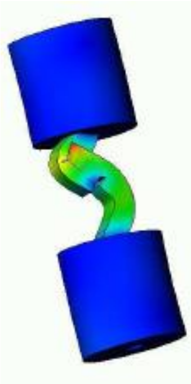
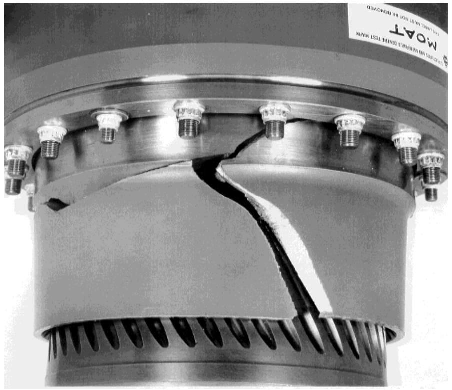
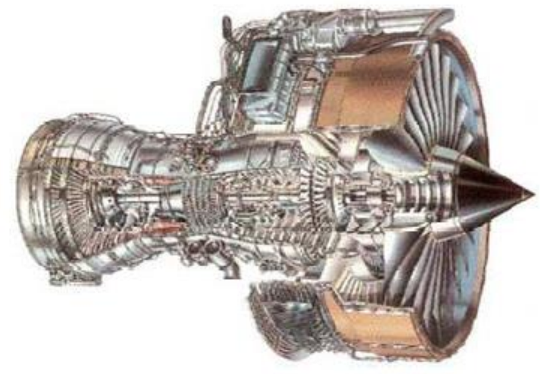
Exceptional service in the national interest







Project 6: Acoustoelasticity Measurements and Modifications

Students: Deborah Fowler (UMass Lowell), Garrett Lopp (U. of Central Florida), and Dhiraj Bansal (CU Boulder)

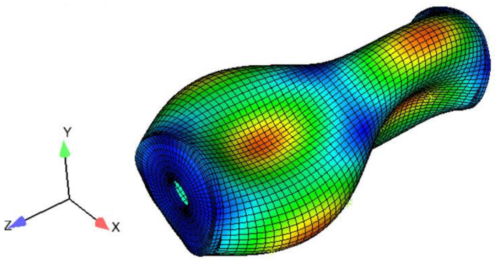
Mentors: Ryan Schultz (SNL), Matt Brake (Rice), and Micah Shepherd (Penn St.)

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.
SAND2017-7807 C

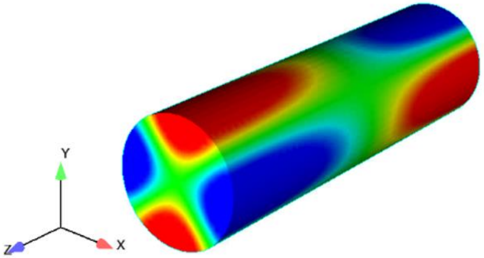
Acoustoelasticity studies the coupling between structural and acoustic modes

- Acoustoelasticity is a subset of the field of structural acoustics
- Structures and acoustics are coupled through the velocity that is equal at the interface surface
- Structures and fluids propagate sound waves that form standing waves with specific patterns (mode shapes) at specific frequencies (resonance)

Structural mode shape



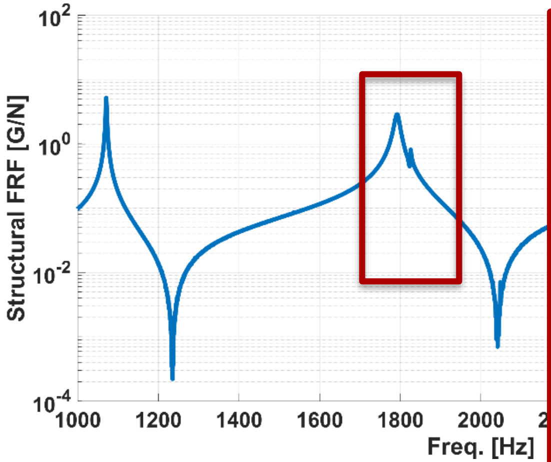
Acoustic mode shape

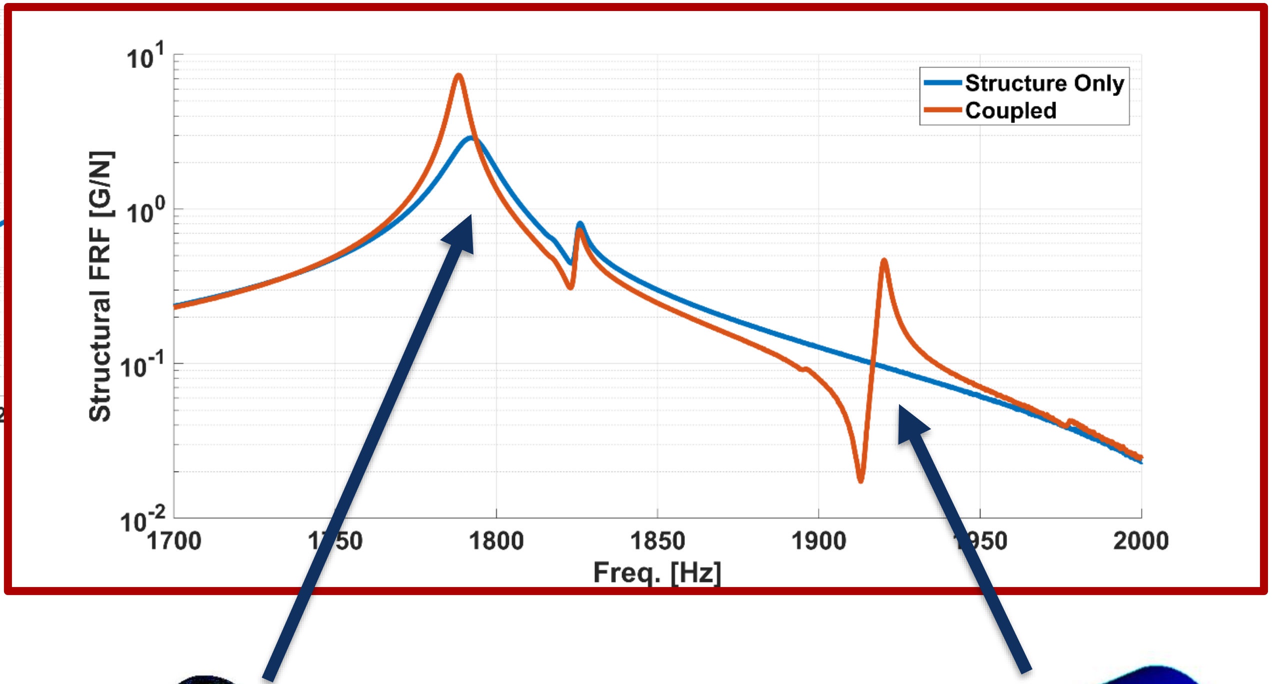


Acoustoelastic Coupling!

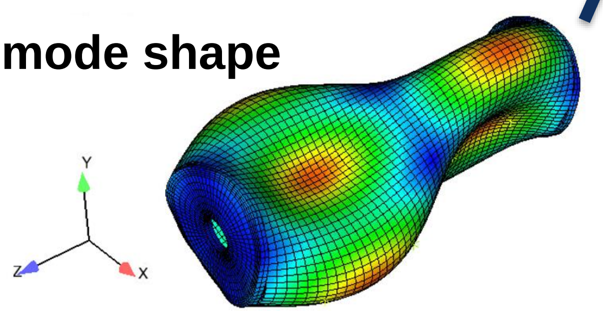
Acoustoelastic coupling generates unexpected peaks in the frequency response

Structural Frequency Response Function (FRF)

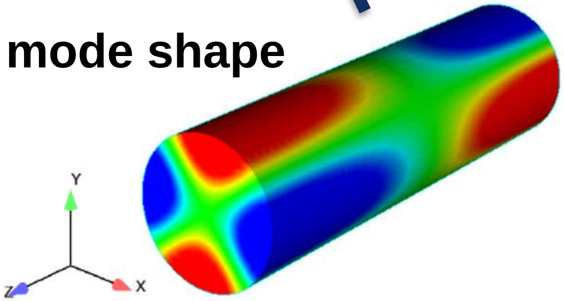




Structural mode shape

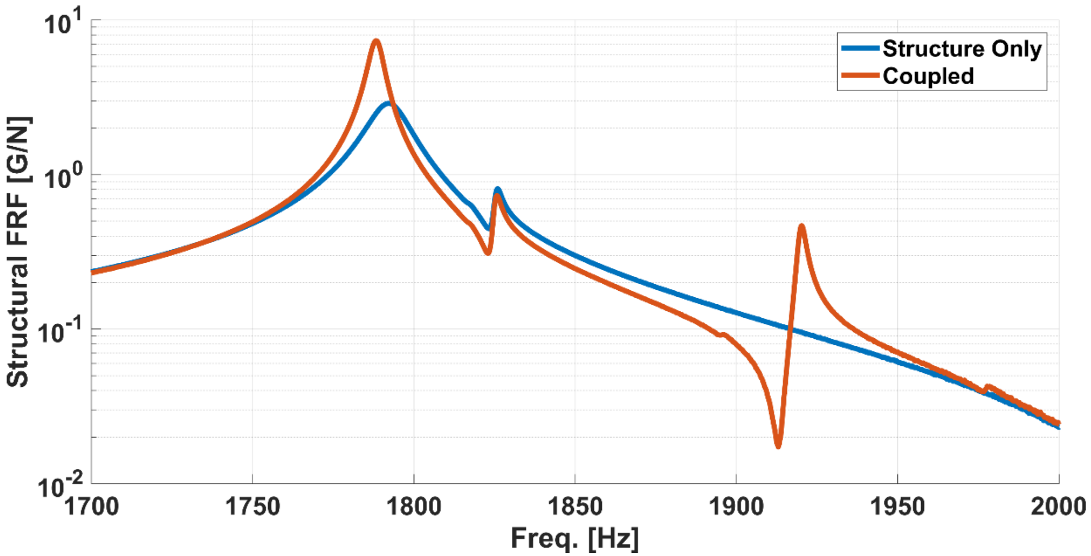


Acoustic mode shape



Presence of coupling causes difficulty in validating analytical models (e.g., finite element)

- One of the main goals of modal testing is to supply experimental data for analytical model correlation
- Finite element models typically assume zero interaction with the surrounding air (in-vacuo, structure-only state)
- Running coupled analyses increase model complexity and computational expense



How can we approach this problem from the experimental side?

We seek to develop methods to…

- Quickly identify when acoustoelastic coupling occurs
- Measure this structural-acoustic interaction
- Decouple the structural response by altering boundary conditions of:
  - Acoustic volume
  - Structure

Presentation Outline

- Acoustoelasticity Theory
- Hardware and Test Setup
- Coupling Identification and Measurement
- Mitigation Strategies
- Conclusions

Presentation Outline

- **Acoustoelasticity Theory**
- Hardware and Test Setup
- Coupling Identification and Measurement
- Mitigation Strategies
- Conclusions

Coupling occurs when mode shapes are similar and frequencies are close in proximity

Modal Equations of Motion:

Structural:

$$M_m \ddot{q}_m + C_m \dot{q}_m + K_m q_m = \boxed{\rho_0 c_0^{\,2} A_F \sum_n \frac{P_n L_{nm}}{M_n^A}} + Q_m^E$$

Acoustic:

$$\ddot{P}_n + (\omega_n^A)^2 P_n = \boxed{-\frac{A_F}{V} \sum_m L_{nm} \ddot{q}_m}$$

Acoustoelastic coupling terms

Coupling coefficient measures the degree of similarity between mode shapes

$$L_{nm} = \frac{1}{A_F} \int_{A_F} \psi_n \phi_m \, dA$$

ψ_n : Acoustic shape

ϕ_m : Structural shape

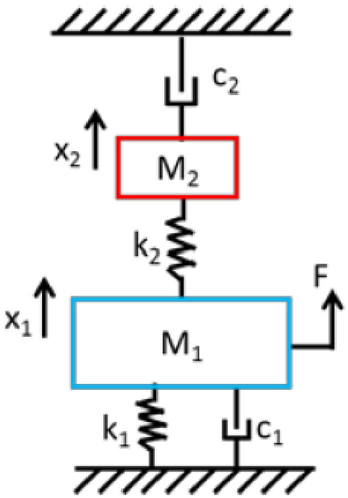
For excitation at the structural resonance frequency, the acoustic modal amplitude is:

$$\overline{P}_n = \frac{A_F}{V} \frac{(\omega_m^s)^2 L_{nm}}{(\omega_n^A)^2 - (\omega_m^S)^2} \overline{q}_m \xrightarrow{\textbf{Minimized when}} \boxed{\begin{array}{c} L_{nm} \text{ small} \\ (\omega_n^A)^2 - (\omega_m^S)^2 \text{ large} \end{array}}$$

[1] Dowell E.H. et al. (1977) “Acoustoelasticity: General Theory, Acoustic Natural Modes and Forced Response to Sinusoidal Excitation, Including Comparison with Experiment,” Journal of Sound and Vibration, **52**(4), 519-542.

