Complex Geometry Effects on Cavity Flows

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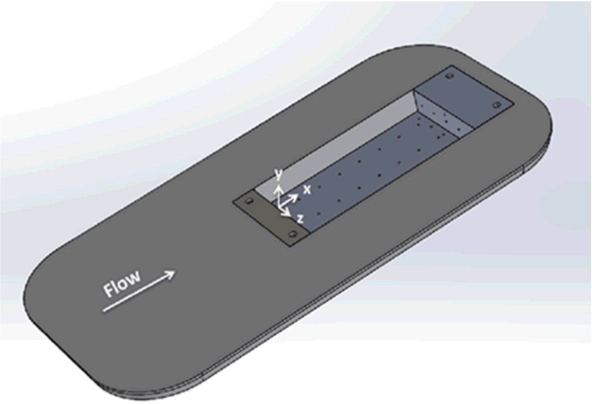

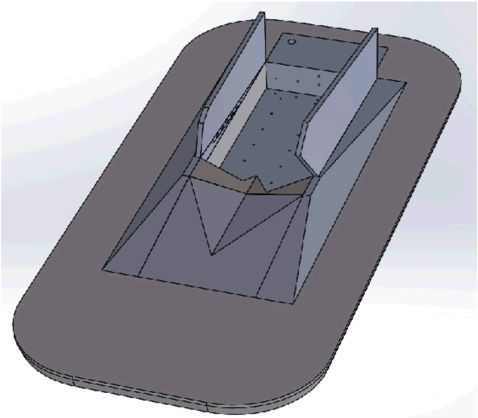

TTCP Meeting, April 2015

Auckland, NZ

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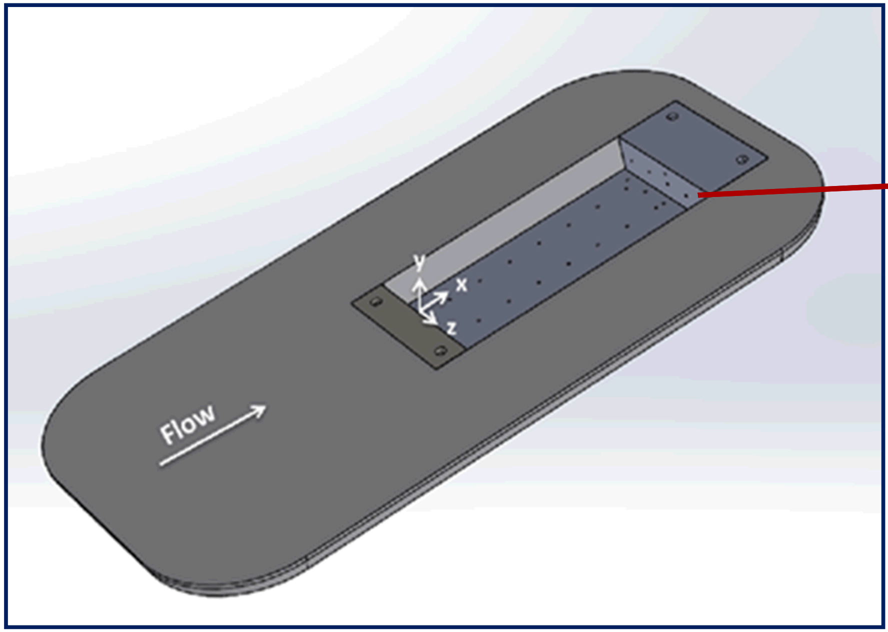
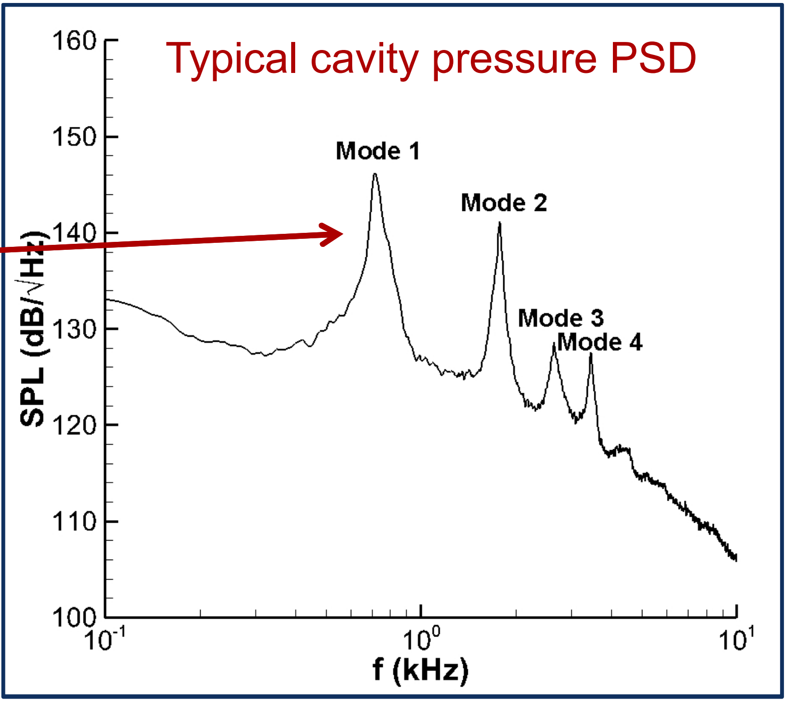
Motivation: Cavity Flows

- Interaction of free shear layer and cavity walls produces resonant tones with high Sound Pressure Levels (*SPL).*
- Resonant tones can have high SPL up to 170 dB in some cases.
- Fluctuations provide a driver for potential large vibrations of internal stores in weapons bays.





Motivation

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Most existing work focuses on simple rectangular cavities.

- Modal frequencies can be predicted using Heller & Bliss's correlation, but not the modal amplitude distribution.
- Simple cavities neglect important geometric parameters that can modify cavity acoustics.

How do complex geometric changes to the bay affect pressure loading?

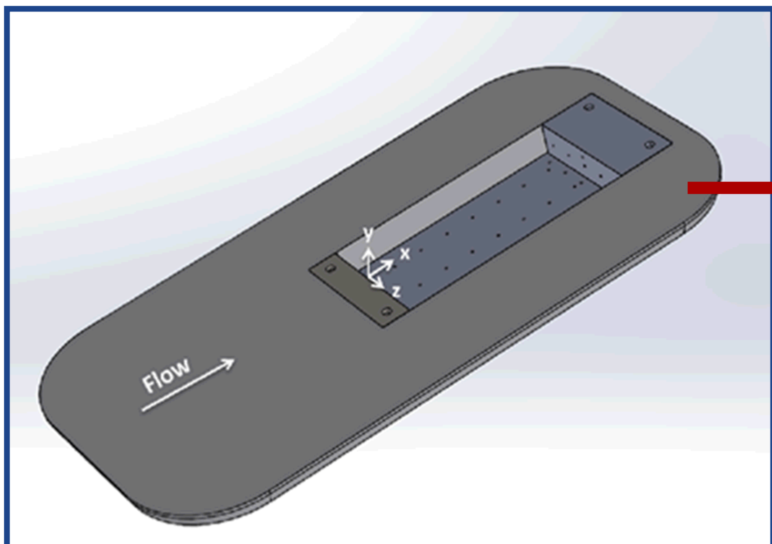
- Asymmetric inflows.
- Complex leading edge geometry.
- Varying internal geometry.
- Doors.

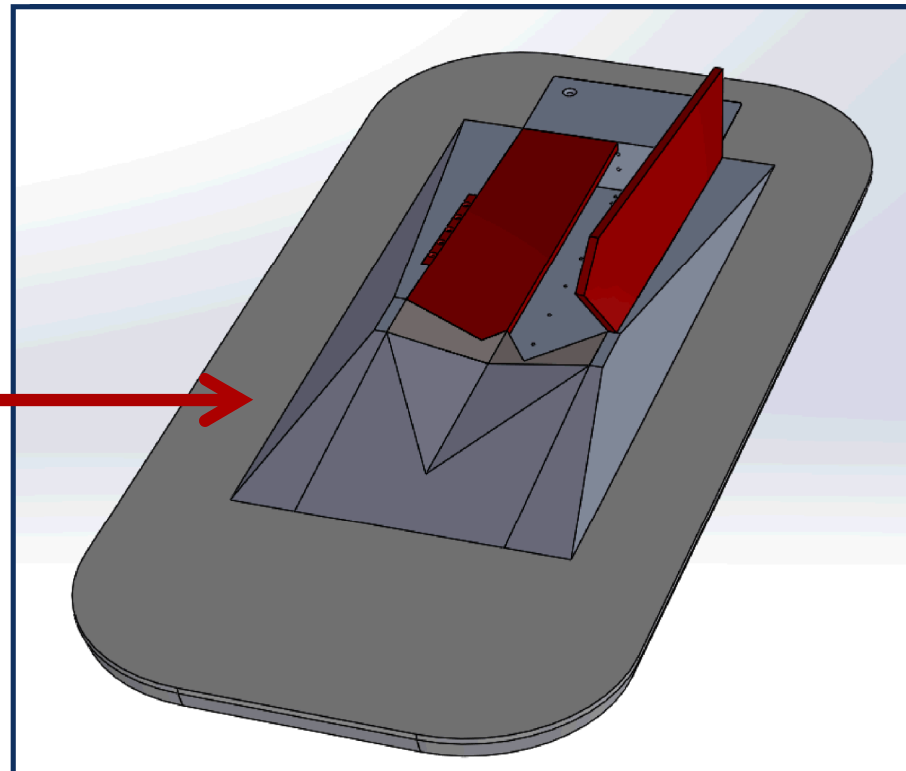

Lockheed Martin: Approved for Public Release

Experimental Approach

Use a building block approach to introduce complex geometric features one at a time into a simple rectangular cavity.

- Baseline configuration: side and front ramps
- Inlet geometry: center and offset scoop and tooth
- Internal variations: side insert and ramped floor
- Doors (open or closed)





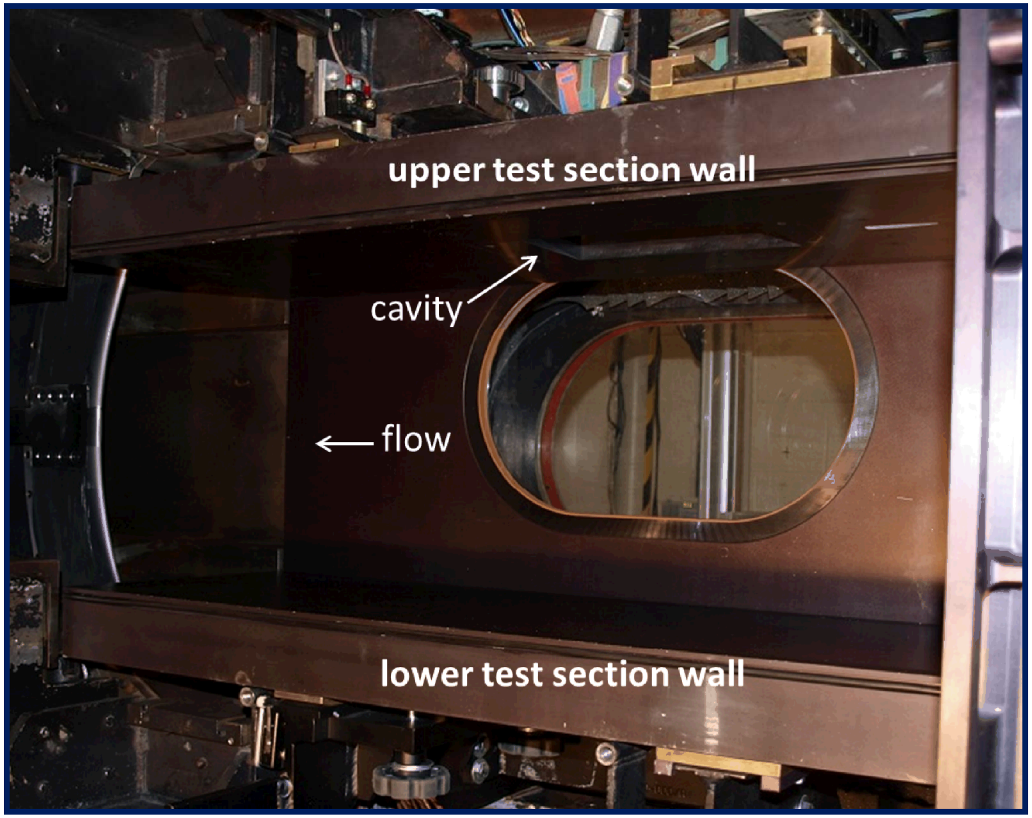
Experimental Approach

Trisonic Wind Tunnel

- Cavity integrated into flat-plate insert on upper wall.
- Incoming turbulent boundary layer.
- M = 0.6—0.9, focused on 0.8
- Re ≈ 10^7 / m

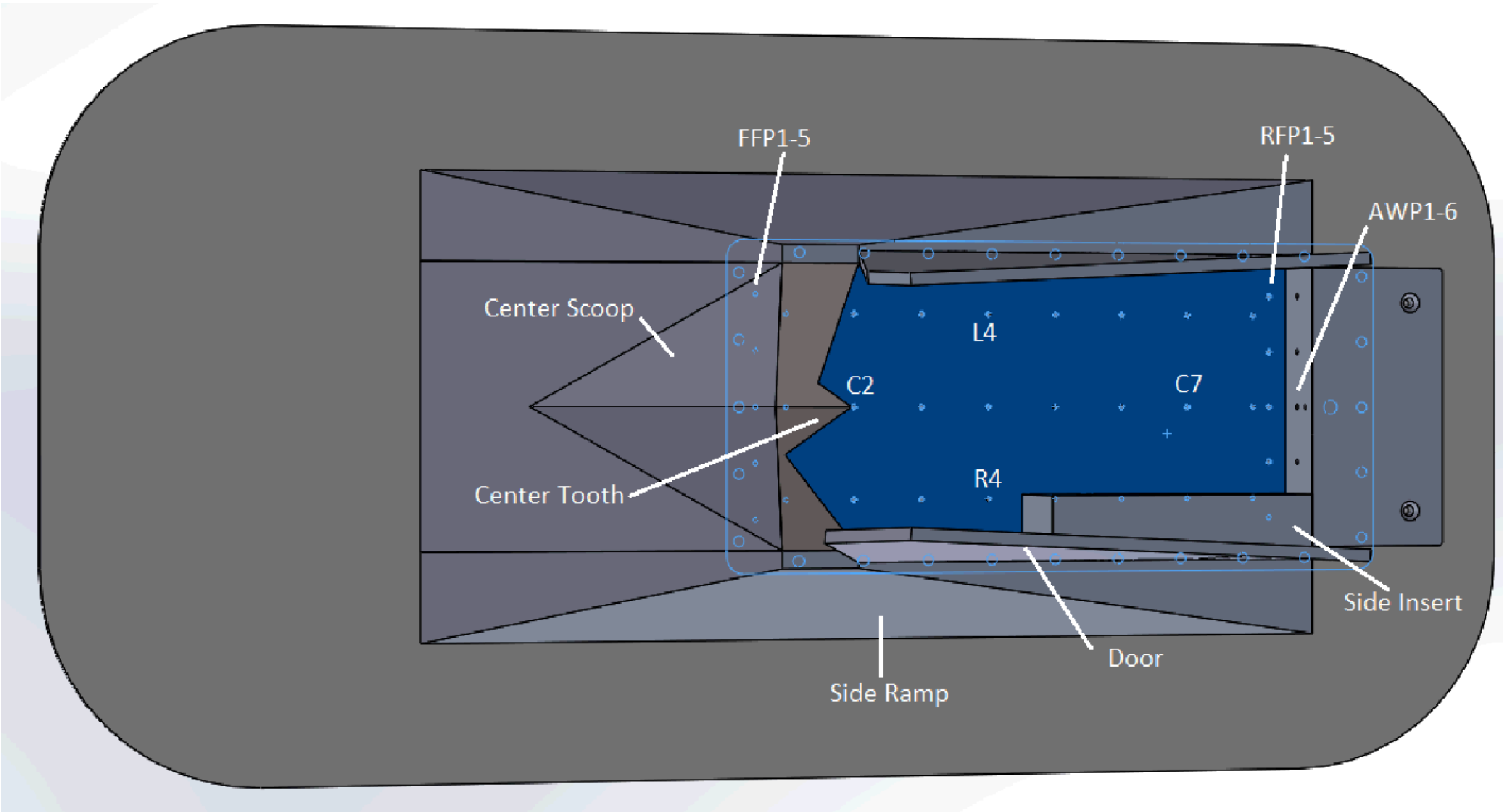
Simple Rectangular Cavity

- *L/D = 7*
- *L/W = 2*



Experimental Approach

Instrumentation consists of pressure sensors located throughout the cavity:

