Aeroelastic Modeling and Full-Scale Loads Measurements for Investigation of Single-Axis PV Tracker Wind-Driven Dynamic Instabilities

Scott Dana and Ethan Young

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Acknowledgments

Key contributors:

Chris Ivanov, Xin He, Jerry Hur, Ryan King,

Jeroen van Dam and Dave Corbus

Brian Wares of Sunpower

A special thank you to Teresa Barnes and DuraMAT!

TOPICS

1. Project Background
2. Study Trajectories
3. Field Campaign
4. Field Results
5. Modeling Approach
6. Modeling Results
7. Comparison and Future Work

Motivation

Wind-related failures are widespread

- Range of wind speeds and geographic locations
- Unclear sources (galloping vs. divergence)
- Unclear stow guidance
- Industry response: Damper or mass add-ons, redesign

Shortcomings to address

- Wind-tunnel-testing-driven design
- Proprietary models/design codes
- Full-scale loads measurements
- Model validation.


[2]

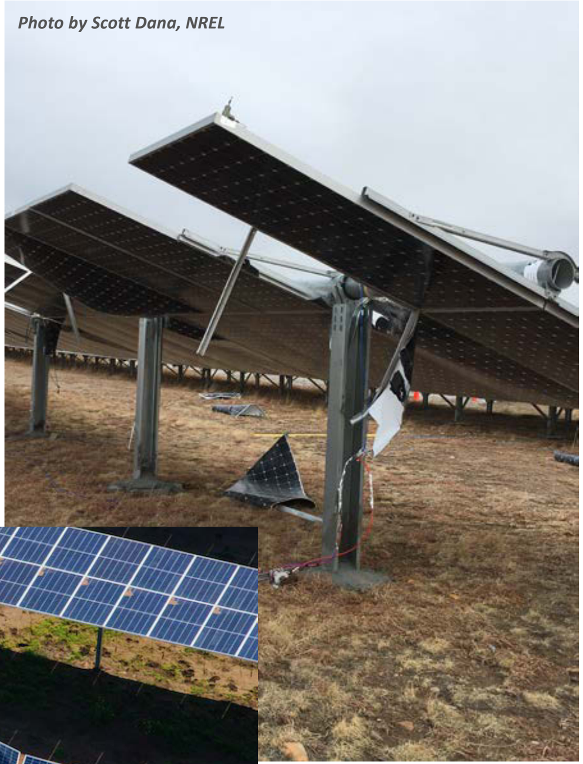


Photo by Scott Dana, NREL

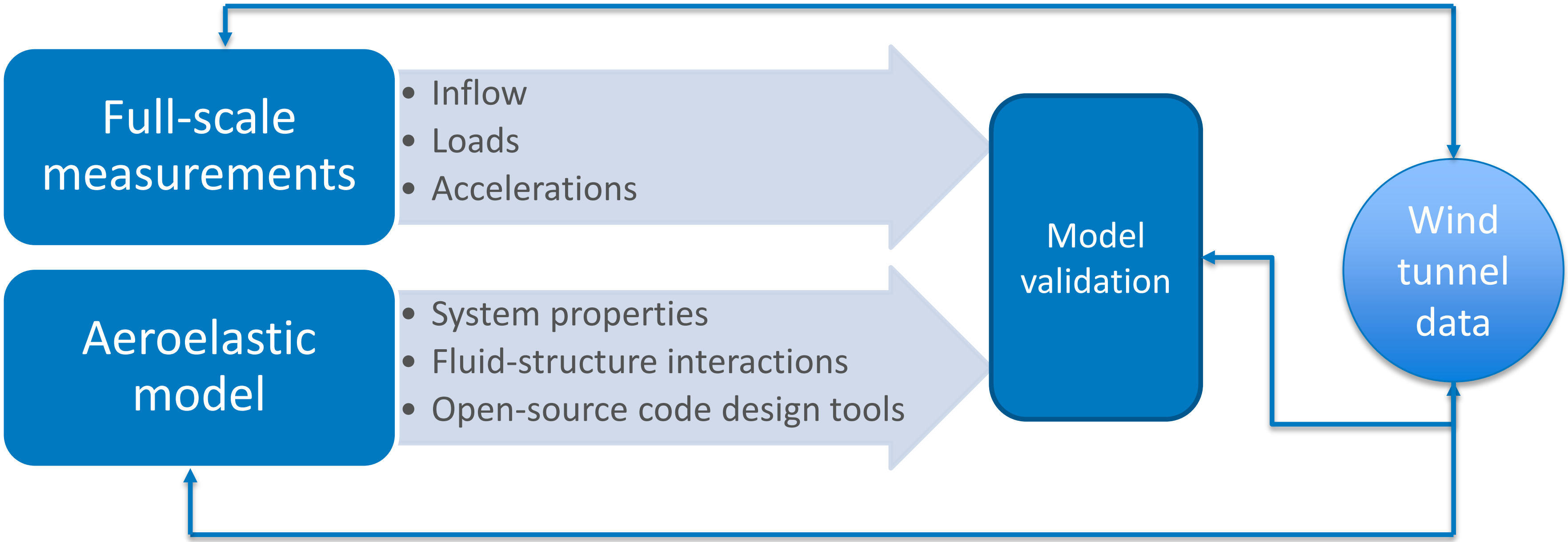

https://www.pv-magazine-australia.com/2019/12/07/long-read-what-broke-at-oakey/

[1] GTM and NEXTracker Webinar, *Driving the Standard: Wind Testing, Solar Trackers, and Peer Review*, December 10, 2019
[2] PV Magazine Webinar, *Can a tracker be as stable as a fixed tilt?* December 10, 2019
[3] PV Magazine Webinar, *High or low tilt angles for single-axis trackers in extreme winds – different approach*, December 16, 2019

Parallel Paths Forward

DuraMAT funding source

– Address PV resilience
– Investigate dynamic instabilities
– Conduct first-of-kind study



NREL–Flatirons Campus Field Campaign

NREL Flatirons Campus (National Wind Technology Center)

- Extreme winds > 110 mph (50 m/s)
- Wind season October through May
- Decades of engineering, research, and field validation of high-wind physics and modeling


Photo by Dennis Schroeder, NREL 25861

Home to DuraMAT Field Campaign

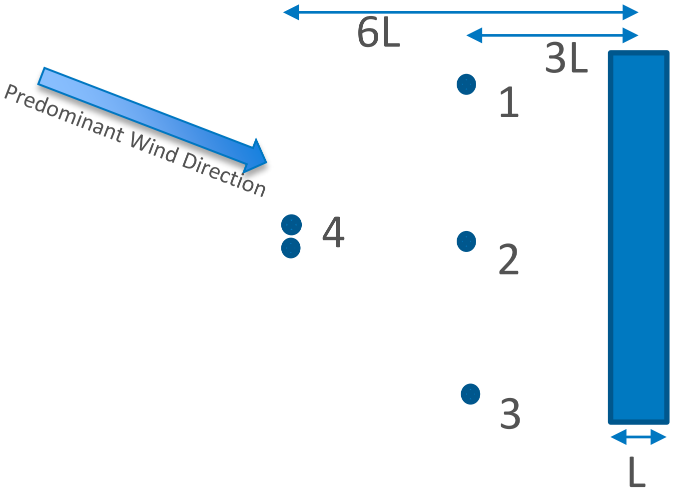
- Single-axis tracker
- Single-slew drive at center
- 24.25-m length
- 4-m width
- 2-m axis height.


