SAND2016-2255C

High-Speed Fluid-Structure Interaction Experiments at Sandia National Laboratories

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Sandia National Labs

TTCP AER/WPN TP-5 meeting

Monterrey, CA

March 2016

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Fluid-Structure Interactions

The potential for fluid-structure interactions occurs when there is a harsh loading environment.

Many potential high-speed applications:

- Shock-wave boundary-layer interactions (SWBLI)
- Cavity flows: captive carry or store separation
- Hypersonic reentry: boundary-layer transition

Limited experimental work on these problems, especially at high speeds.

- We seek to fill this gap by taking advantage of Sandia's broad research base.
- Collaboration between the Aerosciences and Structural Dynamics departments.

Motivation: Captive Carry

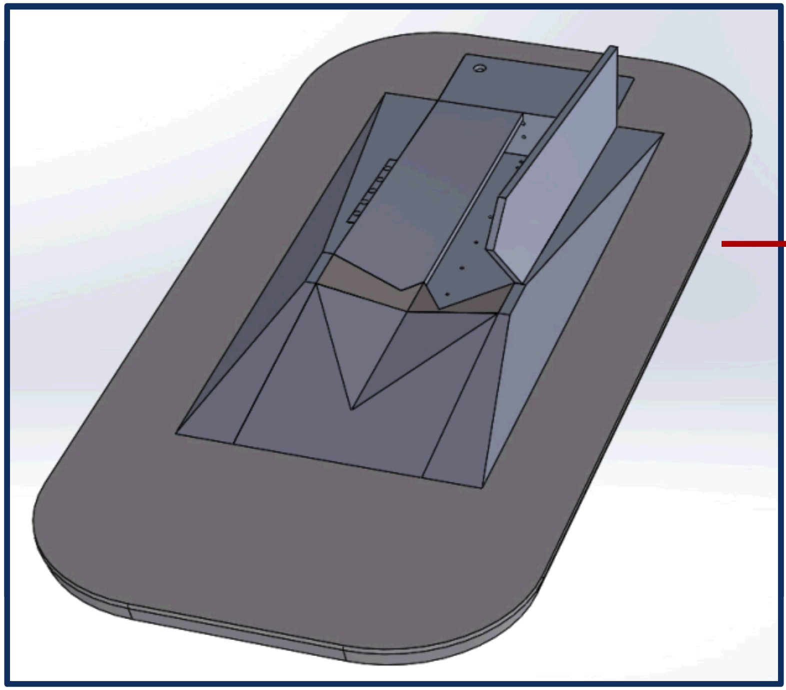
Weapons bays behave similarly to cavity flows.

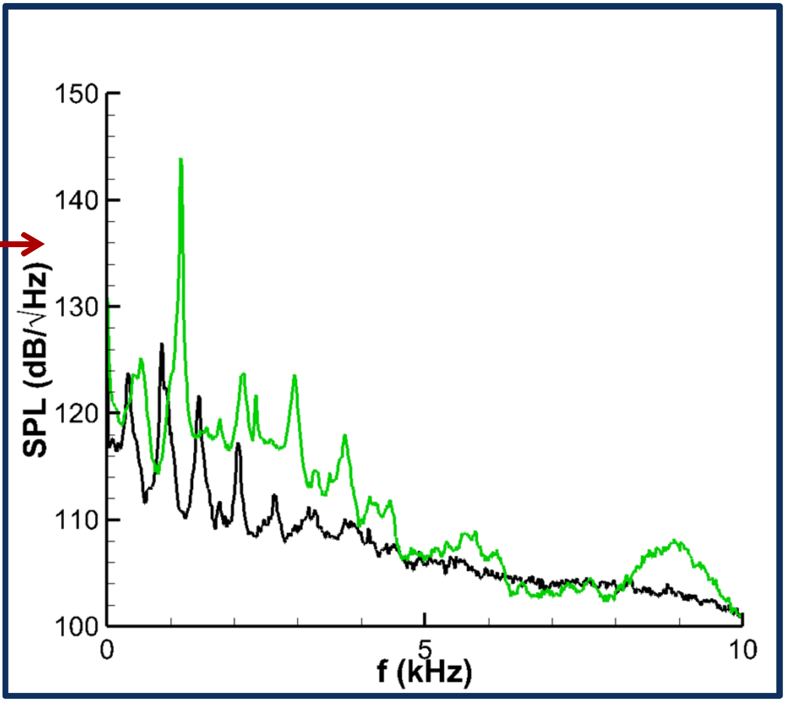
- Interaction of free shear layer and cavity walls produces resonant tones.
- Tones can have high sound pressure levels (SPL), up to 170 dB in some cases.

Fluctuations provide a driver for potential large vibrations of internal stores in weapons bays.


Lockheed Martin: Approved for Public Release

Motivation: FSI in Aircraft Bays





Most bays are represented by rectangular cavities for ground-testing studies.

- Greatly simplifies the actual bay and can underestimate the loading.

Geometric complexities present in flight geometry can couple with cavity resonance to produce a harsh aeroacoustic environment.

- e.g., Casper et al 2014, Ukeiley et al 2008

Experimental Approach

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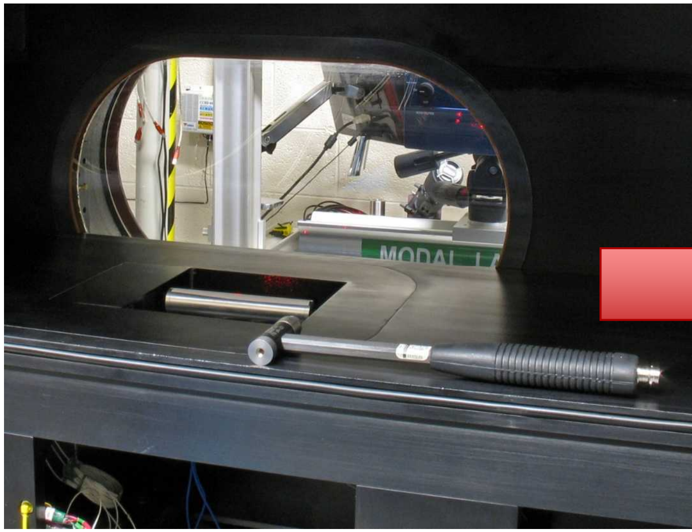
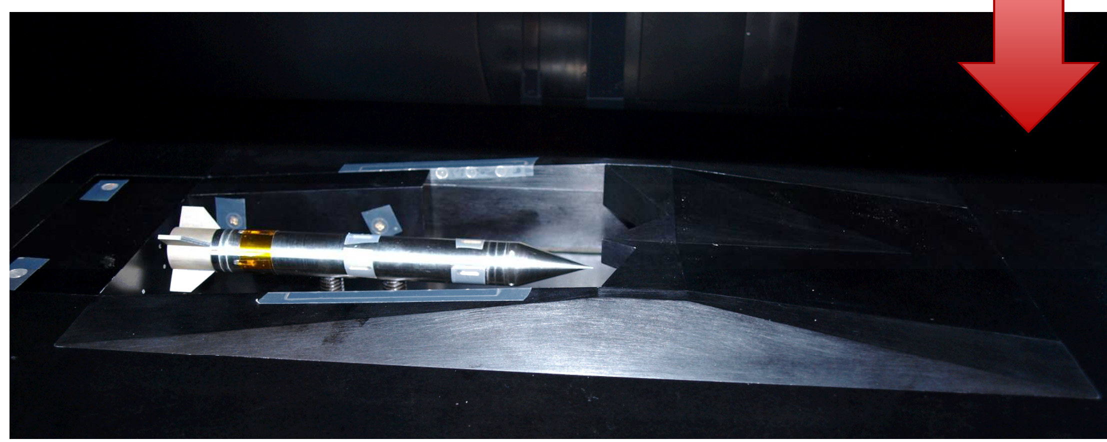
1) Simple Store in Simple Cavity



2) Complex Store in Simple Cavity

3) Complex Store in Complex Cavity



How and why does a fixed, captive store respond in this environment?

What happens when a cavity tone matches a store natural frequency?

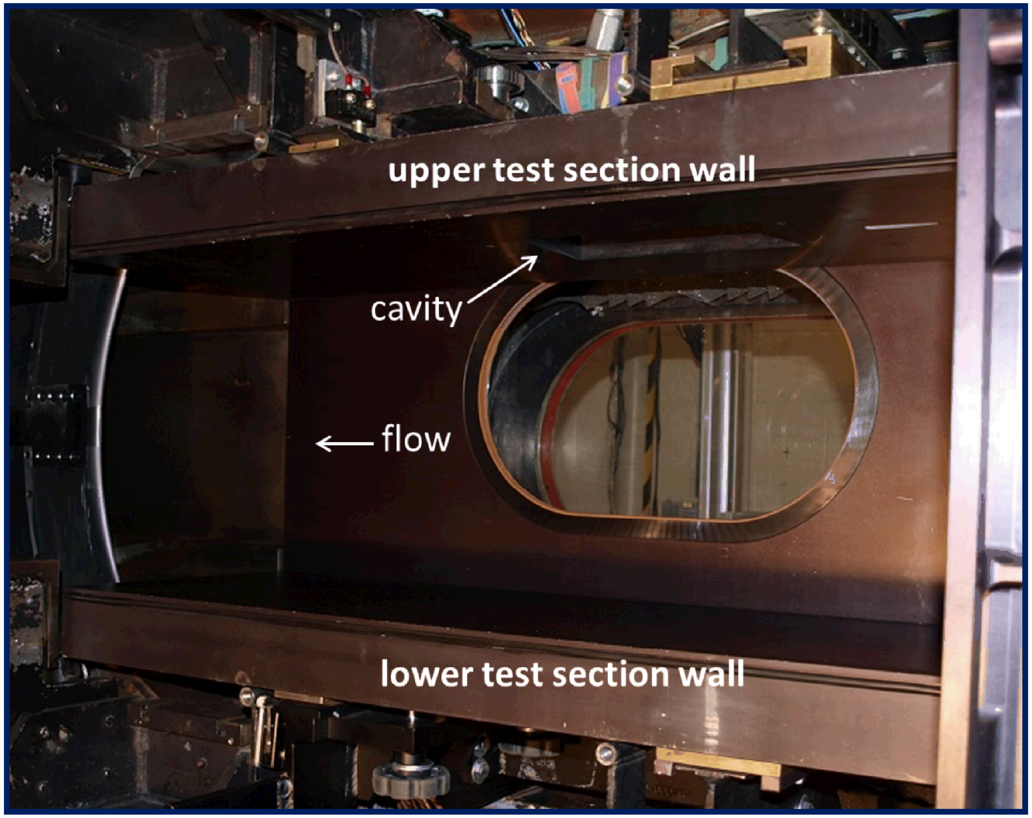
Experimental Approach

Trisonic Wind Tunnel

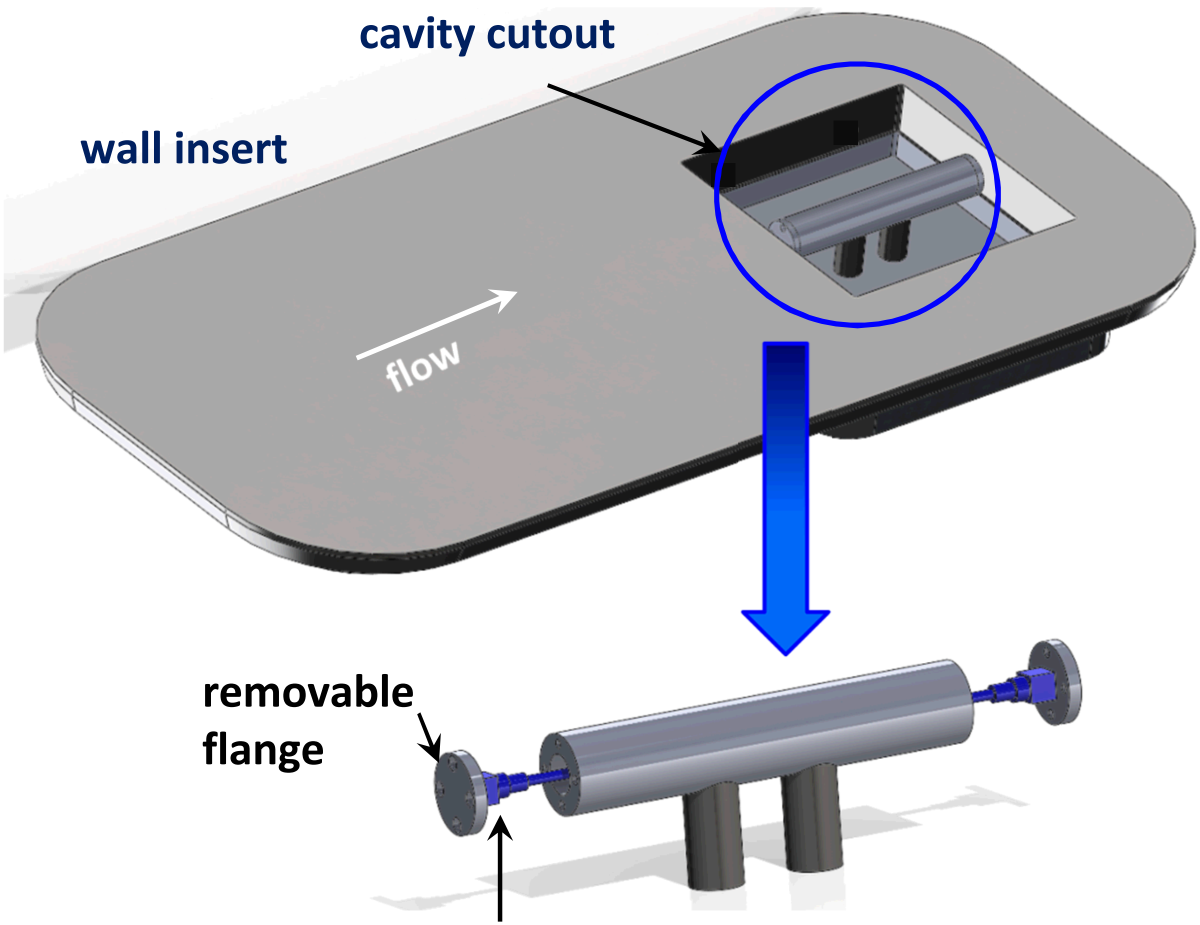
- Cavity integrated into flat-plate insert on test-section wall.
- Incoming turbulent boundary layer.
- M = 0.6—0.9, 1.5, 2.0, 2.5
- Re ≈ 10^7 / m

Simple Rectangular Cavity

- *L/D = 5, 7*
- *L/W = 1, 2*



Simple Cavity FSI



Triaxial accelerometers provided store response.

