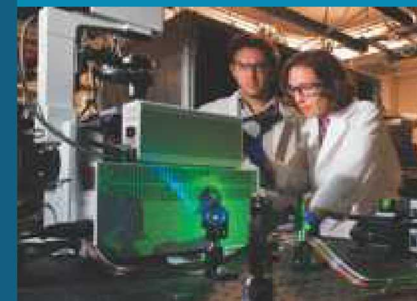
SAND2019-0350PE

Challenges of Modal Testing Hollow Structures: Coupling with Acoustic Modes



PRESENTED BY

Ryan Schultz, 17 January 2019

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Introduction

- Who am I?
  - R&D Engineer at Sandia National Laboratories
  - Work in Engineering Sciences, in the Structural Dynamics Department
- Background:
  - Acoustics, Noise Control, Structural Dynamics
  - B.S. ME – Michigan Tech
  - M.S. ME – Purdue
  - PhD ME – UMass Lowell (in progress)
  - M. Eng. – Penn State (in progress)
- Topics of Interest:
  - Structural dynamics & acoustic field modeling
  - Modal testing, modal analysis
  - Model updating
  - Reduced-order modeling
  - MIMO vibration and acoustic testing

Michigan Tech

PURDUE UNIVERSITY

PennState

UMASS University of Massachusetts Lowell

Topics

- 2 Sections:
- Quick Discussion of Acoustics at Sandia
  - Environmental Testing
  - New Techniques – Multi-shaker Testing
- Challenges of Modal Testing Hollow Structures: Coupling with Acoustic Modes
  - A Bit About Modes
  - Simple Coupled System: Tuned Absorber
  - Modeling of Acoustoelastic Systems
  - Measurements of an Acoustoelastic System
  - Decoupling – Removing the Effects of the Air

Acoustics at Sandia

- Lots of different folks doing lots of different work – not a comprehensive list!
- A Few Highlights:

Infrasound

- Measurement of very low frequency sound
- Design of transducers and arrays
- Data processing for source characterization and localization

Field Measurements

- Acoustic arrays to measure launch vehicle noise
- Embedded pressure transducers to measure skin pressure in flight

Environmental Testing

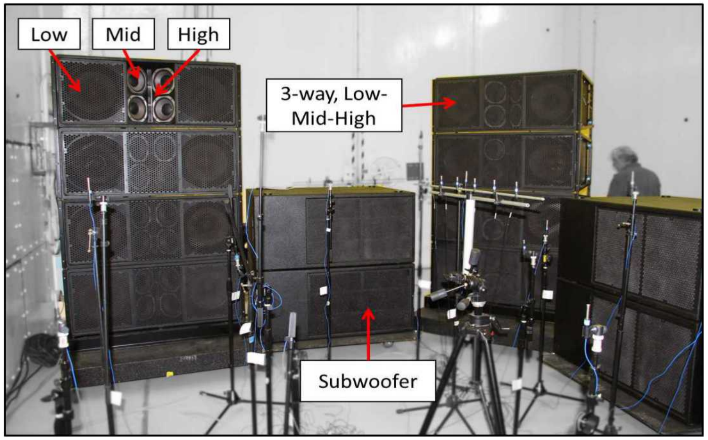
- Reverberation chamber testing
- Direct Field testing
- Simulate field environments in the lab, measure vibration response

Acoustics at Sandia

- Acoustic environmental testing is the best method for simulating some field environments in the lab
  - Flight environments where loads are acoustic or aero-acoustic
  - Much better match to overall response vs. shaker testing
- Difficult to achieve extremely high SPLs (NASA Glenn RATF gets 160+ dB, cost $30M)
- Equipment & Facilities:

Large Reverberation Chamber (20' x 25' x 30')

Large Electrodynamic Loudspeakers Subs & 3-way Cabinets



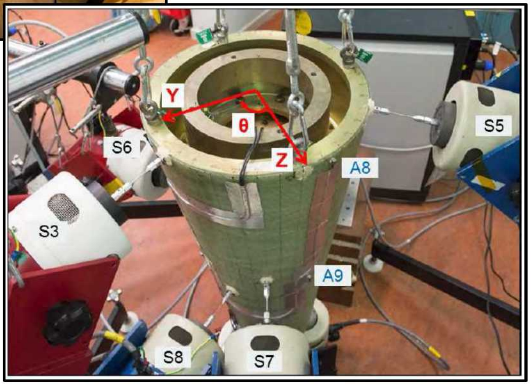
Max. OASPL ≈ 143 dB SISO or MIMO Control

Direct-Field Testing MIMO Control

Acoustics at Sandia: Future Efforts

- Multi-shaker testing or IMMAT
  - Multiple-input/multiple-output control
  - Lots of input freedom = more accurate response at all points on the structure
  - Low power requirements, take advantage of structure's natural vibration modes
- Research Efforts:
  - Control algorithms
  - Weighting of control target data
  - Shaker location optimization
- Combined-inputs testing
  - Shakers + acoustics
  - 6-DOF

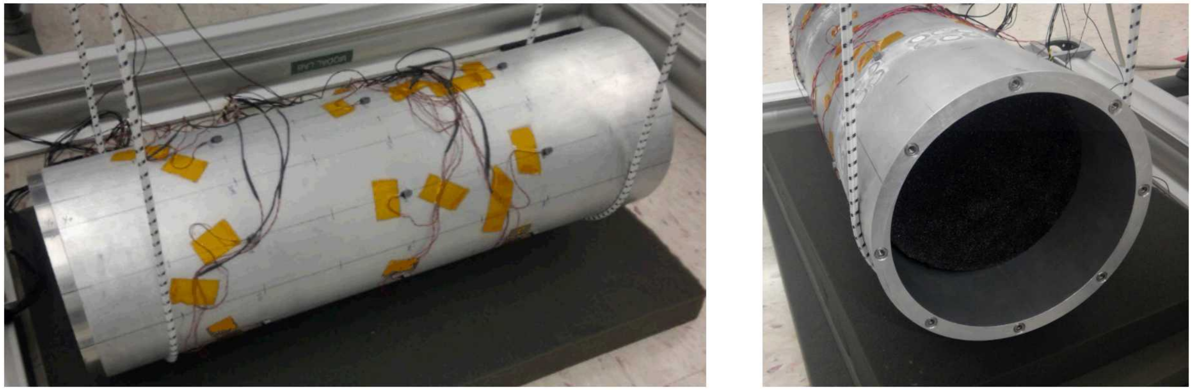
Re-create Response From Acoustics With Many, Small Vibration Shakers



Challenges of Modal Testing Hollow Structures: Coupling with Acoustic Modes

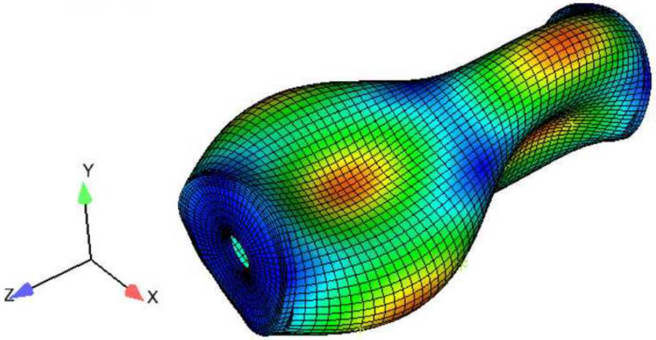
Acoustoelasticity:
Acoustic Modes Coupling With Structural Modes

