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Simultaneous Vibration and Acoustic Measurements of a Store in Compressible Open Cavity Flow

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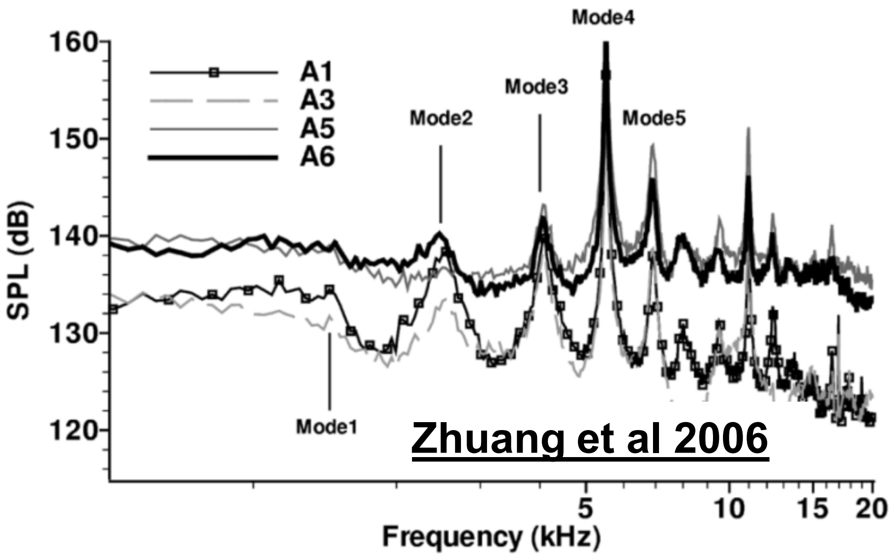
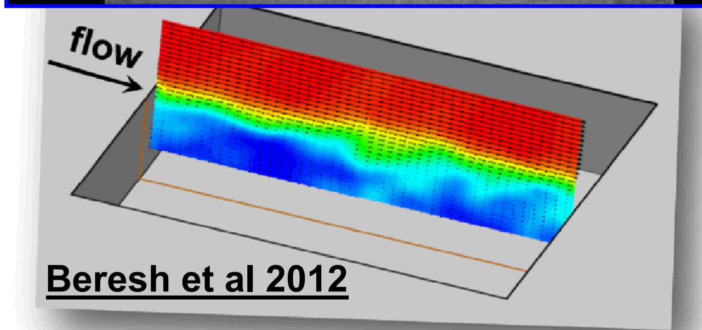
Background: Cavity Flows





Cavity Flows

- Have been an active research area for ≈ 60 years…
- Resonance occurs through the interaction of the shear layer and the cavity acoustic field.
- The cavity frequencies can be predicted by the modified Rossiter relation of Heller and Bliss (1975)

Cavity Mode Shapes

- Over a half century of research has shown that mode shapes are a complex function of cavity geometry and flow conditions.
- ***Pressure measurements remain a reliable way to characterize the acoustic loading in the cavity.***

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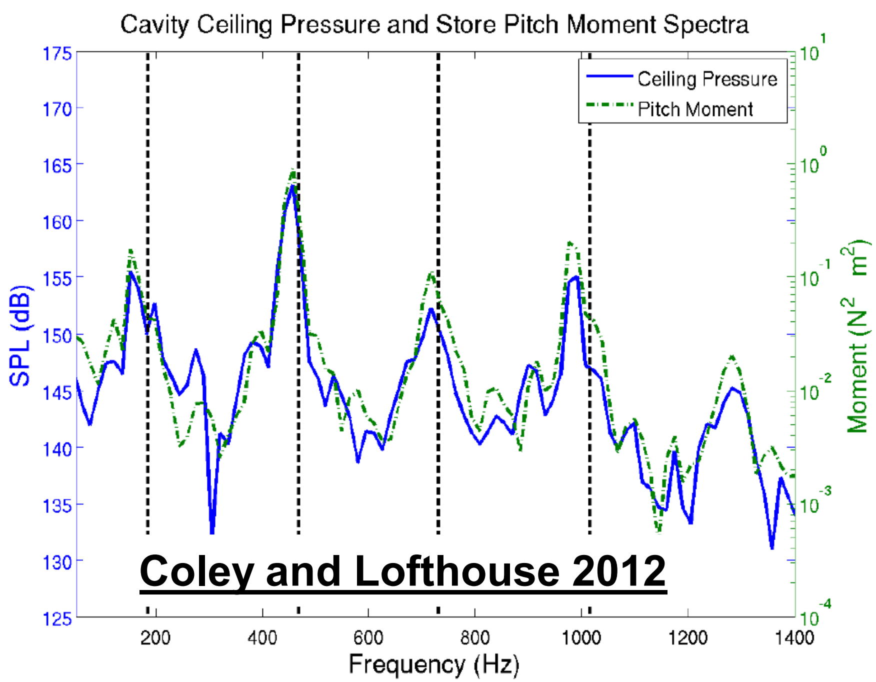
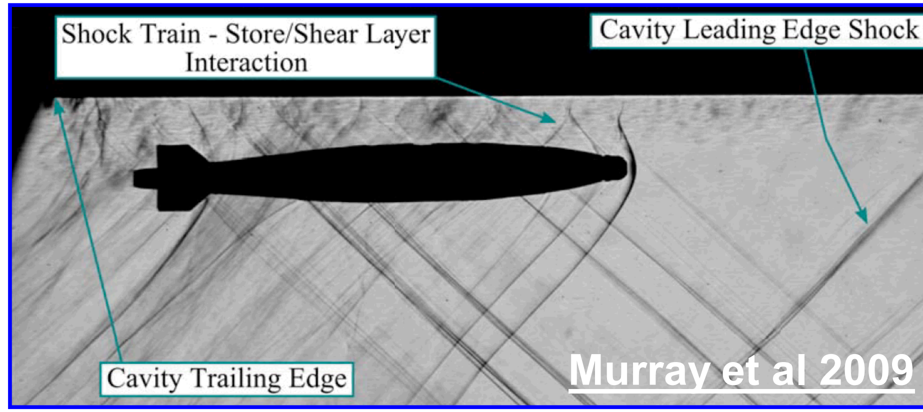
Background: Cavity-Store Interactions

Store Separation

- The type (i.e., open, closed) of cavity flow affects store separation behavior (Stallings 1987, 1991).
- Store's trajectory is a function of release time (Murray et al 2009).
- Store forces / moments correlate strongly with cavity pressures (Coley and Lofthouse 2012).

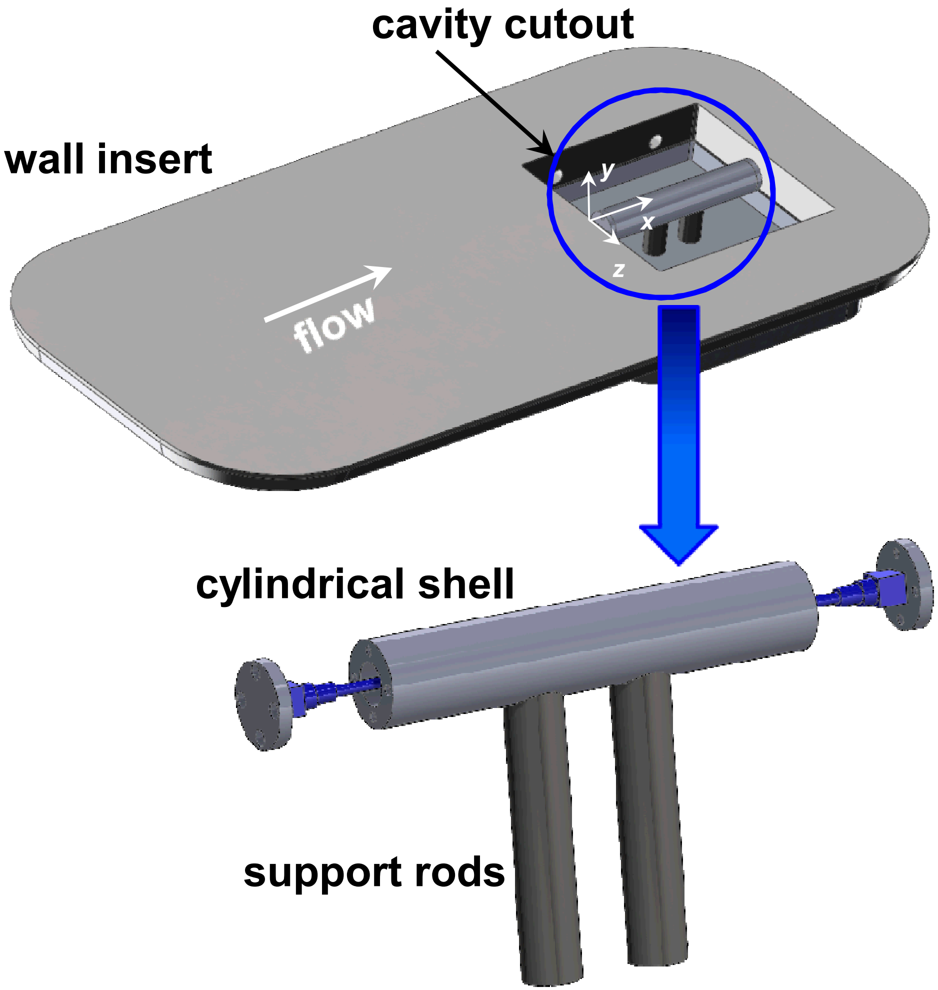




Fluid-Structure Coupling

- Cavity pressure fluctuations can result in significant structural damage (Shaw and Shimovetz 1994).
- ***Despite the potential consequences, little work has focused on the fluid-structure coupling mechanism responsible for store vibrations during internal carriage.***
- ***Simultaneous acoustic loading and store vibration measurements are required.***

Store and Cavity Geometries



Trisonic Wind Tunnel

- Blowdown-to-atmosphere
- Test section: 305 mm x 305 mm
- Unless specified data for M_∞ = 0.80, Re = 13 × 10^6/m, q_∞ = 33 kPa

Cavity

- *D* = 38 mm (≈ 0.4 δ)
- *L* / *D* = 3.33, *L* / *W* = 1
- Pressures along floor and aft-wall with nine Kulites (XCQ-062)

Simplified Store

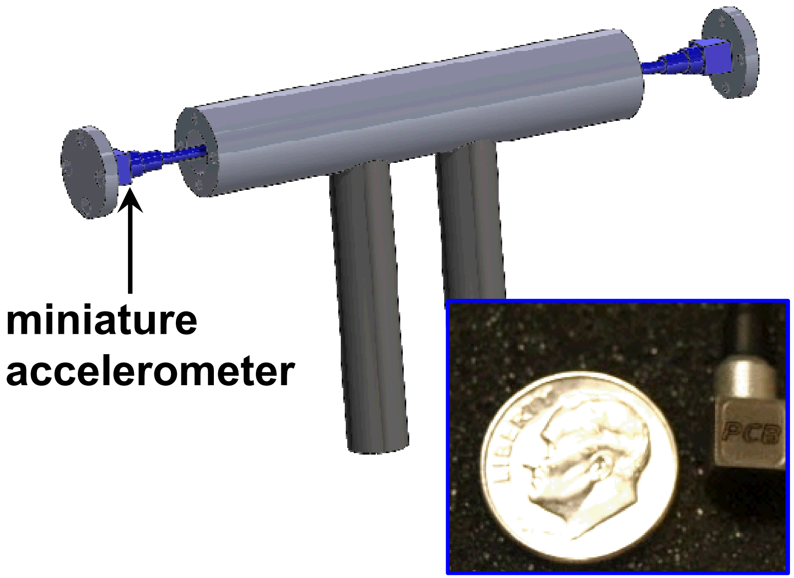
- Cylindrical geometry (0.5 *D* × 4.5 *D*)
- Fixed to 12.7 mm threaded rods
- Rods fixed to floor with hex nuts