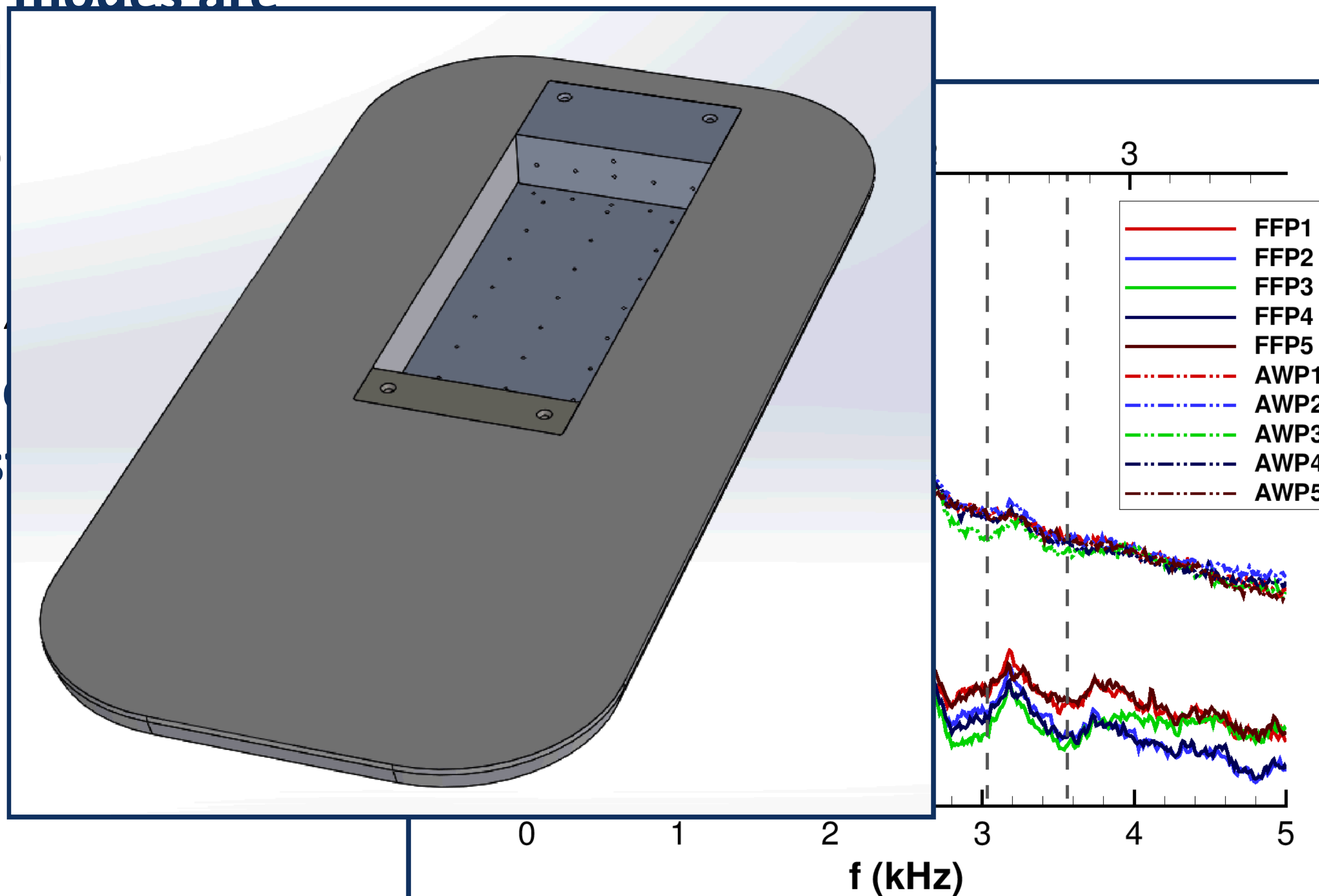


Simple Rectangular Cavity, PSD’s

Cavity (Rossiter) modes are clearly observed

- Frequencies p correlation of using α = 0.25

Amplitude of flu increases downs



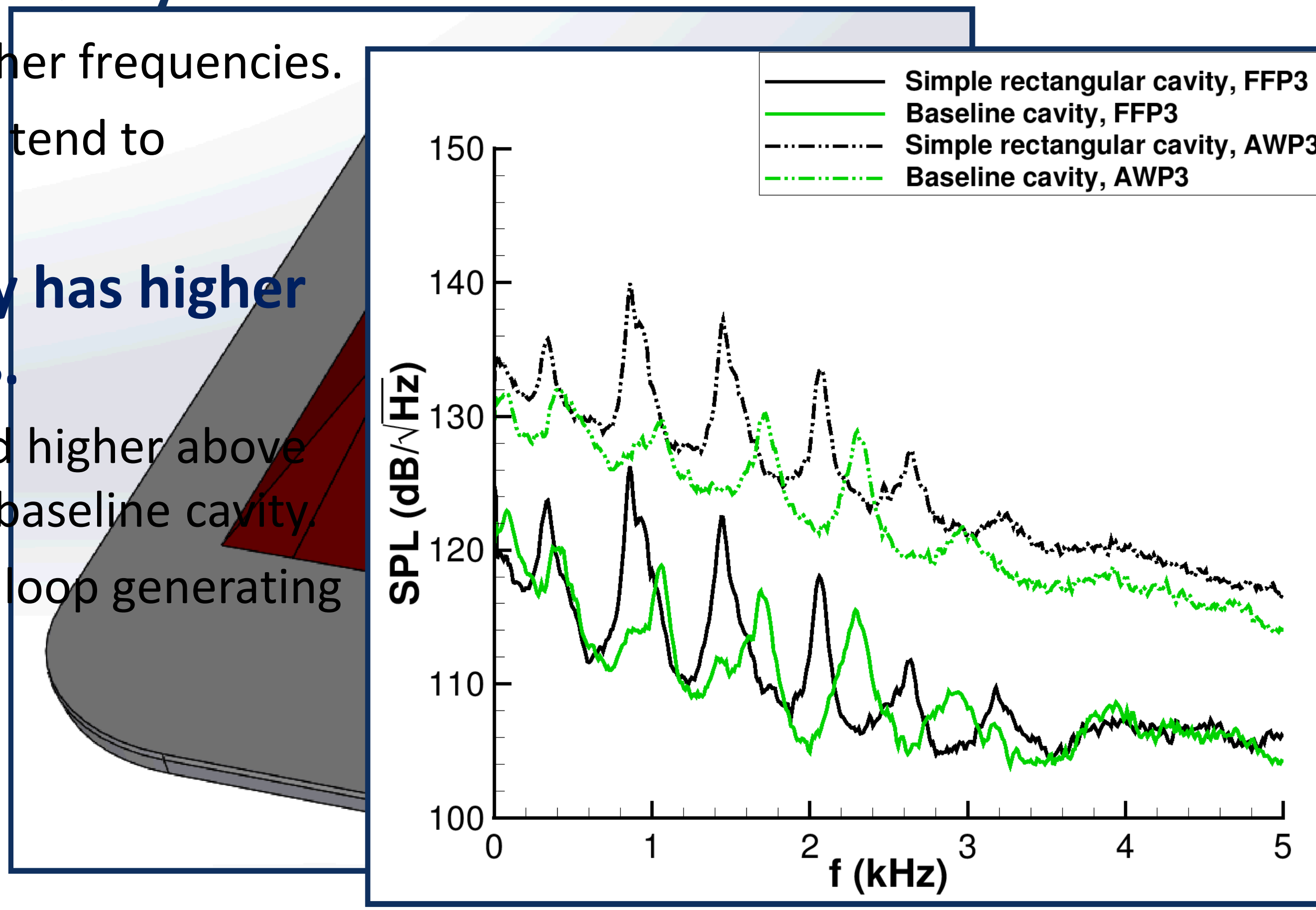
Baseline Cavity, PSD's

Similar presence of Rossiter modes in baseline cavity.

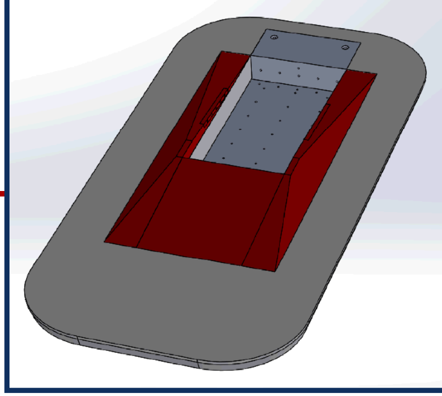
- Modes shift to higher frequencies.
- Modal amplitudes tend to decrease.

Rectangular cavity has higher aft-wall pressures.

- Shear layer is lifted higher above rear cavity wall in baseline cavity.
- Reduces feedback loop generating acoustic tones.



Baseline Cavity, Coherence

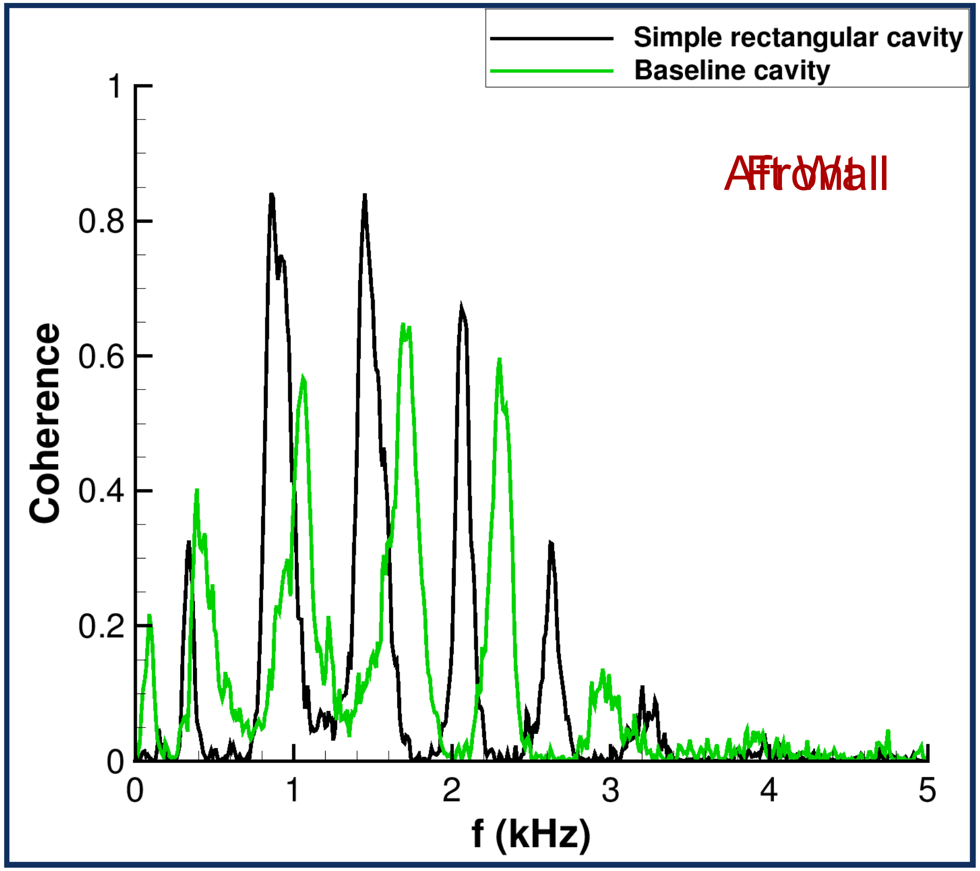


Front coherence (FFP2-FFP4):

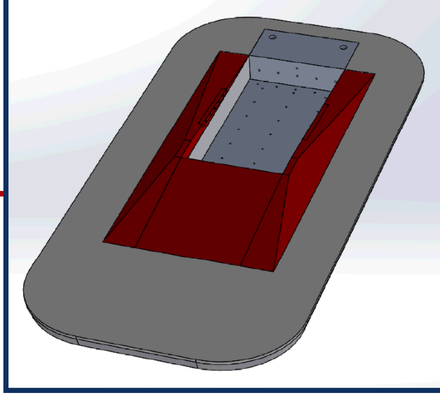
- High coherence of first 4 modes in simple cavity.
- Baseline cavity has lower coherence levels, consistent with lower modal amplitudes in PSD's.

Aft wall coherence (AWP2-AWP4):

- Coherence much lower overall for both configurations.
- Consistent with trends in simple cavities: more turbulent and less coherent fluctuations at rear of cavity.