We Often Deal With Hollow Structures



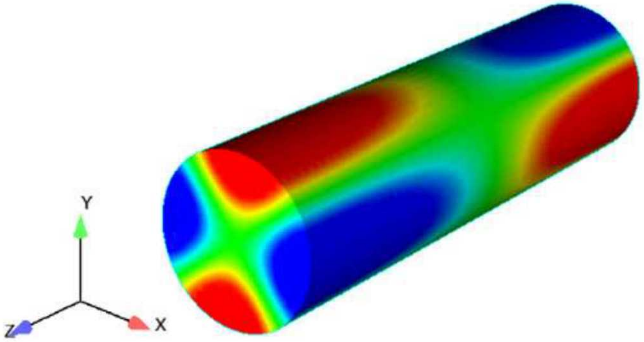
Example Hollow Structure

Structure Has Modes of Vibration



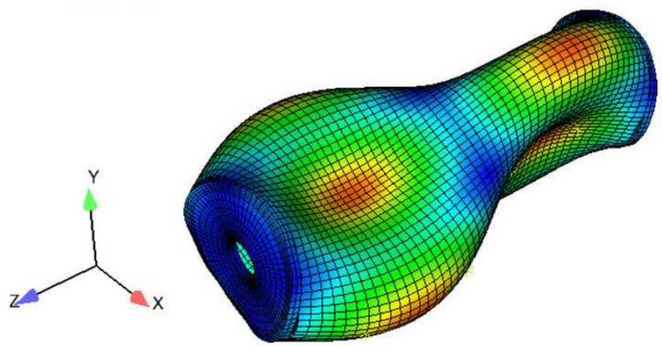
2,1 Ovaling Mode, 1800 Hz

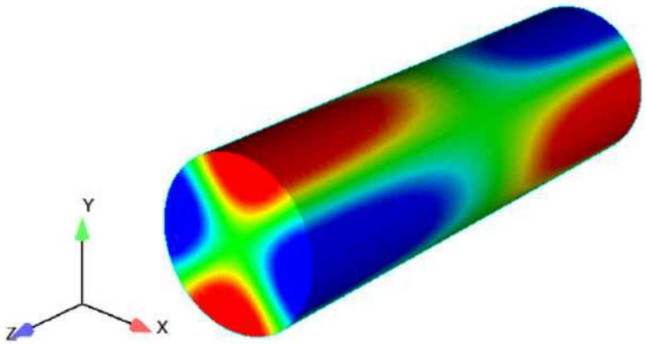
Acoustic Cavity Also Has Modes



2,1 Ovaling Mode, 1900 Hz

Acoustoelastic Coupling Occurs When…

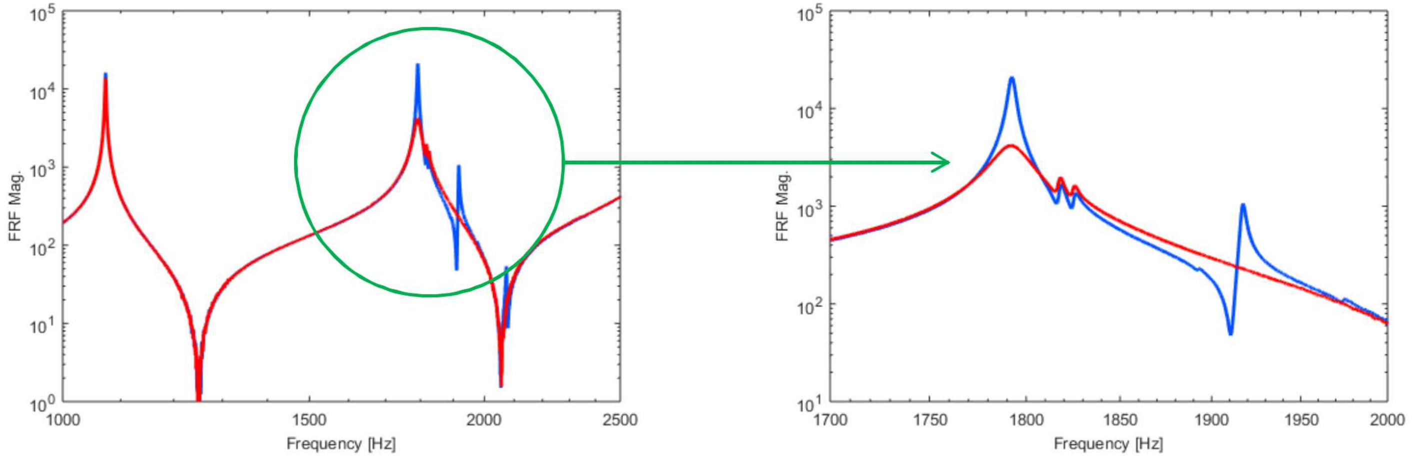




2,1 Ovaling Mode ⟷ *2,1 Ovaling Mode*
1800 Hz ⟷ *1900 Hz*

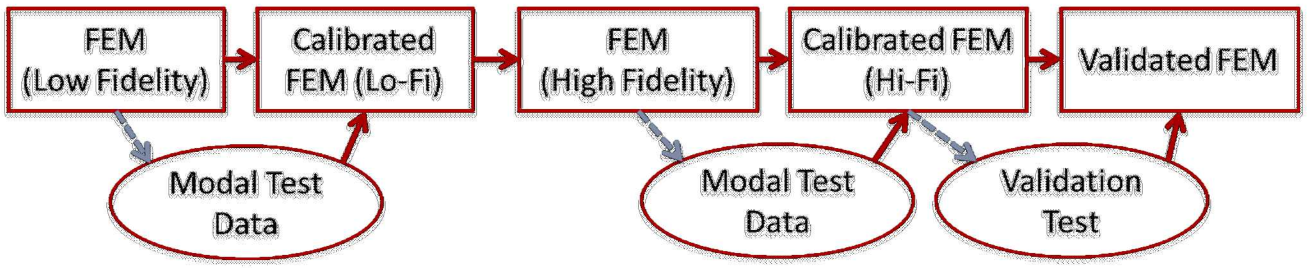
Modes are Similar in Terms of Both Shape & Frequency

Effect: Structural Response Shows Additional Peaks, Frequency Shifts, Etc.



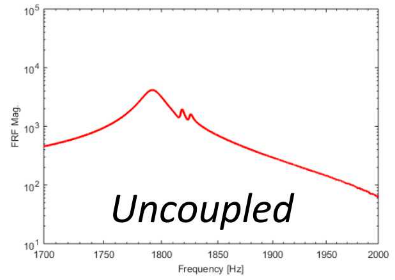
Who Cares?

