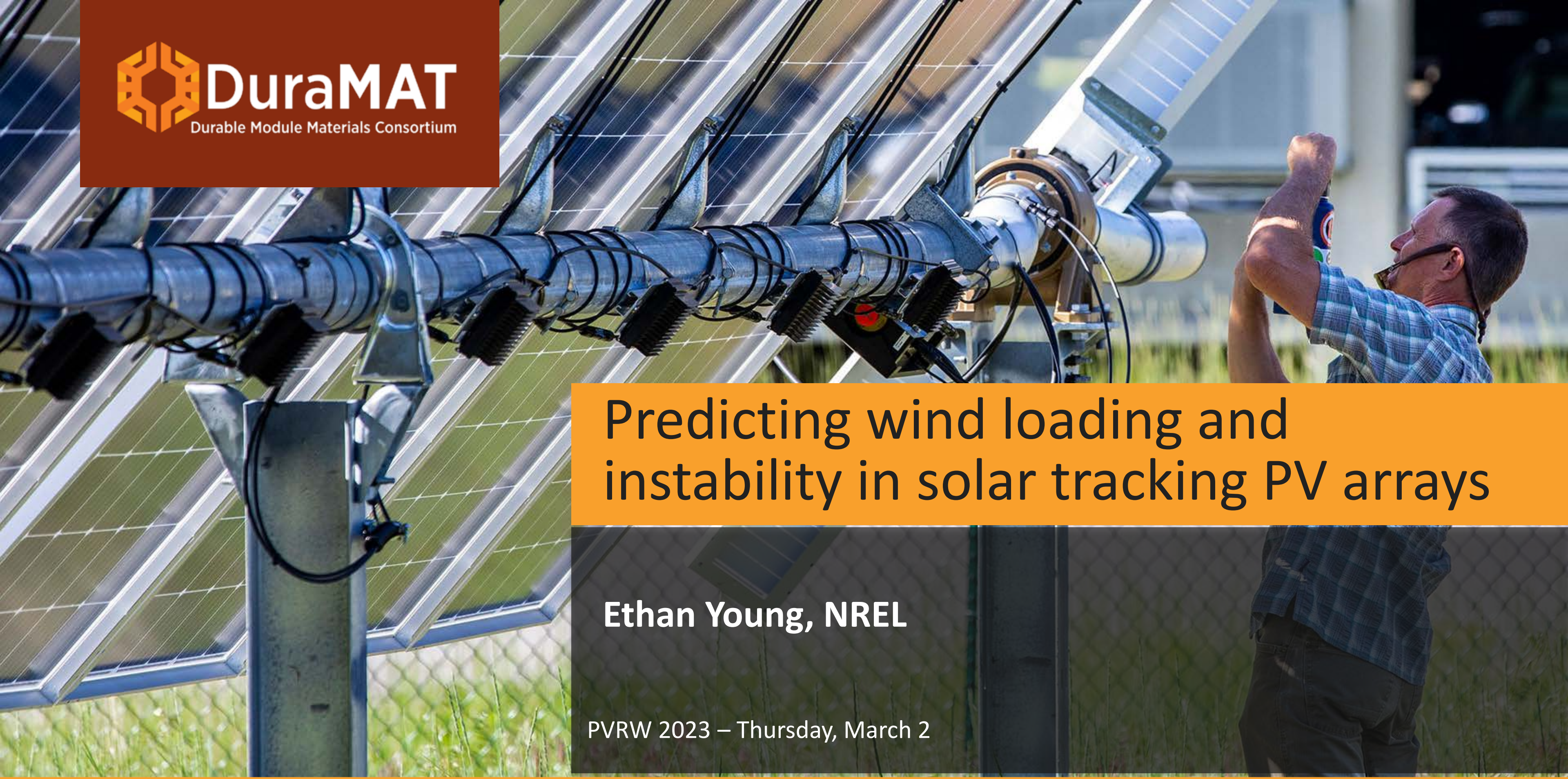


DuraMAT
Durable Module Materials Consortium

Predicting wind loading and instability in solar tracking PV arrays

Ethan Young, NREL

PVRW 2023 – Thursday, March 2

Motivation

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

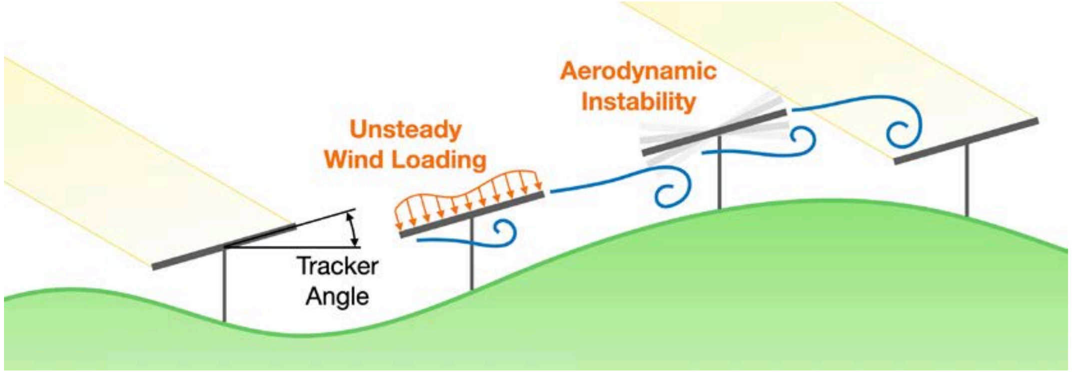
- Higher wind speeds can initiate unsteady aerodynamic instabilities (galloping) which can **initialize cracks** and/or **destroy sections of the array.**
- Moderate wind loads create unsteady, reversing that lead to the **worsening of existing cell cracks** over time.

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 site layout
- Non-universal stow strategies

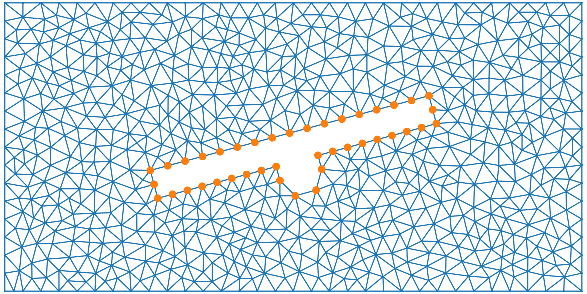


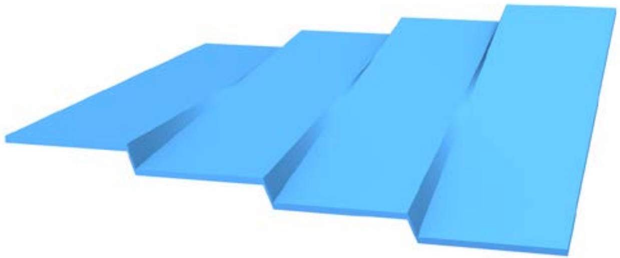
Goal: Understanding the **fluid-structure interaction (FSI)** driving this instability can improve panel stow guidelines and inform stabilizing layout and hardware design.

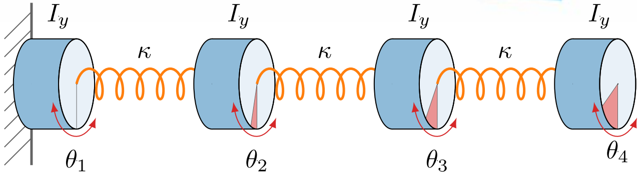
Previous Work on Aerodynamic Stability

Modeling Approach

- Solving the incompressible Navier-Stokes equations yields a torque at each node on the panel surface.
- Panels are treated as **rigid masses linked with rotational springs**.
- This mass-spring approximation is used to model the FSI problem.

