Fluid-structure coupling of a compliant panel installed in a compression ramp at Mach 6: Experiments

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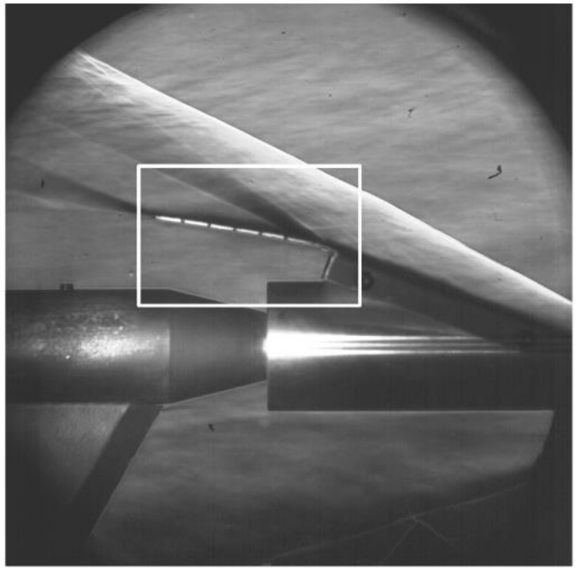
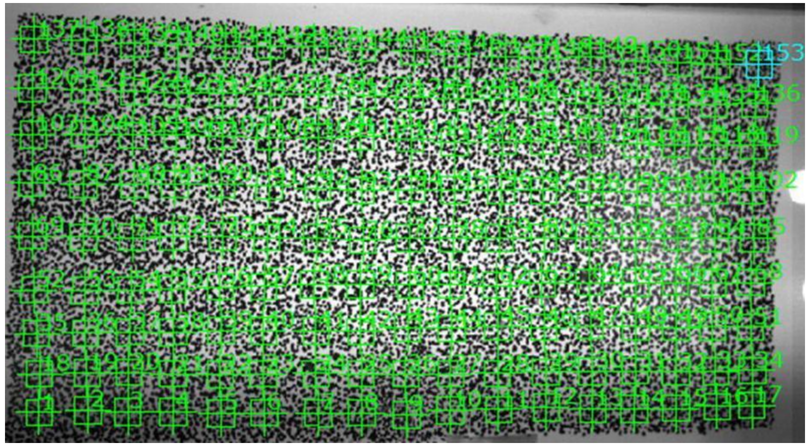
Previous fluid-structure-interaction experiments in high-speed flows

- Very few hypersonic FSI experiments previously been conducted
- Supersonic SWBLI/FSI investigated by Spottswood et al. (2013)
- Cantilevered plate in Mach-6 flow studied by Currao et al. (2016)
- Casper et al. (2016) investigated response of flexible panel to turbulent spots

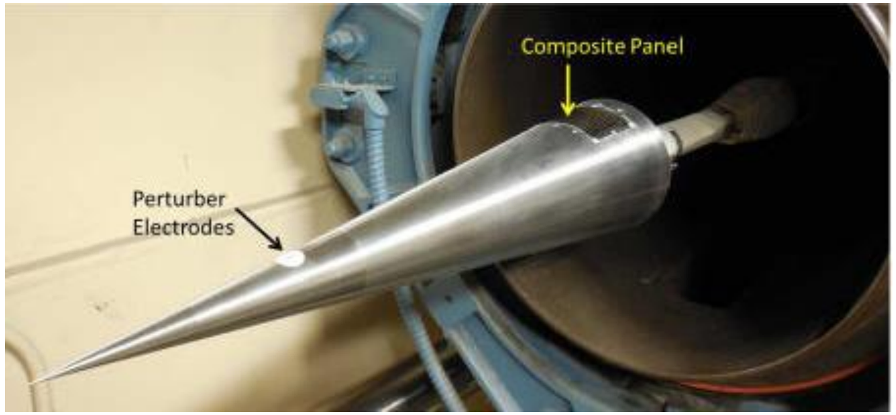


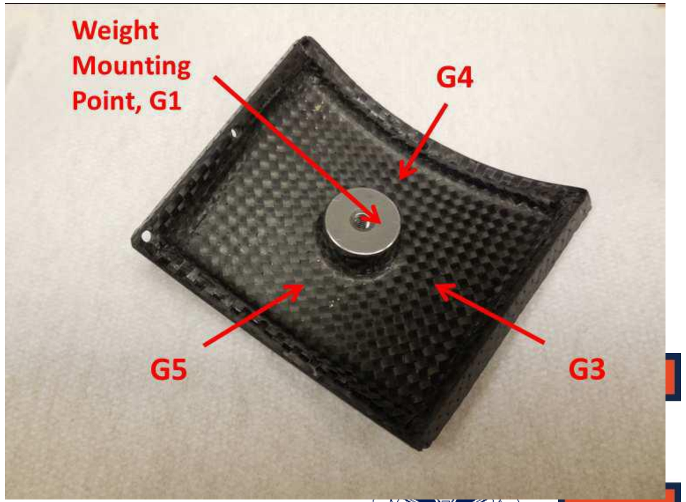
Schlieren image from Currao et al. (2016)



DIC-patterned panel from Spottswood et al. (2013)

Experimental configuration of Casper et al. (2013)

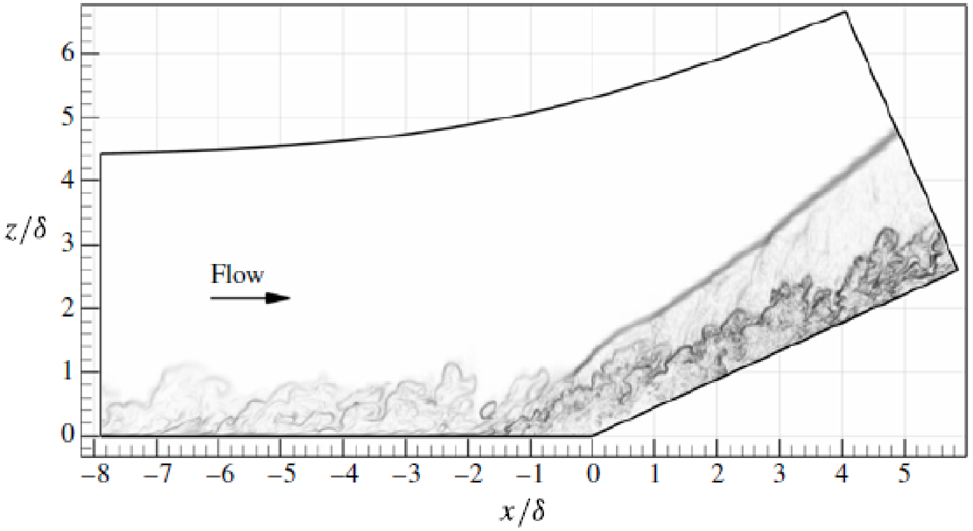




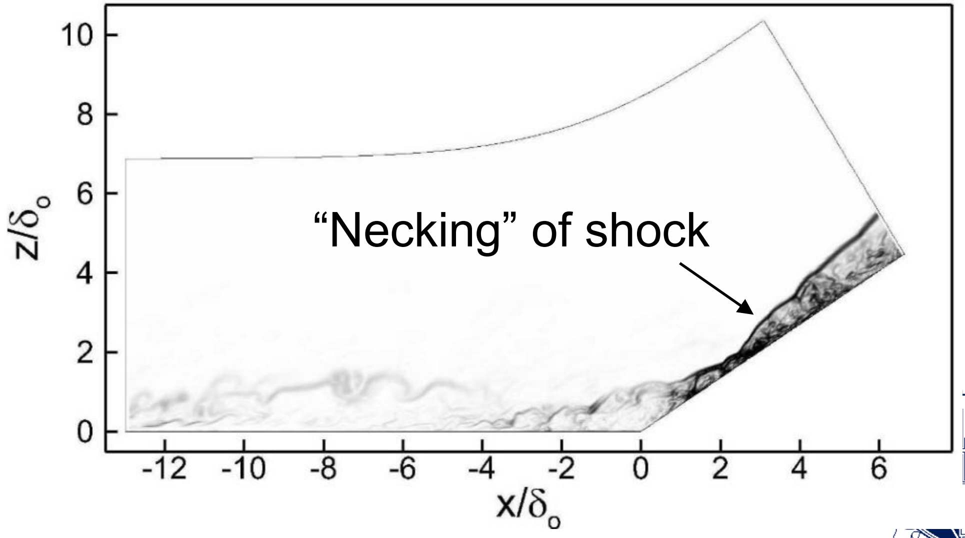
Why shock-wave/boundary-layer interactions?

- No previous FSI measurements on ramp-induced hypersonic SWBLIs in open literature
- Hypersonic interactions show notable differences from supersonic ones, producing extremely high pressure fluctuation levels, also with significant low frequency content and large subsonic region in separated cases
- Therefore, might expect ramp-induced SWBLI to be worst-case scenario for external FSI

Mach 2.9 (Priebe & Martin, 2012)



Mach 9.6 (Helm & Martin, 2016)