Baseline Cavity, Cross Correlation

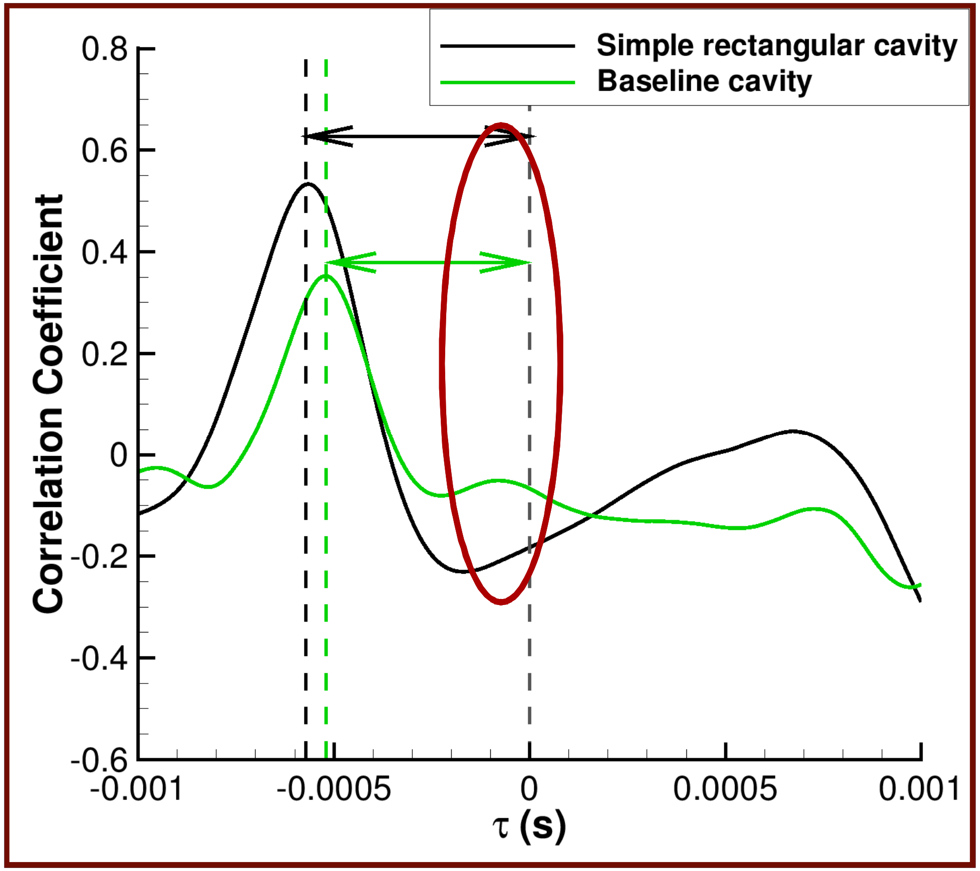


Cross correlation computed between front and rear of cavity (FFP3-AWP3).

- Baseline cavity show much lower correlation levels.

Dominant peak in cross correlation near 0.5 ms, corresponding to propagation time across the cavity.

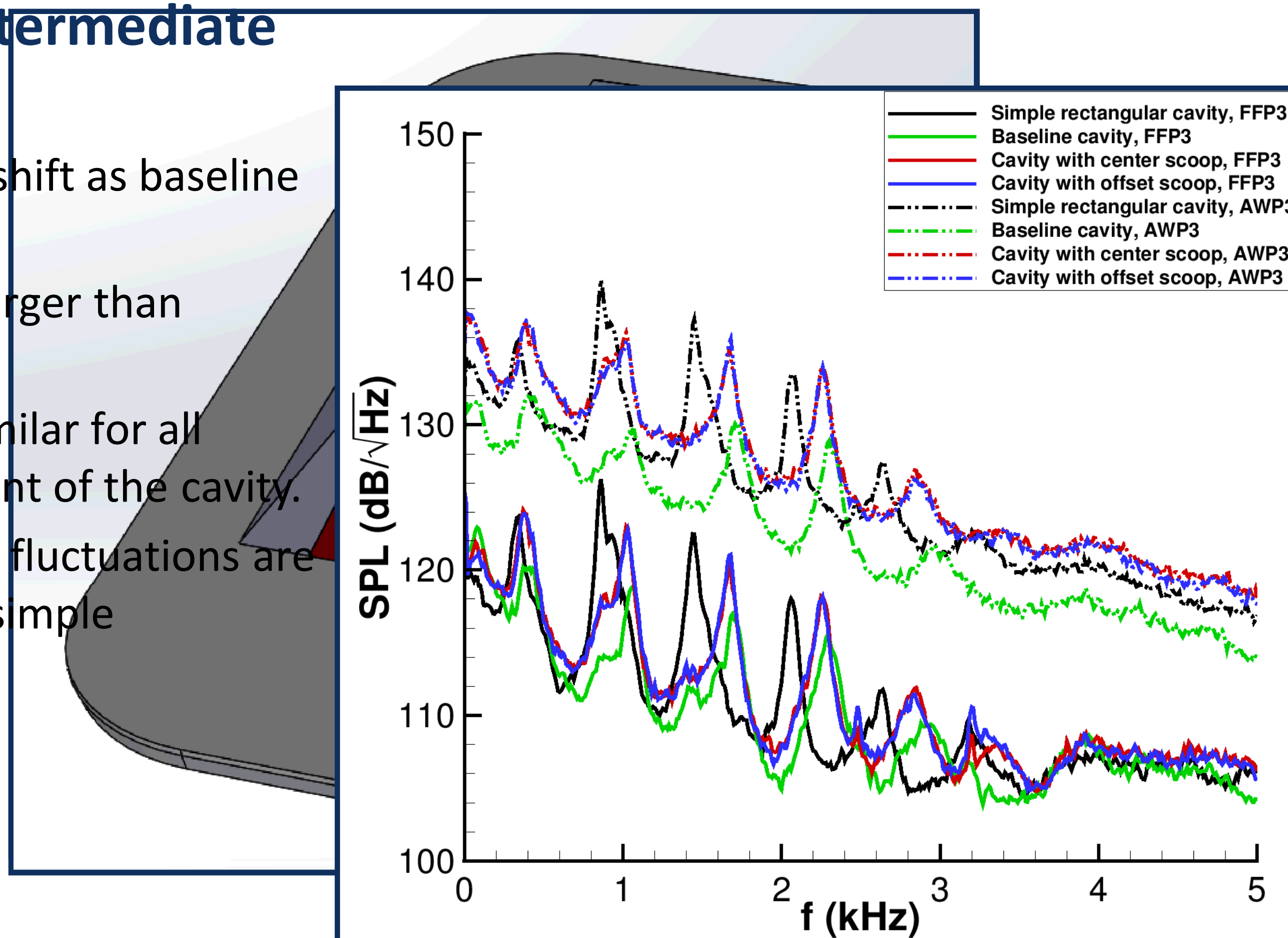
- Propagation time is smaller in baseline cavity, which leads to higher Rossiter mode frequencies.
- Consistent with frequency shift seen in PSD's.



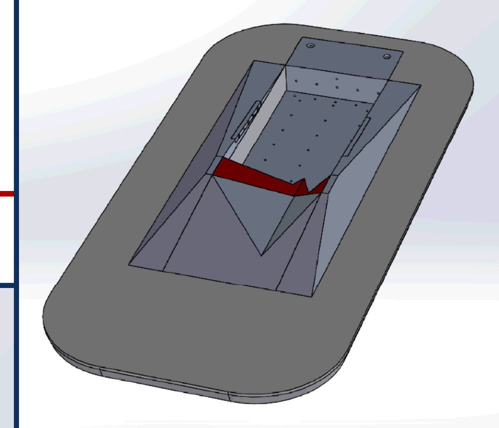
Effect of Inlet Geometry, PSD's

Inlet design has an intermediate effect on the flow.

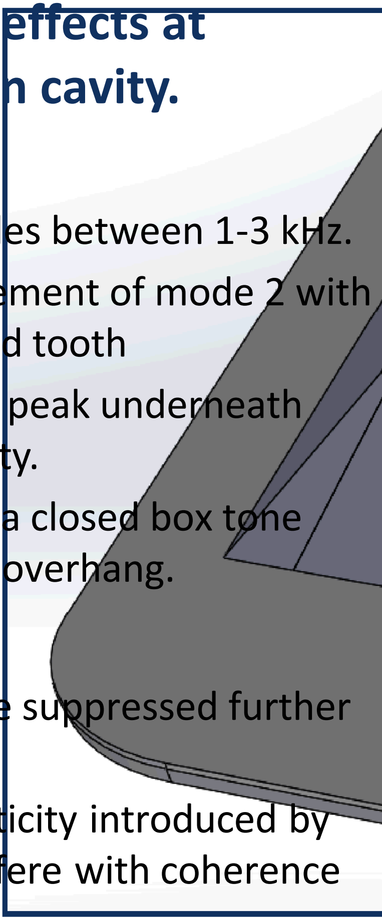
- Same modal frequency shift as baseline cavity.
- Modal amplitudes are larger than baseline cavity.
- Broadband levels are similar for all configurations at the front of the cavity.
- Amplitude of rear cavity fluctuations are elevated and approach simple rectangular cavity level.



Effect of Leading-Edge Tooth, PSD's



Tooth has different effects at different locations in cavity.

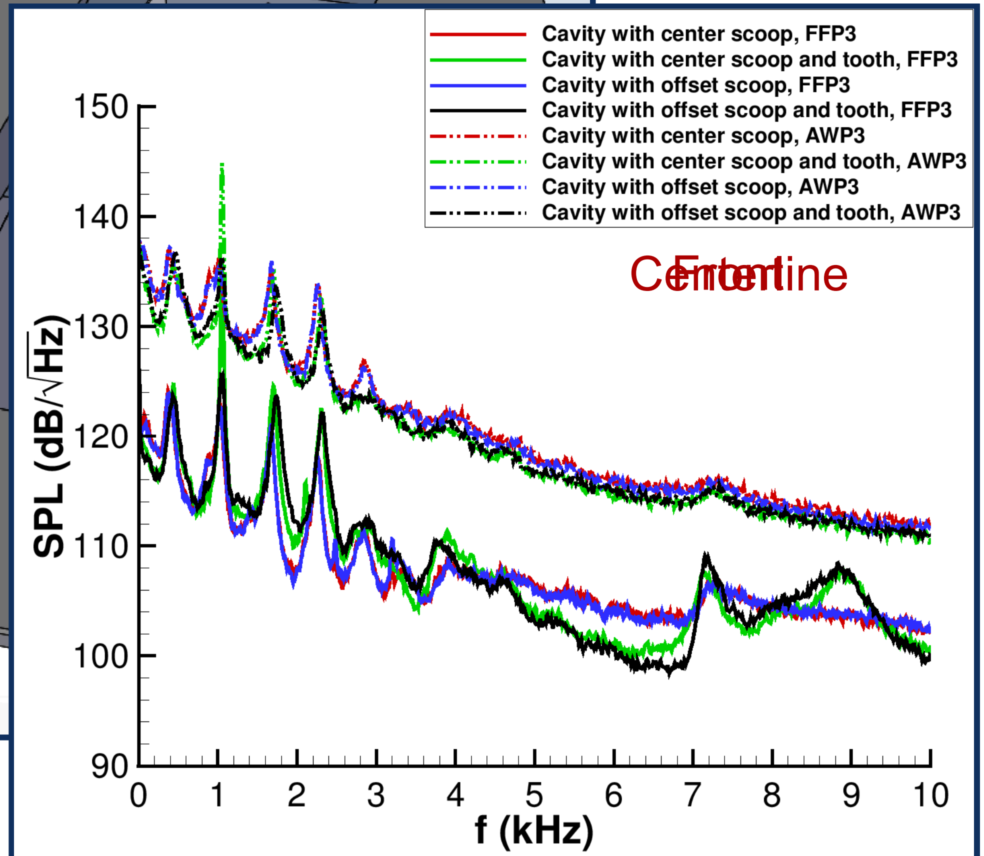


Cavity front:

- Tooth enhances modes between 1-3 kHz.
  - Largest enhancement of mode 2 with center scoop and tooth
- Approximately 8 kHz peak underneath tooth at front of cavity.
  - Corresponds to a closed box tone under the front overhang.

Cavity rear:

- Mode amplitudes are suppressed further downstream.
  - Streamwise vorticity introduced by tooth may interfere with coherence of shear layer.



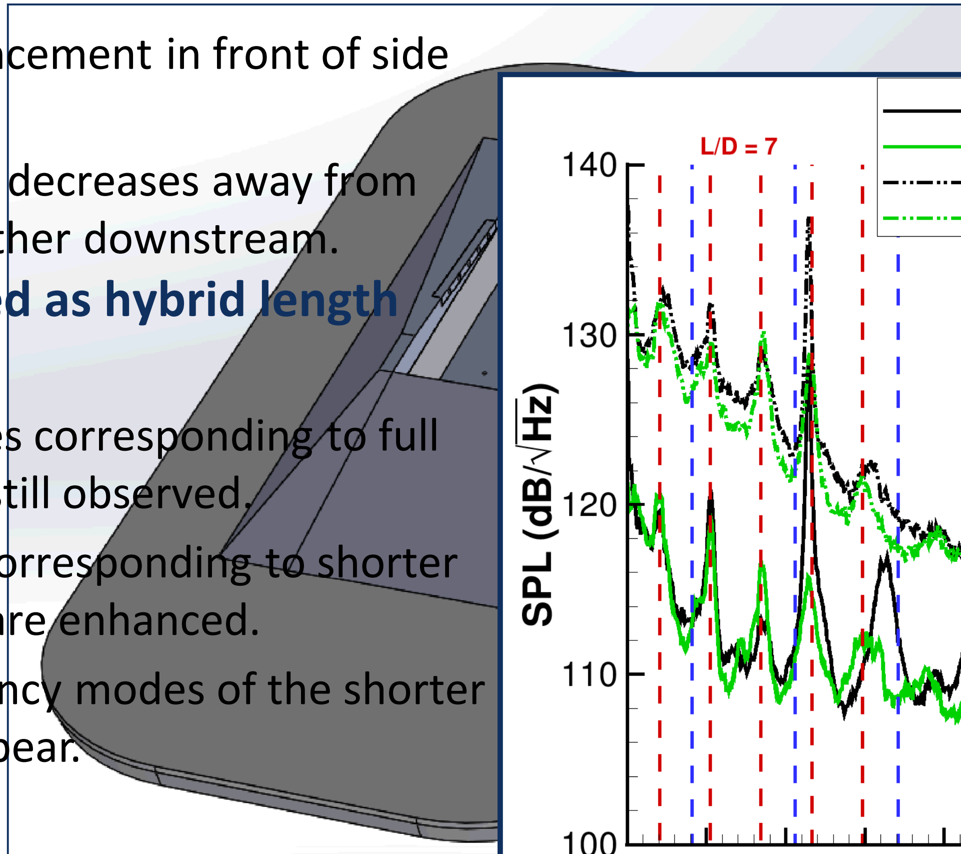
Effect of Side Insert, PSD's

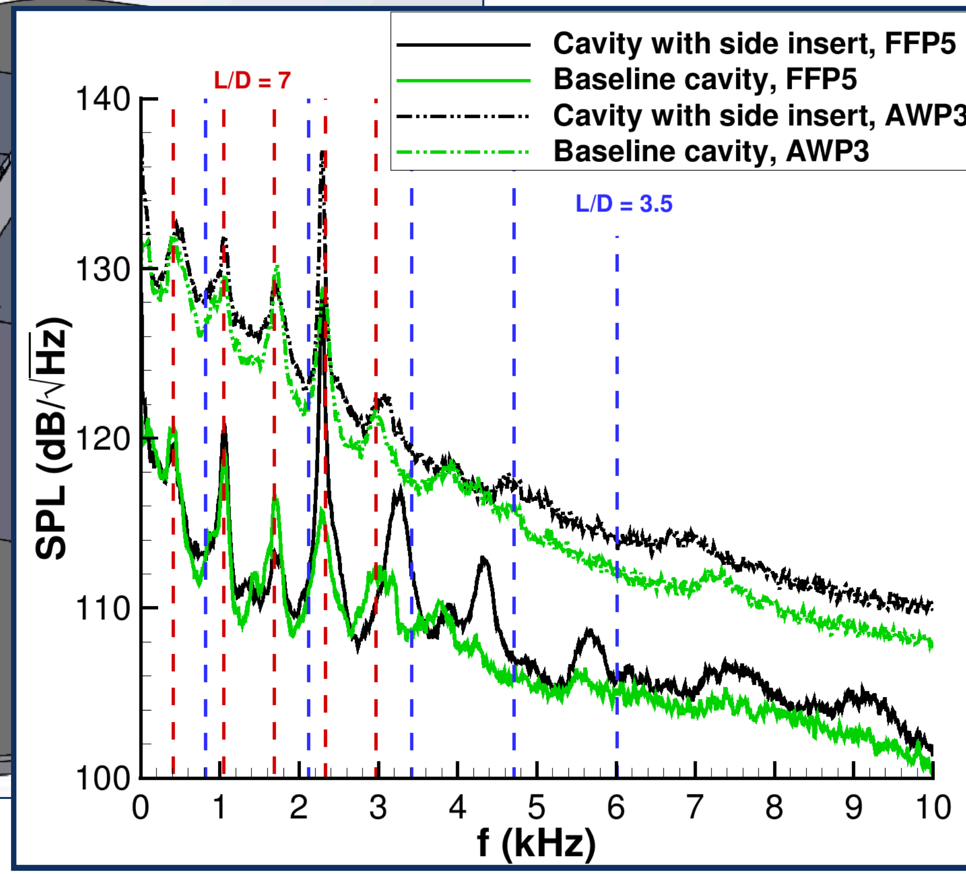
Mode amplitudes are enhanced with the presence of side insert.