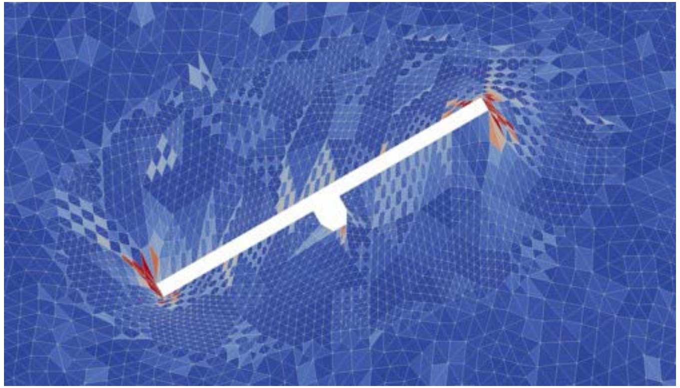




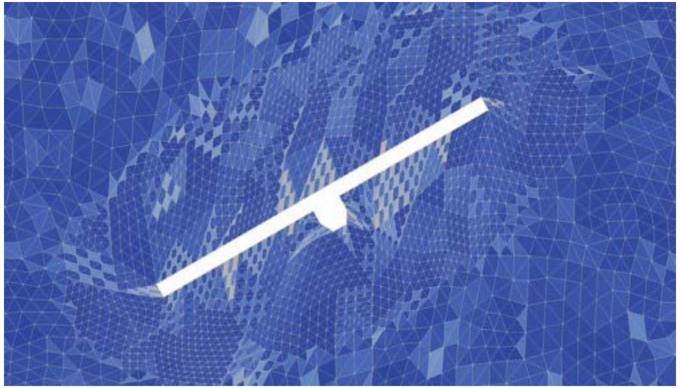


Modeling Approach

- Fluid solution updates the position of the panel, new panel position (updated mesh) is used to solve the fluid.