A system with acoustoelastic coupling behaves similar to a tuned mass damper

Tuned mass damper



Reproduced from [2]

Acoustic System (Air Volume)

Structure System (Cylinder)

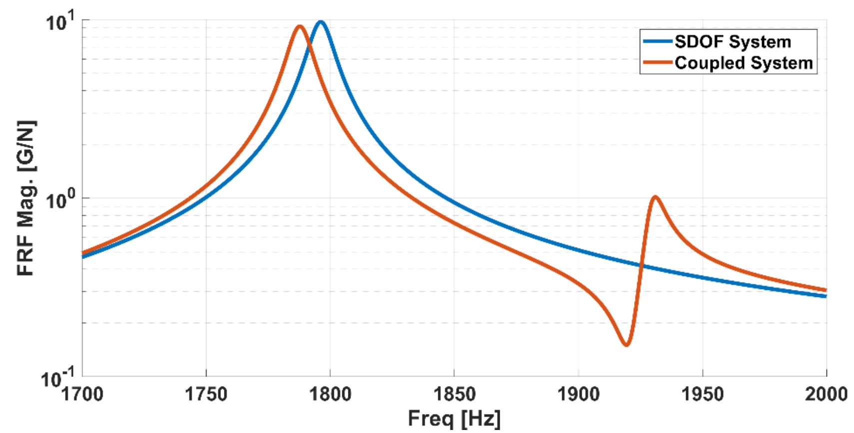
Frequencies

$$f_{1,2} = \frac{1}{2^{3/2}\pi}\left(\frac{k_1+k_2}{M_1}+\frac{k_2}{M_2}\mp\left[\left(\frac{k_1+k_2}{M_1}+\frac{k_2}{M_2}\right)^2-4\frac{k_1k_2}{M_1M_2}\right]^{1/2}\right)^{1/2}$$

Mode Shapes

$$\begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix}^{(i)} = \begin{Bmatrix} 1 \\ 1+\frac{k_1}{k_2}-\frac{M_1}{k_2}(2\pi f_i) \end{Bmatrix}$$

Frequency response of M_1



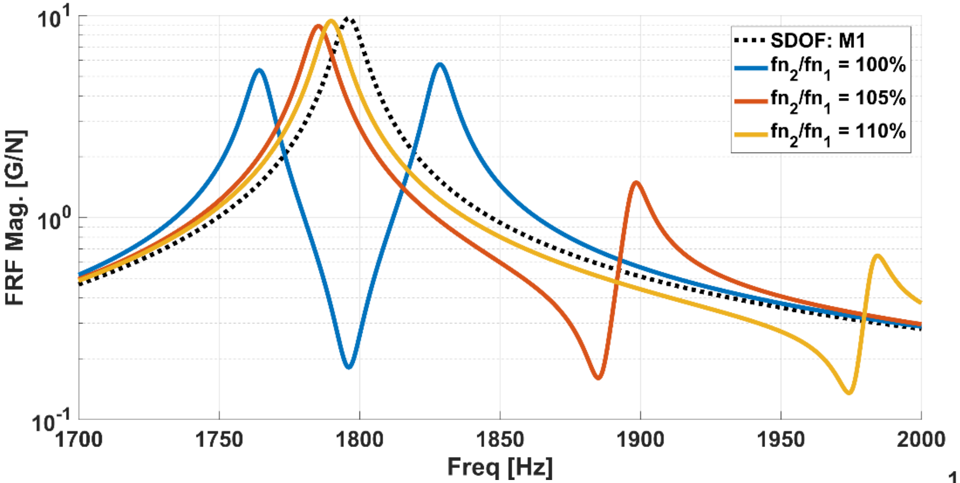
Parameters:

- M_1: structural mass
- M_2: air mass
- k_1: structural stiffness
- k_2: air stiffness
- c_1: structural damping
- c_2: air damping

[2] Schultz R., Pacini B. (2017) “Mitigation of Structural-Acoustic Mode Coupling in a Modal Test of a Hollow Structure,” Conference Proceedings of the Society for Experimental Mechanics Series,

Adjusting air properties can decouple the structural system

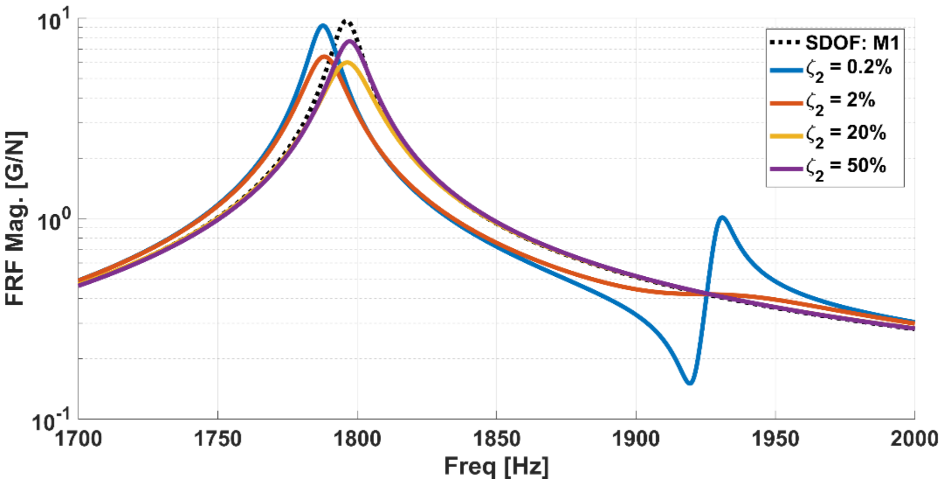
Vary air "stiffness" k_2



Increasing air stiffness causes the coupled acoustic frequency to shift away from structural frequency

Vary air damping c_2

Increasing air damping causes the structural response to first decrease, then increase towards SDOF response



[2] Schultz R., Pacini B. (2017) "Mitigation of Structural-Acoustic Mode Coupling in a Modal Test of a Hollow Structure," Conference Proceedings of the Society for Experimental Mechanics Series,

Presentation Outline

- Acoustoelasticity Theory
- **Hardware and Test Setup**
- Coupling Identification and Measurement
- Mitigation Strategies
- Conclusions

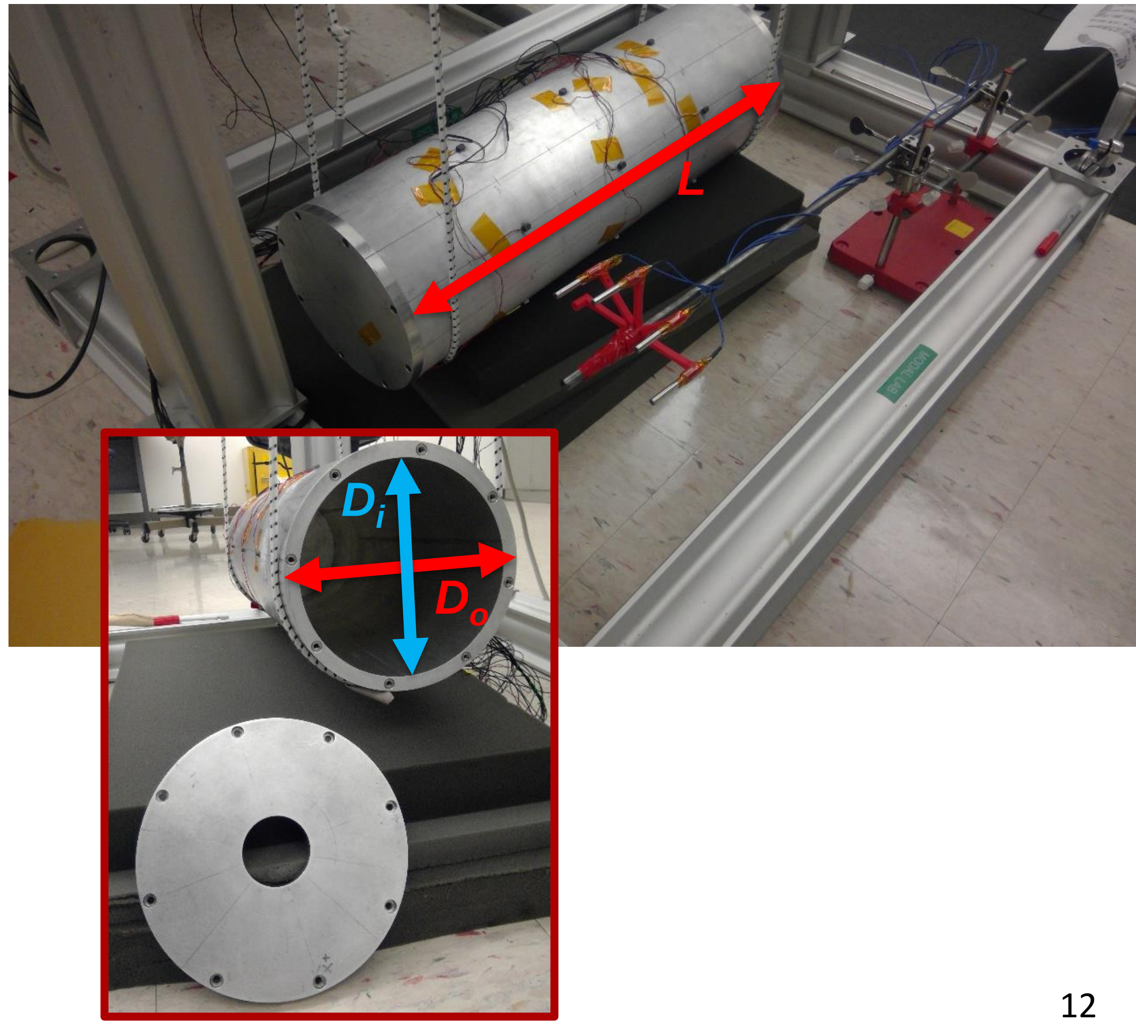
A hollow aluminum cylinder provided a test article that exhibits acoustoelastic coupling

Cylinder dimensions:
Length L: 24 in.
Inner diameter, D_i = 7 in.
Outer diameter, D_o = 8 in.
Wall thickness, t = ½ in.