- Highest enhancement in front of side insert.
- Enhancement decreases away from insert and further downstream.

Can be explained as hybrid length cavity.

- Rossiter modes corresponding to full length cavity still observed.
- Frequencies corresponding to shorter cavity length are enhanced.
- Higher frequency modes of the shorter cavity also appear.

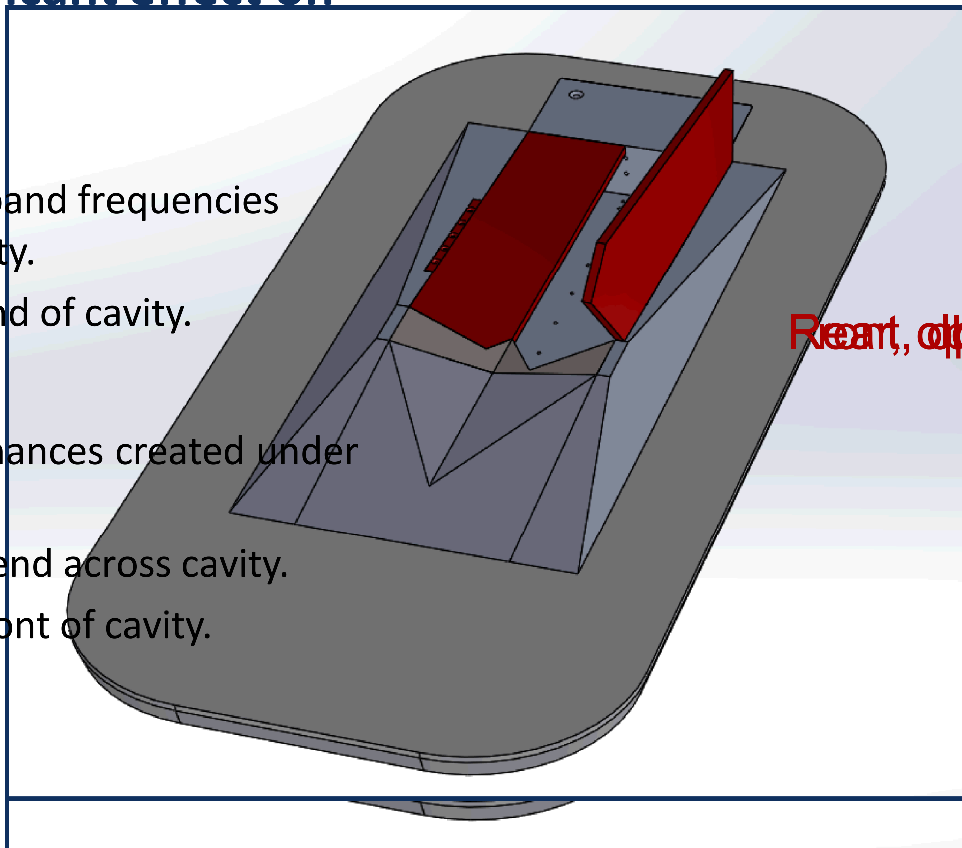


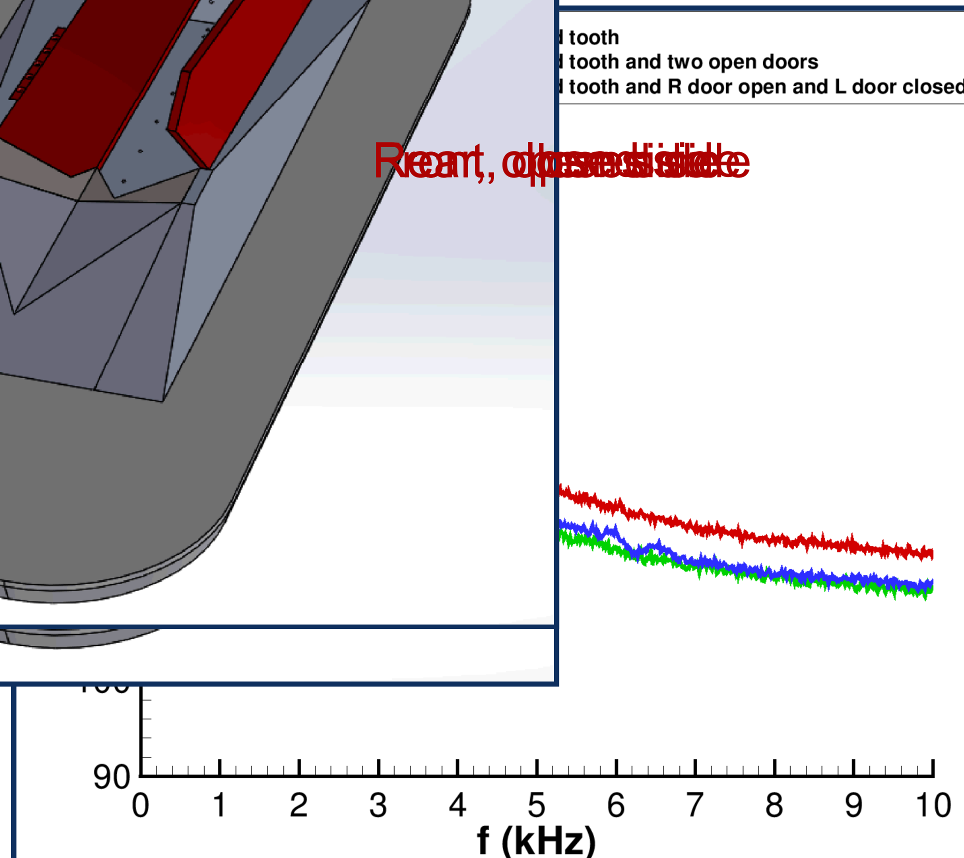


Effect of Doors, PSD's

Doors have a significant effect on measured spectra.

- Two open doors.
  - Elevated broadband frequencies throughout cavity.
  - Worst case at end of cavity.
- One open door.
  - Additional resonances created under closed door.
  - Resonances extend across cavity.
  - Worst case at front of cavity.





Effect of Ramped Floor, PSD's

Literature for simple rectangular cavities indicates

ramped floors.

- We see this fo

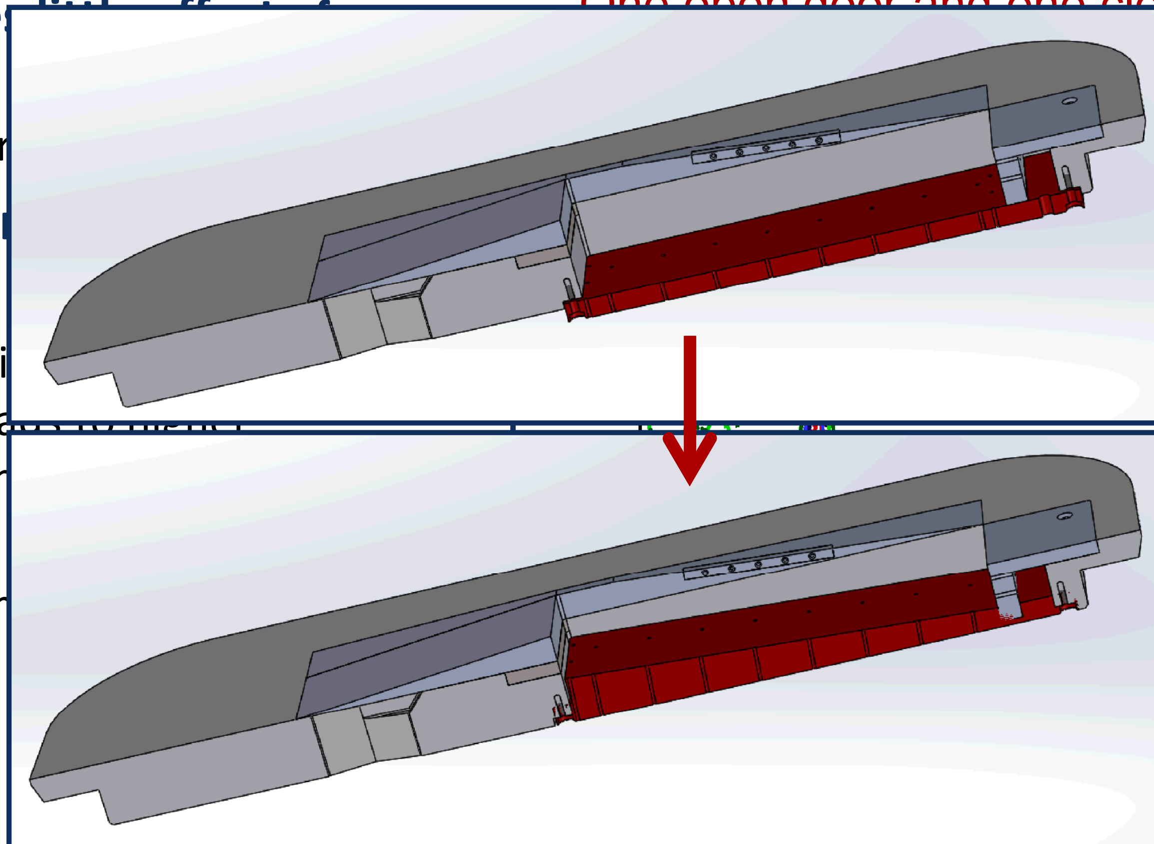
Sometimes the

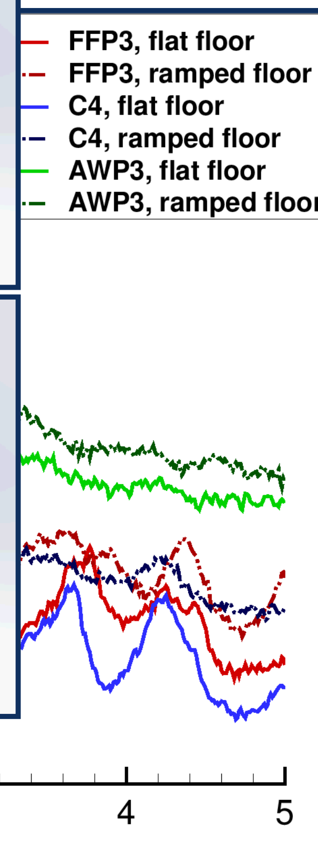
interactions.

- Ramped floor i closed door lea broadband co amplitudes.
- Worst case co

One open door and one closed door

e insert





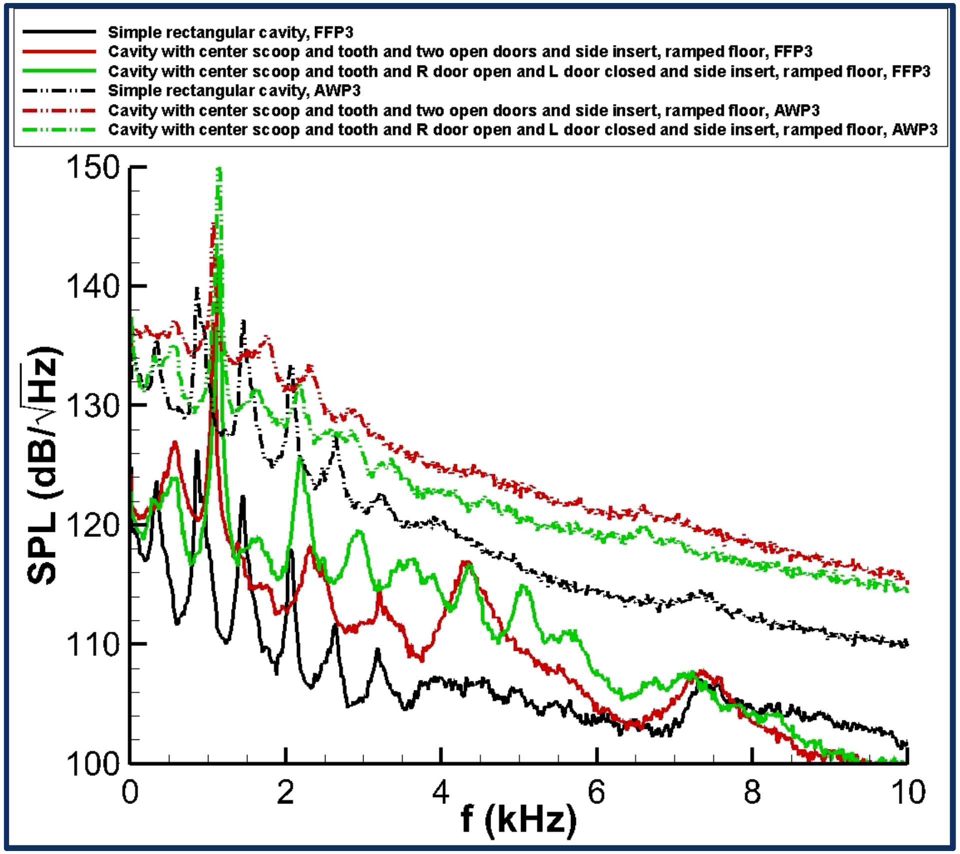
Complex Configurations, PSD's

Can compare most complex configurations to a simple rectangular cavity.