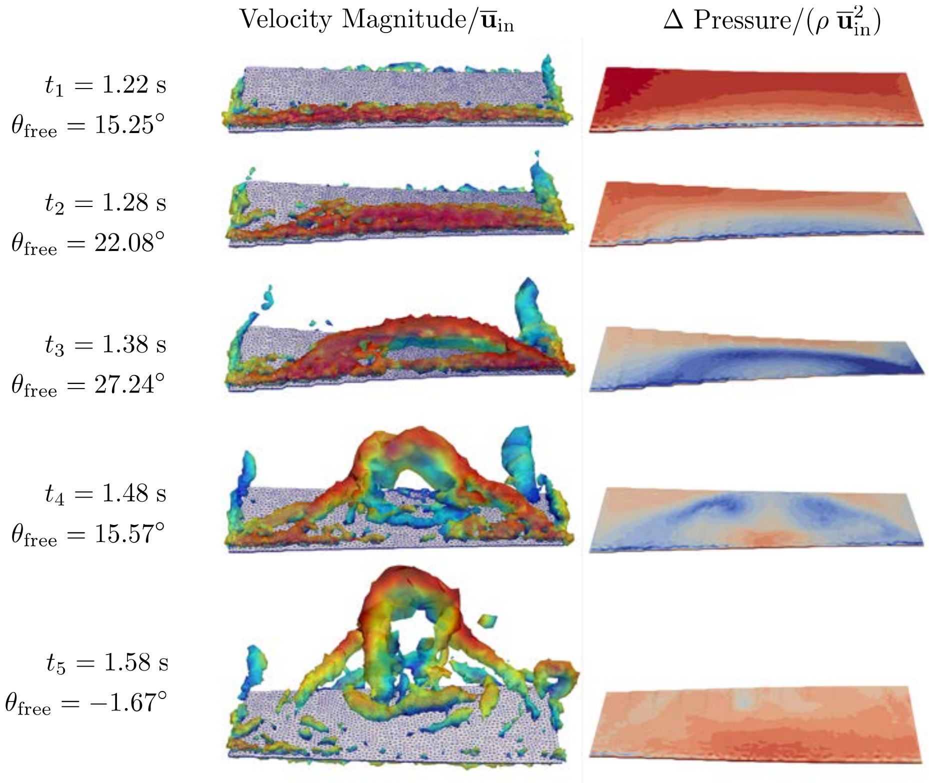


Constant diffusivity: $\nabla^2 \hat{x} = 0$

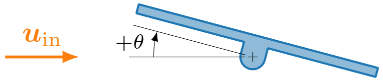


Quadratic diffusivity: $\frac{1}{d^2} \nabla^2 \hat{x} = 0$

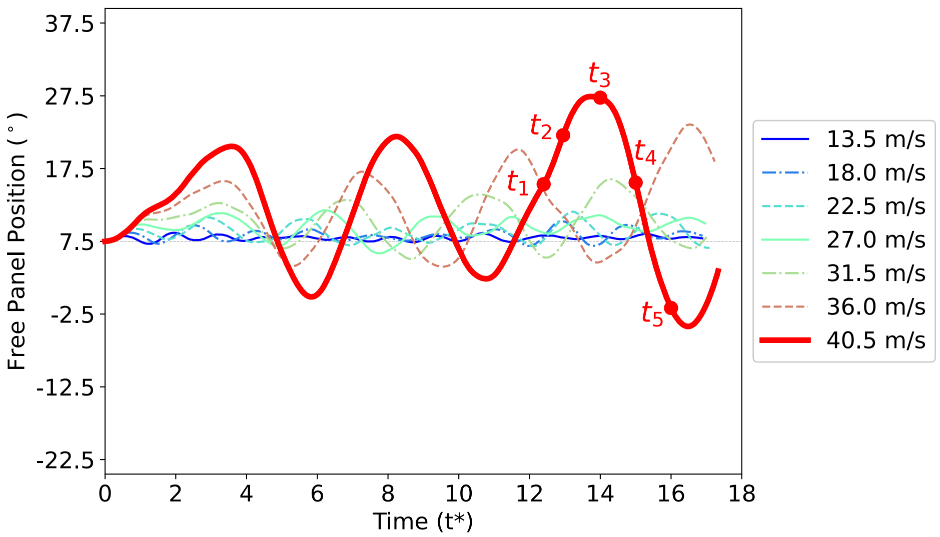
Results

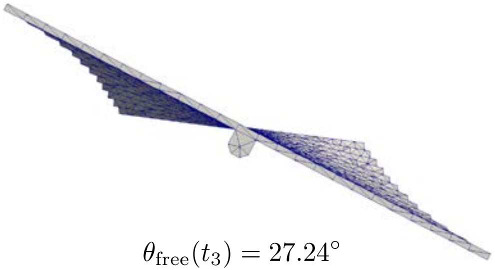


Tracking angle: $\theta = +7.5°$
Constant 40.5 m/s wind



Results





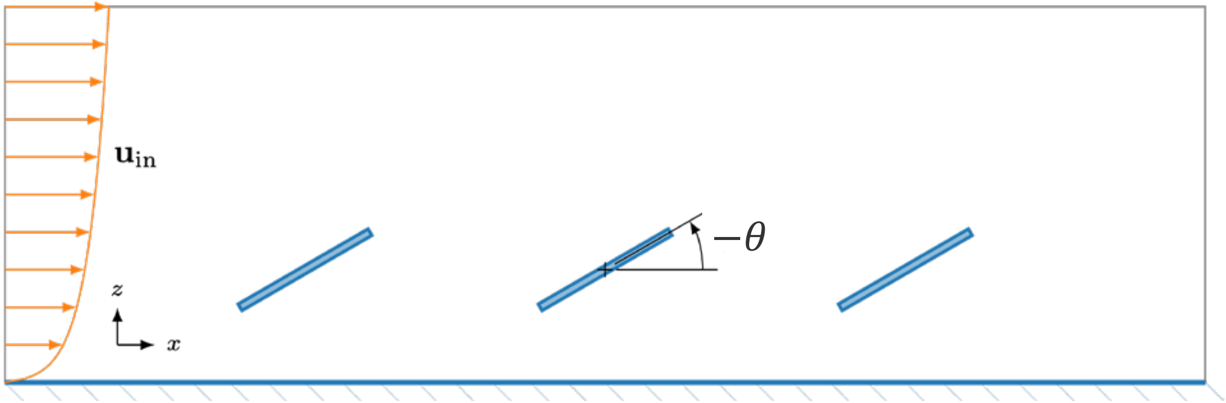
$\theta_{\text{free}}(t_3) = 27.24°$

$\theta_{\text{free}}(t_5) = -1.67°$

E. Young, X. He, R. King, and D. Corbus, “A Fluid-Structure Interaction Solver for Investigating Torsional Galloping in Solar-Tracking Photovoltaic Panel Arrays”, Journal of Renewable and Sustainable Energy, Nov 2020

Previous Work on Fixed-Angle Pressure Loading

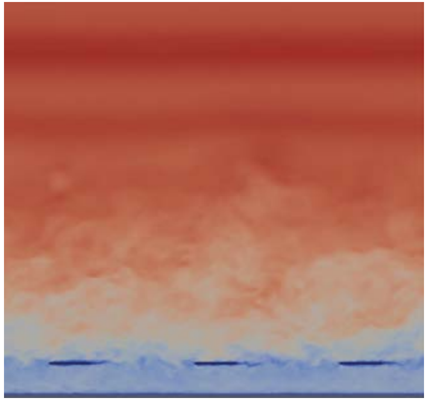
Modeling Approach



- Solution of Navier-Stokes equations using `FEniCS`
- Traction is measured along the surface of a downstream panel
- **Wind speed** at panel height and **(fixed) panel angle** are easily adjustable inputs

Results

- Without the complication of mesh motion, we can run these cases at a much higher fidelity.
- Inputs are simplified to enable large parameter sweeps.