Store Natural Frequencies

Impact Hammer Tests

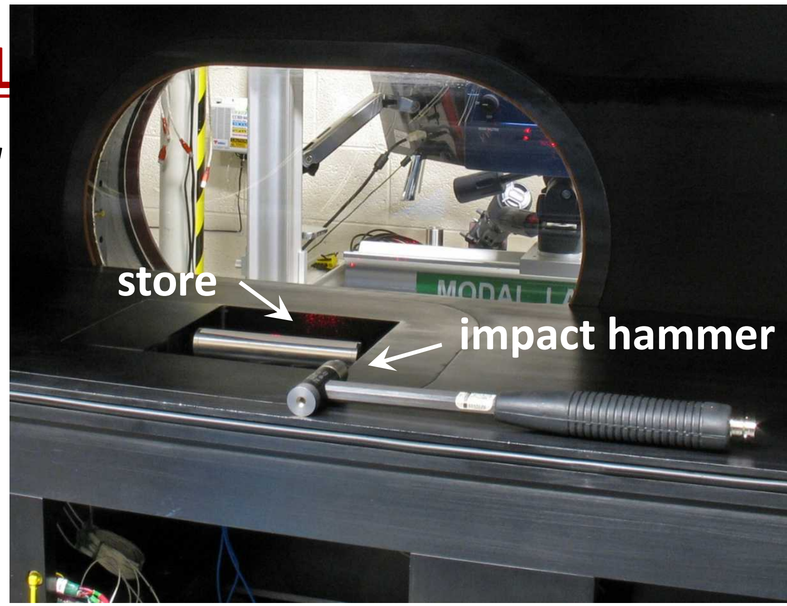
Post Modes

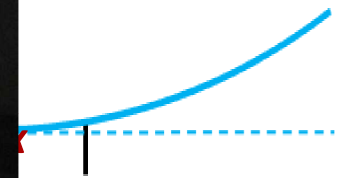
Cylinder Bending Modes

Z1 @ 1

kHz

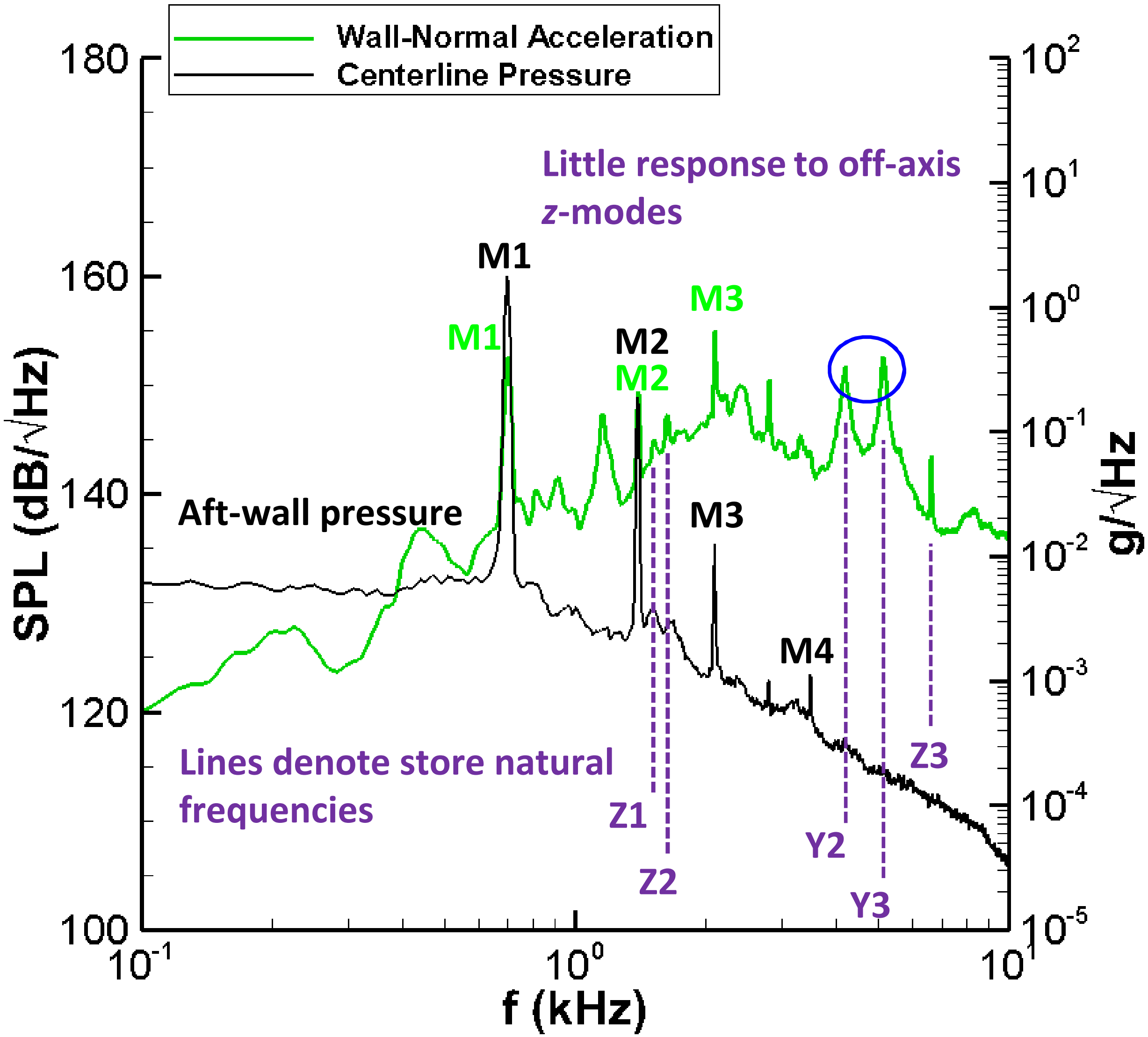
undeflected





5 natural frequencies measured below 10 kHz

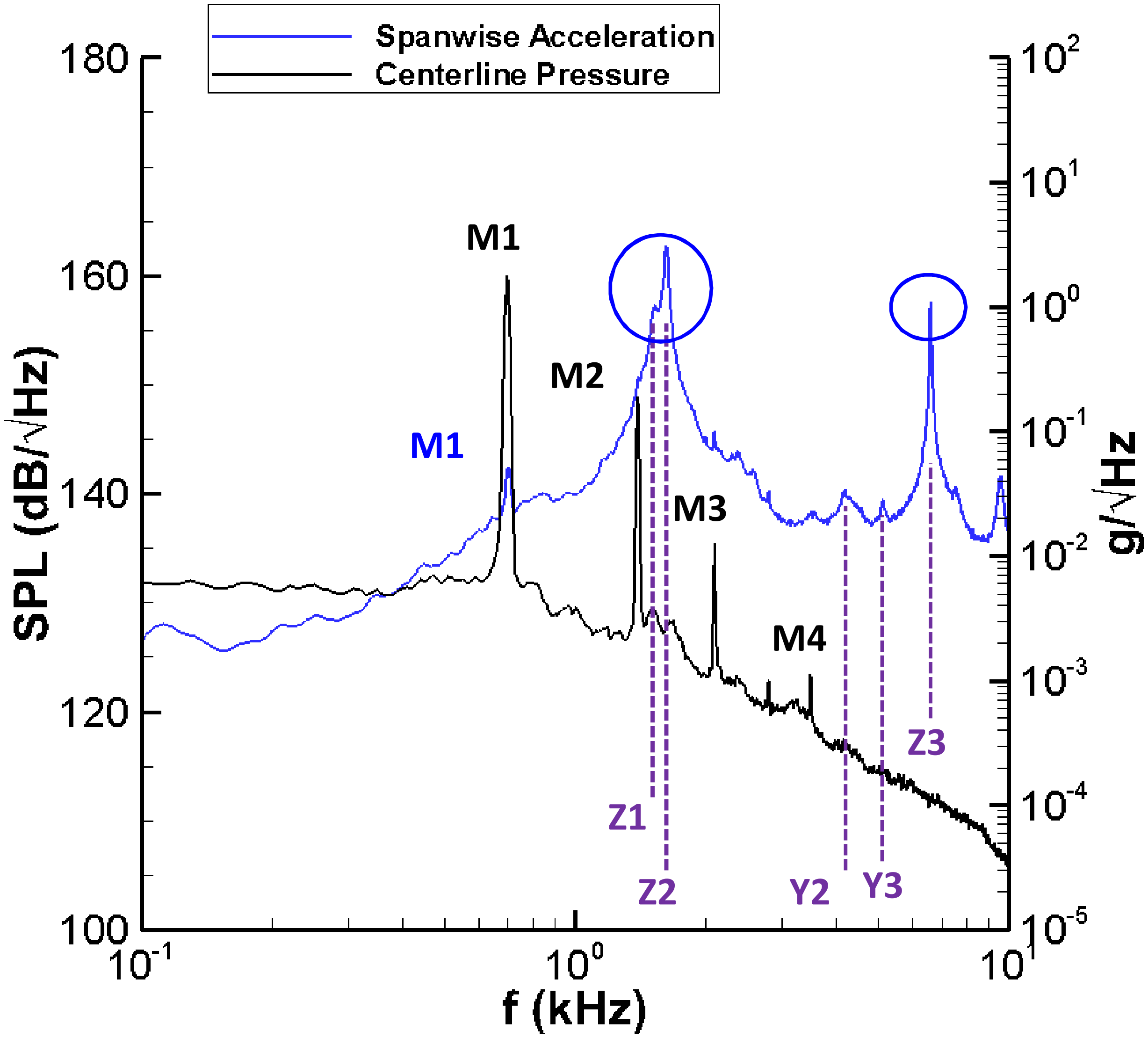
Simple Cavity FSI



- Response at cavity modes M1-M3.
- Response at wall-normal natural frequencies Y2 and Y3
- Similar behavior in *x*.

In *x* and *y* directions, store responds at on-axis natural frequencies and to cavity resonant modes

Simple Cavity FSI



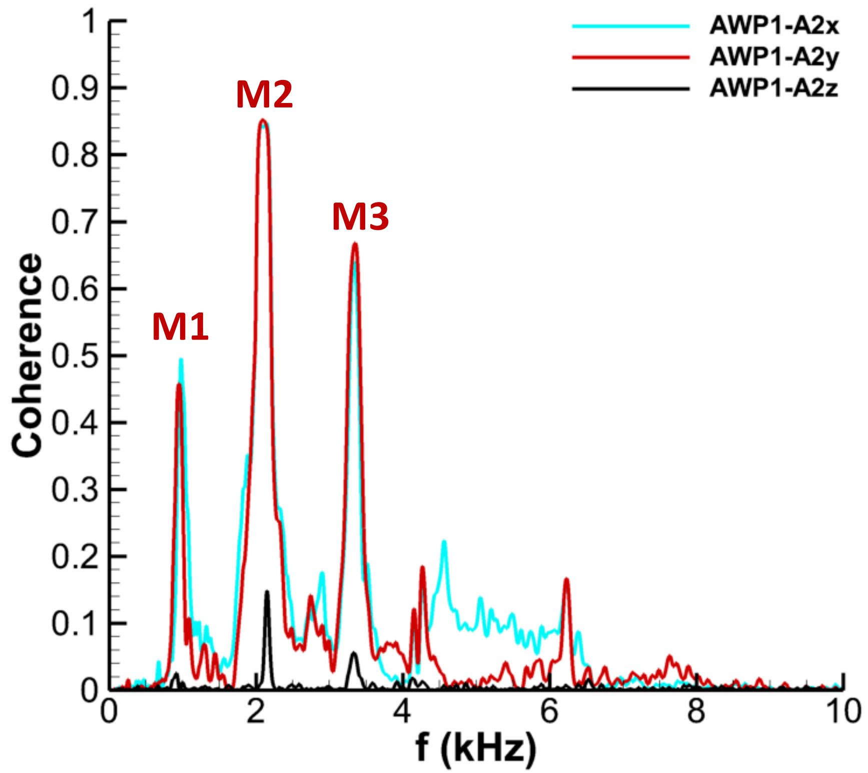
- Little response to cavity modes
- Clear response at spanwise natural frequencies Z1 – Z3

Every natural frequency of the store was excited.

Store responded to cavity tones in x and y only.

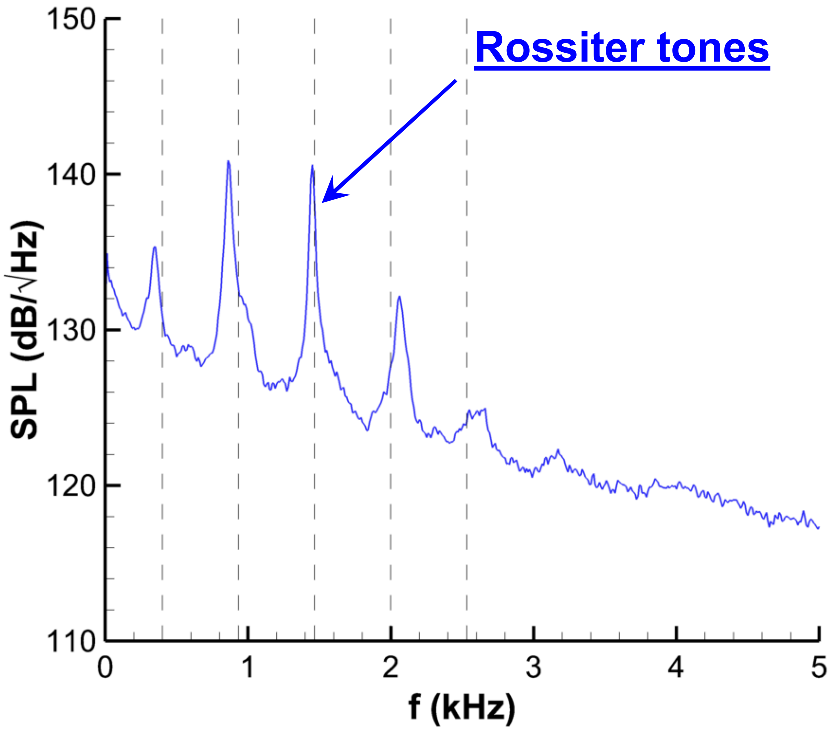
Simple Cavity FSI

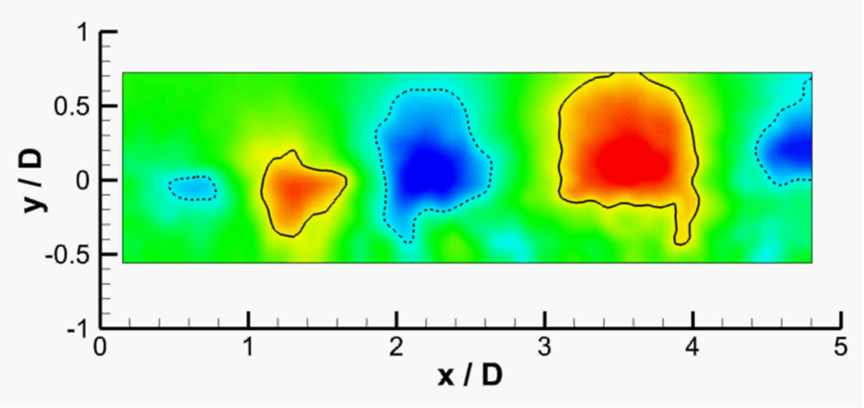
Correlation of Pressure and Acceleration



Strong response to cavity tones in streamwise and wall-normal directions, but little spanwise response.