- Much larger modal amplitudes and broadband acoustics.
- Different modal frequencies not predicted by Heller & Bliss correlation.
- Additional higher frequency content.

Significant potential impact on internal stores.

- Structural coupling could be different with shifted modal frequencies.
- Dominant modes can shift with configuration changes.
- Loading significantly underpredicted in a simple rectangular cavity.



Conclusions

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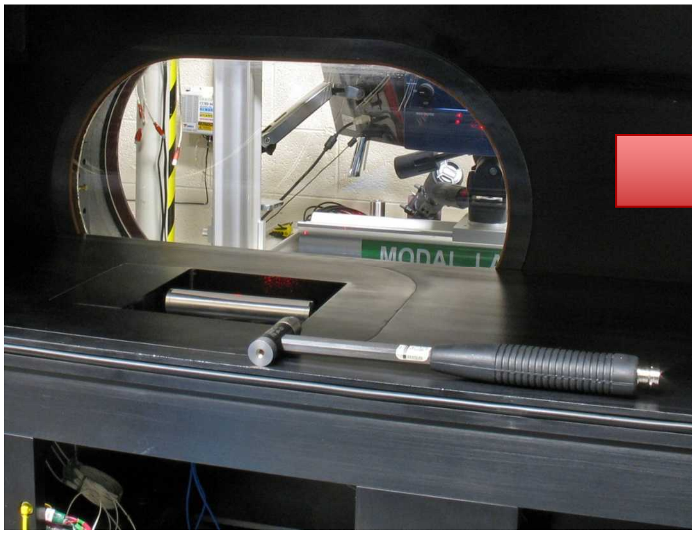
What complex cavity variations alter the cavity acoustics?

- **Configurations that change the shear layer position with respect to the aft wall.**
  - Lofting the shear layer leads to reduced amplitude of modes and broadband fluctuations.
    - i.e., baseline configuration, center scoop and tooth configurations.
- **Configurations that constrict the flow.**
  - Leads to higher frequency content and additional resonances in the spectra.
    - i.e., leading edge overhang, closed doors, ramped floors and internal side inserts.
- **Configurations can interact and create significantly higher pressure fluctuations at different modal frequencies than predicted by a rectangular cavity.**
  - These changes must be accounted for when designing for flight.

What’s Next?

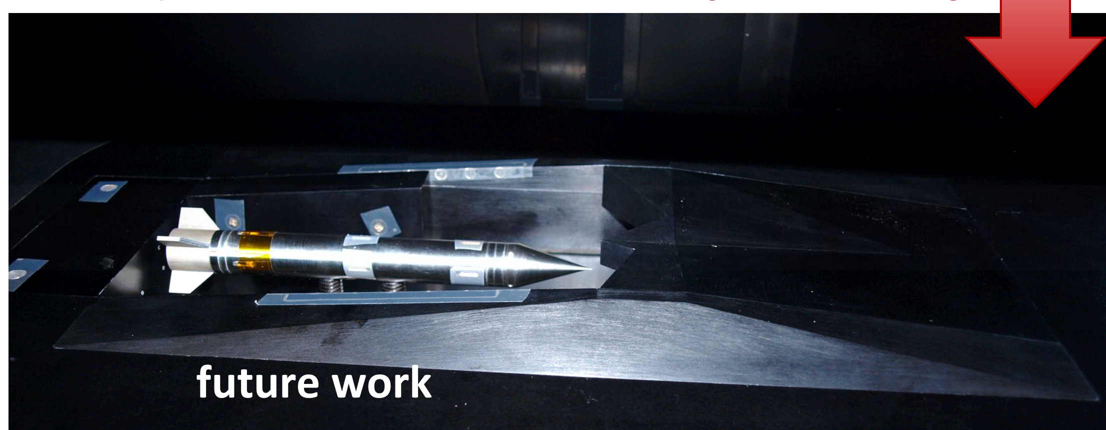
Fluid-Structure Interactions in these flows.

1) Simple Store in Simple Cavity

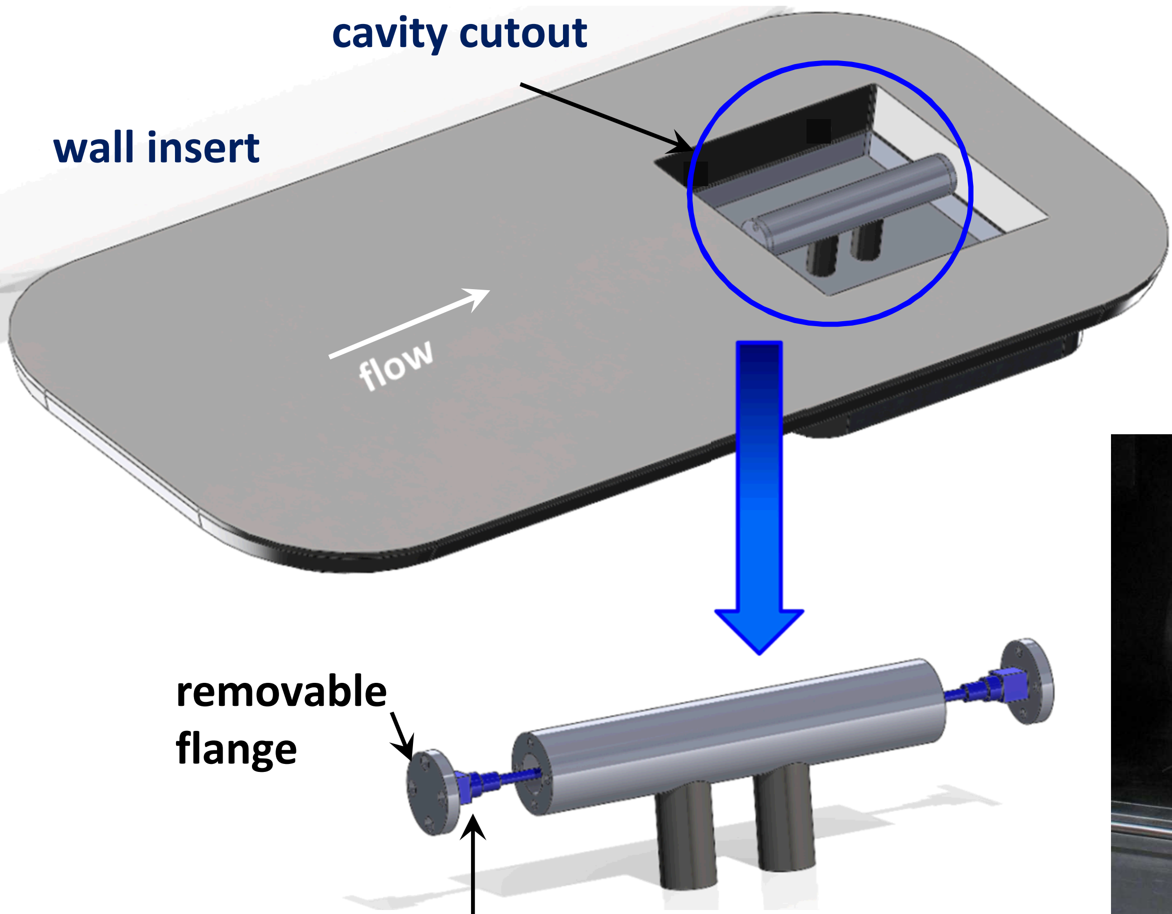


2) Complex Store in Simple Cavity

3) Complex Store in Complex Cavity

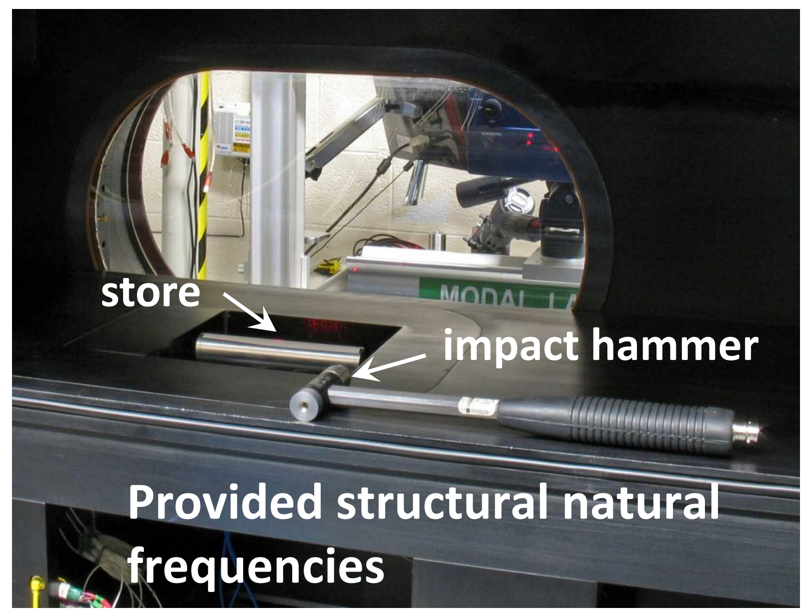


Simple Cavity FSI in TWT



Triaxial accelerometers provided store response.

Impact Hammer Tests



Previous Cavity FSI in TWT

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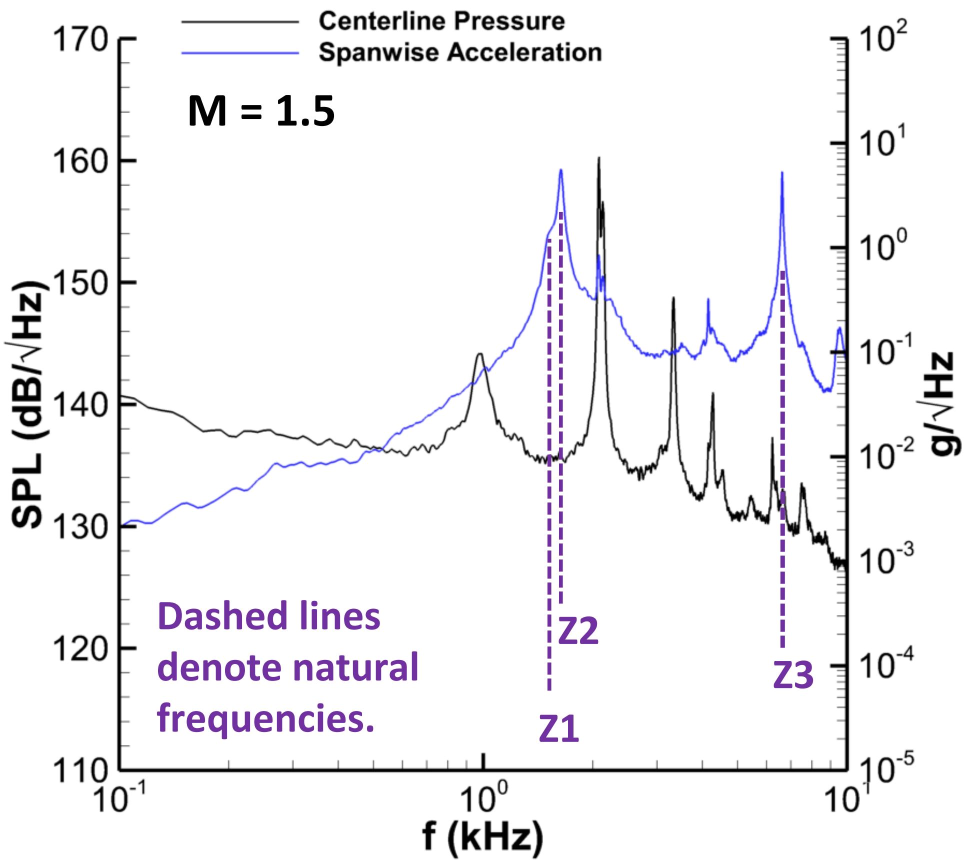
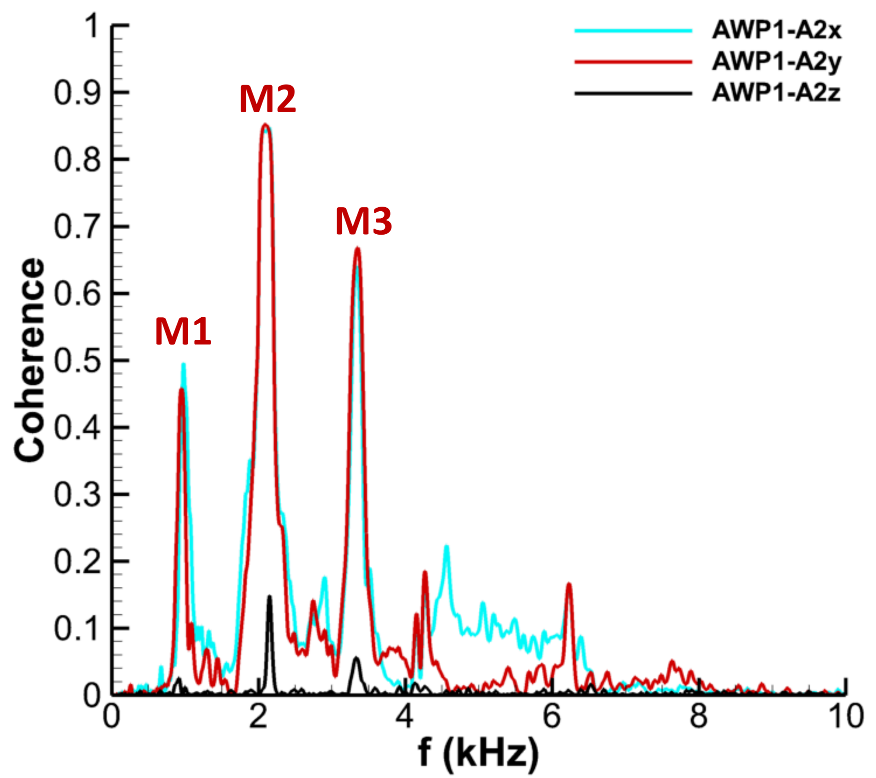
Simultaneous Pressure and Acceleration



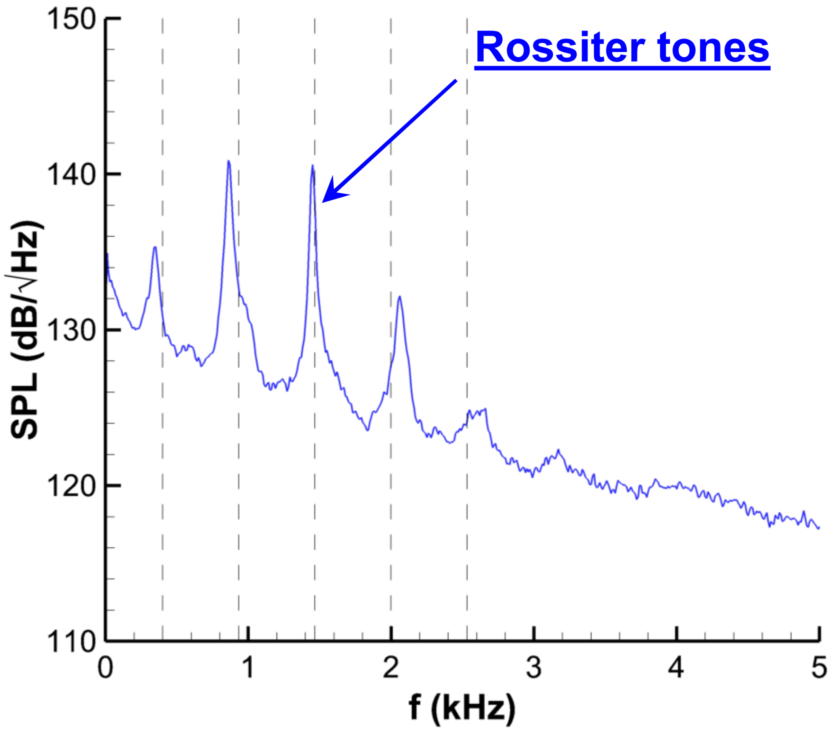
Each structural natural frequency was excited by the cavity flow.