Photo by Scott Dana, NREL

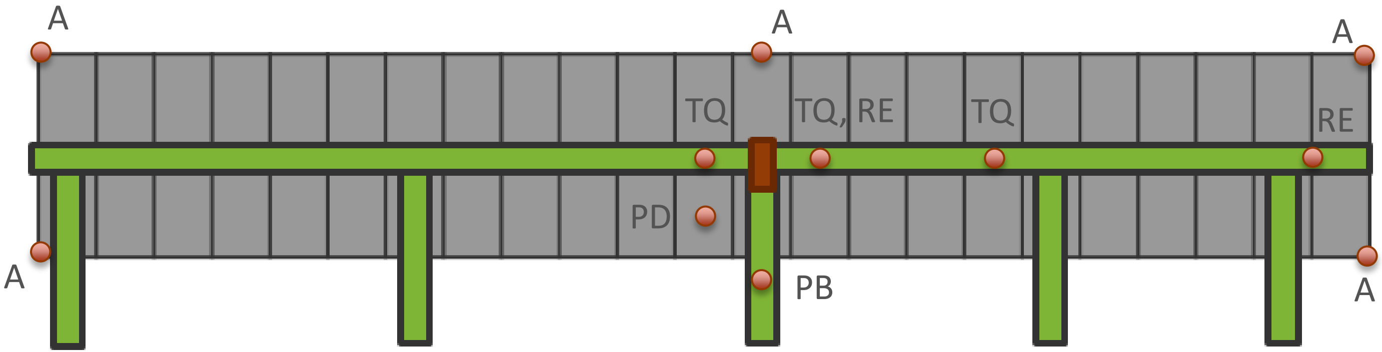

Photo by Scott Dana, NREL

Instrumentation Setup

- Inflow and atmospheric
- Torque loads = TQ
- Pier bending = PB
- Rotary encoders = RE
- Panel deflections = PD
- Accelerations = A



Sonics = 1,2,3
Cup & vane = 4
Temp, humid, press = 2



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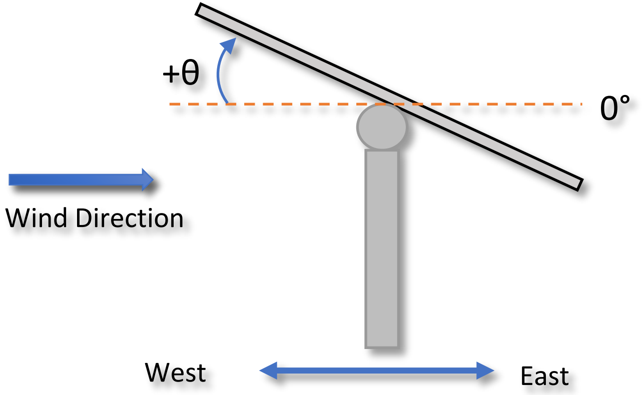
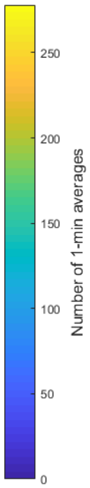
Data Collection and Analysis Approach

- Cycle through discrete tracker stow angles
  - -52, -40, -20, -10, -5, 0, 5, 10, 20, 40, 52
  - Start with “safe” stow angles
  - Move to “riskier” stow angles
- Time-series data collected
- 50-Hz and 1-Hz storage rates
- Inflow sector filter: 255° to 285°
- Postprocess for loads
- Calculate 1-minute statistics
- Bin stats
  - By wind speed
  - By tracker angle.



Capture Matrix

Tracker Angle [deg] \ Wind Speed Bin Center [m/s]	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
52	101	68	72	98	131	167	135	109	54	20	21	36	34	27	19	12	3		1	
40	278	250	188	134	145	112	86	95	61	44	30	19	10	9	6	1				
20	265	178	100	50	19	16	13	7	6	2	2	1								
10	203	222	91	25	11	12	18	11	16	12	2									
5	254	255	214	176	142	106	56	36	24	10	7	5	2	2						
0	211	193	146	74	45	39	23	26	16	13	2	2								
-5	79	98	105	87	84	46	30	29	24	8	8	8	6	1						
-10	158	73	34	22	20	14	19	31	12	9	5	1	2							
-20	15	34	21	30	15	2	1													
-40	253	210	221	162	149	106	104	91	85	75	103	57	48	35	15	3				
-52	134	133	120	106	103	68	62	47	36	24	15	6	1							



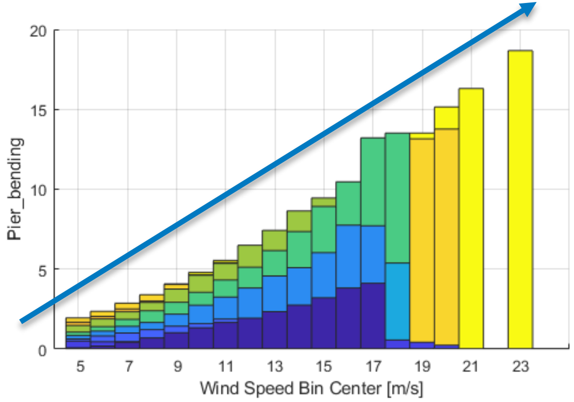
Pier Bending Moment

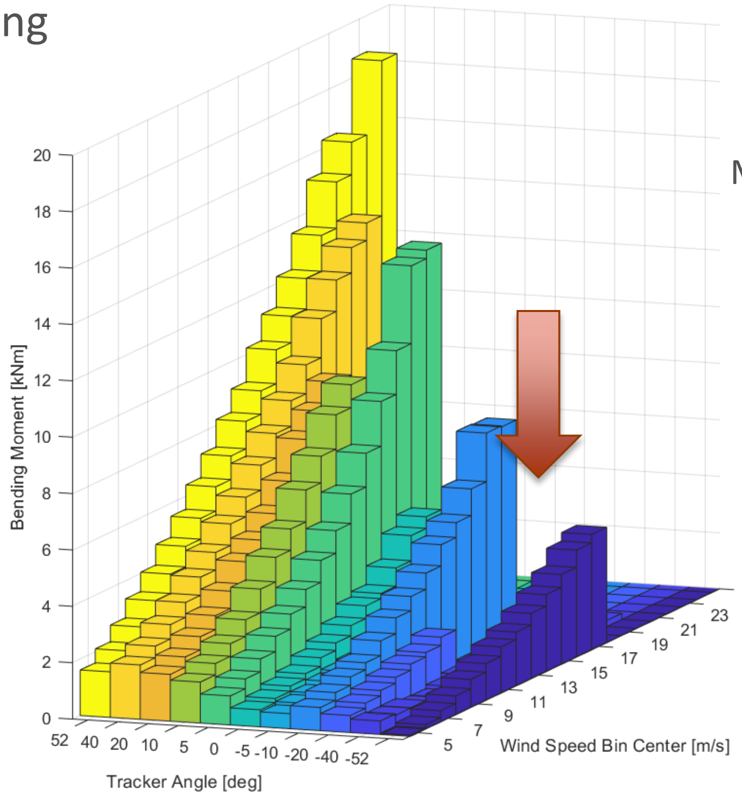
Absolute values of mean bending moment

Wind speed range limitations

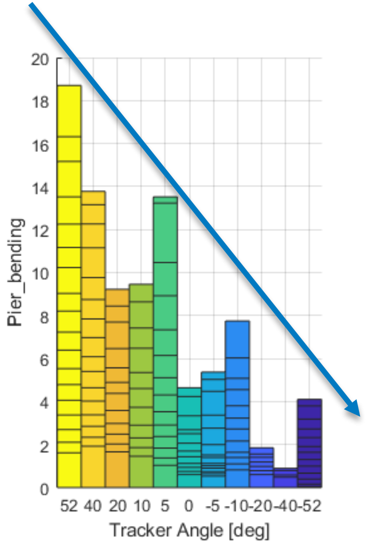
- -20 degrees
- Most bins beyond 17 m/s.

