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Effects of internal acoustic coupling on the response of a base-excited hollow structure

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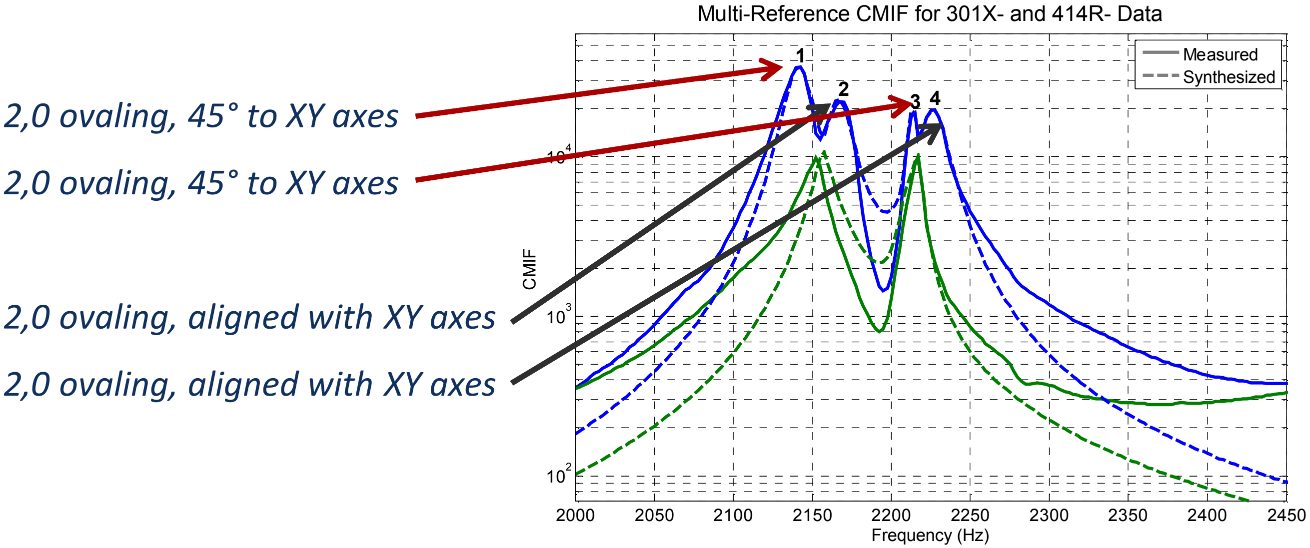
Motivation

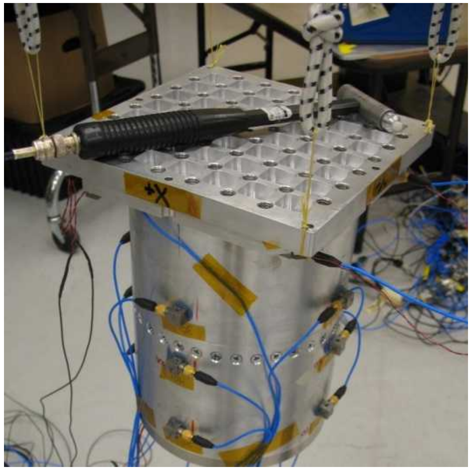
- Sandia does a lot of structural dynamics modeling and testing
  - Make predictions of system/component response in dynamic (vibration/aero-acoustic) environments
  - Large effort toward validated structural dynamics FE models
- We usually assume our structures are not affected by air in hollow cavities because…
    - *The cavities are small!*
    - *It's just air!*
    - *How would we know!*
- But – what if these assumptions are not valid?
  - Acoustic modes of the cavity could couple with the structure
  - We would get strange modal test results (repeated shapes)
  - Our model wouldn't correlate well to the modal test results
  - Our model response predictions would be wrong

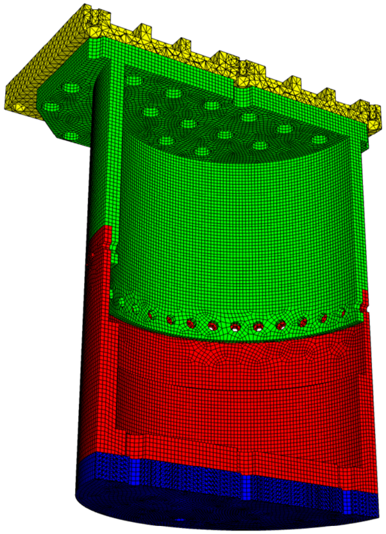
Recent examples of coupling in modal tests at Sandia: Closed Can on a Baseplate*