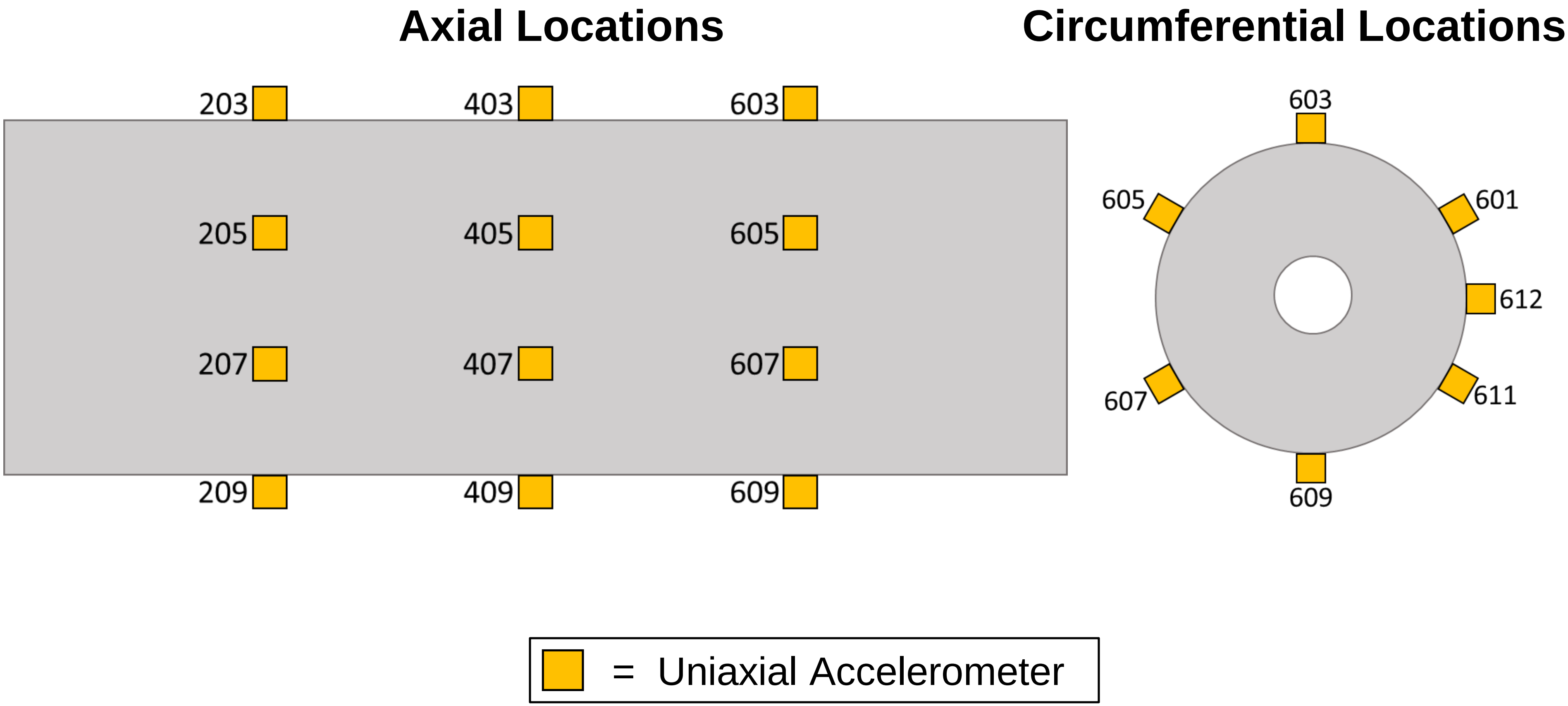
Measurements:
Accelerometers bonded to surface measure the structural response

Microphones located on rod measure the acoustic pressure

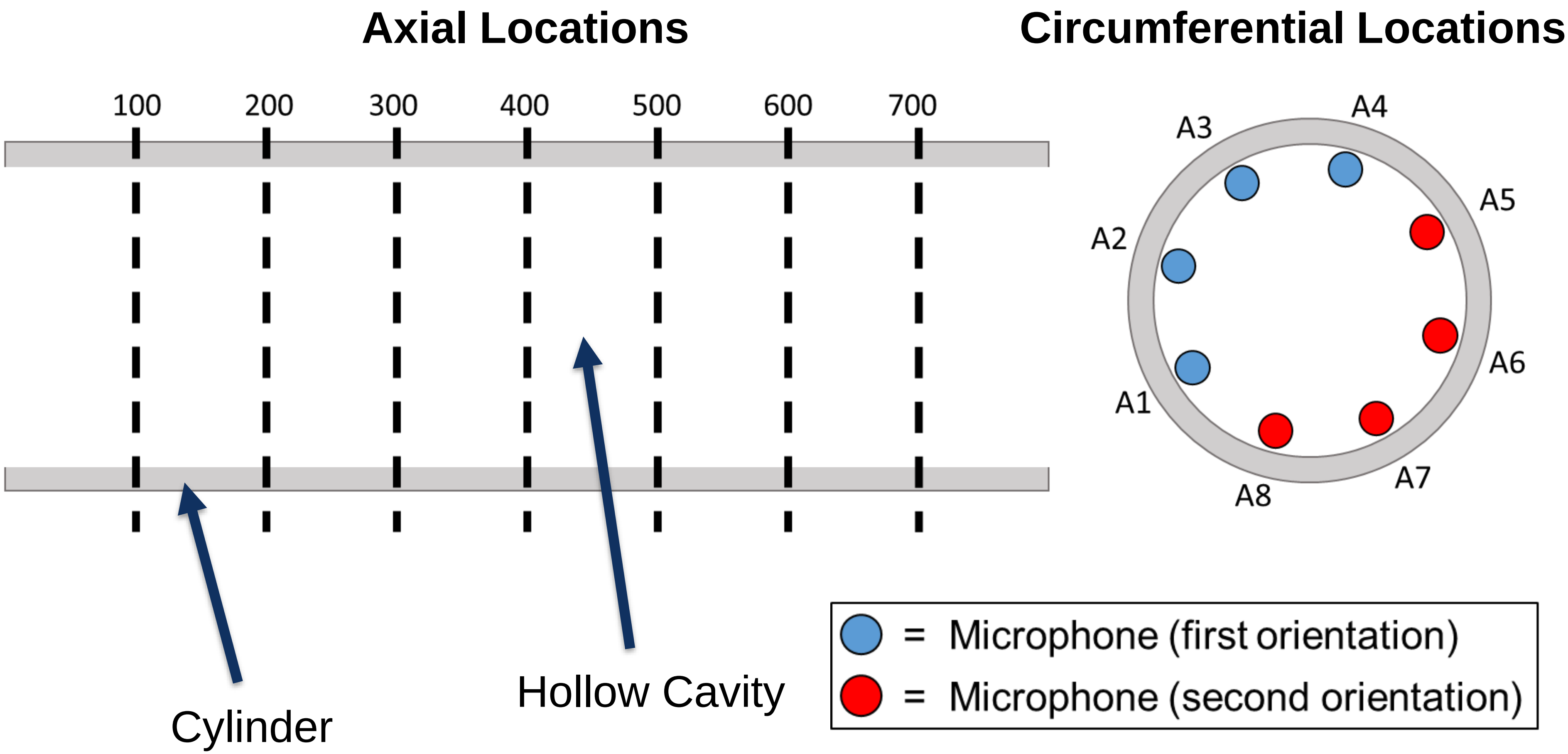
Cylinder suspended from soft bungee cords



Accelerometers located to adequately capture the structural modes of interest



Roving microphone array used to adequately capture acoustic modes of interest

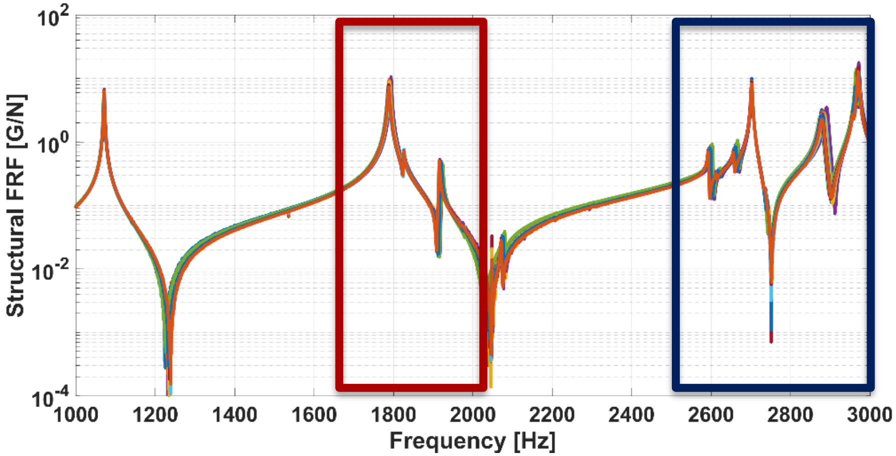


Presentation Outline

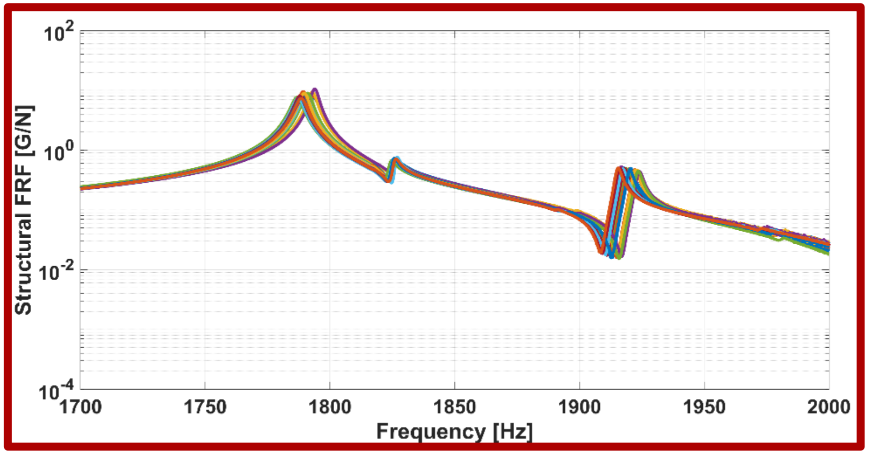
- Acoustoelasticity Theory
- Hardware and Test Setup
- **Coupling Identification and Measurement**
- Mitigation Strategies
- Conclusions

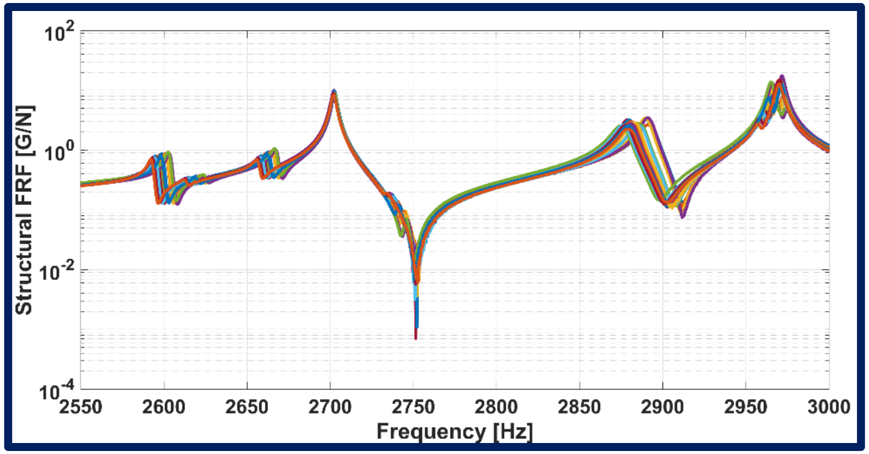
Baseline tests from different days / times altered the system frequency response

FRF variations at various points in time



Zoomed FRF



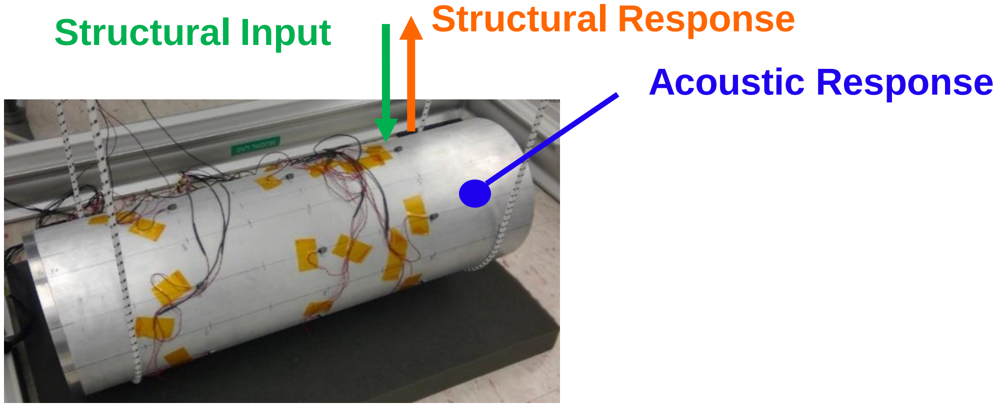


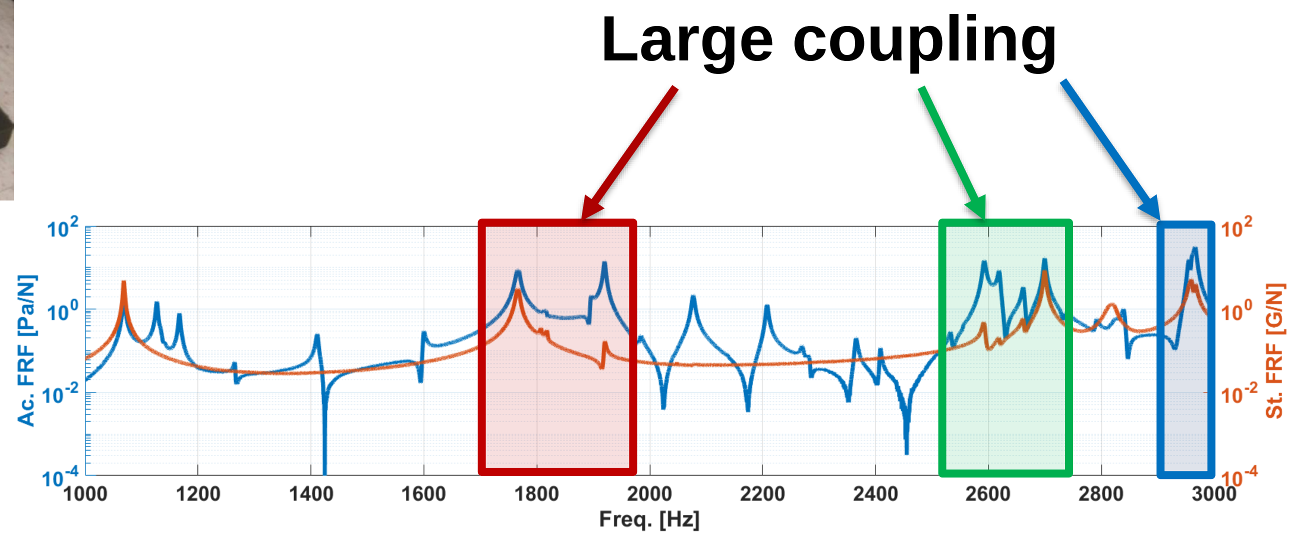
Frequency shifts of up to 0.5%

Identified causes include:

- Bungee cord tension / location
- Cylinder end cap removal / reattachment
- Variations in air properties

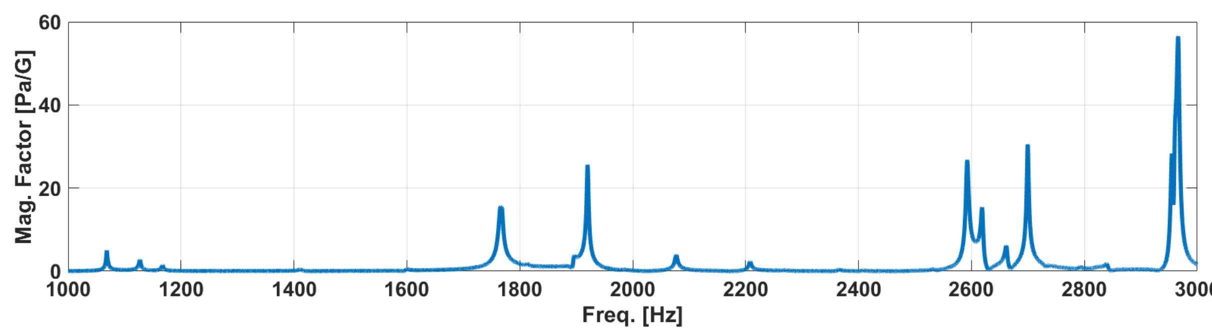
Acoustic response magnified in frequency ranges where coupling exists



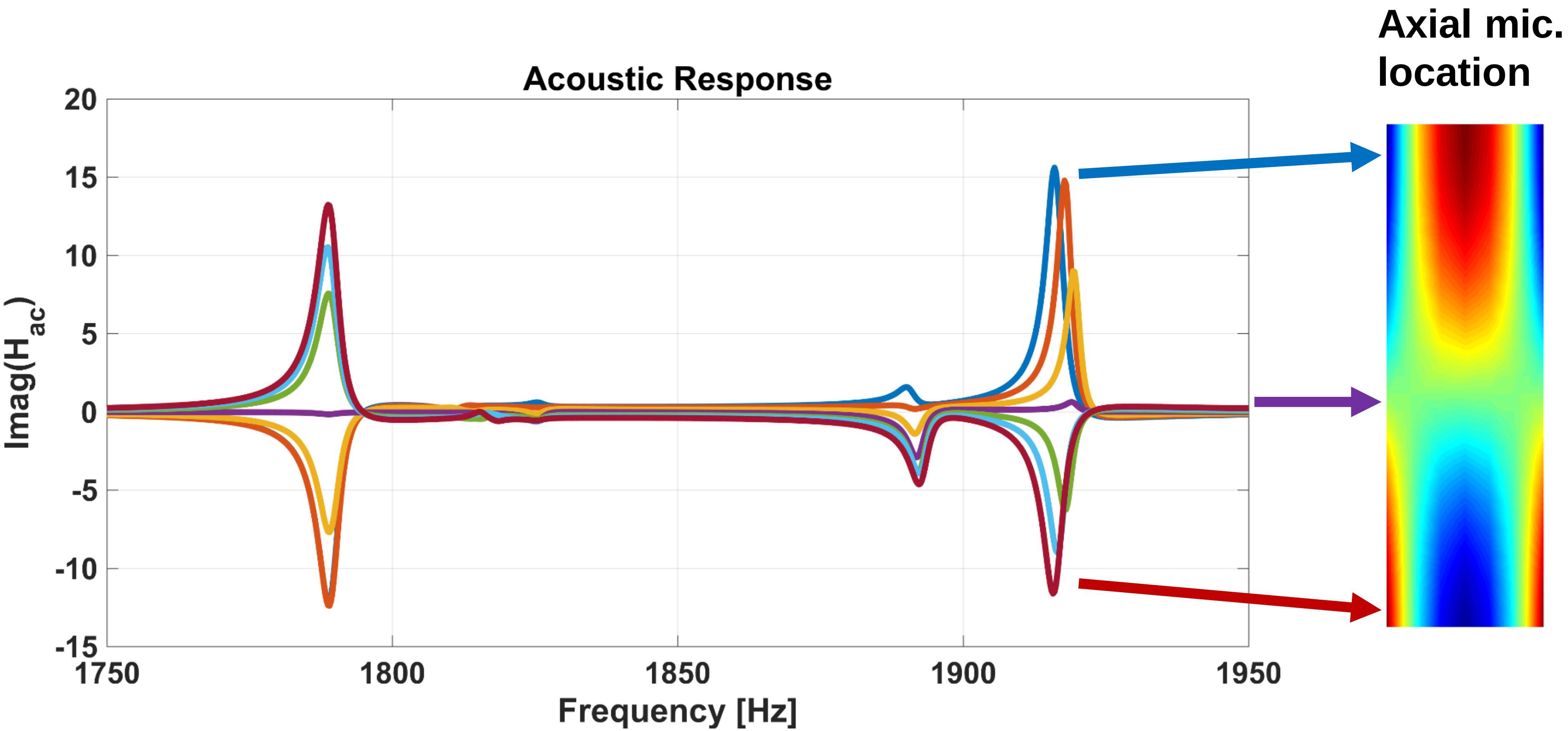


Magnification Factor

$$\mathrm{MF} = \frac{H_{Ac}}{H_{St,RMS}}$$

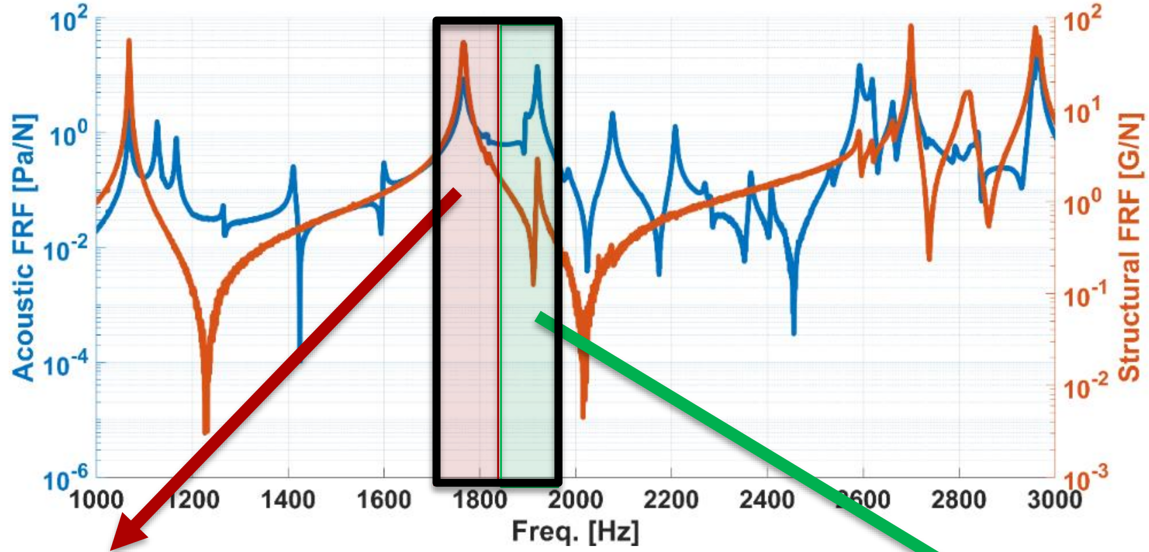


Location of microphones shows appreciable effect on the coupled frequency



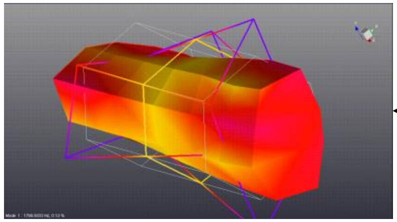
Requires acoustic modal parameters to be extracted at each microphone location!