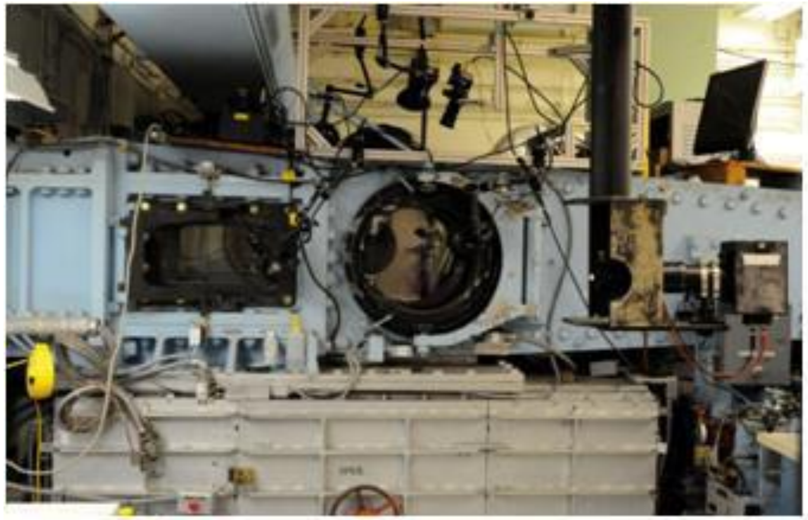

“Necking” of shock

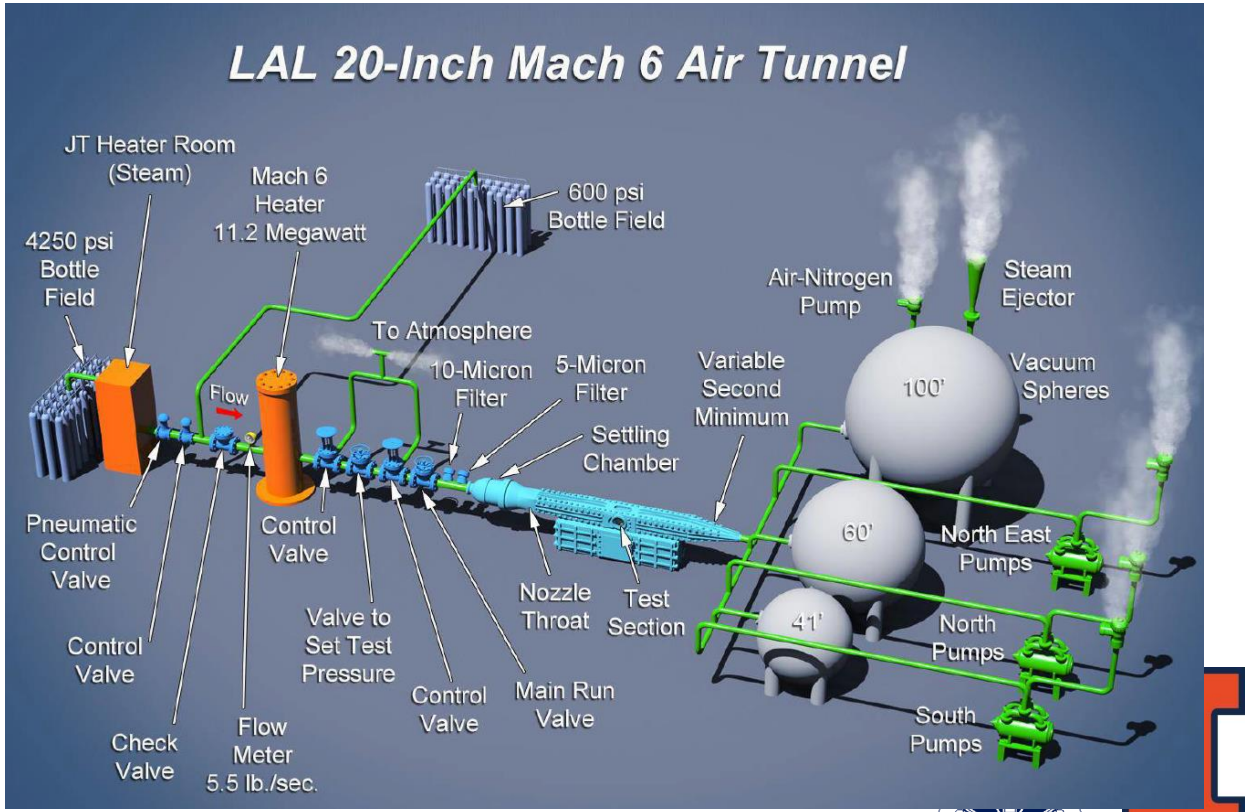
I. Experimental apparatus

Test facility

- Tests performed in NASA Langley 20” Mach 6 tunnel
- Test times potentially up to minutes, but limited here to a few seconds by camera memory
- Two test conditions to investigate influence of incoming boundary-layer state
- Total pressure and temperature variations during run <0.1%

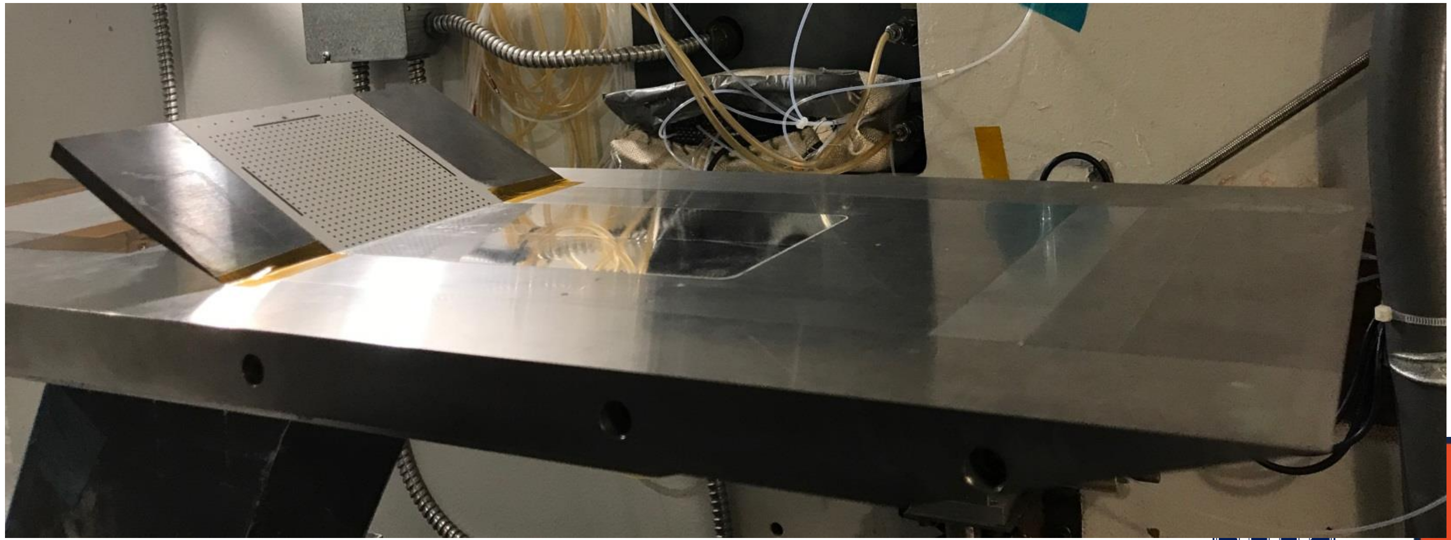
Condition	A	B
M_∞	5.96	6.04
Re_∞ [10^6 1/m]	6.6	23.6
P_∞ [kPa]	0.57	2.04
T_∞ [K]	62.7	63.6
ρ_∞ [kg/m^3]	0.113	0.032
u_∞ [m/s]	946	962





Experimental model

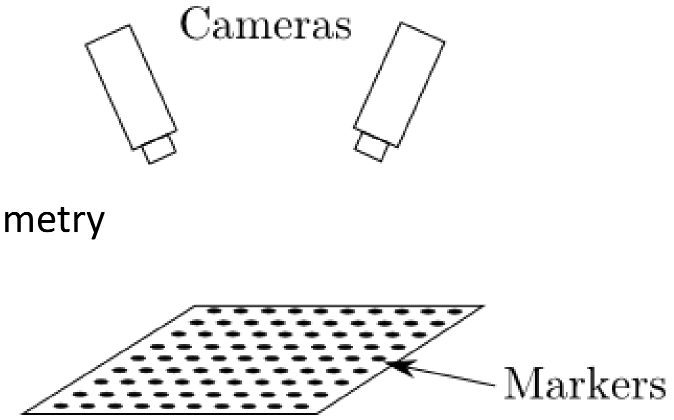
- Flat plate/compression ramp with angles of 10°, 20°, 30°-35°
- Ramp corner located 356 mm from leading edge - transitional and turbulent incoming boundary-layer states for Conditions A & B respectively
- Compliant structure incorporated in ramp:
  - 4140 steel, 0.032” thick, 3.5” wide by 3.475” long
  - Well below flutter boundary at tested conditions
- Flush-mounted Kulite pressure sensors on centerline upstream and downstream of panel
- 25 x 25 grid of markers on panel for photogrammetry, recorded at 30 kHz (Phantom v2512s)
- Pressure beneath panel uncontrolled (but measured)



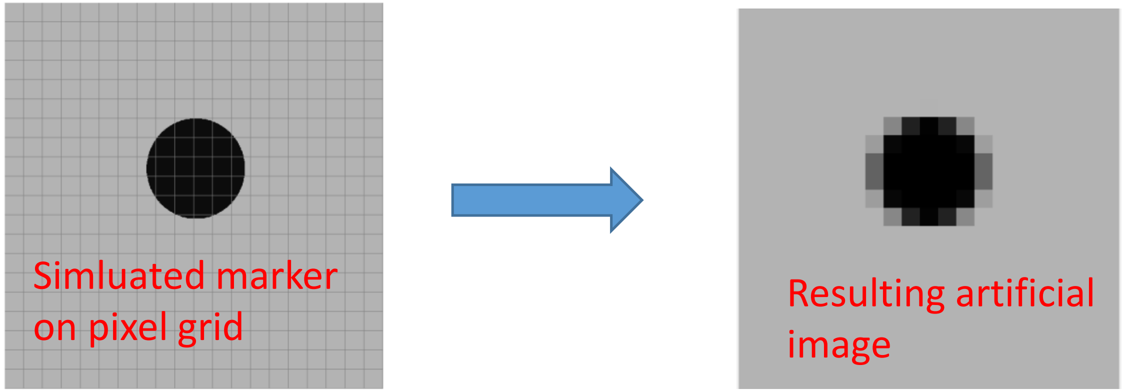
Development of high-accuracy photogrammetry

- Photogrammetry allows sparse, localized markers and absolute position measurements, though displacement accuracy traditionally lower than DIC
- Marker position evaluated through least-squares fitting of intensity profile instead of center-of-mass calculation
- Accuracy evaluated through artificial image analysis
  - Average position error ~0.015 pixels (comparable to DIC), relatively insensitive to marker diameter

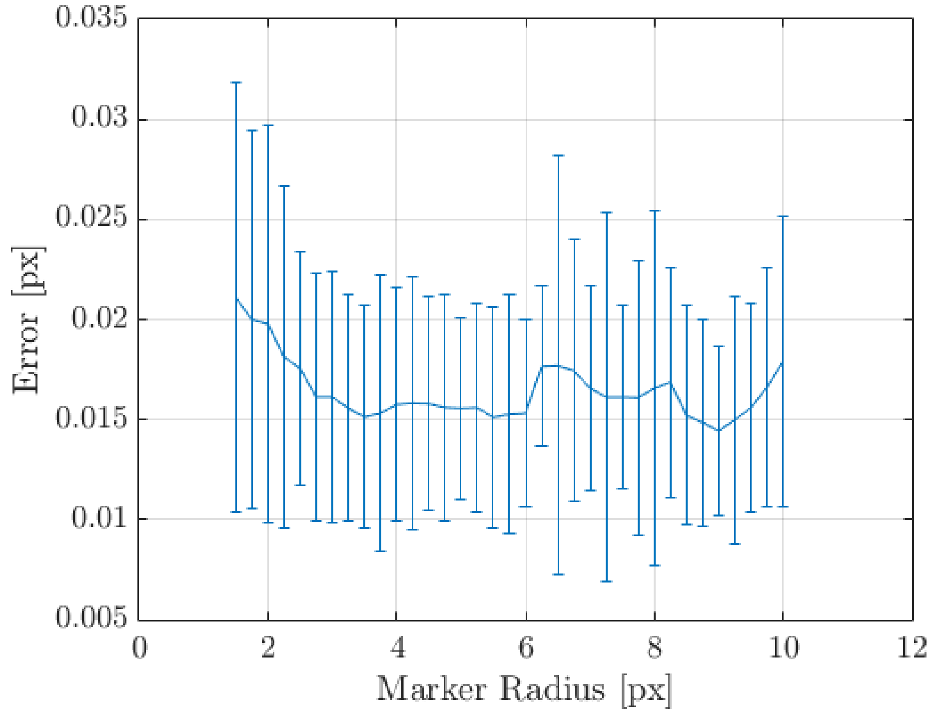
$$I = A\left\{\tanh\left[p\left(\sqrt{(\tfrac{x'}{a})^2+(\tfrac{y'}{b})^2}+1\right)\right]-\tanh\left[p\left(\sqrt{(\tfrac{x'}{a})^2+(\tfrac{y'}{b})^2}-1\right)\right]\right\}$$