Two main objectives for this simplified geometry:

1) **Development of vibrational diagnostics including miniature accelerometers and laser Doppler Vibrometry (LDV)**
2) **Discovery of the key physical parameters for future experiments**

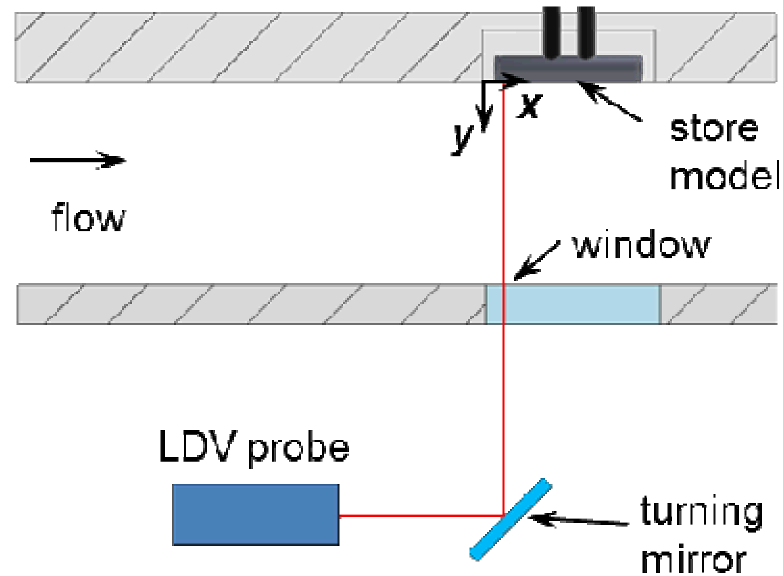
Vibration Measurement Systems

Triaxial Accelerometers



- Internal accelerometers (PCB 356A03) form one of two independent vibration measurement systems.
- Frequency response of 8 kHz
- ***Upstream and downstream accelerations are compared along all three axes.***

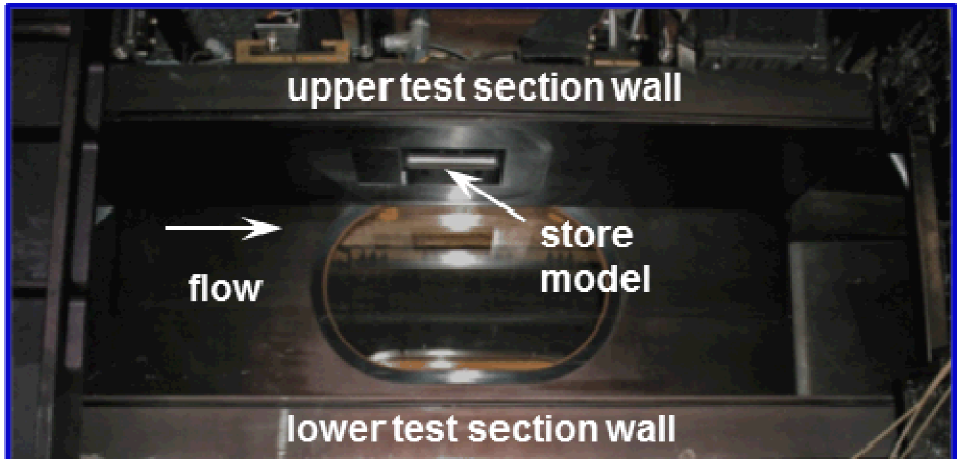
Laser Doppler Vibrometry (LDV)



- Polytec (PSV 400) **single-component, scanning** LDV system
- The system measures the surface velocity of the target from the Doppler shift produced by the interference between a reference beam and surface-scattered-light.
- Frequency response ≈ 100 kHz

Objectives of Simultaneous Measurements

Cavity / Store in Test Section



- ***Longitudinal cavity modes provide the highest potential loading to drive store vibrations*** whose natural frequencies are a function of its geometry.
- If a cavity mode matches a natural longitudinal frequency of the store, we expect that intense vibrations will occur.

What do we hope to learn from the simultaneous diagnostics

Some open questions include:

1. **Ability of the cavity flow to excite additional structural modes such as vertical and lateral modes?**
2. **The response of the store to spatially non-uniform loading?**

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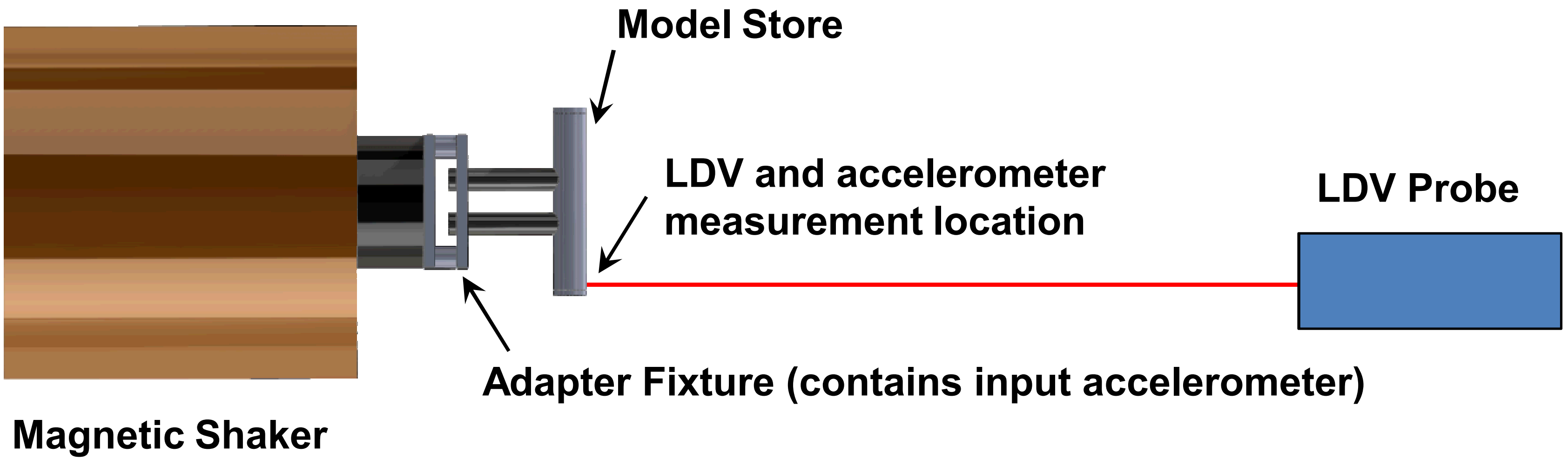
Evaluation of Vibration Measurement Systems

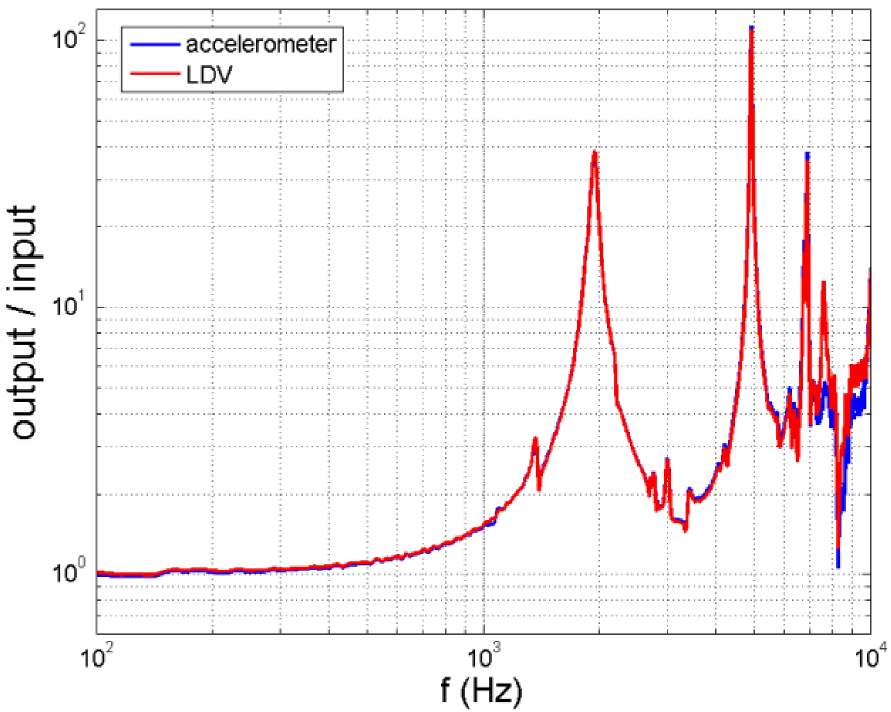


- The model store was mounted to a magnetic shaker with an adapter fixture.
- The shaker generated a 0-7 kHz, pseudorandom motion along the *y*-axis only.
- Although the store is subjected to much more complicated motions under cavity flows, the shaker tests provide a good method for comparison of the two independent vibration systems.

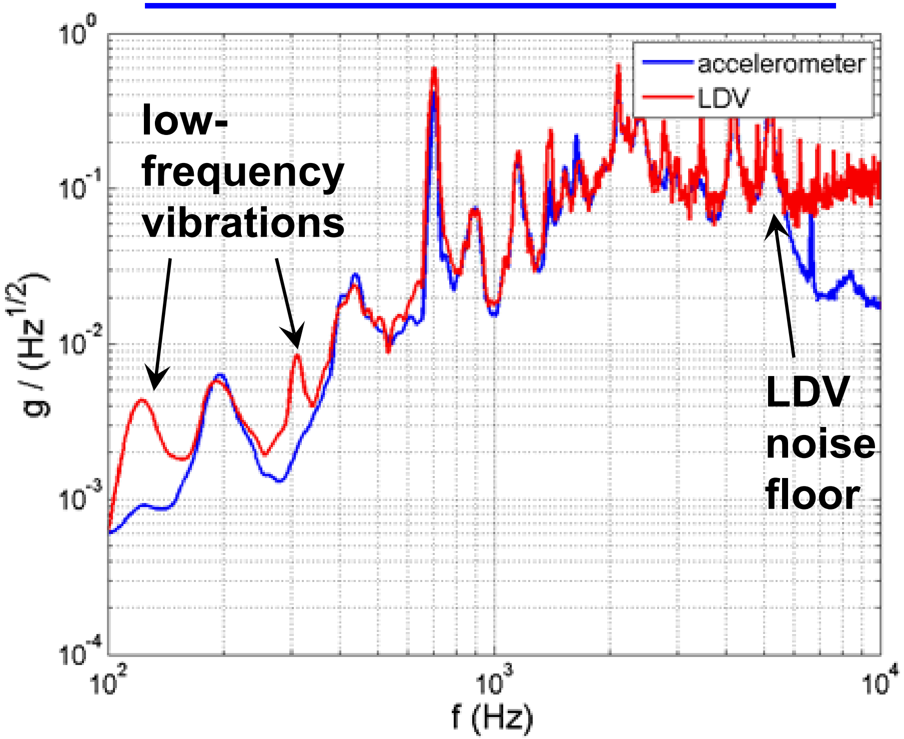
Evaluation of Vibration Measurement Systems