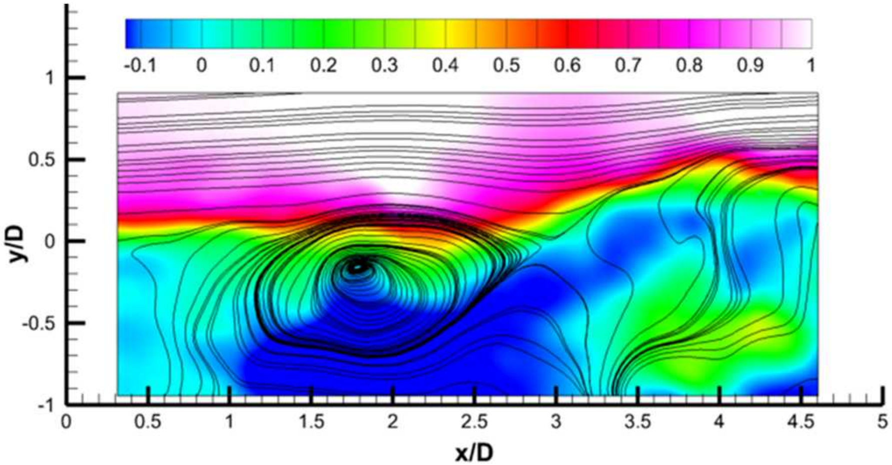
Correlation of Pressure and Acceleration



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

Response to Cavity Tones?



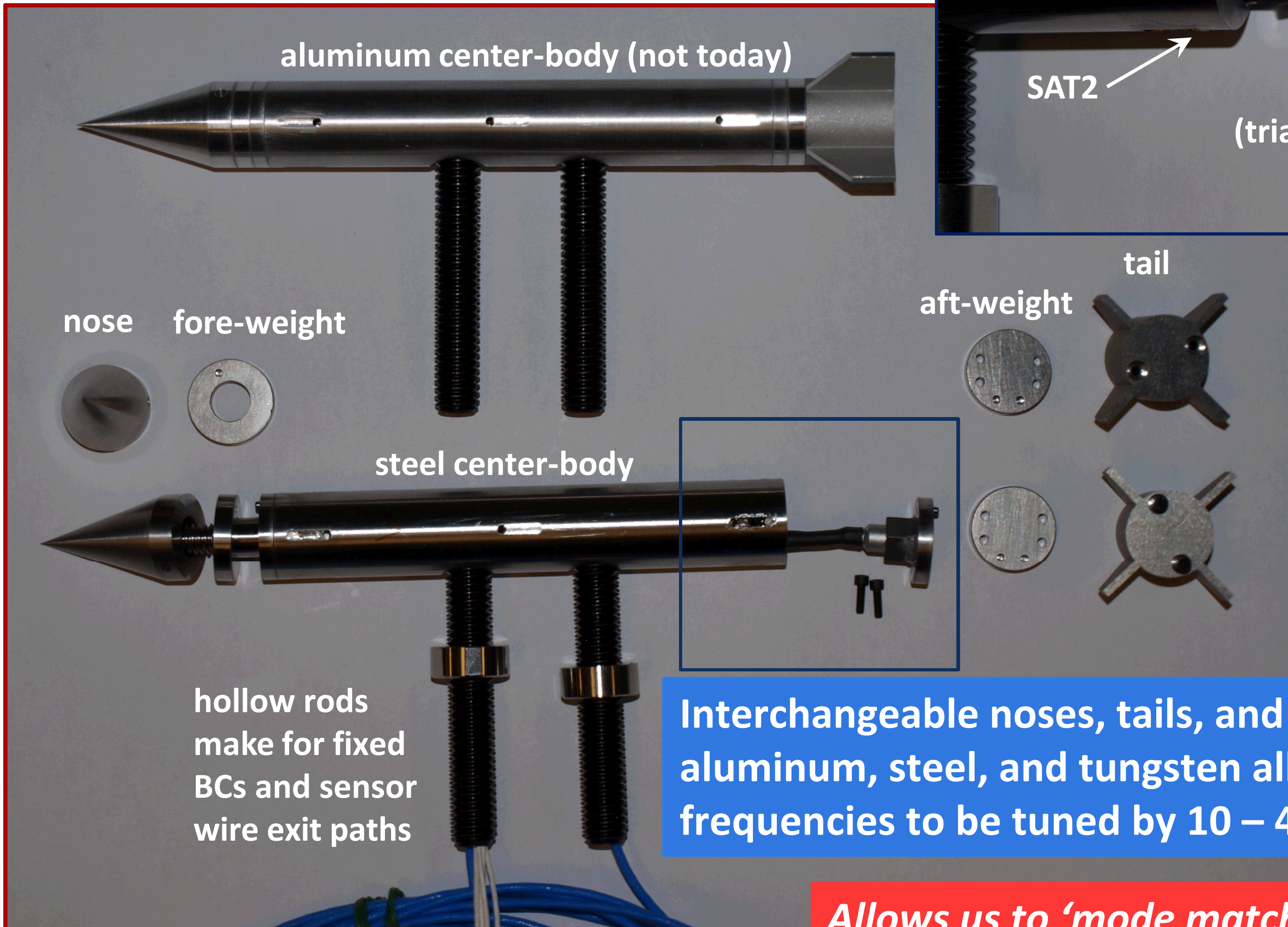


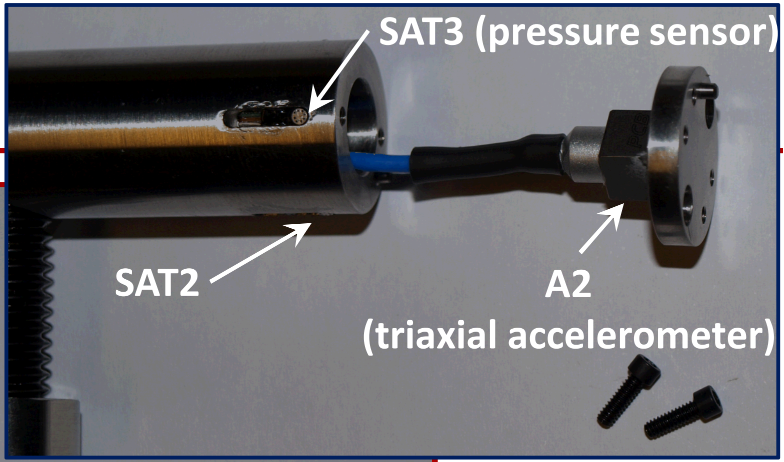
- Cavity flows have ***longitudinal pressure waves***
- Spanwise vorticity results in ***wall-normal gradients***

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.

Store Assembly Details

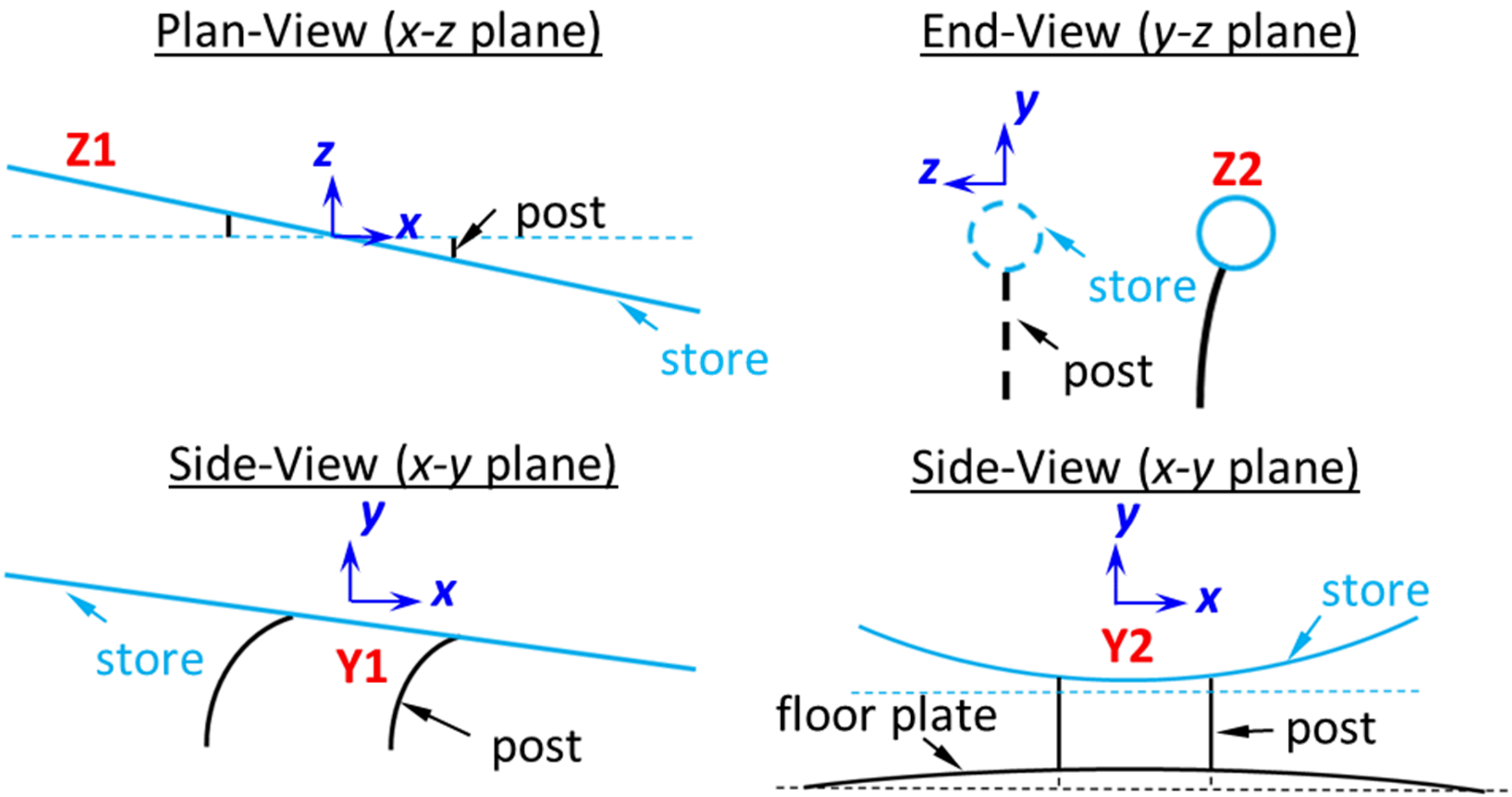




Interchangeable noses, tails, and weights of aluminum, steel, and tungsten allow natural frequencies to be tuned by 10 – 400 Hz.

Allows us to 'mode match' cavity tones and store natural frequencies

Store Natural Frequencies



- Natural frequencies labeled by their predominant direction of motion
- Five natural frequencies measured below 4 kHz
- Today we will focus on Z1, Z2, and Y1, the least damped (strongest) modes.

Variation of Natural Frequencies

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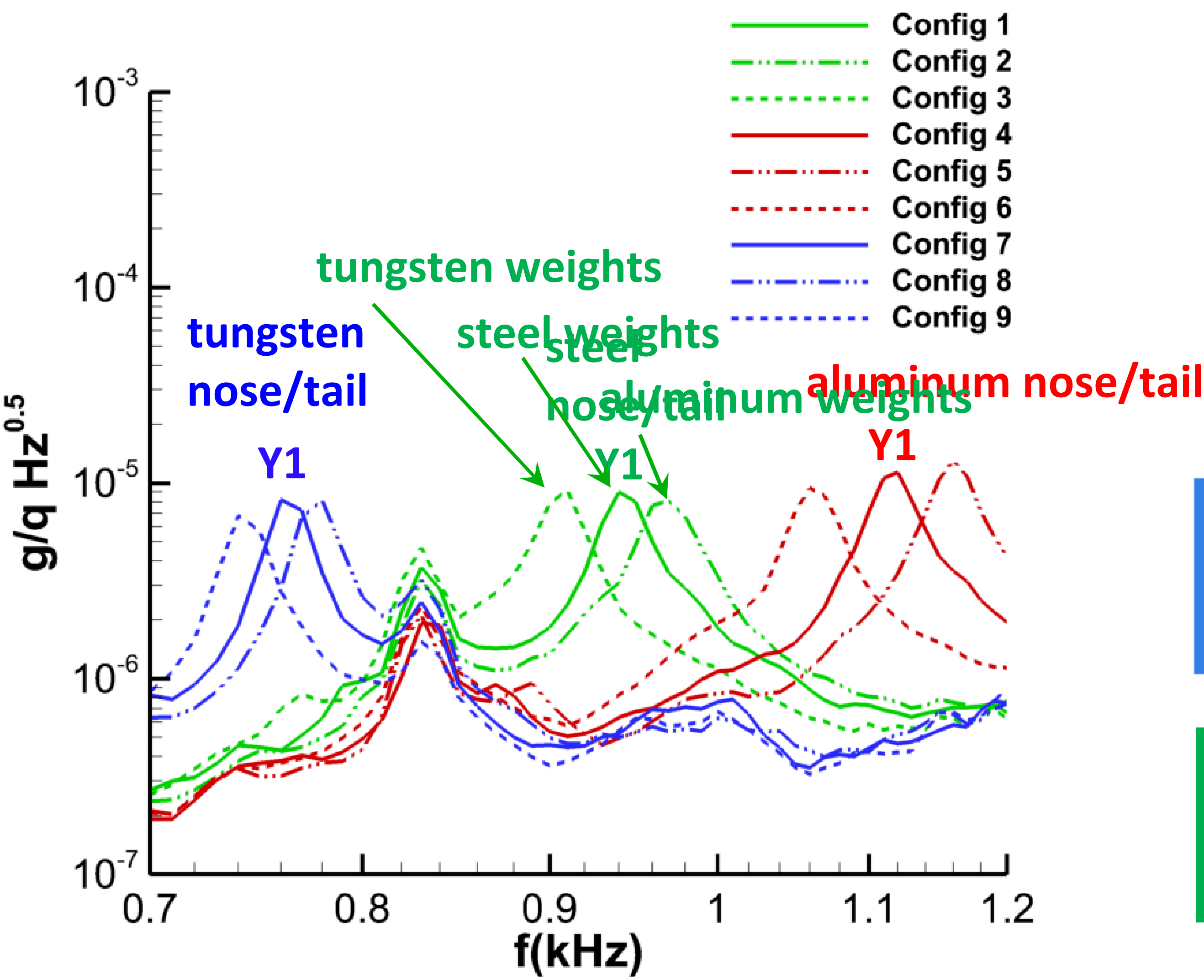
Streamwise Accelerations at A2 in Mach 0.8 Cavity Flow

