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Fluid-Structure Interactions in High-Speed Flow

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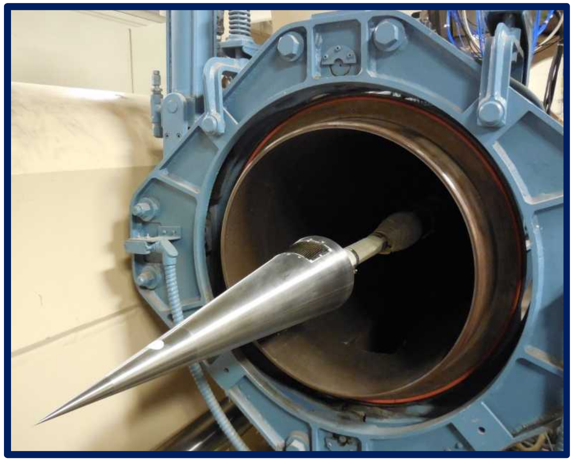

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Fluid-Structure Interactions

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

Many potential high-speed applications:

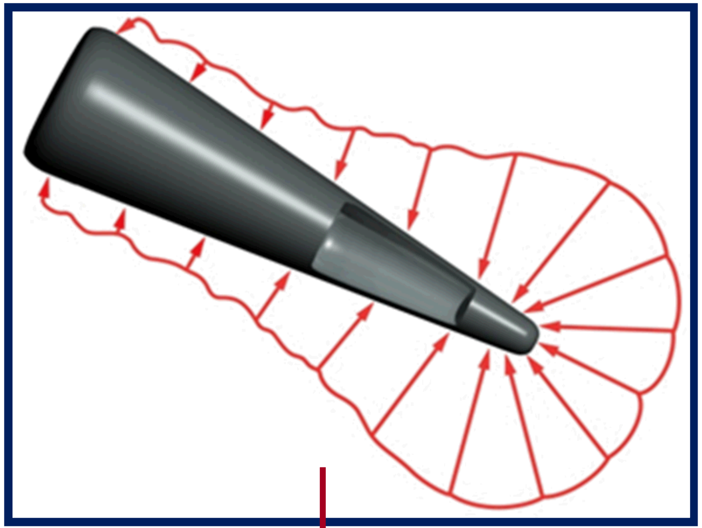
- Shock-wave boundary-layer interactions (SWBLI)
- Hypersonic reentry: boundary-layer transition
- Cavity flows: captive carry or store separation

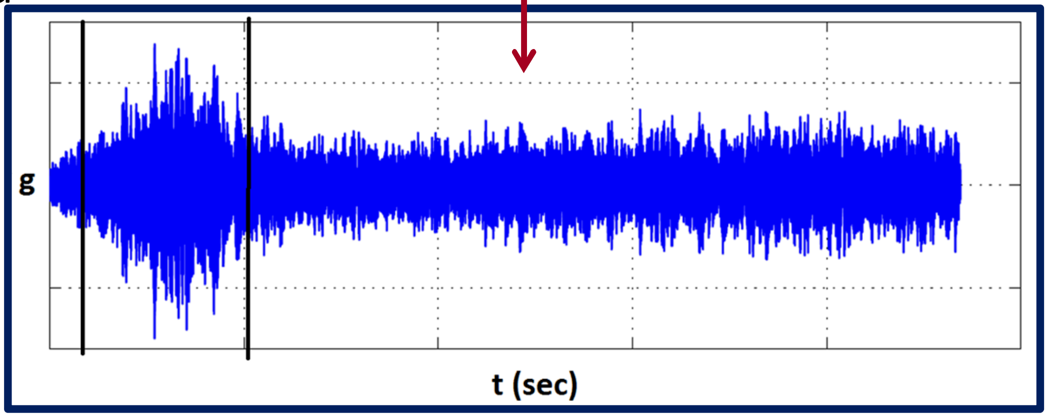
Limited experimental work on these problems, especially at high speeds.

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.

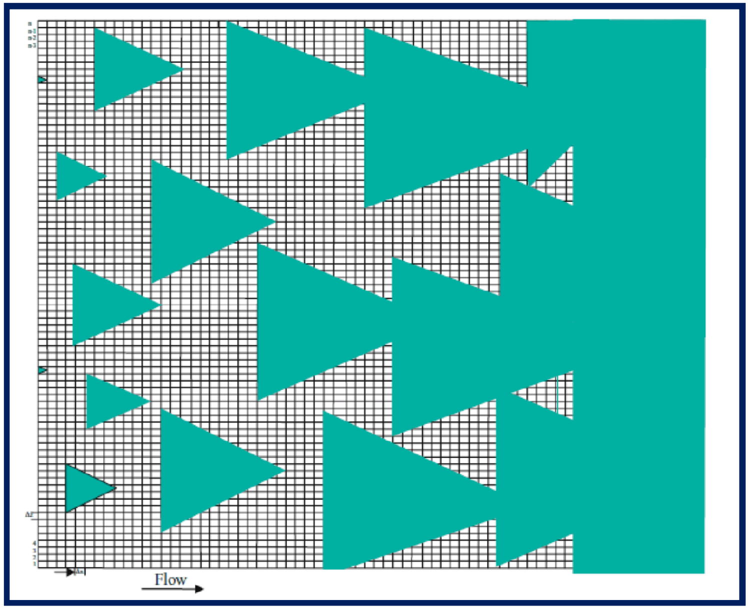




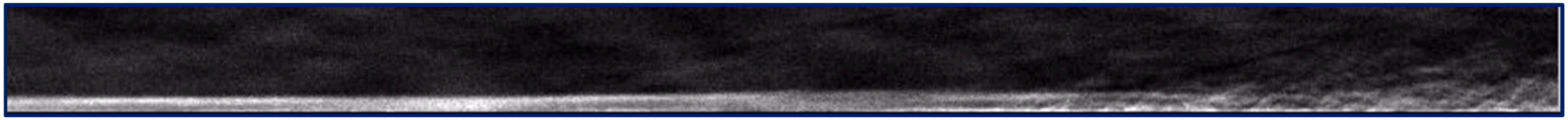
Characterizing Pressure Loading on Relevant Geometries

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

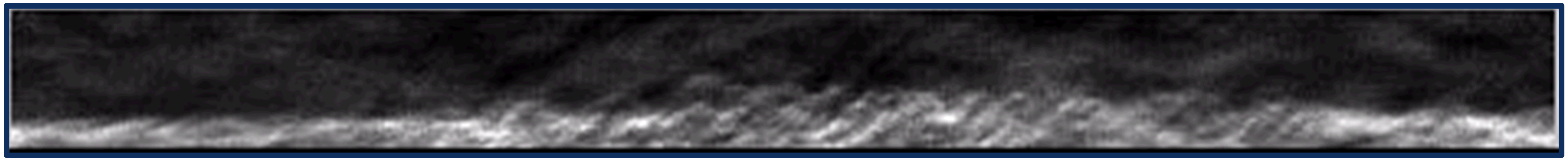
- At low speeds, the boundary layer switches between smooth laminar flow and turbulence.
  - Characterized by intermittency, burst rate, and average burst length at a given point.
- At hypersonic Mach numbers, second-mode waves are important and occur at the same time as turbulent spots during the transitional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



Turbulent-spot model simulation, Vinod (2007).



Transitional Boundary Layer, Mach 5



Transitional Boundary Layer, Mach 8

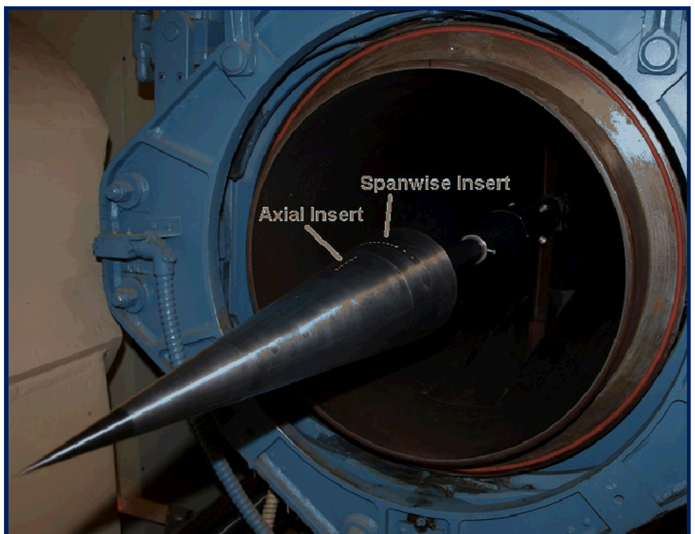
Experimental Setup

We want to study natural transitional boundary layers on a cone at Mach 5 and 8 to obtain transitional statistics.

- Simultaneous schlieren imaging and high-frequency pressure measurements.

Seven degree stainless-steel sharp cone in Sandia's Hypersonic Wind Tunnel.

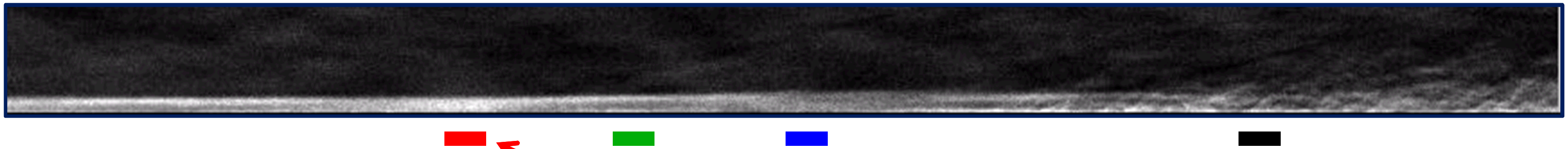
- Axial array with closely spaced high-frequency pressure transducers.
- Directly beneath schlieren viewing area.



Model installed in HWT.

Axial pressure-transducer array.

Mach 5 Measurements, Re = 9.75 x 10^6/m



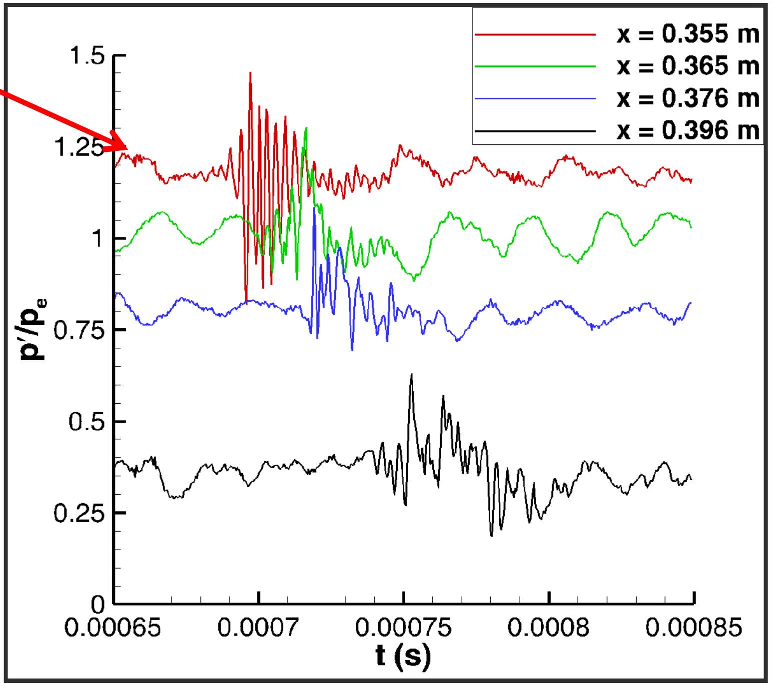
Schlieren Videos

Intermittent formation of second-mode wave packets that then break down to isolated turbulent spots.

- Observed in both schlieren videos and simultaneous pressure measurements.

Disturbances are surrounded by a smooth laminar boundary layer.

- To model this behavior, need to be able to distinguish instability waves from turbulence.



Pressure Traces

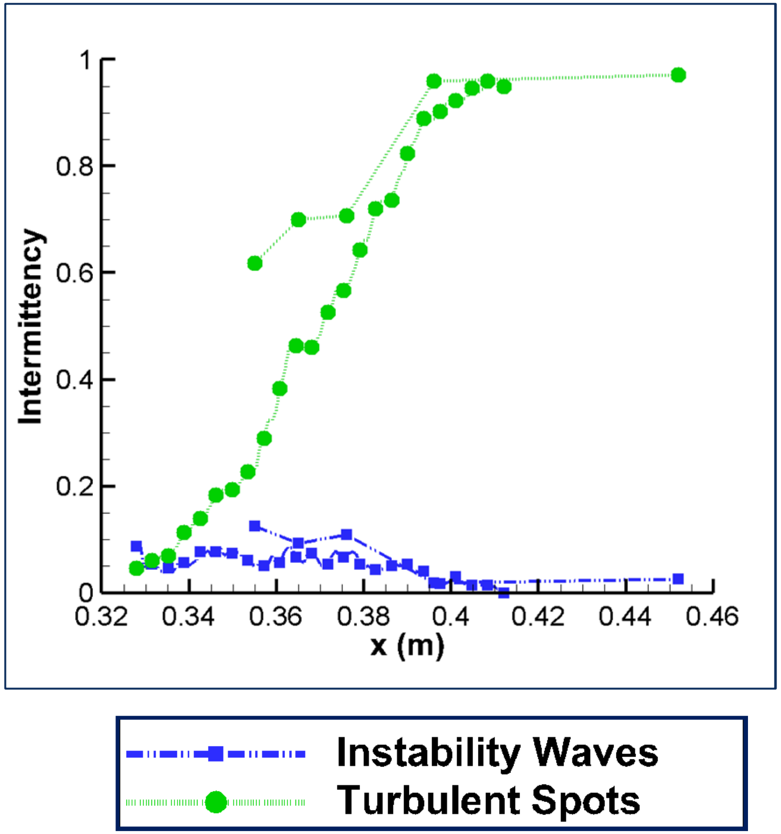
Mach 5 Transition Statistics

Developed techniques to separate waves from turbulence in both pressure measurements and schlieren videos.

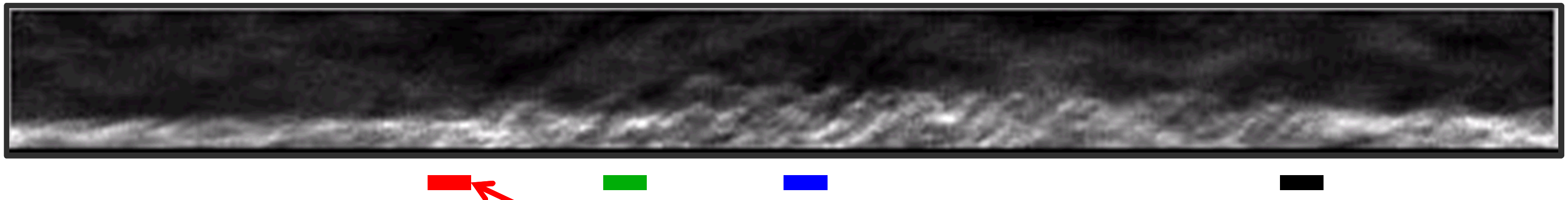
- Compute separate statistics for instability waves and turbulent spots.
- Both measurement techniques show reasonable agreement.

Waves remain a small part of transitional region.

Turbulent intermittency rises rapidly through transition.



Computation of Boundary-Layer Statistics, Mach 8, Re = 9.74 x 10^6/m



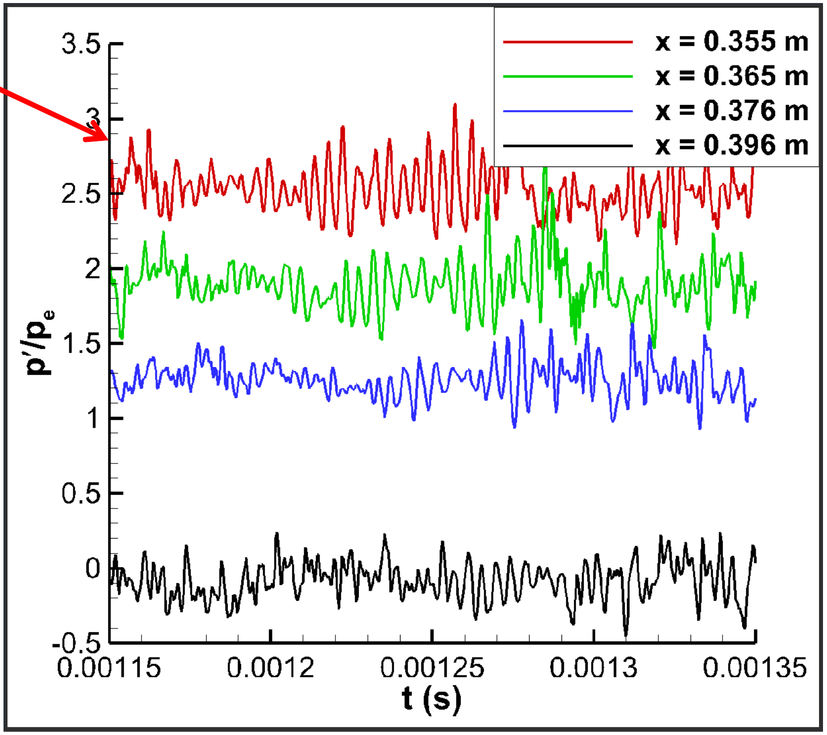
Schlieren Videos

Flow alternates between second-mode waves and turbulence.

- Smooth, laminar boundary layer not observed in transitional region.

Important to separate waves from turbulence in this case.

- Wavelet transform technique used to do this.
- Then, use this to compute boundary-layer intermittency and burst rates for waves and turbulence.



Pressure Traces

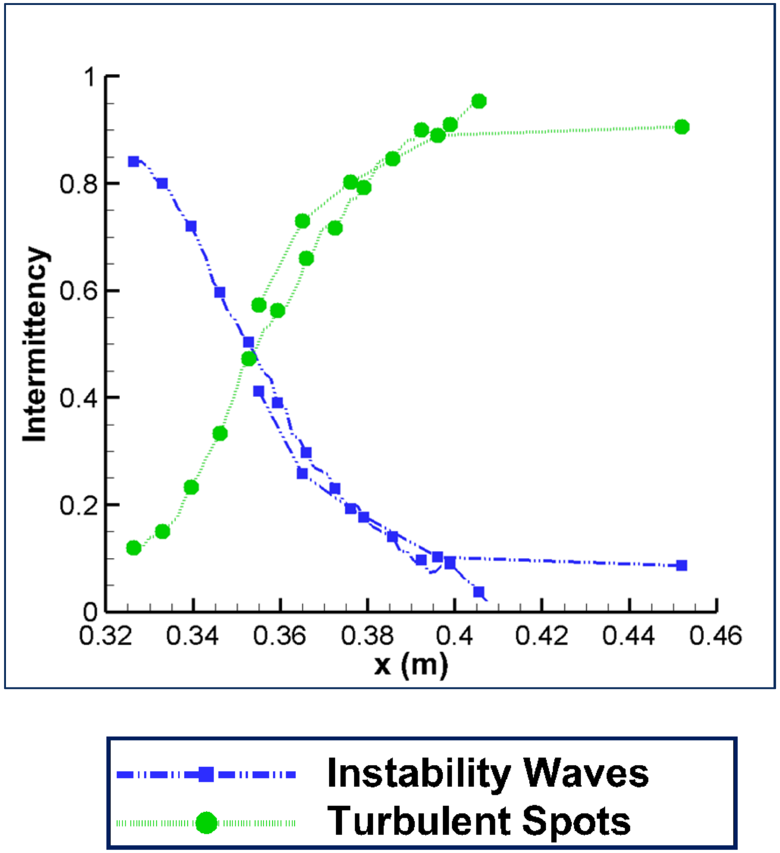
Natural Transition Statistics: Intermittency

Instability waves

- Significant part of the flow prior to development of turbulent spots.