- **Modal tests of structures are often performed for model development**
- **Models are updated to match the test modes, responses**



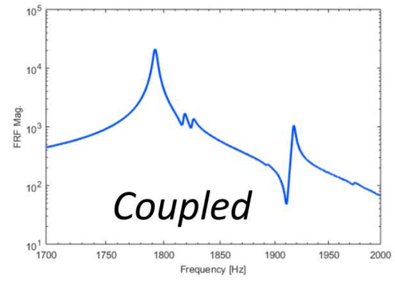
- **What if the model is a different system than the test?**
- **We generally assume air does not affect vibration of thick-walled structures**
- **What is the risk of not modeling the air in the system?**
  - **Environmental Response Predictions, Component Response, Design**

Model It Like This



vs.

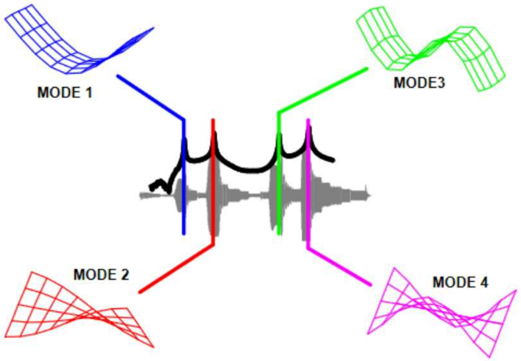
Actual Response Is This



A Bit About Modes

- Modes: Natural deformation patterns of a structure, which are strongest at particular, natural frequencies

https://www.theolympian.com/news/local/article42065382.html



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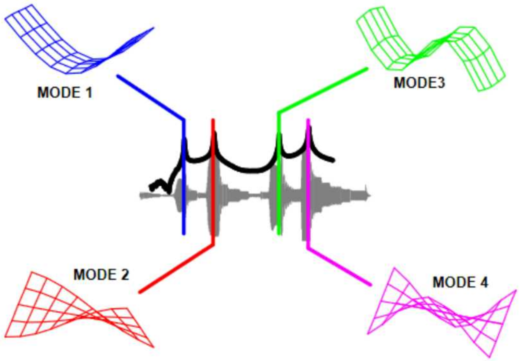

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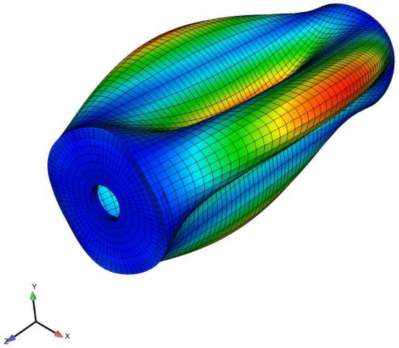
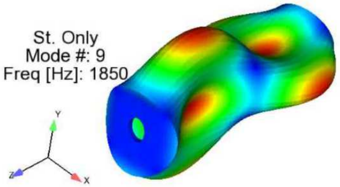
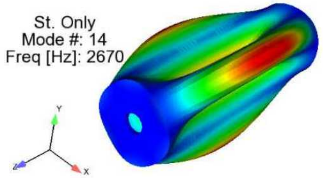
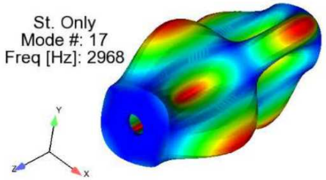


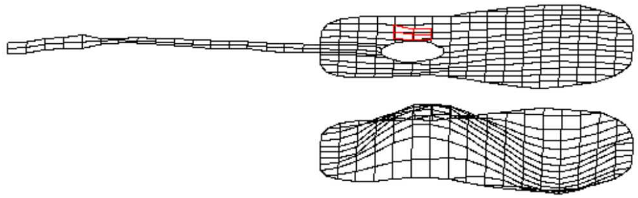




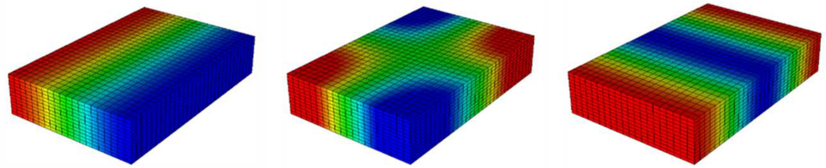


A Bit About Modes

- Just like structures, acoustic cavities have modes as well
- Just vibration of air vs. vibration of a structure
- Have pressure patterns (shapes) at natural frequencies
- Examples:
  - Loudspeaker in a cabinet
  - Musical instruments
  - Rooms & halls
  - Automotive or aircraft cabins
  - Liquid fuel tanks

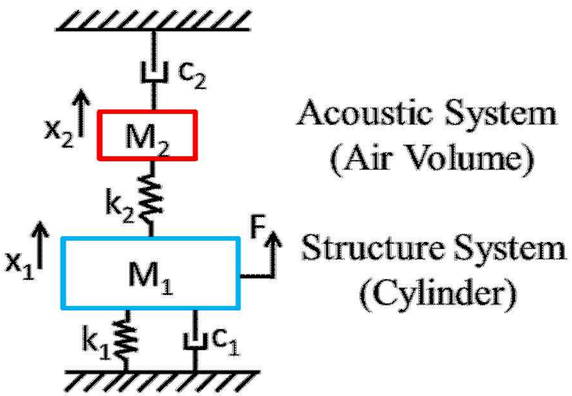


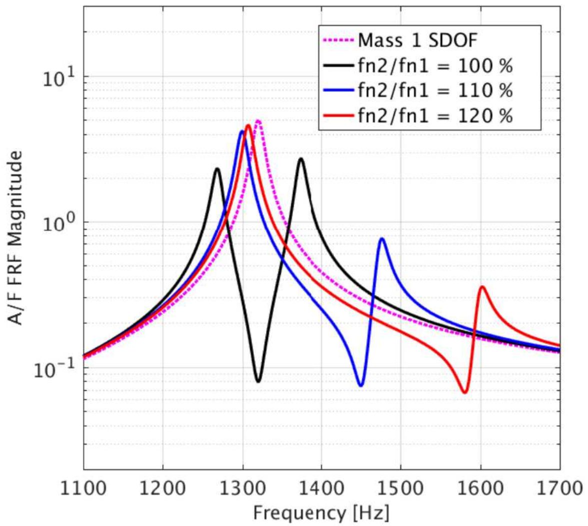
https://www.acs.psu.edu/drussell/guitars/hummingbird.html



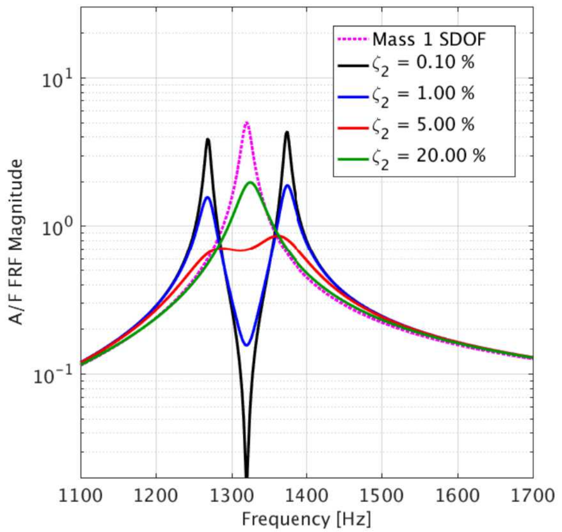
Simple Coupled System: 2 DOF Tuned Absorber

