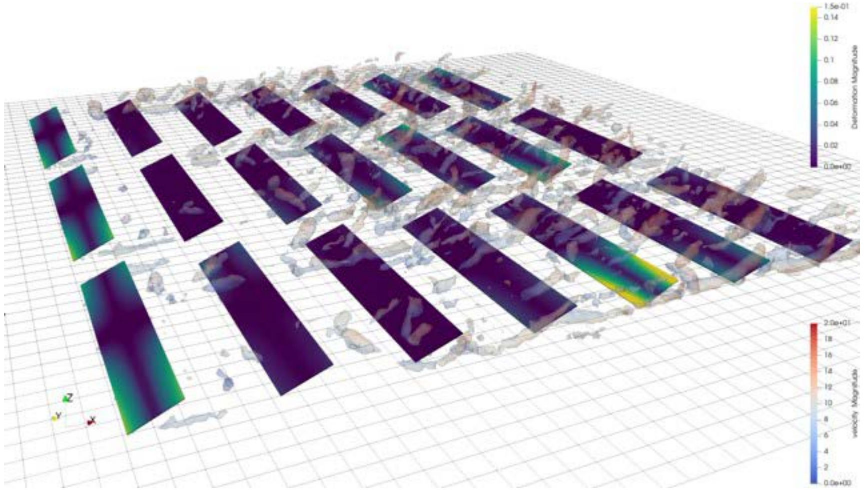
Progress and Outcomes: Multi-Row Effects

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**.