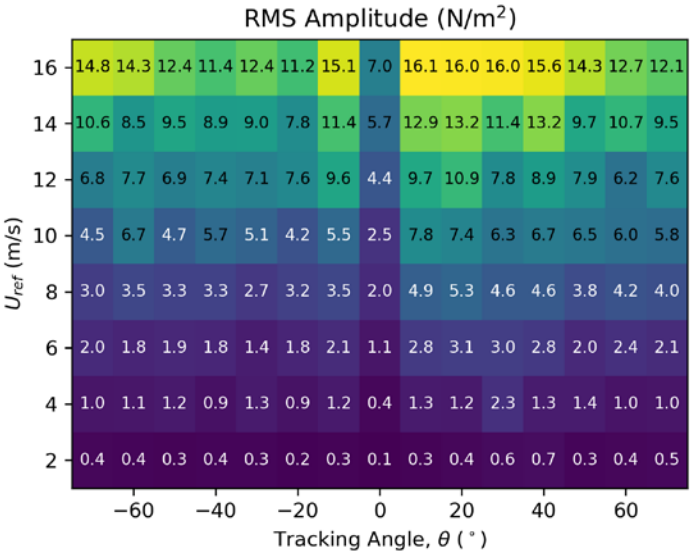


$\theta = 0^\circ$

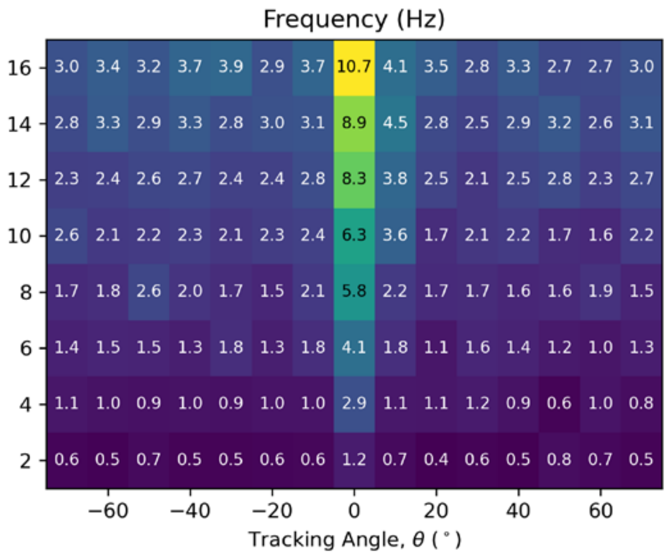
$\theta = -20^\circ$

$\theta = -40^\circ$

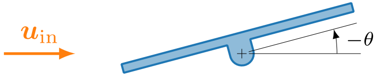
Results



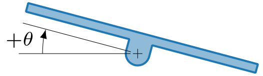
RMS Amplitude (N/m²)
16 14.8 14.3 12.4 11.4 12.4 11.2 15.1 7.0 16.1 16.0 16.0 15.6 14.3 12.7 12.1
14 10.6 8.5 9.5 8.9 9.0 7.8 11.4 5.7 12.9 13.2 11.4 13.2 9.7 10.7 9.5
12 6.8 7.7 6.9 7.4 7.1 7.6 9.6 4.4 9.7 10.9 7.8 8.9 7.9 6.2 7.6
10 4.5 6.7 4.7 5.7 5.1 4.2 5.5 2.5 7.8 7.4 6.3 6.7 6.5 6.0 5.8
8 3.0 3.5 3.3 3.3 2.7 3.2 3.5 2.0 4.9 5.3 4.6 4.6 3.8 4.2 4.0
6 2.0 1.8 1.9 1.8 1.4 1.8 2.1 1.1 2.8 3.1 3.0 2.8 2.0 2.4 2.1
4 1.0 1.1 1.2 0.9 1.3 0.9 1.2 0.4 1.3 1.2 2.3 1.3 1.4 1.0 1.0
2 0.4 0.4 0.3 0.4 0.3 0.2 0.3 0.1 0.3 0.4 0.6 0.7 0.3 0.4 0.5
U_ref (m/s)
−60 −40 −20 0 20 40 60
Tracking Angle, θ (°)