Mean Load Wind Speed Envelope

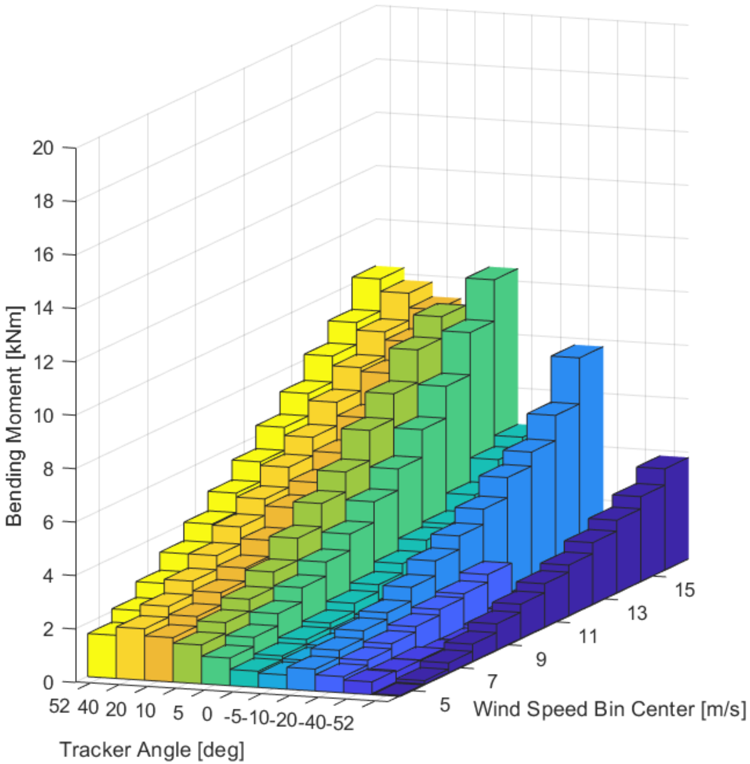




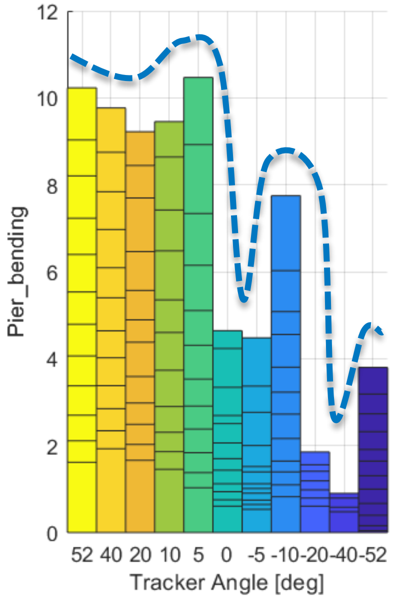
Mean Load Stow Angle Envelope

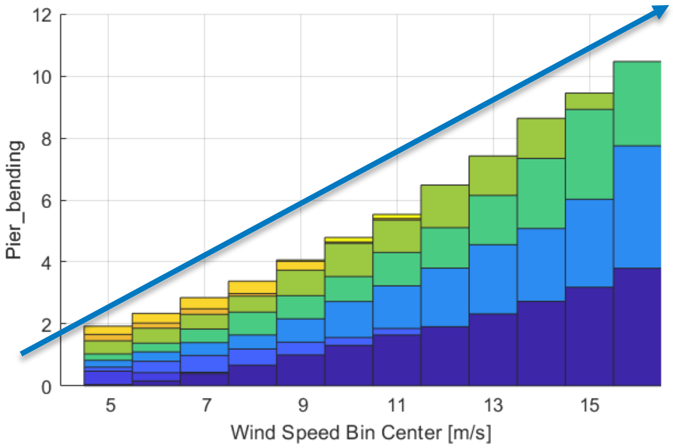


Pier Bending Moment—Closer Look



- Slice data to evaluate bin parity
- Statistical confidence up to 16 m/s
- -20° limited beyond 9 m/s—ignore, although trend present
- Tracker angle trend generally favors negative stow angle > 10°.