Comparison of vertical accelerations given by the accelerometer and the LDV

Shaker Test



Wind Tunnel Test at Mach 0.83

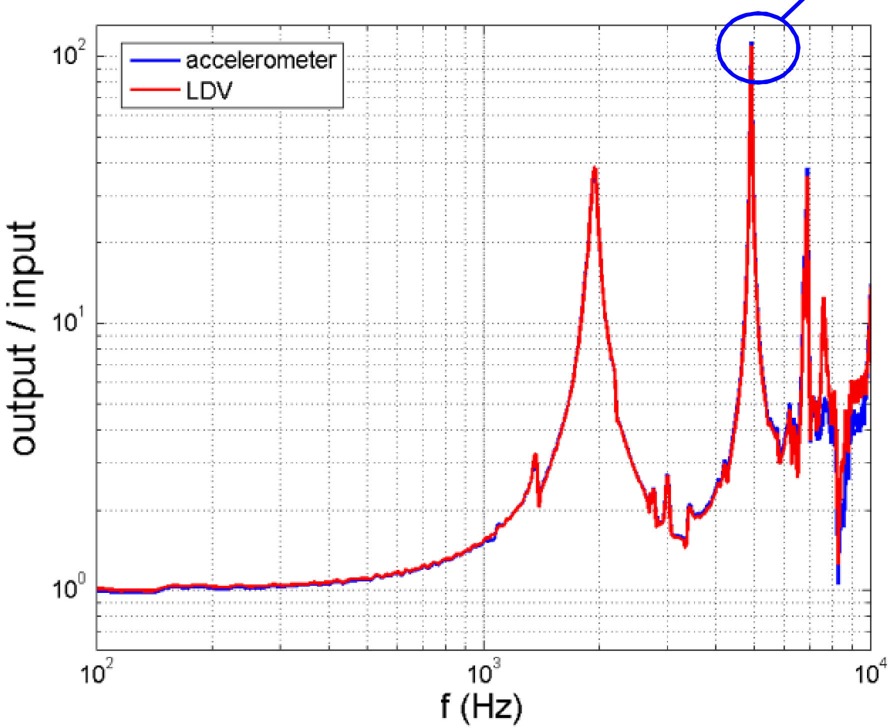


- The bench-top tests show excellent agreement between the independent measurements up to about 8 kHz, which is the frequency response of the accelerometer.

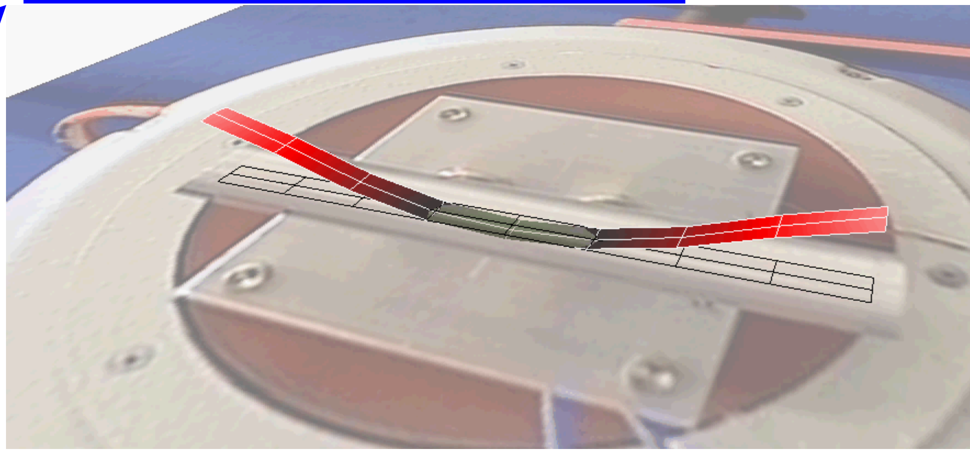
- ***The accelerometer and LDV are in good agreement from about 0.5 kHz – 5.5 kHz, a very active frequency range in cavity flows.***

High-Frequency Bending Modes

Shaker Test



4.9-kHz Bending Mode Movie



- A 27-point-scan was used to reveal the mode shapes associated with the peaks in the frequency response function.

- Shaker test is useful for measurement comparisons and illustration of natural frequencies but…
- The presence of the adapter plate and the shaker make it difficult to truly determine the true store modes.
- Look to modal hammer tests for accurate natural frequencies.

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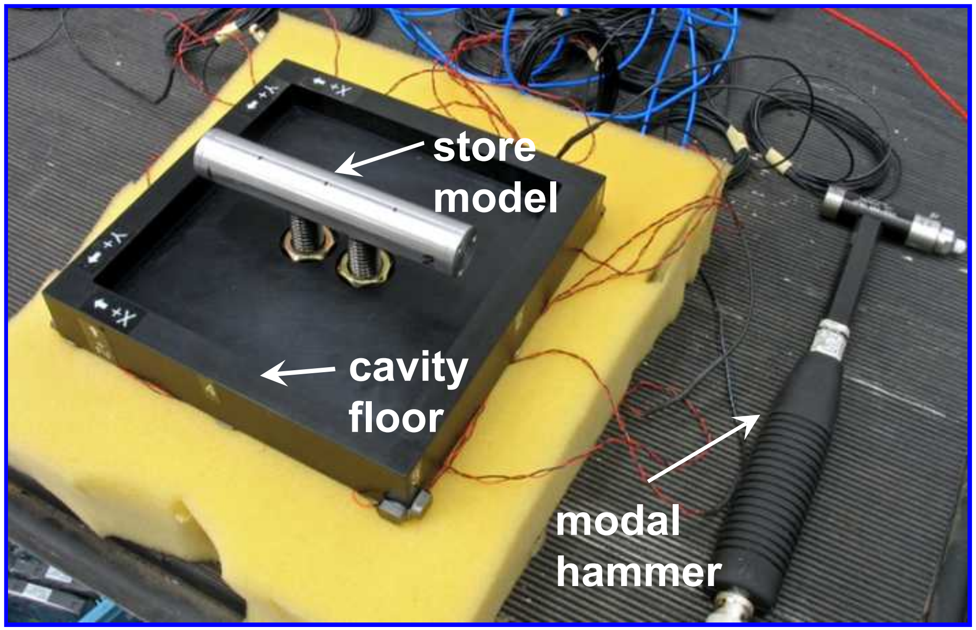
Modal Hammer Tests

- Interpretation of the vibration data requires knowledge of the store's natural frequencies.
- Modal hammer tests were performed to measure the store response up to about 10 kHz.

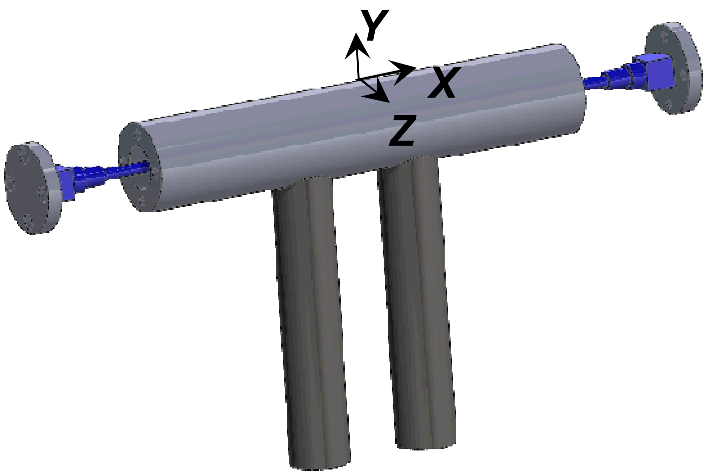
- A force transducer on the hammer tip measured the input.
- The output was measured with the two internal accelerometers.

Modal Hammer Test



- Bench top foam tests provided detailed mode information for frequencies up to 4 kHz.
- Natural frequencies greater than 4 kHz were measured with the model installed in the wind tunnel only.
- Compared to the tunnel test, the bench top test gave more mode shape information.

Modal Hammer Tests



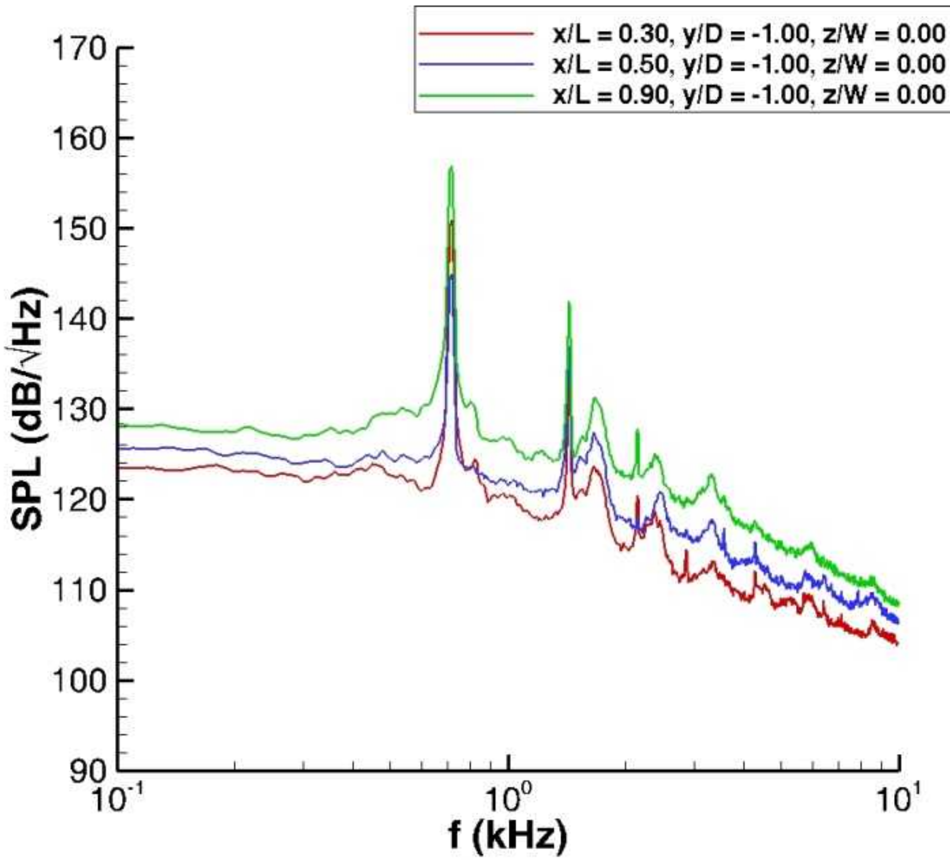
- The store response in the wind tunnel was similar to the perfectly fixed case
- **How will the store respond to the cavity flow at its wall-normal and spanwise natural frequencies?**

Structure Modes

Mode	Fixed Frequency, kHz	Fixed Damping, %	Wind Tunnel Frequency, kHz	Wind Tunnel Damping, %	Mode Description
Z1	1.49	0.38	1.52	1.46	z-post-bending
Z2	1.62	0.20	1.64	0.40	z-post-twisting
X1	2.10	0.20	not detected	not detected	x-post-bending
Y2	not measured (N/M)	N/M	4.24	2.44	y-store-bending
Y3	N/M	N/M	5.16	1.27	z-store bending
Z3	N/M	N/M	6.64	0.32	y-store-bending