- Parasitic mass (M2) attached to main structure (M1)
- Spring connecting M2 is tuned to coincide with mode of M1
- Result:
  - Peak in FRF of M1 splits into two, amplitude and frequency shifts
  - As frequency of M2 moves away, coupling effects on M1 are reduced
  - As damping on M2 increases, coupling effects on M1 are reduced





Frequency Proximity



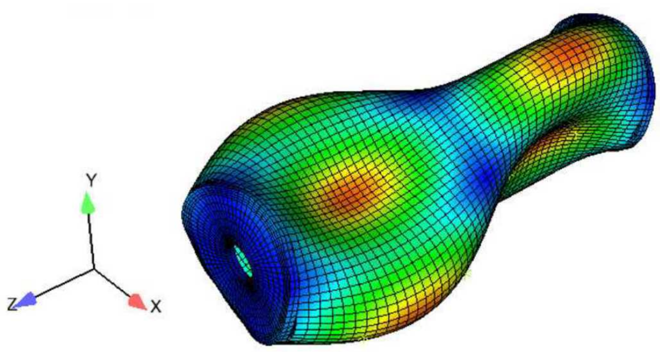
Damping

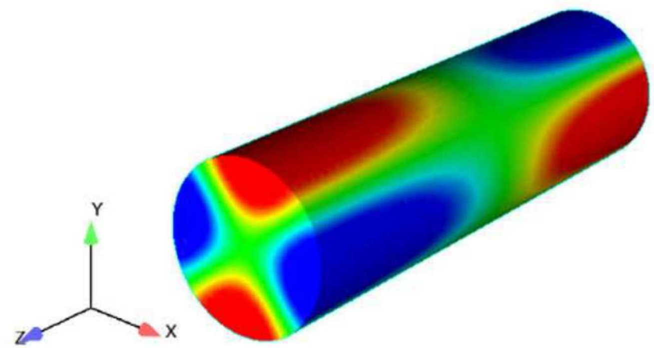
Modeling of Acoustoelastic Systems

- Two-component system
  - When both components are structures, no big deal
  - Here, one component is acoustic fluid
- Surprisingly Challenging…
  - Direct solutions – no big deal, just large & slow (need a bigger computer)
  - Modal solutions – more challenging mathematically, fast if it solves
- Result: Gyroscopically-coupled system (quadratic eigenvalue problem)

$$(K + D\lambda + M\lambda^2)u = 0$$

  - Full QEVP solution: 2x size, much more expensive, different types of quantities in the matrices (numerical challenges), etc.
  - Component mode synthesis (CMS) methods: modes from structure-only combined with modes of acoustic-only. Makes some assumptions, accurate in the limit, sensitive to basis vectors

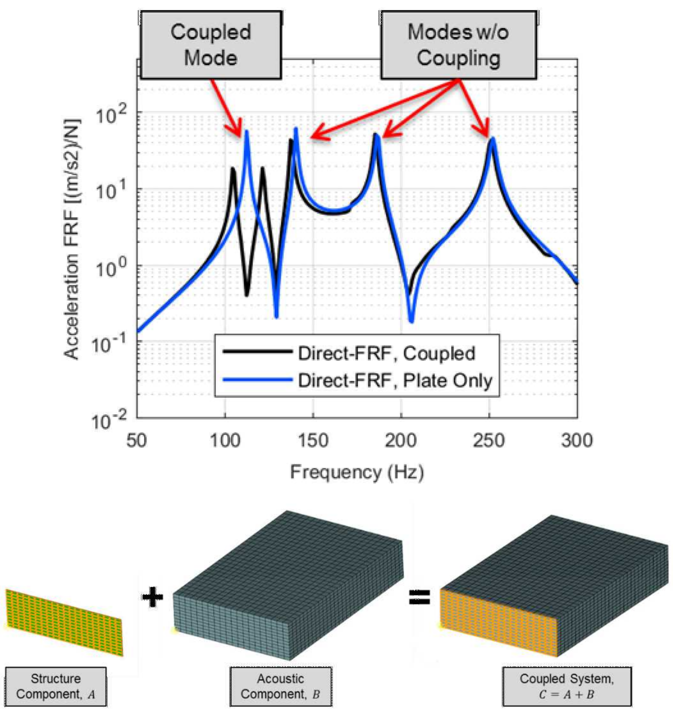




Modeling of Acoustoelastic Systems

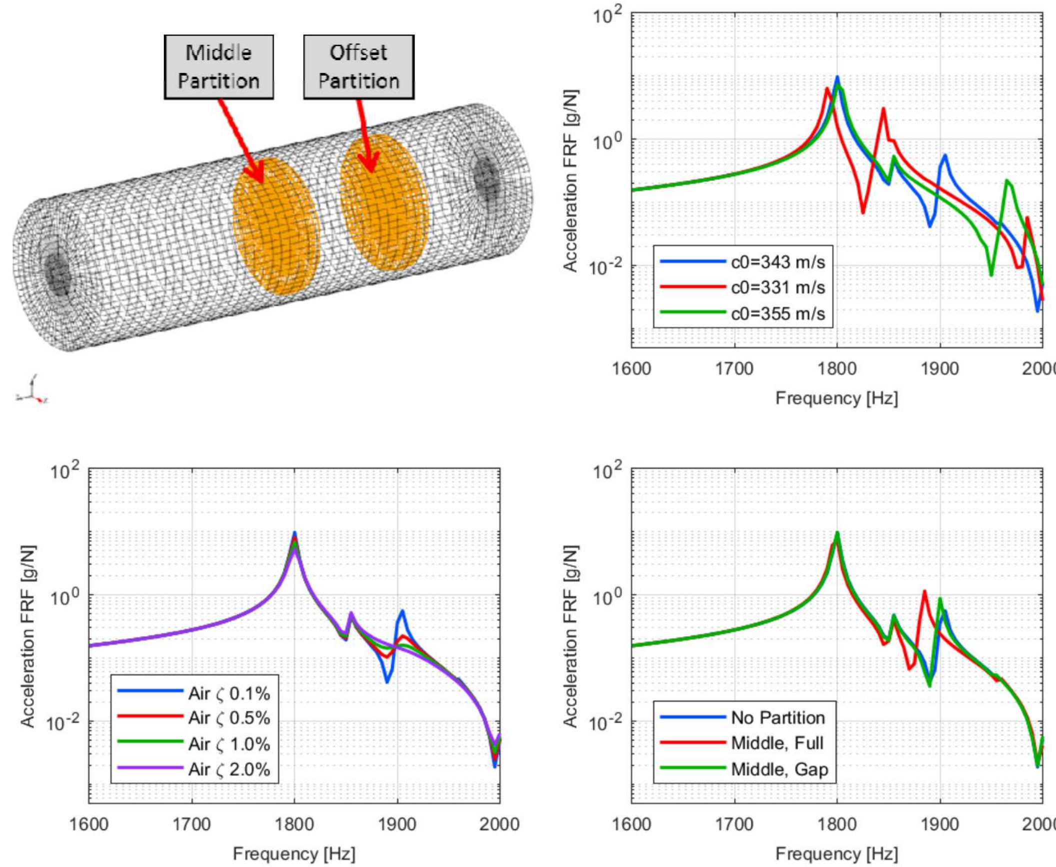
- Example of using models: FRF predictions