Photogrammetry setup

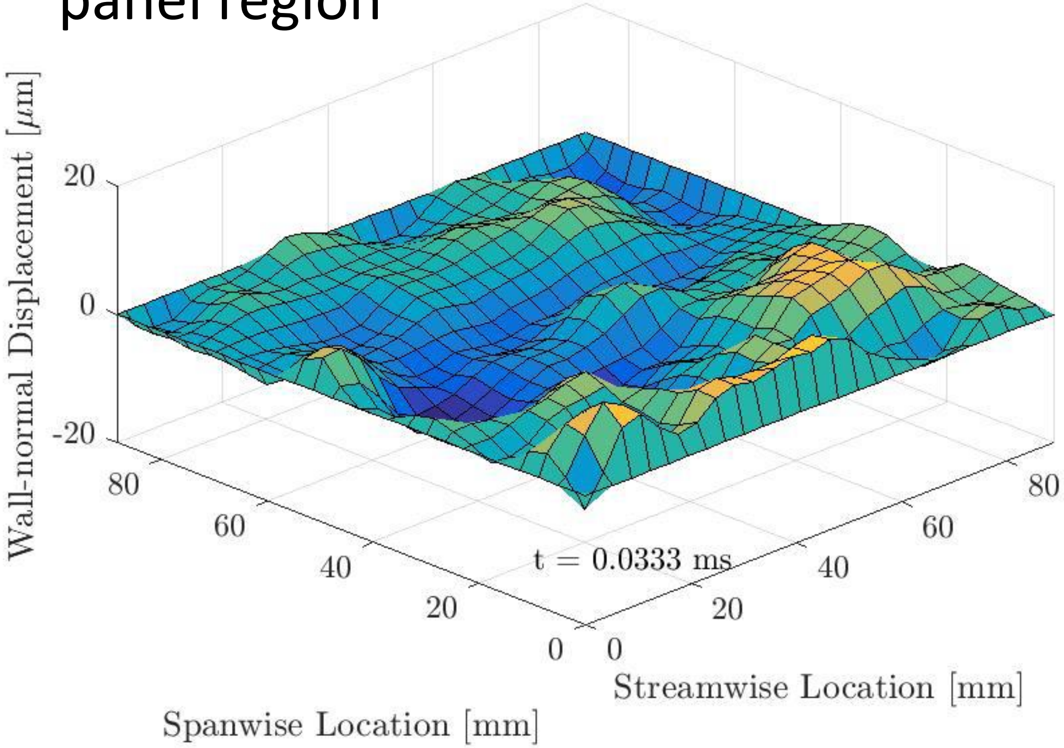

Simluated marker on pixel grid

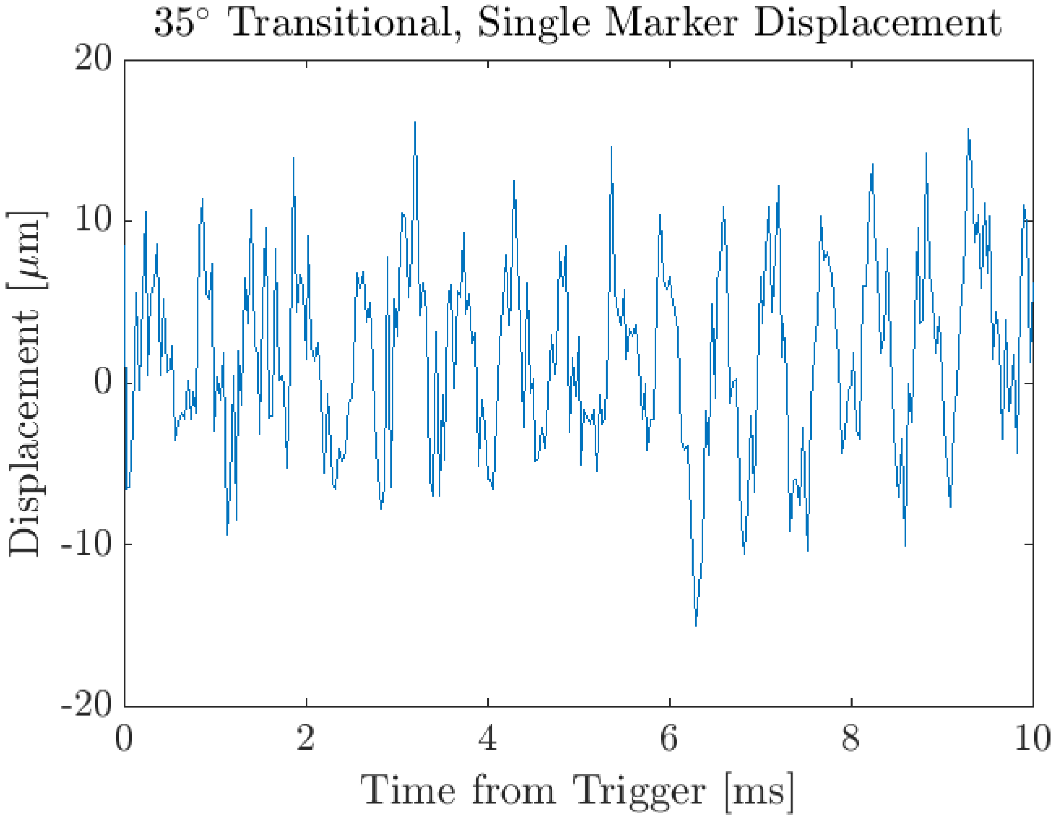
Resulting artificial image



Development of high-accuracy photogrammetry

- Ray-tracing analysis of DNS of shock-wave/boundary-layer interaction indicated refractive errors should be negligible for present application
- Experimental errors (out-of-plane) estimated as 2-4 μm
- Allows high-speed (>10 kHz) micron-level out-of-plane measurements over entire panel region





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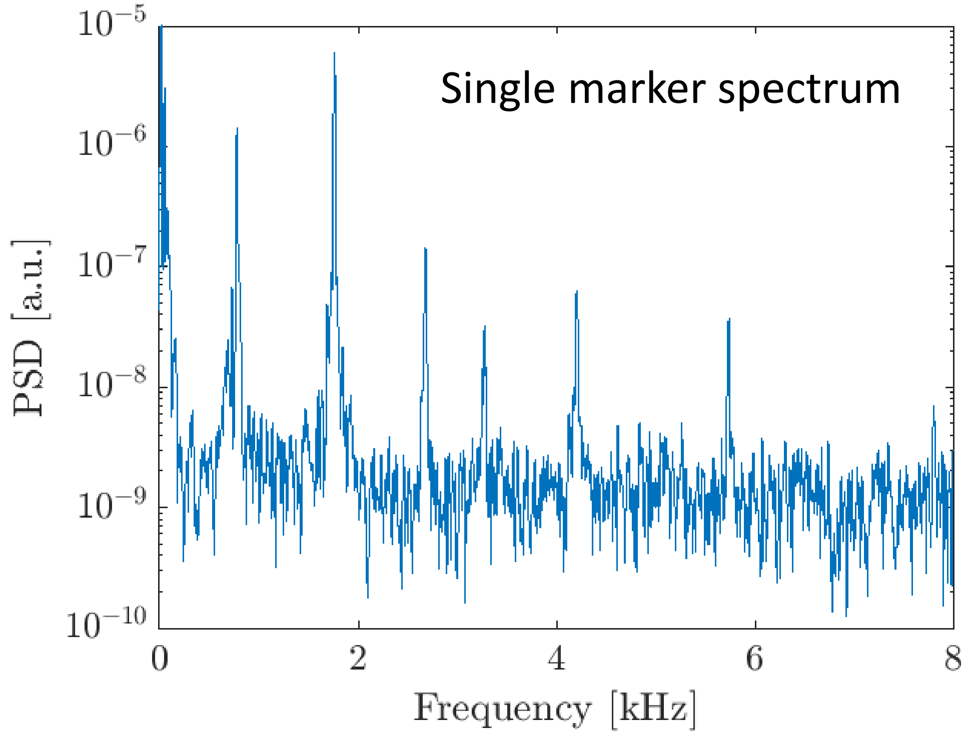
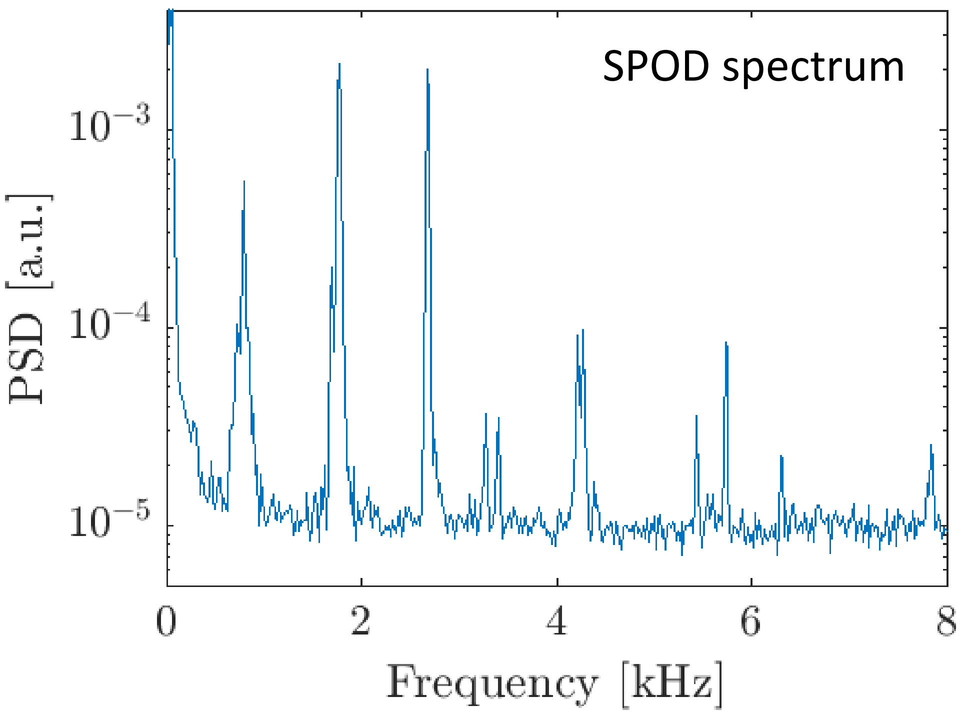
Integration with Spectral POD method

- Spectral Proper Orthogonal Decomposition (SPOD) (re-)introduced to community by Towne et al. (2018)
- Uses data from all markers to determine dynamic modes at each frequency
- Characterizes panel motion as a whole rather than at discrete points