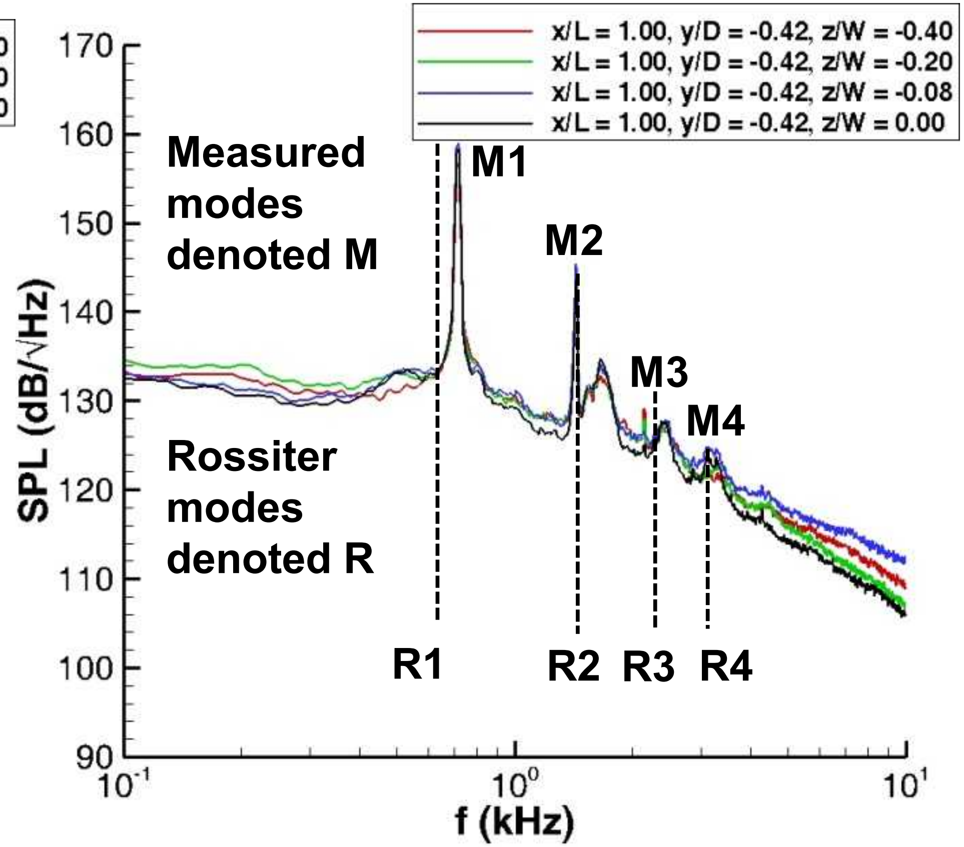
Empty Cavity Pressures (Mach 0.80)

Floor Pressures: Streamwise Variation



- Pressures at aft-end of the cavity are 2-4 times greater than at the fore-end.

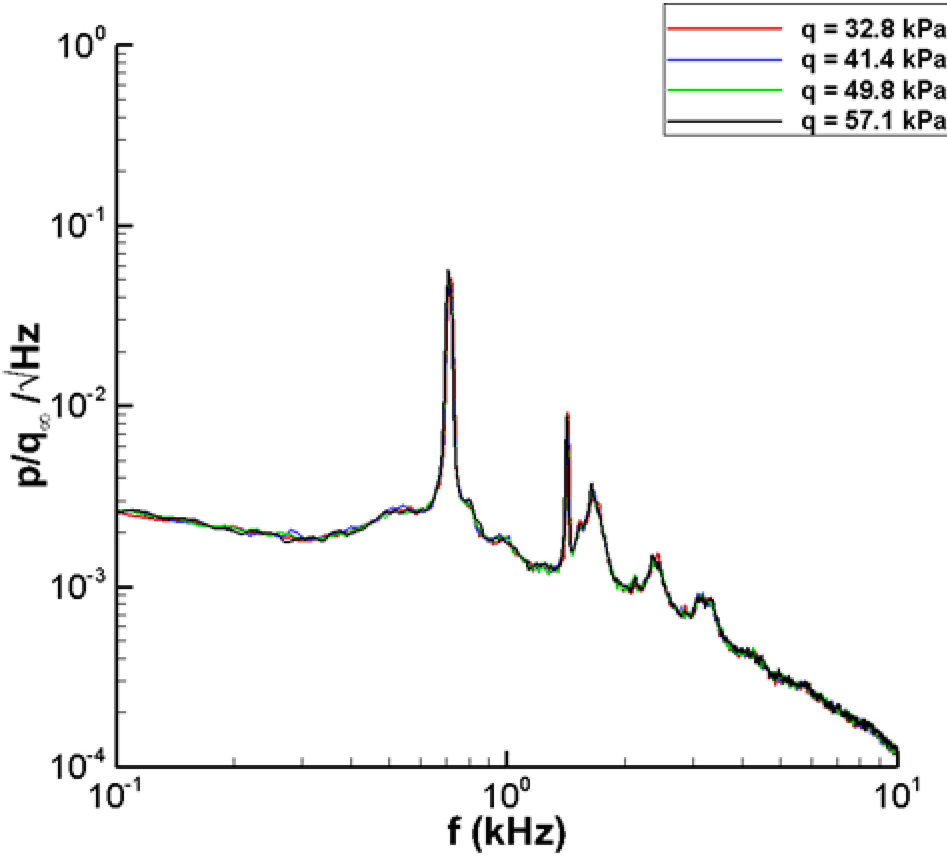
Aft-Wall Pressures: Spanwise Variation



- Little variation with span.
- Measured mode frequencies are within 15% of those predicted by Heller and Bliss (1975).

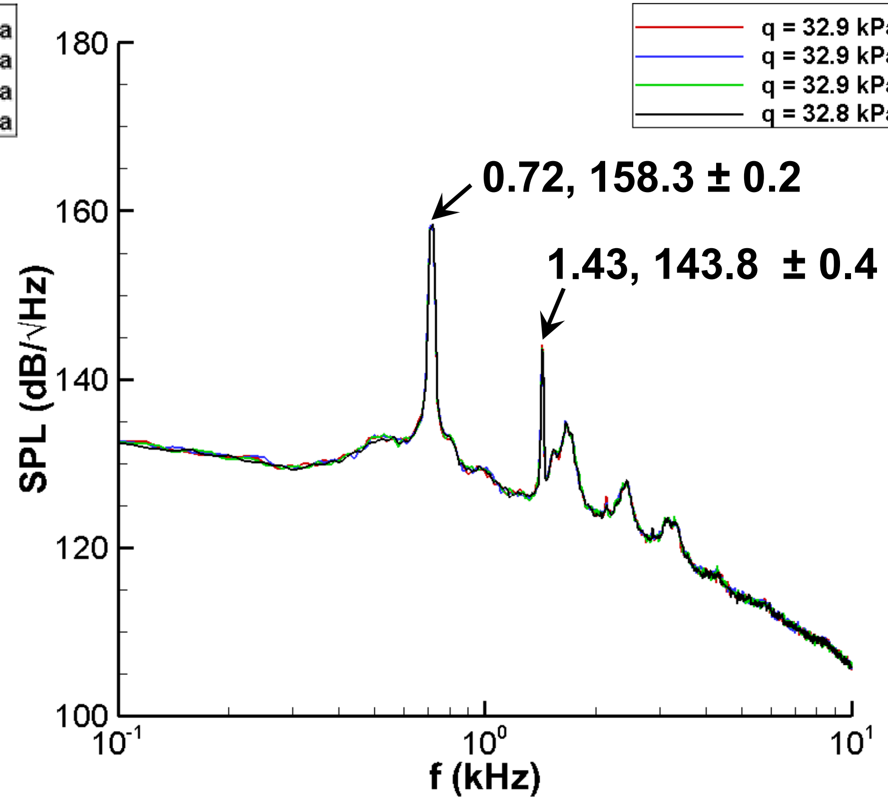
Empty Cavity Scaling and Repeatability

Scaling with Dynamic Pressure



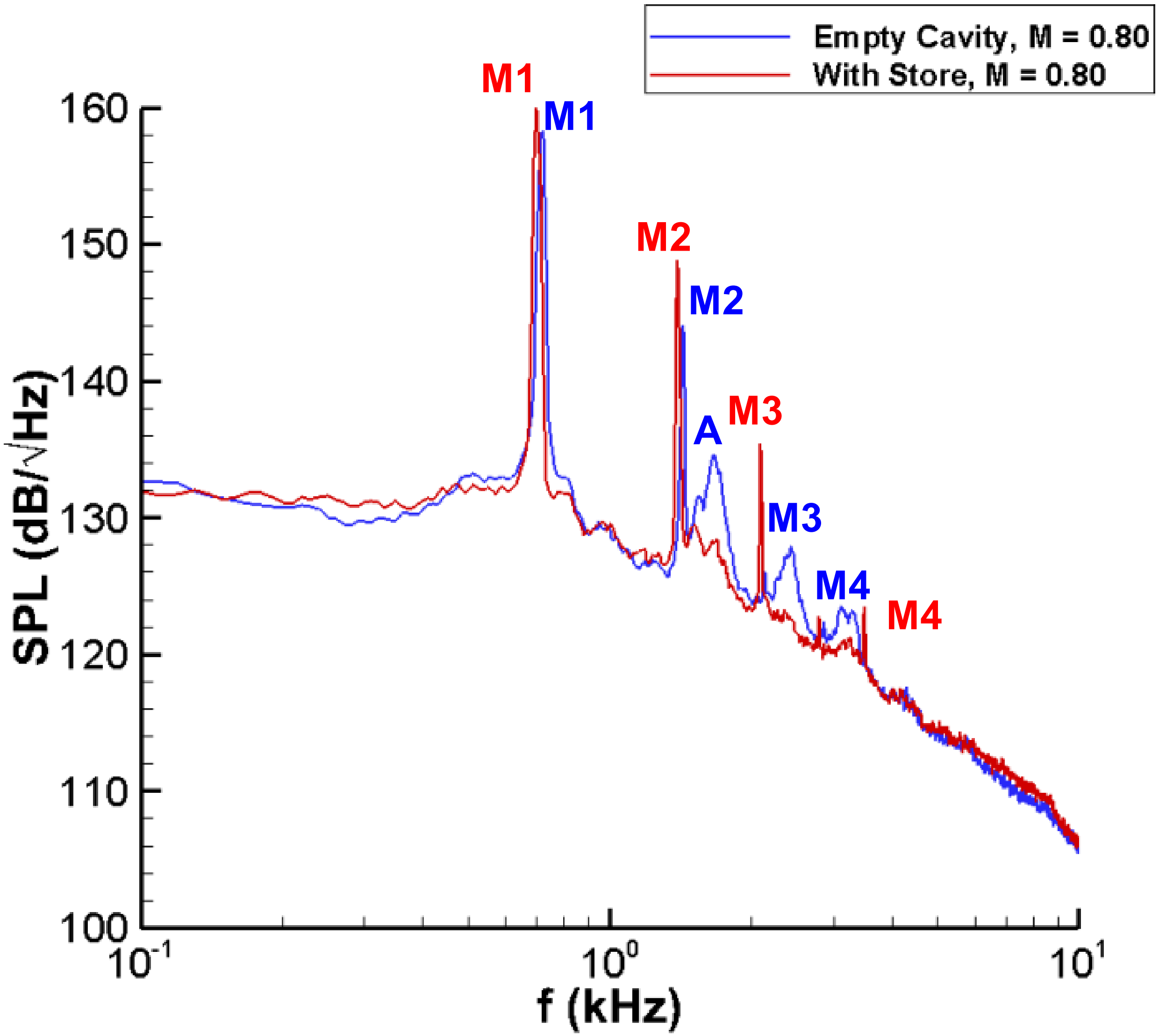
- Pressures scale with q_{∞}, a result expected from previous works (e.g., Tracy and Plentovich 1993, Murray et al 2009)

Repeatability



- The pressure spectra were very repeatable.
- *Empty cavity flow well characterized.*
- ***What about with a store?***

Pressures with a Model Store



- Previous studies (e.g. Dix and Bauer 2000, Lee 2010) have shown modified cavity acoustics with a store installed.