CMS Coupling/Decoupling Research



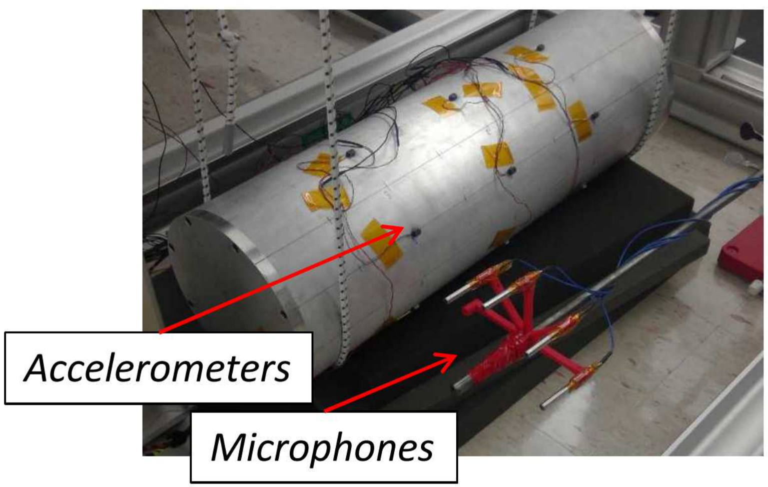
Design Studies

Decoupling Effects, Correlate to Test

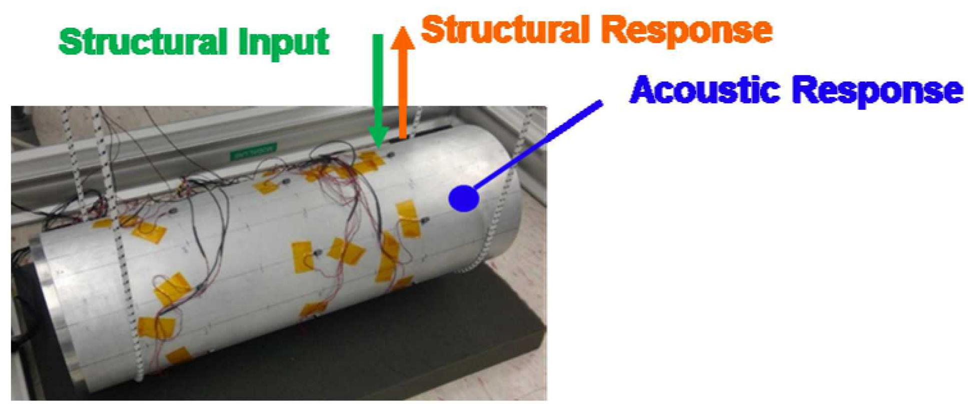


Measurements of an Acoustoelastic System

- Designed toy hardware purposely to have acoustoelastic coupling
- Used by student group in Sandia's NOMAD summer research institute
  - Students measured response of the shell, and response of the acoustic cavity
- Used typical modal analysis software to determine modes of the coupled system
  - Obtained coupled system frequencies
  - Mode shapes of the shell (structural vibration)
  - Mode shapes of the acoustic cavity (acoustic pressure)



Shell, Free-Free Boundary Conditions



Hammer Impact Excitation
Measure Accel. & Mic. Response

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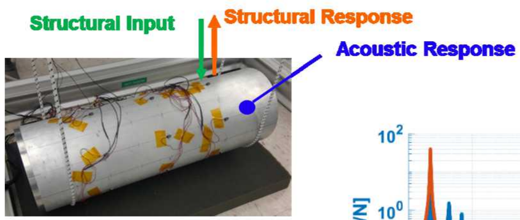
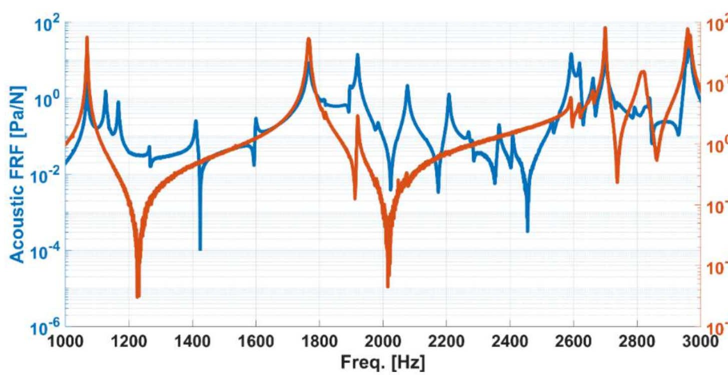
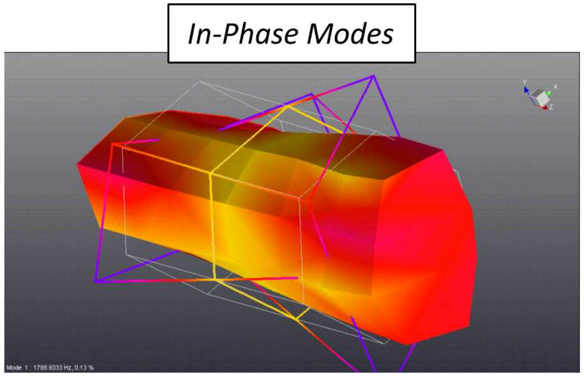
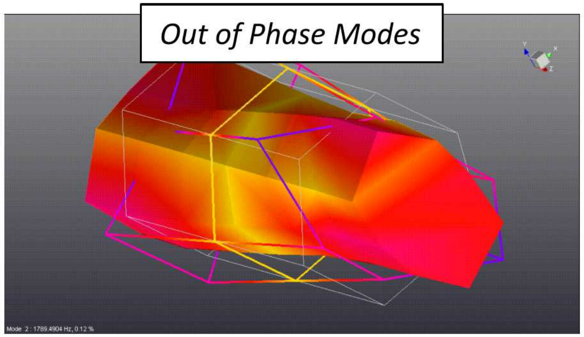




Process Response Into
Pressure & Acceleration FRFs



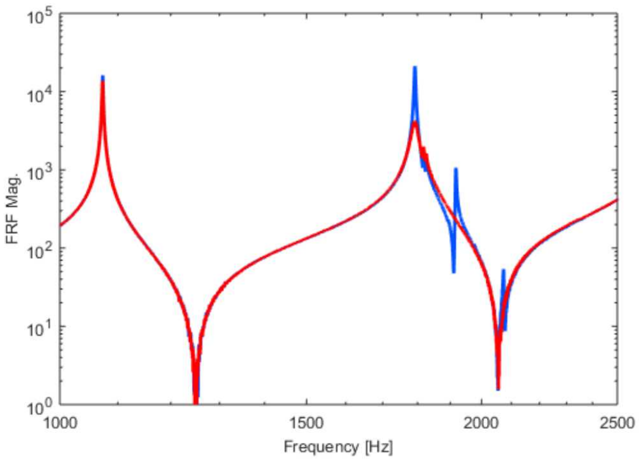


Modal Parameter Estimation

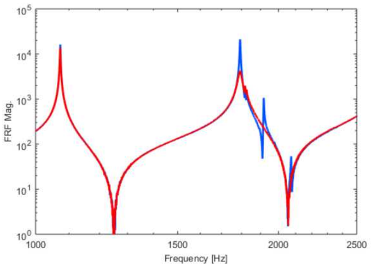
Removing the Coupling – Experimental Methods