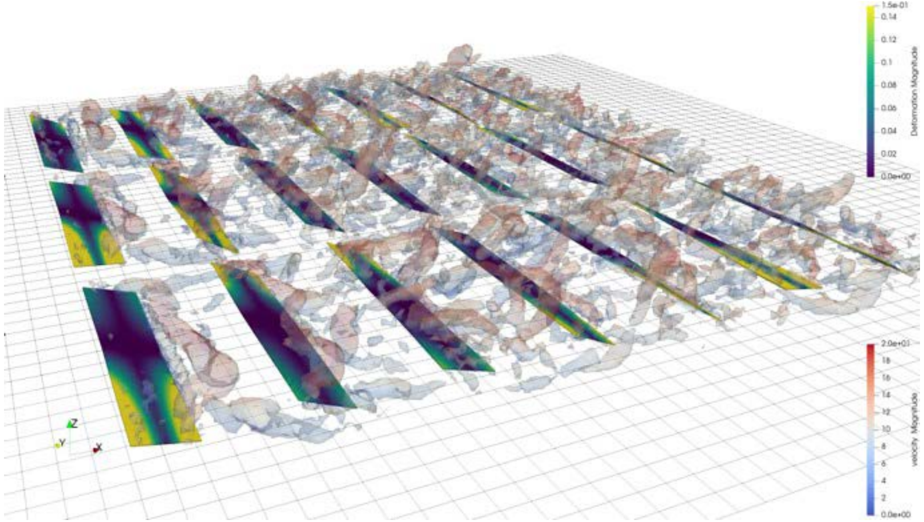


Progress and Outcomes: Multi-Row Effects

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

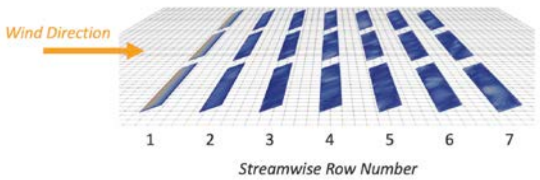


Wind Speed = 12 m/s,
Tilt Angle = -20°

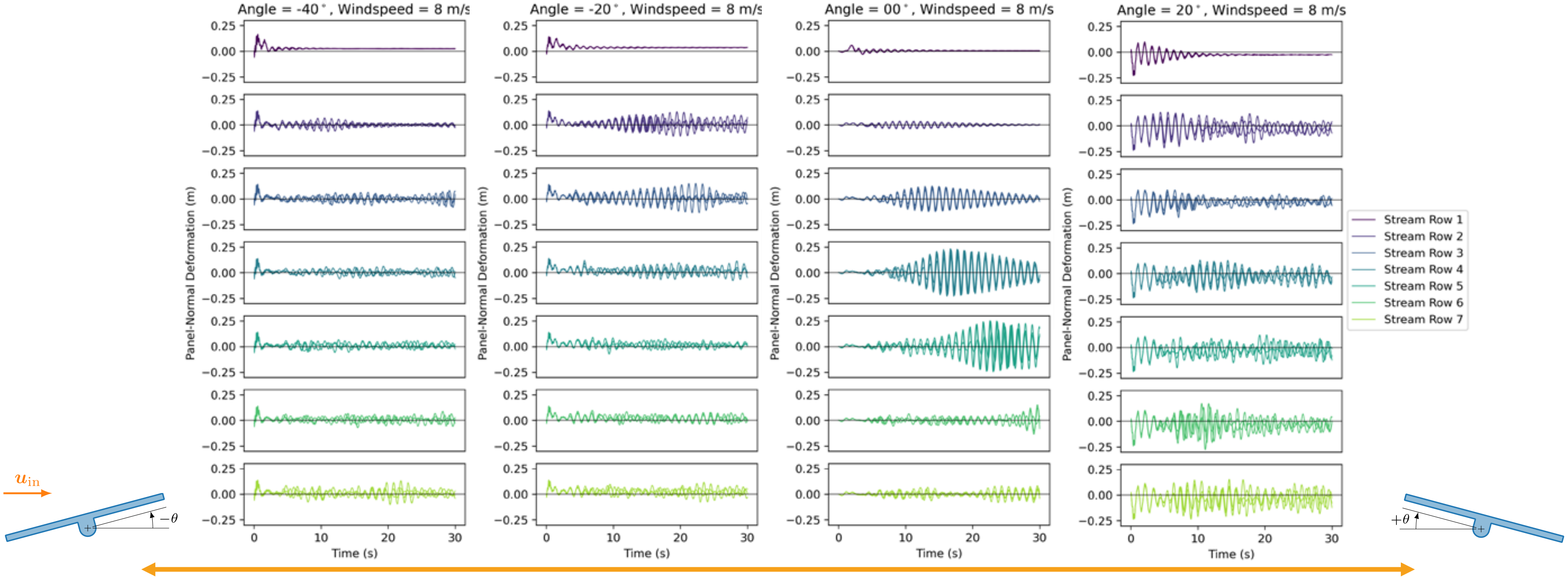


Wind Speed = 12 m/s,
Tilt Angle = 20°

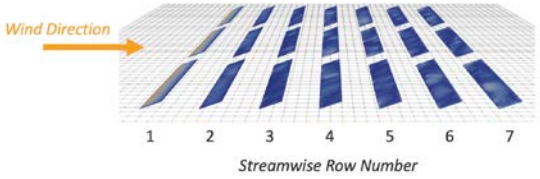
Progress and Outcomes: Multi-Row Deformation at 8 m/s