Frequency (Hz)
16 3.0 3.4 3.2 3.7 3.9 2.9 3.7 10.7 4.1 3.5 2.8 3.3 2.7 2.7 3.0
14 2.8 3.3 2.9 3.3 2.8 3.0 3.1 8.9 4.5 2.8 2.5 2.9 3.2 2.6 3.1
12 2.3 2.4 2.6 2.7 2.4 2.4 2.8 8.3 3.8 2.5 2.1 2.5 2.8 2.3 2.7
10 2.6 2.1 2.2 2.3 2.1 2.3 2.4 6.3 3.6 1.7 2.1 2.2 1.7 1.6 2.2
8 1.7 1.8 2.6 2.0 1.7 1.5 2.1 5.8 2.2 1.7 1.7 1.6 1.6 1.9 1.5
6 1.4 1.5 1.5 1.3 1.8 1.3 1.8 4.1 1.8 1.1 1.6 1.4 1.2 1.0 1.3
4 1.1 1.0 0.9 1.0 0.9 1.0 1.0 2.9 1.1 1.1 1.2 0.9 0.6 1.0 0.8
2 0.6 0.5 0.7 0.5 0.5 0.6 0.6 1.2 0.7 0.4 0.6 0.5 0.8 0.7 0.5
−60 −40 −20 0 20 40 60
Tracking Angle, θ (°)



u_in
−θ



+θ

New Project: PVade

Awarded FY22

Core Modelling Call

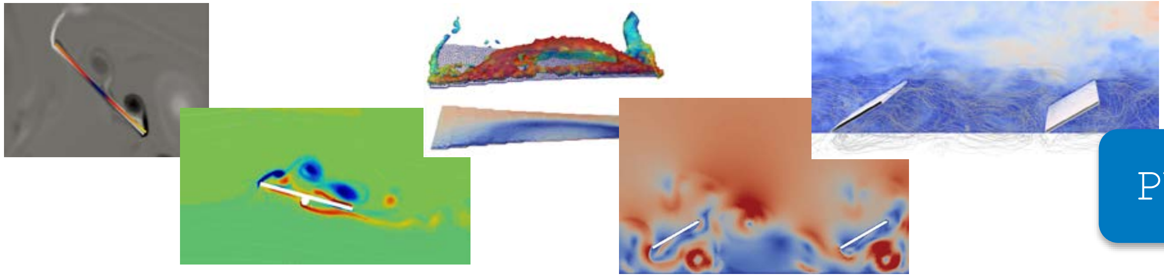
U.S. DEPARTMENT OF ENERGY

NREL

Sandia National Laboratories

BERKELEY LAB

New Project: PVade

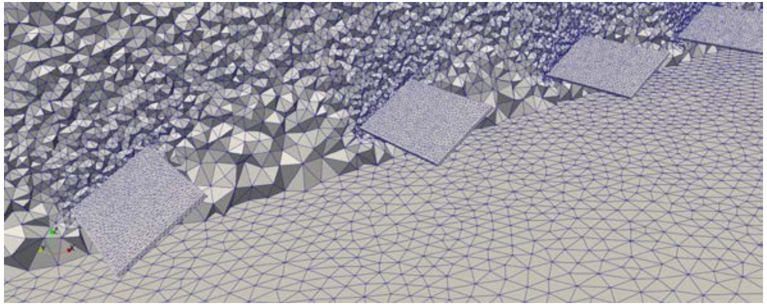


						PVade
3D Simulation			✓		✓	✓
Large Rigid Body Motion		✓	✓			✓
Structural Deformation	✓					✓
HPC Scalable				✓	✓	✓
Accelerated Test Outputs				✓		✓
Optimization						✓
Terrain						✓

PVade Overview

Developed using elements of DOLFINx, an open-source software for solving partial differential equations. Currently implemented features include:

- Ability to easily specify different panel geometries and layouts via input file
- **Automatic generation of high-fidelity computational meshes**
- **Validated solution of Navier-Stokes** using a fractional step method
- High-performance computing **(HPC) ready implementation** of all methods



$$\frac{\boldsymbol{u}^* - \boldsymbol{u}^k}{\Delta t} = \nu \nabla^2 \boldsymbol{u}^k - \boldsymbol{u}^k \cdot \nabla \boldsymbol{u}^k - \frac{1}{\rho} \nabla P^k \quad (1)$$

$$\nabla \cdot \boldsymbol{u}^* = \Delta t \nabla^2 \phi \quad (2)$$

$$\boldsymbol{u}^{k+1} = \boldsymbol{u}^* - \Delta t \nabla \phi \quad (3)$$

$$P^{k+1} = P^k + \phi$$

Performance

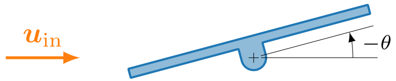
- Each new method is written and tested to ensure scalable performance