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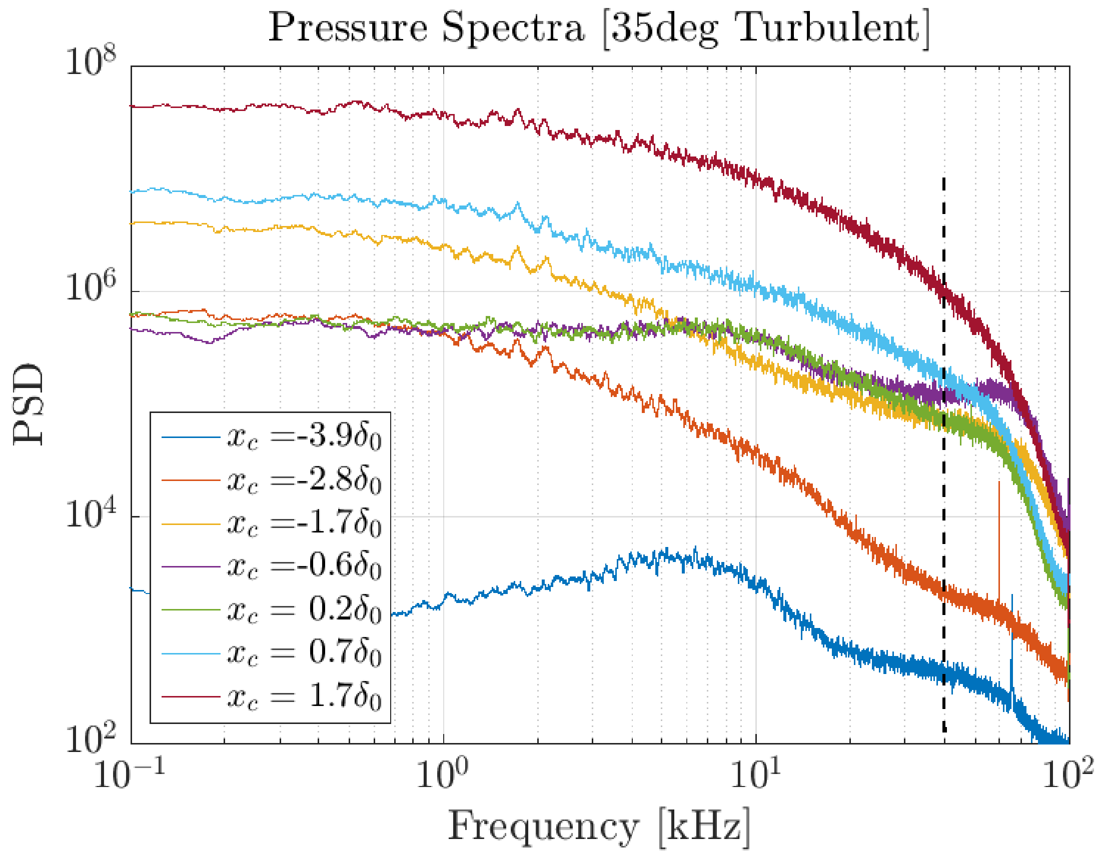
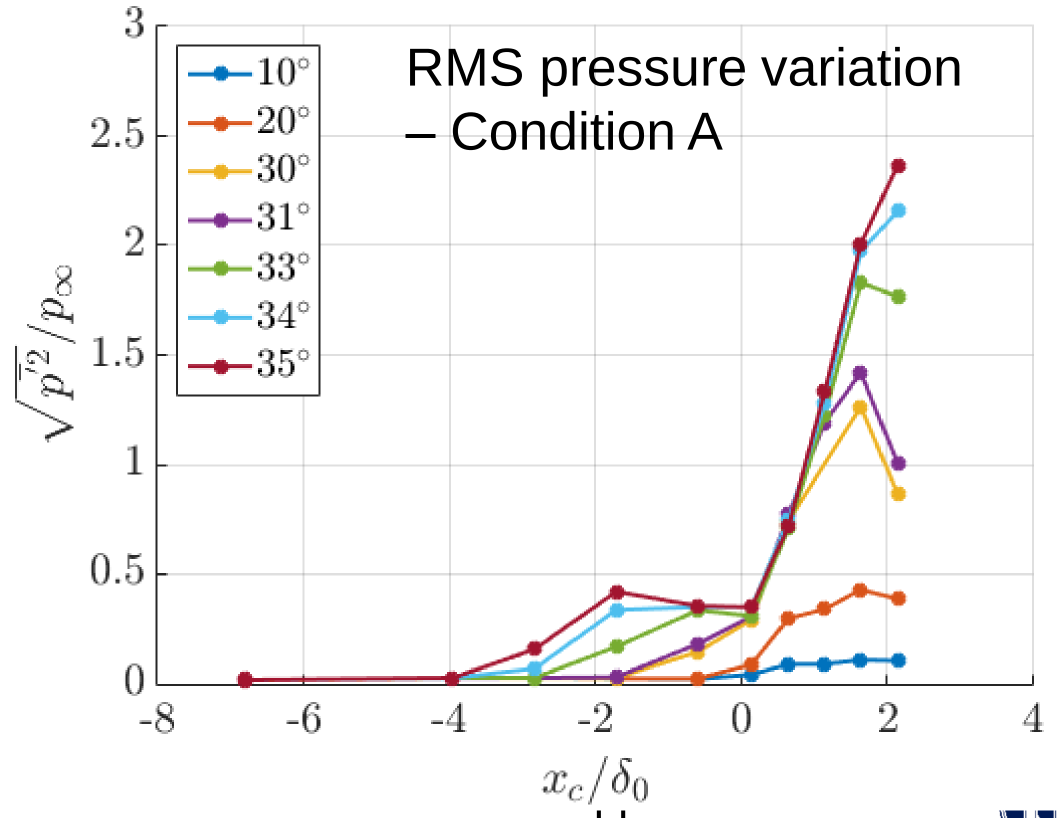
II. Rigid ramp characterization

High-frequency pressure measurements

- Flush-mounted Kulites have flat frequency response up to ~40 kHz
- Significant amplification of pressure fluctuations through SWBLI – maximum of 12% of mean pressure for 35 degree ramp



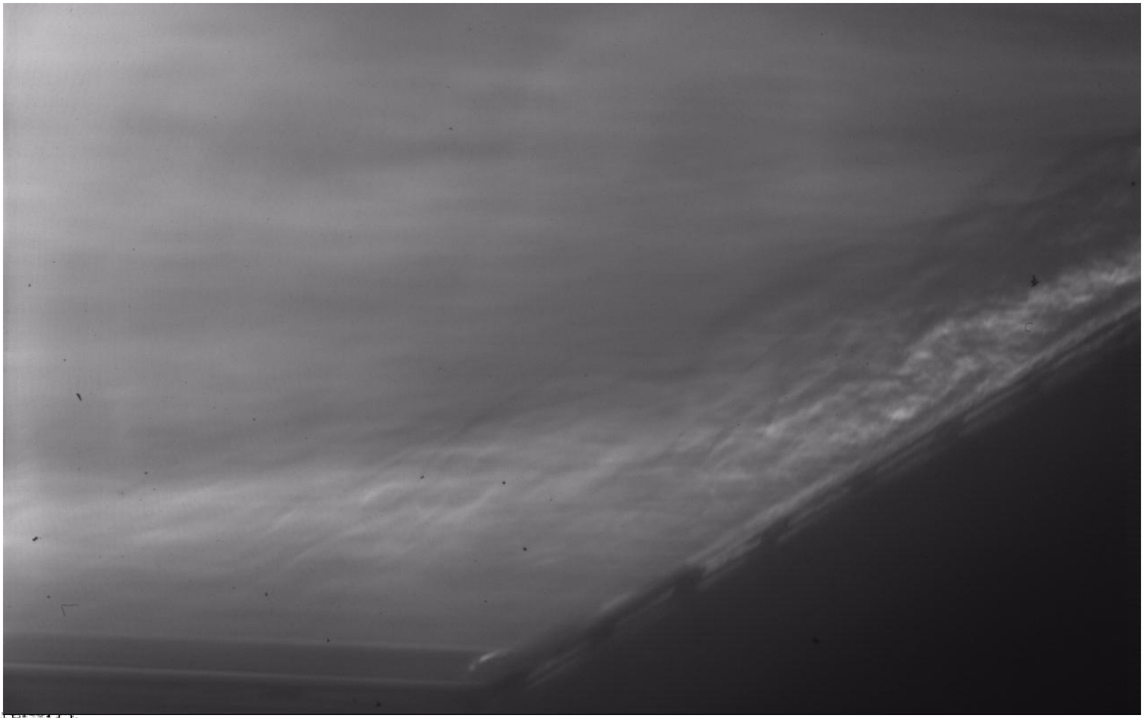


RMS pressure variation – Condition A

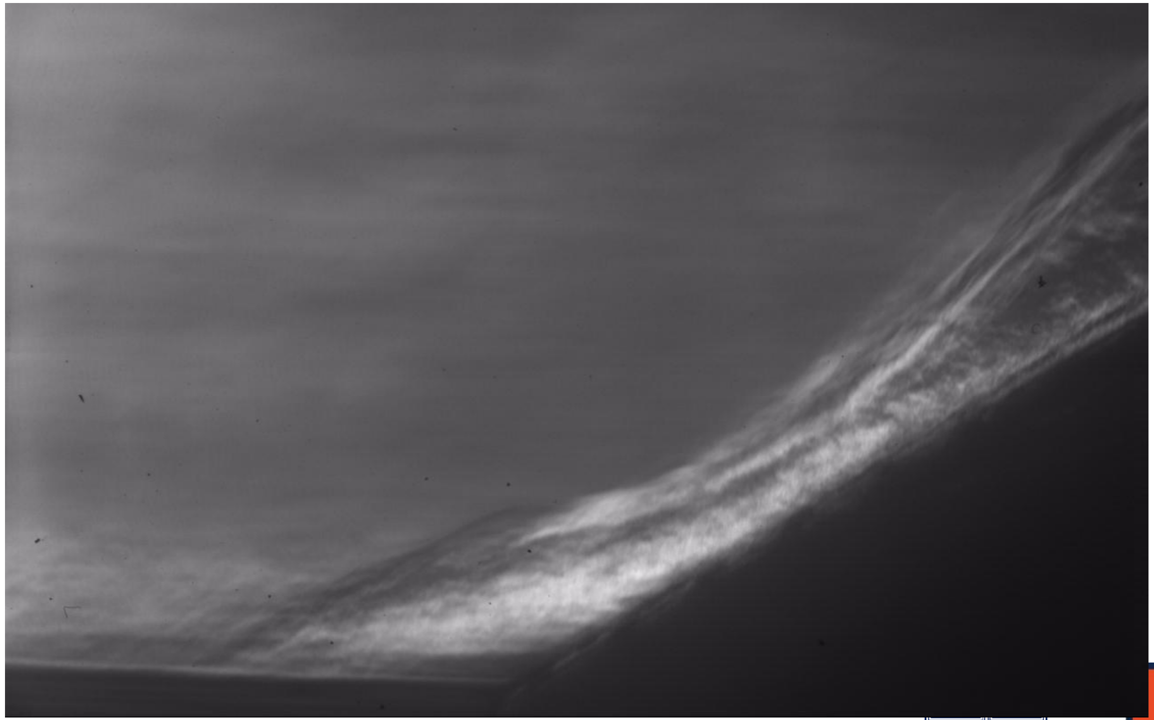
Focusing schlieren visualizations

- Focusing schlieren allows visualization of flow structures near centerline
- Cavilux Smart and Phantom v2512 allow double-pulsed operation for structure tracking
- More information was given in AIAA 2019-1127