- If test data is used for model updating, we want the in vacuo (structure-only) modes
- Need to modify the test hardware to remove the acoustic cavity coupling effects
- How do we do that?
- Pull a vacuum.. ✗
- Fill the cavity… ✗
- Get clever! ✓

Important: Do not alter the dynamics of the structure!
(That's what we need to measure)



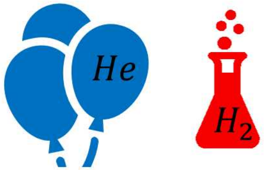
Removing the Coupling – Experimental Methods



- Get clever!
  - Shift the mode frequency
  - Add damping to the air
  - Change the boundary conditions for the air

Shift the Frequency

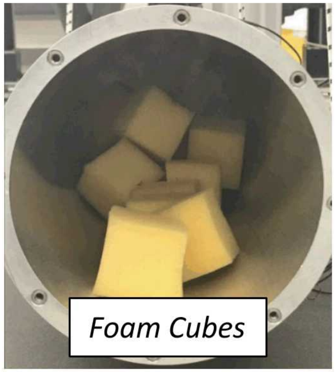
- Change the Mass
- Change the Stiffness
- …Change Gas?



(Denied by Management)

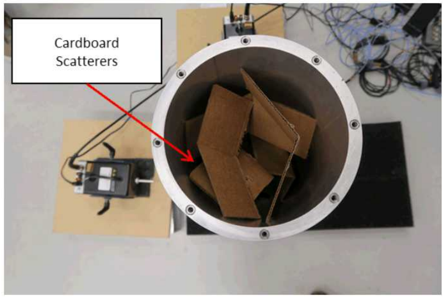
Add Damping to the Air

- With a dashpot?
- High flow resistivity
- Foam, fiberglass



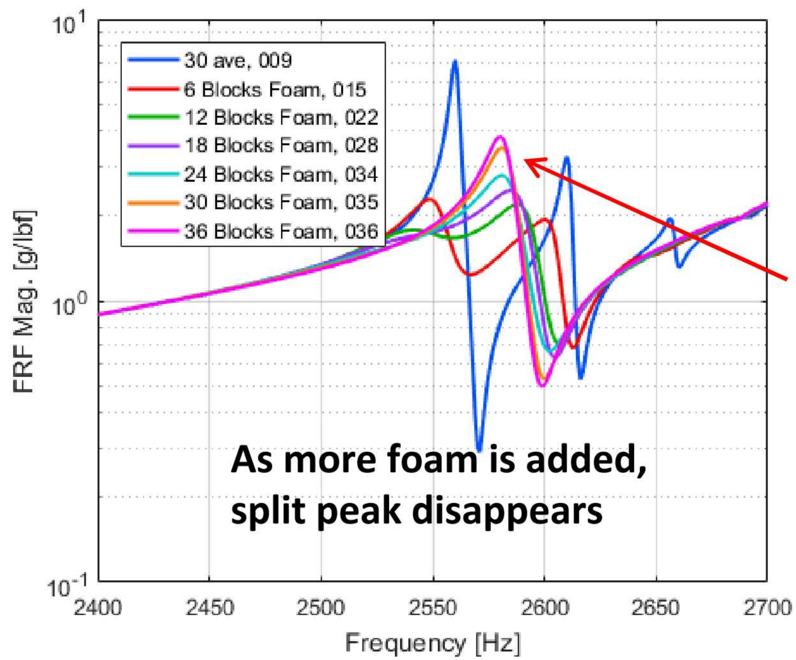
Change the Boundary Conditions

- New boundary conditions = different mode shape
- Add a barrier



Removing the Coupling – Experimental Methods

- Foam is light & flimsy, does not affect the structure
- Open-cell foam has lots of tiny open passageways through which air can flow, but with resistance
- This resistance absorbs energy (why foam is used to absorb sound)
- How much foam is needed?



Resultant peak appears highly damped....

Add Damping to the Air

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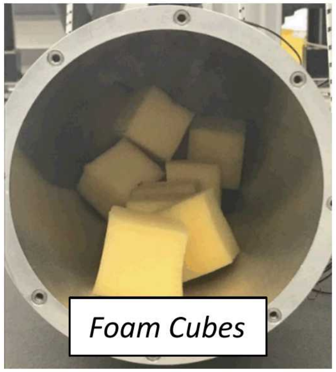

Removing the Coupling – Experimental Methods

- Changing the boundary conditions changes the acoustic mode by:
  - Changing the size/shape of the cavity
  - Making reflective surfaces, changing the admissible modes in the cavity
- Luckily, air is light so a barrier is easy to create
  - Just need a sufficient impedance mismatch

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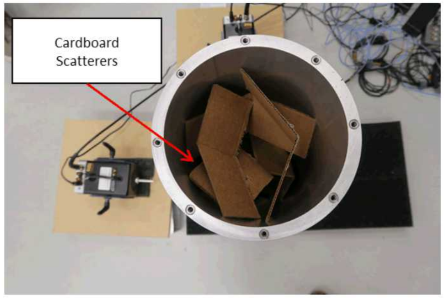