Turbulent spots

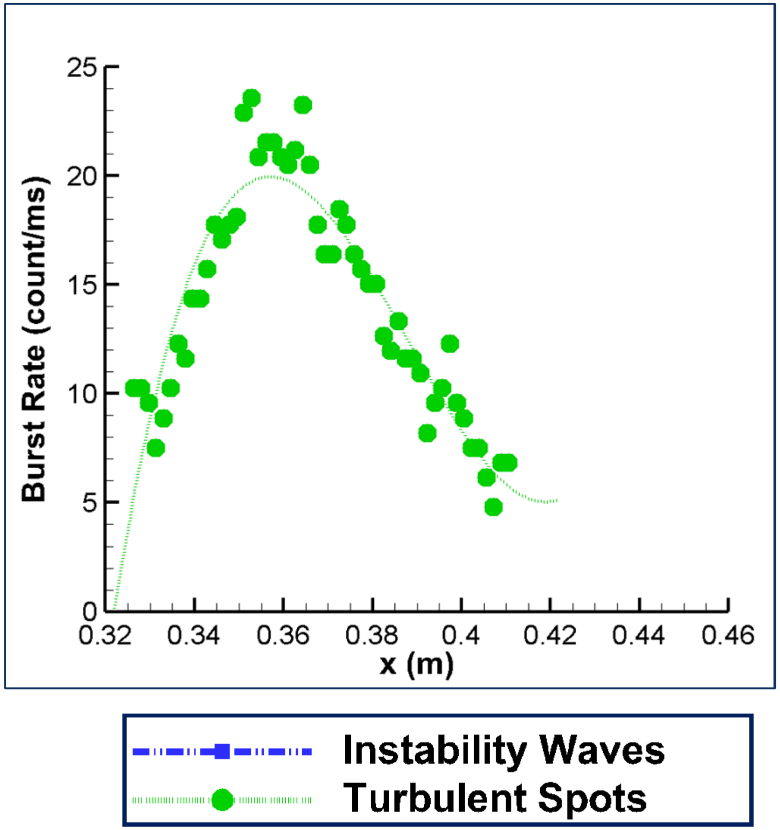
- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.



Natural Transition Statistics: Burst Rate

Burst-rate computations shows flow switches between turbulence and waves.

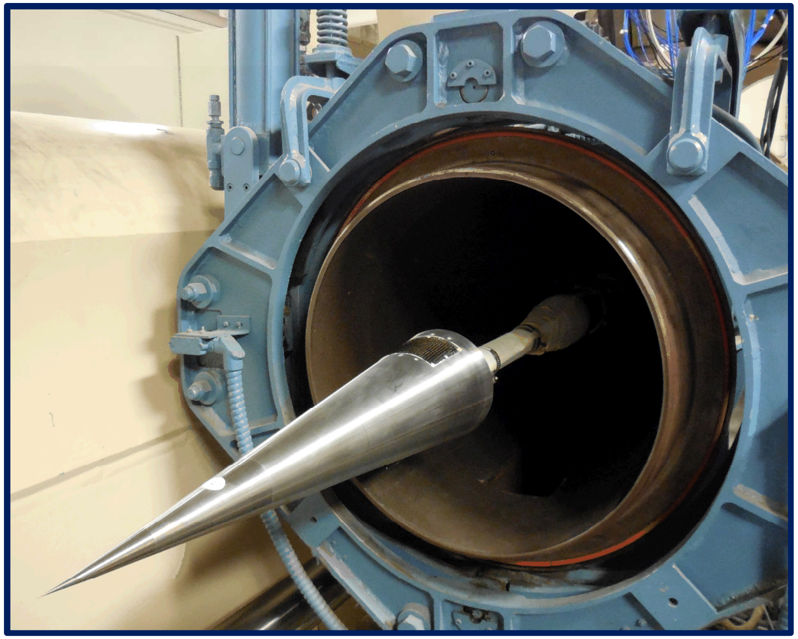
- Equal burst rate for instability waves and turbulence.
- High burst rate when intermittency is near 0.5.
- Burst rate decreases as spots merge into turbulence at locations further downstream.



Characterizing Structural Response to this Loading

We now have a better description of the fluid dynamics side of the problem.

Now we want to know how these disturbances couple to vehicle vibration!



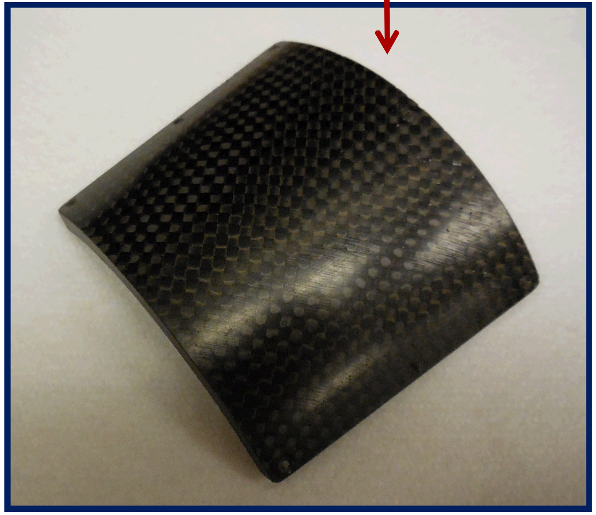
Experimental Design

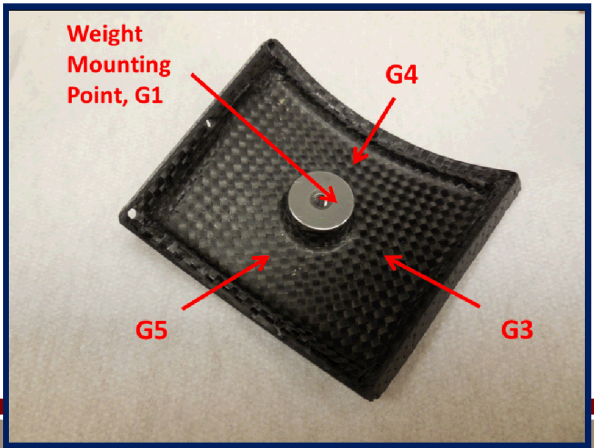
Designed a cone with integrated thin panel that will vibrate from flow excitation.

- 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

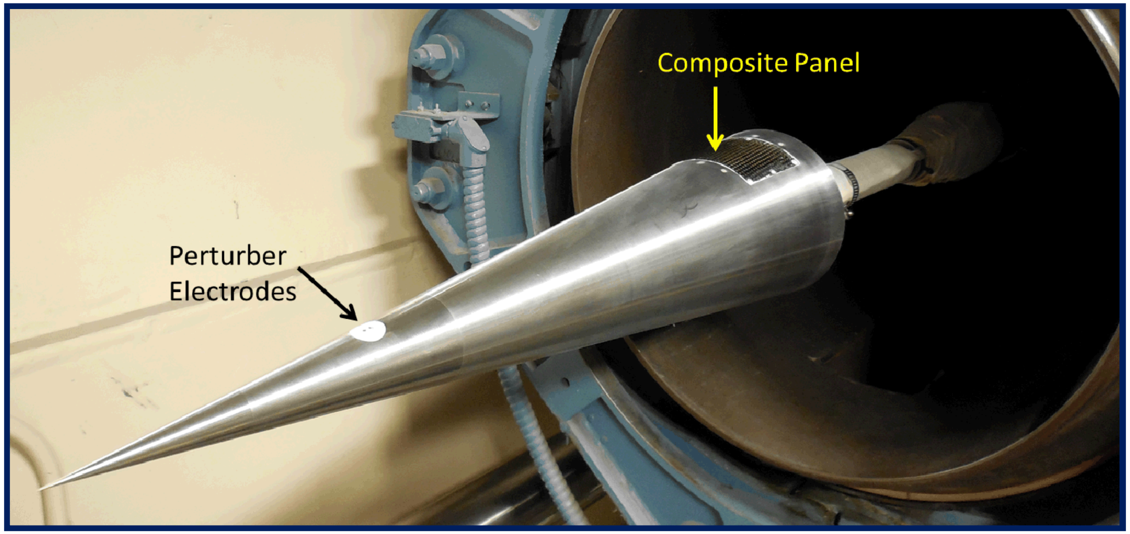
Pressure sensors upstream and downstream of panel were used to characterize the boundary layer.

- Schlieren measurements also acquired.

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

- Adjustable frequency up to 10 kHz.
- Initial plan was to match the perturbation frequency to the structural natural frequencies of the panel.

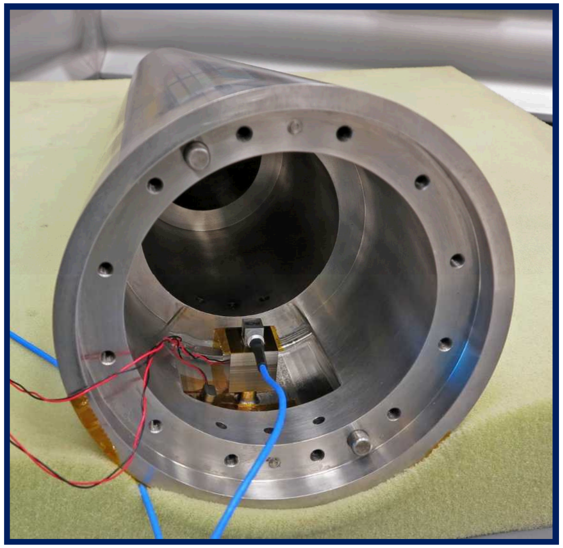
Controlled perturbation off for 15 s, and then on for 15 s during a run.

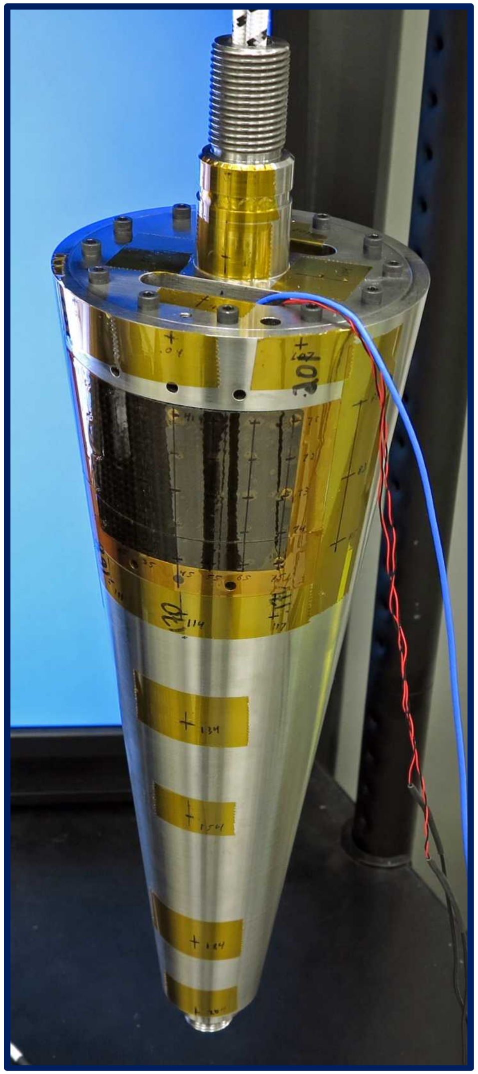


Structural Characterization

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.

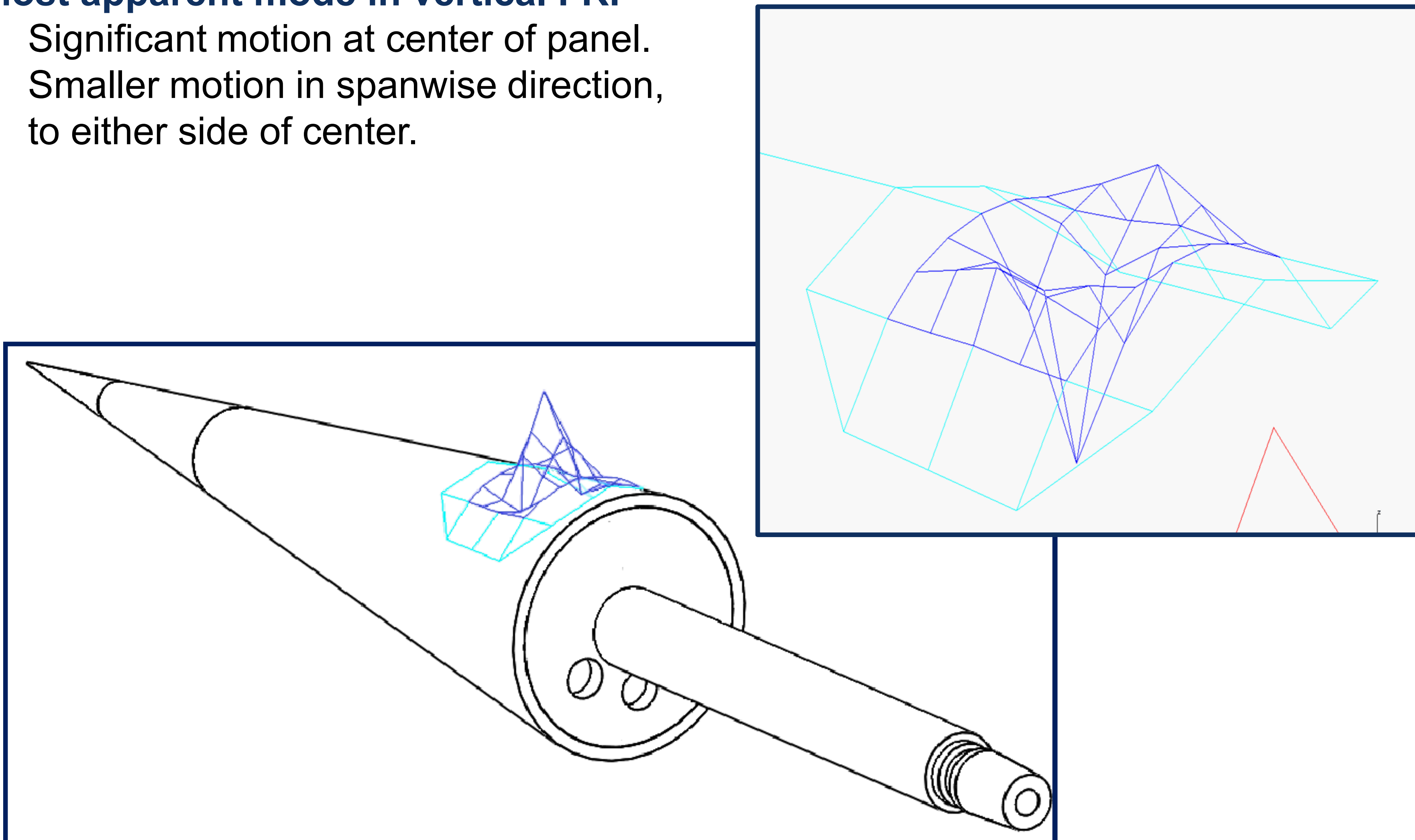




Three-lobe panel mode, P_z

Most apparent mode in vertical FRF

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

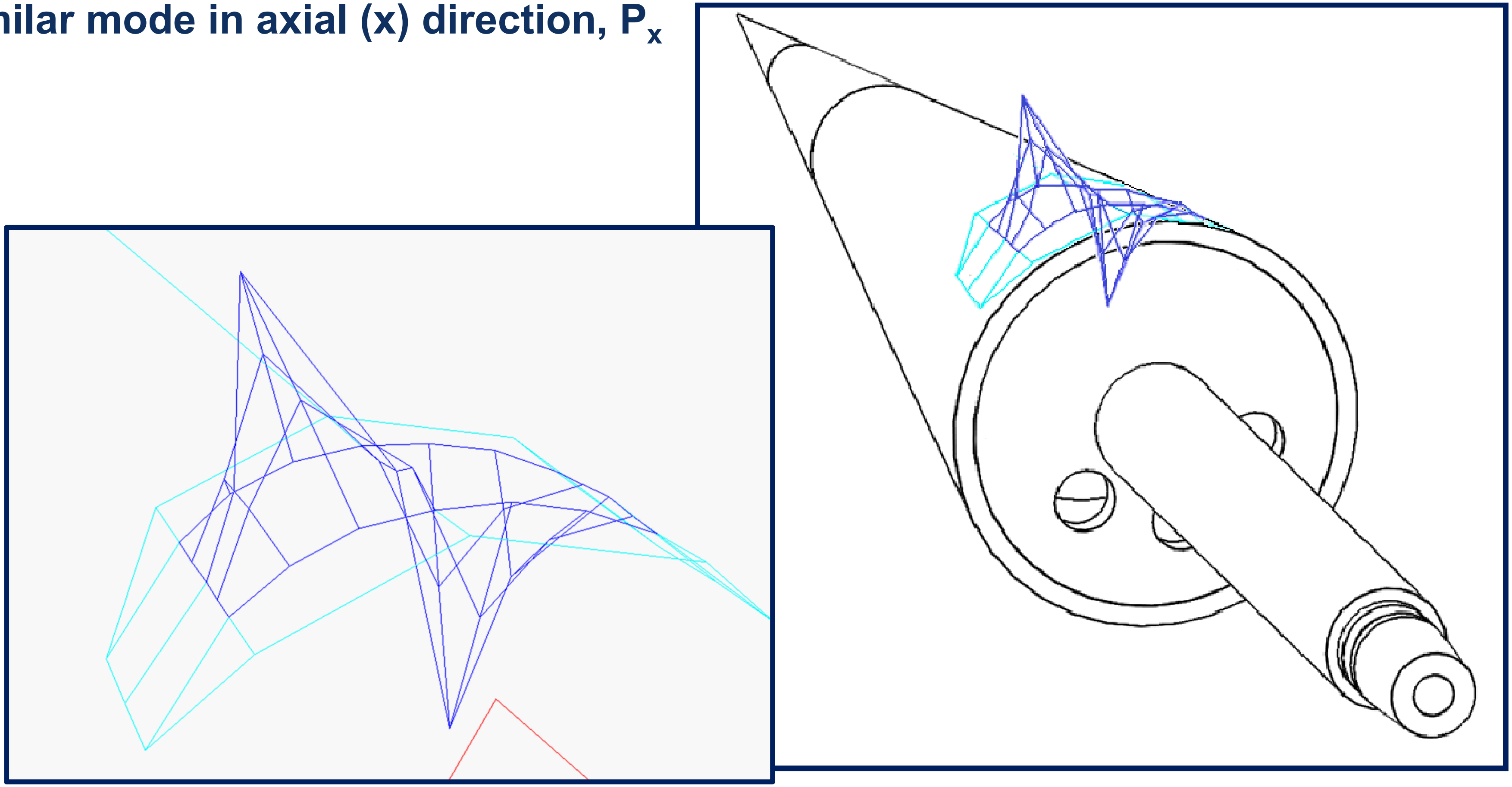


Two-lobe panel mode, P_y

Sinusoidal mode shape in spanwise (y) direction.

- Oscillates with time.
- Peak amplitude away from panel center.

Similar mode in axial (x) direction, P_x



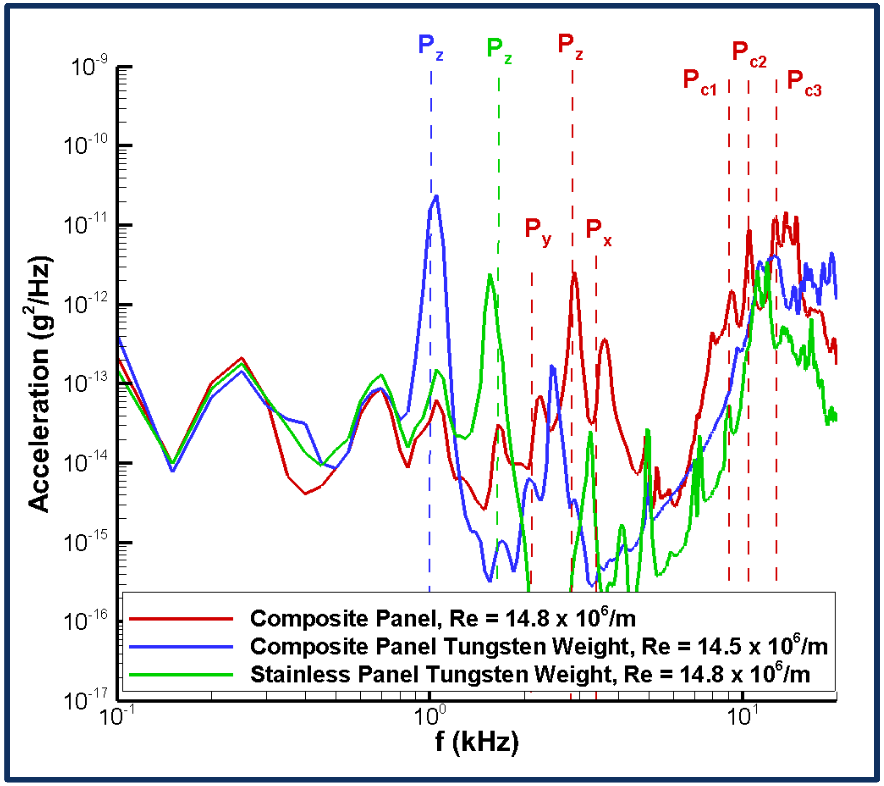
Panel Response to Turbulent Boundary Layers

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.

Higher-frequency panel response also occurs (P_{c1}-P_{c3}).