Transitional boundary layer, 33° ramp



Turbulent boundary layer, 34° ramp



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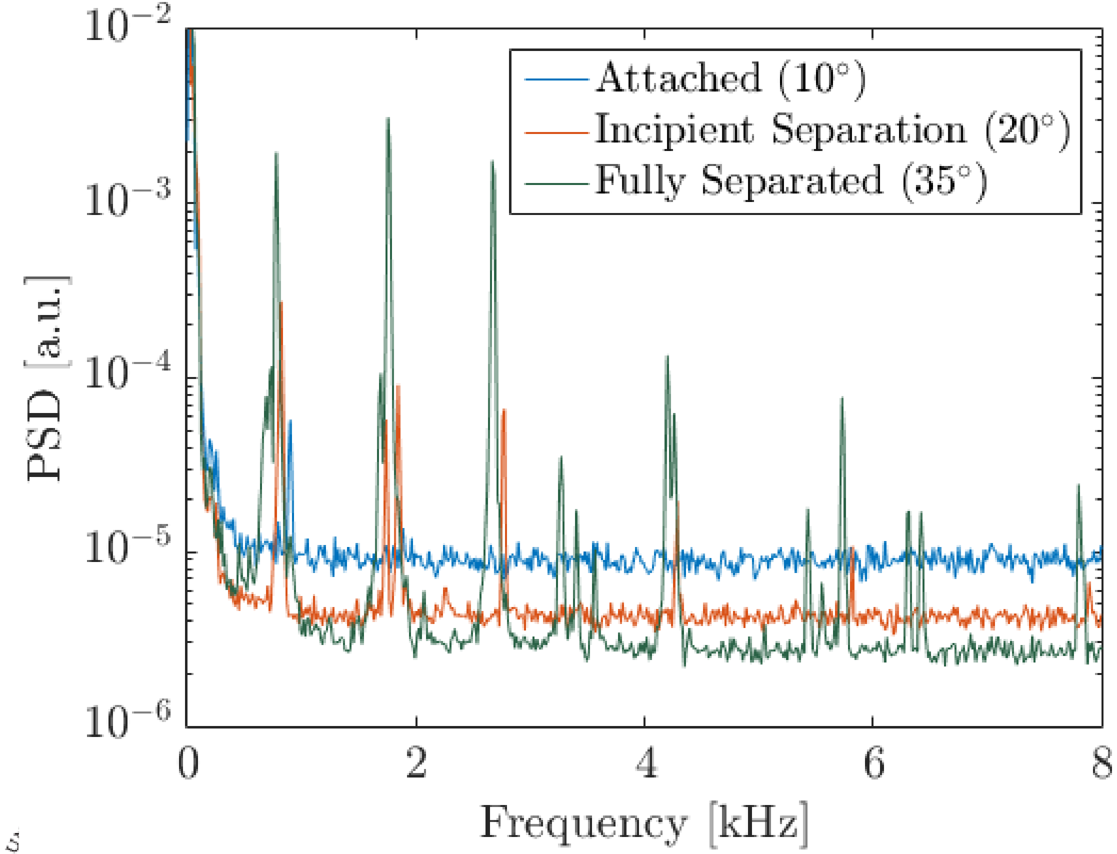
III. Compliant panel results

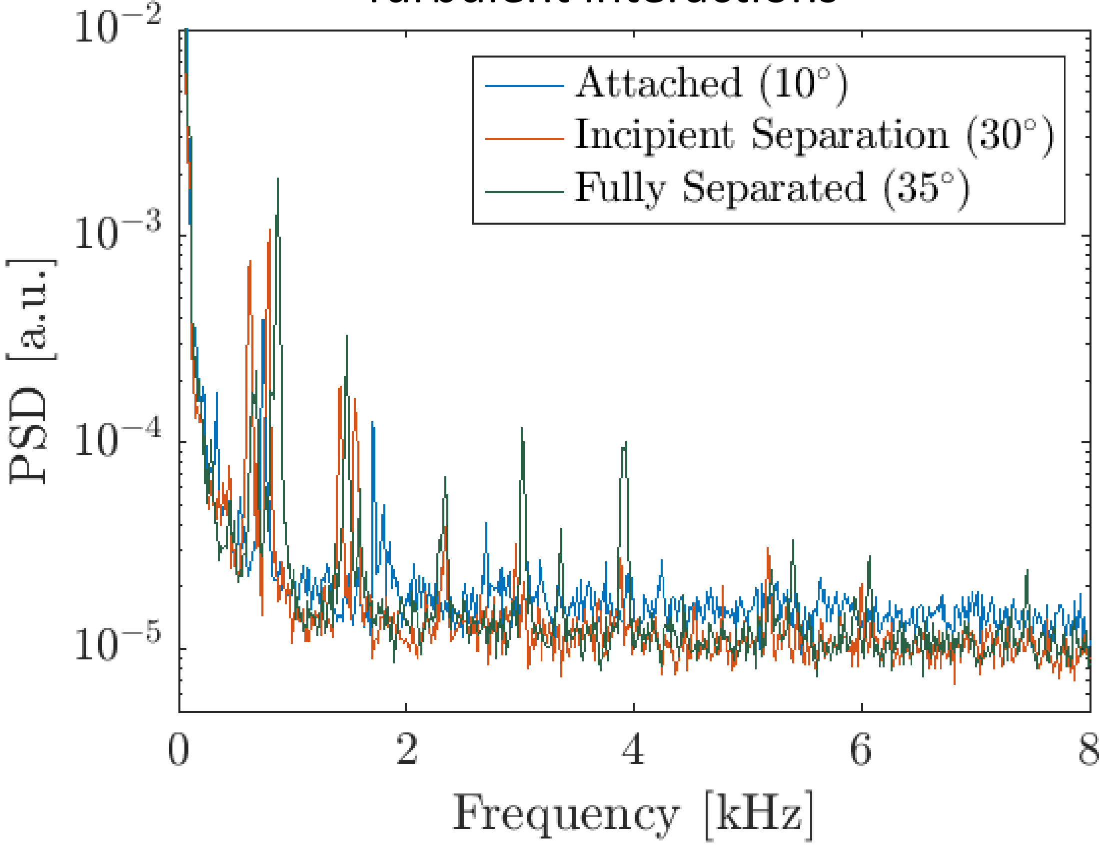
Influence of ramp angle on panel modes

- Fully separated cases show largest panel responses
- Transitional interactions appear to excite broader range of panel modes (esp. asymmetric)
- Shifting of panel modes to lower frequencies with increased interaction strength