Response to Cavity Tones?



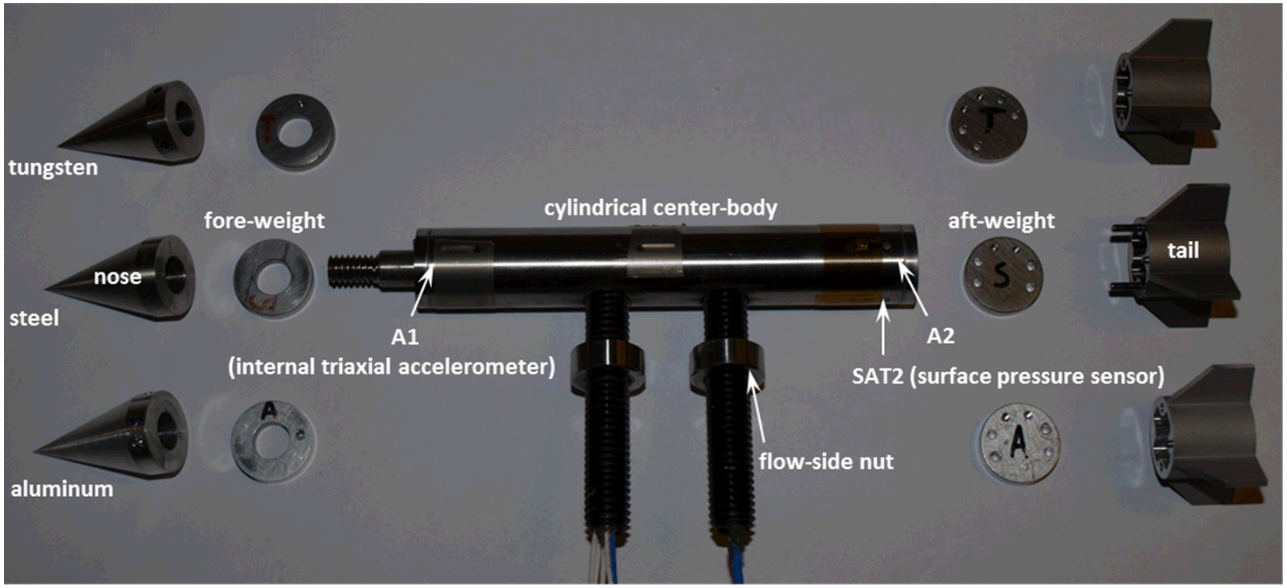


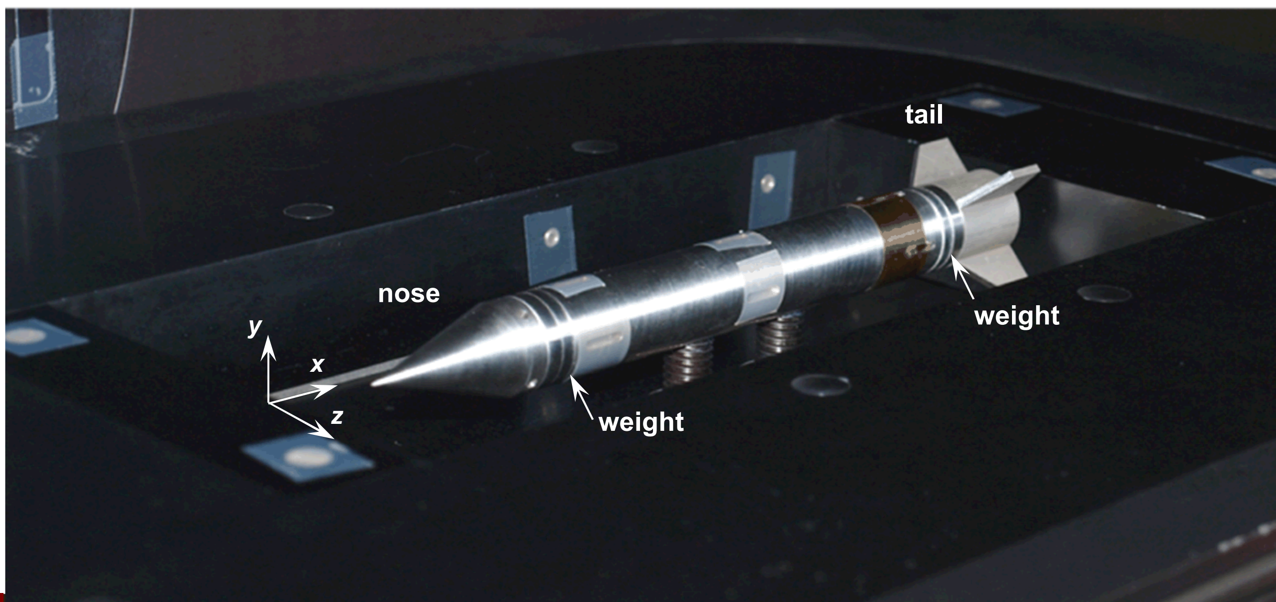
- Cavity flows have ***longitudinal pressure waves***
- Spanwise vorticity results in ***wall-normal gradients***

Cavity resonance produces longitudinal and wall-normal gradients to drive the store in *x* and *y*. The lack of spanwise response indicates small gradients in *z*.

Simple store tests taught us a lot, but to go further we need an improved store.

Complex Store





Coarse adjustments in natural frequencies of 100 – 400 Hz by varying nose and tail material.

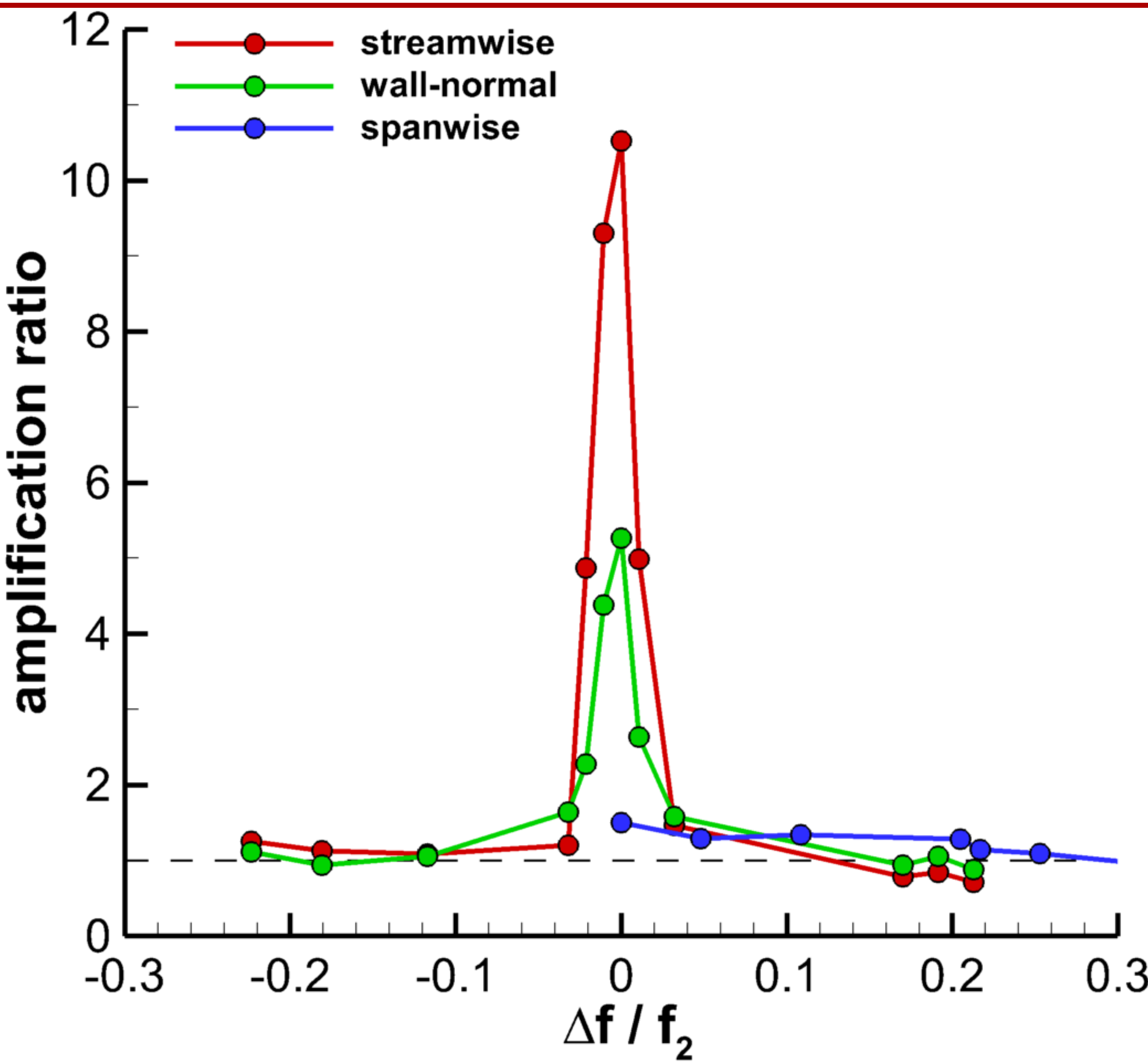
- Aluminum
- Steel
- Titanium

Fine adjustments of 10 – 100 Hz by varying smaller weights.

Study scenarios where a structural natural frequency matches a resonance cavity tone.

- Combine with complex geometry and its strong tones.

Mode Matching



Mode-match to a streamwise natural frequency:

Strong amplification

Mode-match to a wall-normal natural frequency:

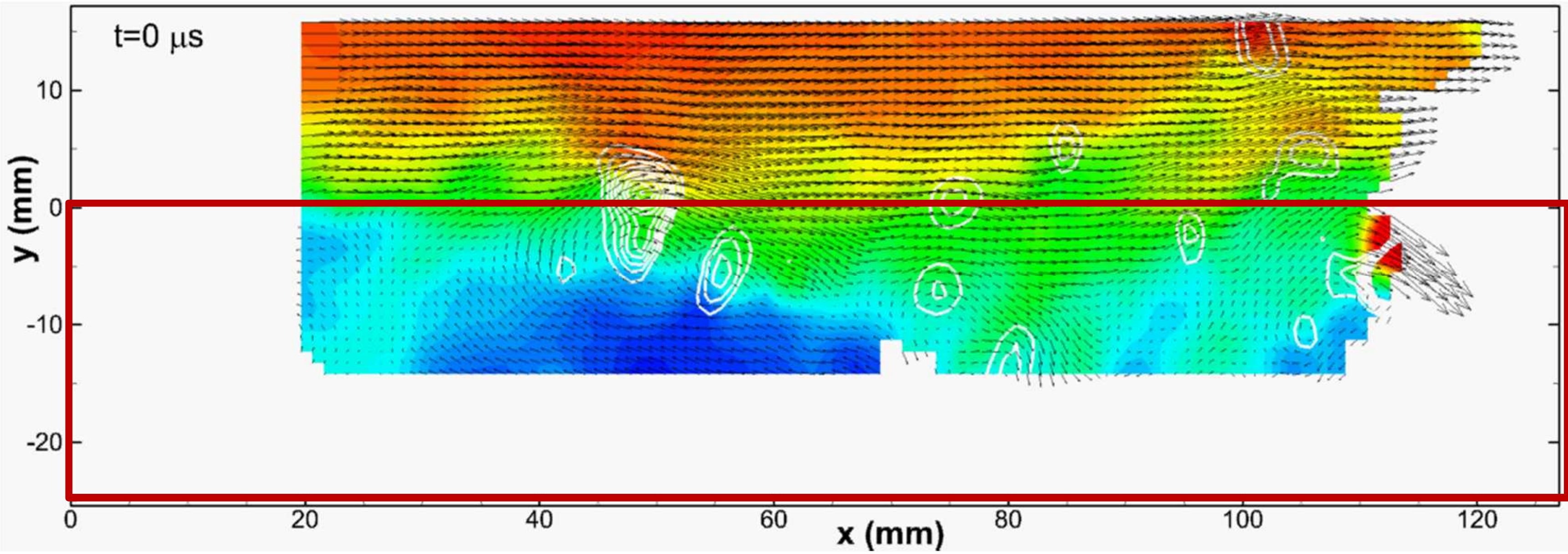
Significant amplification

Mode-match to a spanwise natural frequency:

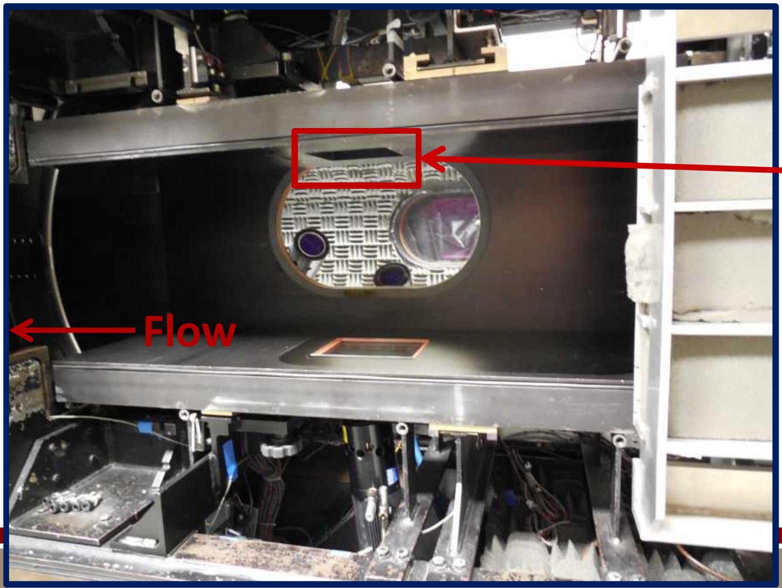
Minimal amplification

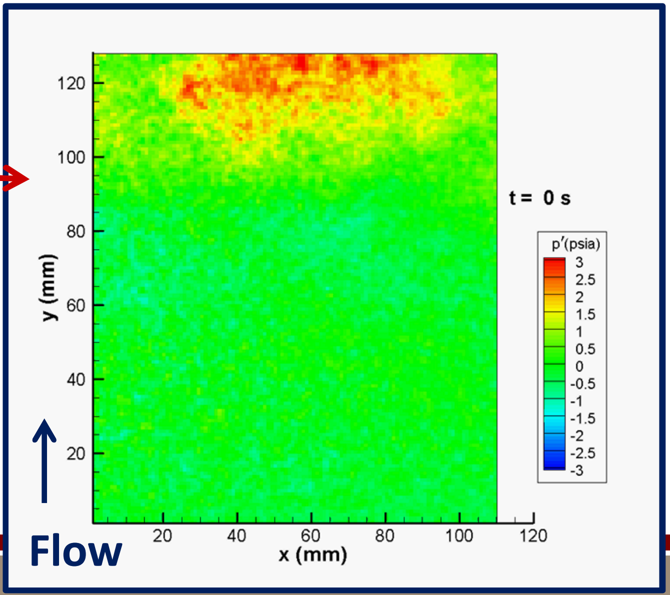
Future / Ongoing Work

TR-PIV:



TR-PSP:





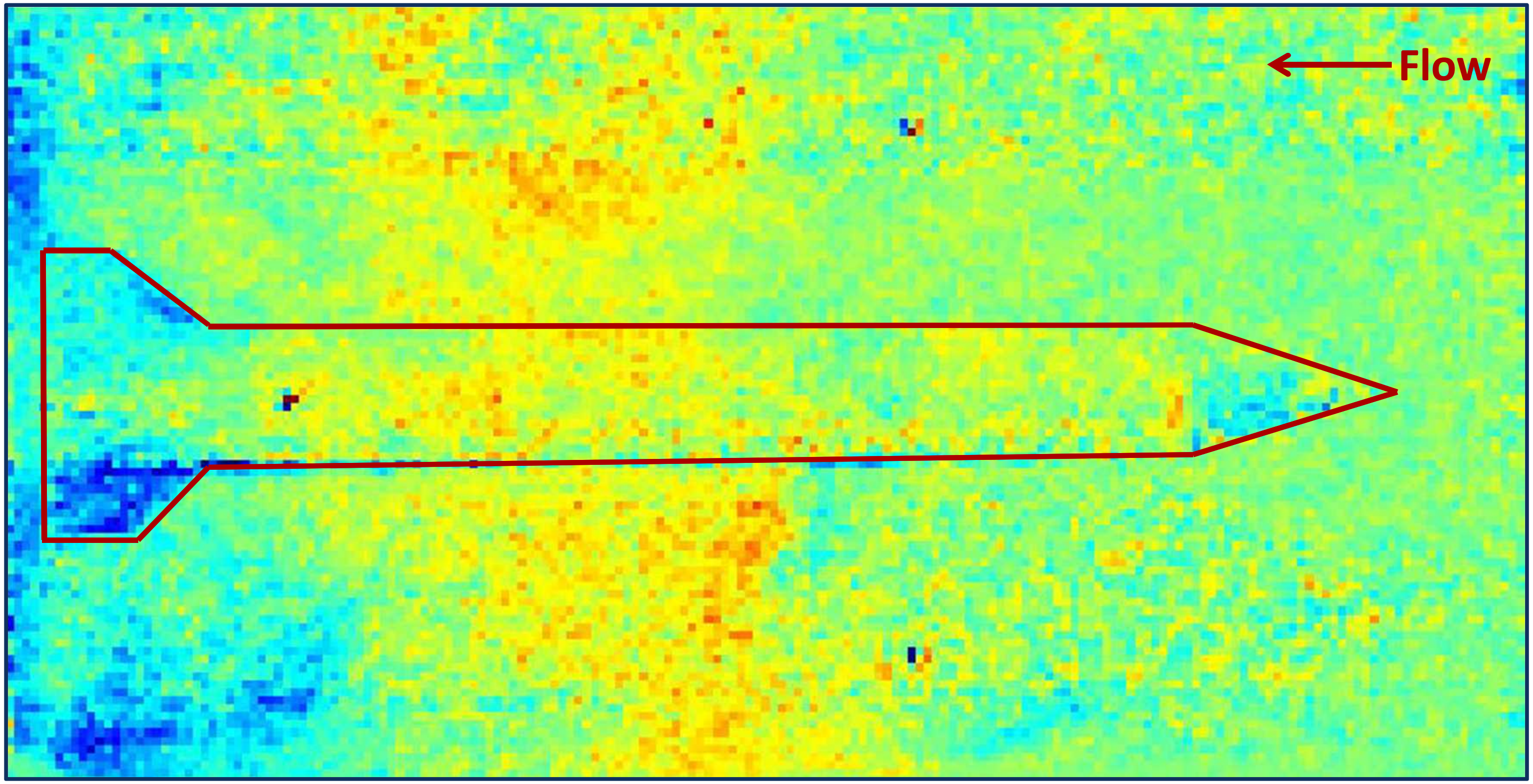
Newest Result: PSP on a Complex Store

PSP shows unsteady fluctuations on cavity floor

- Higher fluctuations at aft cavity wall, as expected.

Unsteady store loading is similar to unsteady floor pressures.

- Additionally see coherent structures moving down store.



Bring all of these capabilities together

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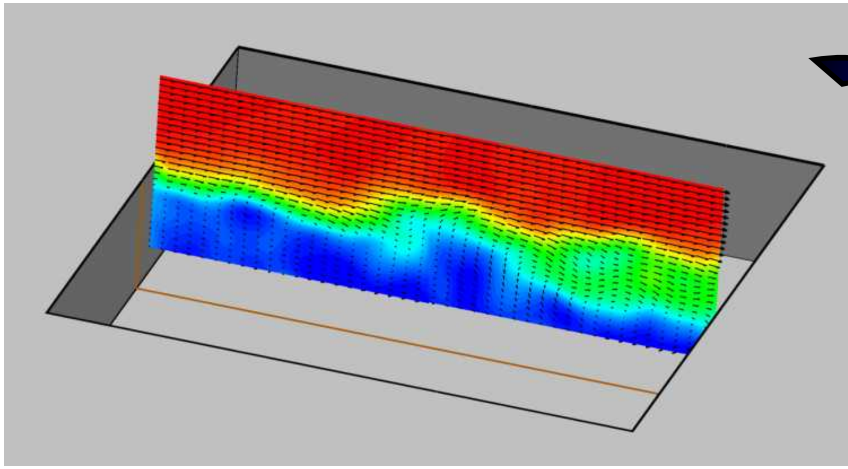
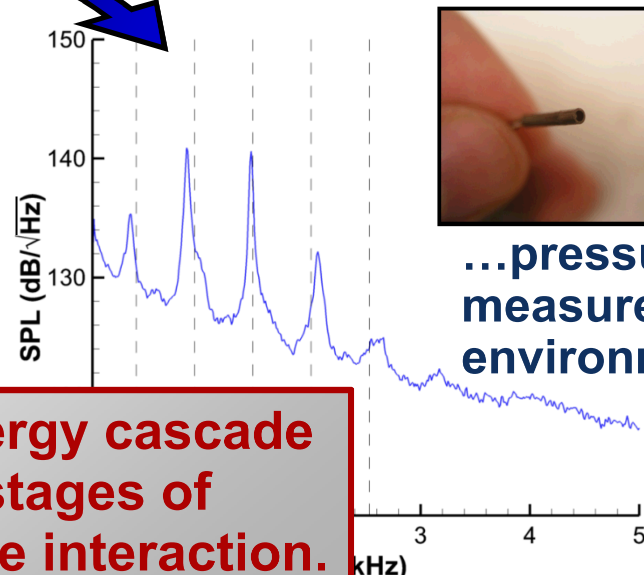
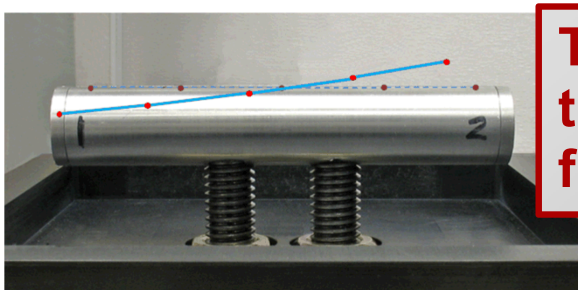


Pulse-burst PIV measures the flow structure…

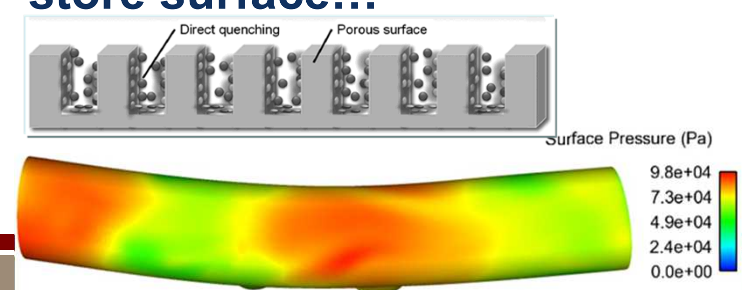


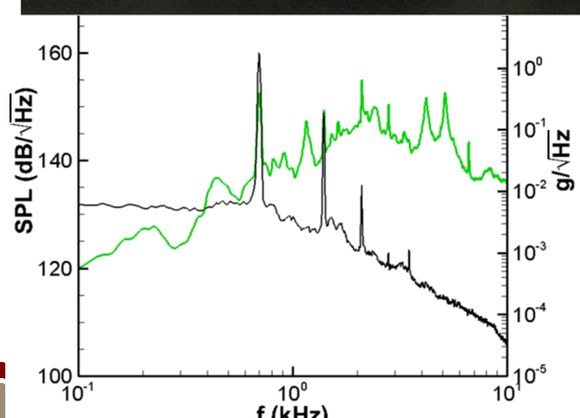
…pressure sensors measure the acoustic environment…

Track the energy cascade through the stages of fluid-structure interaction.



…plus we will have high-speed Pressure Sensitive Paint for the store surface…



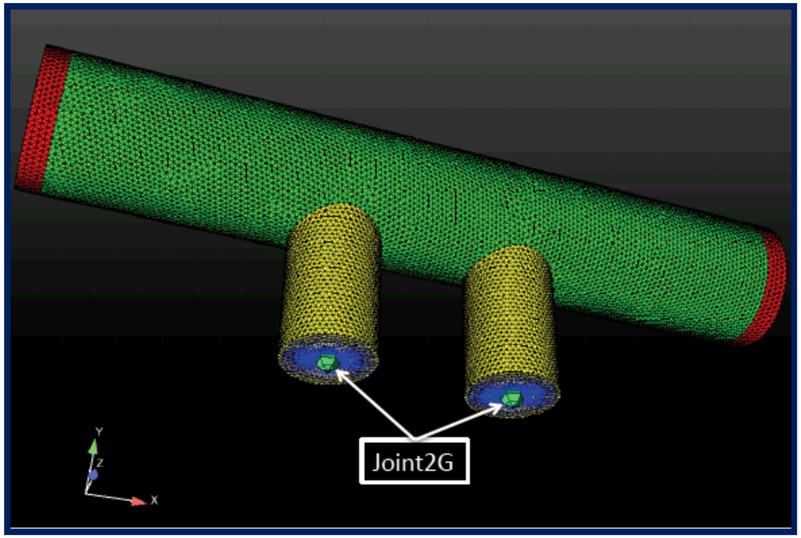


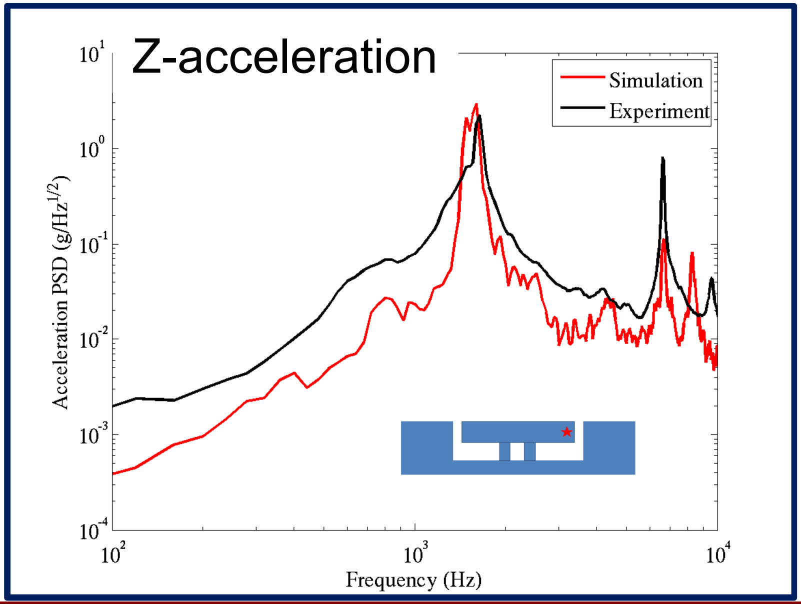
…and then we can measure the structural response.

Future / Ongoing Work

Cavity and FSI Simulations

Arunajatasen et al. (2013-2014).