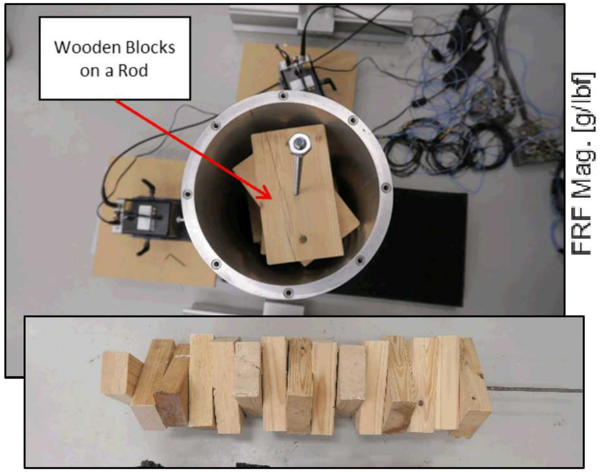

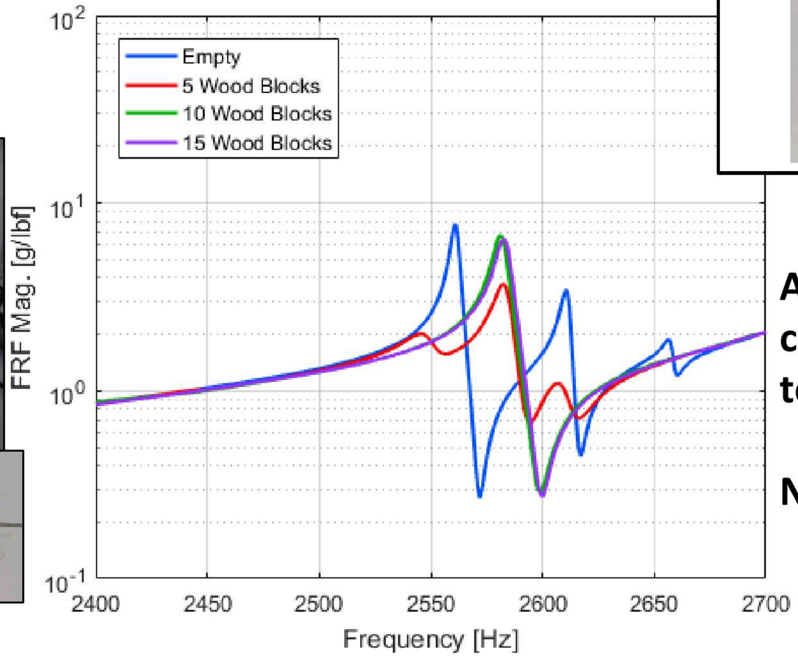

A large chunk of material changes the BCs enough to decouple…

Not practical…

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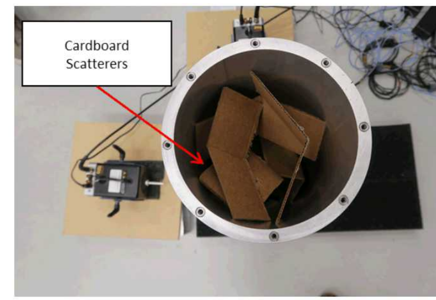

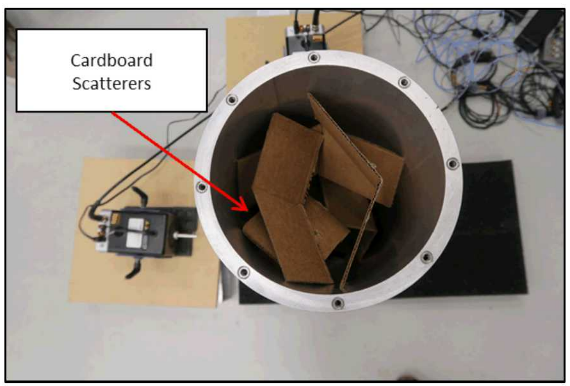

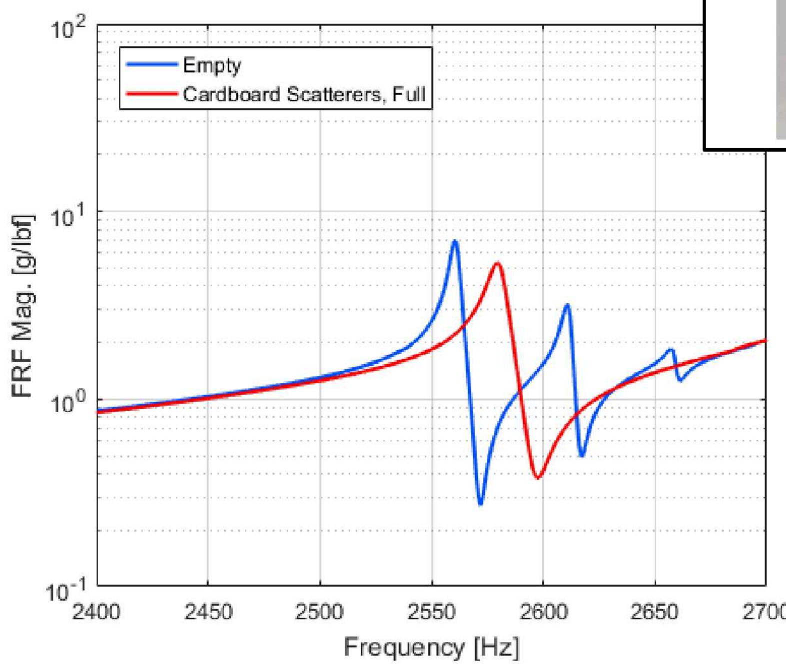

Random Cardboard Pieces Create Sufficient Scattering to "Break Up" the Mode

Getting Better...

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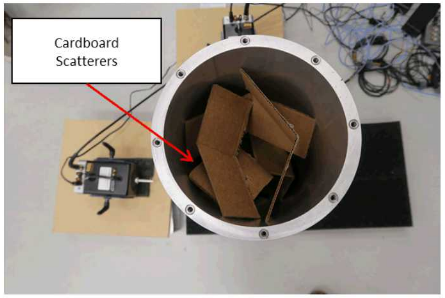

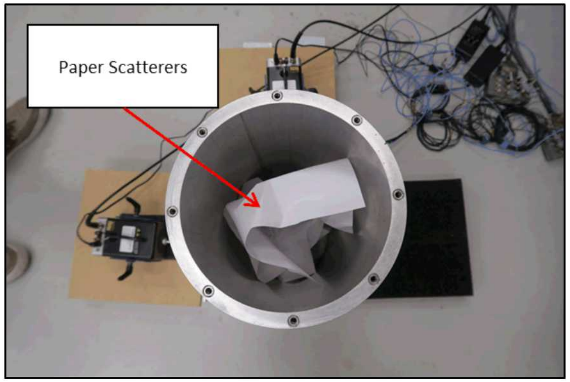

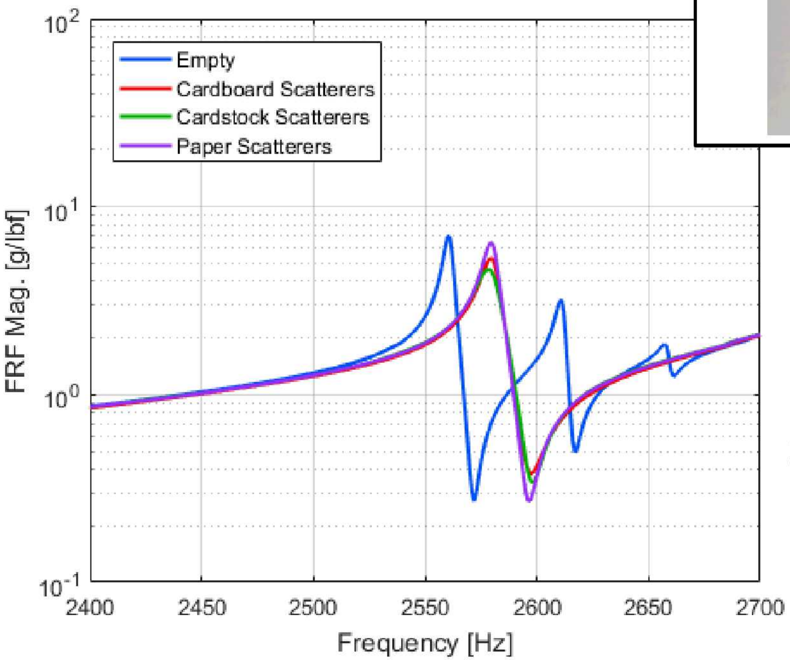

Even Paper Can Act Like a Decent Scatterer

Now We're Getting Somewhere!