Transitional interactions

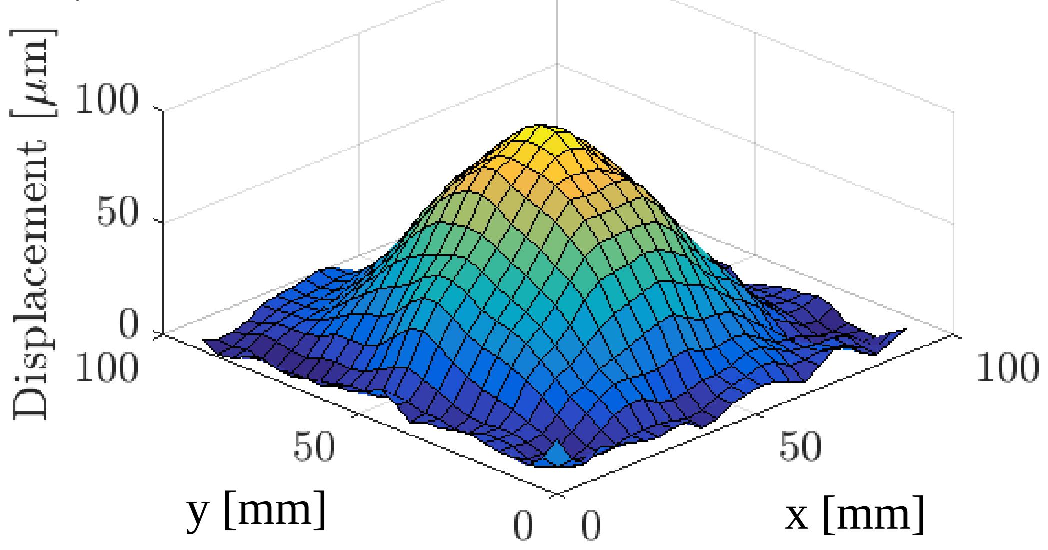


Turbulent interactions

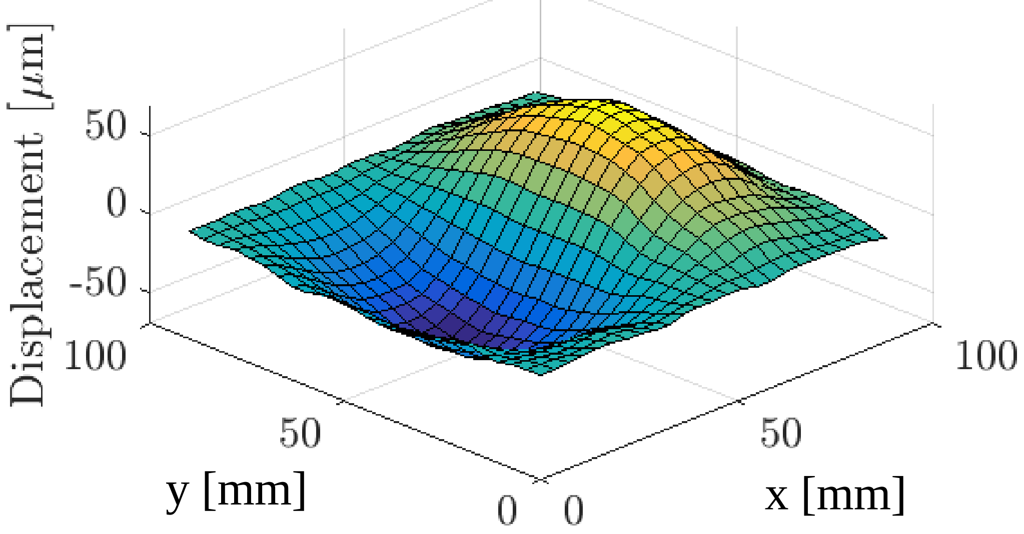


Mode shapes: 35° ramp, transitional boundary layer

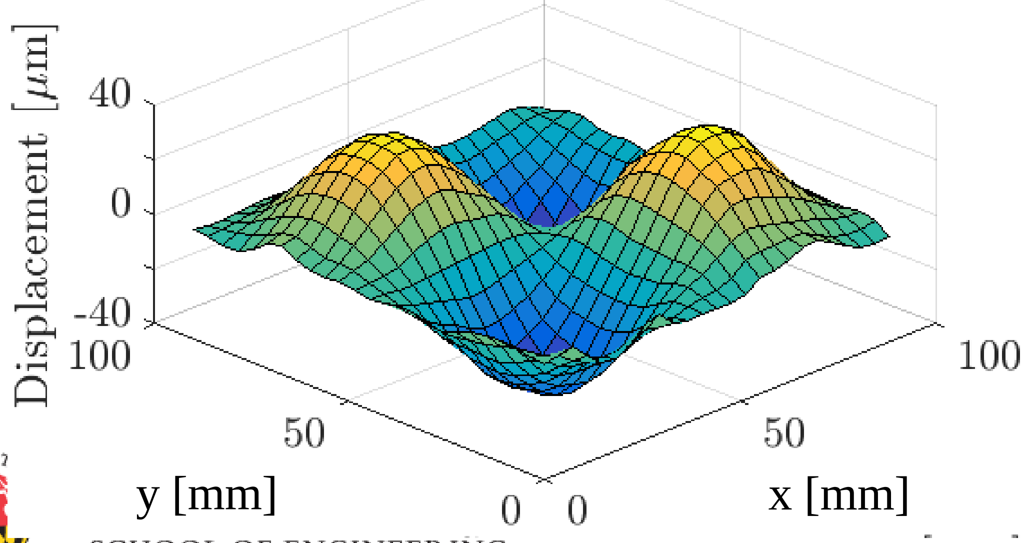
Mode 1,1: 795 Hz



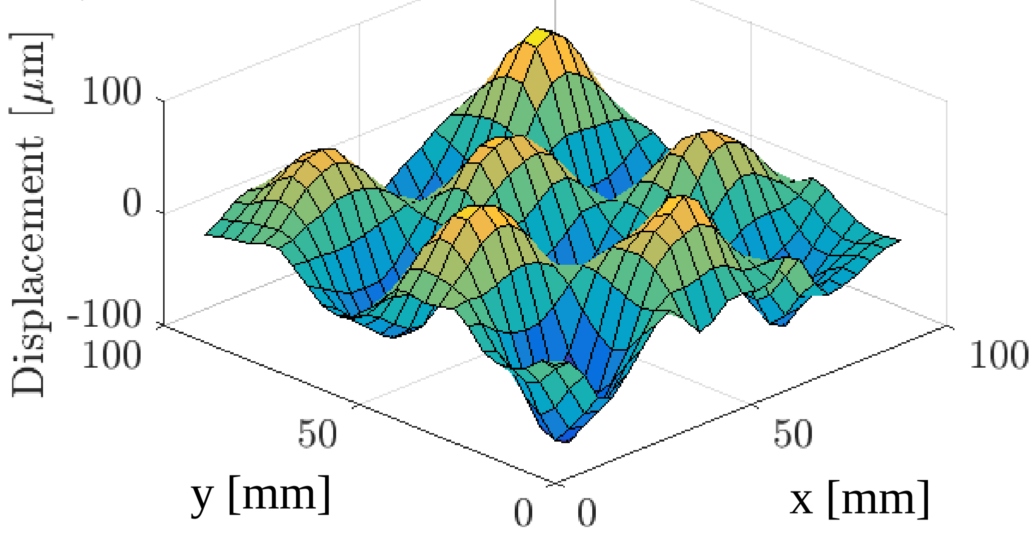
Mode 2,1: 1.77 kHz



Mode 2,2: 2.67 kHz

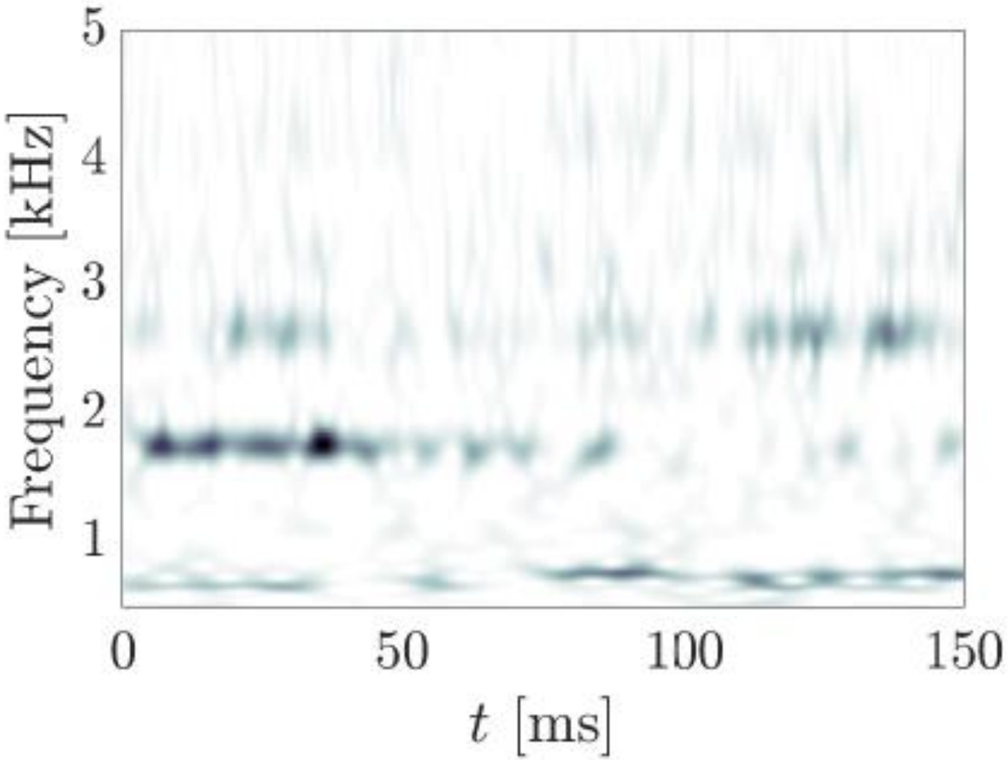


Mode 3,4: 7.8 kHz

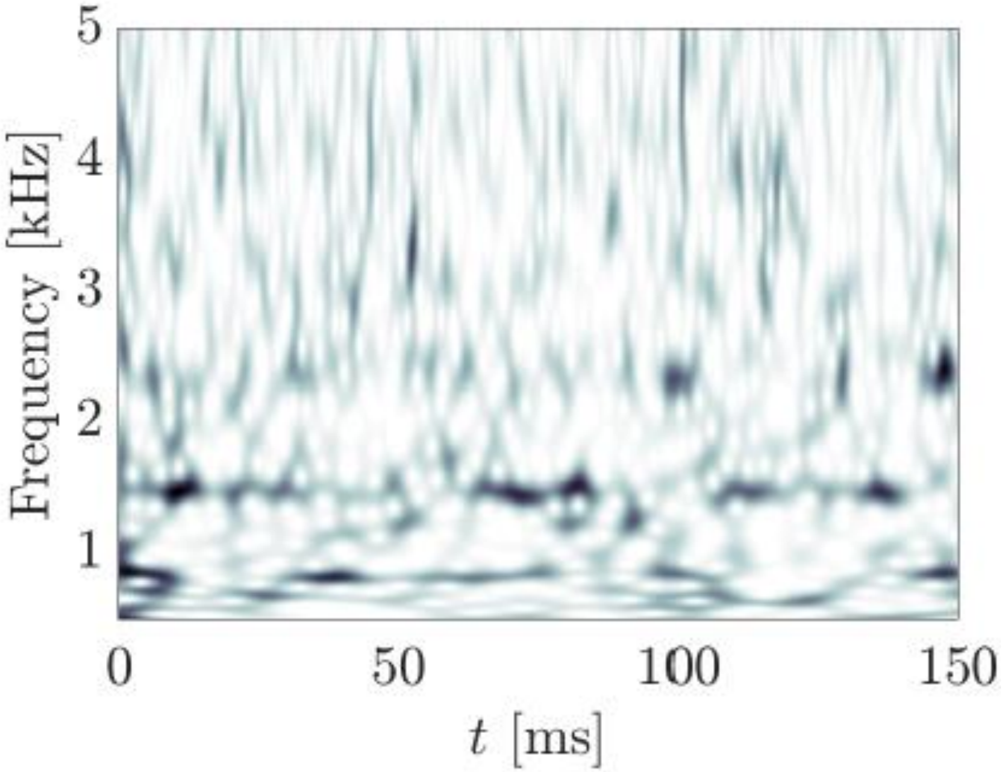


Time series data, 34° ramp

Condition A

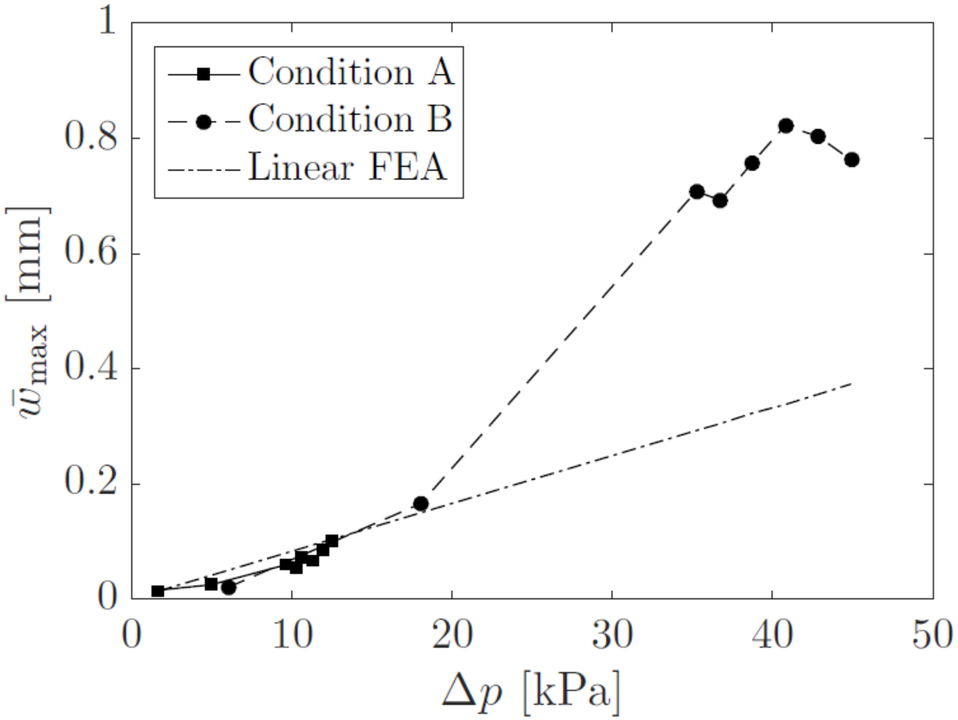


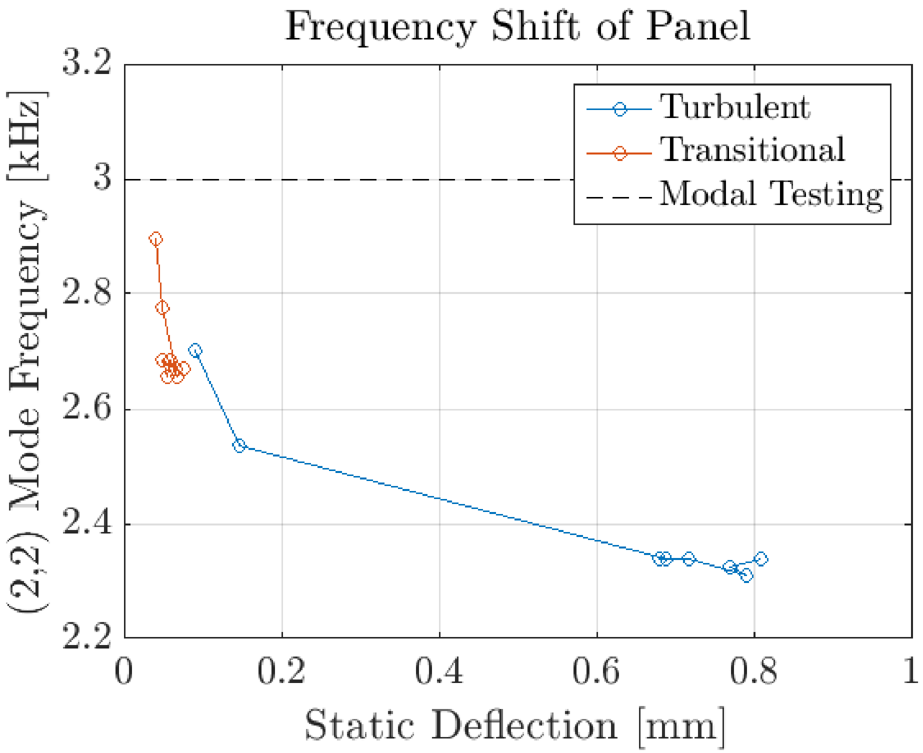
Condition B



- Calculated using wavelet transform of single marker displacement
- Forcing in turbulent case appears far more sporadic
- No discernible link to upstream pressure content on centerline

Static deformation and frequency shifting





- Panel also underwent substantial static deformations, especially for turbulent condition
  - Not well predicted by finite-element analysis
- Shifting of modal frequencies noted earlier appears to be linked to these deformations