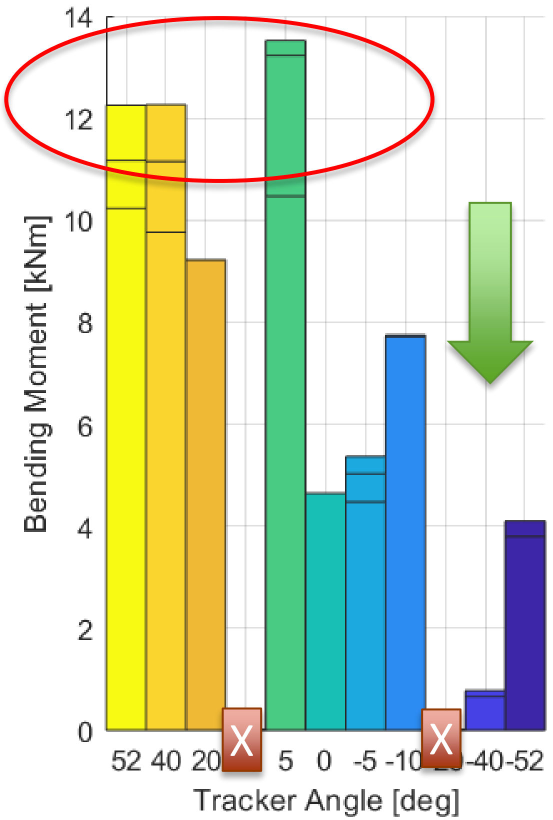




Pier Bending Moment—Closer Look

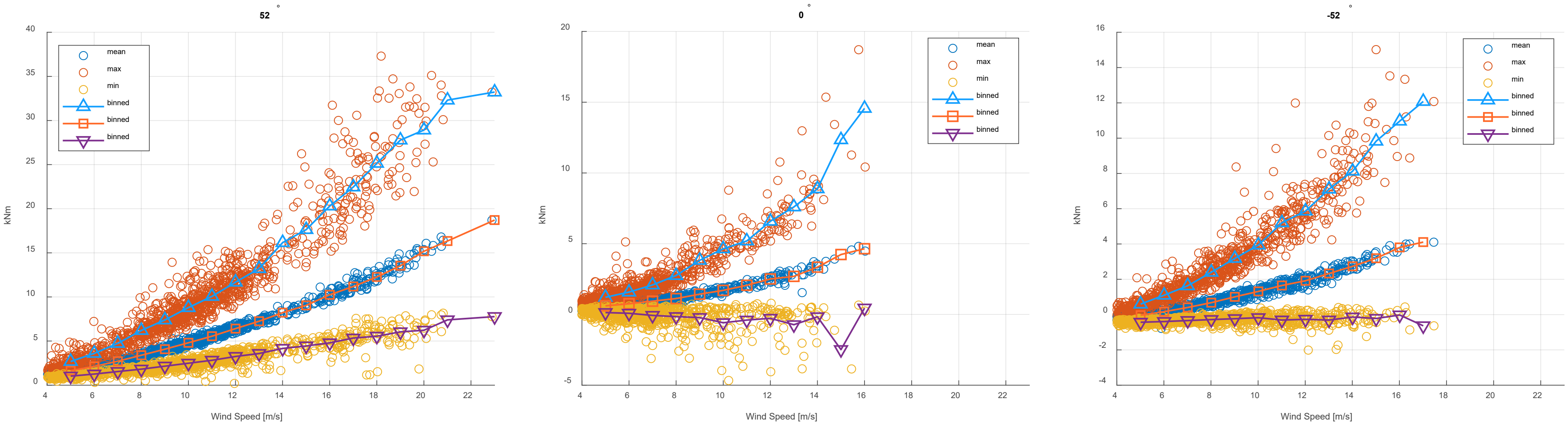
- Higher wind speeds
- 17 m/s and 18 m/s are statistically complete
  - Exception of +10° and -20° stow angles

- -40° remains most favorable
- Positive angles, consistently higher loads.



Pier Bending Moments—Scatter and Binned

- Examples of statistical scatter and binning



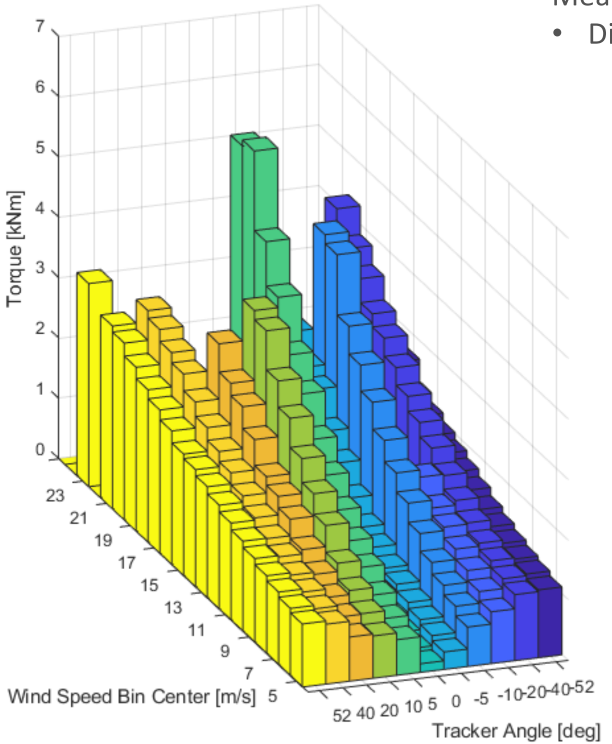
- Generally, other tracker angles follow these trends
- Torque scatter displays similar trends.

Torque Tube Loads

Absolute value of mean torsional loads at drive only

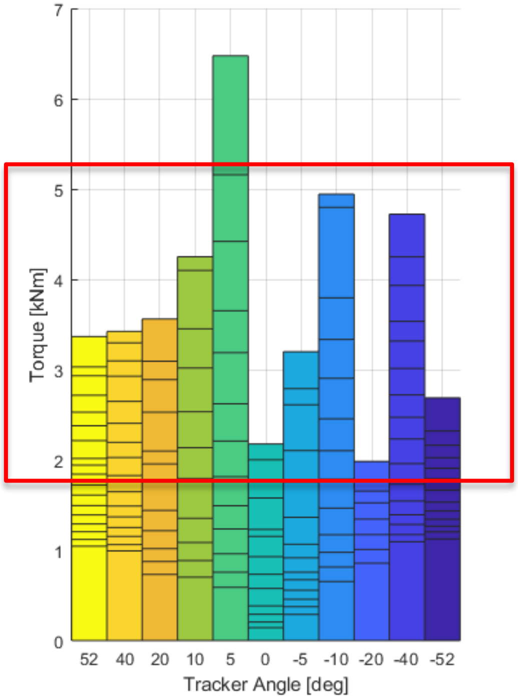
As with all data, some limitations:

- -20 degrees
- beyond 17m/s



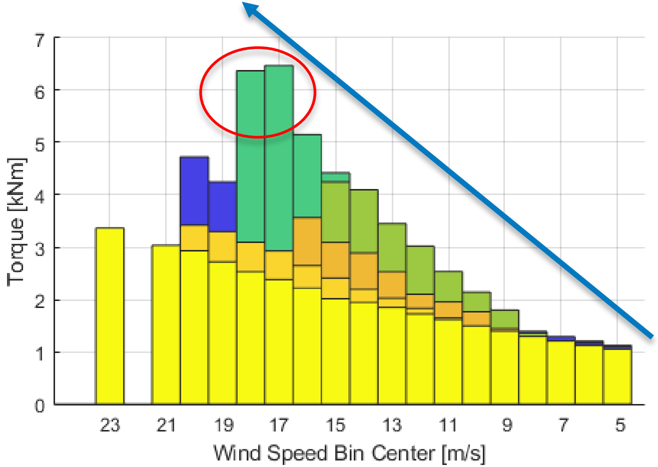
Mean Torque Stow Angle Envelope

- Difficult to ID trend or "favorable" angle



Mean Torque Wind Speed Envelope

- Trends with wind speed
- +5° possible outliers—no statistical relevance



Panel Deflections

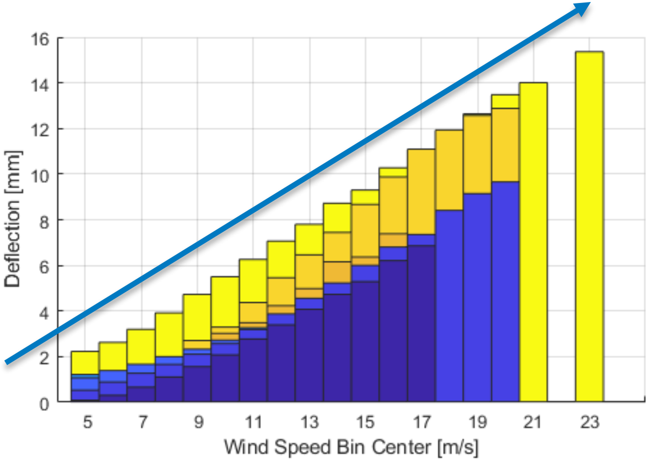
Absolute value of mean deflections at midpanel only