- Most apparent in G5 measurements in front of panel center.
- Also see coupling with dominant modes in other directions (P_x, P_y).



Vertical Acceleration, G5

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

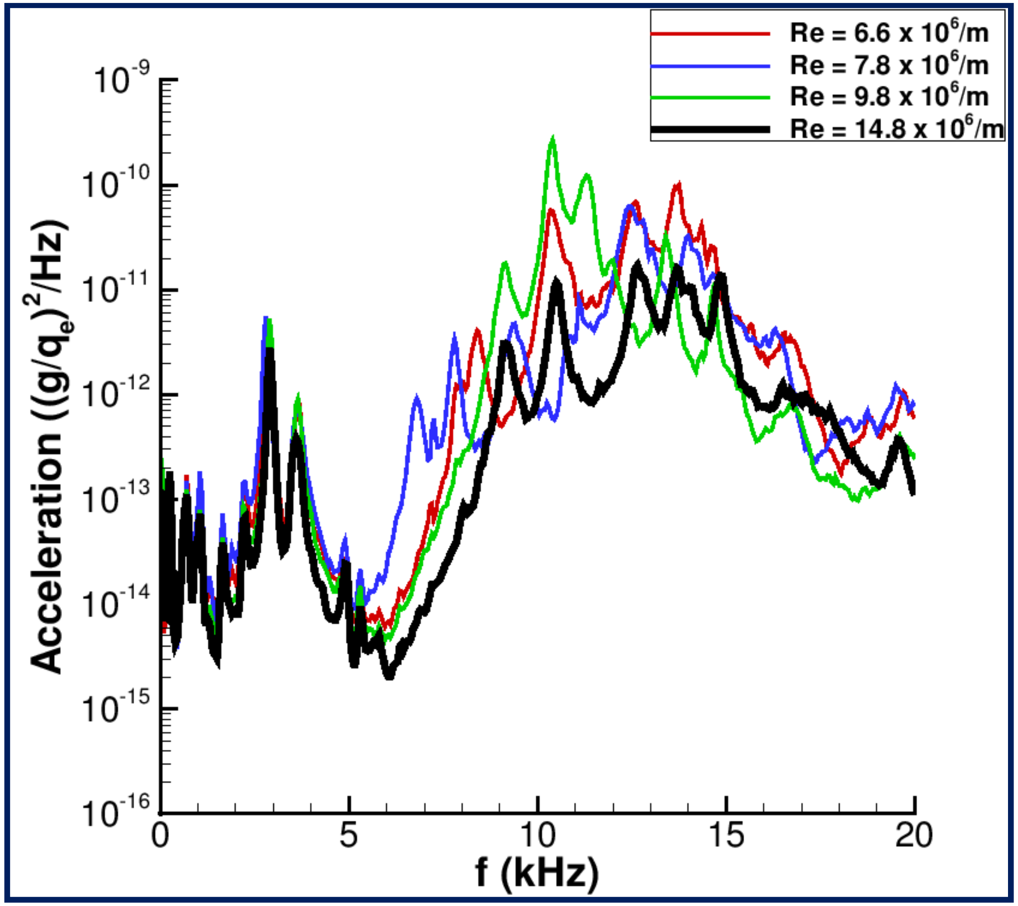
Lower response to turbulent boundary layers.

- 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

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Consider effect of perturber operated at f = 7.9 kHz.

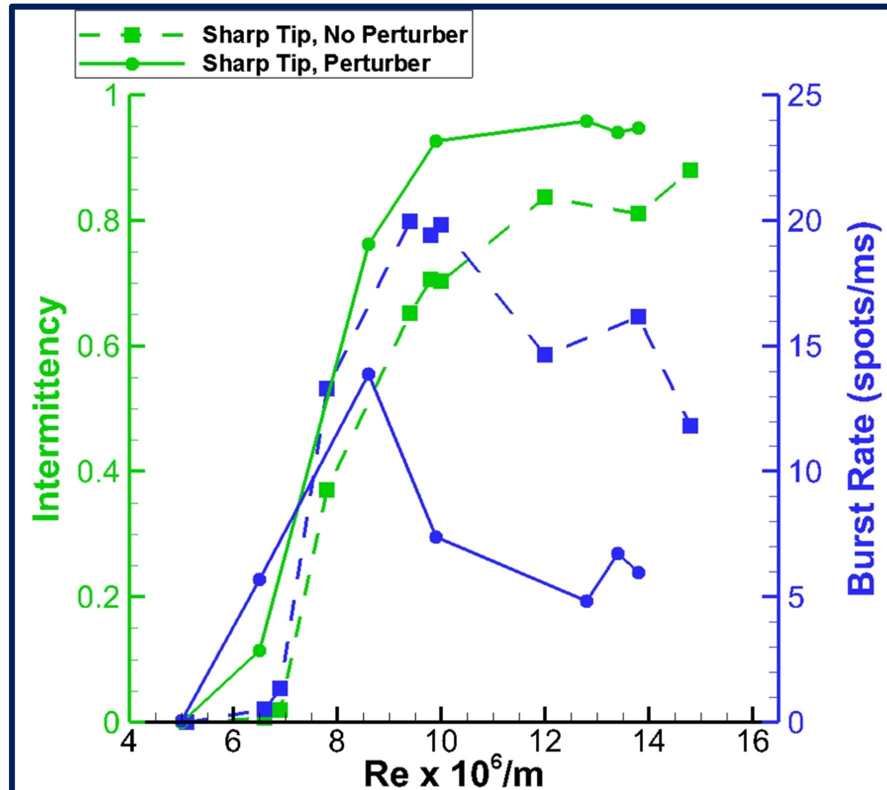
- At a given Reynolds number, the perturber creates:
  - Higher intermittency.
  - Higher burst rate at low Re, lower burst rate at higher Re.

Note the burst rate is at 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?



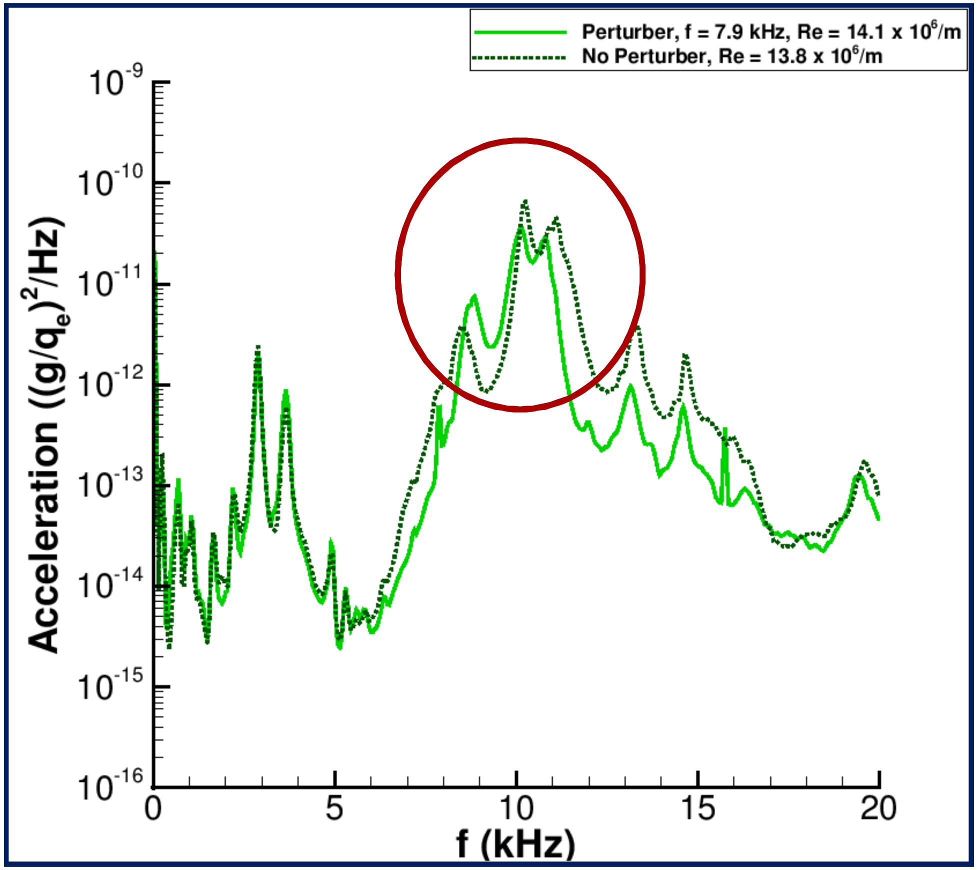
Boundary-Layer Statistics

Carbon-Composite Panel Response With and Without Controlled Perturbations

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.

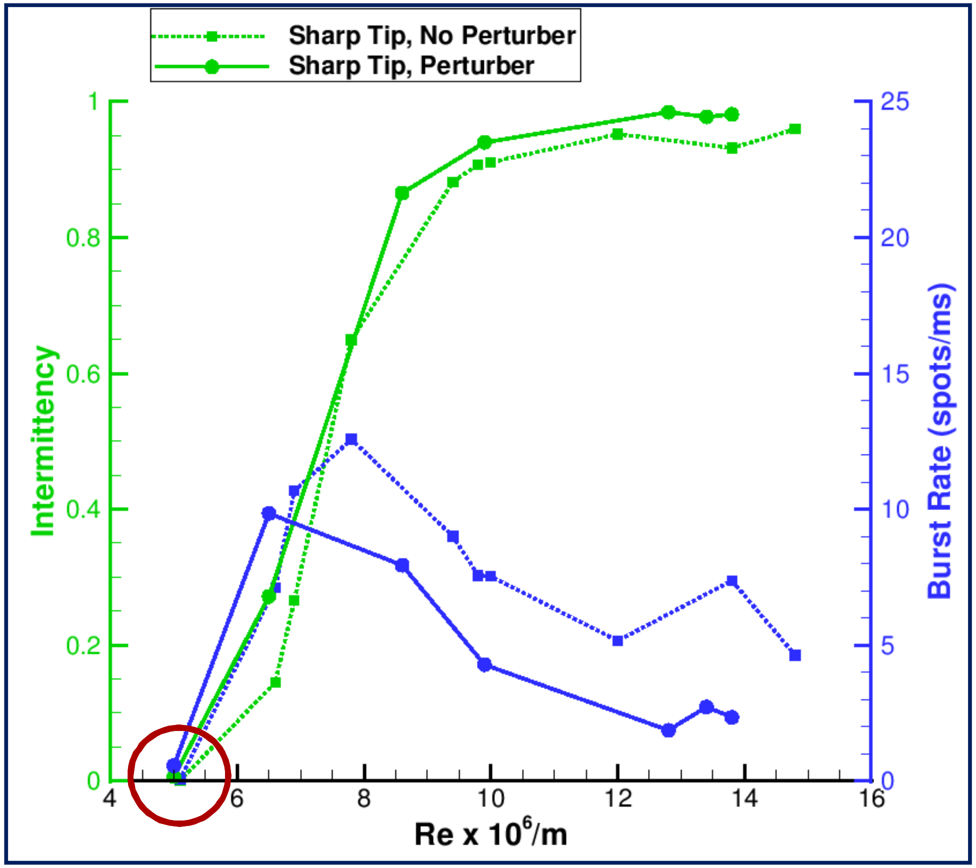


Vertical Acceleration, G5

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

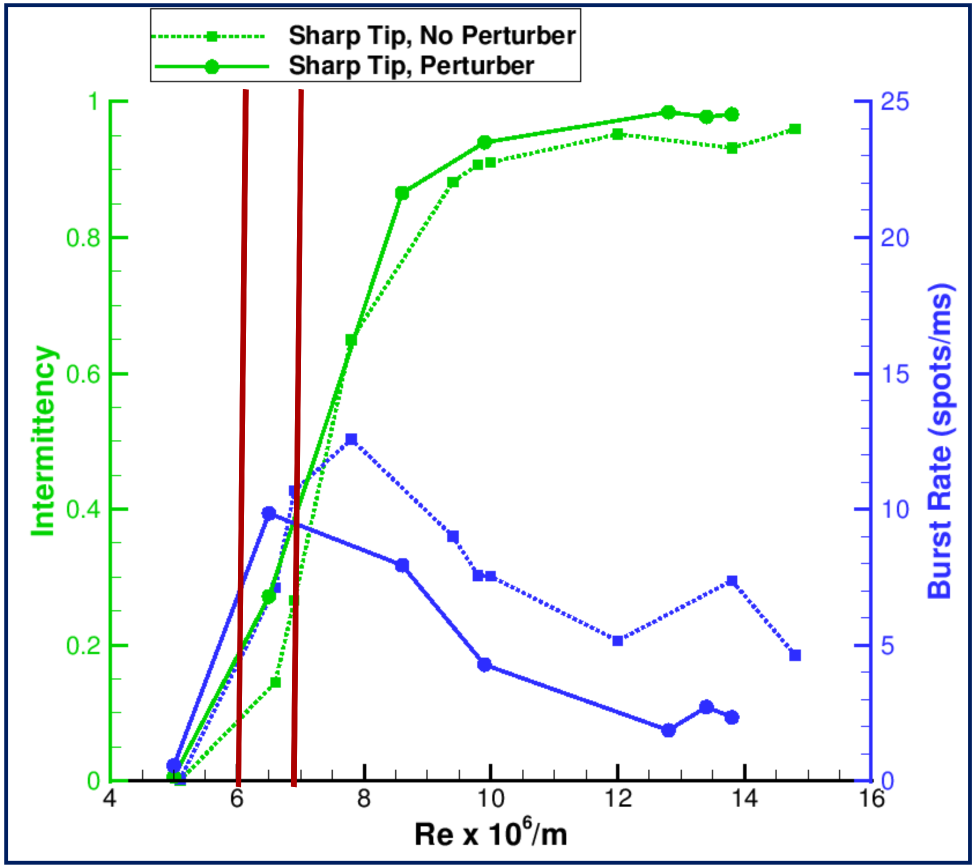
Carbon-Composite Panel Response to Controlled Perturbations

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

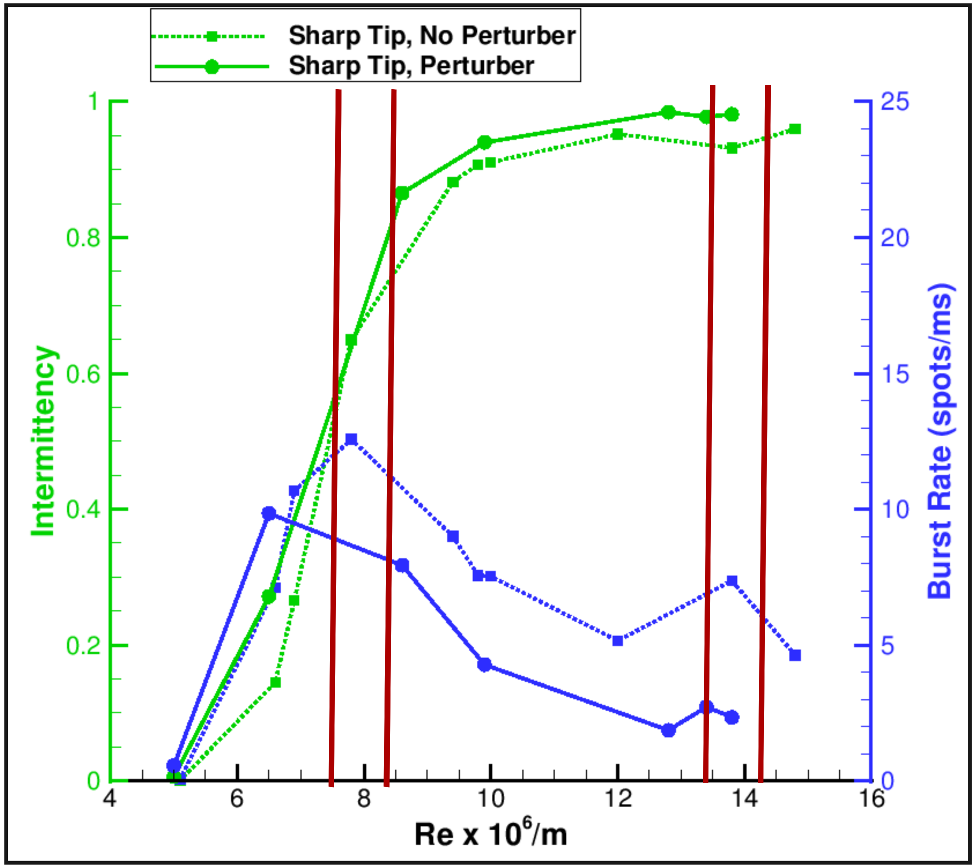
Carbon-Composite Panel Response to Controlled Perturbations

At higher Re, near 8 and 14 x 10^6/m, the vibration levels are lowered with the perturber firing.

- Intermittency is higher.
- Burst rate is lower.

Need a quiet tunnel test for a clearer story.

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



Turbulent Spot Statistics

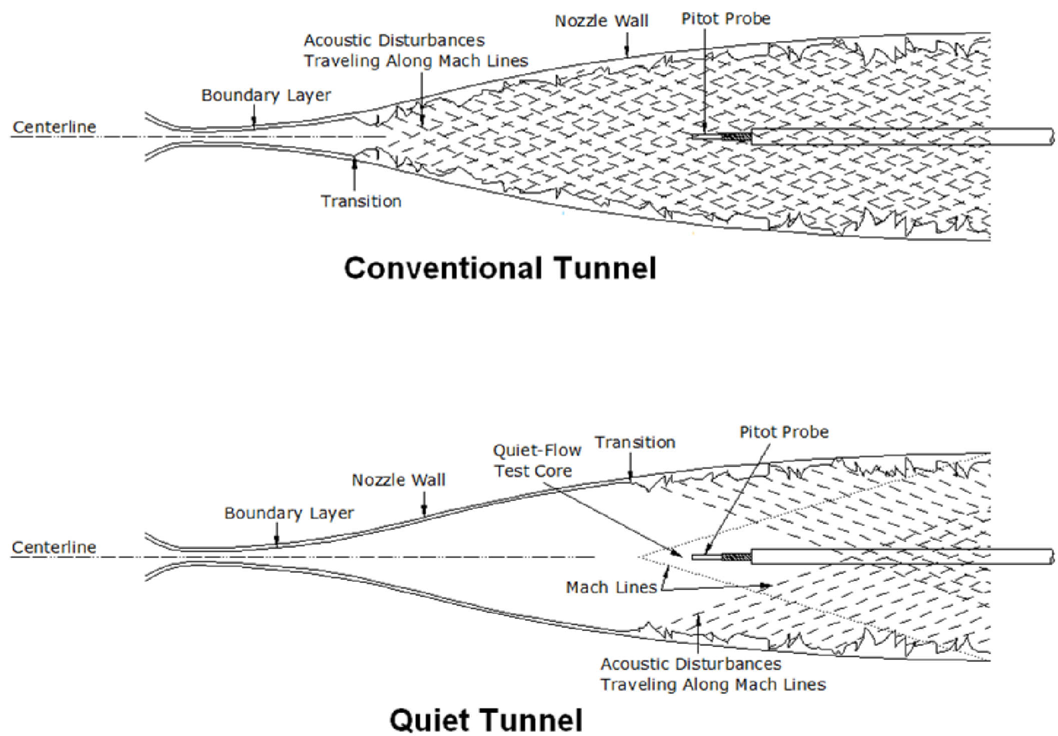
Conventional vs. Quiet Tunnels

Conventional Tunnels:

- High noise near 2-5% of the mean.
- Noise can cause much earlier transition than flight.

Quiet Tunnel:

- Low noise around 0.05%.
- Comparable to flight.

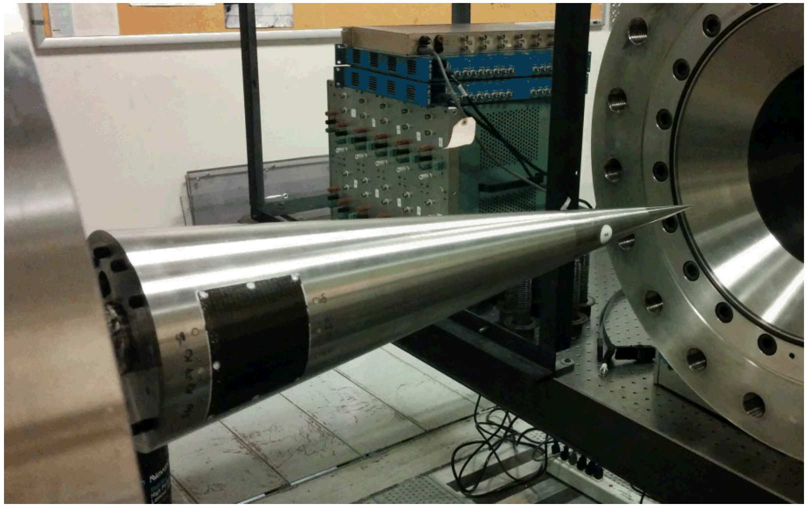


Schematic of difference between conventional and quiet tunnels, from Segura (2007).