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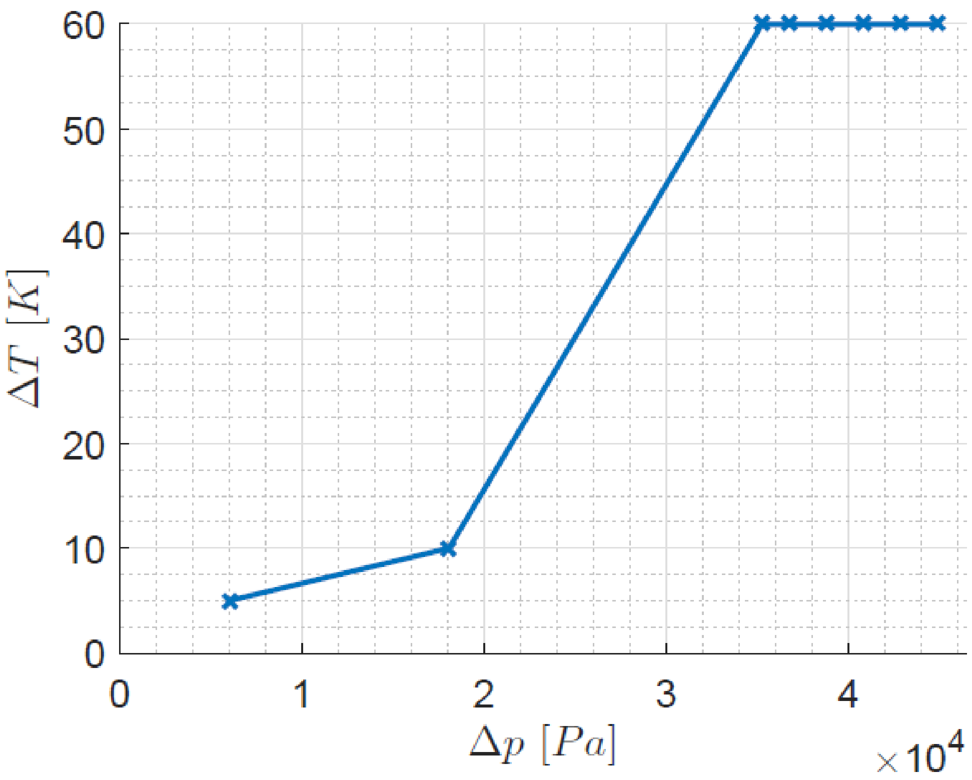
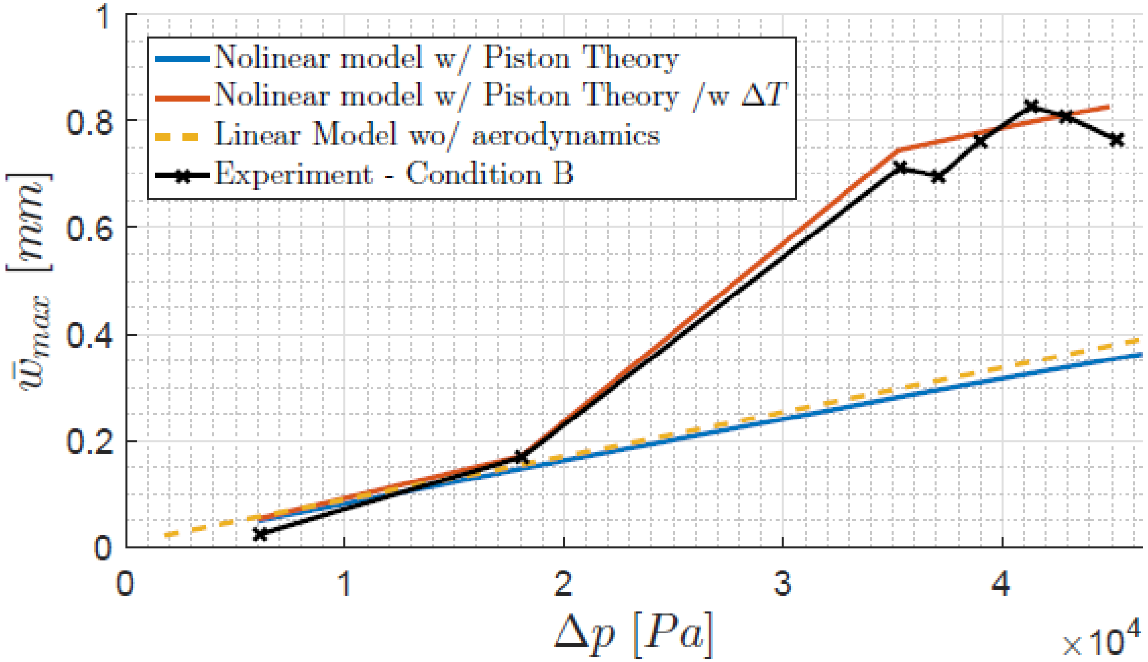
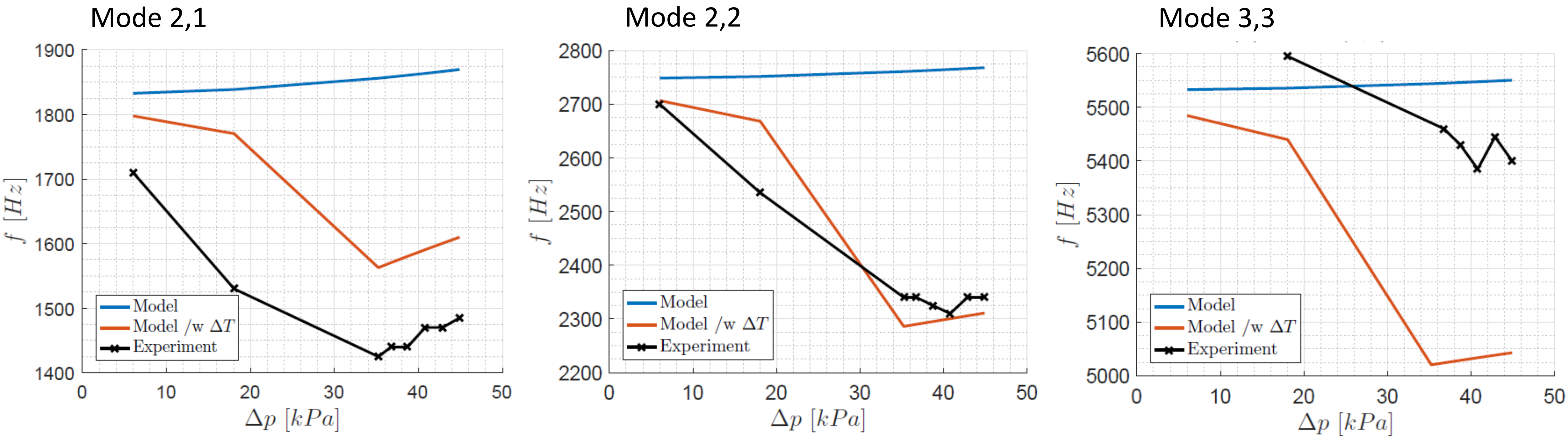
Static deformation, thermal stresses, and frequency shifting





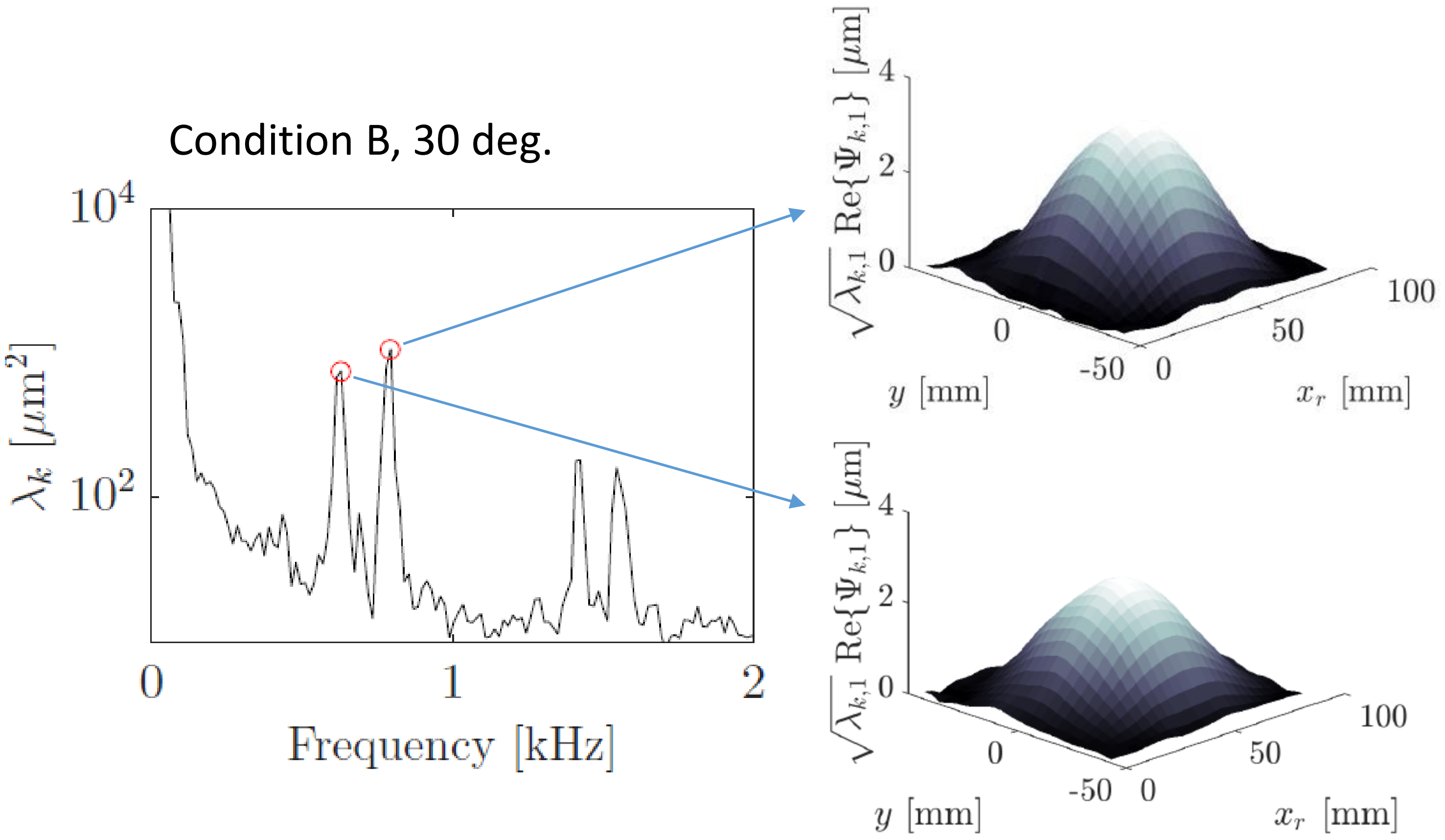
- Static deformation could be a result of thermal stresses induced by temperature differential between panel and surrounding structure
- Temperature differential ΔT chosen to best match measured deflections for Condition B

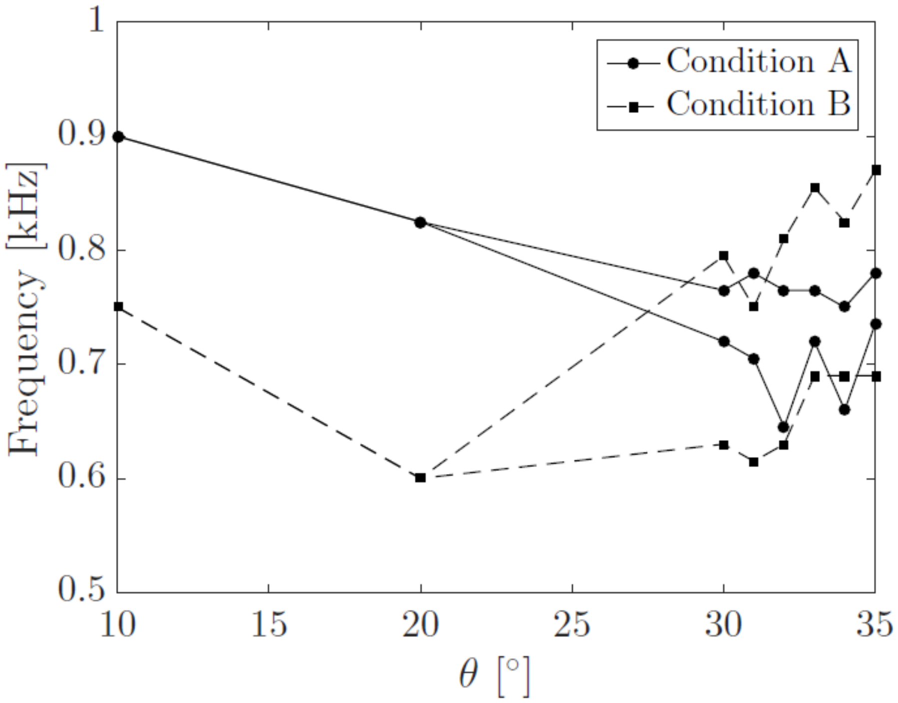
Static deformation, thermal stresses, and frequency shifting