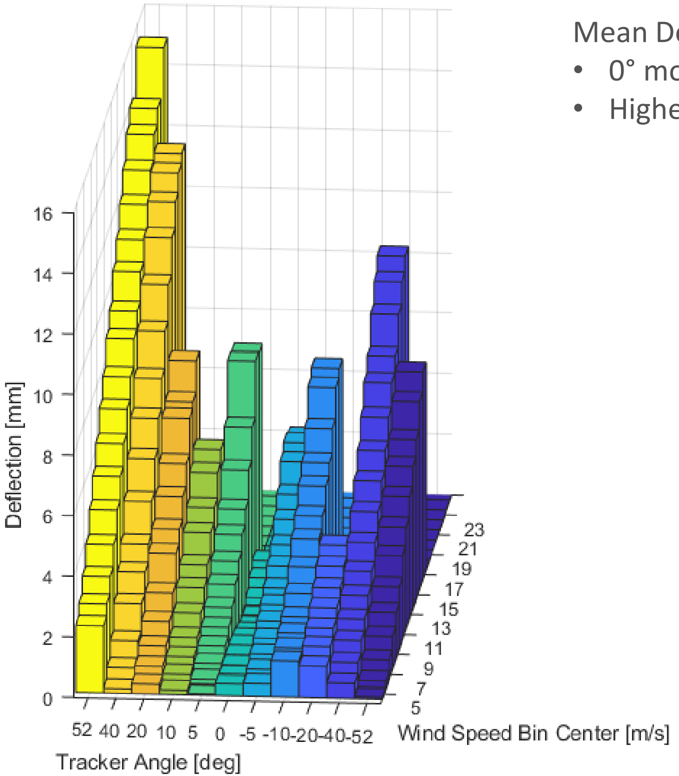
As with all data, some limitations:

- -20 degrees
- beyond 17 m/s

Mean Deflection Wind Speed Envelope

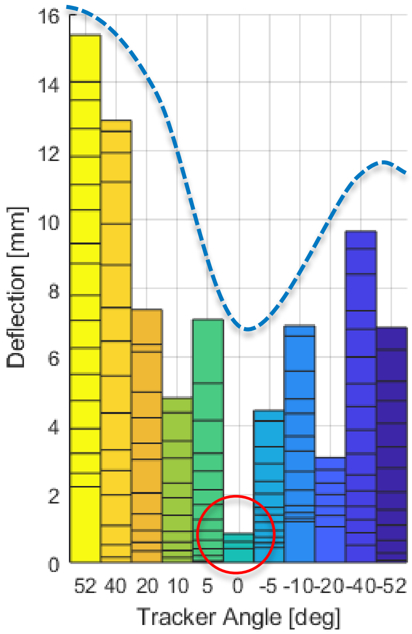
- Trends with wind speed
- Common artifact among all components



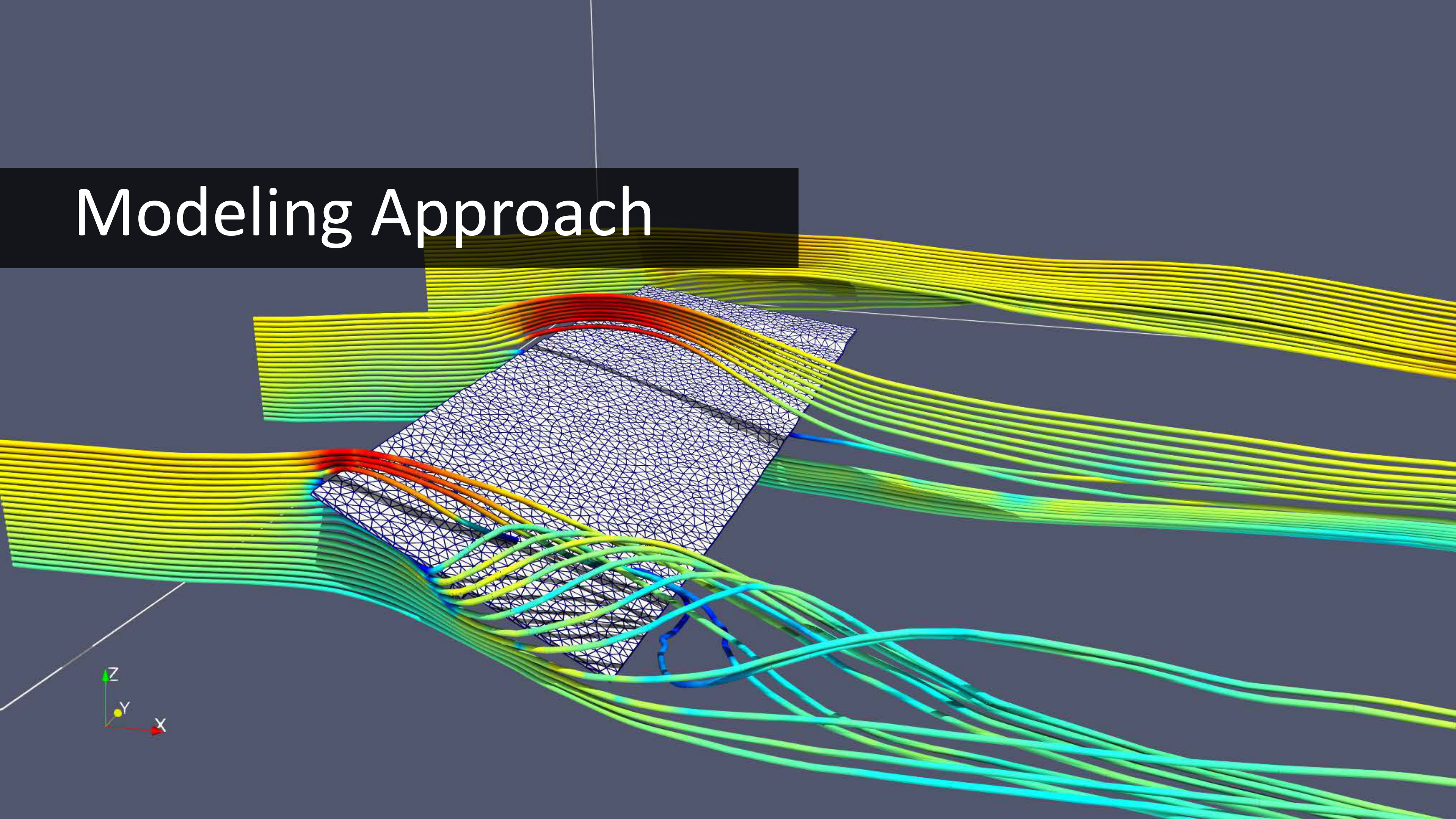


Mean Deflection Stow Angle Envelope

- 0° most favorable, as expected
- Higher angles result in largest deflections



Modeling Approach

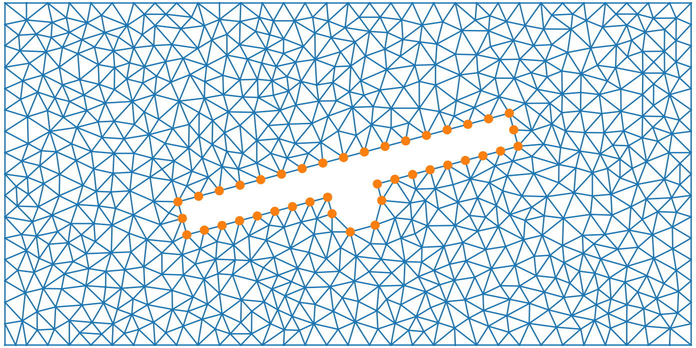


Methodology

- A pressure correction scheme is used to solve the Navier-Stokes equations while enforcing incompressibility.