Purdue Boeing/AFOSR Mach-6 Quiet Tunnel Test

Under quiet-flow conditions:

- Boundary layer (without perturber) remains laminar even at maximum quiet Reynolds number.
- When the perturber is used, it is the only disturbance source.
- Can target different structural natural frequencies of the panel independently of natural transition.



Panel Response to Laminar and Turbulent Boundary Layers

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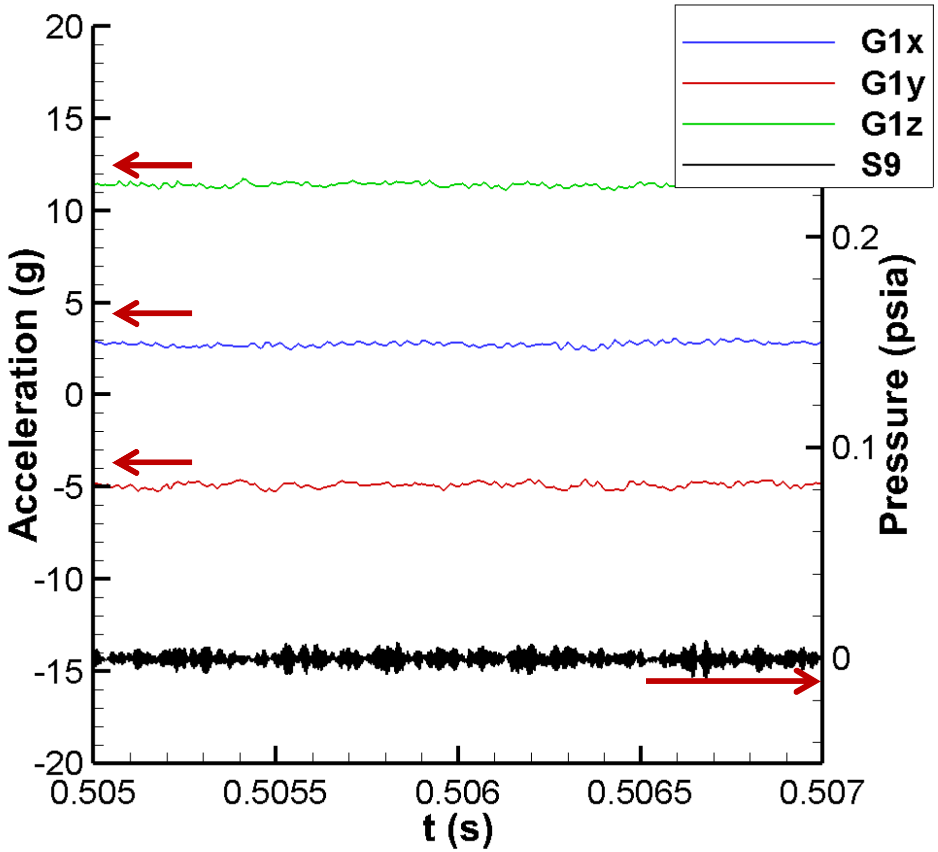
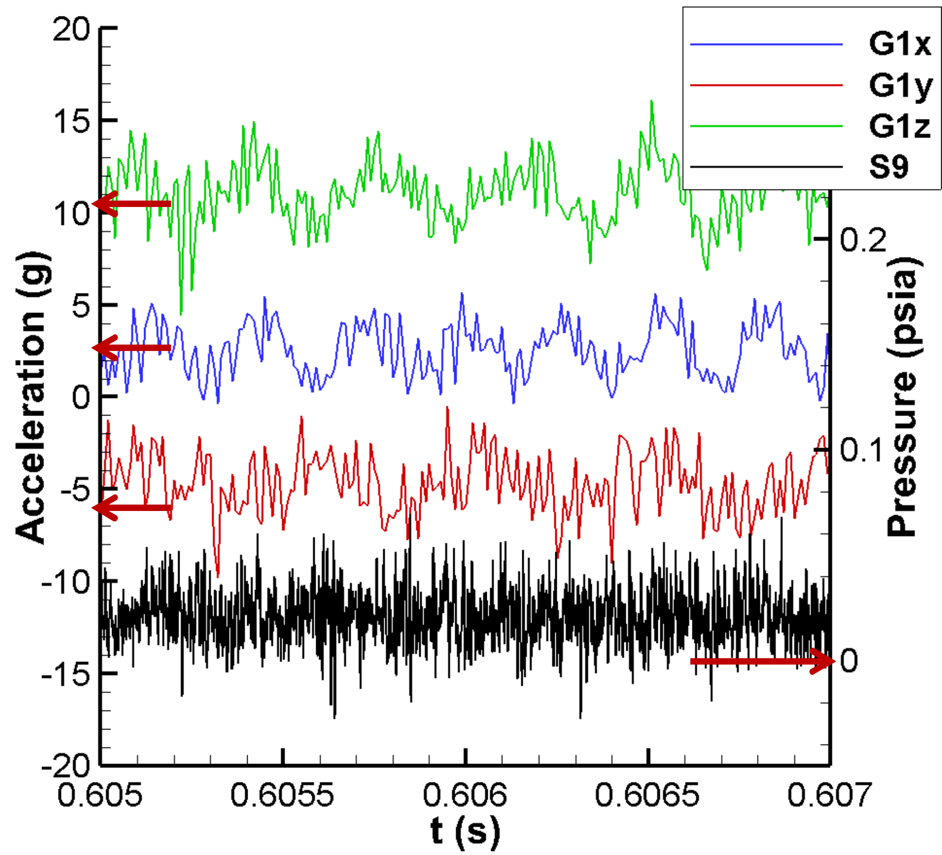
Laminar Boundary Layer



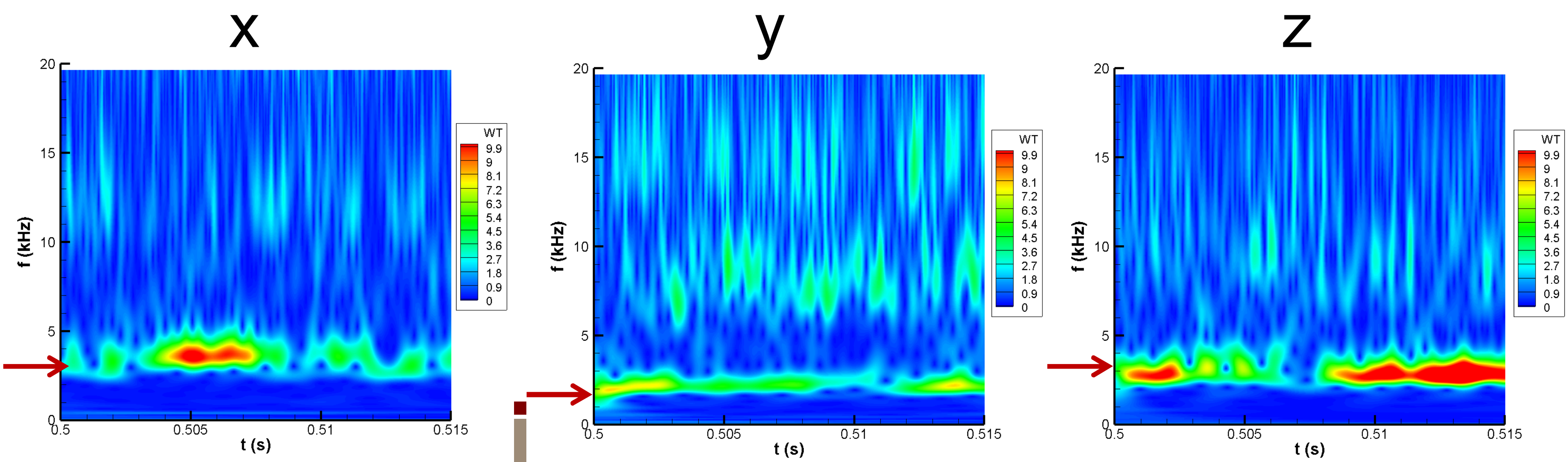
Turbulent Boundary Layer



Turbulent Boundary Layer (Noisy Flow)

Broadband turbulent forcing causes dominant modes to respond

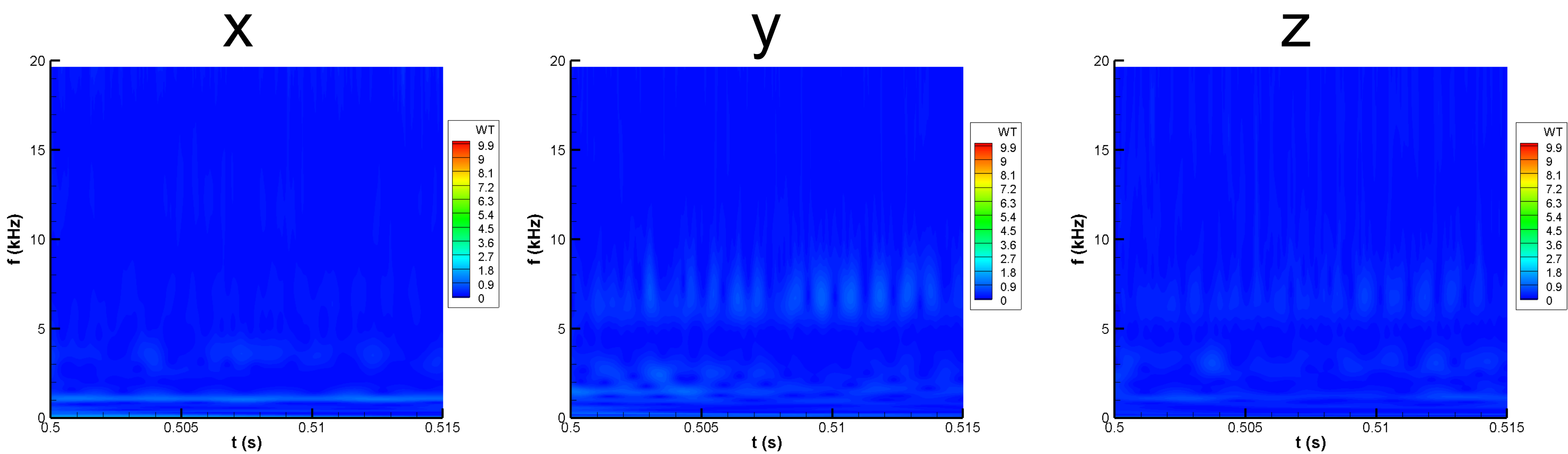
- **X-direction:** 2 lobe panel mode near 3.3 kHz
  - Also mode near 12.5 kHz
- **Y-direction:** 2 lobe panel mode near 2.1 kHz
  - Also modes near 7-8 and 15 kHz
- **X-direction:** 3 lobe panel mode near 2.8 kHz



Laminar Boundary Layer (Quiet Flow)

Much lower levels of panel excitation

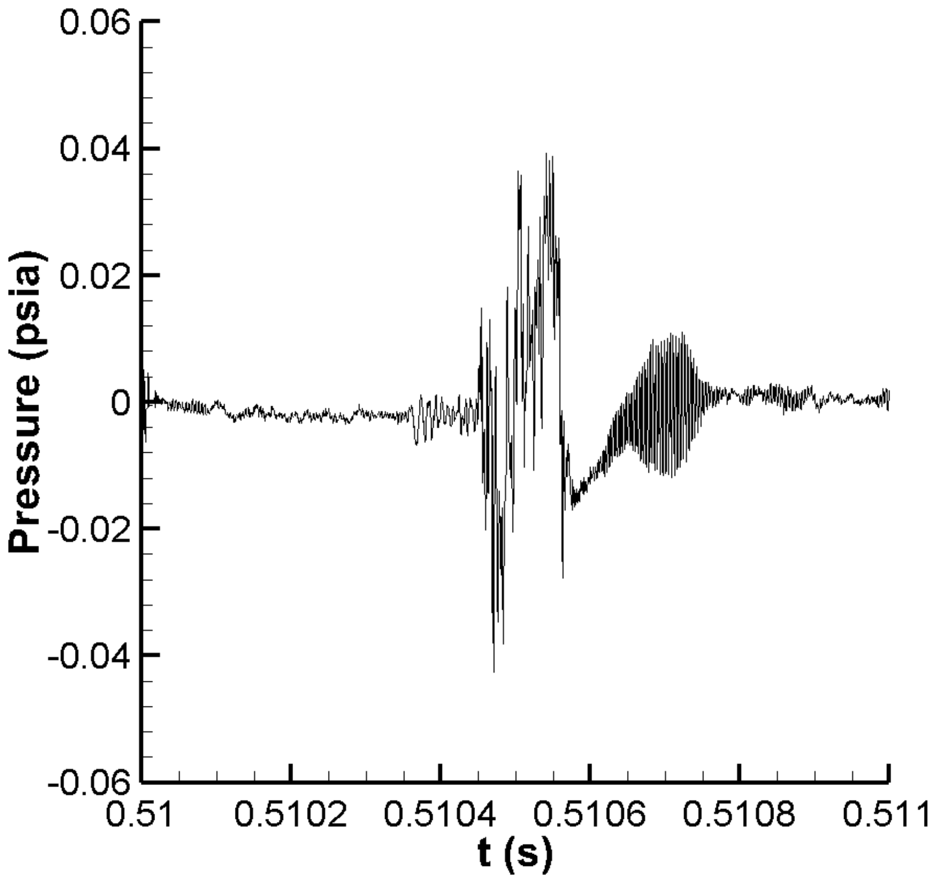
- Similar dominant modes as under turbulent flow
- Stronger low frequency vibration near 1 kHz



Controlled Spot Excitation in Quiet Flow

Perturber operated at low repetition rate of 0.1 kHz. Generates isolated turbulent spot in the boundary layer.

- Higher mean pressure within spot.
- Lower pressure laminar calmed region behind it.
- High frequency second-mode instability waves form at the end of the calmed region.



Controlled Spot Excitation in Quiet Flow

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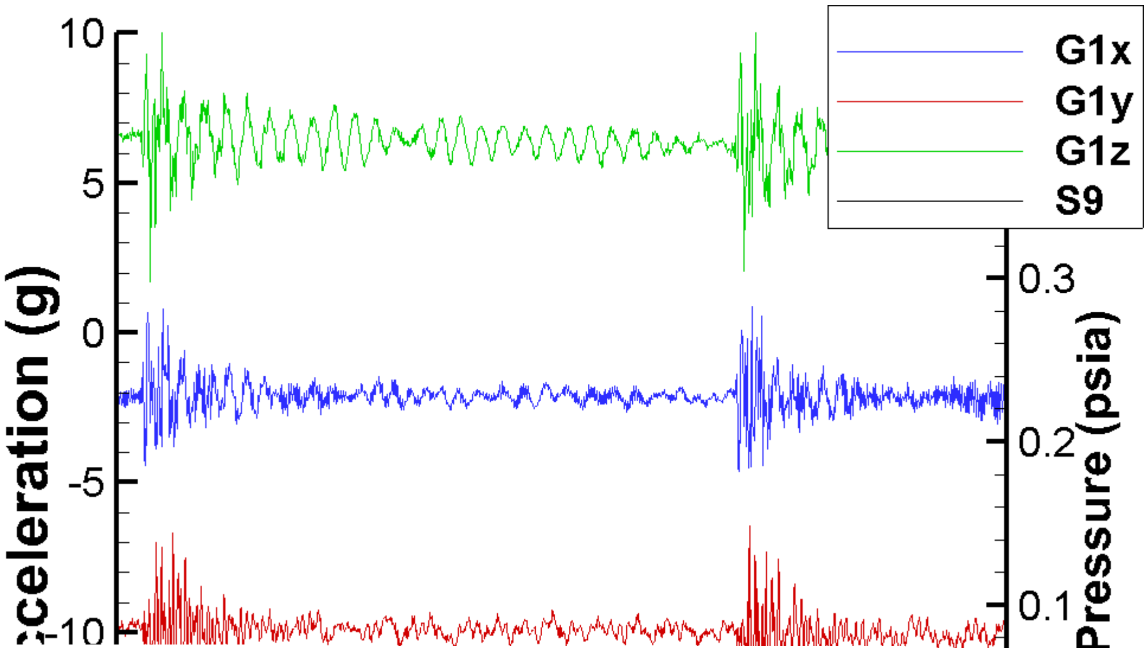
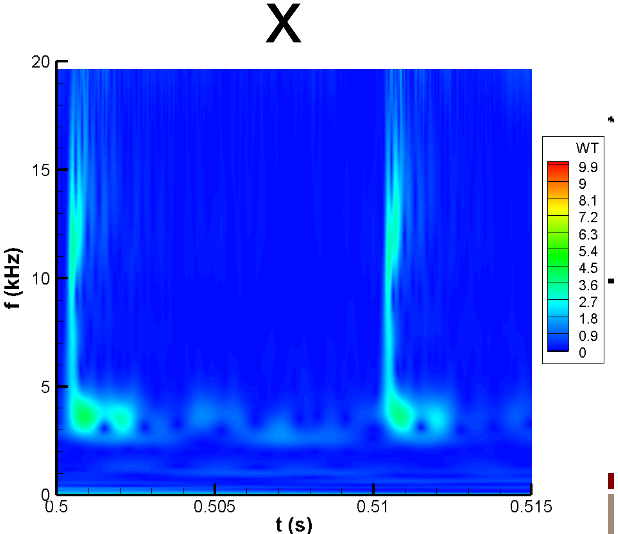
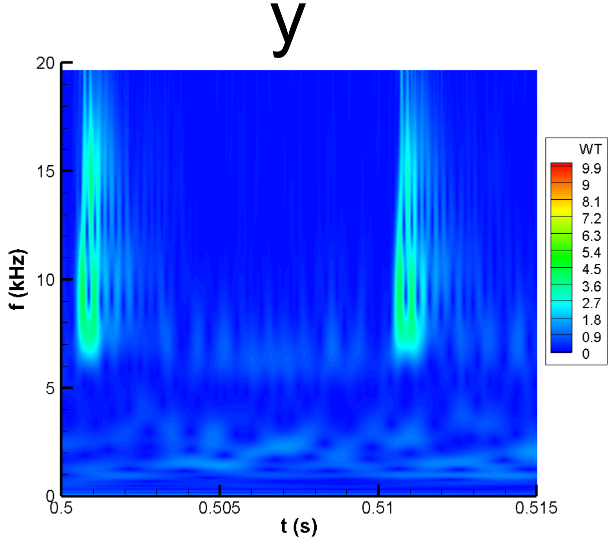
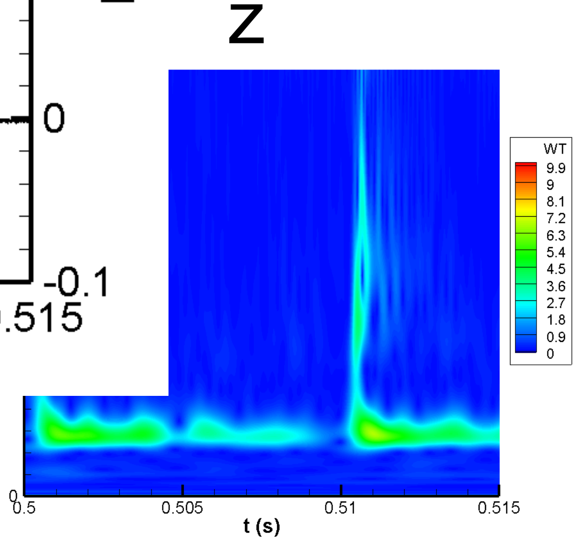