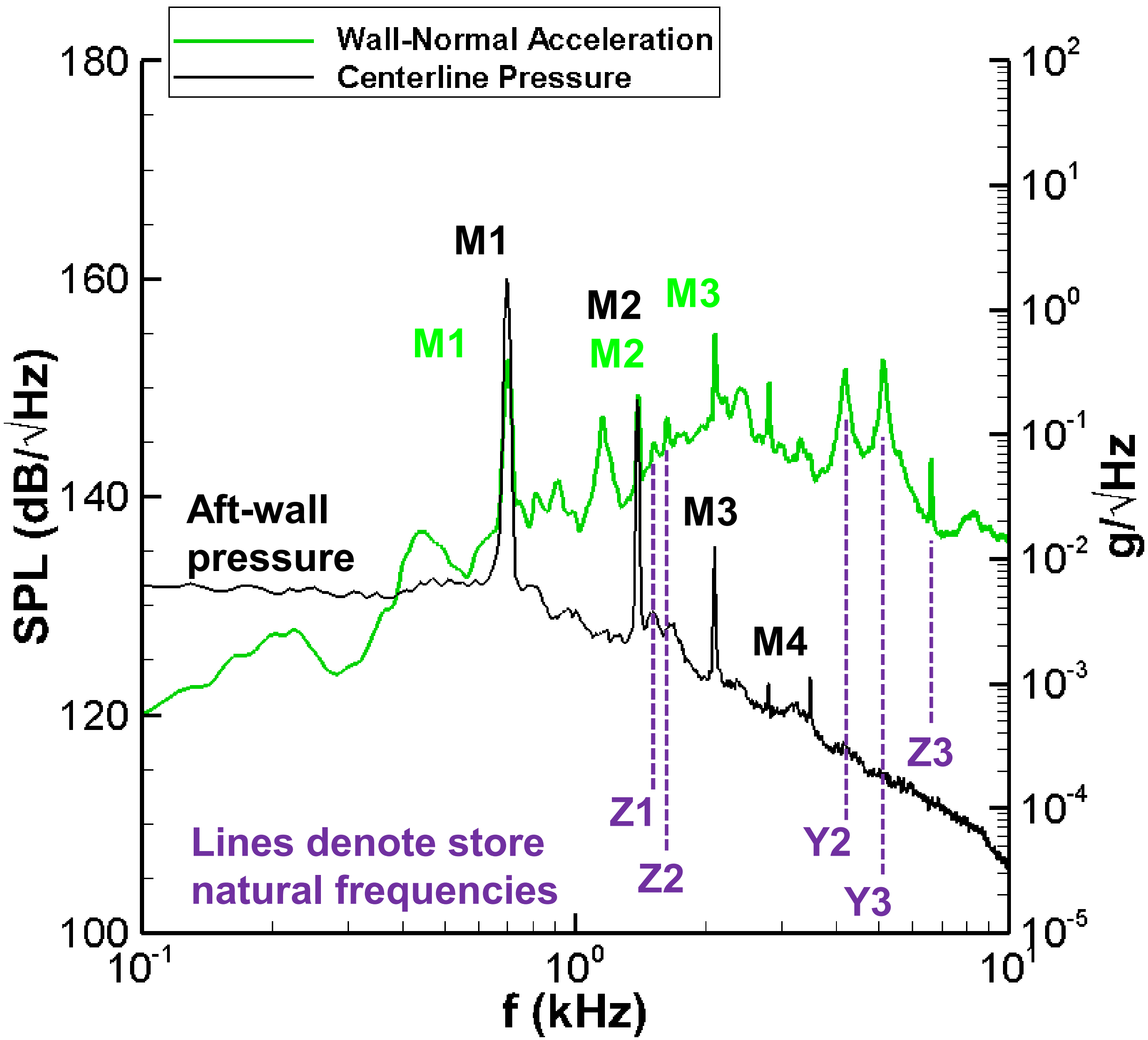
Observations

- The model store results in significant changes in the cavity acoustics.
- The second, third and fourth modes are all sharpened with shifted frequencies.
- Ongoing work looking at other Mach #s

- ***How does the store respond to these cavity pressures?***

Simultaneous Measurements

Wall-Normal Response of Upstream Accelerometer



- Clear peaks in the wall-normal accelerations exist at the store's high-frequency modes Y2 and Y3.

- The store responds to the first three cavity modes M1-M3.

- ***Greatest response at cavity mode M3***

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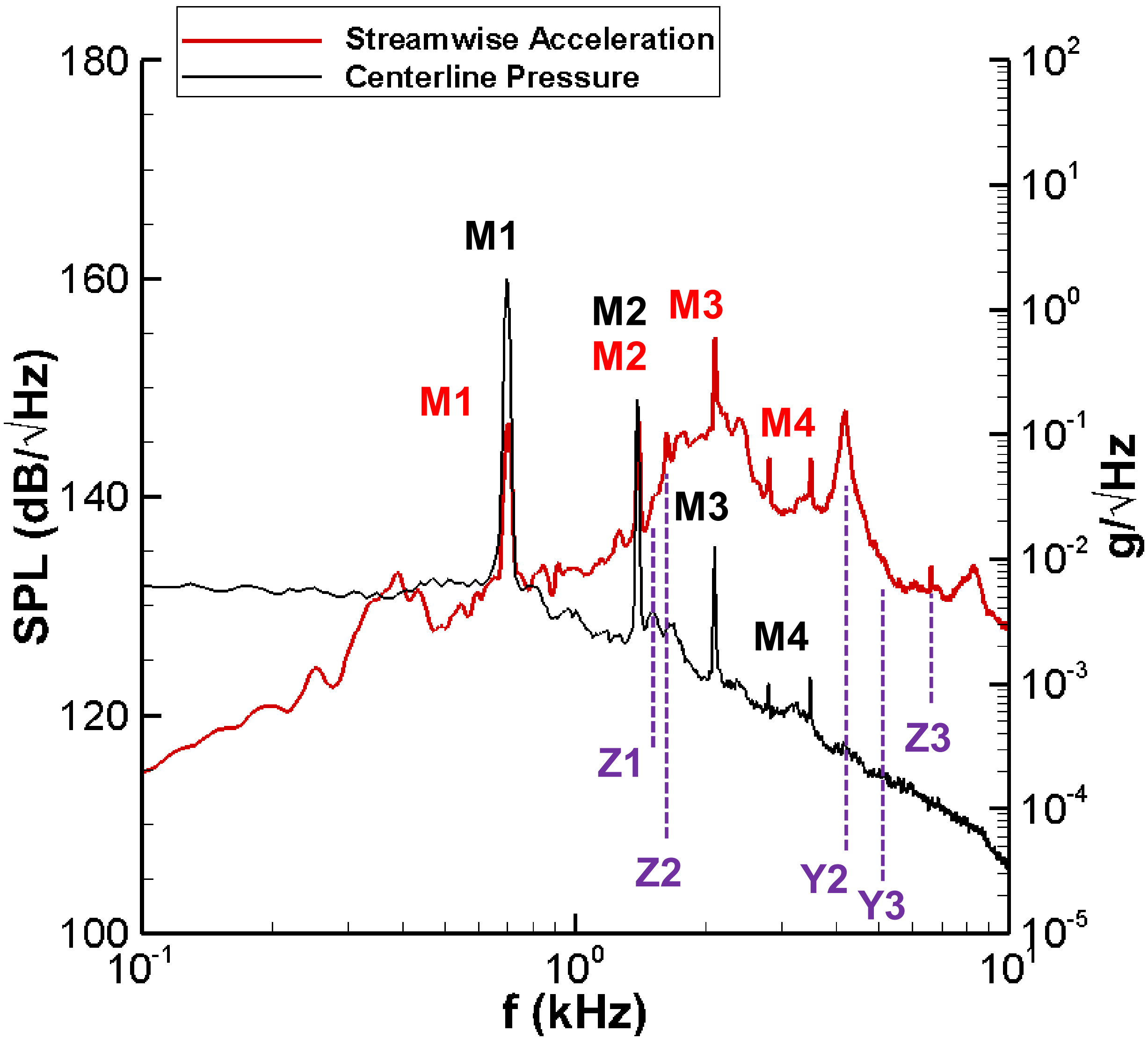
Simultaneous Measurements

Streamwise Response of Upstream Accelerometer



- Peak at wall-normal store mode Y2 is observed, which likely indicates coupling between *x*- and *y*- store modes.

- The store responds to all four cavity modes M1-M4.

- ***Largest vibration levels correspond to cavity mode M3***

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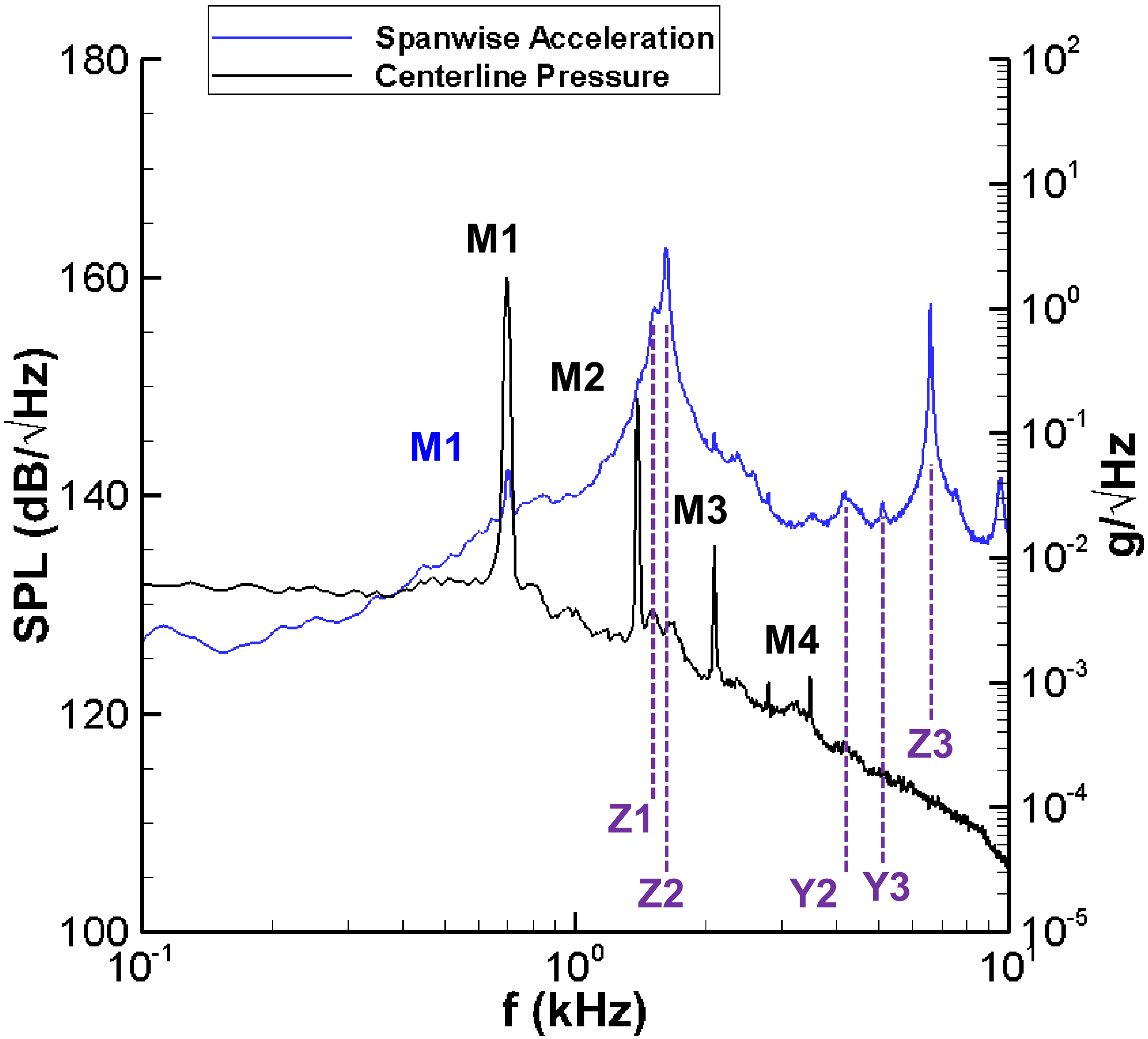
Simultaneous Measurements