The two peaks of the coupled structural-acoustic pairs have opposite phasing

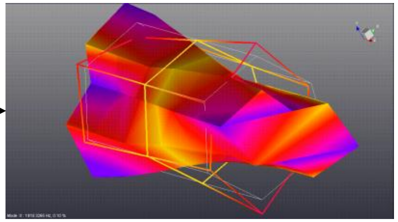


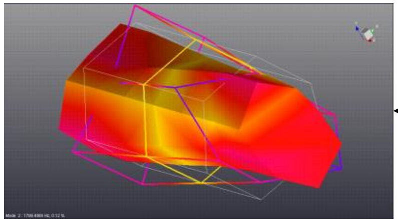
Modes in phase

Modes out of phase

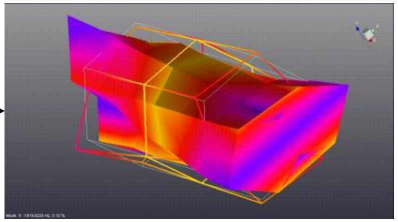


Coupled Pair 1





Coupled Pair 2

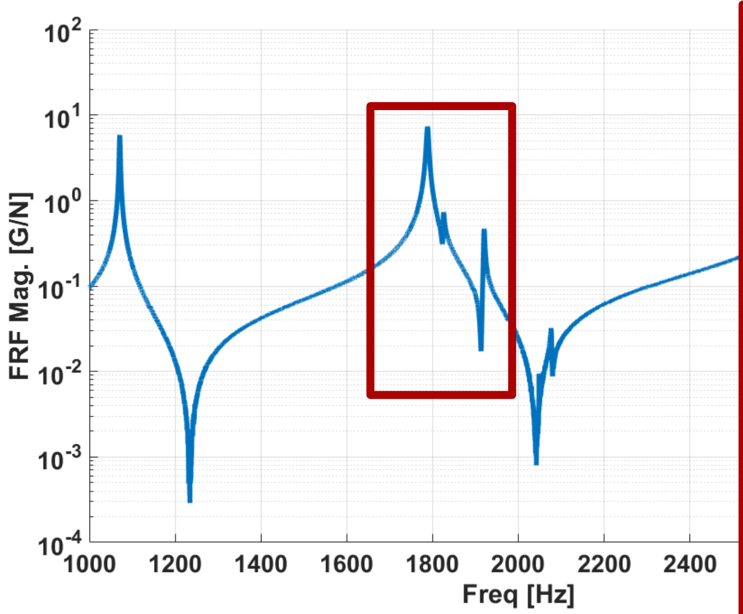


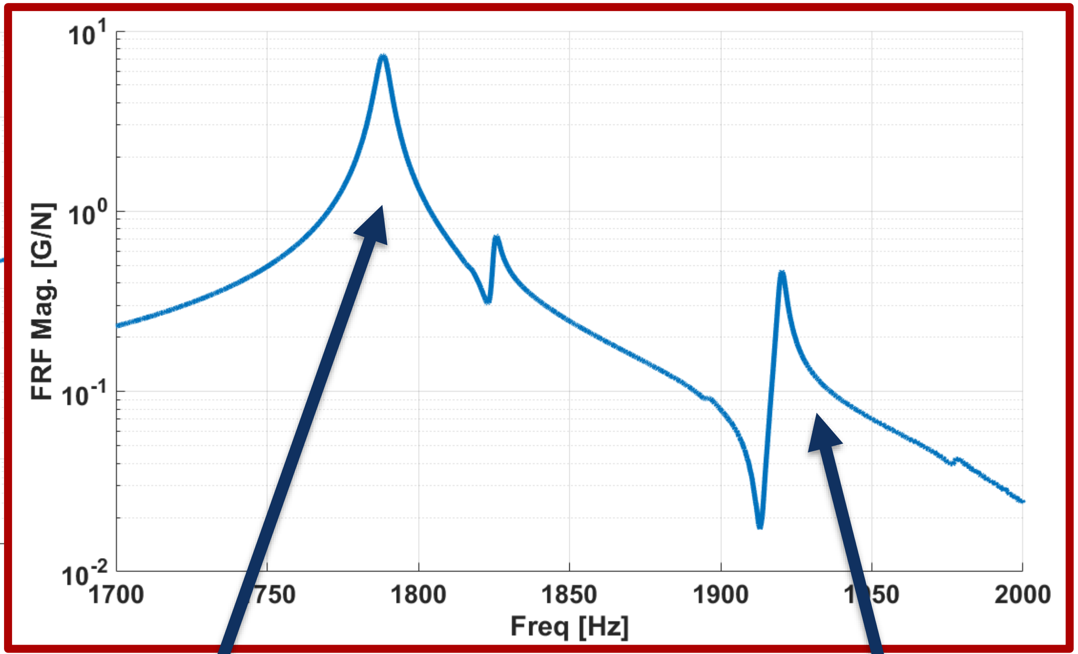
Presentation Outline

- Acoustoelasticity Theory
- Hardware and Test Setup
- Coupling Identification and Measurement
- **Mitigation Strategies**
- Conclusions

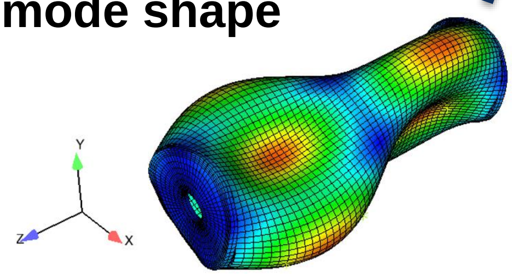
Mitigation strategies analyzed using the coupled modes in the 1700-2000 Hz frequency range

Typical Structural FRF

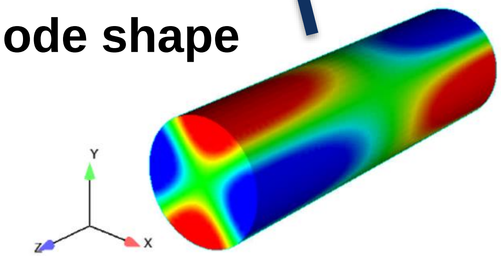




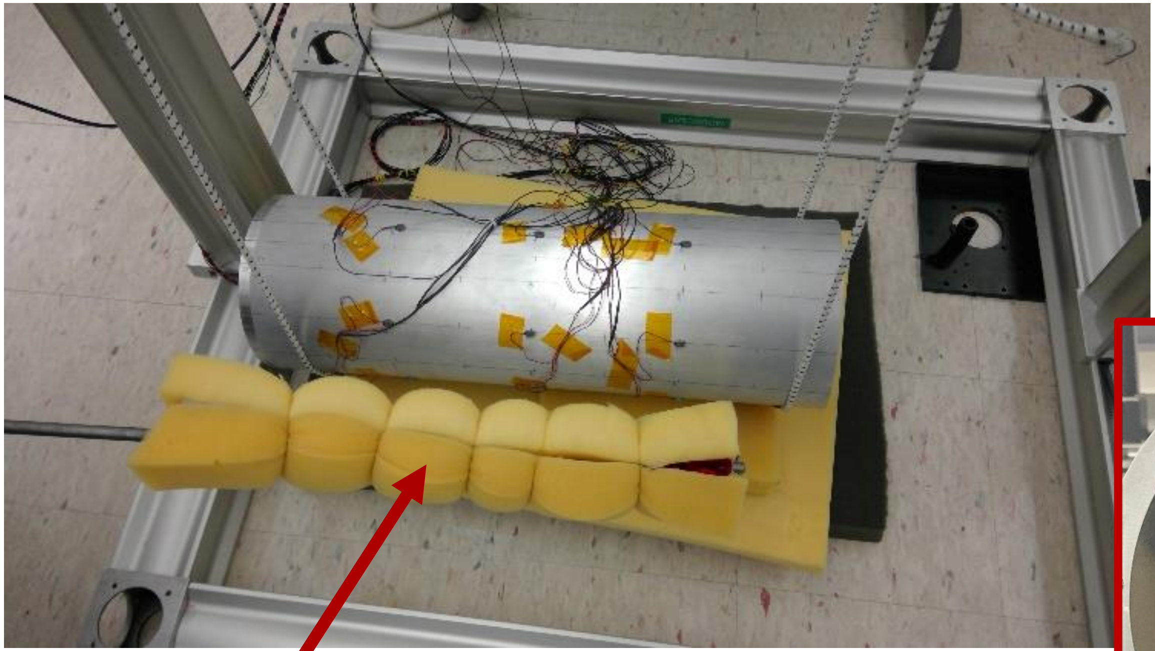
Structural mode shape

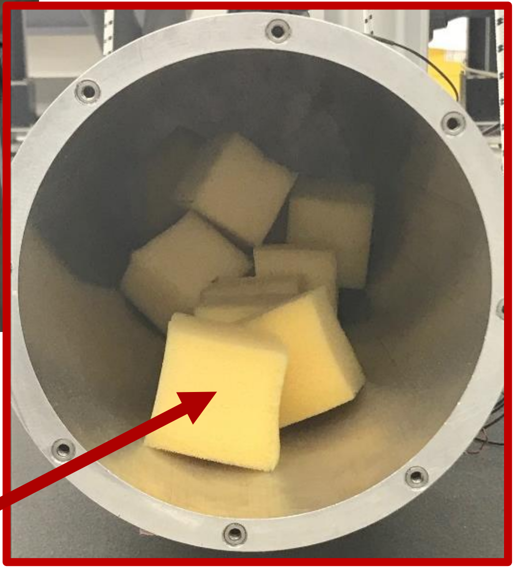


Acoustic mode shape



Introducing foam into cavity adds a source of acoustic damping



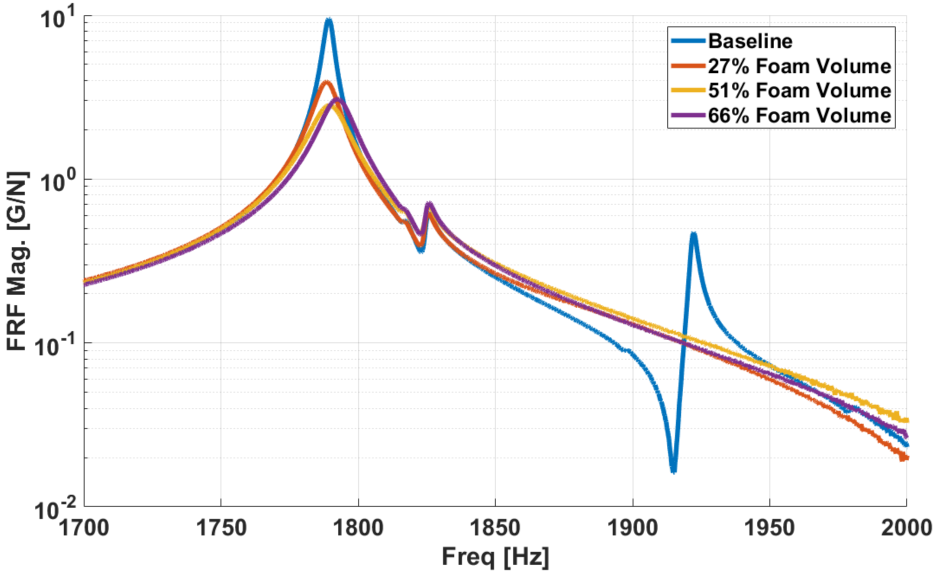


Foam covered rod
(non-contact approach)

Foam cubes
(contact approach)

Using the foam rod (non-contact), increasing the foam volume decouples the structural response

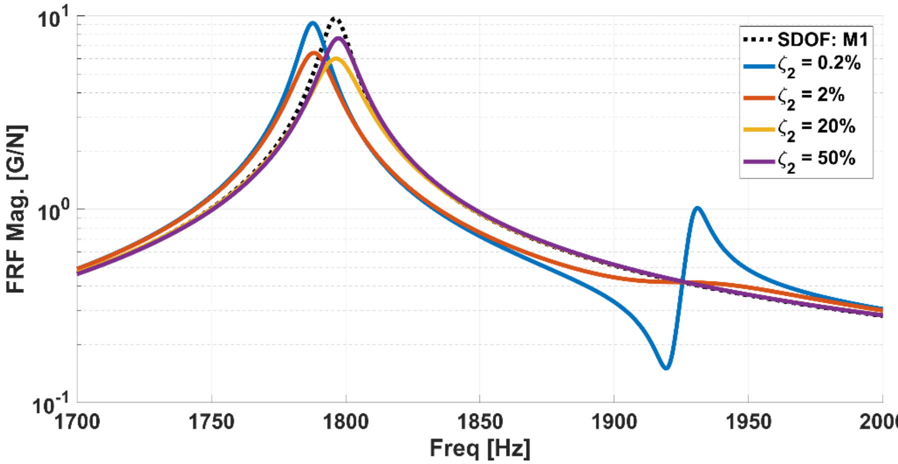
Increasing acoustic damping



Coupled acoustic response damped out with around 25% of cavity filled with foam

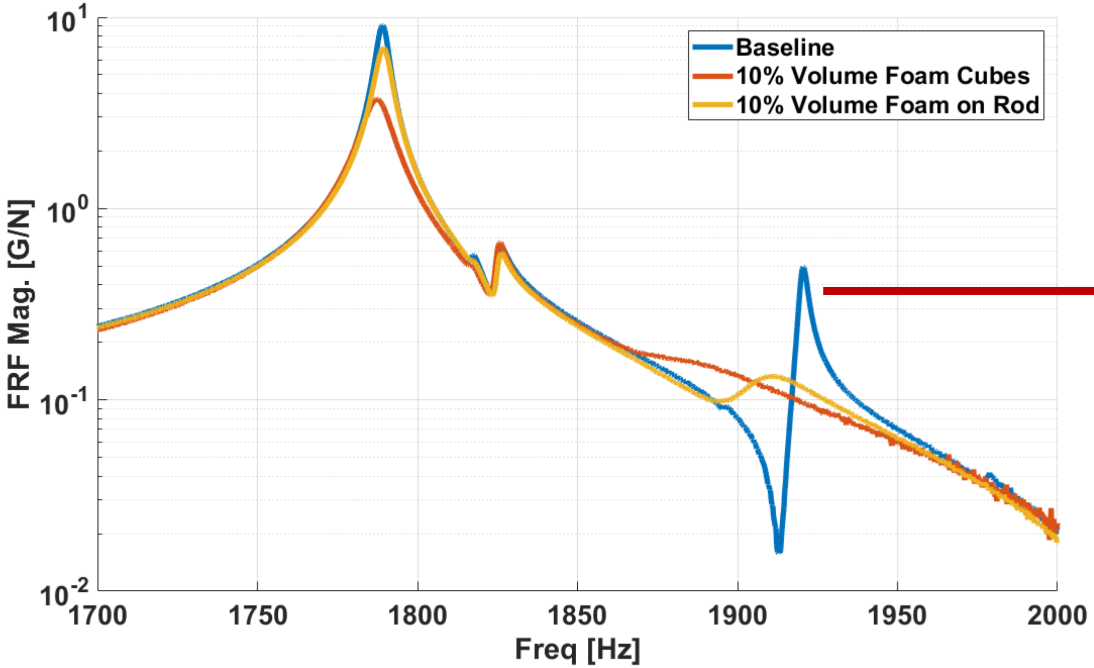
Increasing foam causes structural peak to first decrease, then increase and shift in frequency; similar to a tuned mass damper