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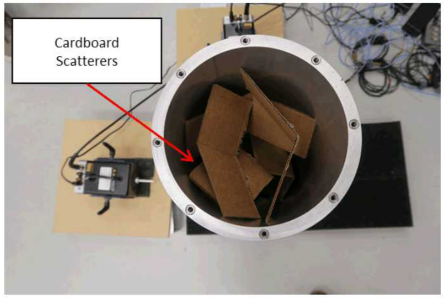
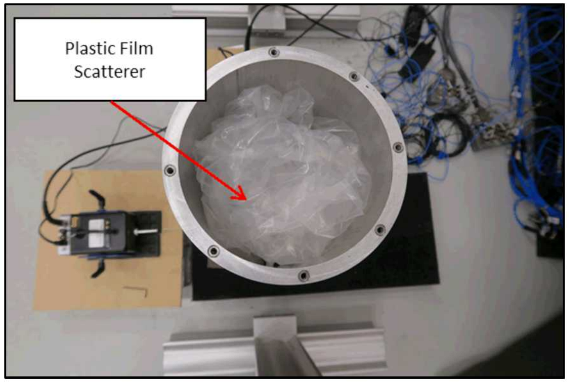
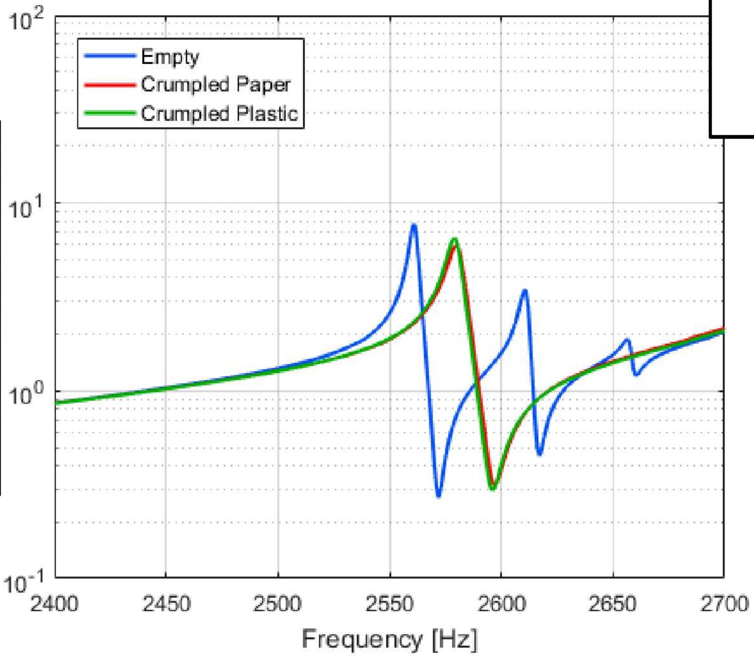




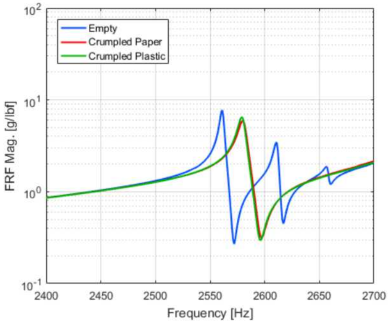


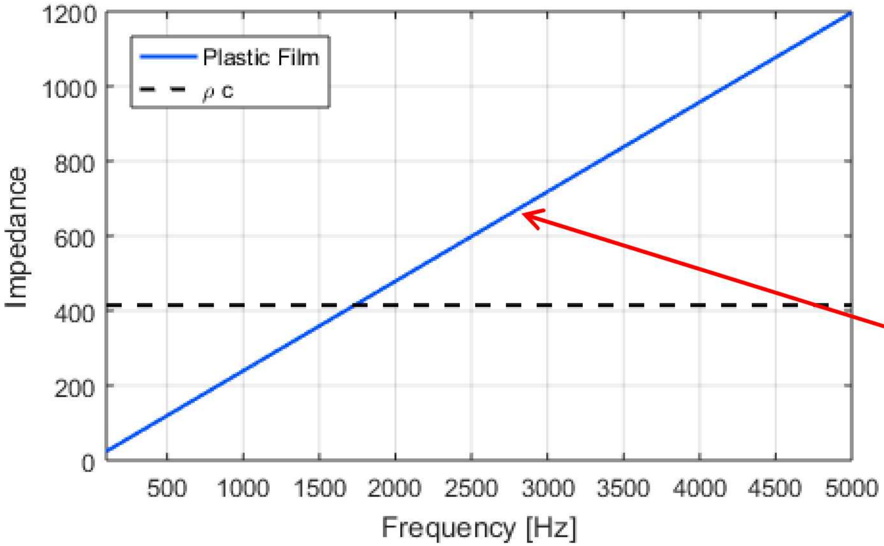
Thin Plastic Film Also Works Great!

- **Disrupts the acoustic mode (Boundary Conditions)**
- **Does not affect the structure (very light, very flimsy)**

Removing the Coupling – Experimental Methods

- Why does this work?
- Plastic film is so flimsy & light…
- All comes down to impedance!
  - If the impedance of the film is >> than the air, then the acoustic waves will be reflected
  - When the impedance of the film becomes large, it acts like a (decent) barrier – creating lots of randomly-oriented surfaces, breaking up the nice mode shape



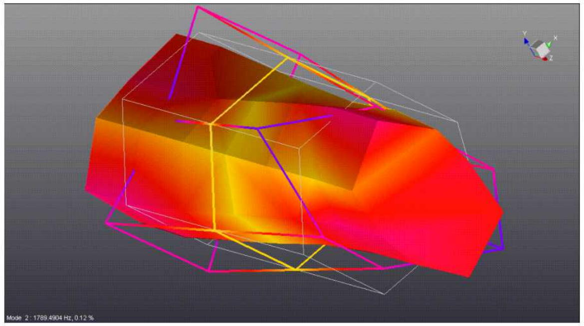


Impedance of Mass-Like Barrier:

$$z(\omega) = j\omega m_s$$

Plastic Film is Acoustically Massive

Remarks



What did this study tell us?

1. Thick-walled structures can be affected by air
2. Structures of the size & shape we care about may be susceptible to acoustoelastic coupling
3. We can measure modes of coupled systems, including acoustic mode shapes
4. Coupling can be mitigated by adding damping or acoustic scatterers
5. Something as simple as a plastic bag can provide sufficient impedance mismatch to alter the acoustic modes, as long as high enough in frequency
6. Understanding coupling is important to making accurate predictions or to calibrating models to test structures

Where do we go from here?

- Be cautious when testing anything hollow…
- Model the coupled system for higher accuracy response predictions

Structural-Acoustic Mode Interactions

PRESENTED BY

Ryan Schultz, 17 January 2019

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