Spanwise Response of Upstream Accelerometer



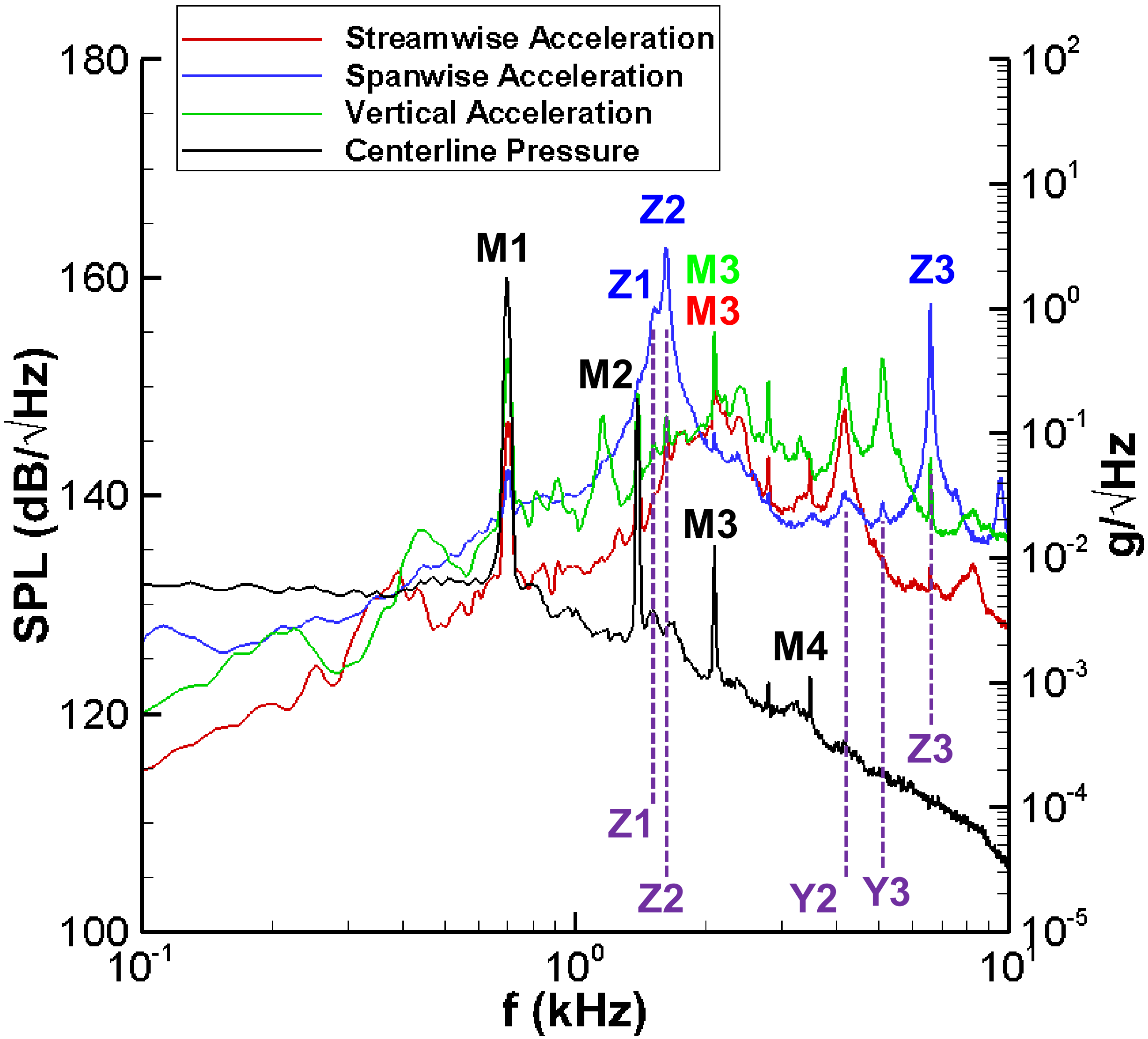
- In comparison to other axes, the spanwise spectrum is markedly different.

1. The spanwise accelerations show little response to the cavity modes.

2. ***The spectrum is dominated by the three lateral modes Z1-Z3***

Simultaneous Measurements

All Three Components with Aft-Wall Pressure



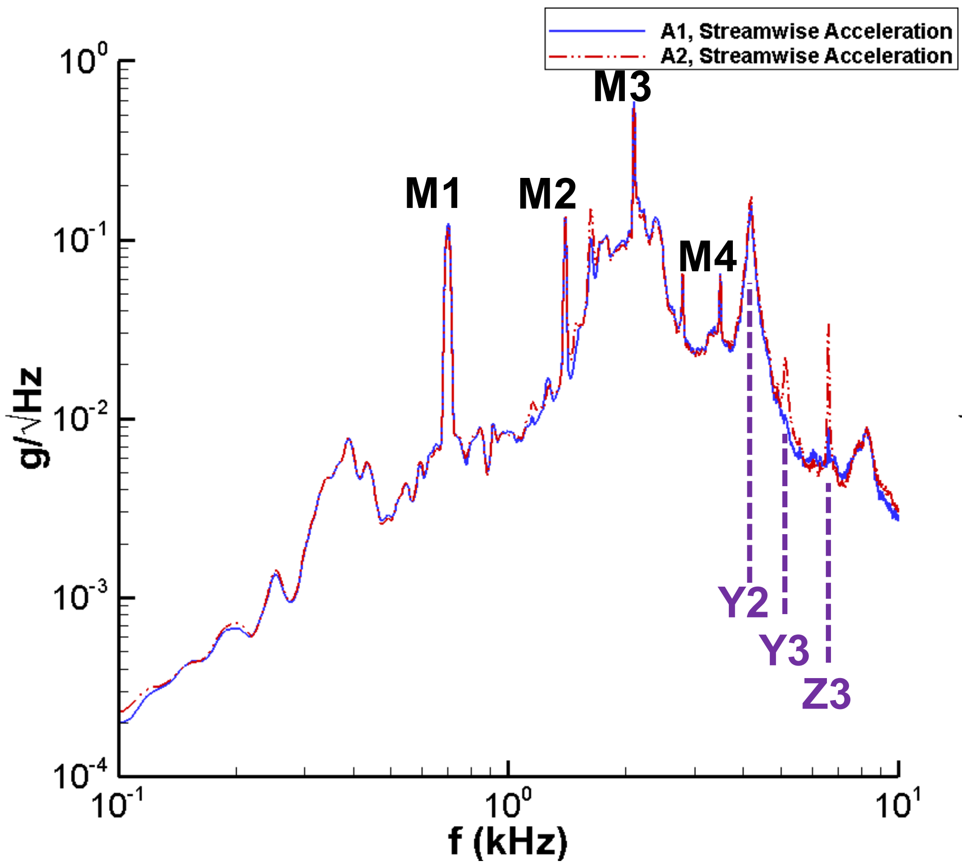
- The streamwise and wall-normal accelerations are greatest at cavity modes.

- The spanwise response is dominated by the store's structural dynamics.

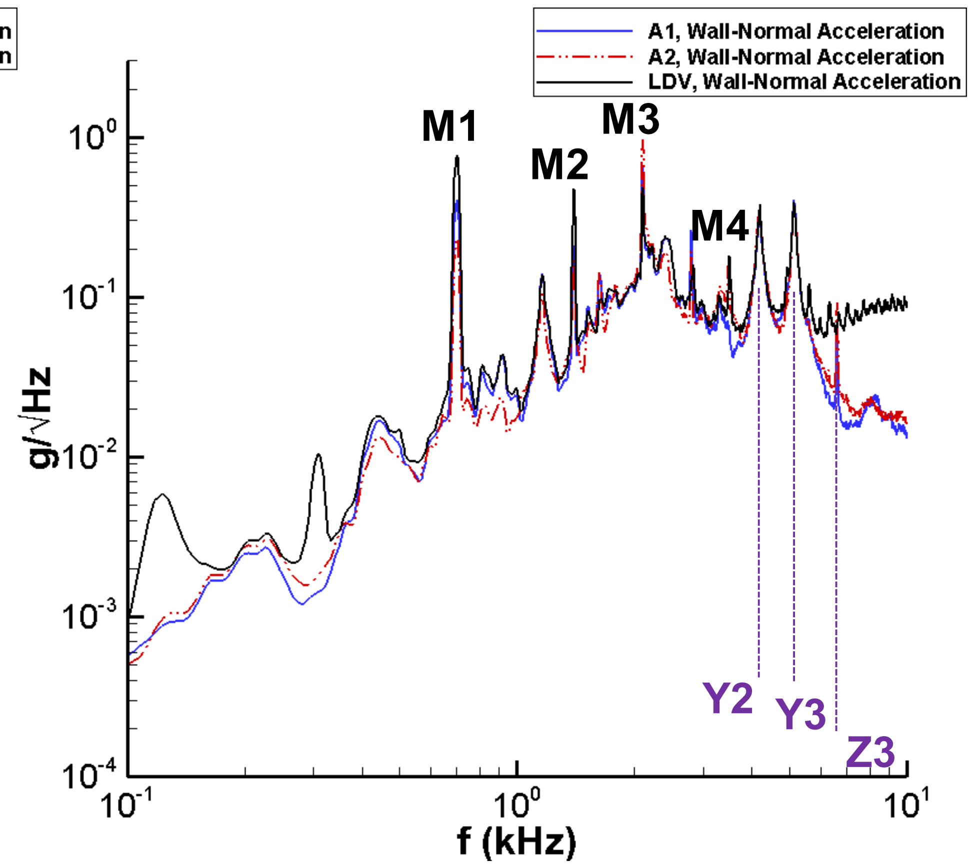
- *These data emphasize the importance of characterizing the structural modes of the store.*