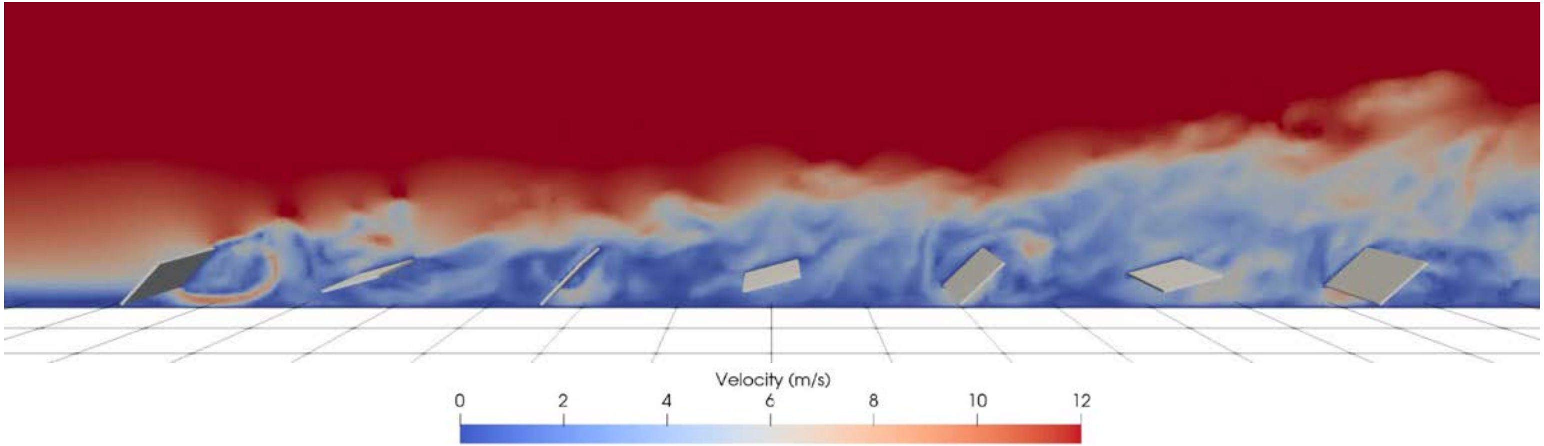
Number of Threads	Process Binding	Solver for Eq. (1, 2, 3)	Precond. for Eq. (1, 2, 3)	Time per Iteration (s)	Speedup
18	Bind by board	(GMRES, GMRES, CG)	(HYPRE, HYPRE, Jacobi)	16.8	1x
9	No binding	(GMRES, GMRES, CG)	(HYPRE, HYPRE, Jacobi)	9.53	1.76 x
1	**Bind by L2 Cache**	(GMRES, GMRES, CG)	(HYPRE, HYPRE, Jacobi)	**1.45**	**11.58 x**

Number of Threads	Process Binding	Solver for Eq. (1, 2, 3)	Precond. for Eq. (1, 2, 3)	Time per Iteration (s)	Speedup
1	Bind by L2 Cache	(GMRES, GMRES, CG)	(None, None, HYPRE)	8.74	1.92 x
1	Bind by L2 Cache	(GMRES, GMRES, GMRES)	(Jacobi, None, Jacobi)	4	4.2 x
1	Bind by L2 Cache	**(GMRES, CG, CG)**	**(Jacobi, Jacobi, Jacobi)**	**0.910**	**18.46 x**

7-Panel Case Study

- 8 m/s constant wind speed
- 7 m spacing between rows
- Tracking angle is *prescribed* $\theta(t) = -30^\circ + 15^\circ \sin(2\pi f t)$