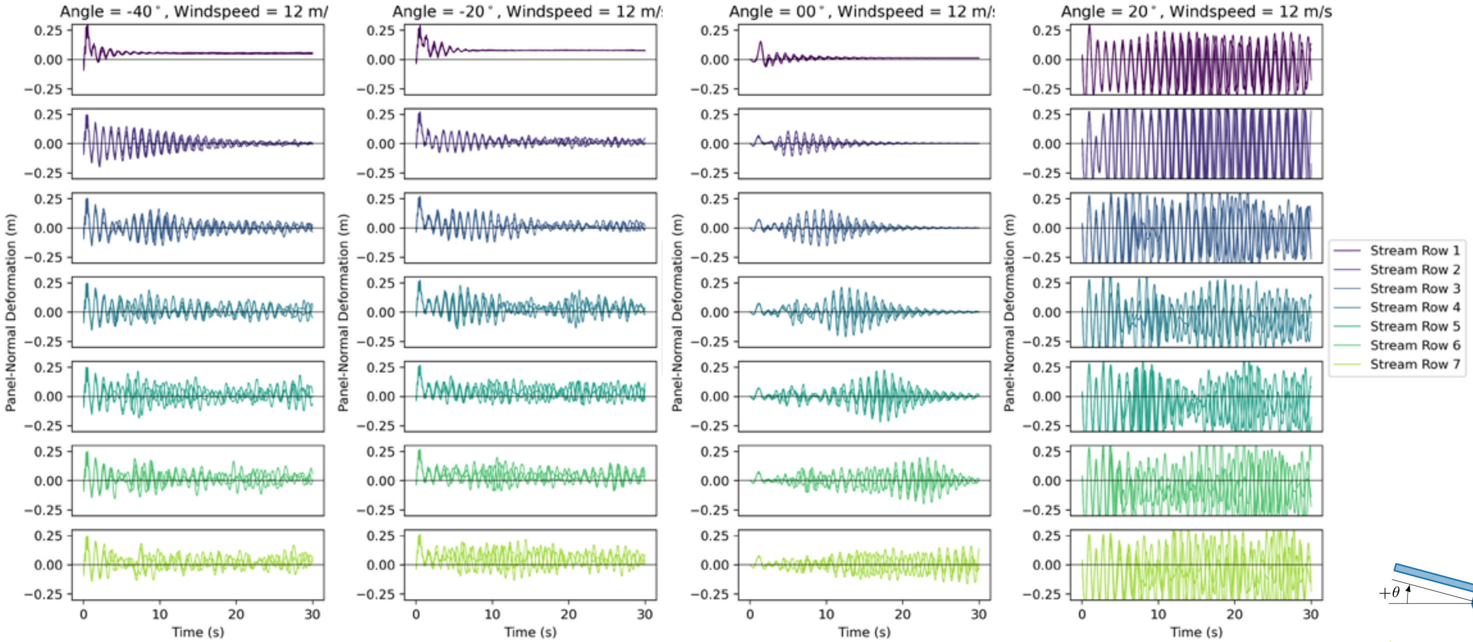
Negative tilt angles experience less deformation

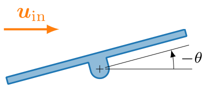


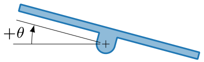
Progress and Outcomes: Multi-Row Deformation at 12 m/s



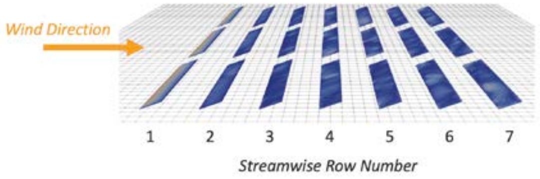
Smaller tilt angles are less predictable