Tuned mass damper

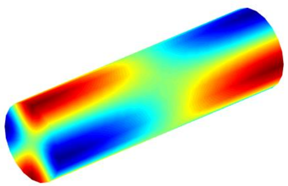


Foam cubes in contact with cylinder increased decoupling potential for same volume of foam

Non-contact vs. contact foam comparison



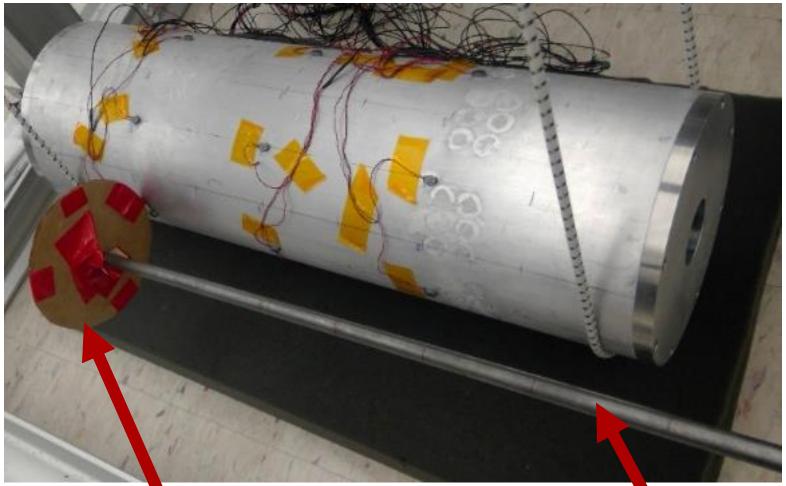
Acoustic (2,1,1) mode shape

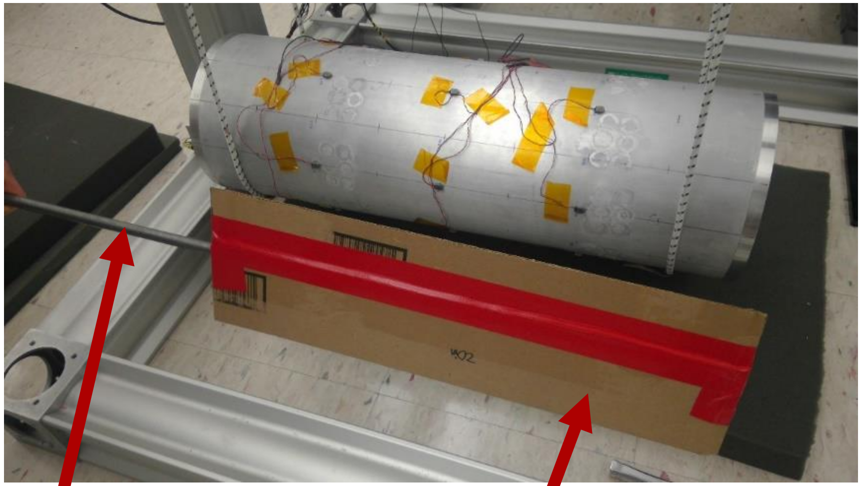


Foam in cavity

- Foam cubes inserted incrementally through hole in endcap
- Foam cubes are less compressed, leading to more effective acoustic absorption

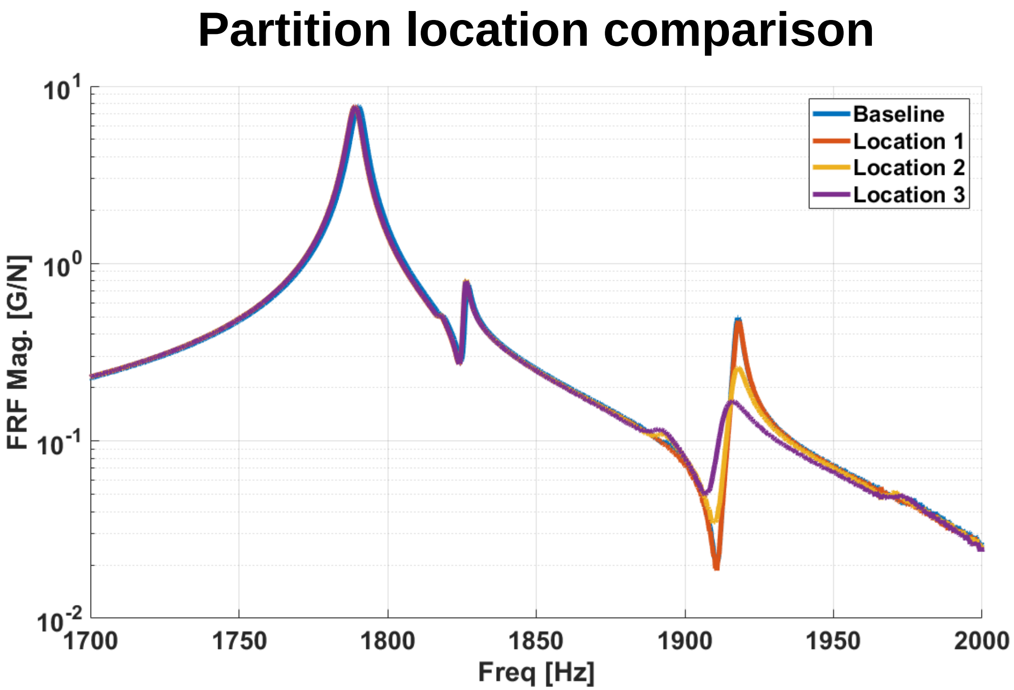
Including partitions in the cavity alters the acoustic mode shape

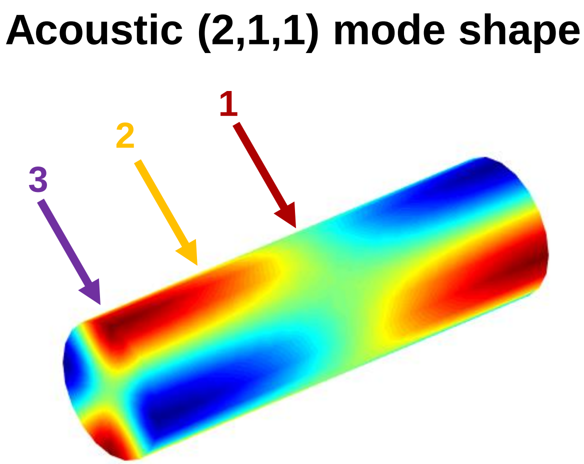




Cardboard disk **Insertion Rod** **Axial Cardboard Partition**

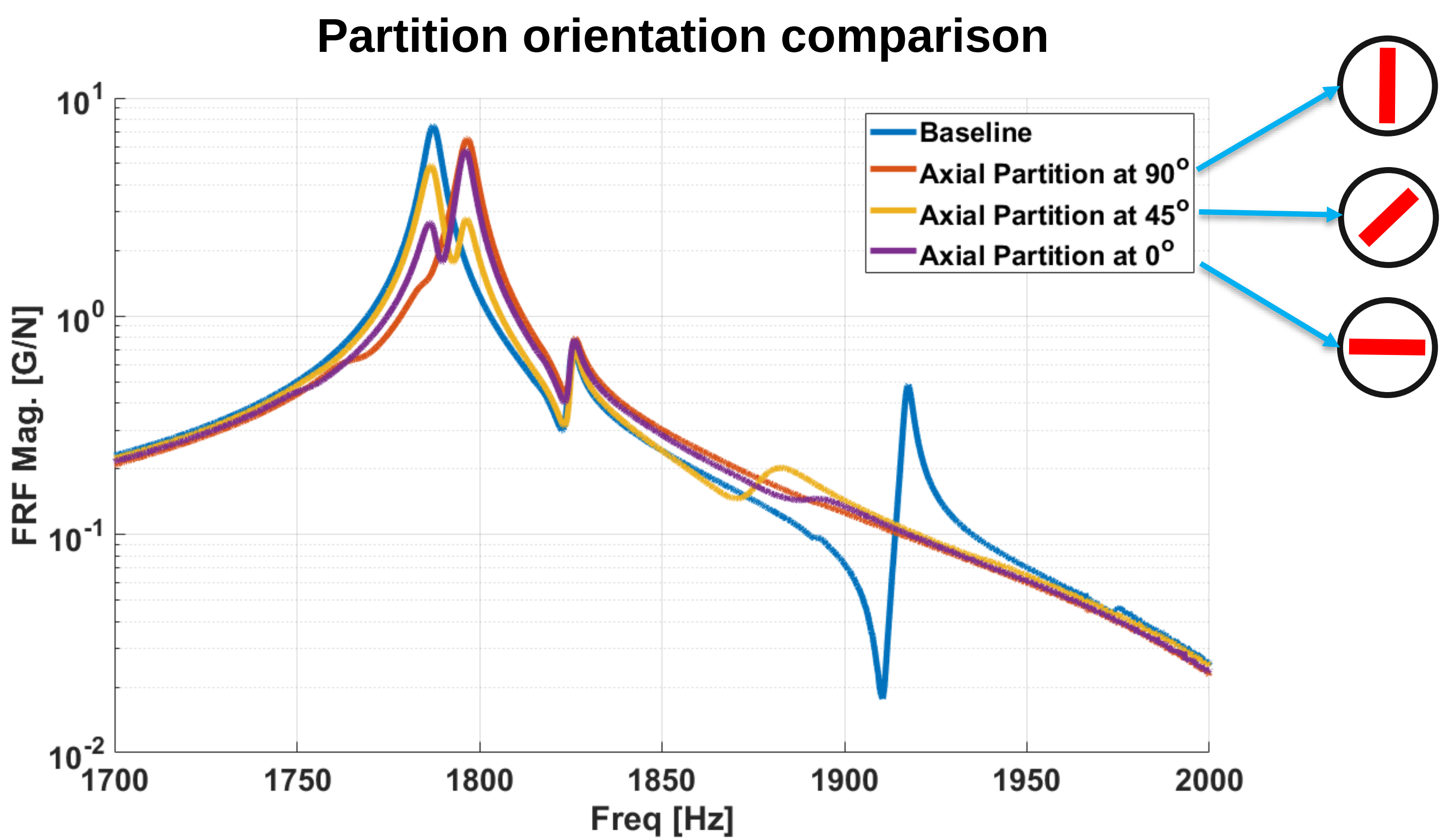
Locating cardboard disk partition at max acoustic pressure reduces coupling





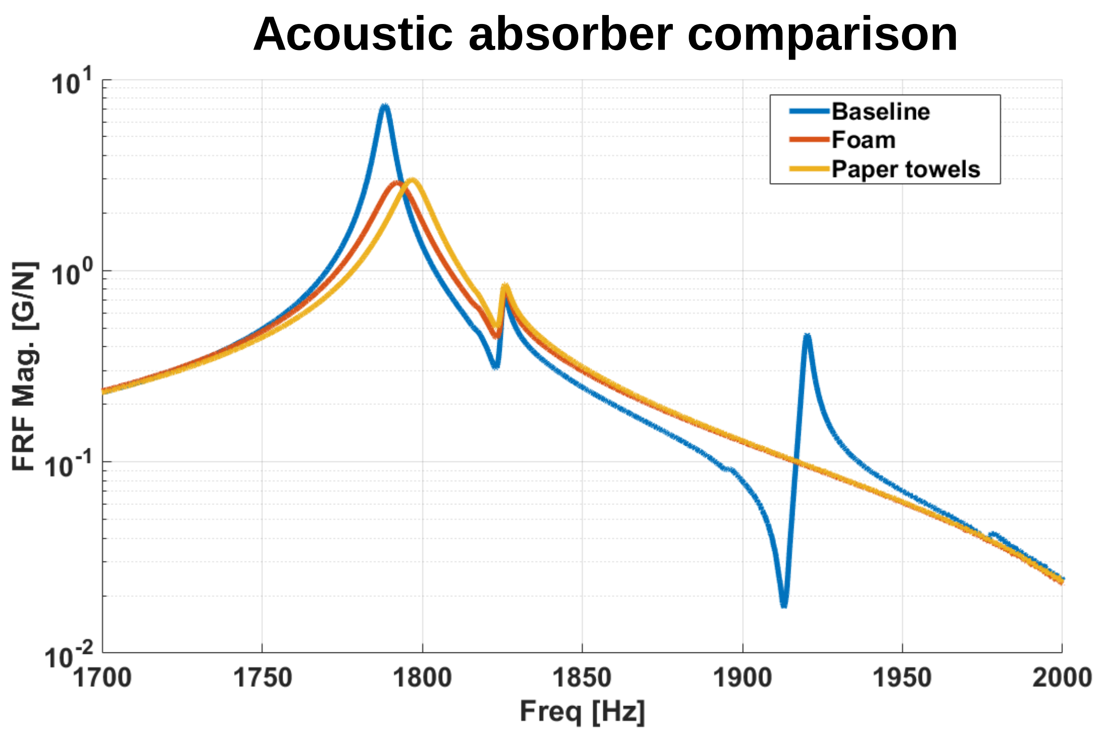
- Single cardboard disk did not adequately remove coupling
- Requires knowledge of mode shape to effectively place partition to reduce coupling