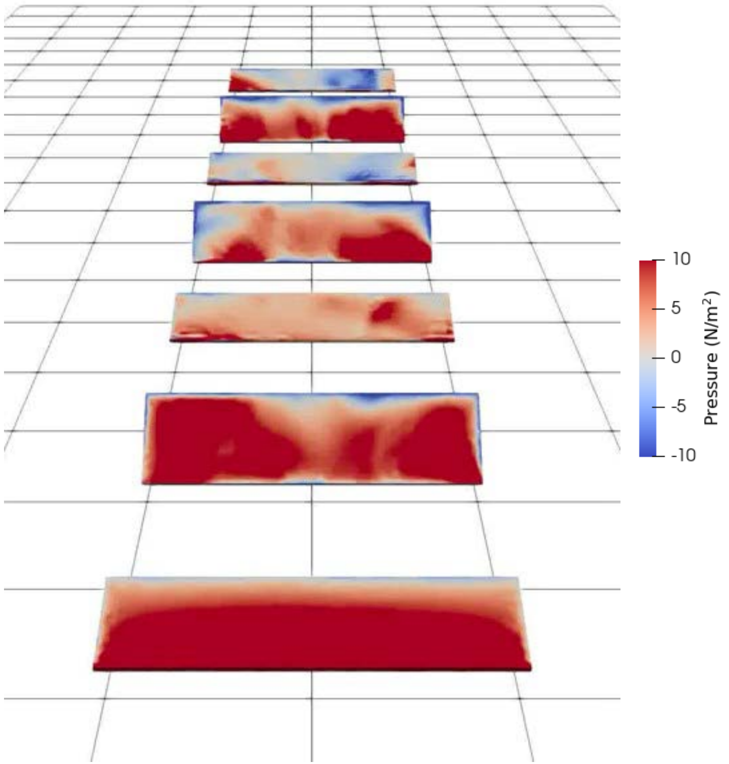




Comparison to previous FSI study: 95K vs 22M fluid cells (**230x larger problem**)

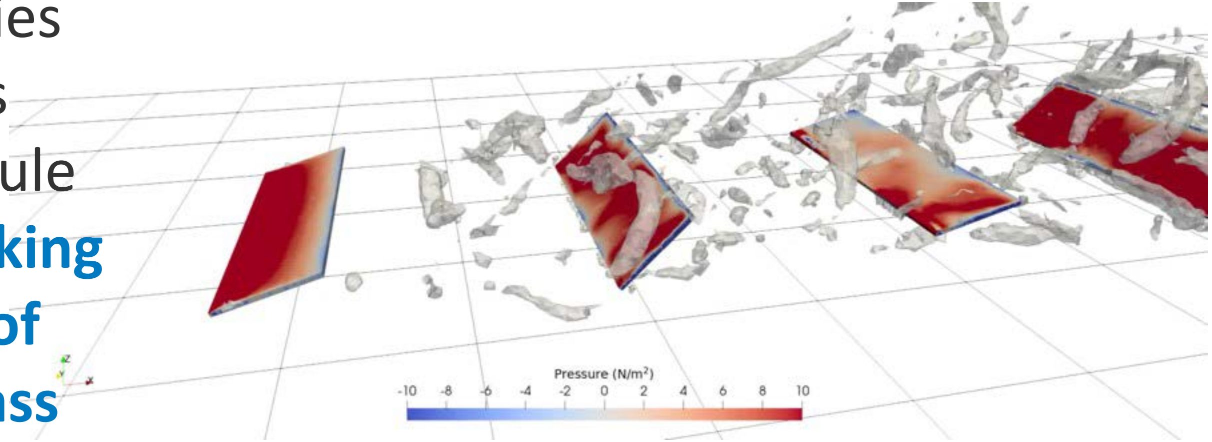
7-Panel Case Study

Pressure profiles and inertial load time series can be used as inputs into mechanical module models to **study cracking of cells, weathering of cracked cells, and glass breakage**



7-Panel Case Study

Pressure profiles and inertial load time series can be used as inputs into mechanical module models to **study cracking of cells, weathering of cracked cells, and glass breakage**



Future Work

- Public release of `PVade`
- Add solution of **structural problem**
- **Couple fluid and structural solver** at panel interface
- Add effects of **complex terrain** and enable **optimization problem definitions**
- **Validation campaign**

Contributing Researchers

- Walid Arsalane
- Xin He
- Scott Dana
- Chris Ivanov
- Ryan King
- Mike Deceglie
- Tim Silverman
- David Corbus

Thank You

Questions? ethan.young@nrel.gov

www.duramat.org

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