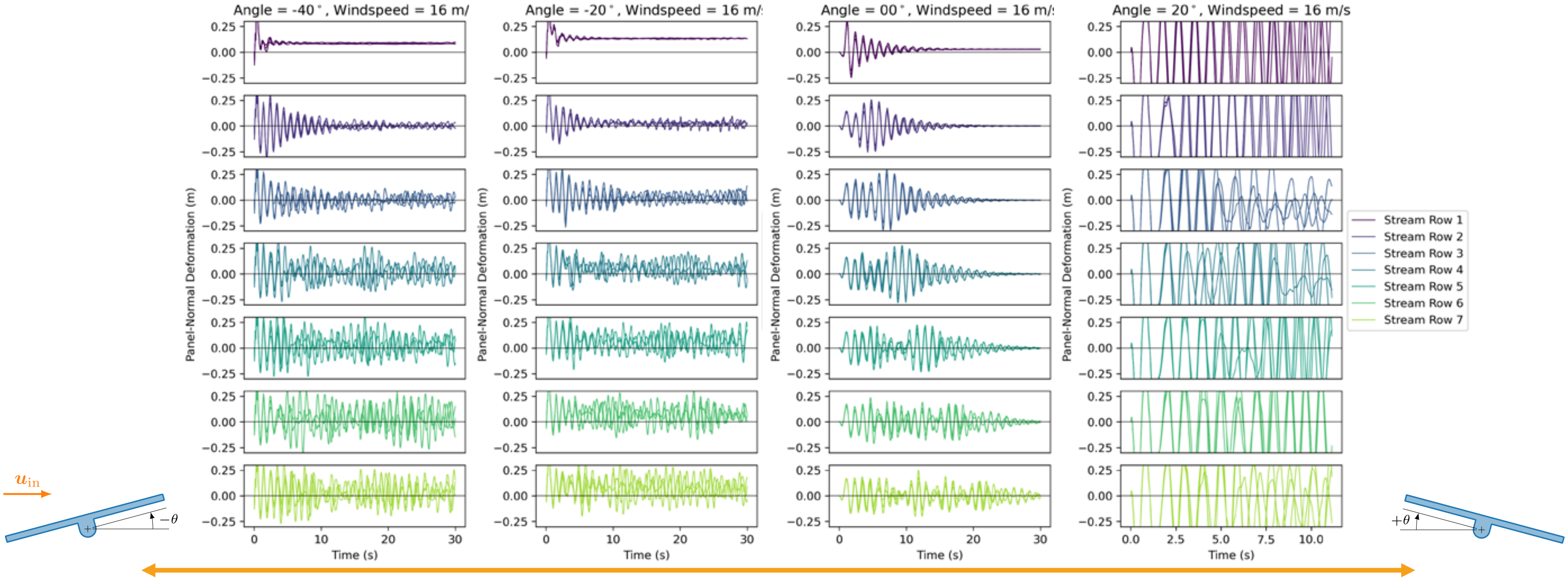




Progress and Outcomes: Multi-Row Deformation at 16 m/s

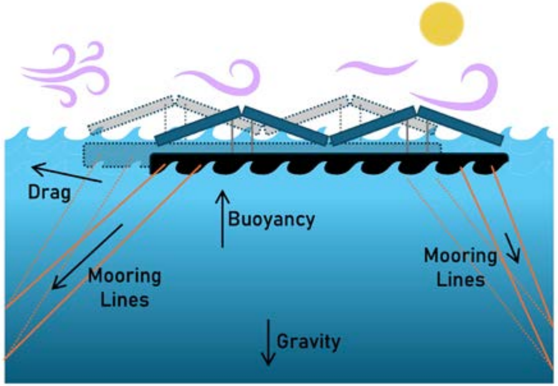


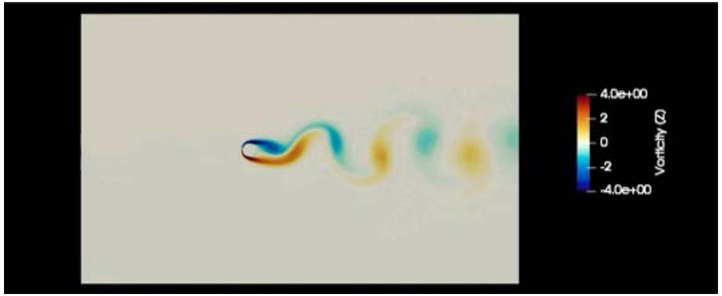
Larger wind speeds generate more deformation