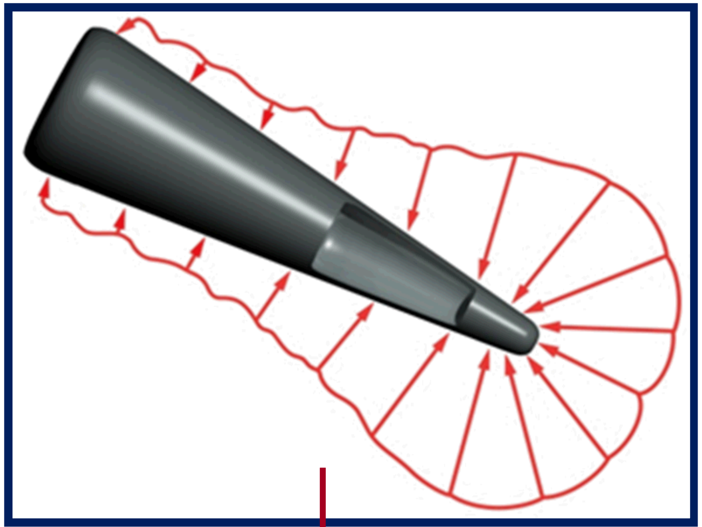


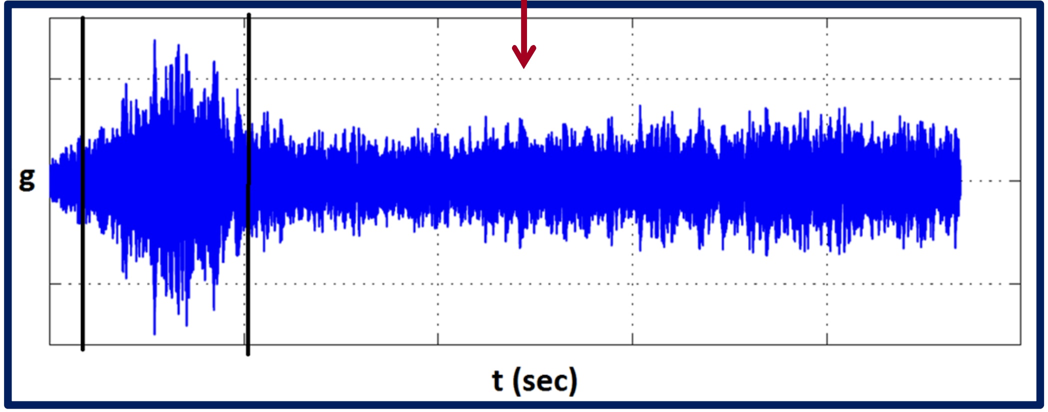


Motivation: Reentry-Vehicle Vibration

Vehicle vibration is a maximum when a reentry vehicle undergoes boundary layer transition.

- Pressure fluctuations peak during boundary-layer transition.
  - Need to model fluctuations and spatial distribution as input to studying potential fluid-structure interactions.
- Need to understand physics behind fluid-structure interactions.
  - No hypersonic experimental FSI work that we are aware of.

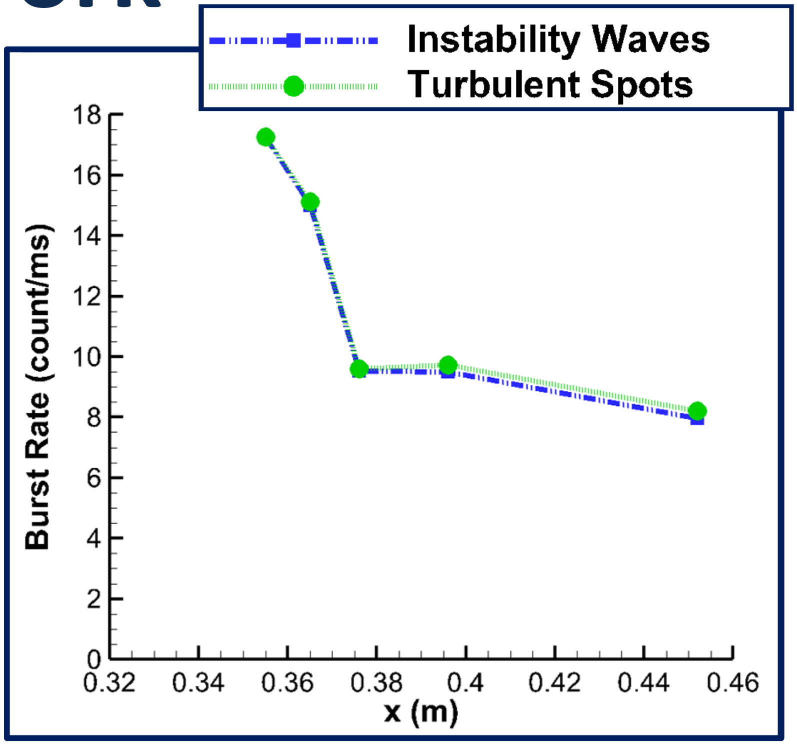


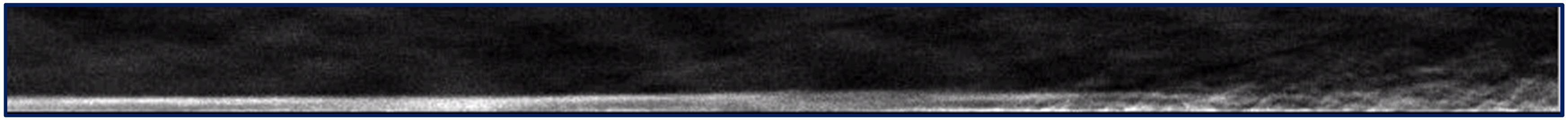


Previous Work

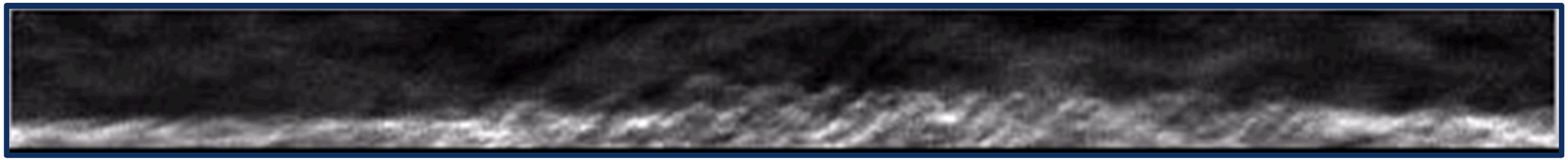
Previous work focused on developing more accurate models of the pressure fluctuations using a turbulent-spot approach.

- At low speeds, the boundary layer switches between smooth laminar flow and turbulence.
  - Characterized by intermittency, burst rate, and average burst length at a given point.
- At hypersonic Mach numbers, second-mode waves are important and occur at the same time as turbulent spots during the transitional region.





Transitional Boundary Layer, Mach 5



Transitional Boundary Layer, Mach 8

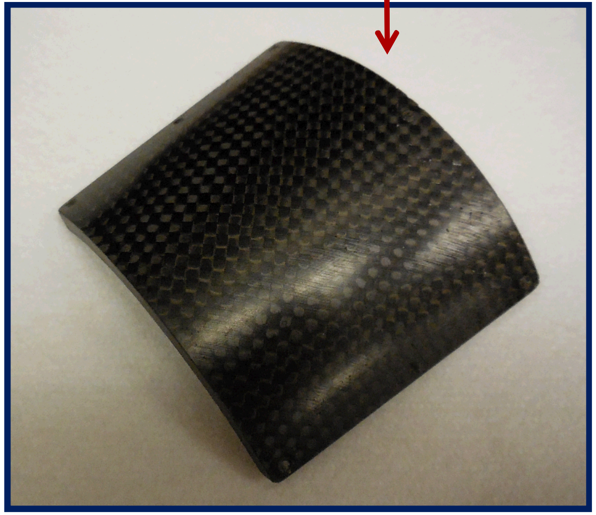
Experimental Design

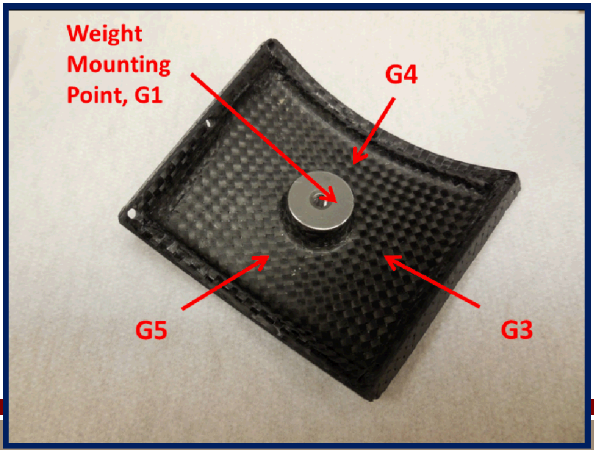
Designed a cone with integrated thin panel that will vibrate from flow excitation.

- Thin plate becomes a sensor for the excitation loads produced by flow.
- Adjustable material and attached weights to fine tune structural natural frequencies.
  - Carbon-composite and stainless steel panels.
  - Aluminum, stainless steel, and tungsten weights.

Panel response measured with accelerometers on inside of panel.

- G1, triaxial accelerometer on weight.
- G5, uniaxial accelerometer upstream of weight.





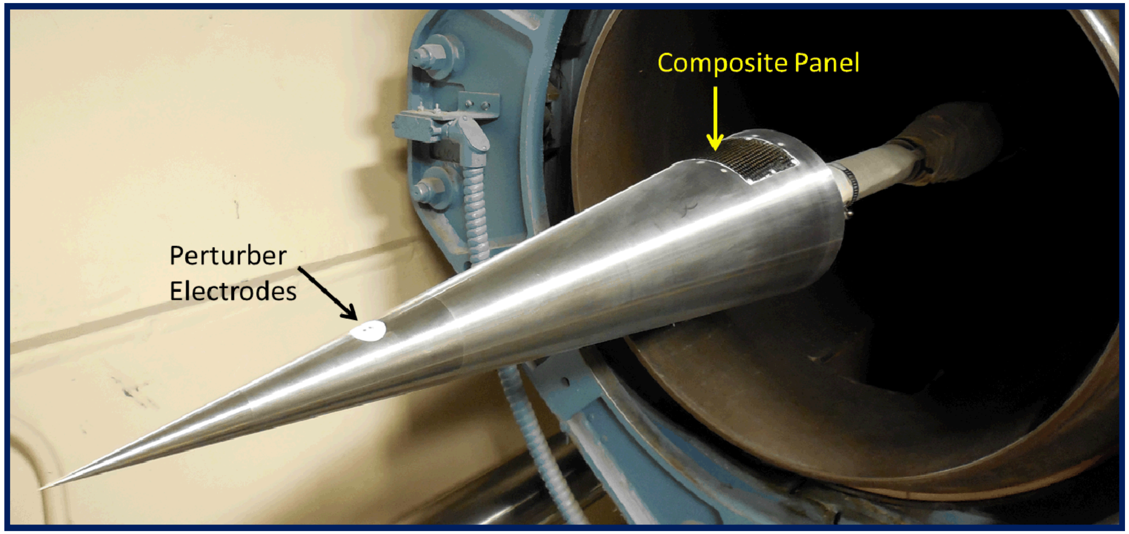
Experimental Design

Pressure sensors upstream and downstream of panel were used to characterize the boundary layer.

- Schlieren measurements also acquired.

Developed a spark perturber to create controlled disturbances in boundary layer.

- Adjustable frequency up to 10 kHz.



Composite Panel Response to Natural Boundary-Layer Transition

See an elevated response to transitional boundary layers.

- Re = 6.6 – 9.8 x 10^6/m

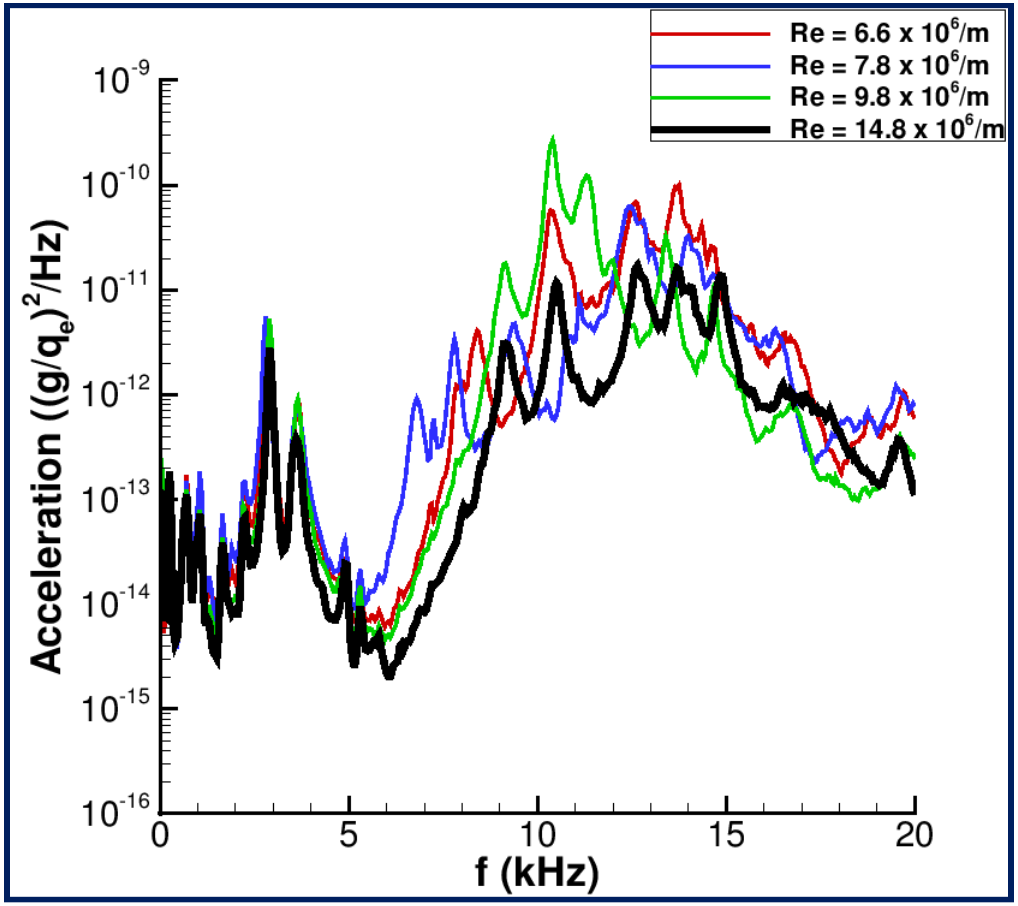
Lower response to turbulent boundary layers.

- Re = 14.8 x 10^6/m

Largest differences occur at higher frequencies (5 – 20 kHz).

- This was unexpected!

We can gain more insight into this behavior from controlled disturbance experiments.



Vertical Acceleration, G5

Perturber Effect on Boundary-Layer Statistics

Consider effect of perturber operated at f = 7.9 kHz.