Upstream and Downstream Accelerations

Streamwise Accelerations at Store-Ends



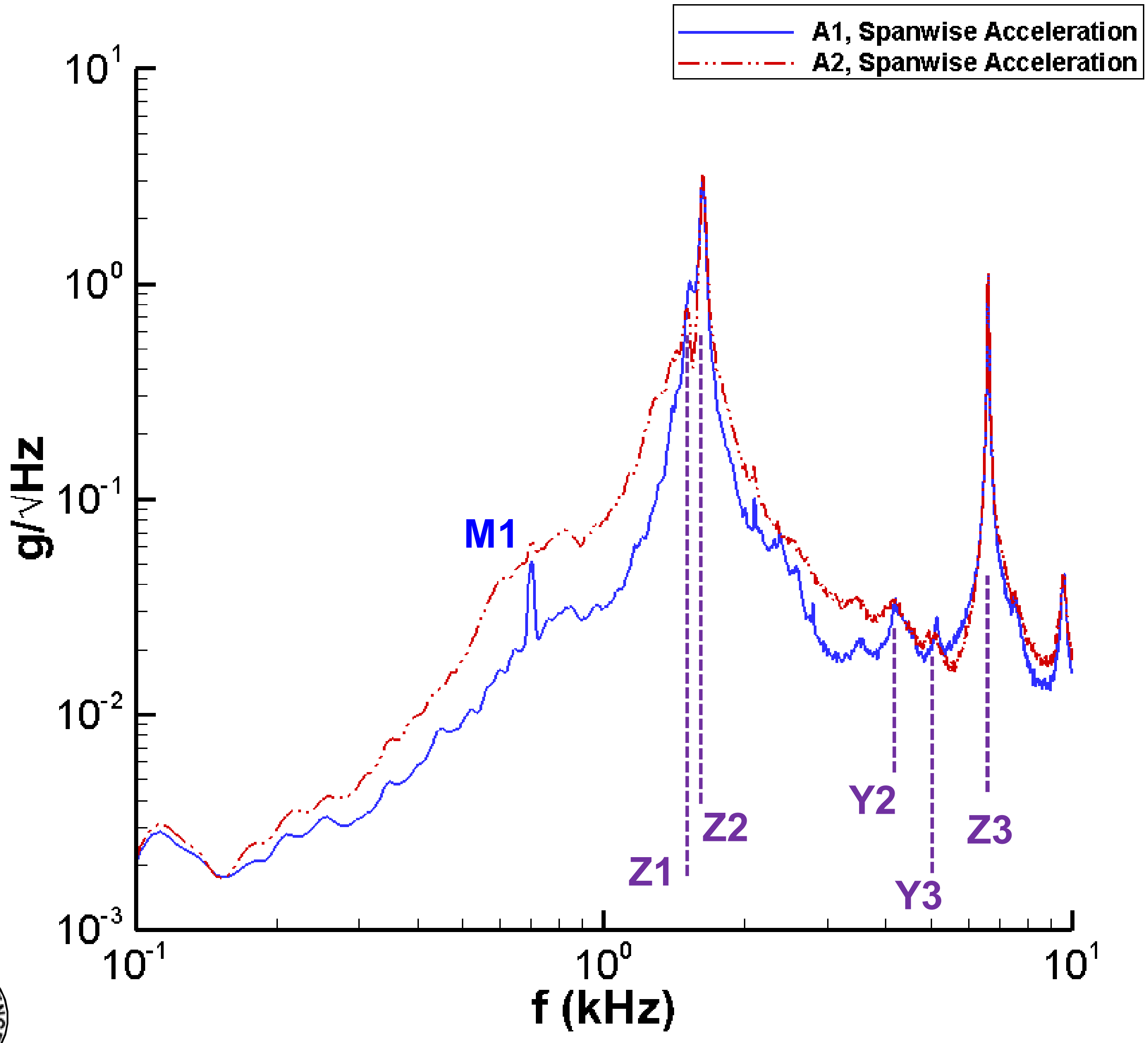
Wall-Normal Accelerations



- **The streamwise accelerations at opposite store ends are nearly identical.**
- **The wall-normal accelerations are similar at opposite ends**, but there are small differences between locations that are further confirmed with the LDV measurements (made at the location of A1).

Upstream and Downstream Accelerations

Spanwise Accelerations at Opposite Store-Ends

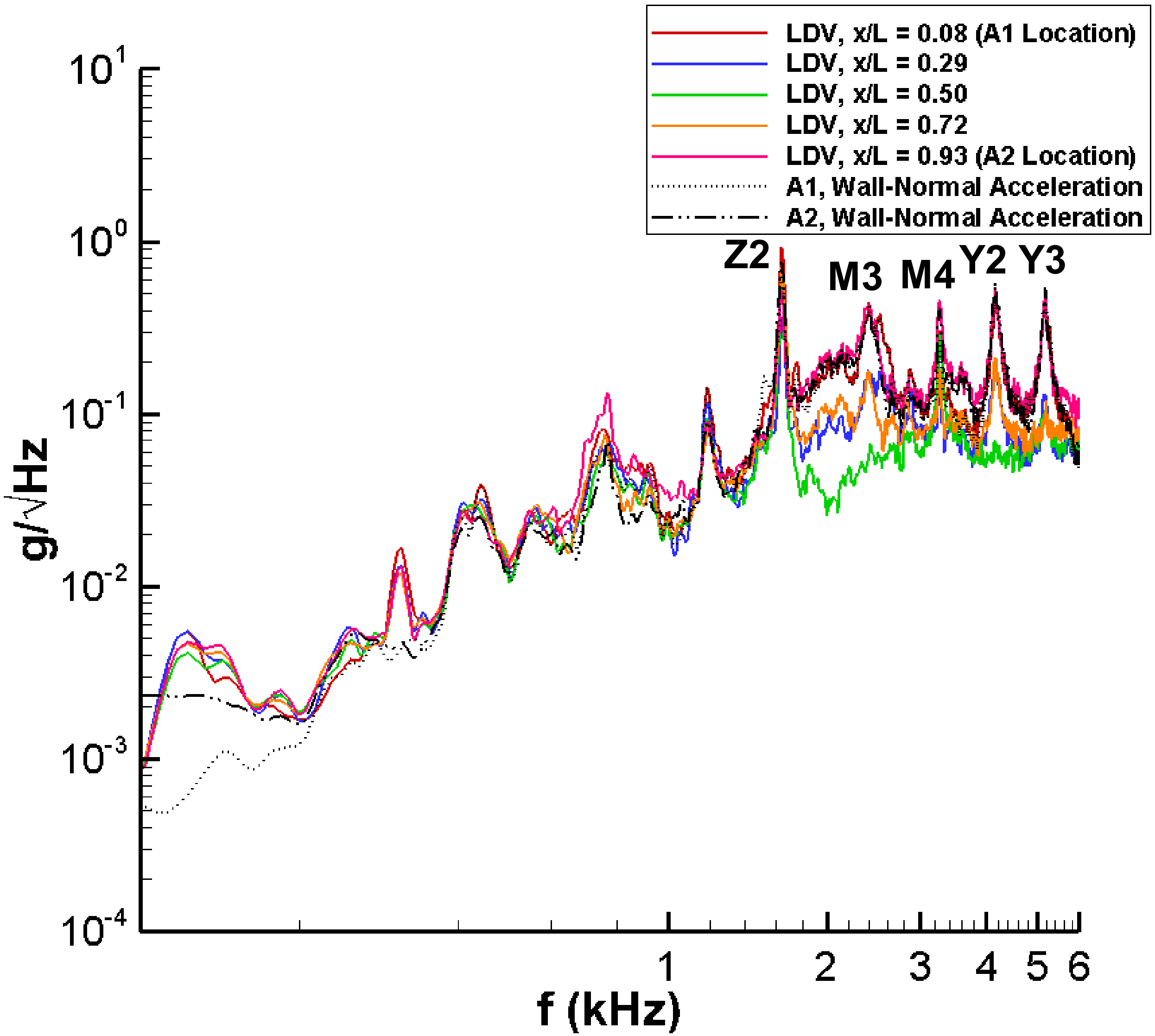


- ***Unlike the other two axes, the accelerations are greatest downstream where the pressure fluctuations are the highest.***
- ***The peak accelerations (at store-resonance) remain equal***
- ***Data show importance of triaxial measurements***

- **But what about other locations?**

Scanning LDV Data (Mach 0.90)

Wall-Normal Accelerations at Five Locations Along the Length of the Store

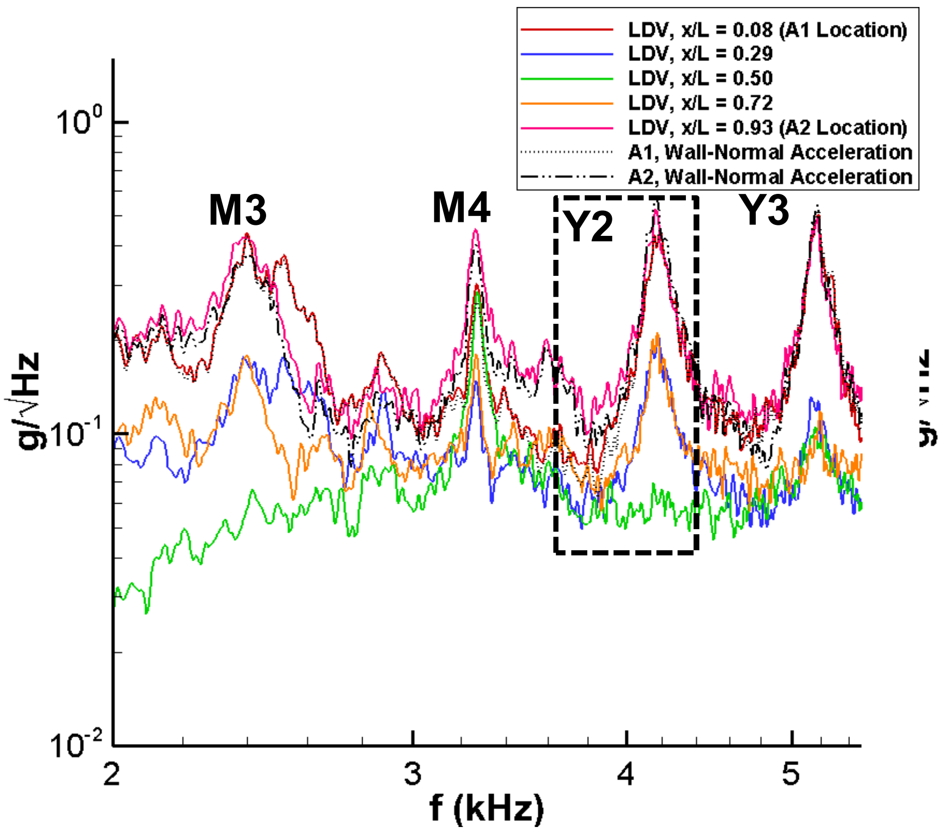


- Data shown at Mach 0.90 where most interesting trends were seen.