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{c}\cdot\nabla\mathbf{u}\right) = -\nabla P + \mu\nabla^2\mathbf{u}$$

$$\mathbf{c} = \mathbf{u} - \hat{\mathbf{u}}$$

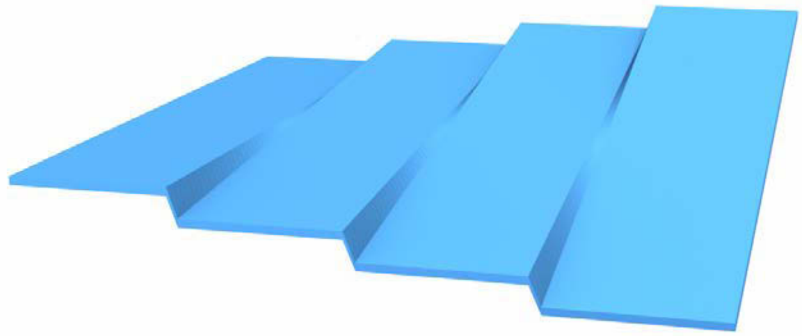


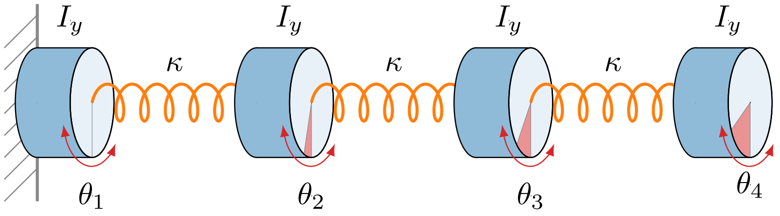
- The fluid stress around the immersed surface creates a torque, τ, on each panel.

Methodology

- Panels are treated as **rigid masses** linked with **rotational springs**.
- This mass-spring approximation is used to model the fluid-structure dynamics.

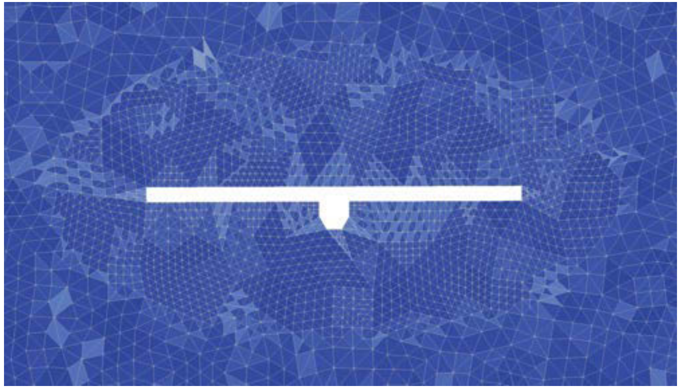
$$I_y \alpha + \kappa \theta = \tau$$



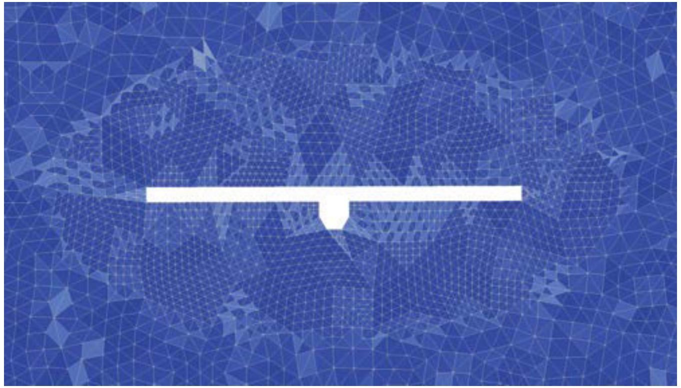


Methodology

- A Laplacian smoothing strategy **preserves cell quality** near the panel surface during mesh motion.