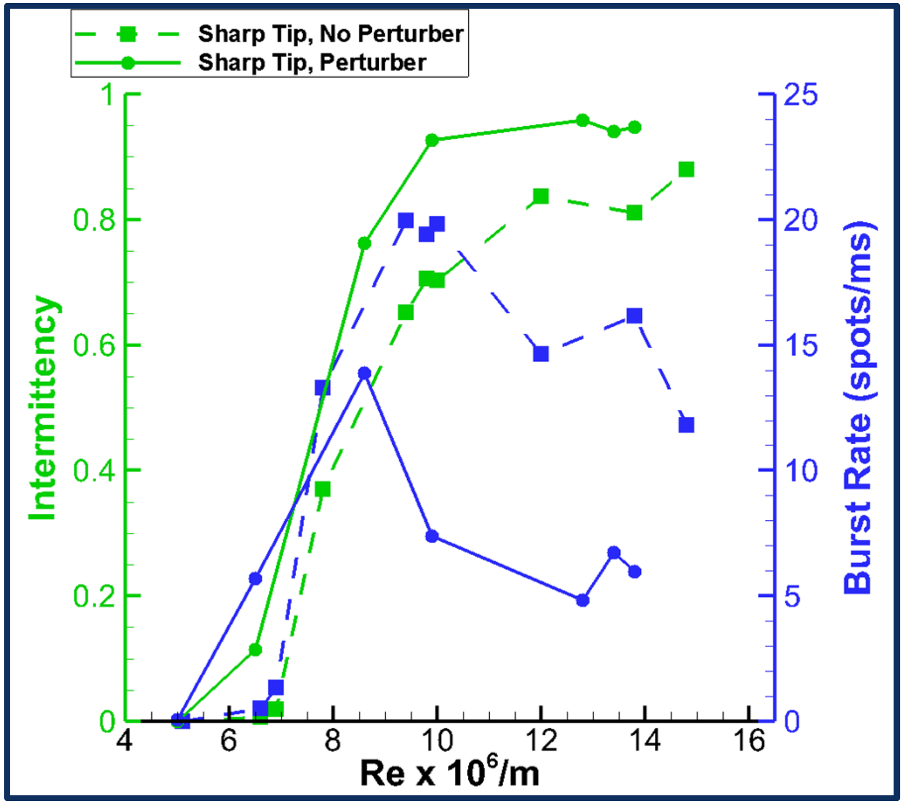
- At a given Reynolds number, the perturber creates:
  - Higher intermittency.
  - Higher burst rate at low Re, lower burst rate at higher Re.

Note the burst rate is not 7.9 spots/ms!

- Effective burst rate is a combination of natural and controlled disturbances.

The perturber is not the driver for boundary-layer state, instead it modifies the effects of natural transition.

How does this affect the panel vibration?



Carbon-Composite Panel Response With and Without Controlled Perturbations

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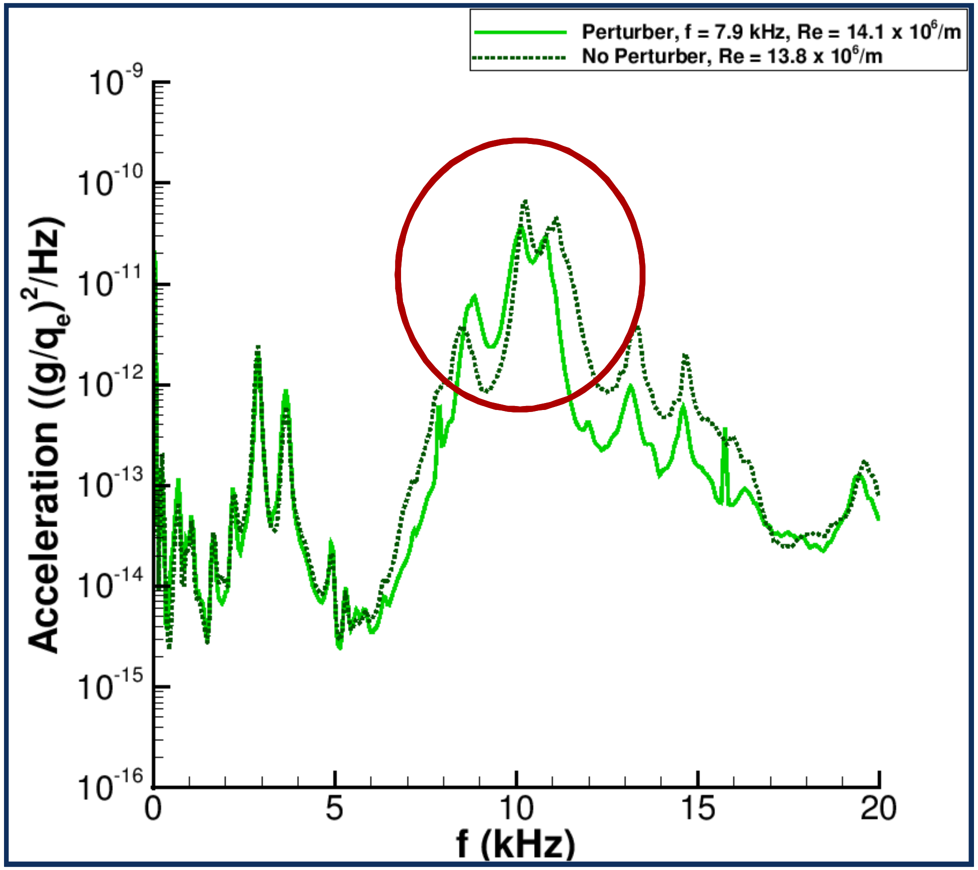
Effect of perturber at high repetition rates (7.9 kHz):

- Similar response when the boundary layer remains laminar.
- Elevated response near 10 kHz during boundary-layer transition.
- Smaller response over a broad range of frequencies (5-20 kHz) once turbulent.

Effect can be explained by considering the boundary-layer statistics for these cases.

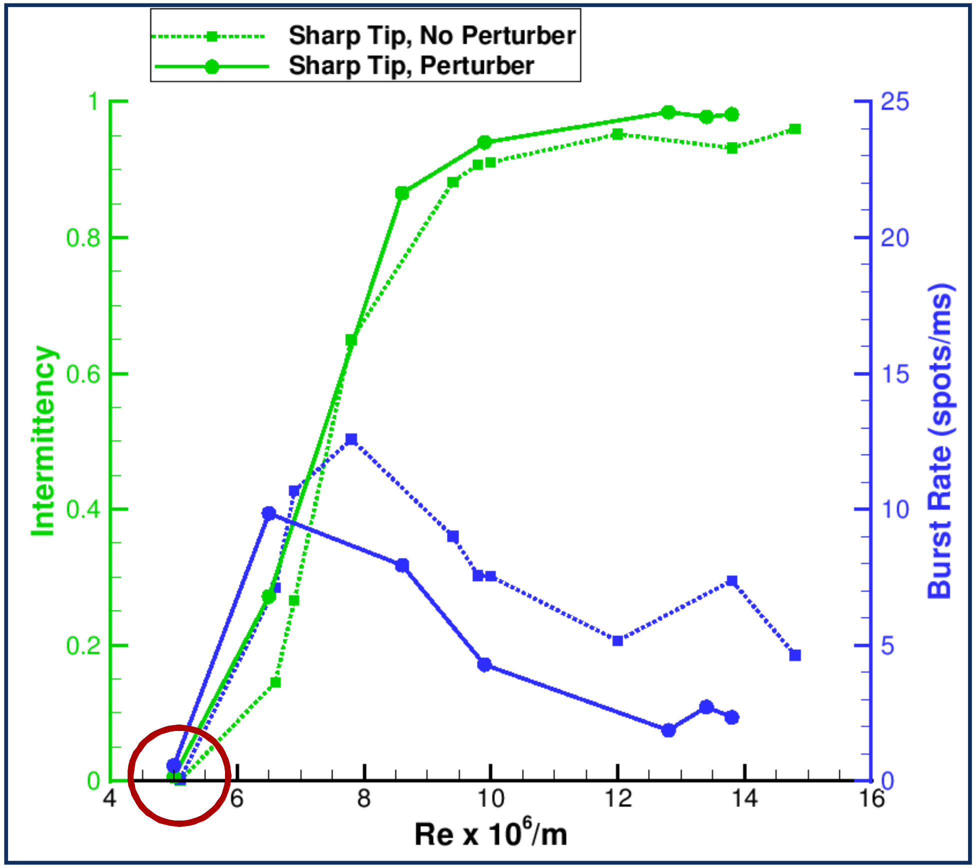


Vertical Acceleration, G5

Carbon-Composite Panel Response to Controlled Perturbation

At low Re of 5 x 10^6/m, the intermittency and burst rate are zero, both with and without the perturber firing.

- Boundary layer is laminar (dominated by second-mode waves) in both cases.
- Panel response remains the same.



Turbulent Spot Statistics

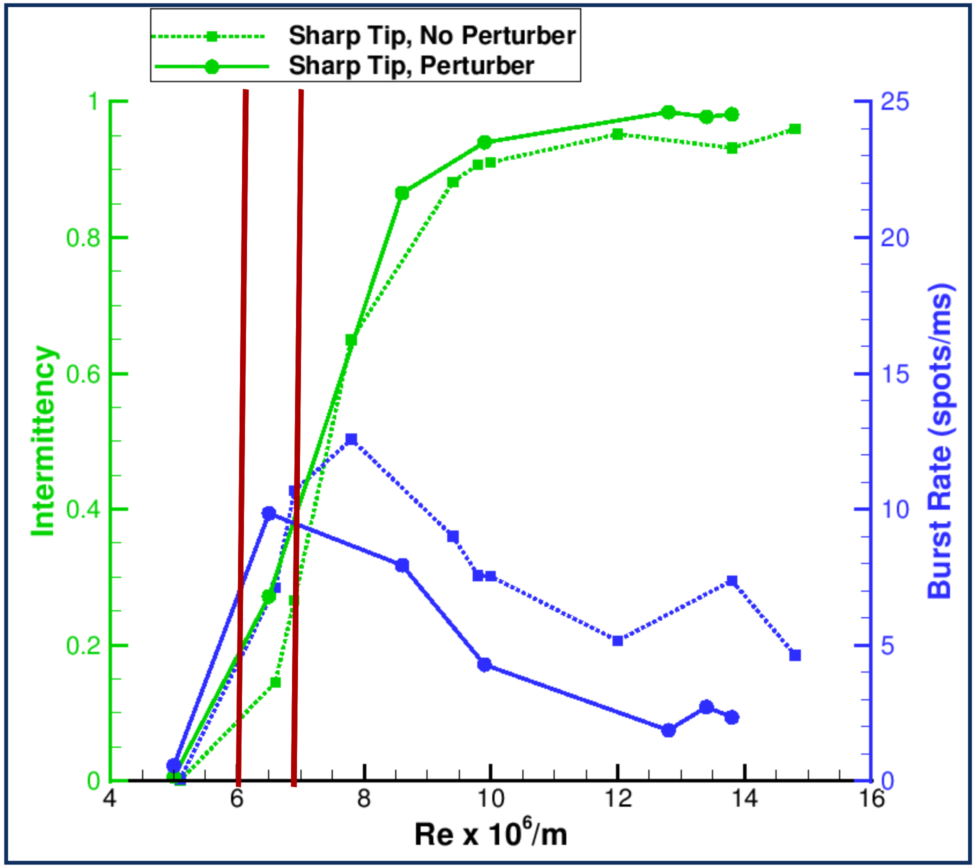
Carbon-Composite Panel Response to Controlled Perturbations

At a transitional Re of 6.5 x 10^6/m:

- Perturber increases intermittency from 0.15 to 0.3.
- Burst rate peak shifts to lower Re, and is actually higher than natural transition at this Re.

Burst rate is about 10 spots/ms with perturber firing.

- Expected to correspond to flow excitation with a distribution centered around 10 kHz.
- Consistent with elevated frequencies of vibration near 10 kHz.



Turbulent Spot Statistics

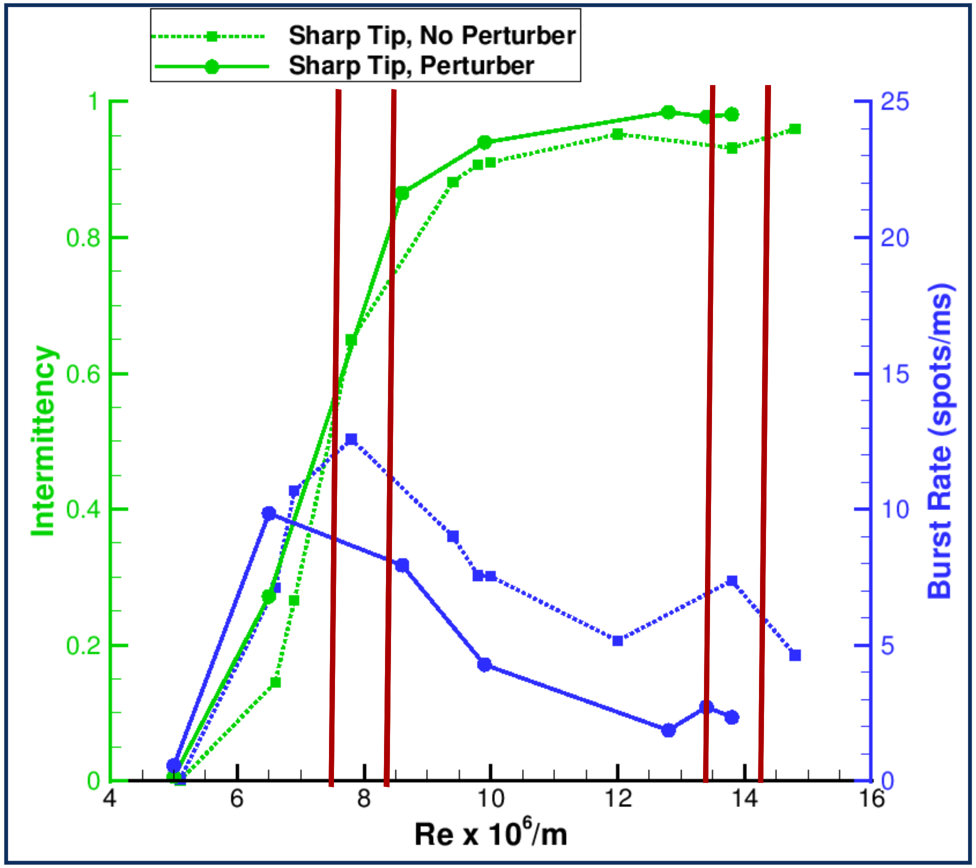
Carbon-Composite Panel Response to Controlled Perturbations

At higher Re near 8 and 14 x 10⁶/m, lower vibration levels are measured with the perturber firing.

- Intermittency is higher.
- Burst rate is lower.

There is less intermittent switching between laminar and turbulent flow, consistent with a lower panel response.

These results suggest a tie between the turbulent burst rate and panel vibration.



Turbulent Spot Statistics

Future Work

Tests are also planned in the Boeing/AFOSR Mach-6 Quiet Tunnel at Purdue University in April 2016.

- Allows tests under noisy and quiet flow conditions.
- Under quiet flow, perturber should be the only important disturbance source, to force panel vibration.
- Can then target various structural natural frequencies and study the mode-matching response of the panel.