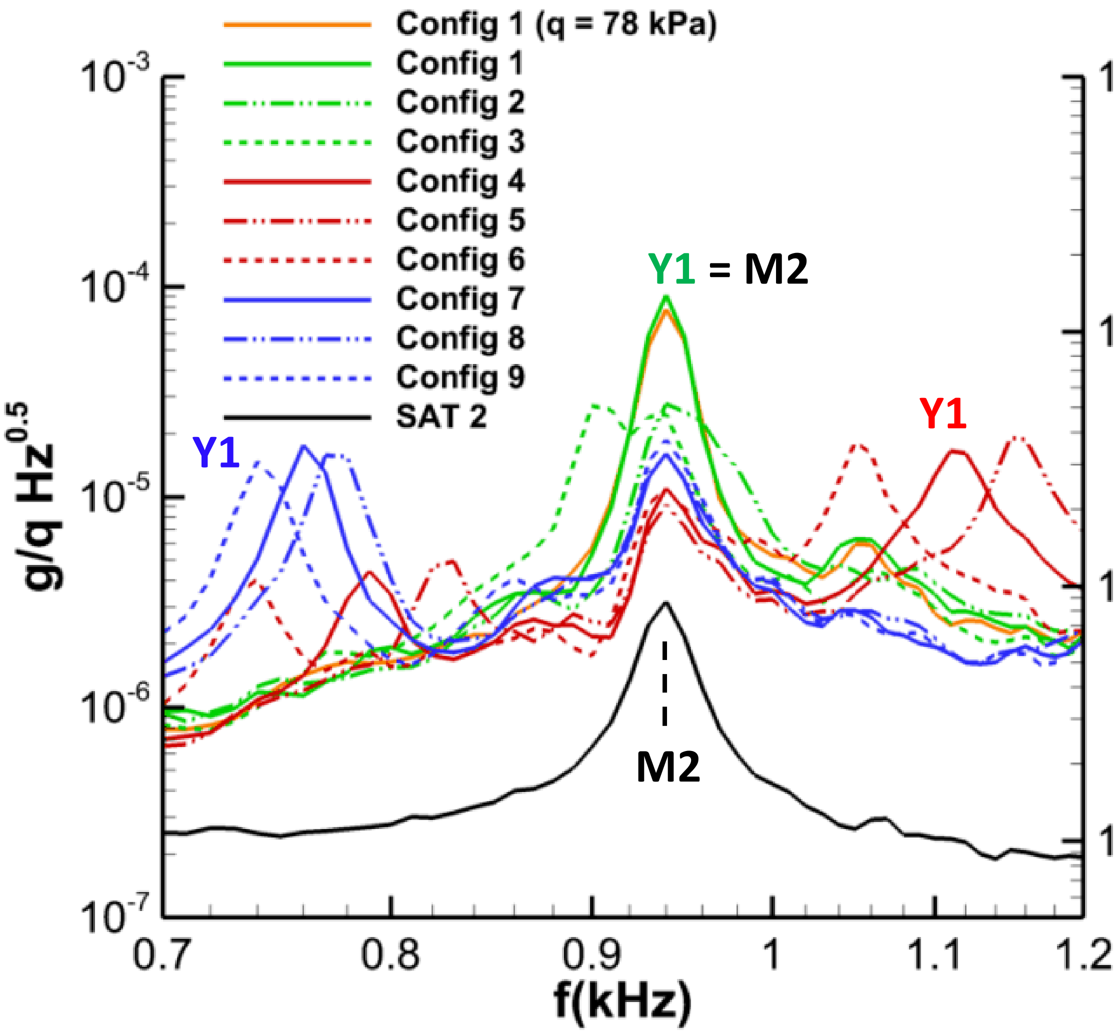


Changing nose and tail results in large natural frequency variations.

Smaller variations can be achieved through weight changes.

Wall-Normal Mode Matching (M = 0.94)

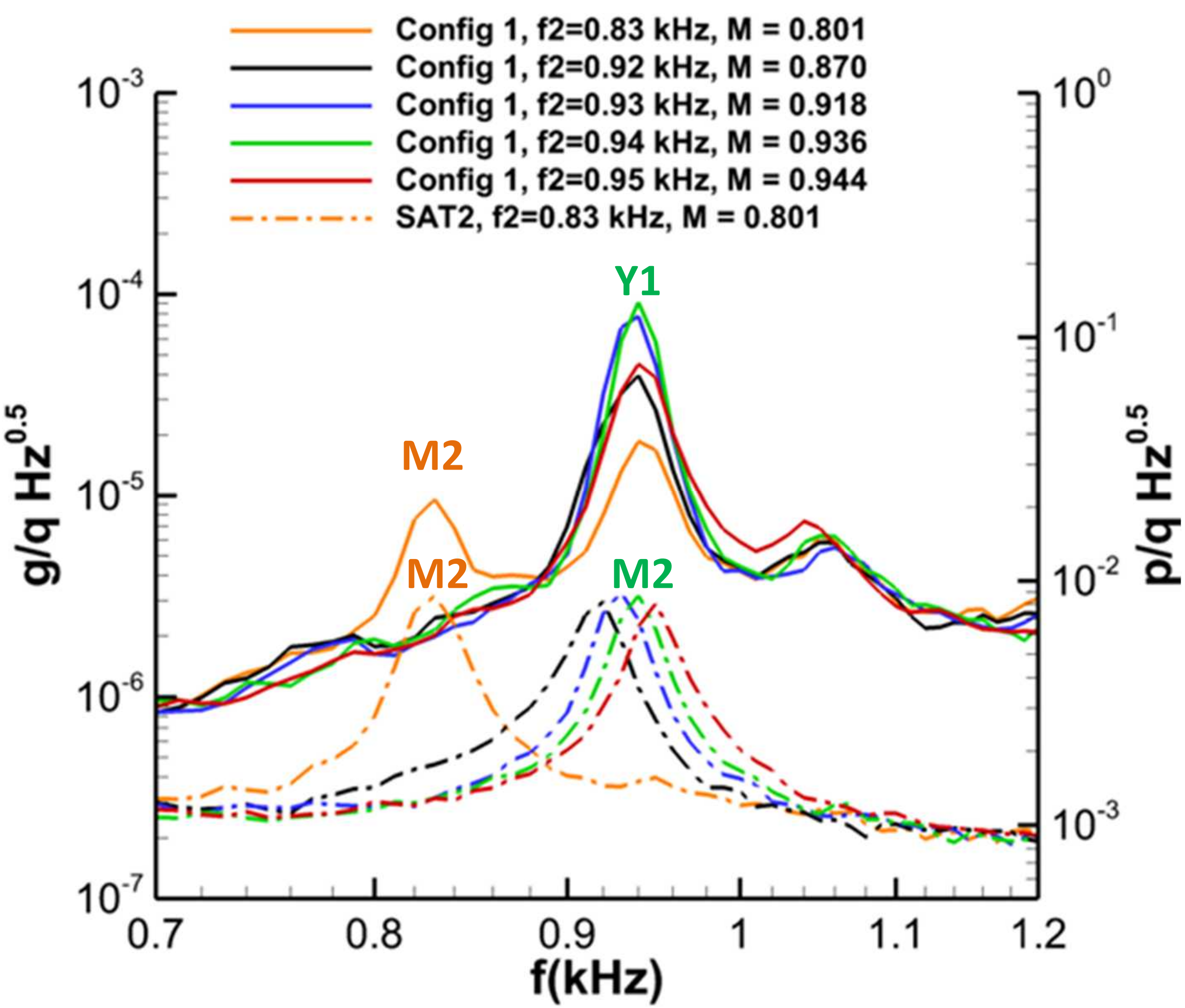
Simultaneous pressure and *y*-accelerations at A2



- Mode-matched case *exhibits five times greater vibrations* than tungsten or aluminum structures.
- Even during mode matching, *response remains linear with q*

When Y1 natural frequencies are within about 3% of M2, response remains elevated (50% greater than configurations 4-9).

Mach # Sensitivity Near Mode Matching

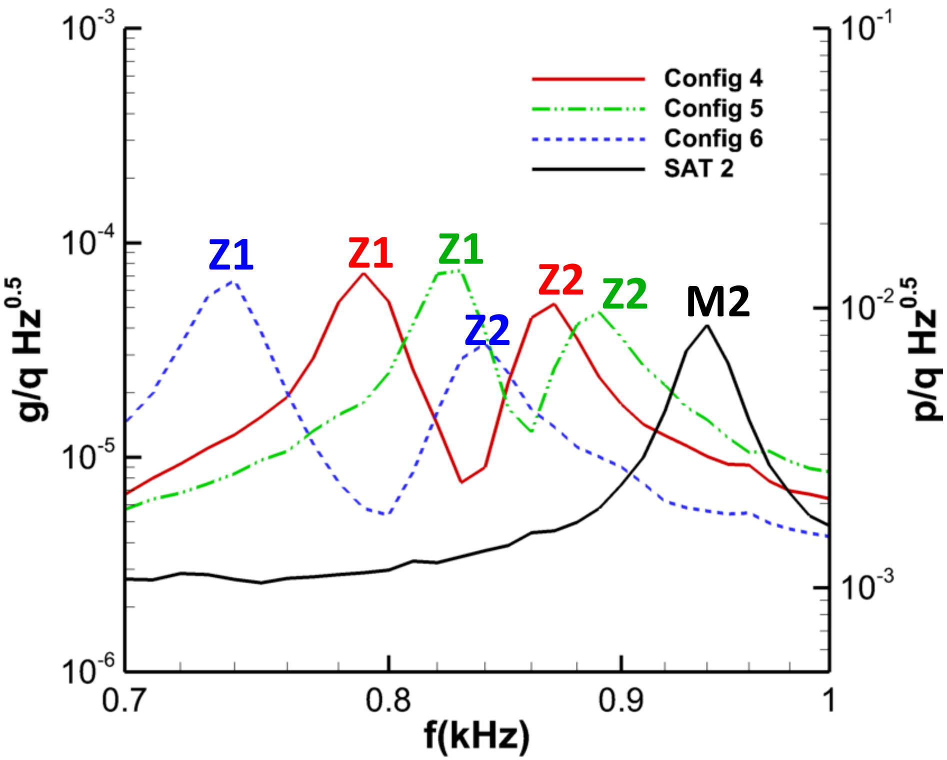


- Amplitude of Y1 doubles when cavity tone frequency is within 1-2% of structural natural frequency.
- When f_2 within 0-1%, Y1 response increases by a factor of 5.
- This sensitivity is similar to varying Y1 frequency about fixed cavity tone frequency

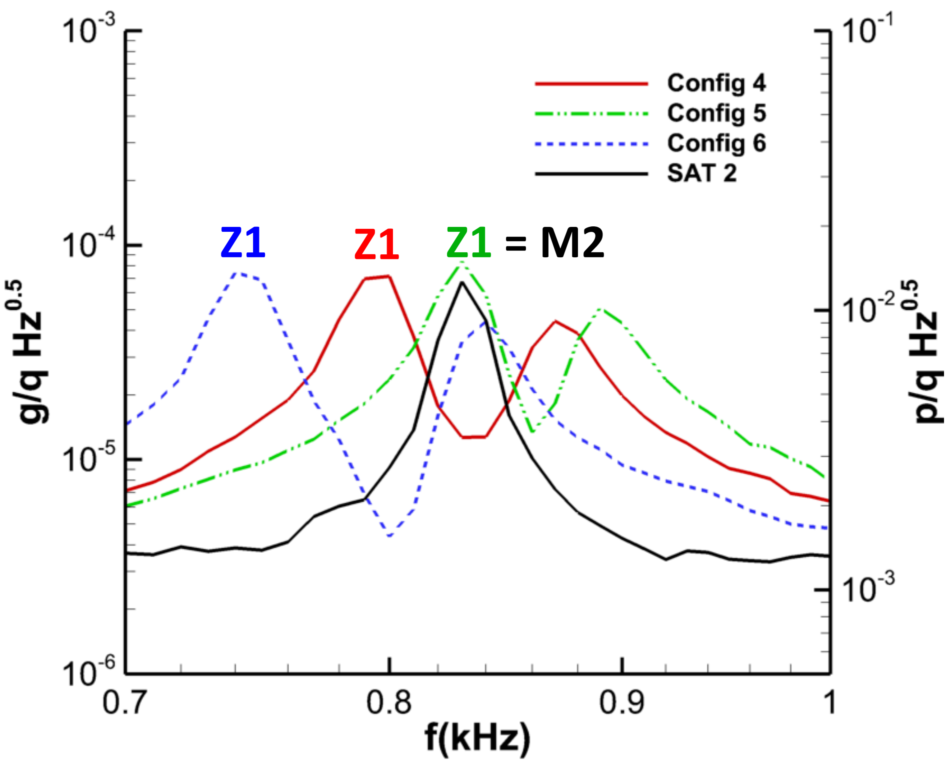
Similar observations on mode matching made in streamwise direction…

Spanwise Mode Matching

Not Mode-Matched (M = 0.94)



Mode-Matched (M = 0.79)



- When M2 = Z2, the amplitude of Z2 remains unchanged.
- *Energy transfer in spanwise mode-matching is much less efficient.*

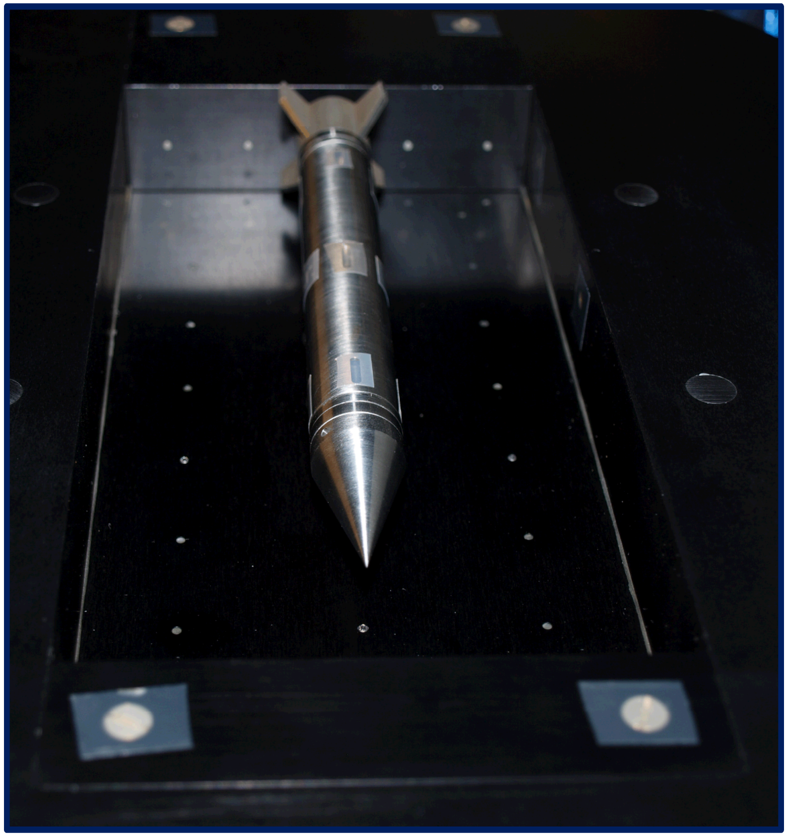
Conclusions

The complex store responds to cavity tones in the streamwise (*x*) and wall-normal (*y*) directions, but not the spanwise (*z*).