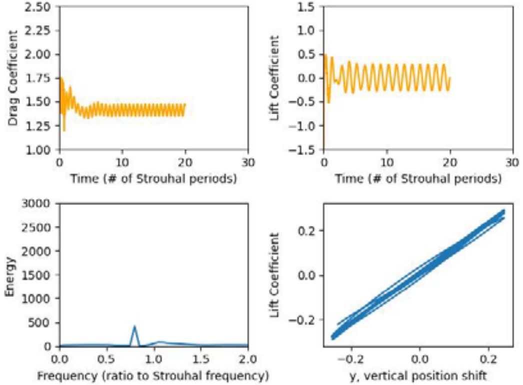


New Use Cases and Work

Growing User Base: VELOCITI Floating PV Study

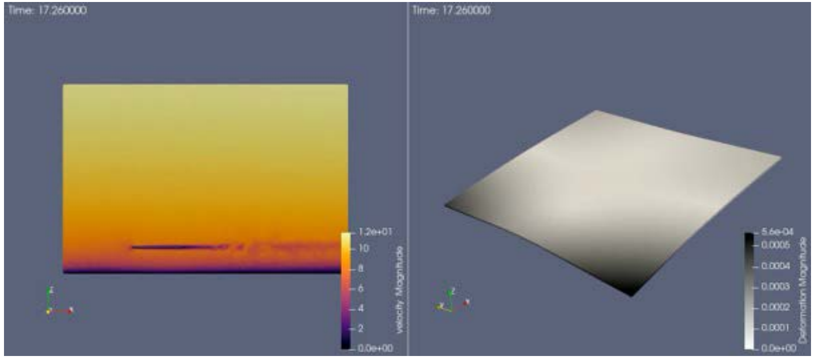


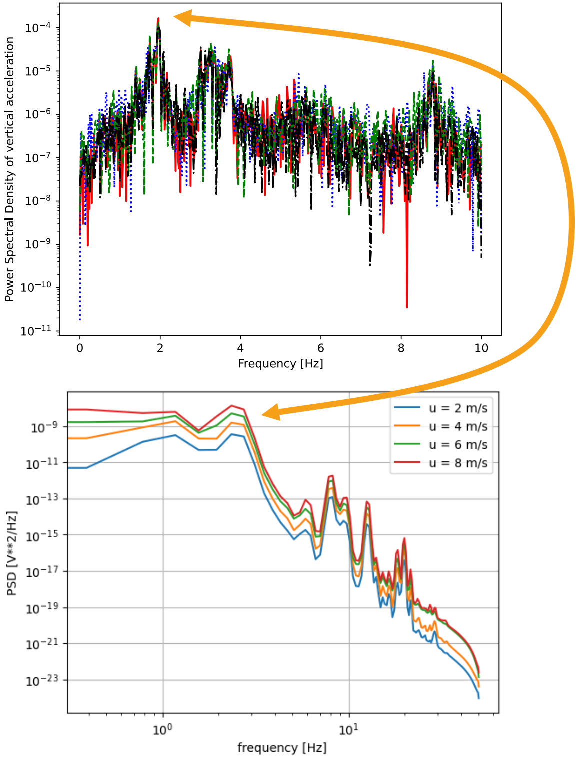




Our CSGF fellow, Melissa Rasmussen, has been working on developing and validating extensions to our mesh-moving routines to account for **whole-array motion due to floating PV dynamics**.

Growing User Base:
CSP Wind-Loading Studies

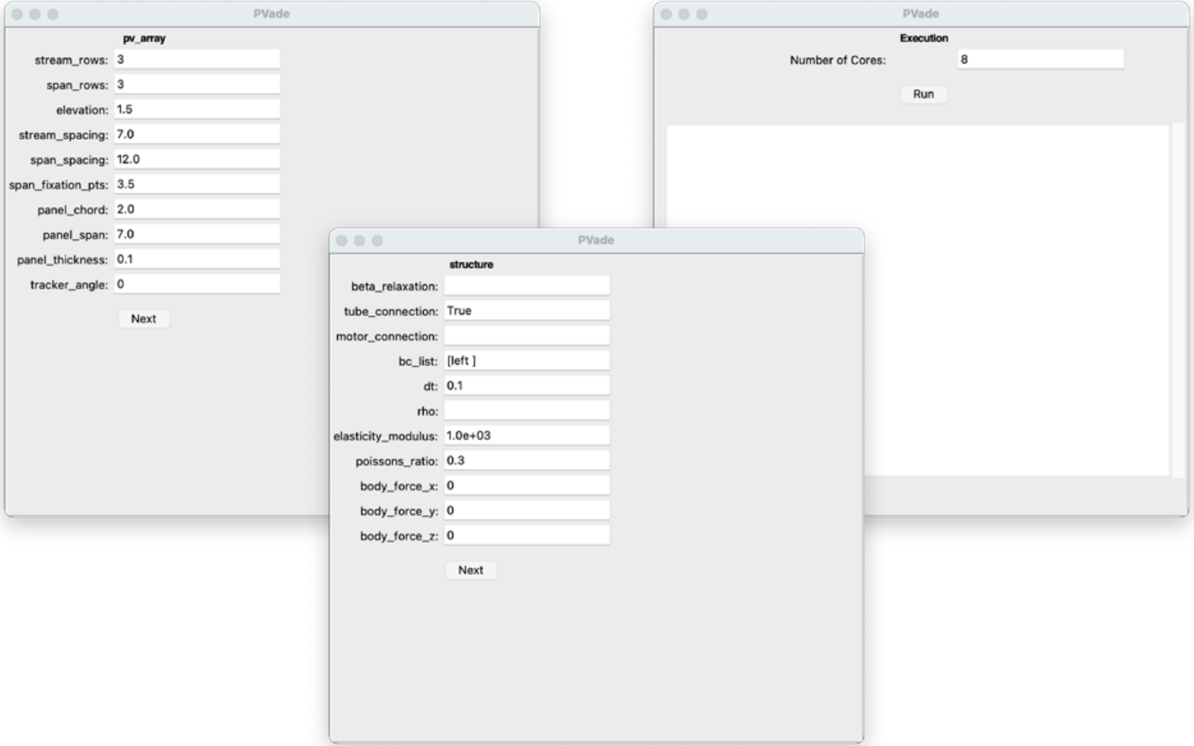




Very preliminary, but both experimental (top) and simulated (bottom) display peaks in the power spectral density at ~2 Hz.