Future / Ongoing Work

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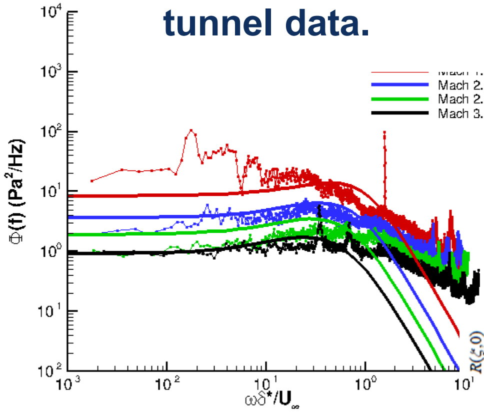
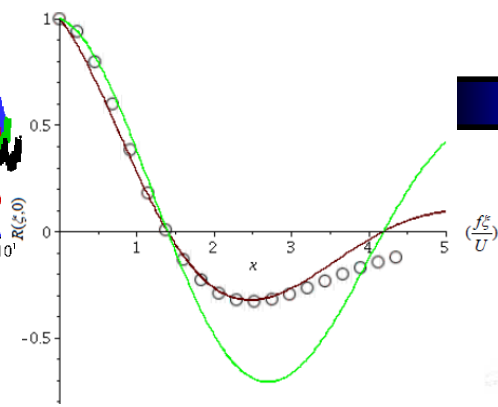
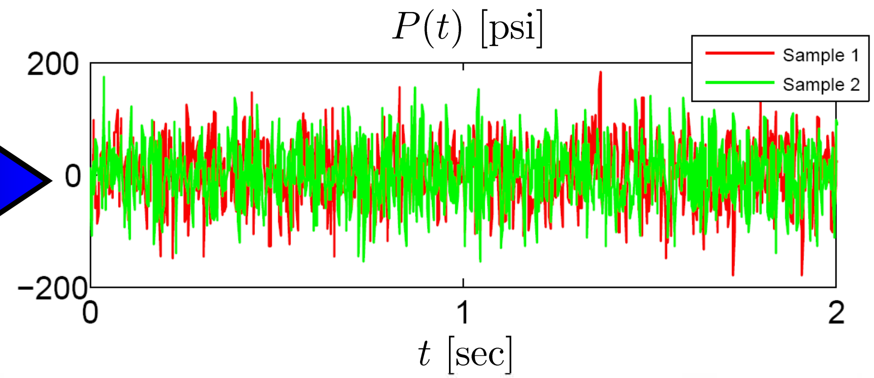
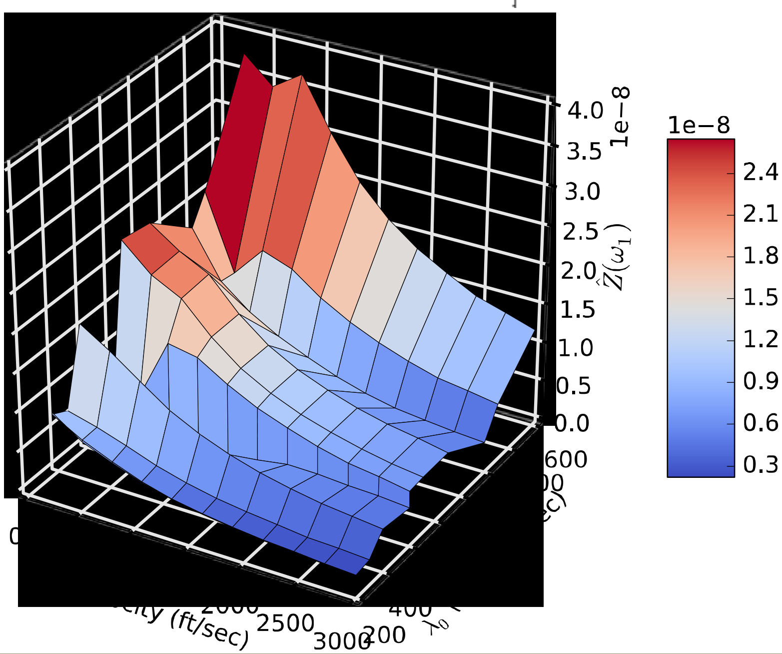
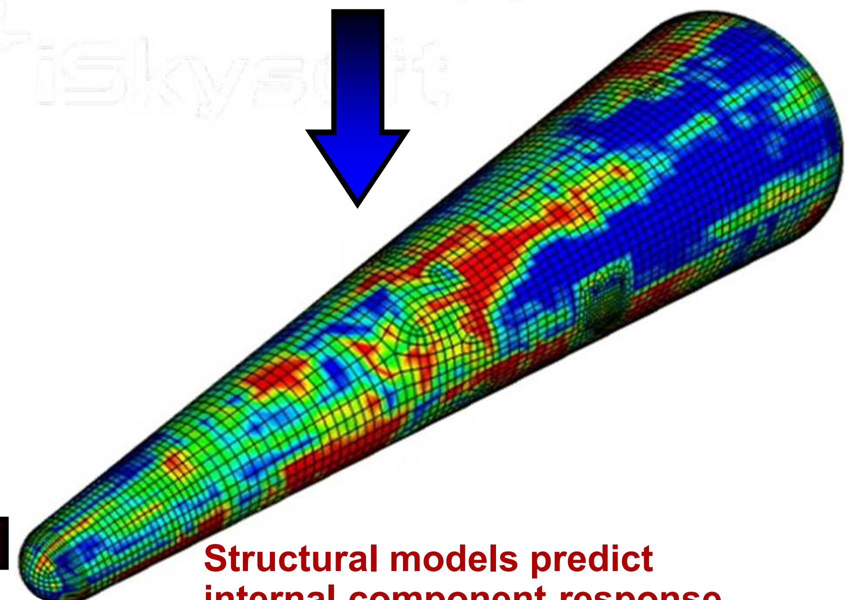
Pressure fluctuation model based on wind tunnel data.











Structural models predict internal component response.

Concluding Remarks

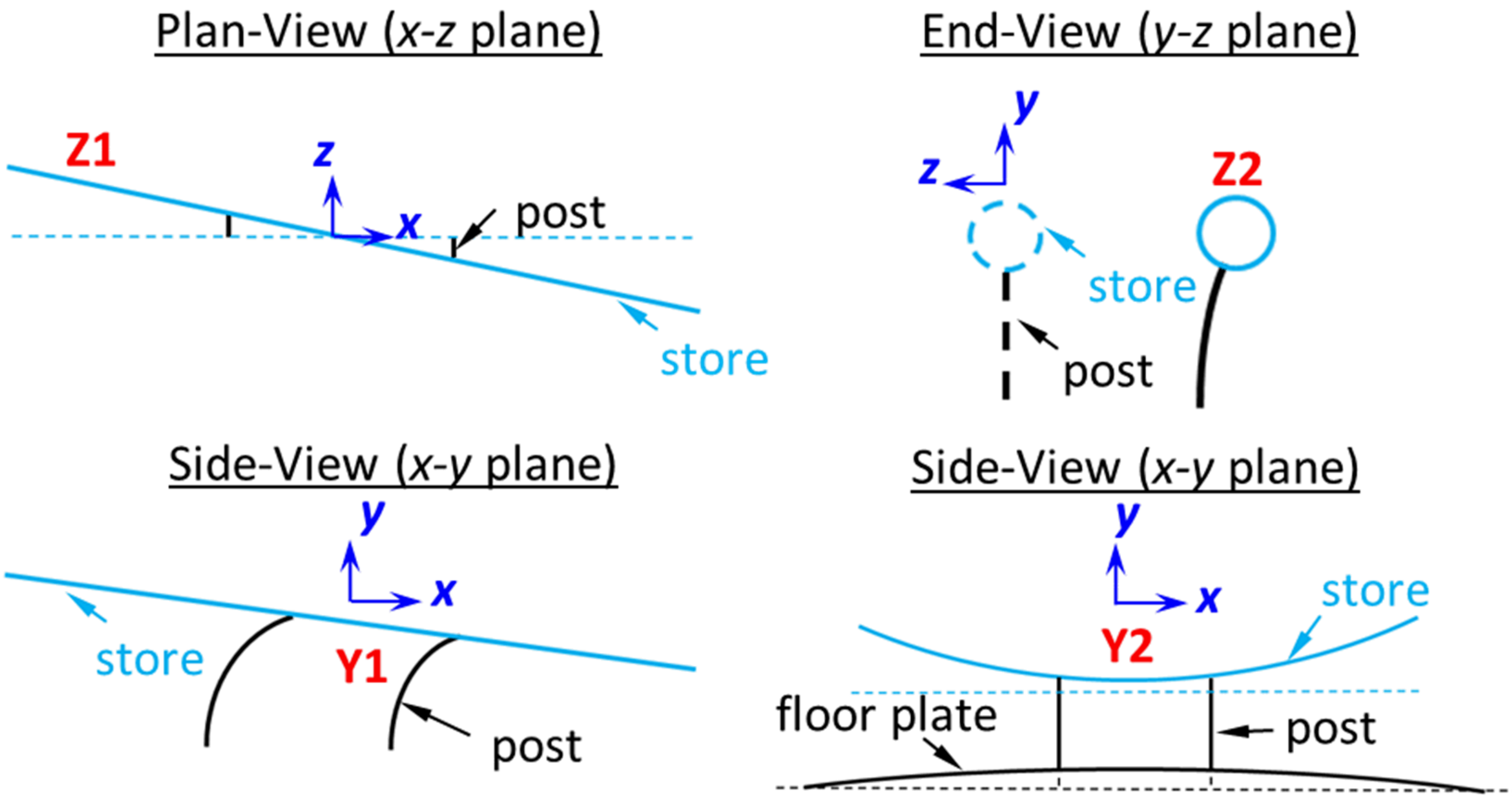
We can leverage several powerful tools at Sandia:

- **Advanced diagnostics to measure:**
  - **Flowfield:** Stereoscopic PIV, TR-PIV, High-speed Schlieren
  - **Surface Loading:** High-frequency pressure sensors, TR-PSP
  - **Surface Response:** Accelerometers, Laser-Doppler Vibrometry, eventually DIC
- **Structural expertise** for hammer testing and understanding modes and mode shapes.
- **Computational expertise** to compute experiments and compare/help understand experimental results.

To make progress in understanding complex high-speed FSI problems.

Backup Slides

Store Natural Frequencies



- Natural frequencies labeled by their predominant direction of motion
- Five natural frequencies measured below 4 kHz

Variation of Natural Frequencies

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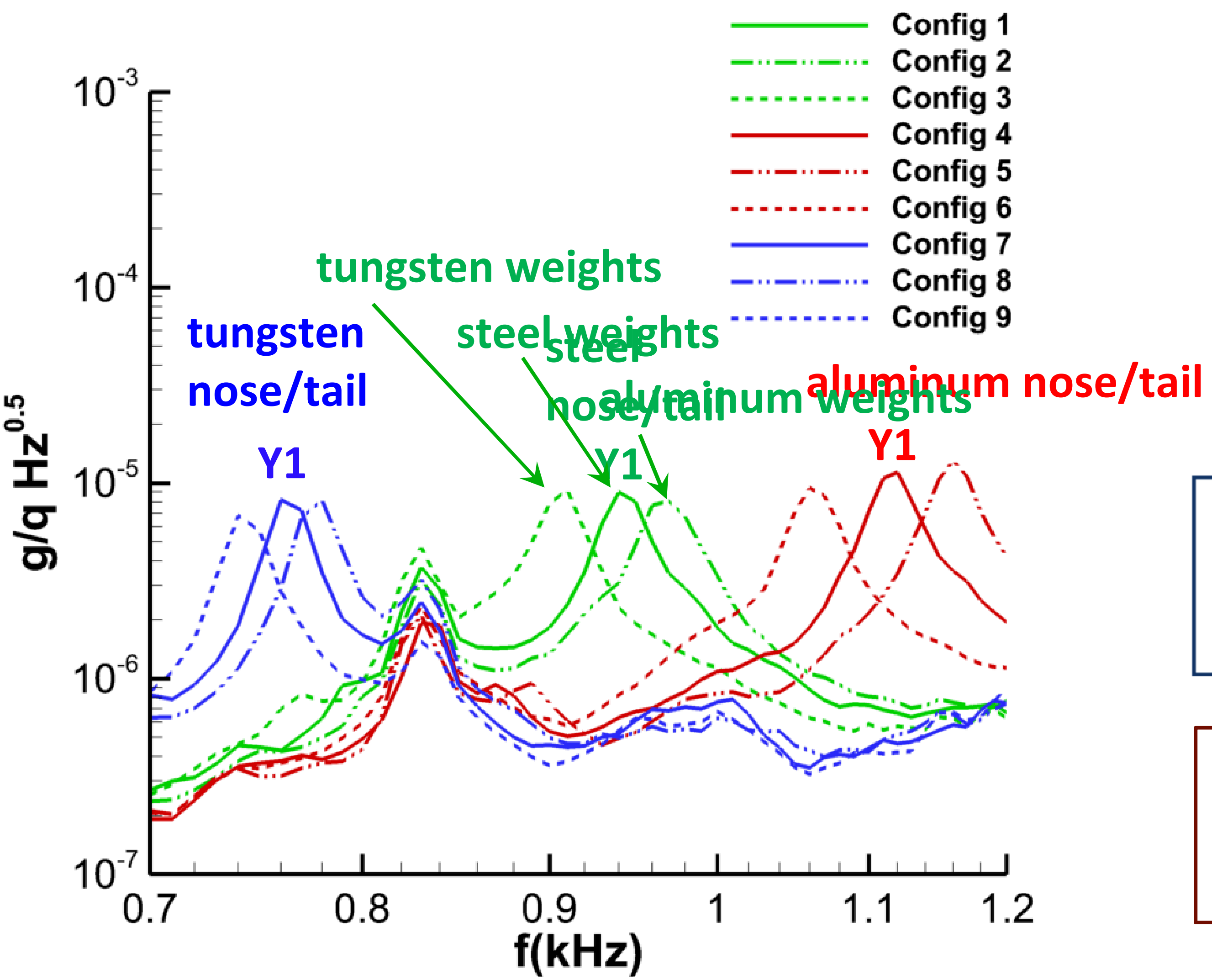
Streamwise Accelerations at A2 in Mach 0.8 Cavity Flow



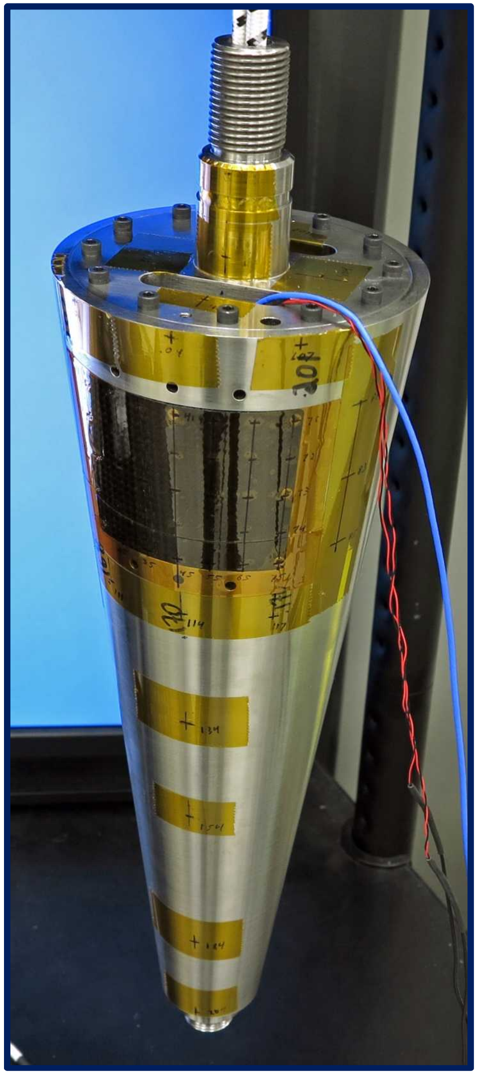
Changing nose and tail results in large natural frequency variations.