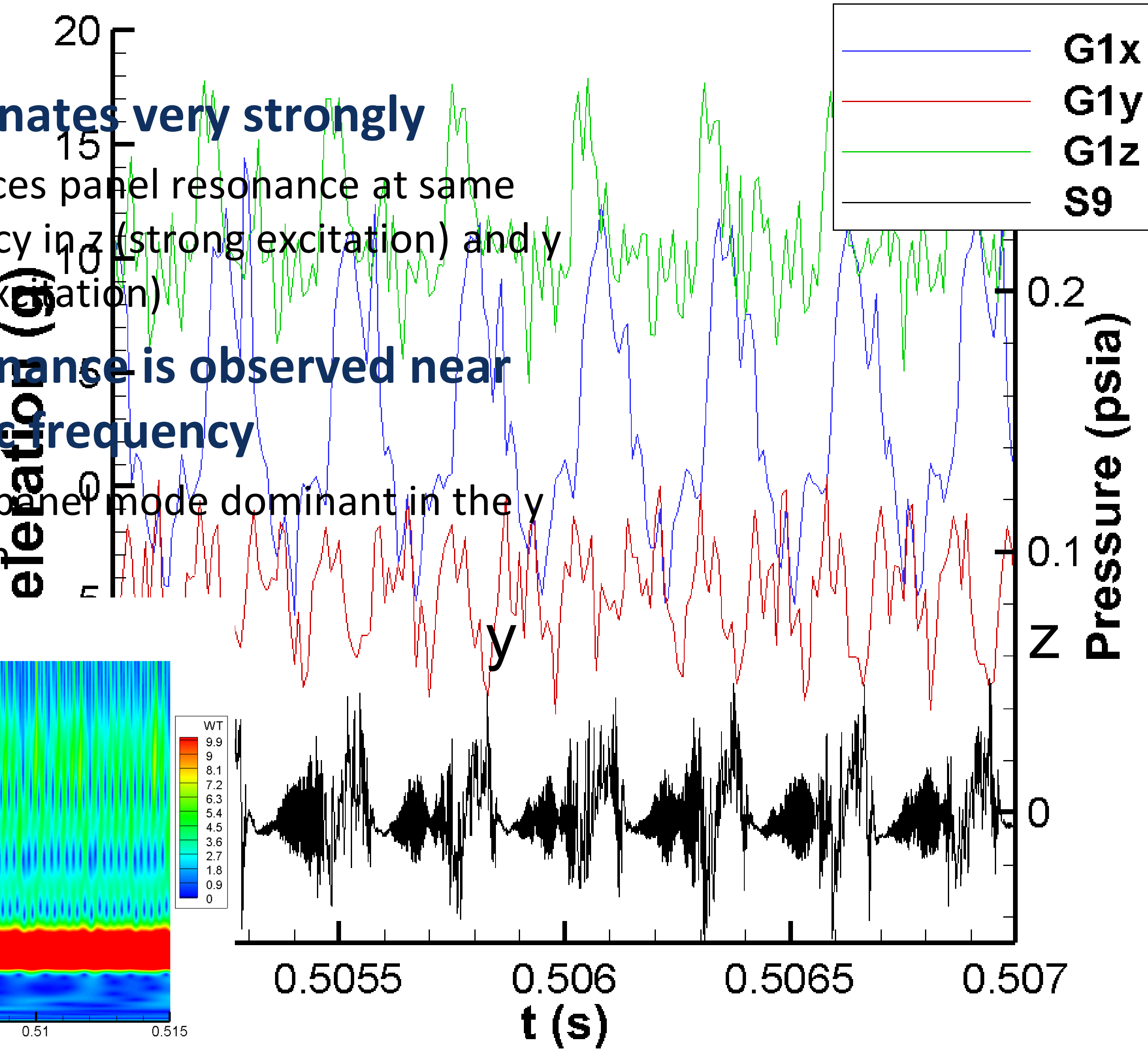
3.6 kHz forcing of dominant x-mode

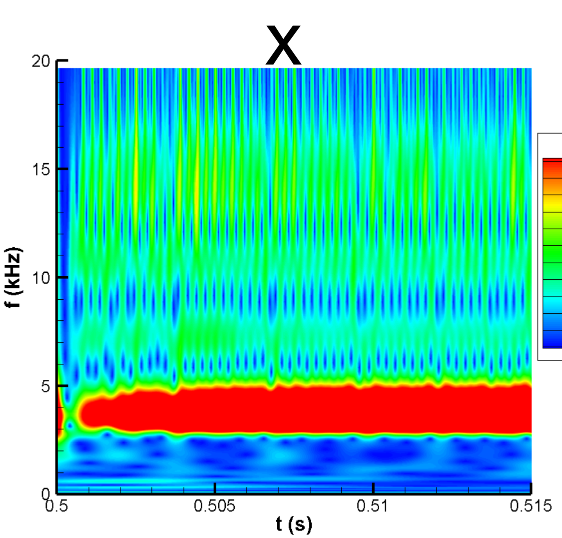
X mode resonates very strongly

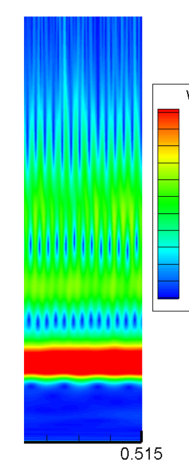
- Also forces panel resonance at same frequency in z (strong excitation) and y (weak excitation)

Y mode resonance is observed near the harmonic frequency

- 7.2 kHz panel mode dominant in the y direction





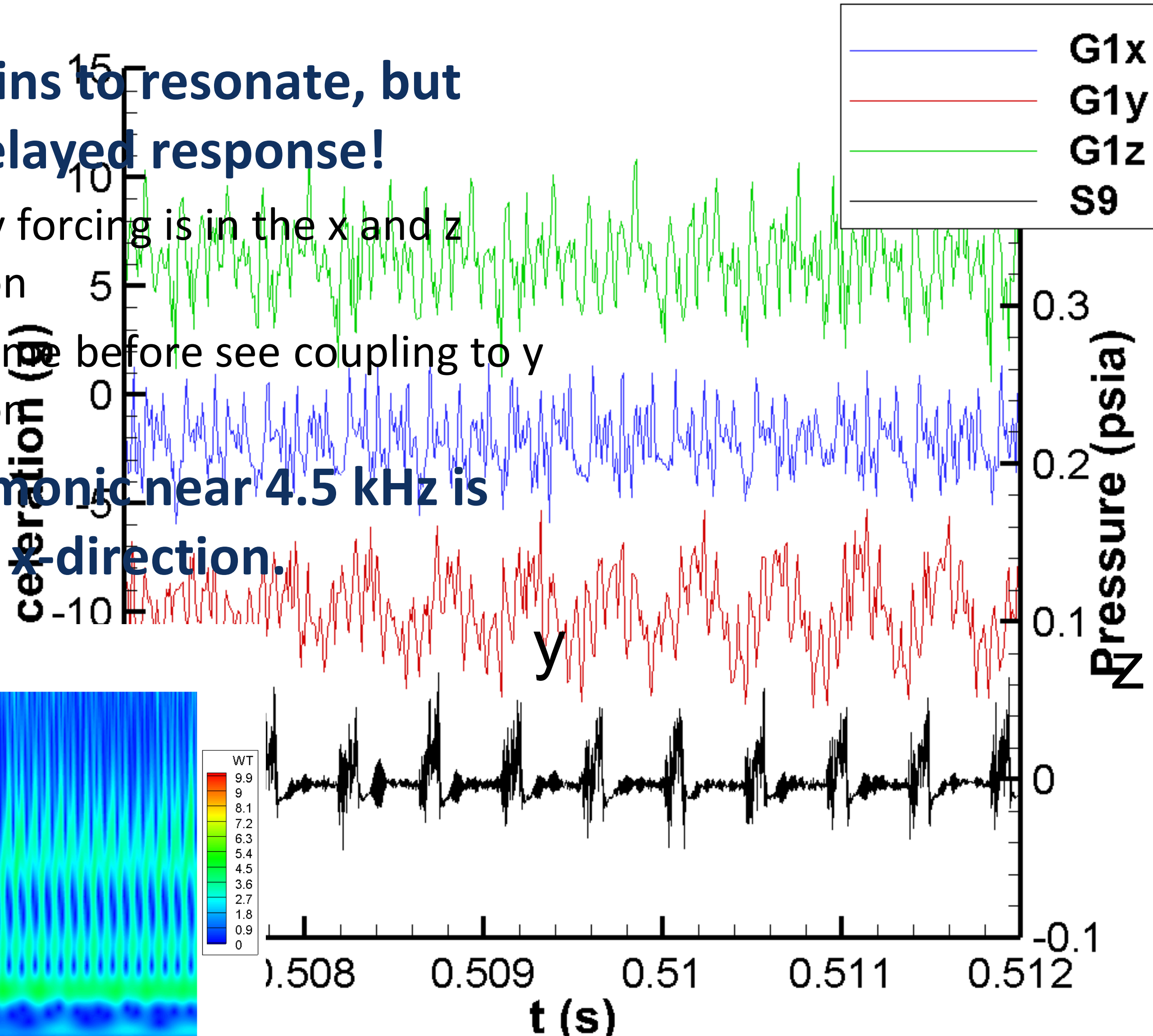


2.1 kHz forcing of dominant y-mode

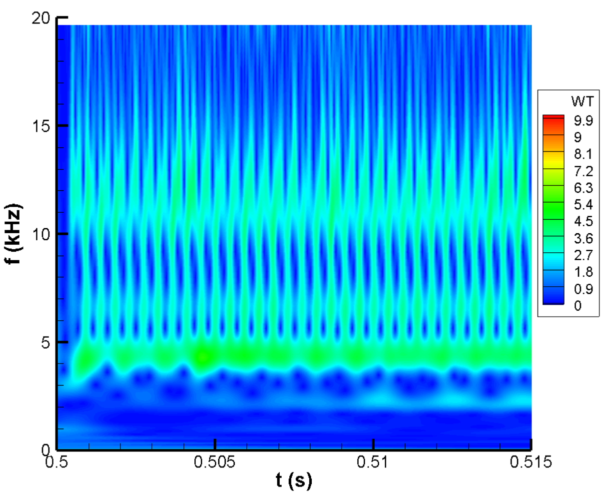
Y mode begins to resonate, but there is a delayed response!

- Primary forcing is in the x and z direction
- Some time before see coupling to y direction

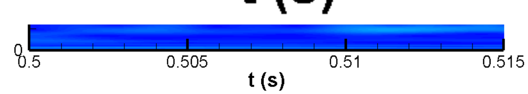
Second-harmonic near 4.5 kHz is amplified in x-direction.



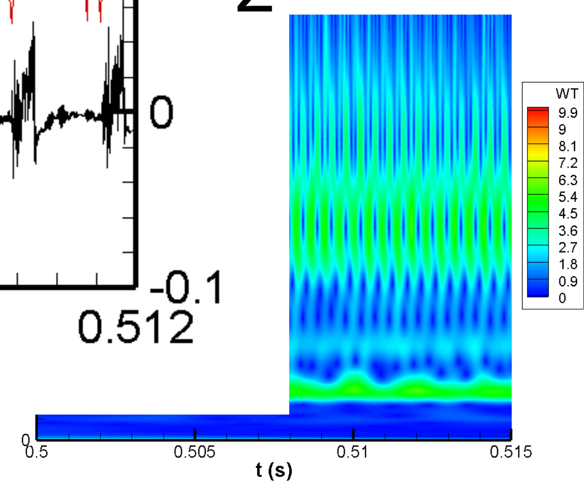
x



y



z



2.9 kHz forcing of dominant z-mode

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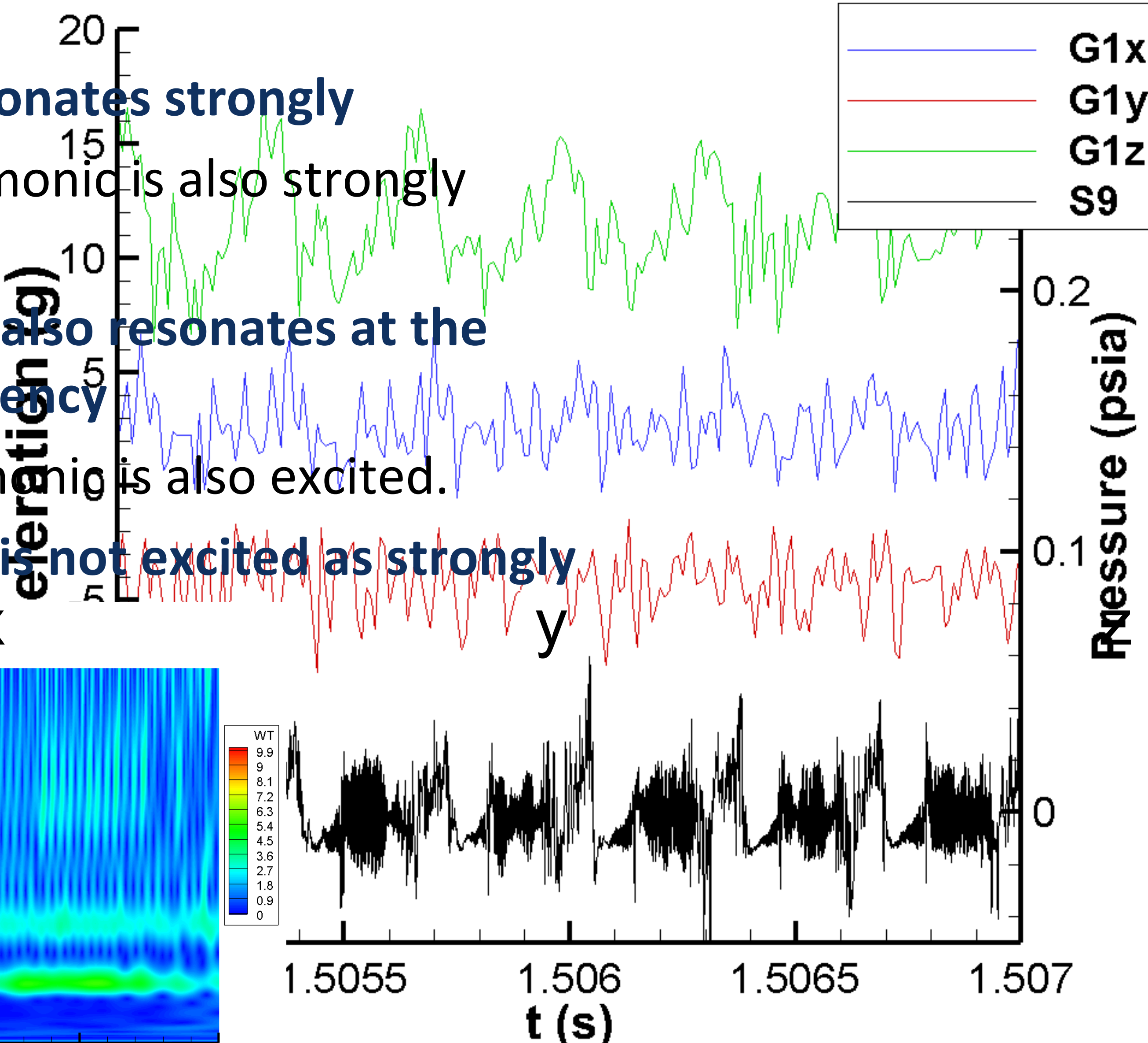
Z mode resonates strongly

- 2^{nd} harmonic is also strongly excited.

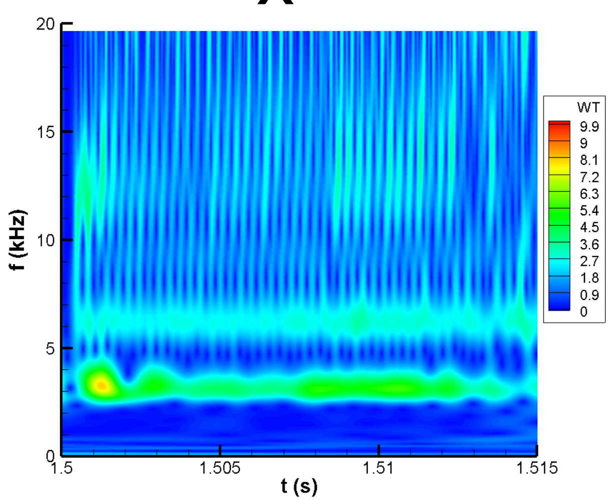
X direction also resonates at the same frequency

- 1^{st} harmonic is also excited.

Y direction is not excited as strongly



x



y

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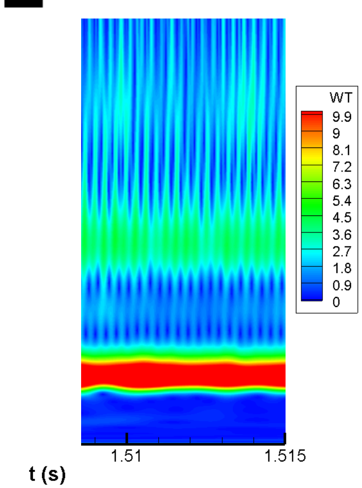


Future Work

Data shows we can use mode matching to force panel vibration in different directions.

- Still more analysis needed to understand and predict panel response, especially under turbulent boundary layers.
- Continued comparison to computations/modeling efforts as a validation case.

Future experiments will include Mach 5 testing at Sandia.

- Easier boundary layer to perturb than at Mach 8.
- Less tunnel noise to drive natural transition.
- Expected that perturber will be more of a driver for vibration at Mach 5 in comparison to Mach 8.

Motivation: Captive Carry

Weapons bays behave similarly to cavity flows.

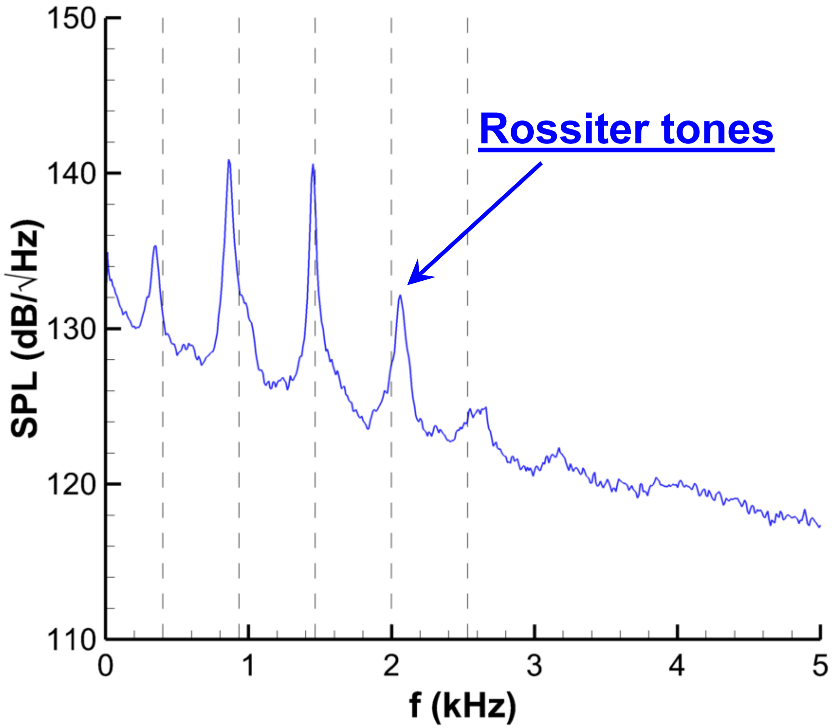
- Interaction of free shear layer and cavity walls produces resonant tones.
- Tones can have high sound pressure levels (SPL), up to 170 dB in some cases.

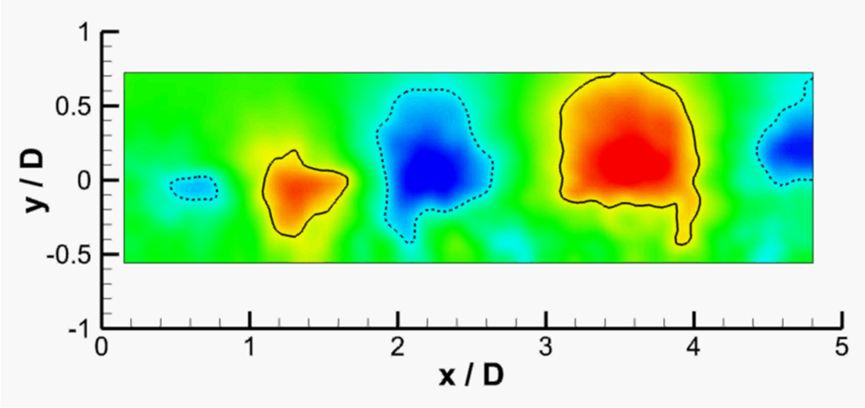
Fluctuations provide a driver for potential large vibrations of internal stores in weapons bays.


Lockheed Martin: Approved for Public Release

Response to Cavity Resonance?