Future Work: Graphical User Interface

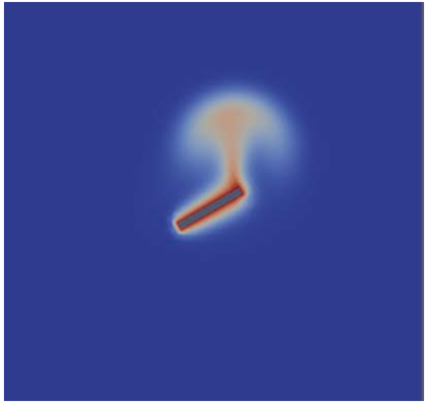
Experimenting with a simple **graphical user interface (GUI)** developed with the **`tkinter` package** to lower PVade's barrier to entry.

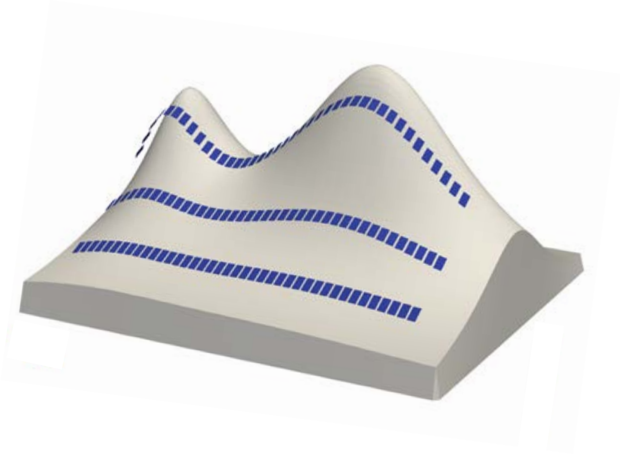


Future Work: Temperature and Terrain Effects

Work planned for FY25:

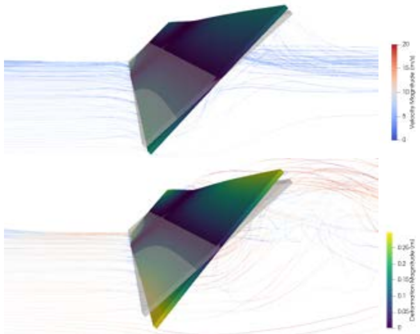
- (left) the addition of thermal effects enables critical **buoyancy-driven phenomena** and **predictions of panel cooling**
- (right) the interaction of wind, panels, and (extreme) complex terrain will allow us to predict **site-specific stow and stability strategies**

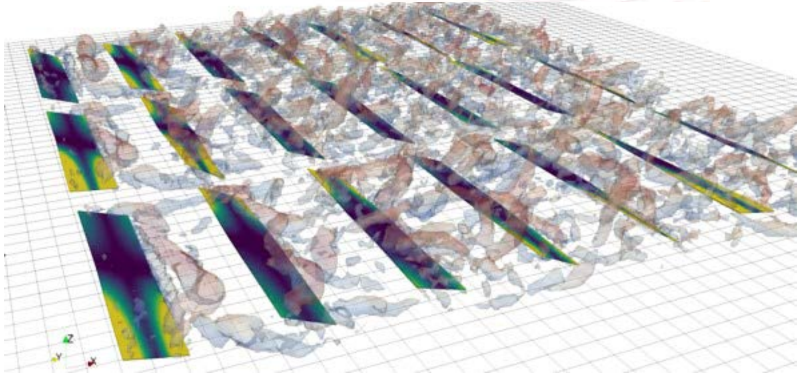




Concluding Remarks

- We have developed an open-source solver to predict the effect of unsteady wind loading on single-axis tracking PV systems.
- ***Last Year:***
  - **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 nor uniform tilt angles
- ***Next Year:***
  - **Add turbulent inflow option**
  - More detailed structural properties
  - Temperature driven flow effects
  - Implement site-specific terrain





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PVade Project

Thank You

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