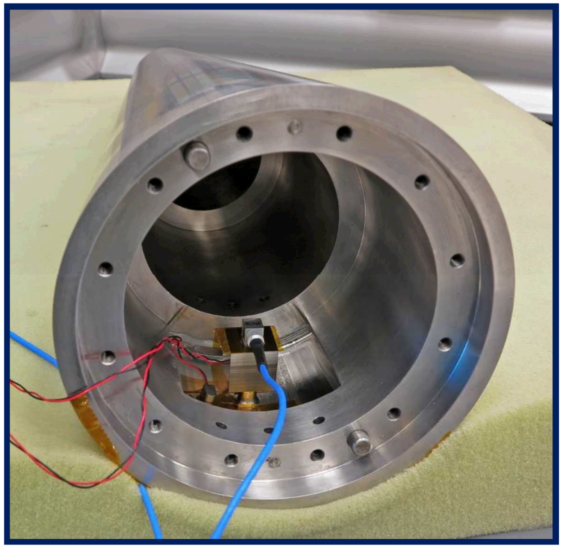
Smaller variations can be achieved through weight changes.

Structural Characterization

Hammer test was performed to determine the structural natural frequencies of the panel and model.

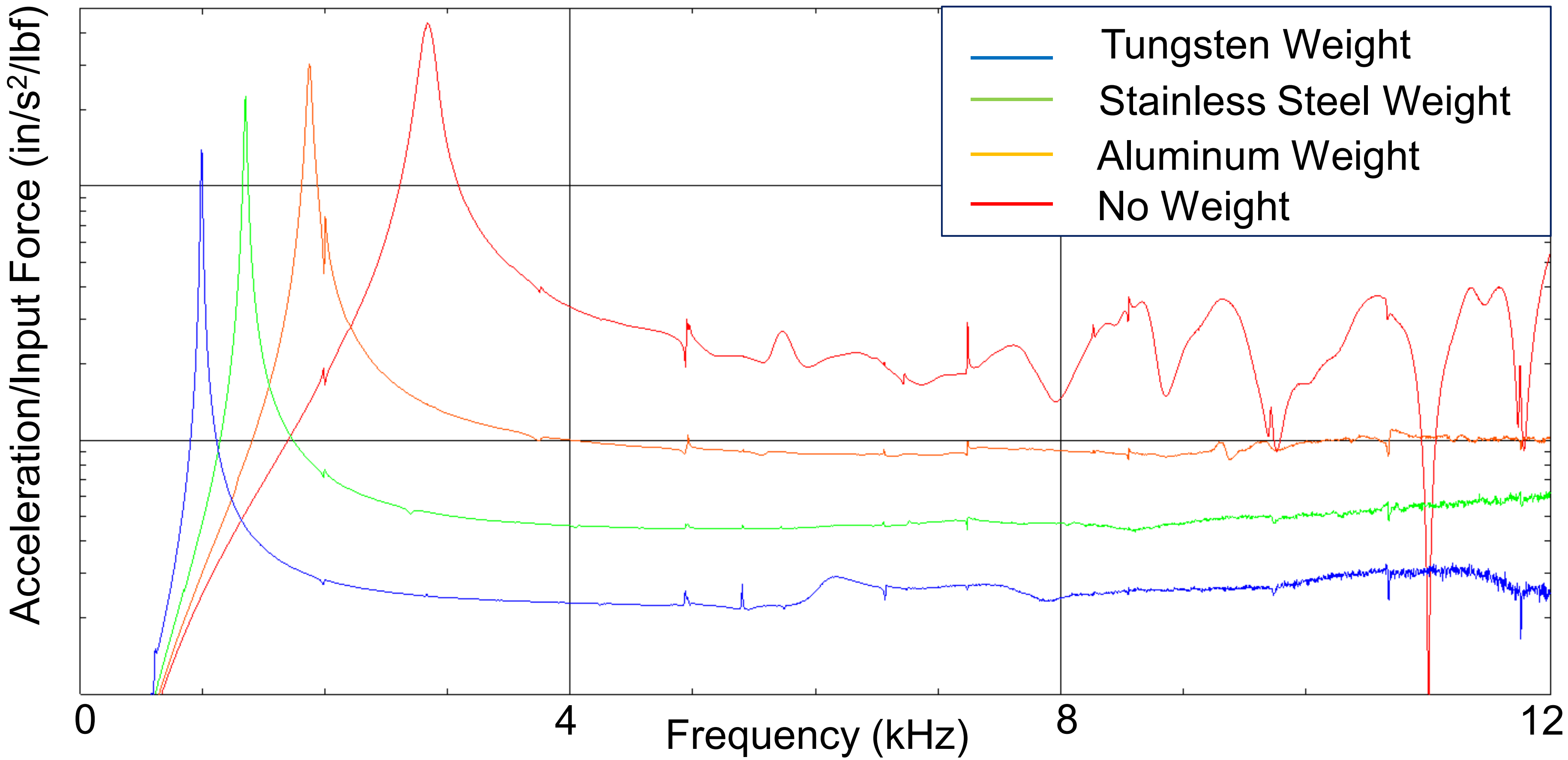
- Measure structural response to a known input.
- Generates a Frequency Response Function (FRF) in all three directions.
- Mode frequencies are obtained up to 10 kHz.
- Can also obtain mode shapes.





Carbon-Composite Panel FRF

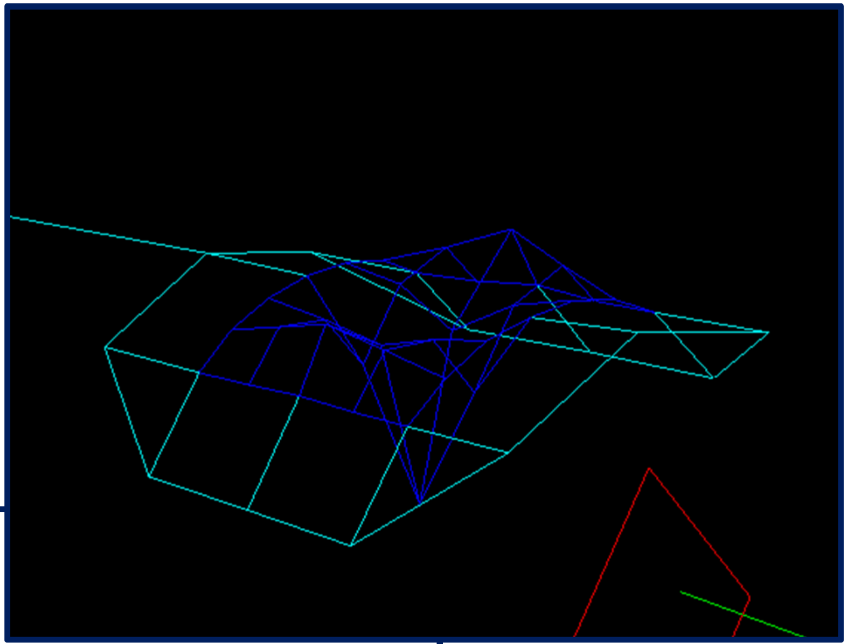
- Example shown for vertical (z) acceleration
  - Three-lobe panel mode, P_z is the dominant mode in this case.
- FRF shows varying natural frequencies with panel configuration.

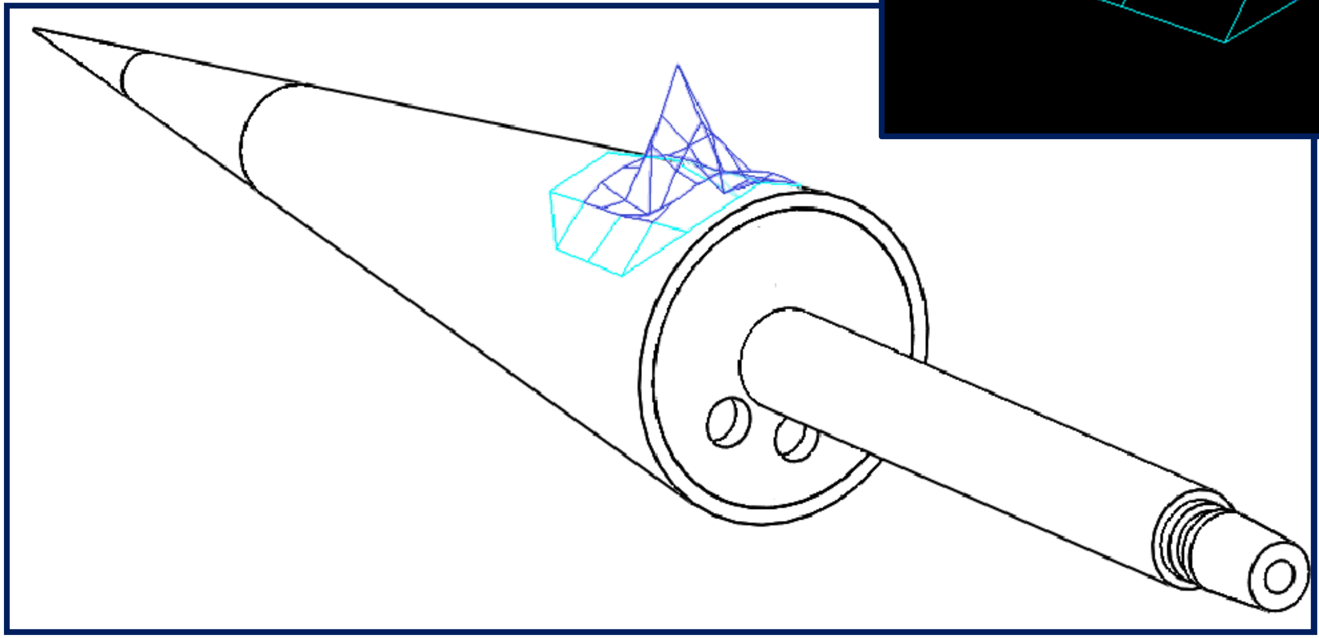


Three-lobe panel mode, P_z

Most apparent mode in vertical FRF

- Significant motion at center of panel.
- Smaller motion in spanwise direction, to either side of center.





Panel Response to Turbulent Boundary Layers

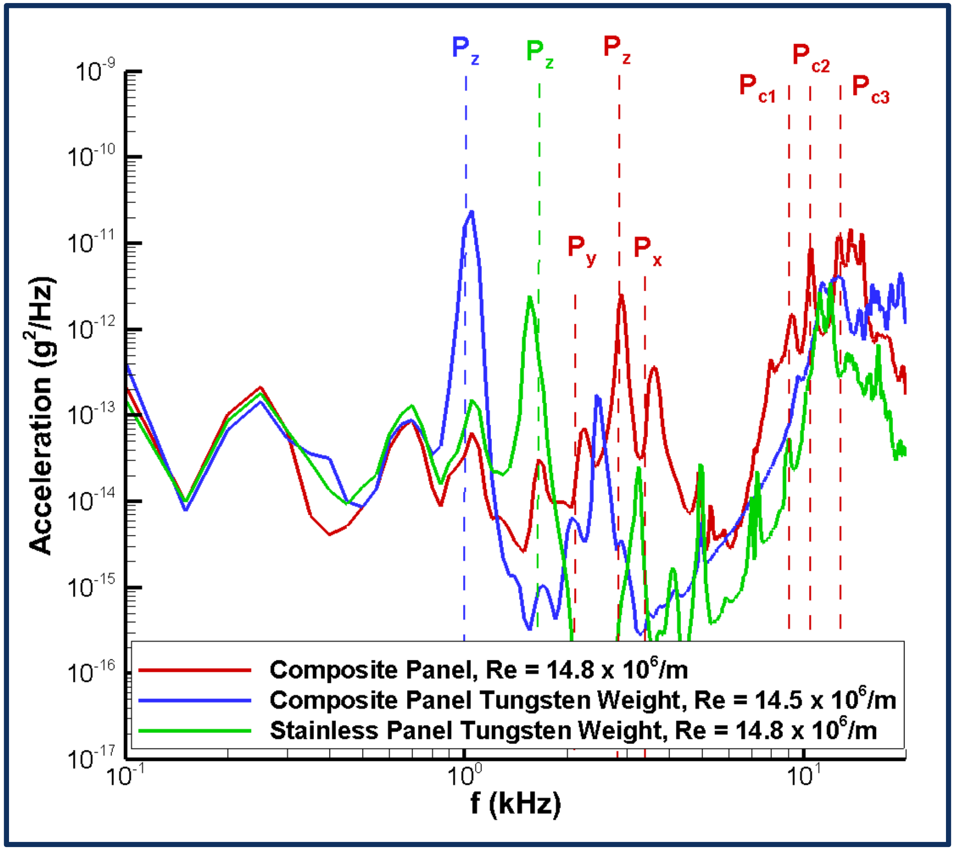
Sandia National Laboratories

Hammer test conducted to identify structural natural frequencies.

- Verified that can tune natural frequencies with panel/weight configurations.

Panel response shows many of the predicted structural natural frequencies.

- Boundary layer excites the panel modes in each direction.
- Can change frequencies of dominant modes by changing panel material and attached weights.



Vertical Acceleration, G5