- Interaction of free shear layer and cavity walls produces distinct dynamics and well known Rossiter (1964) tones





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

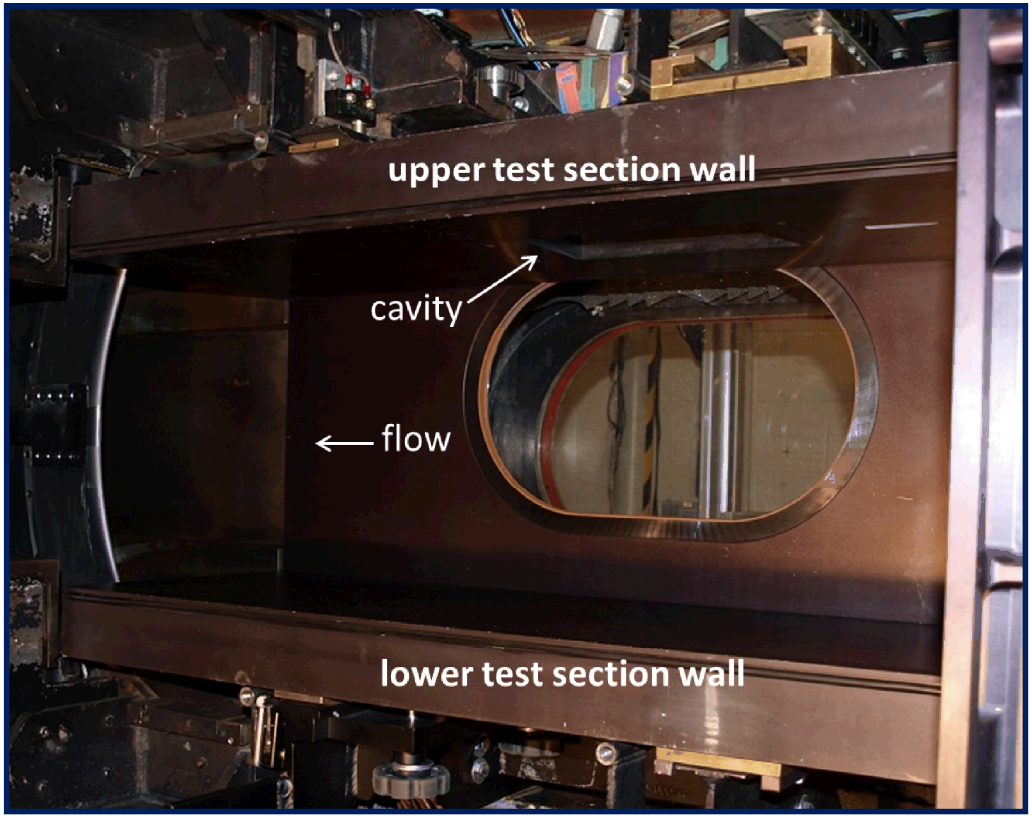
Experimental Approach

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

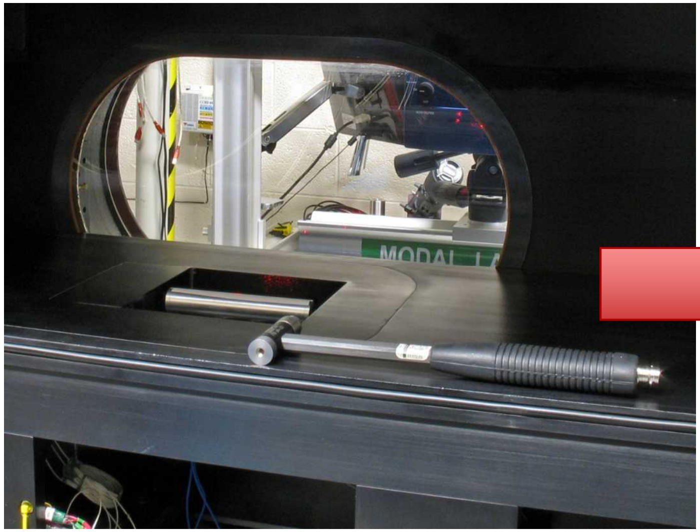
- *L/D = 5, 7*
- *L/W = 1, 2*



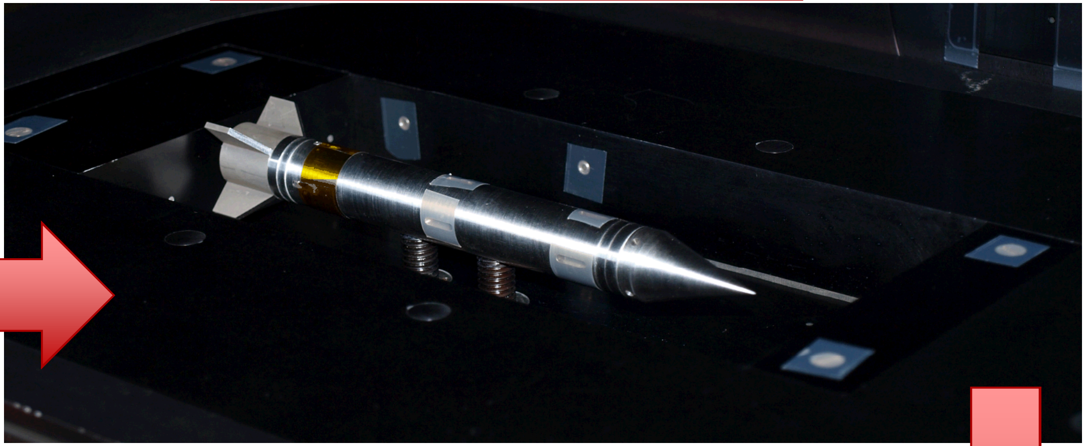
Experimental Approach

Sandia National Laboratories

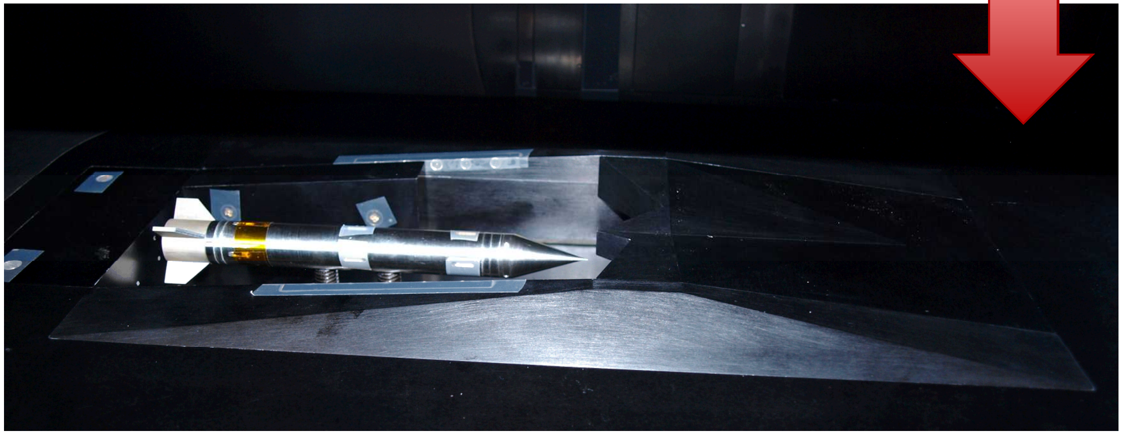
1) Simple Store in Simple Cavity



2) Complex Store in Simple Cavity



3) Complex Store in Complex Cavity



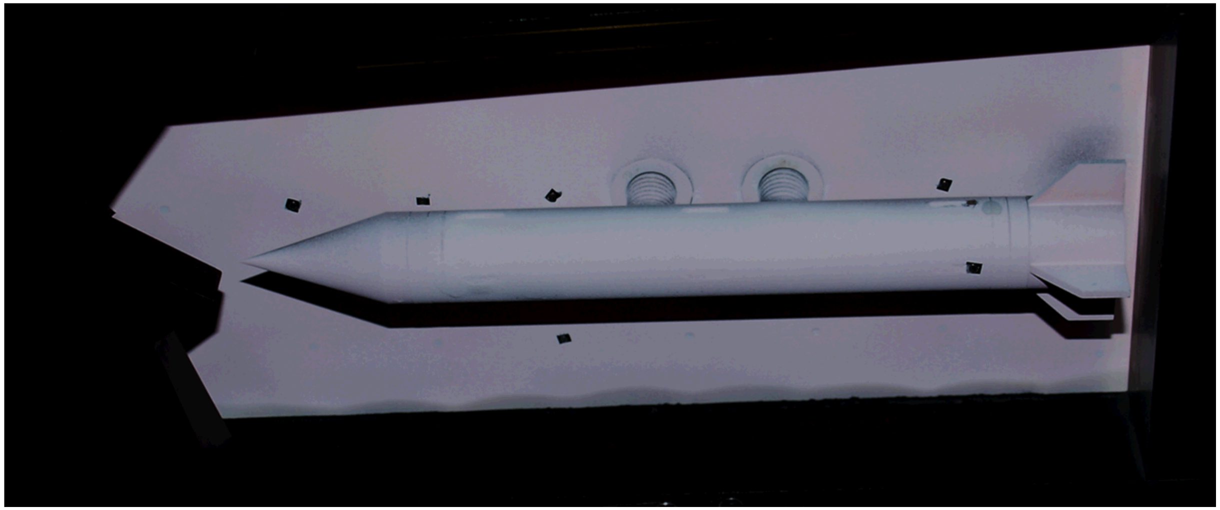
How and why does a fixed, captive store respond in this environment?

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

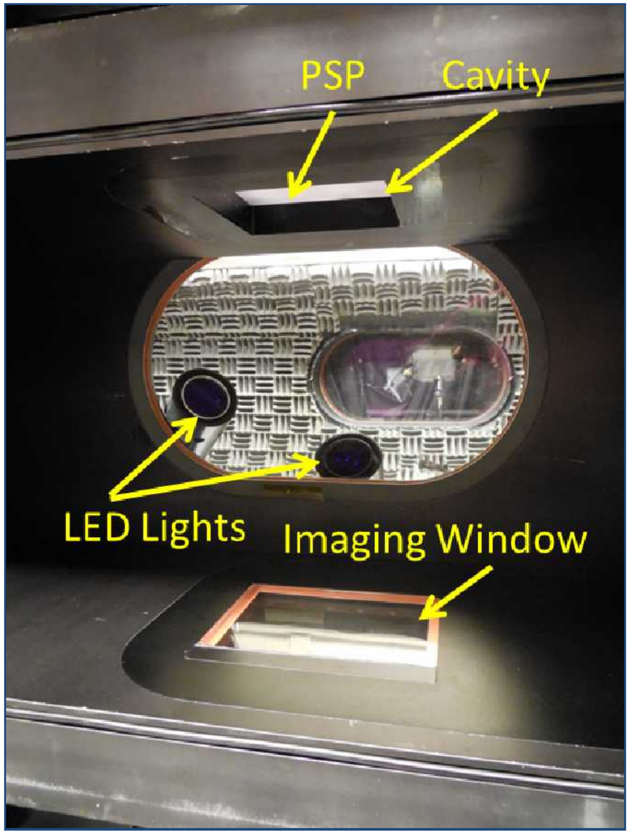
Time-Resolved Pressure Sensitive Paint (TR-PSP)

Used high frequency PSP from ISSI to characterize loading in cavity and on structures

- Photron SA-Z High-Speed Camera
  - Framing rate of 20 kHz.
- Excitation using ISSI 400-nm LEDs



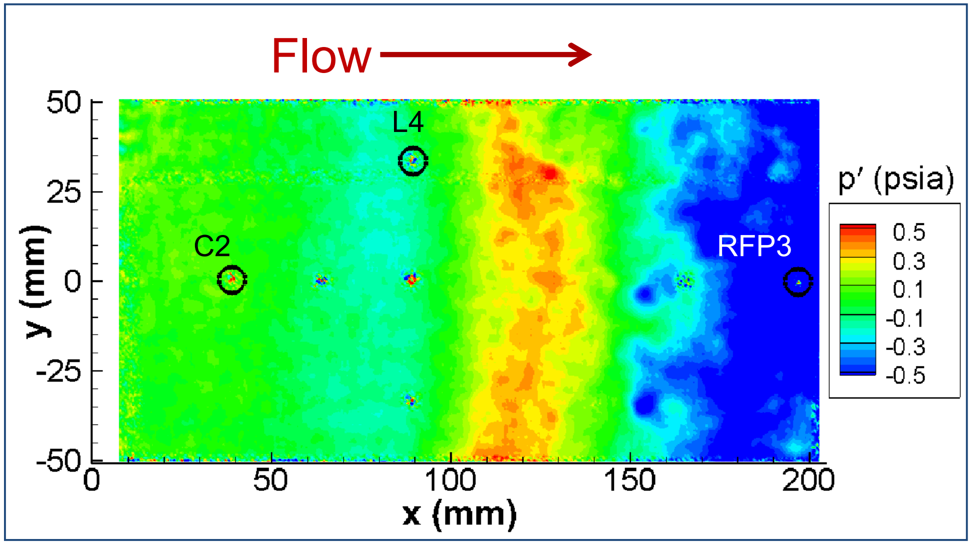
Model painted with PSP



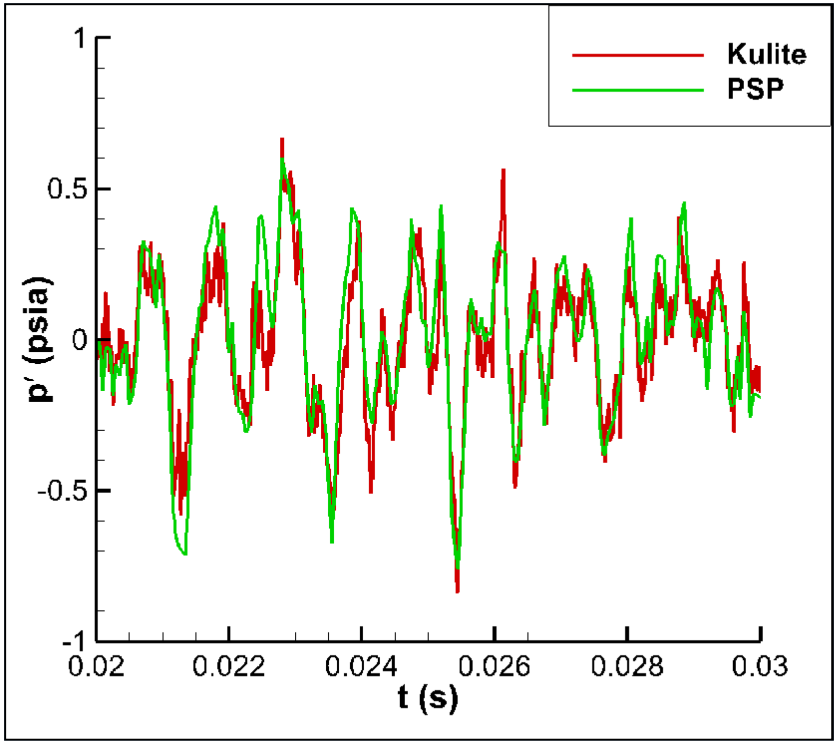
Time-Resolved Pressure Sensitive Paint (TR-PSP)

Results show reasonable comparison to Kulite pressure sensors throughout the cavity.

- Cavity resonance frequencies and amplitudes match well between pressure sensors and PSP.



Snapshot of PSP movie in empty cavity.



Comparison of Kulite pressure sensors and PSP.

Time-Resolved Pressure Sensitive Paint

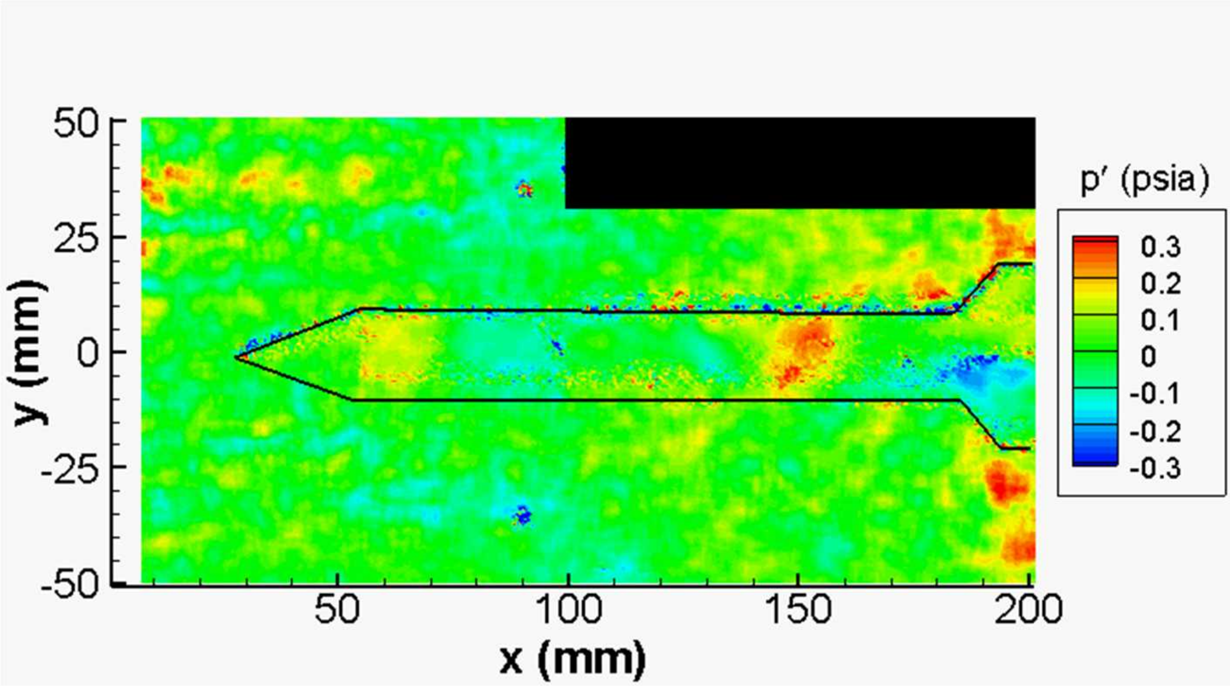
Sandia National Laboratories

PSP clearly shows unsteady pressure field throughout the cavity.

- Wealth of data showing changes with complex cavity features.

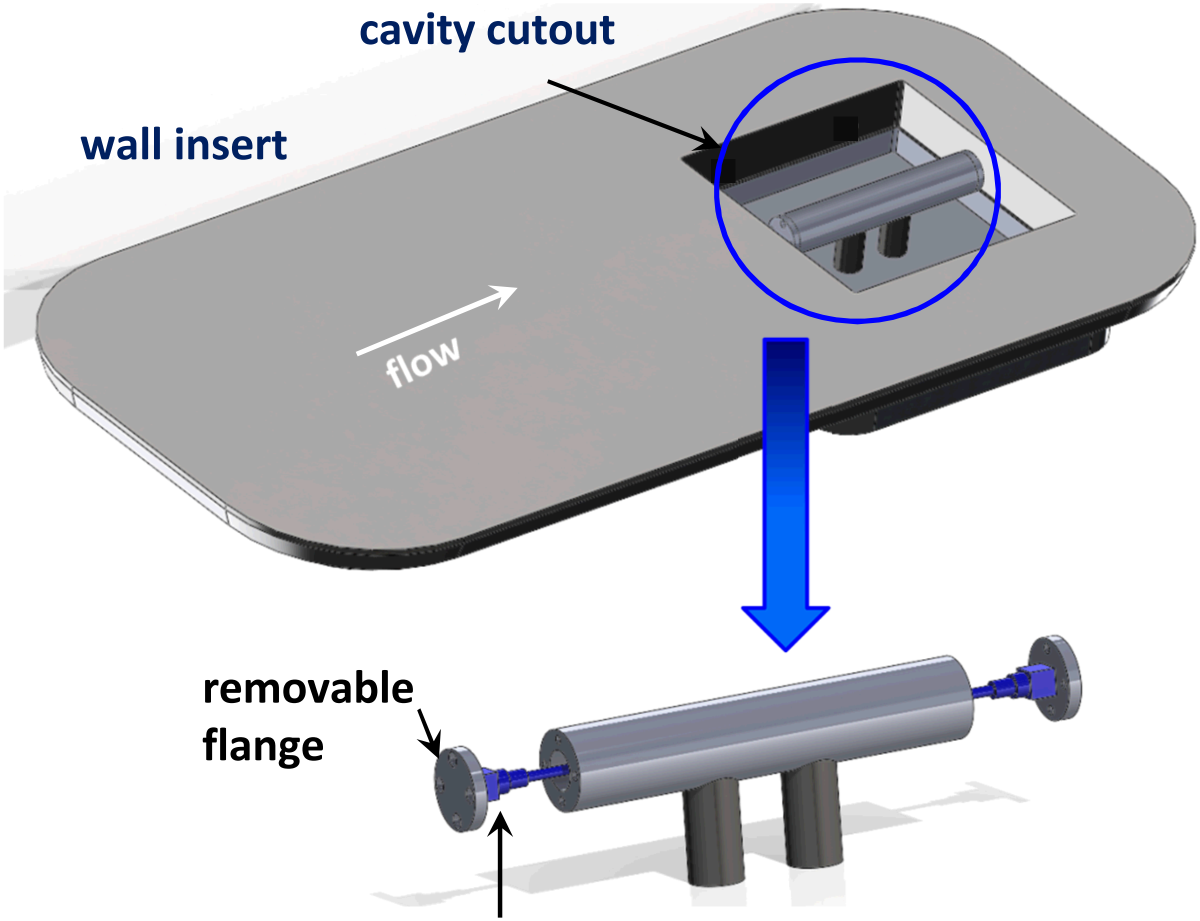
Coherent structures are observed passing along the store.