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

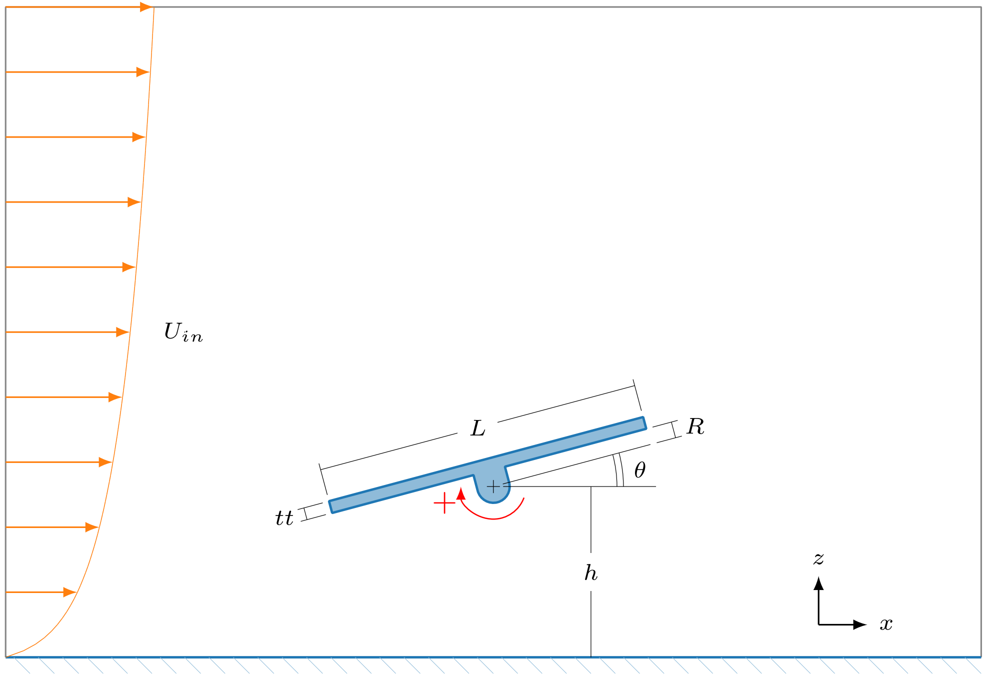


Quadratic diffusivity: $\frac{1}{d^2} \nabla^2 \hat{x} = 0$

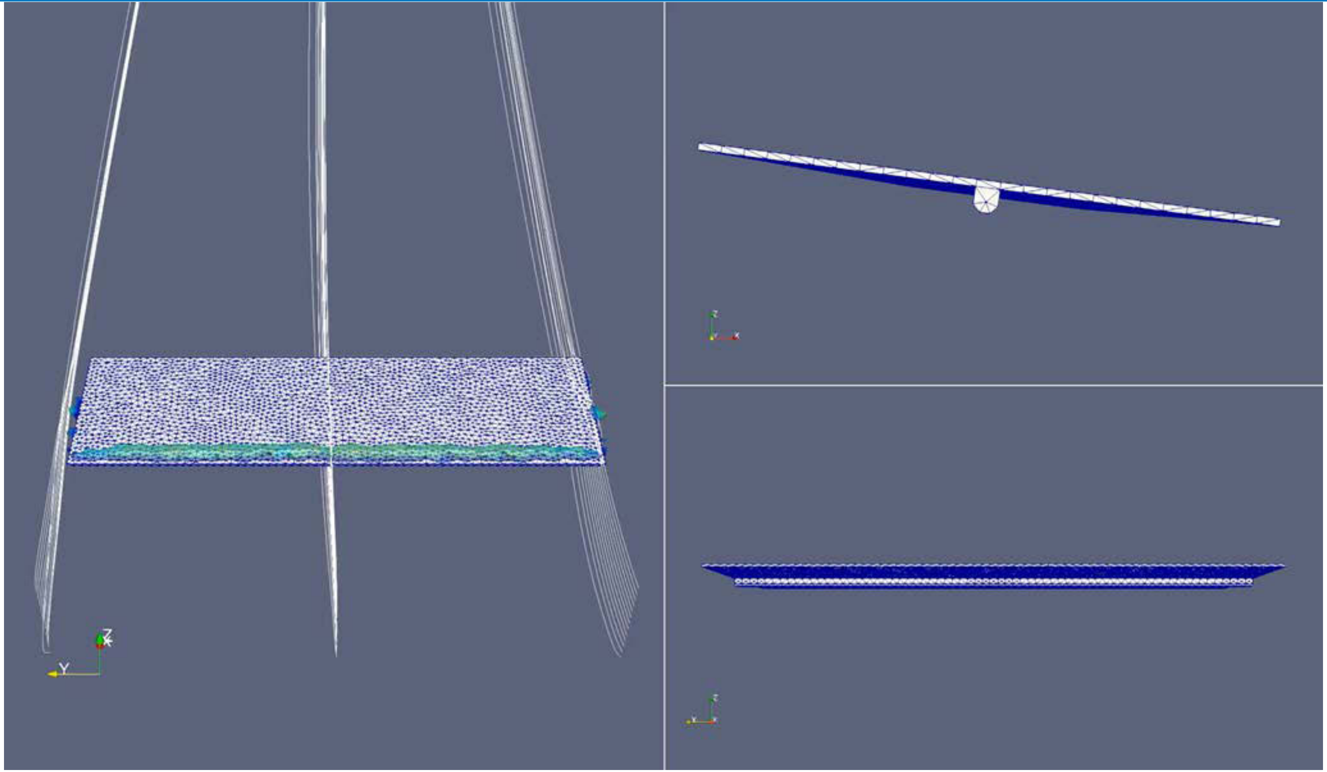
Simulation Setup

Fluid Property	Value
ρ	$1.0\,\mathrm{kg \cdot m^{-3}}$
μ	$1.8 \times 10^{-5}\,\mathrm{Pa \cdot s}$

Structure Property	Value
$L \times W \times tt$	$4\,\mathrm{m} \times 12\,\mathrm{m} \times 0.05\,\mathrm{m}$
h	$2.1\,\mathrm{m}$
R	$0.085\,\mathrm{m}$
E	$148\,\mathrm{GPa}$
m	$50.8\,\mathrm{kg}$