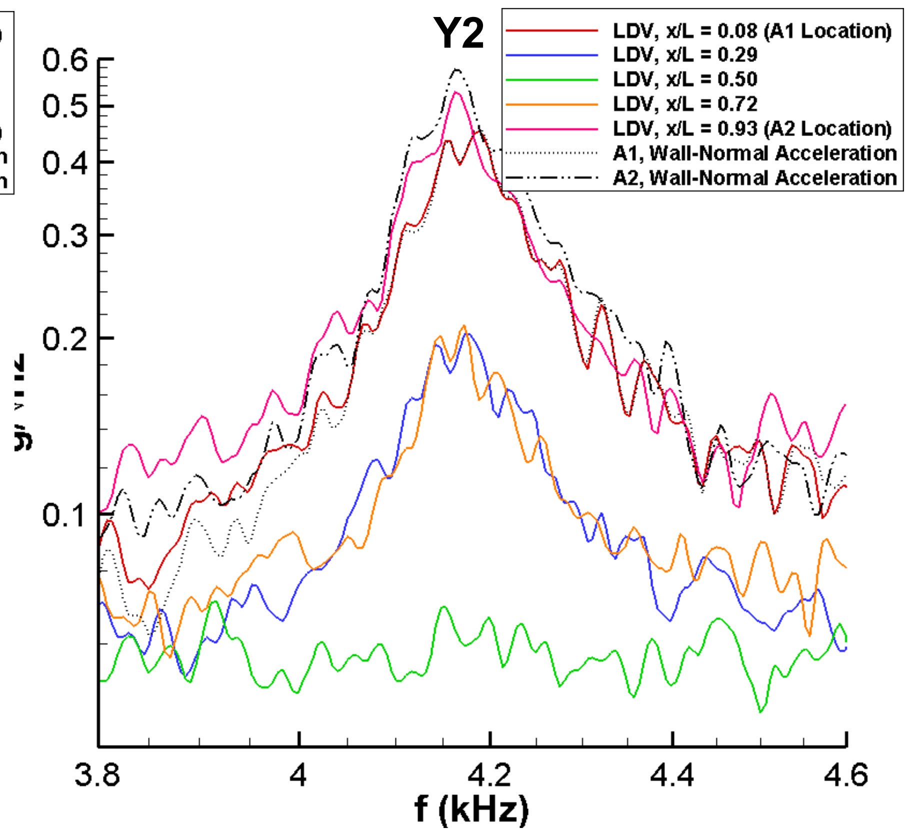
- ***The spectra at all five locations are similar up to the peak corresponding to the second spanwise mode Z2.***
- *A closer look is needed to examine behavior at the subsequent peaks.*

Scanning LDV Data (Mach 0.90)

From 2 through 5.5 kHz



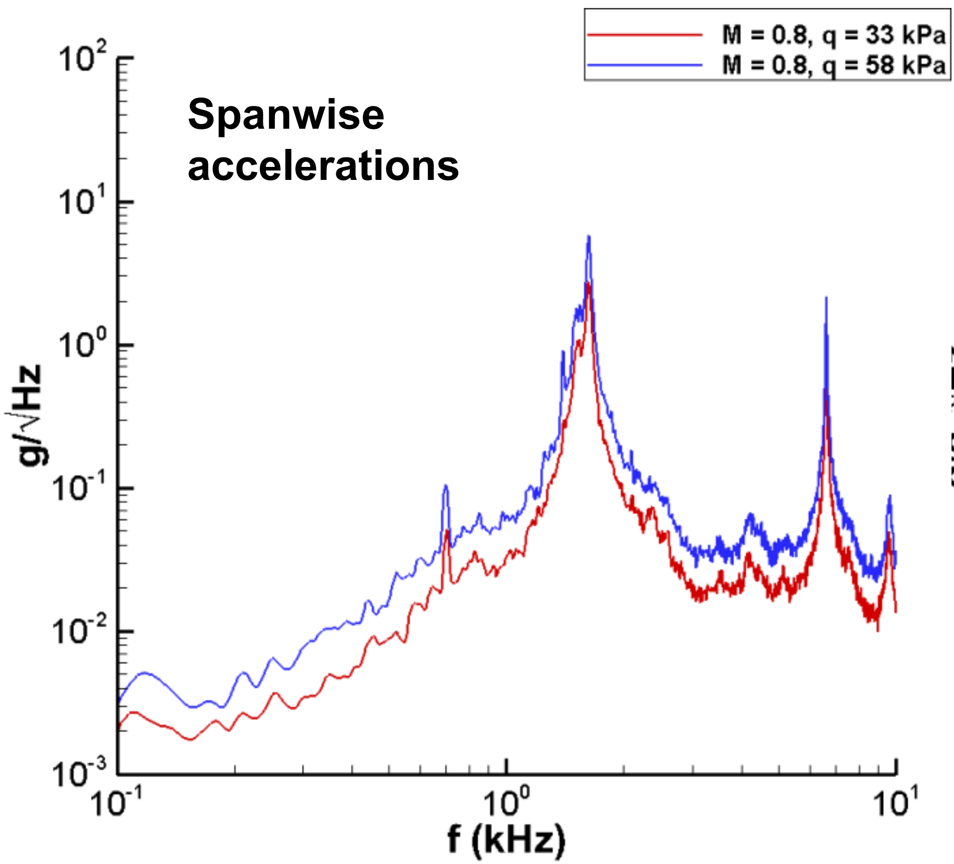
Inset from 3.8 through 4.6 kHz



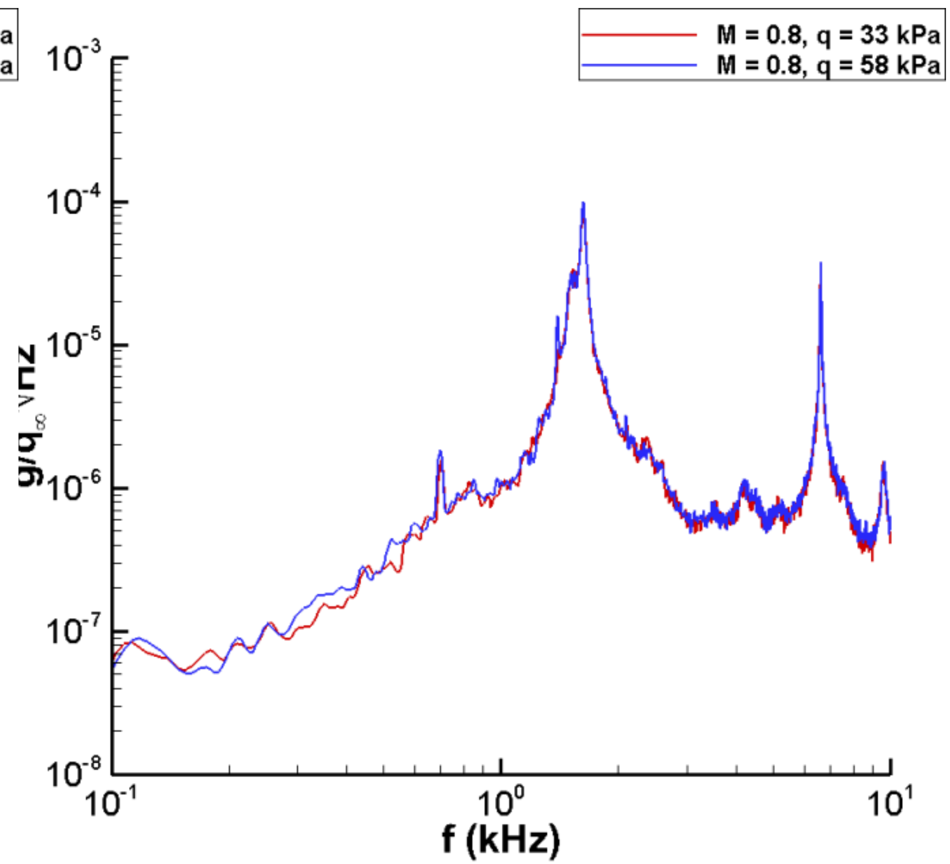
- ***Accelerations are a function of streamwise position and frequency. The scanning LDV data show the importance of making measurements at multiple store locations.***
- ***Such data are valuable for store-response models with non-uniform loading, and show the need for acoustic loading data on the store.***

Scaling of Store Vibrations

Runs with Varying Dynamic Pressure



Normalized by Dynamic Pressure



- Like the cavity pressures, the store accelerations also scale with q_∞

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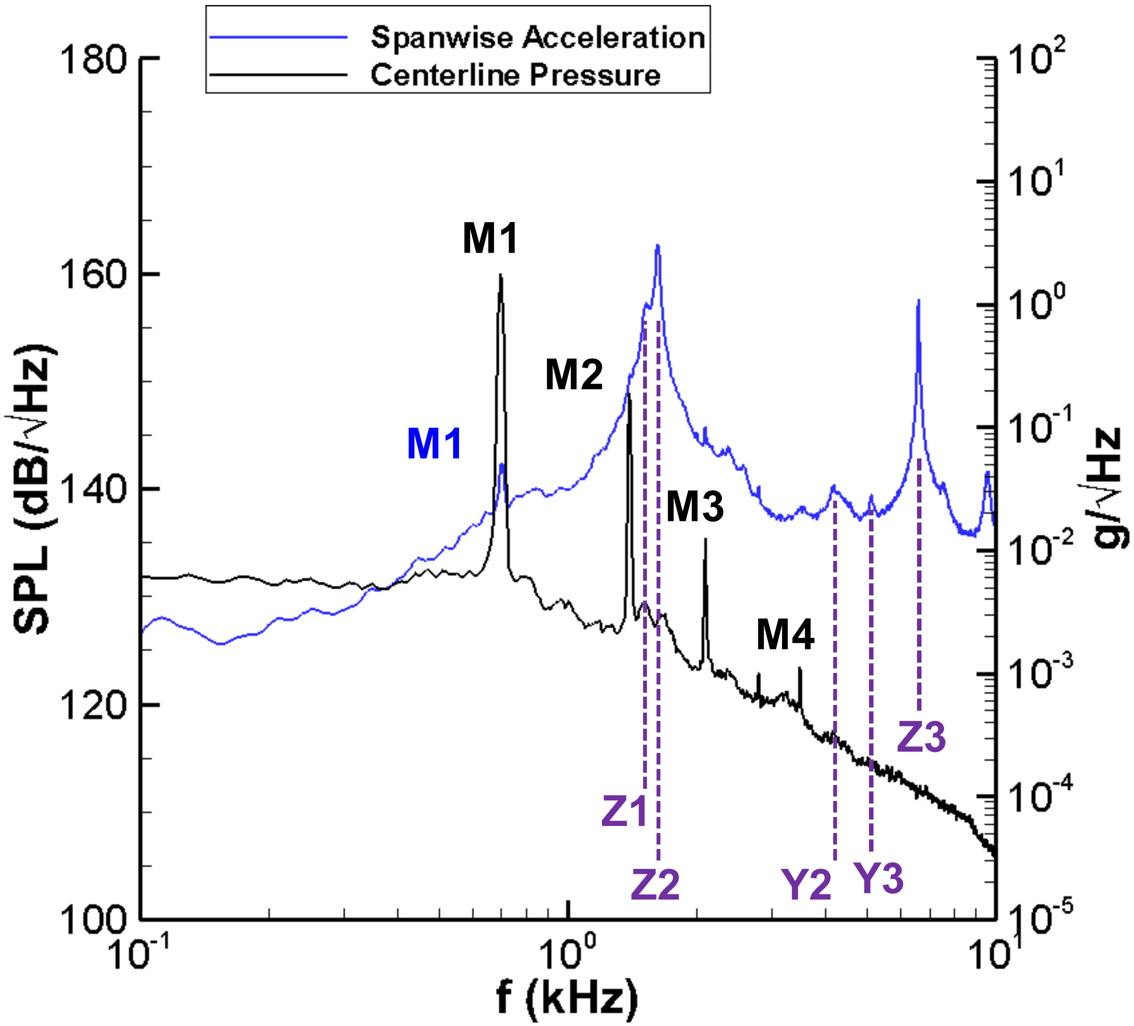
Conclusions

- To understand the complex fluid-structure interactions that occur during internal store carriage, an experimental program has been developed to simultaneously measure the acoustic loading and store vibrations.
- Acoustic loading data, provided by fast response pressure sensors, showed that the presence of the store significantly altered the cavity acoustics.
- Store vibration measurements were provided by triaxial accelerometers and laser Doppler Vibrometry (LDV)
- The scanning LDV provided offered the advantage of increased spatial resolution.
- The accelerometers offered the advantage of providing three-dimensional measurements, which proved highly valuable in making physical observations.
- In the streamwise and wall-normal directions, the store response was dominated by fluid-forcing.
- In contrast, the spanwise loading was primarily driven by the structural dynamics of the store, which demonstrated the need for modal tests to properly characterize the store natural frequencies.

Future Work

Spanwise Response of Upstream Accelerometer



- **To understand how the store-response varies with aeroacoustic loading, additional experiments will be performed over a wide range of Mach numbers.**
- **Such data will provide the store response to a wide range of cavity modes.**
- ***In particular, tests will be conducted for the case of a cavity mode matching a structural mode, where the greatest vibrations are expected.***