- How does this lead to store vibration in each configuration?



Flow →

Simple Cavity FSI



Triaxial accelerometers provided store response.

Store Natural Frequencies

Impact Hammer Tests

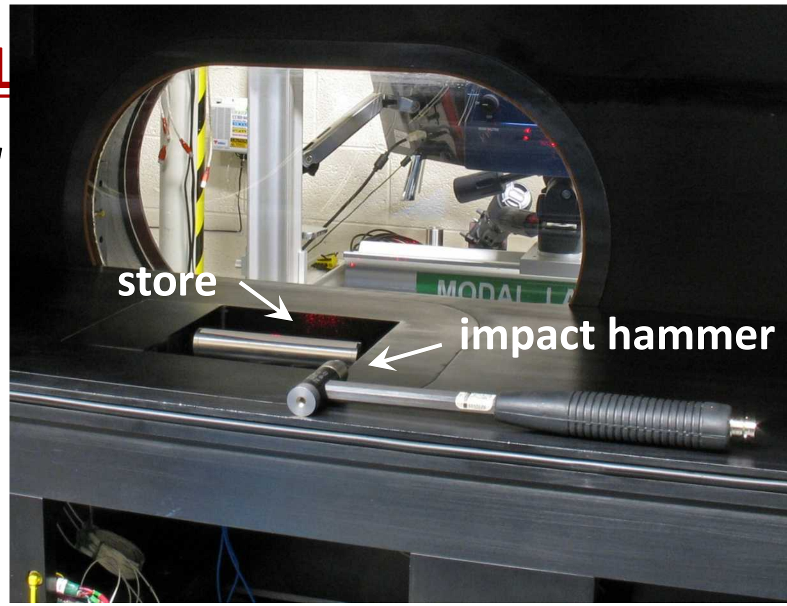
Post Modes

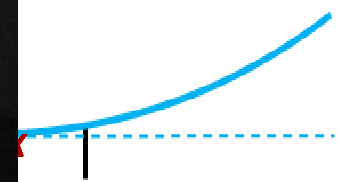
Cylinder Bending Modes

Z1 @ 1

kHz

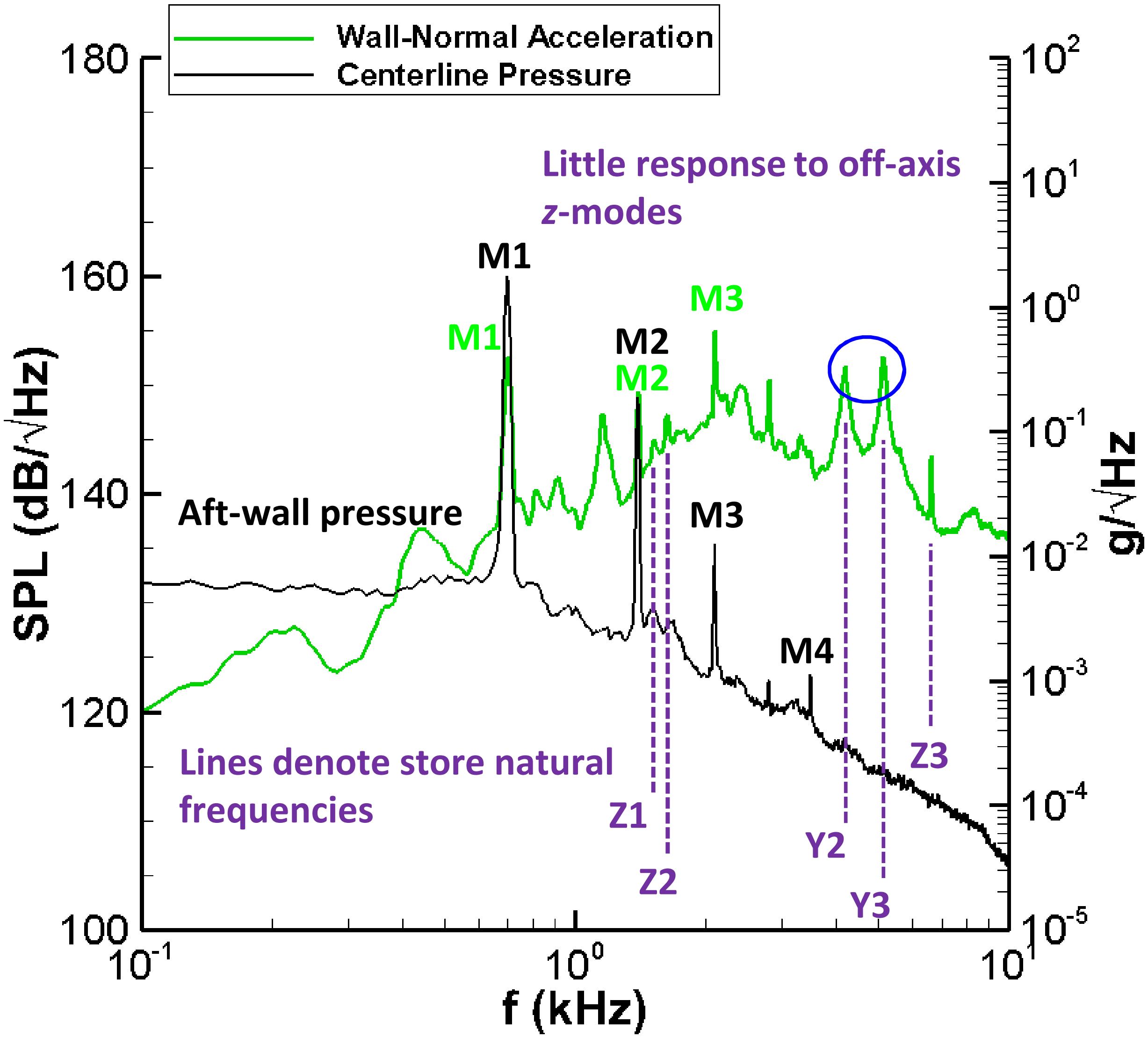
undeflected





5 natural frequencies measured below 10 kHz

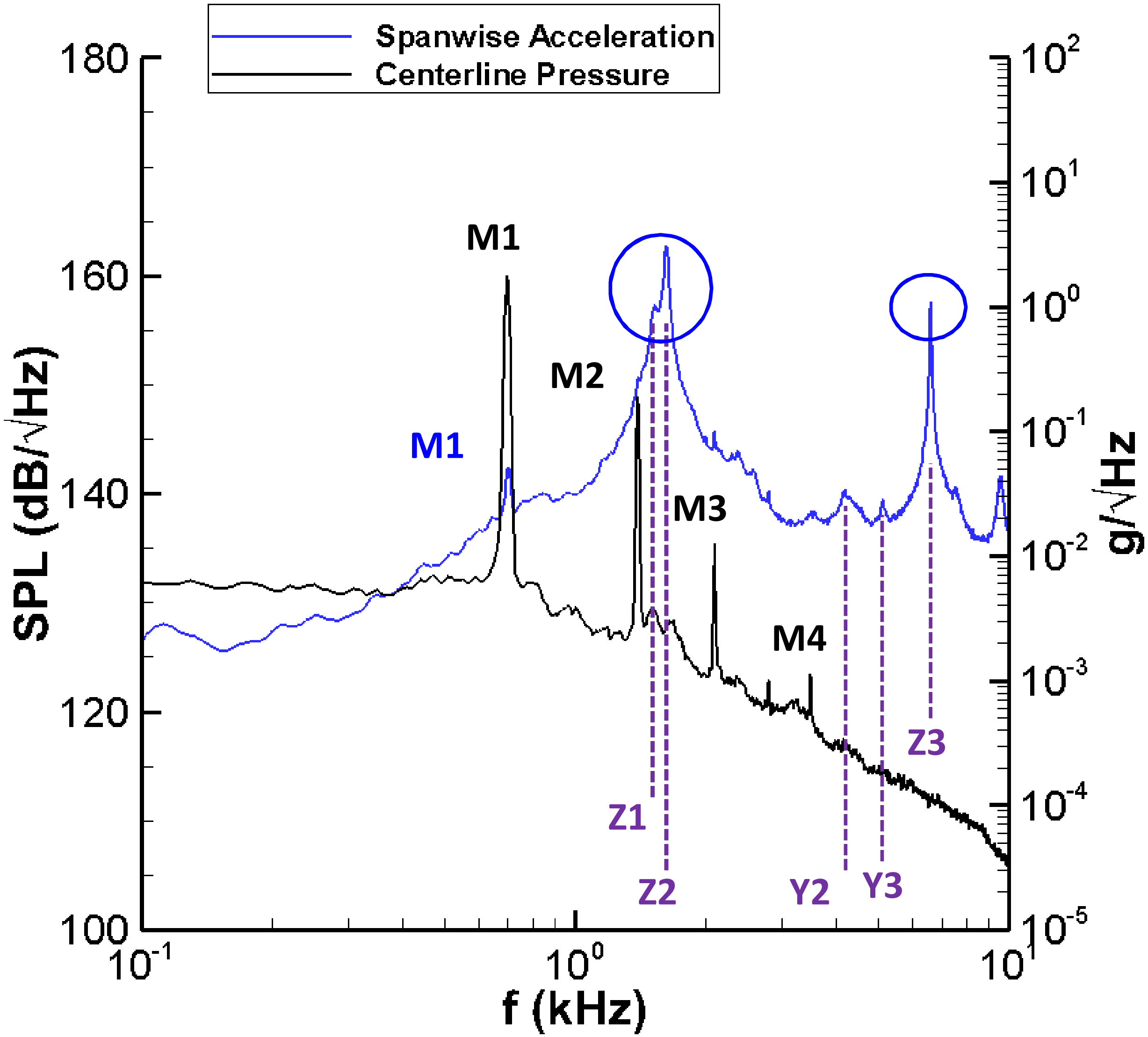
Simple Cavity FSI



- 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



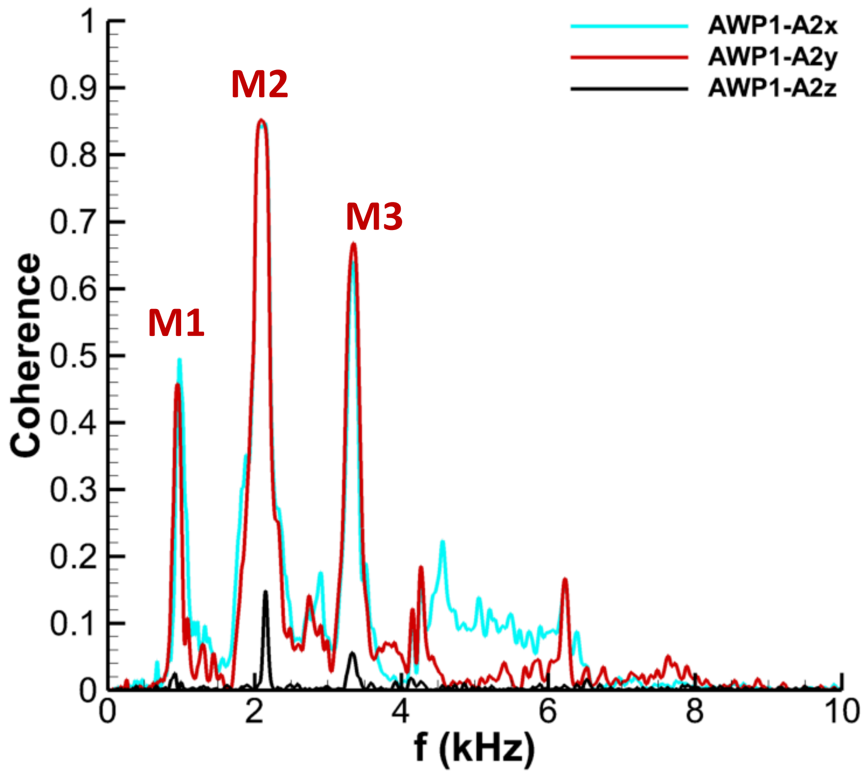
- Little response to cavity modes
- Clear response at spanwise natural frequencies Z1 – Z3

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

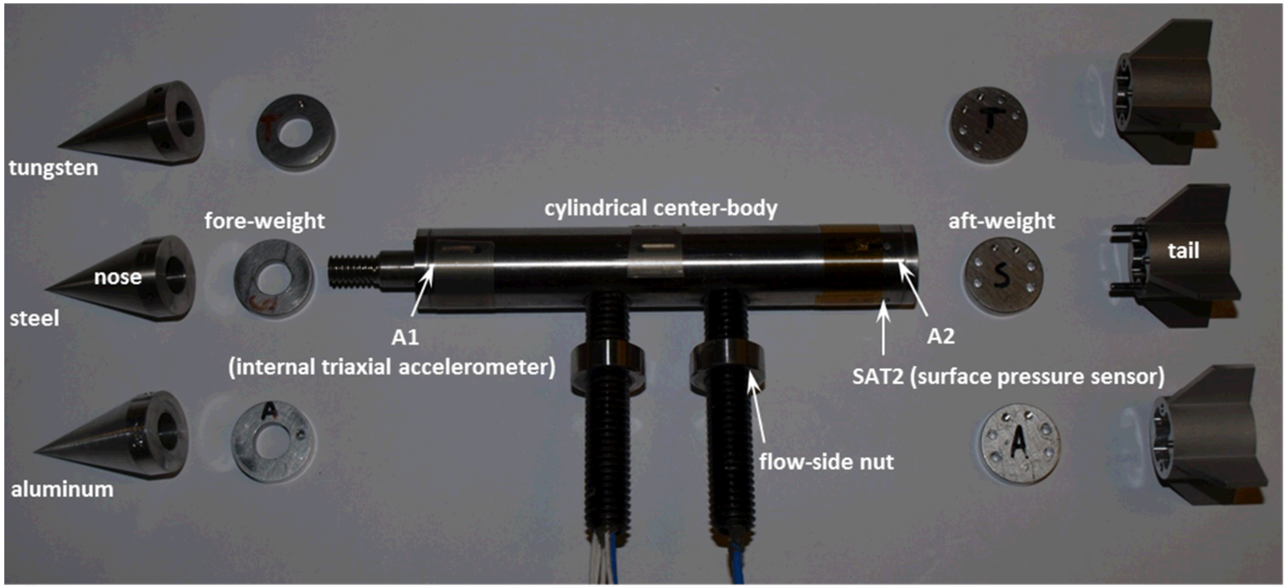


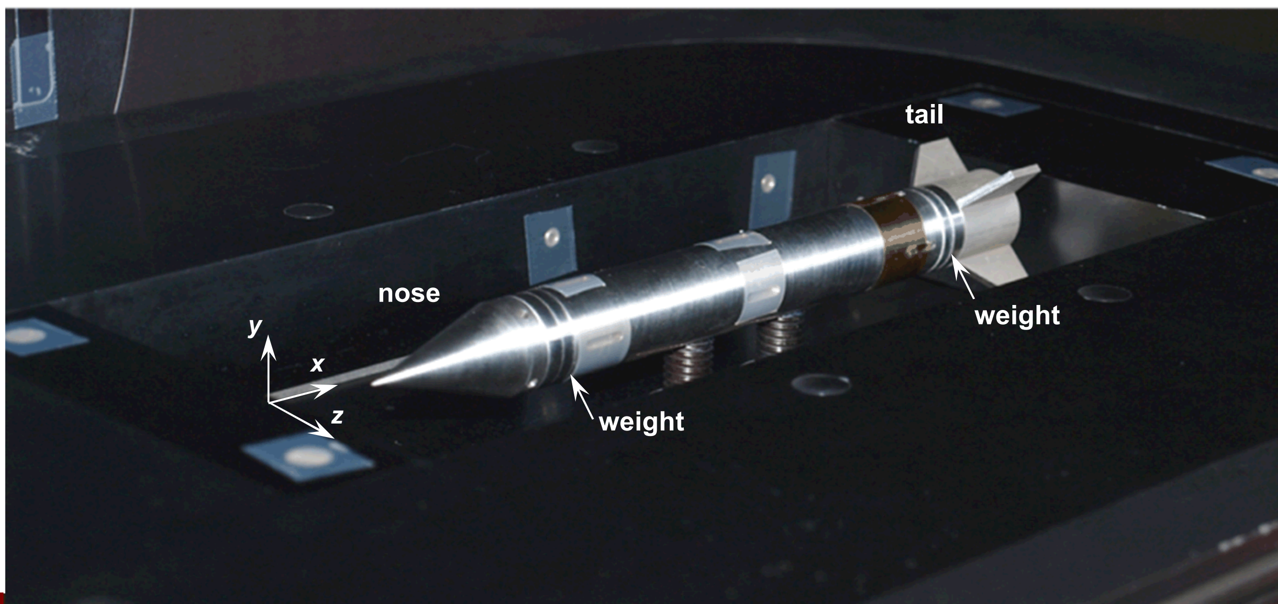
Strong response to cavity tones in streamwise and wall-normal directions, but little spanwise response.

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





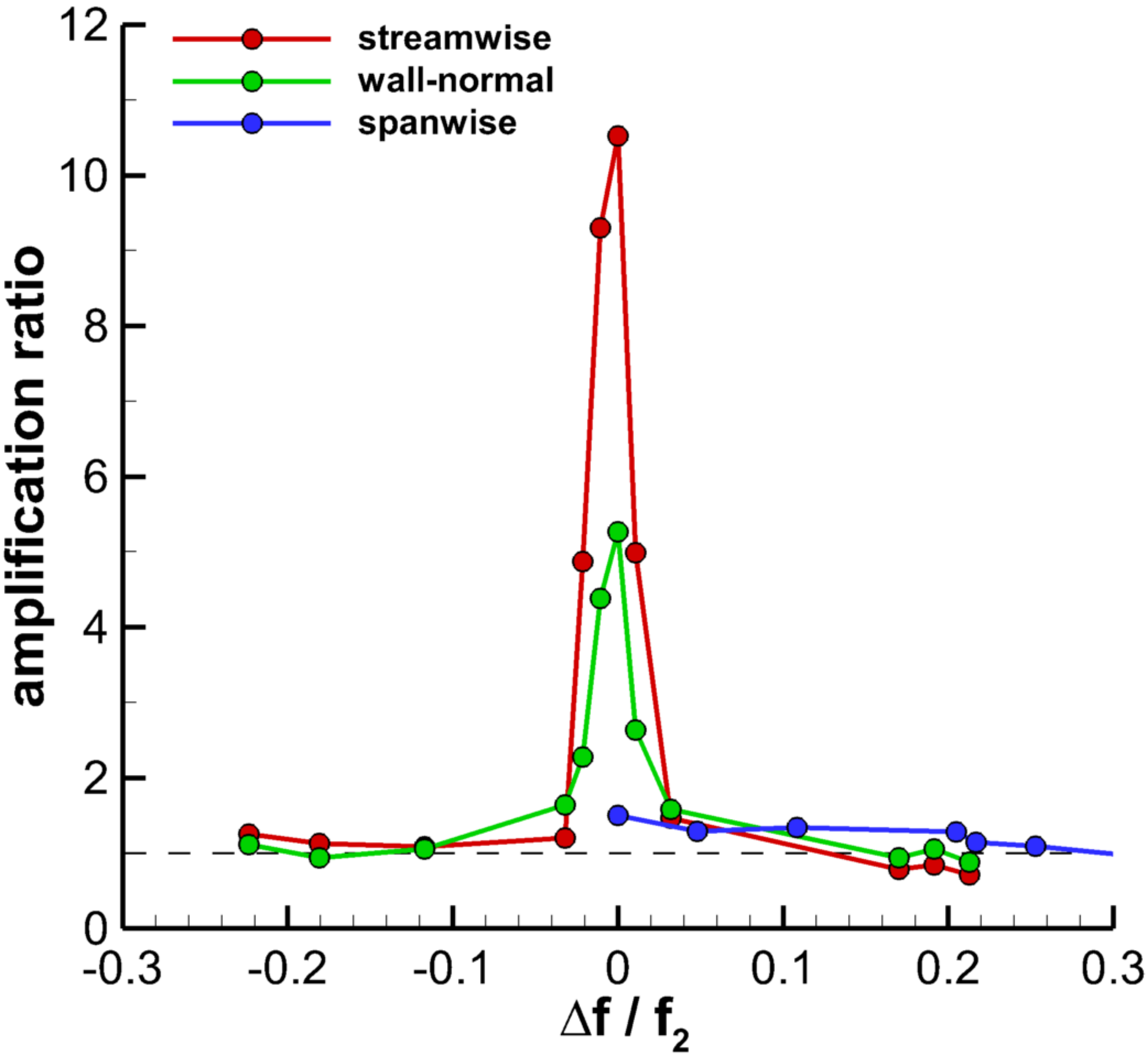
Coarse adjustments in natural frequencies of 100 – 400 Hz by varying nose and tail material.