Fluid-Structure Response



$$\theta = +8.5^\circ, \quad \overline{U}_{in} = 40.5 \text{ m/s}$$

Pressure Interpretation

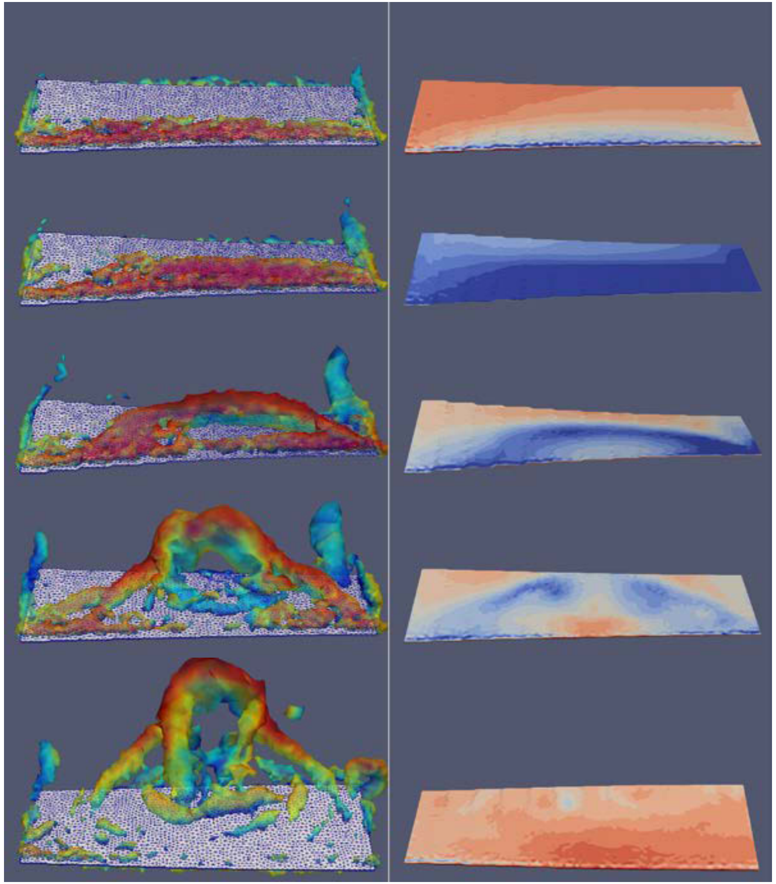
$t^* = 0\,\mathrm{s}$

$t^* = 0.049\,\mathrm{s}$

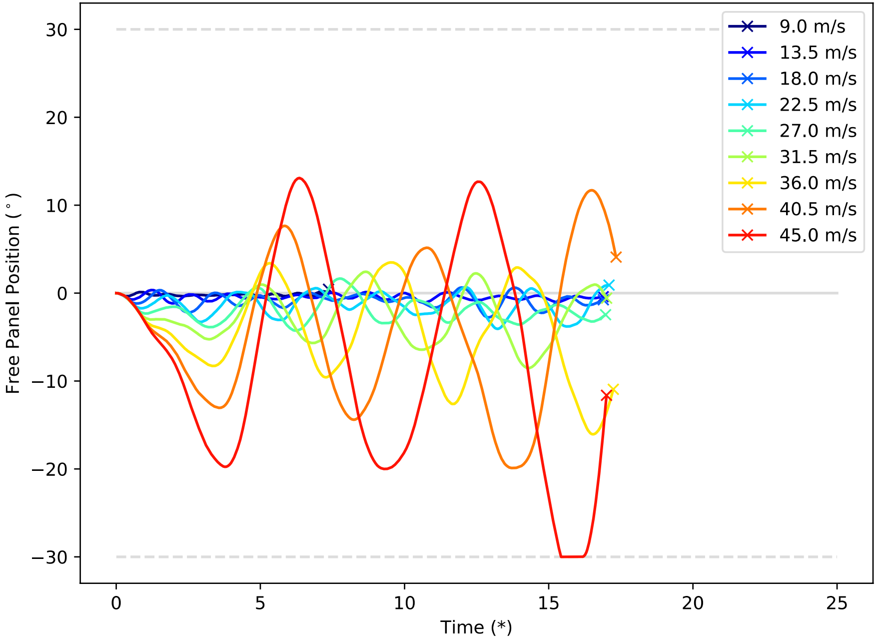
$t^* = 0.148\,\mathrm{s}$

$t^* = 0.247\,\mathrm{s}$

$t^* = 0.346\,\mathrm{s}$

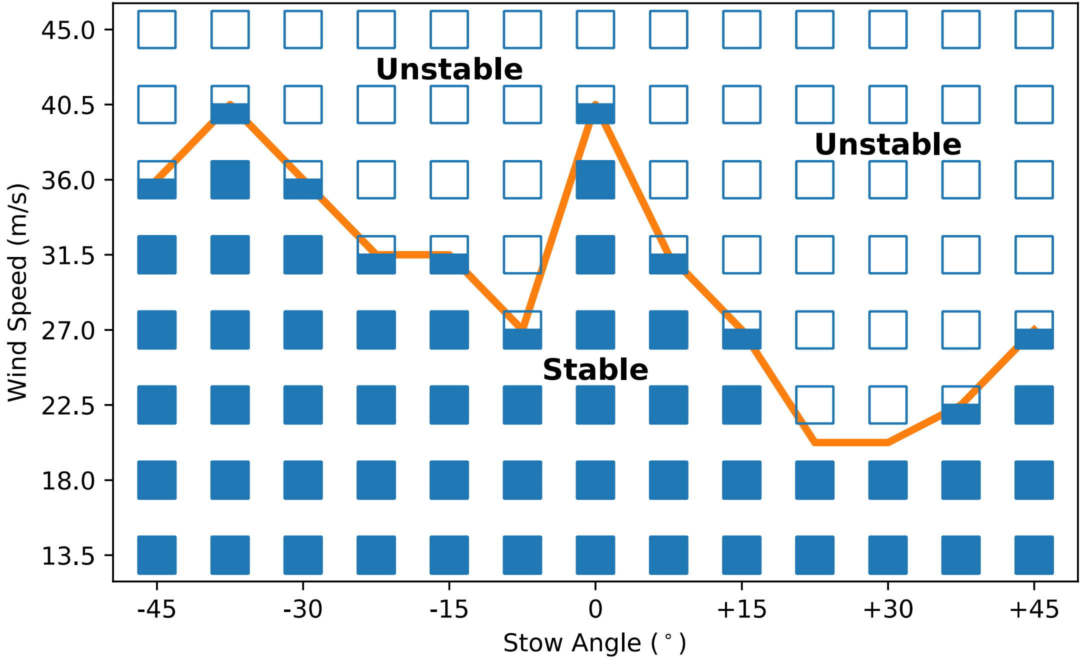


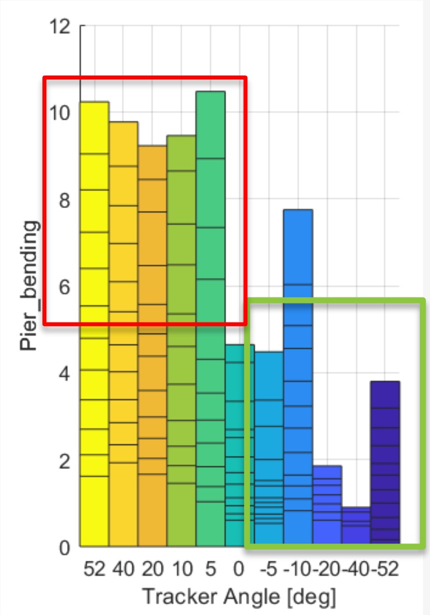
Effect of Wind Speed



Panel stability at $\theta = +8.5^\circ$

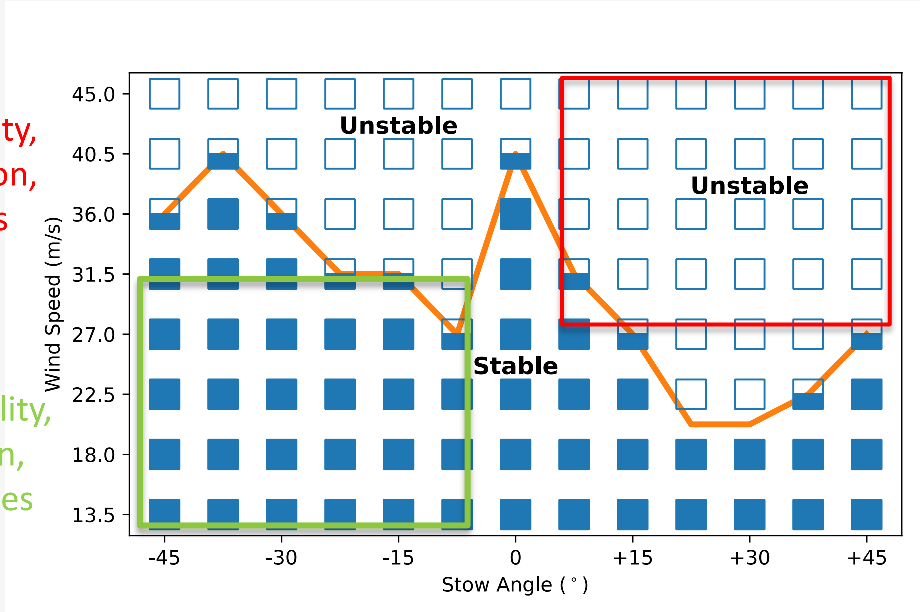
Panel Stability





Lower Stability,
More Rotation,
Larger Forces

Higher Stability,
Less Rotation,
Smaller Forces

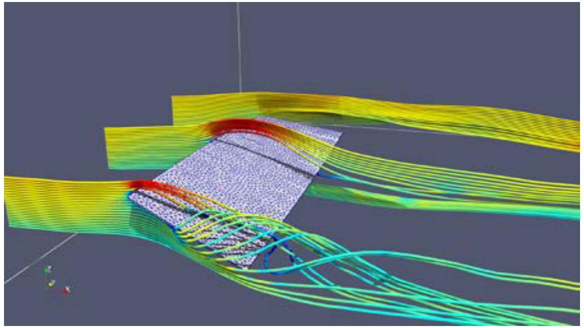


Field & Model Convergence

Both the field campaign and the computational model indicate a significant **sensitivity to panel stow angle**.

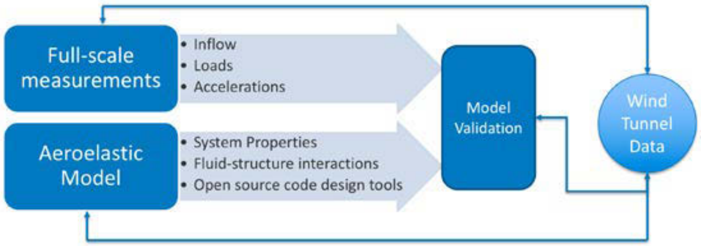
Next Steps

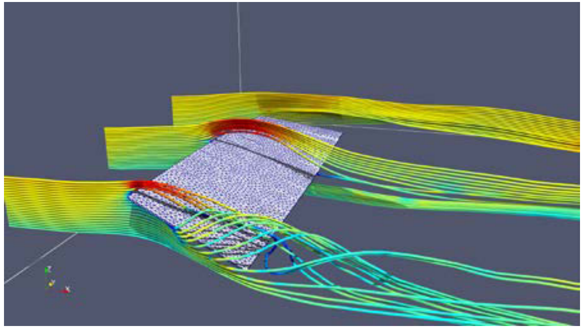
- **Field Campaign**
  - Rich database for ongoing analysis
  - Rigorous study of acceleration trends
    - Operational Deflection Shapes
    - Torsional galloping/divergence ID
  - Component fatigue life studies
  - Round-out database
    - -20° stow angle
    - Higher wind speed bins
    - More stow angles
- **Modeling Approach**
  - Implement improved stability criterion
  - Compounding effect of multiple panel rows
  - High-fidelity model to capture deformation effects.



Next Steps

- **Field-Model Validation**
  - Current efforts have shown good qualitative agreement between field measurements and simulation results regarding stow angle.
  - We currently have a wealth of data to interrogate for the further refinement of both approaches.





Thank You

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