- Similar to simple store response

The worst-case-scenario for vibrations occurs when a strong cavity tone matches an *x* or *y* natural frequency of the store.

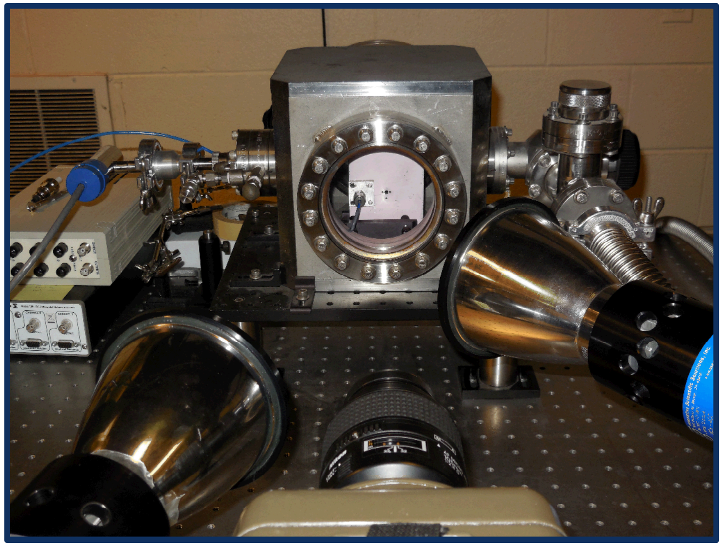
- During mode-matching vibrations increase 5 fold.
- When frequencies within 1 – 3% of mode-matching, store response remains elevated by 50 – 100%.

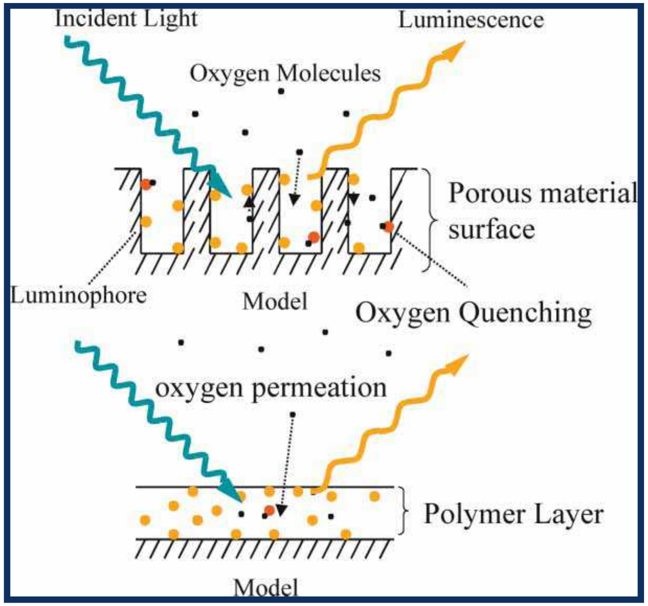


What's Next?

Advanced diagnostics are being implemented.

- High-frequency PSP is being implemented to spatially and temporally resolve loading fields in the cavity.
- Uses porous ceramic binder to increase frequency response of paint.
  - PSP works through oxygen quenching.
  - Increasing surface area for this interaction increases frequency response.





From Gregory (2008)

What’s Next?

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Time Resolved-PIV:

- Obtain PIV movies to provides temporally correlated velocity fields.
- Challenge:
  - TR-PIV has been restricted to ≤ 16 kHz and a few mJ.
  - Inadequate for a high-speed wind tunnel.

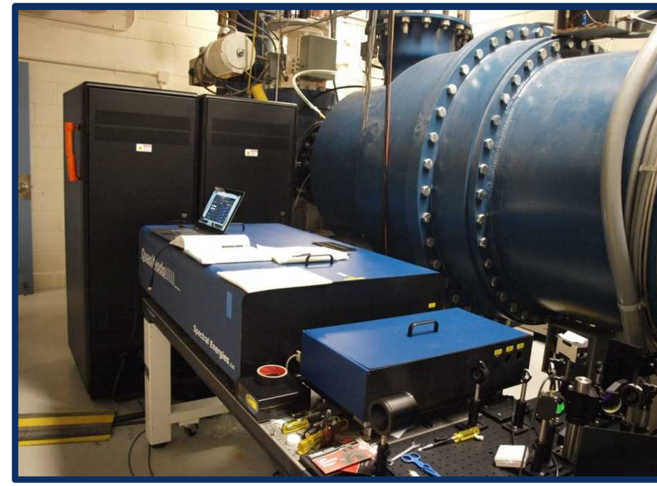
Pulse-Burst Laser:

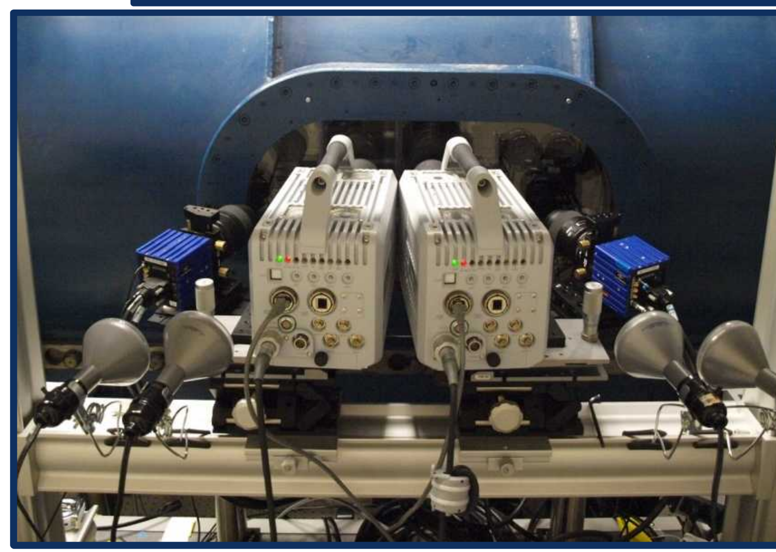
- Manufactured by Spectral Energies, LLC.
- Bursts of pulses for 10.2 ms.
- Up to 500 kHz of pulse pairs, 20-500 mJ.
- But only one burst every 8 sec.

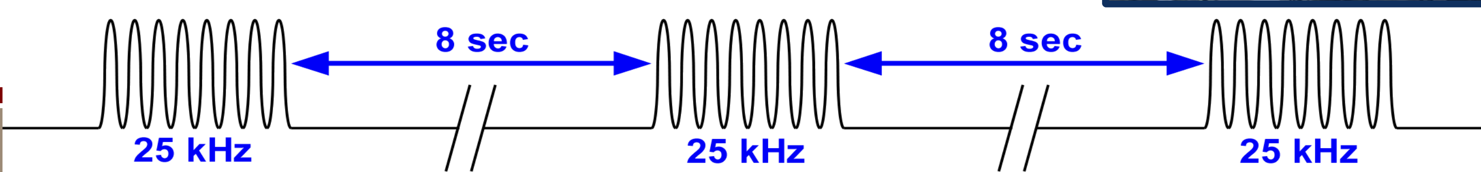
High-Speed Cameras:

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

This is the first application of pulse-burst PIV in a ground-test facility.







What's Next?

A sample TR pulse-burst PIV movie

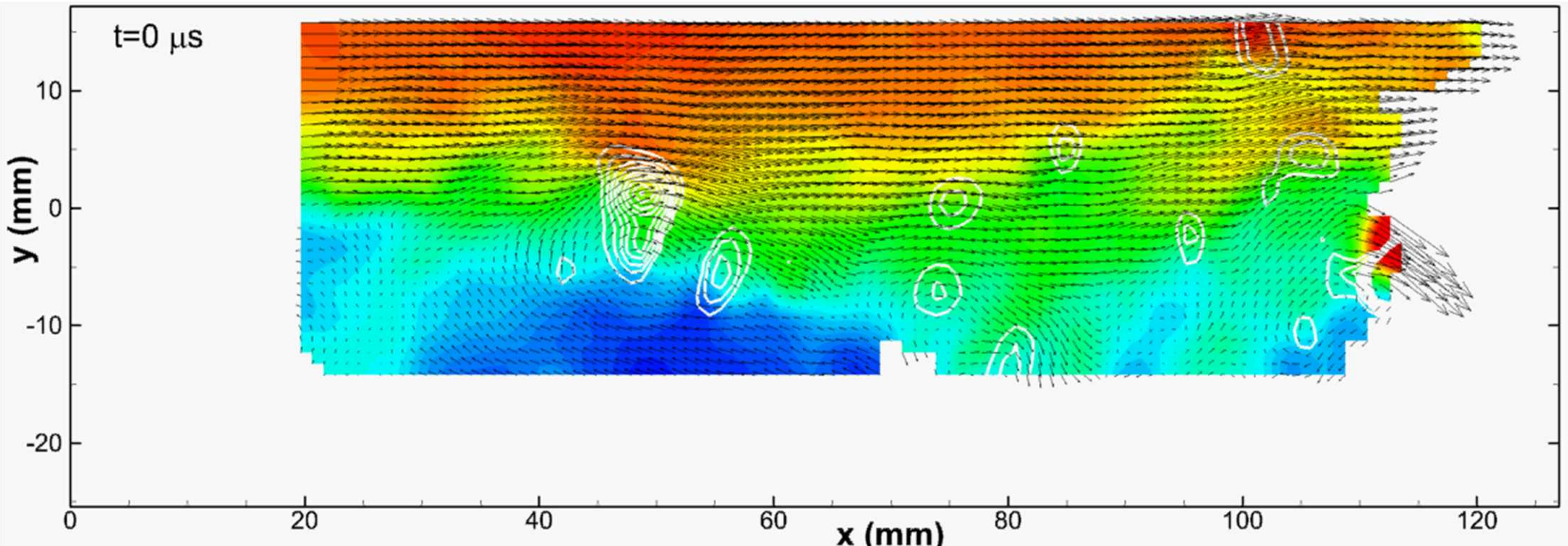
- This is a 10.2 ms movie with 256 vector fields acquired at 25 kHz.

We can visualize:

- Recirculation region shifting position.
- Ejection and impingement events at aft end of cavity.
- Recirculation events enhancing shear layer flapping.
- Growth of shear layer structures and their recirculation TR-PIV.

Such PIV measurements will be made with simultaneous pressure measurements

- Flow structures will be correlated to cavity fluctuations and compared with ongoing computations.



Bring all of these capabilities together

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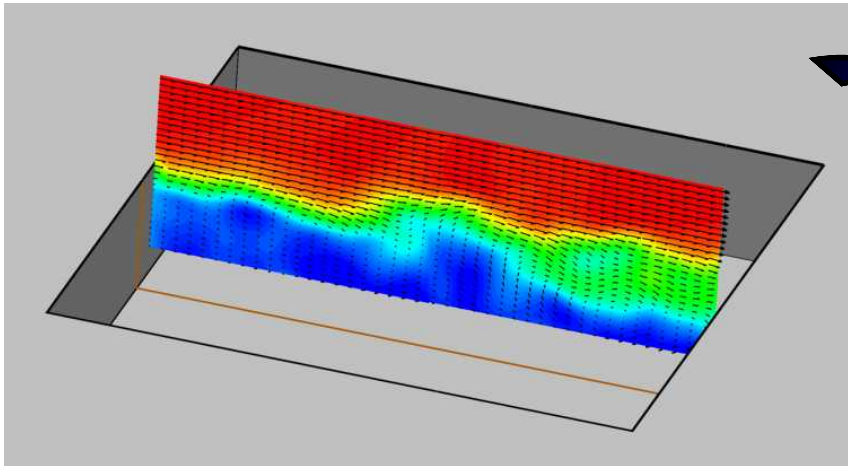
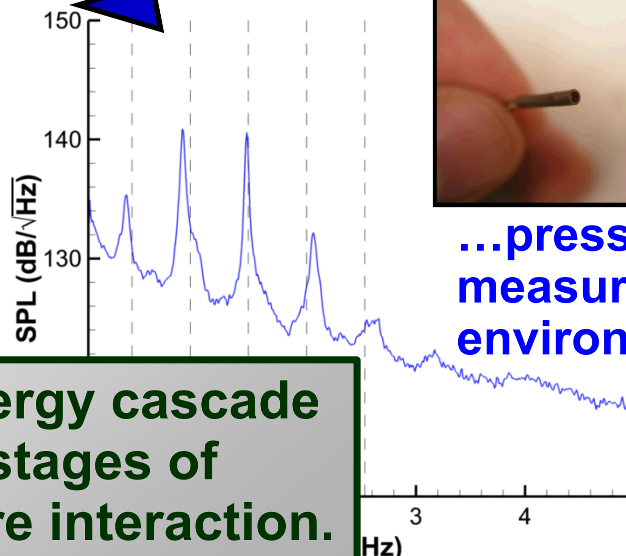
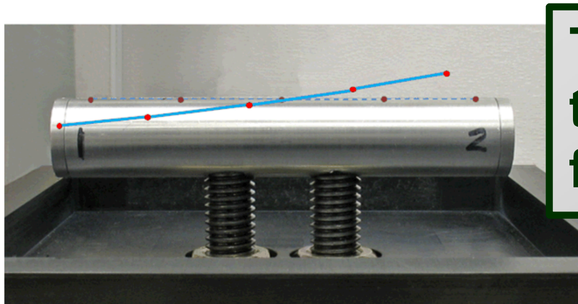


Pulse-burst PIV measures the flow structure…

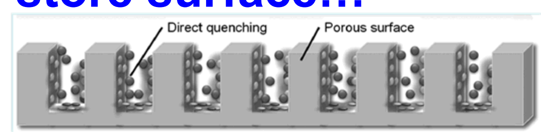


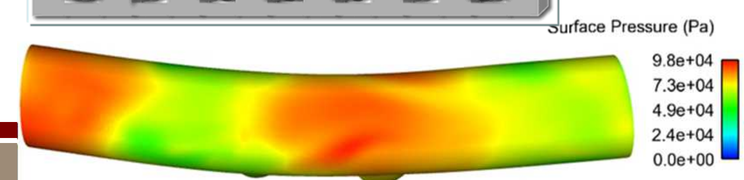
…pressure sensors measure the acoustic environment…

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.