- Thermal stresses will also produce shift in modal frequencies
- Good qualitative agreement between measured frequencies and model predictions

Fundamental mode bifurcation

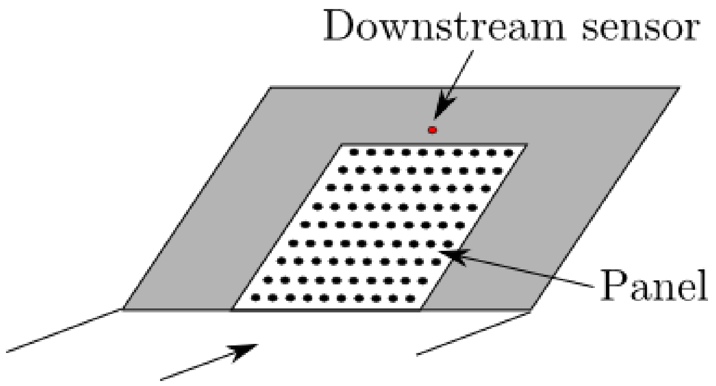

Condition B, 30 deg.

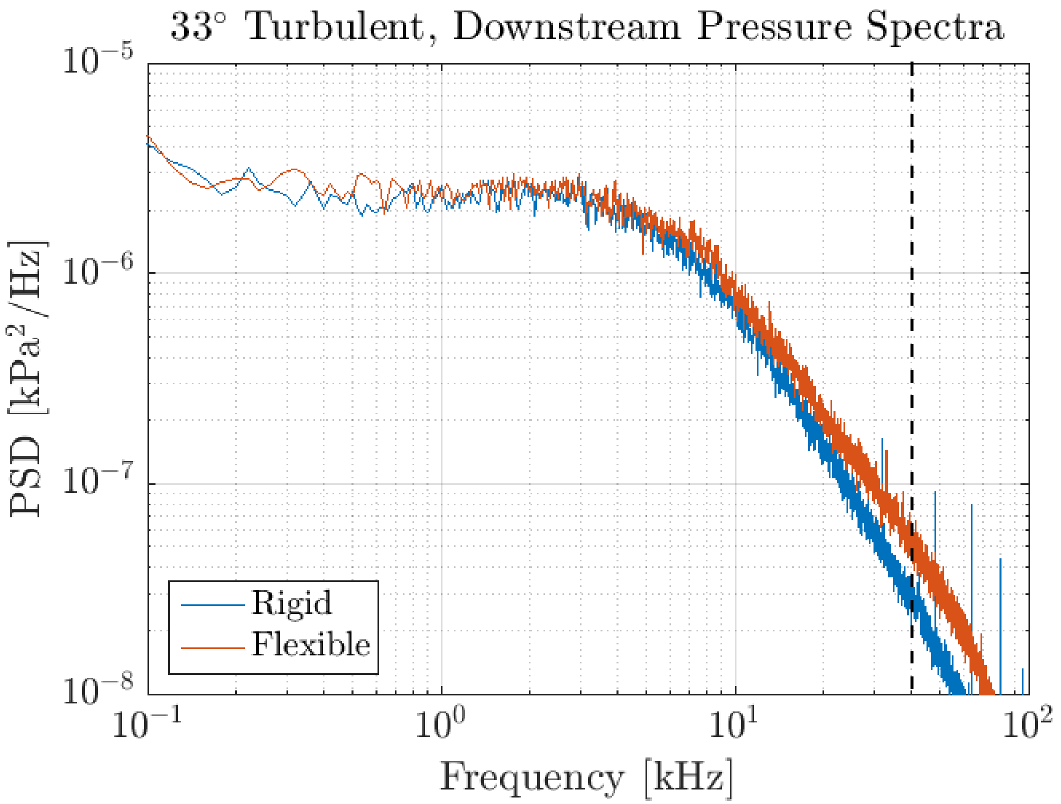


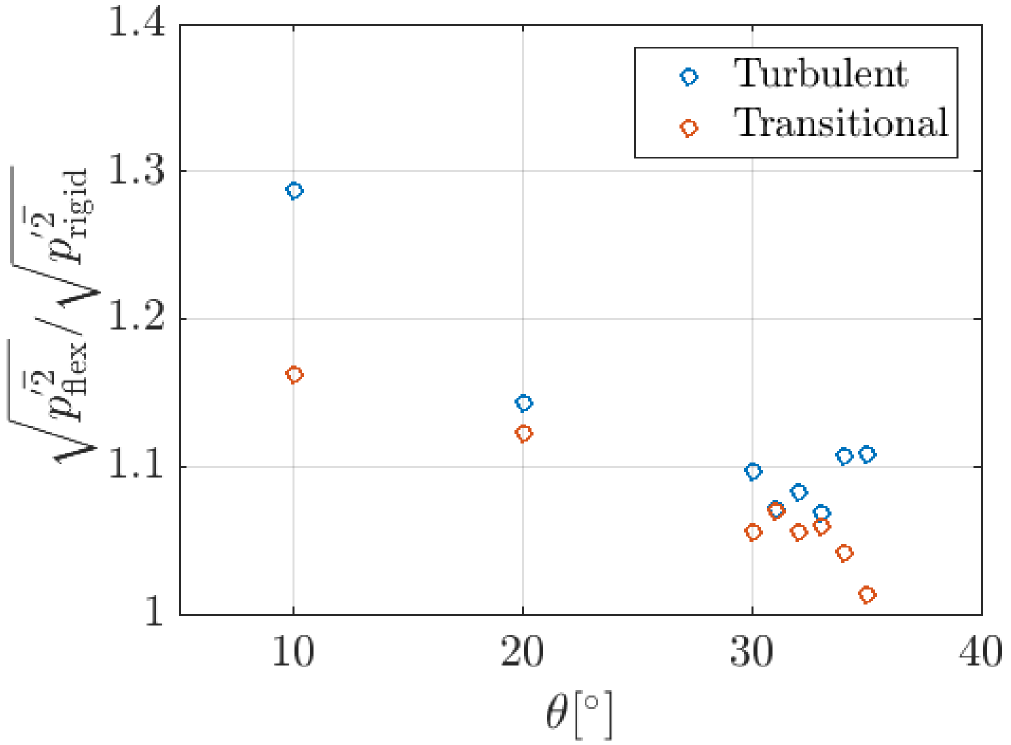
- At larger ramp angles, 1,1 mode appears to split into two discrete frequencies
- Split modes appear alternately, rather than simultaneously
- Origin of this behavior unknown – still need to examine links to static deformation

Influence of panel motion on downstream pressure fluctuations

- Small panel displacements mean limited coupling back to fluid motions, but some effect appears to be present in pressure fluctuations downstream of ramp







Conclusions and Acknowledgements

- High-speed photogrammetry used to study response of compliant panel to hypersonic ramp-induced SWBLI for varying interaction strengths
- SPOD allowed mode shapes and strengths to be evaluated under different conditions
  - For turbulent interactions, 1,1 mode excitation dominant
  - For transitional interactions, higher-order modes showed comparable energy to 1,1
- Higher than expected static deformation and frequency shifting appear to be linked to thermal stresses between panel and support
- Limited intensification of downstream pressure fluctuations also observed – origin not clear

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We would also like to thank all the NASA Langley personnel (Kelly Murphy, Scott Berry, Karen Berger, and the Mach-6 Tunnel technical staff) who made these experiments possible!

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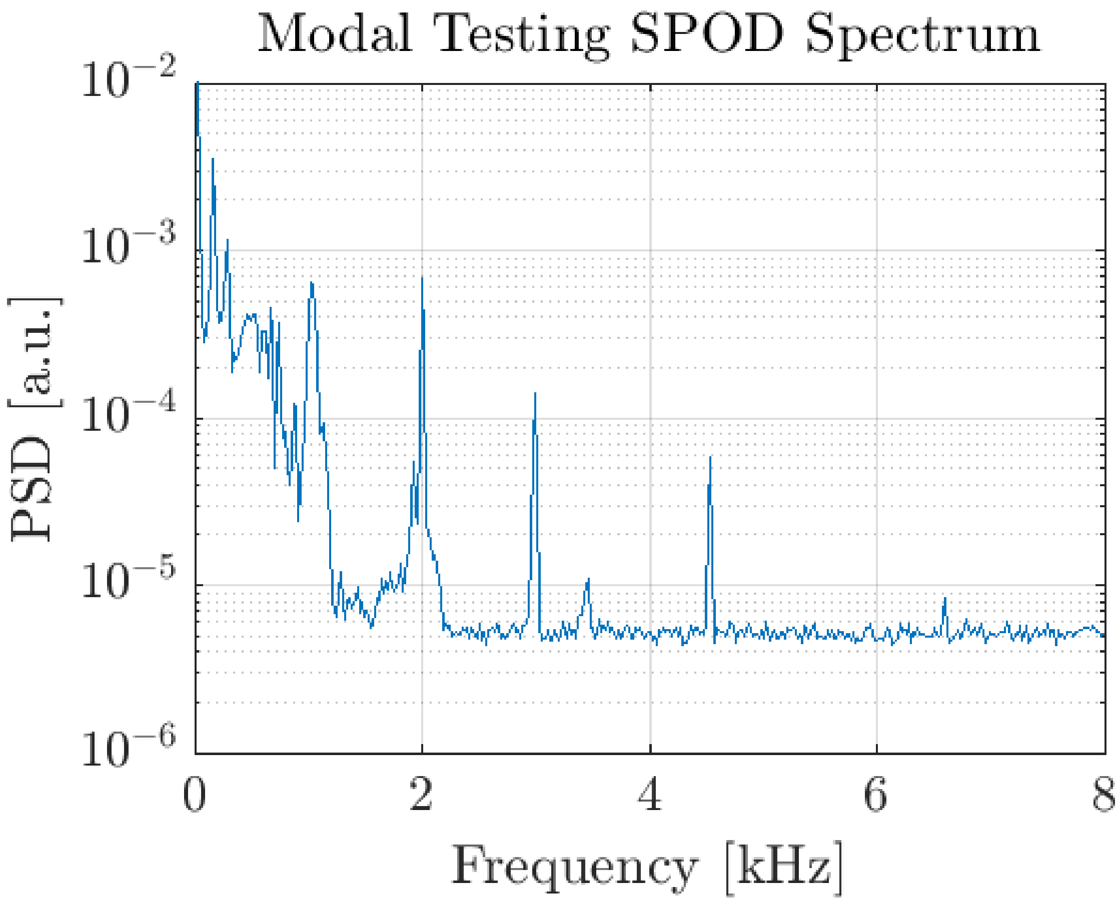
Modal Testing

- Post-campaign modal testing performed



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