- 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.

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

Time-Resolved Particle Image Velocimetry

Allows us to obtain PIV movies to provide temporally correlated velocity fields.

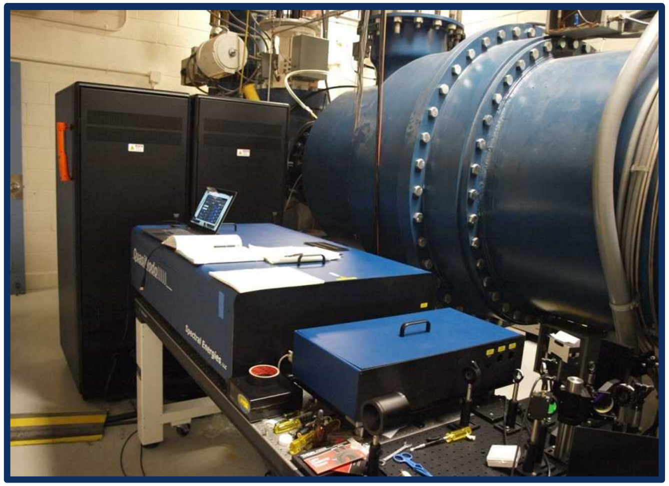
- Challenge: TR-PIV has been typically restricted to ≤ 16 kHz and a few mJ.
    - Inadequate for a high-speed wind tunnel.

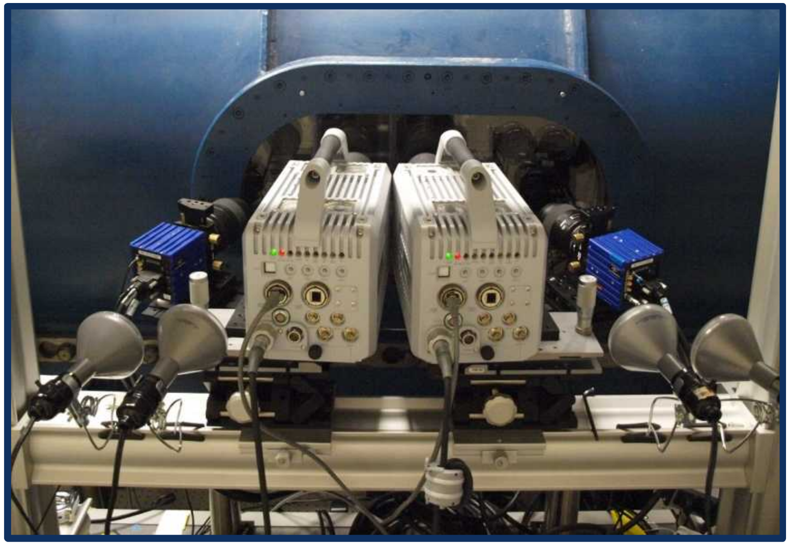
Pulse-Burst Laser:

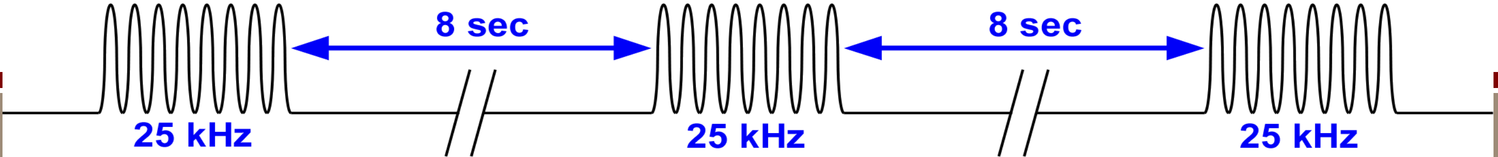
- Manufactured by Spectral Energies, LLC.
- Bursts of pulses for 10.2 ms.
- Up to 500 kHz of pulse pairs, 20-500 mJ.
- But only one burst every 8 sec.

High-Speed Cameras

- Photron SA-X2.
- Two side-by-side for wider field of view.







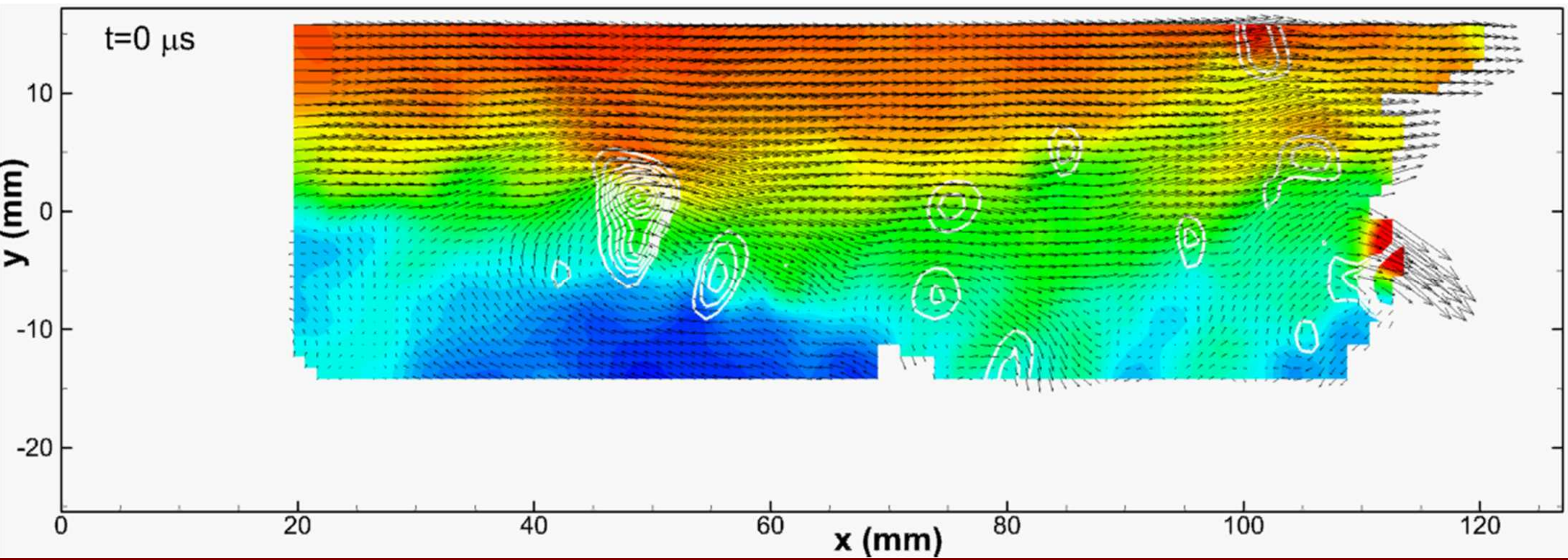
Time-Resolved Particle Image Velocimetry

A sample TR pulse-burst PIV movie

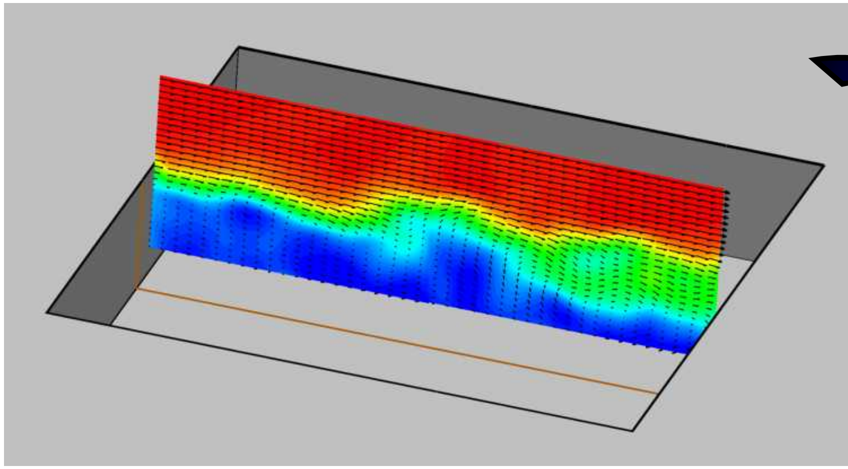
- This is a 10.2 ms movie with 256 vector fields acquired at 25 kHz.

We can visualize:

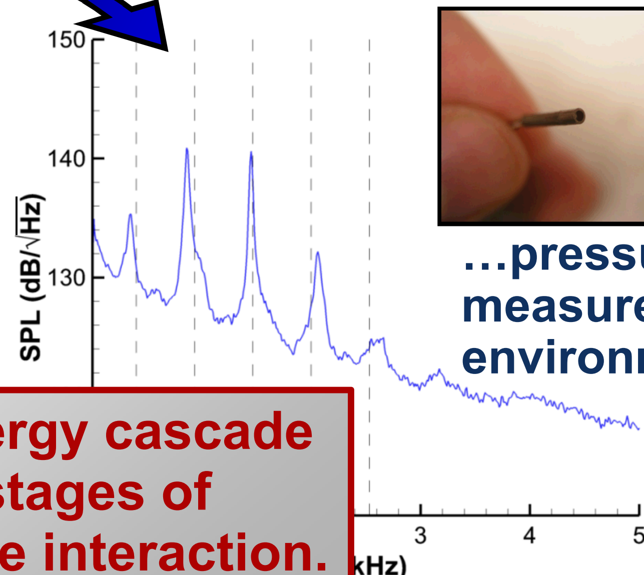
- Recirculation region shifting position.
- Unsteady shear layer flapping enhanced by recirculation events.
- Growth of shear layer structures and their recirculation.
- Ejection and impingement events at aft end of cavity.



Bring all of these capabilities together

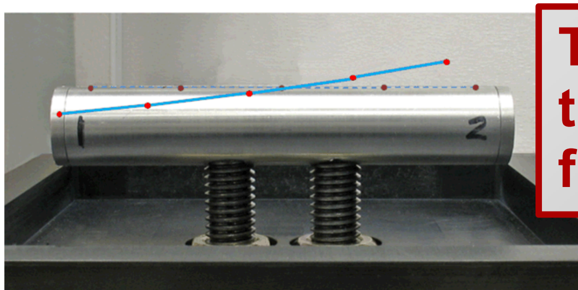


Pulse-burst PIV measures the flow structure…

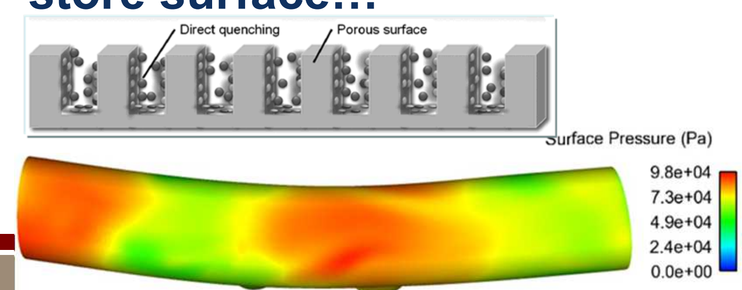


…pressure sensors measure the acoustic environment…

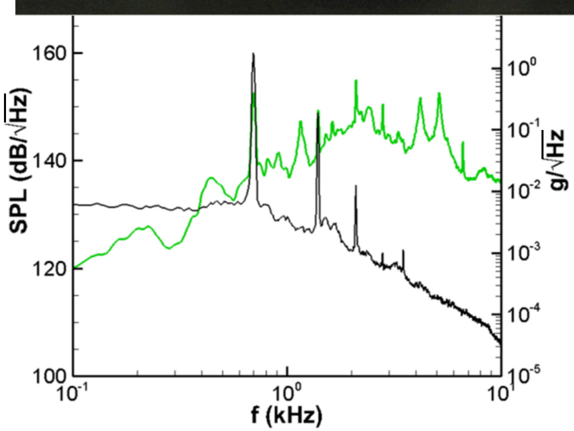
Track the energy cascade through the stages of fluid-structure interaction.



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



…and then we can measure the structural response.

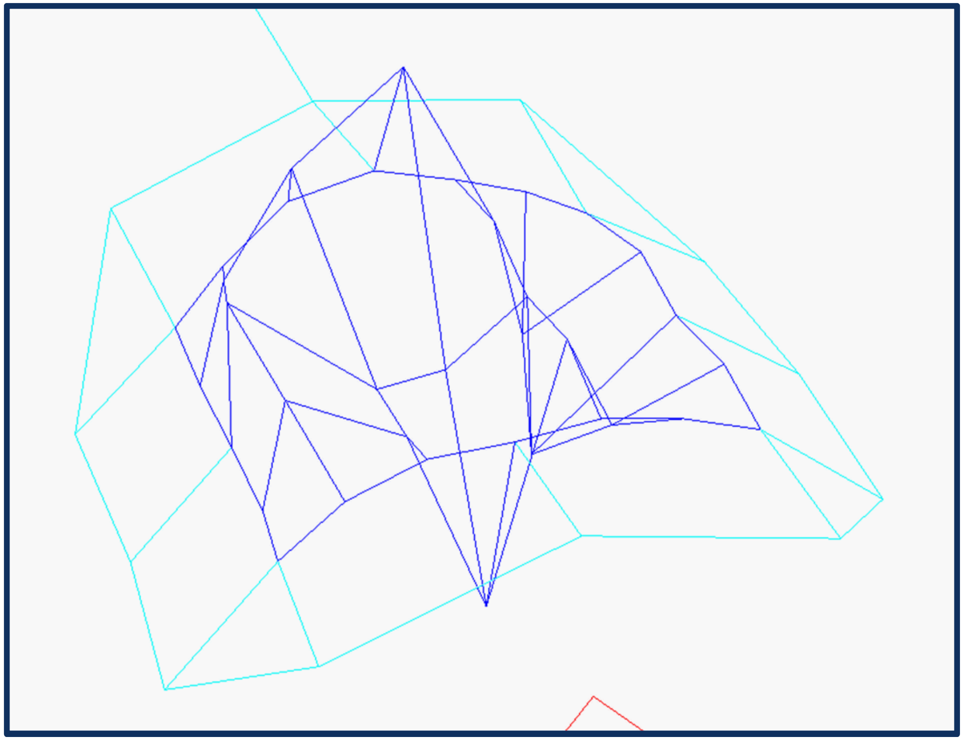


Backup Slides

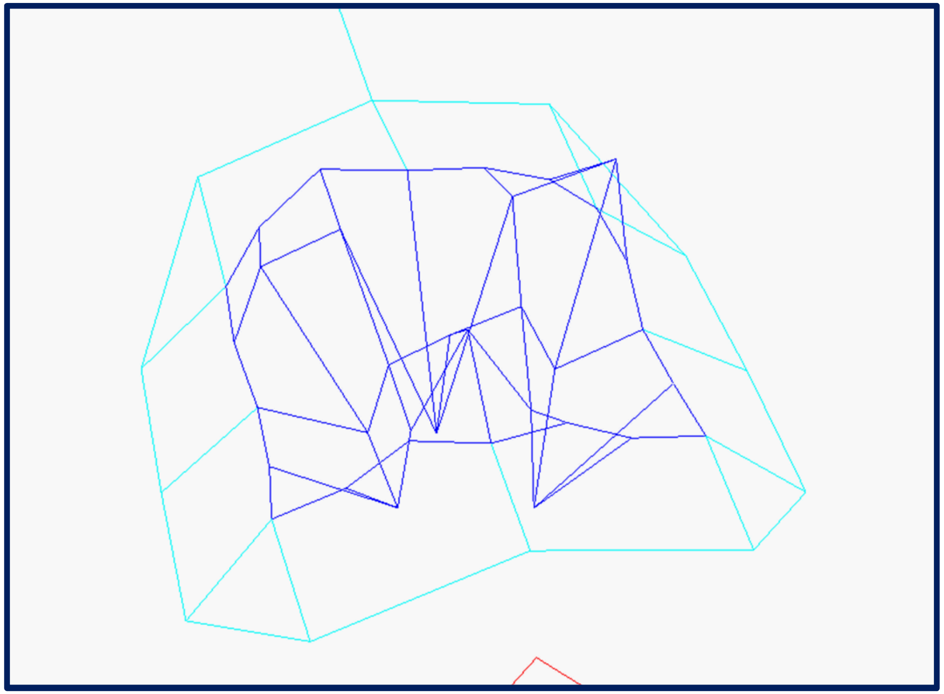
Higher-frequency panel modes, P_{c1-3}

More complex panel motion occurs at higher frequencies.

- Added uncertainty in characterizing these with hammer test.

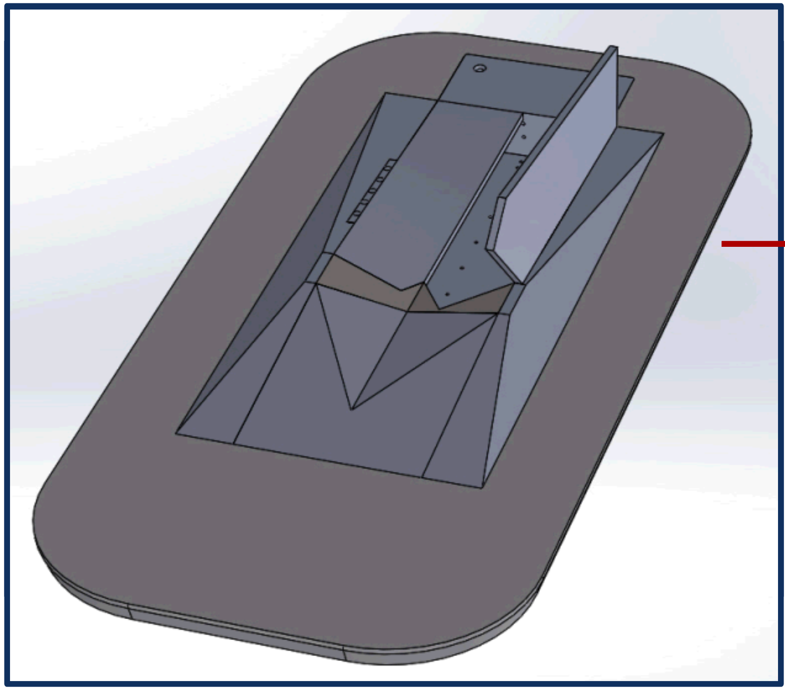


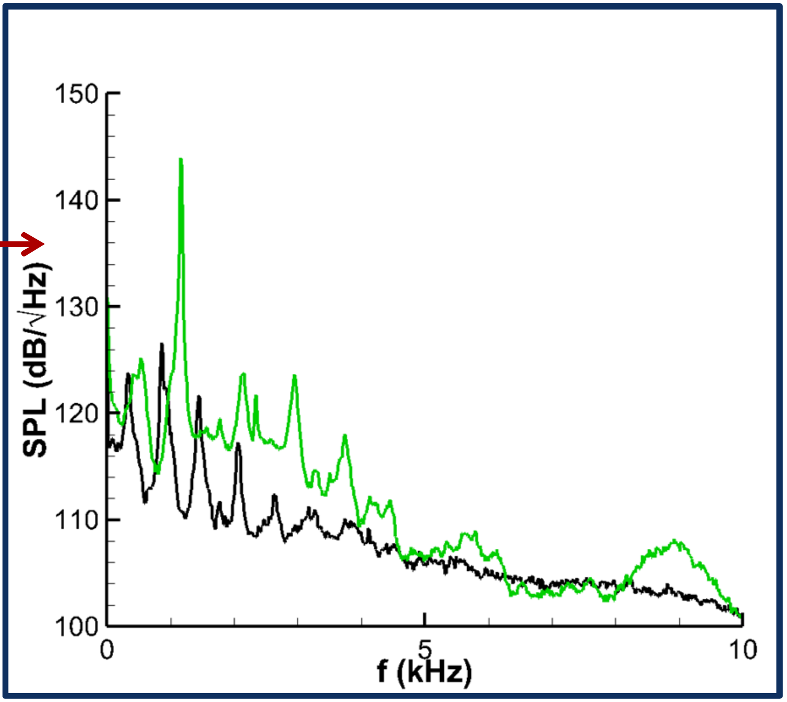
f = 9.1 kHz



f = 12.7 kHz

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