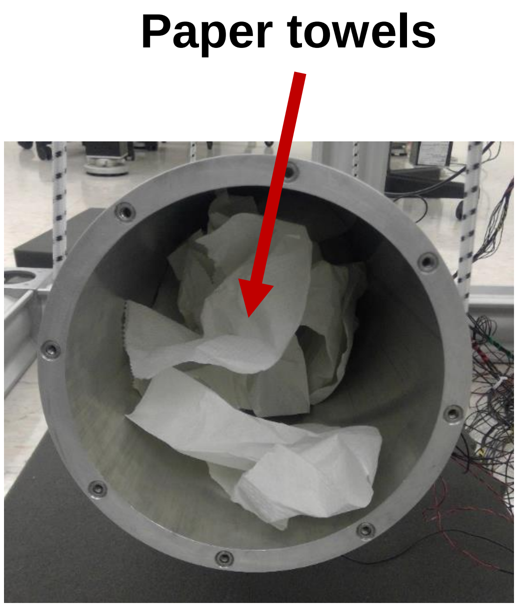
Including the axial cardboard partition further disrupted the coupling behavior



- Unexpectedly induced a frequency splitting in structural peak

Randomly oriented paper towels are most effective and convenient for decoupling



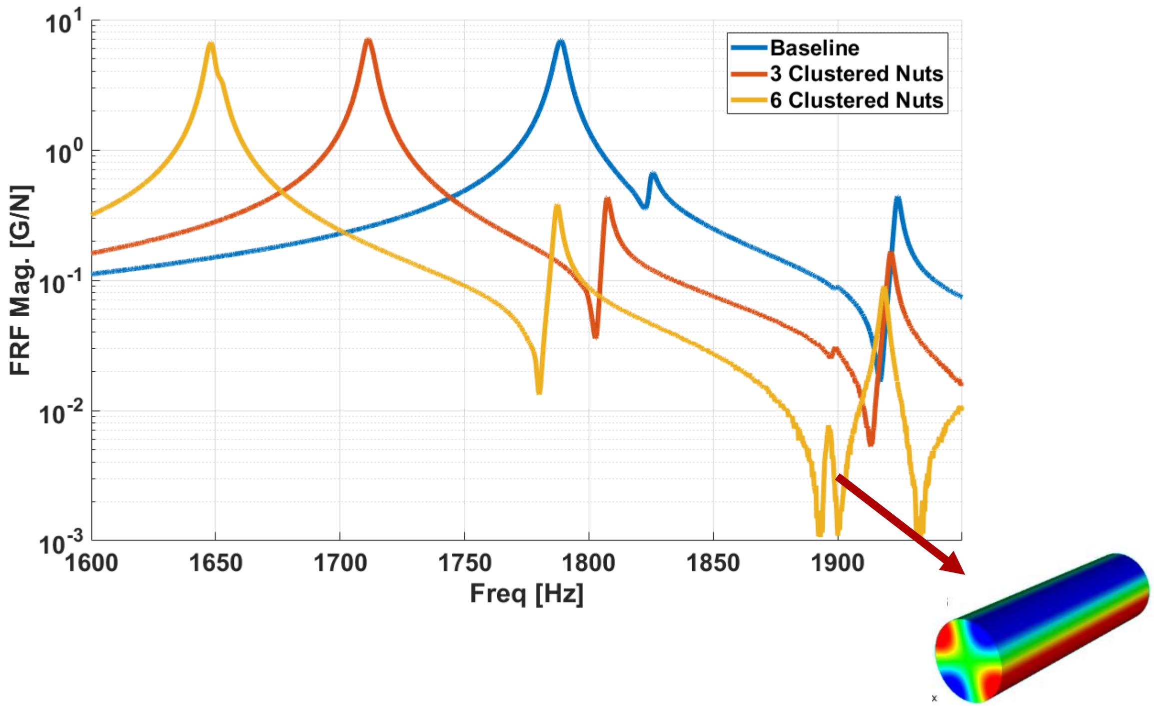


- Paper towels successfully absorb acoustic energy without adding much mass to the system

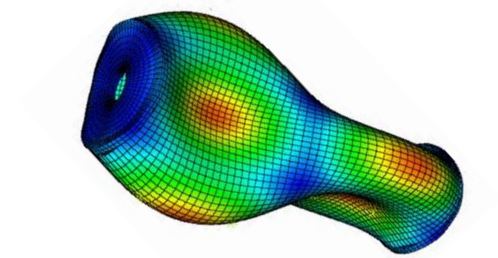
- Cheap and readily available solution to both quickly identify and remove coupling

Adding mass at anti-nodes shifts structural peaks but has minimal effect on coupled peak

Mass modification effects



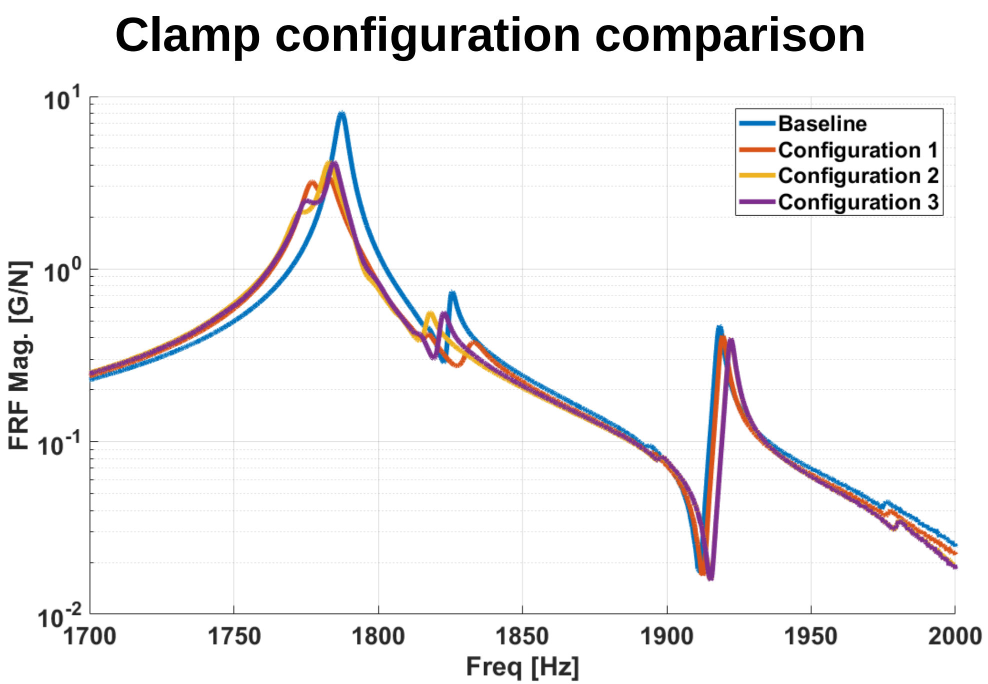
Structural (2,1) Mode Shape

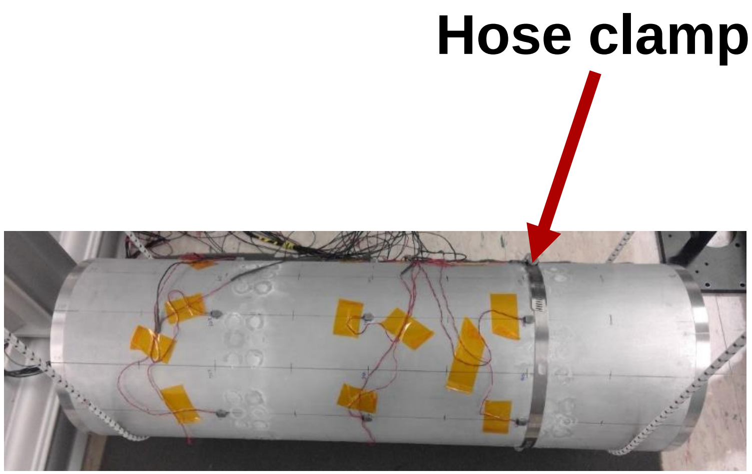


Masses bonded at anti-nodes

- Structural modifications may be necessary if cavity is inaccessible
- The frequency shift caused a second acoustic mode to couple with the structure, though at a small magnitude

Using hose clamps to add stiffness does not have the desired effect





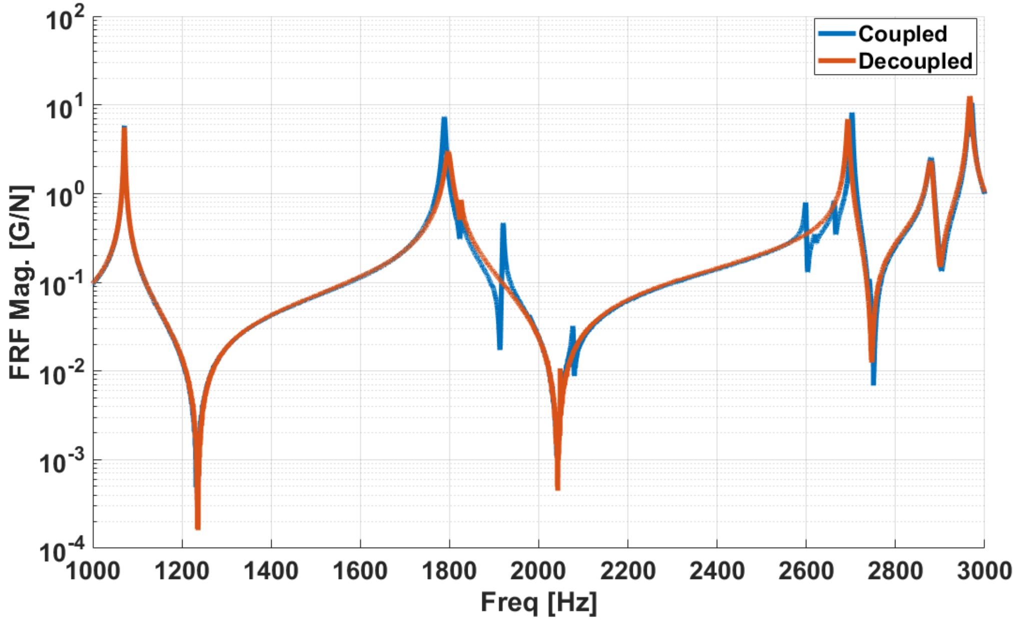
- Structural peak shifted down in frequency, indicating that more mass than stiffness was added to the system
- No effect on decoupling the structure

Presentation Outline

- Acoustoelasticity Theory
- Hardware and Test Setup
- Coupling Identification and Measurement
- Mitigation Strategies
- **Conclusions**

Summary: Successfully measured acoustoelastic coupling and decoupled the structural response

- The air inside the cylindrical cavity caused coupling in multiple structural and acoustic modes
- Coupling identified and measured using typical structural impact excitation
- When the cavity is accessible, paper towels offer an effective and cheap method of quickly identifying and mitigating coupling
- If the cavity is inaccessible, structural modifications have so far been unsuccessful in removing coupling



Acknowledgments

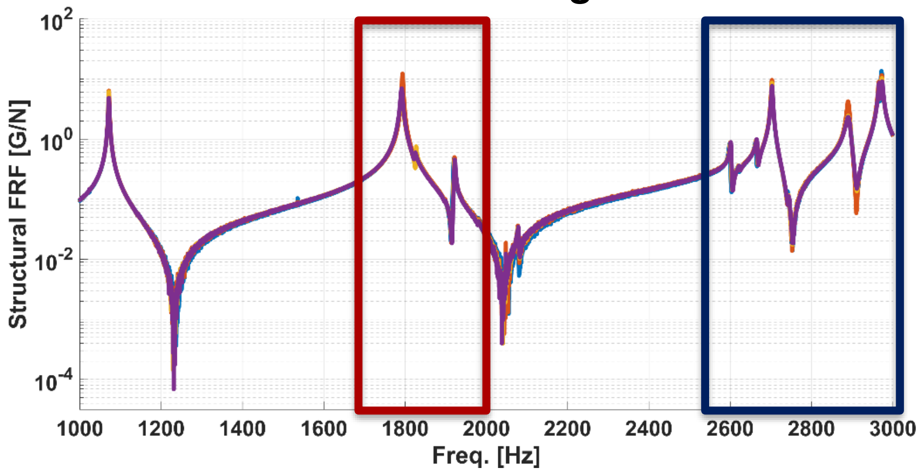
- This research was conducted at the 2017 Nonlinear Mechanics and Dynamics Research Institute supported by Sandia National Laboratories.

- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

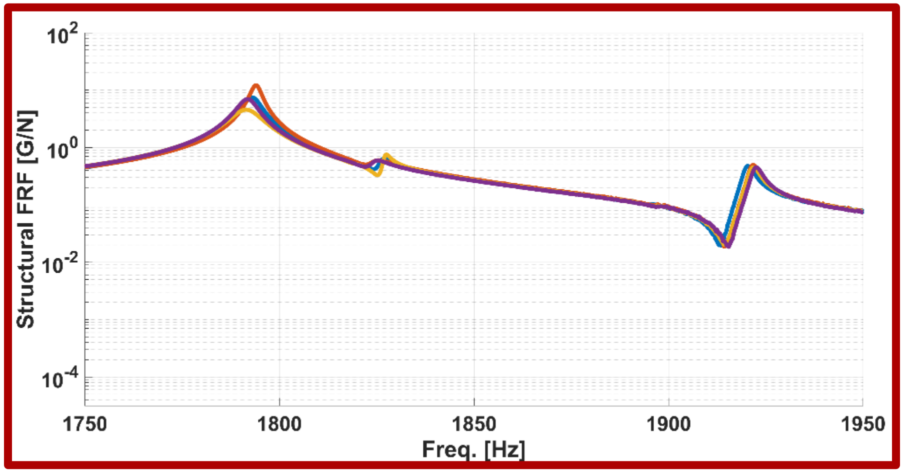
Backup Slides

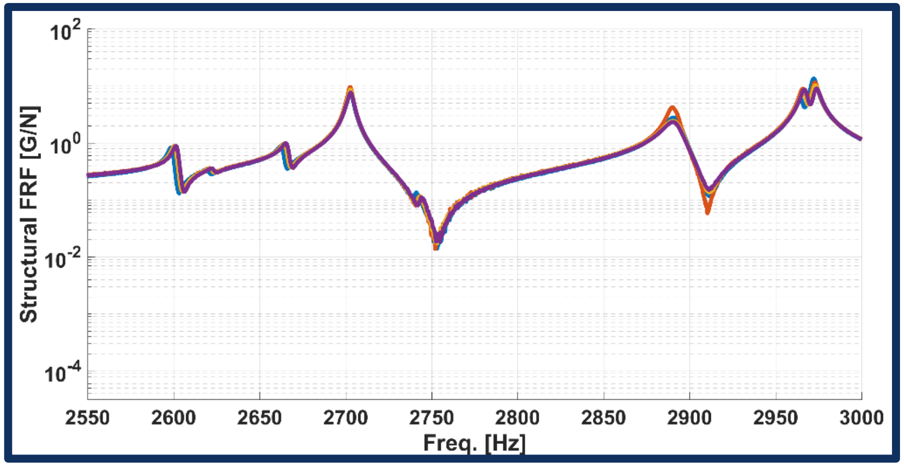
Bungee lengths and connection locations alter amplitudes and shift frequencies

FRF variations due to bungee variations



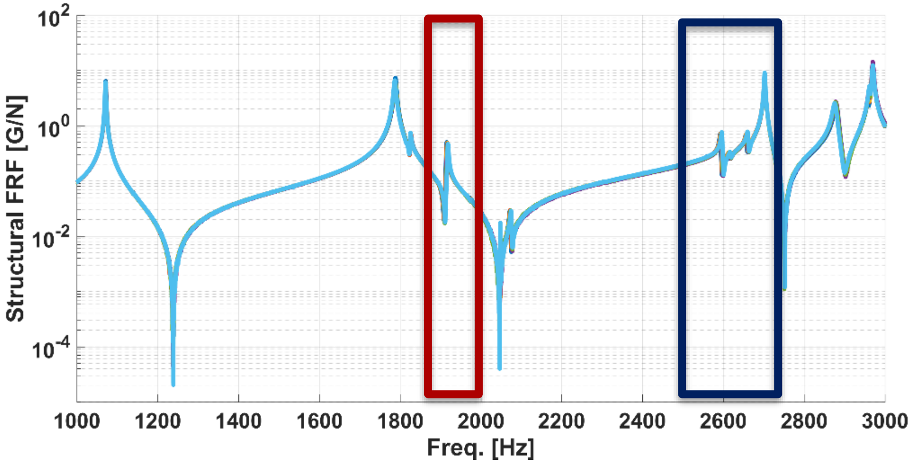
Zoomed FRF



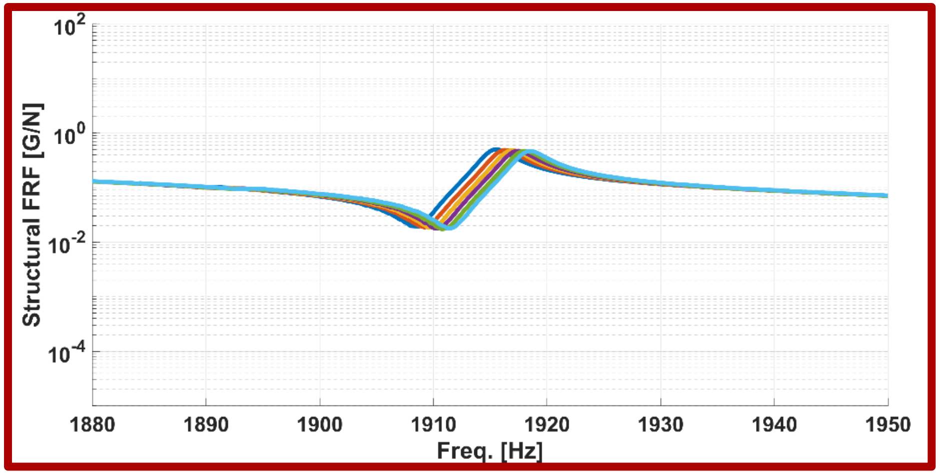


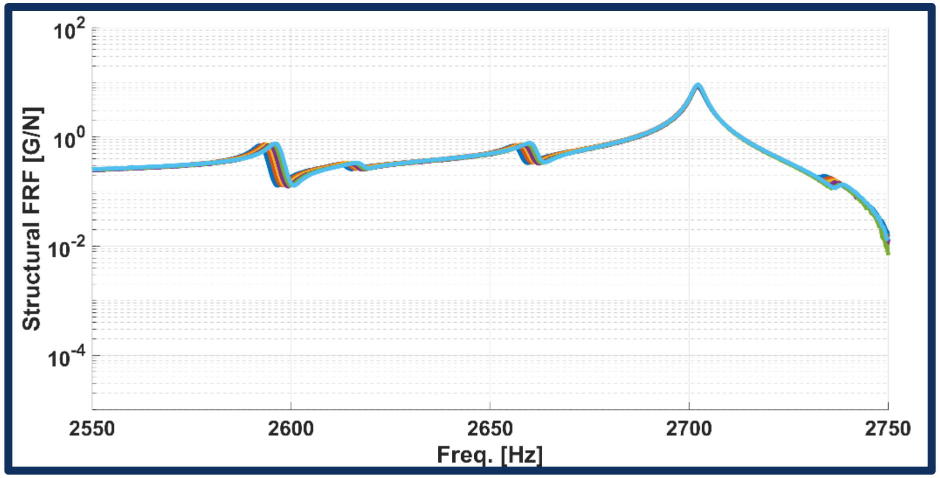
Cylinder end cap removal / reattachment shifts coupled acoustic frequencies

FRF variations due to end cap handling



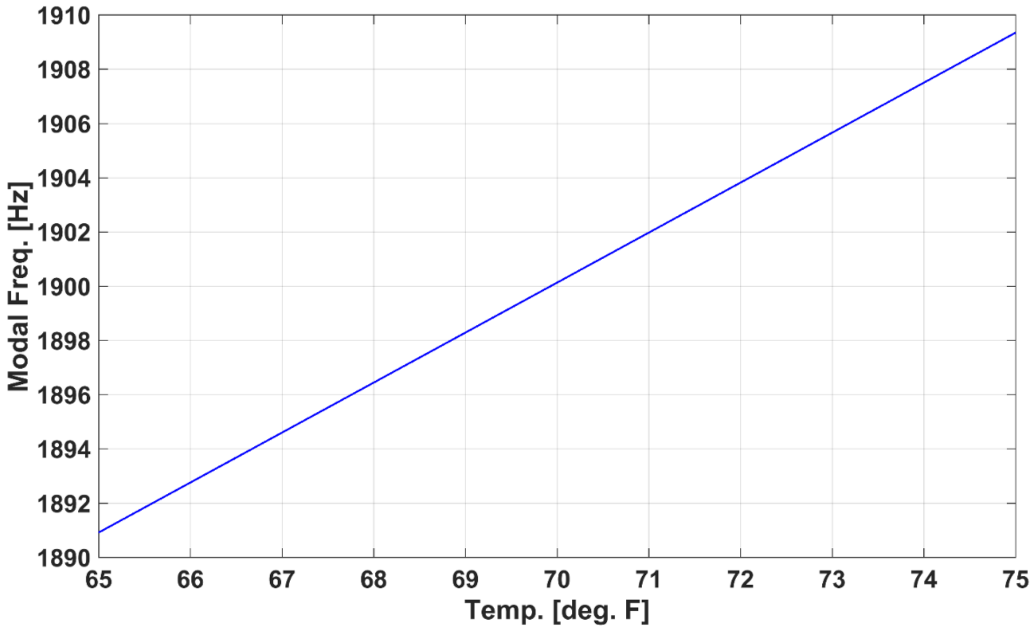
Zoomed FRF



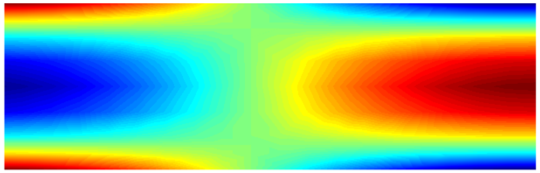


Small temperature changes can shift acoustic mode frequencies significantly

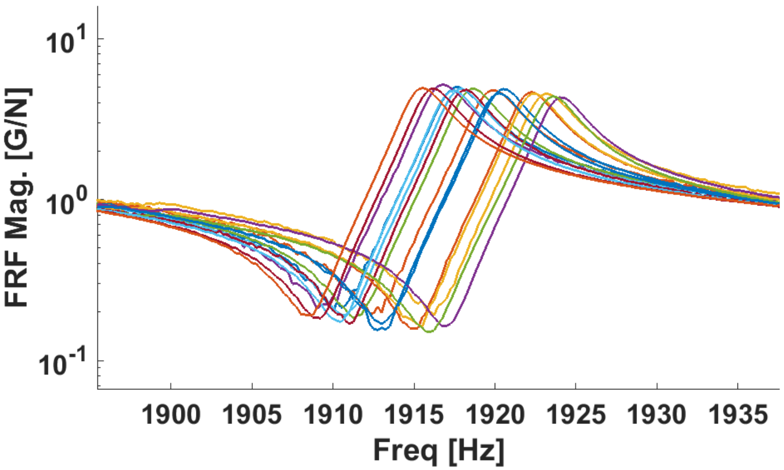
Temperature effects on acoustic (2,1,1) modal frequency



Acoustic (2,1,1) mode shape



Day to Day Changes



- In a similar manner, static pressure fluctuations can also induce frequency shifts