- Modal test of a hollow cylindrical article revealed repeated shapes at different frequencies
- Calculation of the (2,1,0) acoustic mode:
  - $f_{lmn} = \frac{c}{2}\sqrt{\left(\frac{\alpha_{mn}}{\pi a}\right)^2 + \left(\frac{l}{h}\right)^2} = \frac{343}{2}\sqrt{\left(\frac{3.05}{\pi\, 0.080}\right)^2} = 2081\ Hz$



Complex Mode Indicator Function (CMIF)

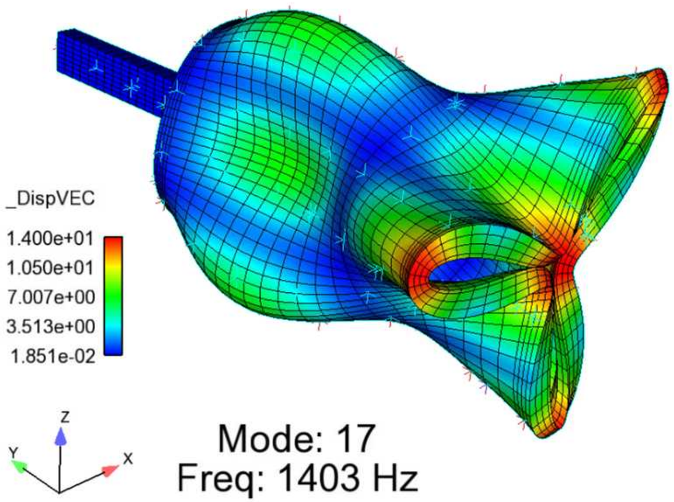




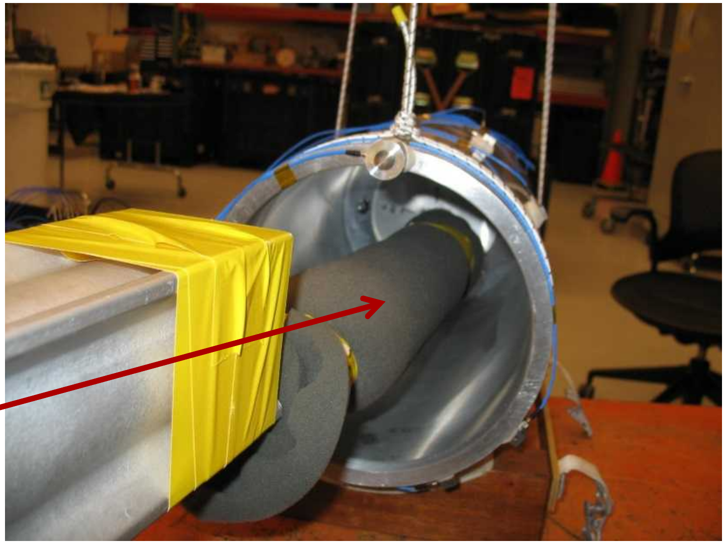
*Example & figures taken from: B. Pacini, D.G. Tipton, “Structural-acoustic mode coupling in a bolted aluminum cylinder,” Proceedings of IMAC XXXIV, 2016.

Recent examples of coupling in modal tests at Sandia: Open-ended Cylinder

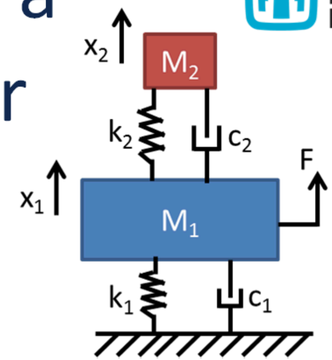
- Modal test indicated repeated (3,1) shapes around 1408 & 1416 Hz
  - Get a double peak in the structural FRF where a single peak is expected
- Calculation of the acoustic modes:
  - *assuming closed cylinder*
  - (2,1,1) acoustic mode right around 1420 Hz
- Mitigated the coupling issue by adding absorbing material to the cavity



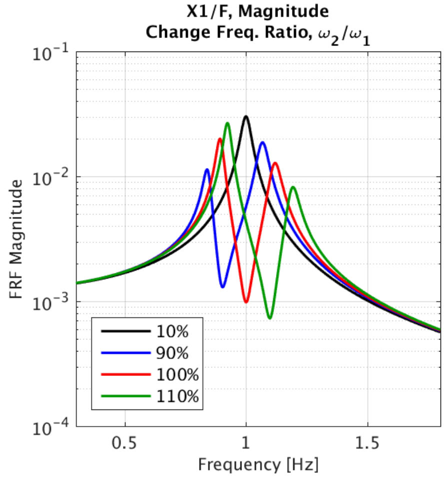
Foam added into cavity



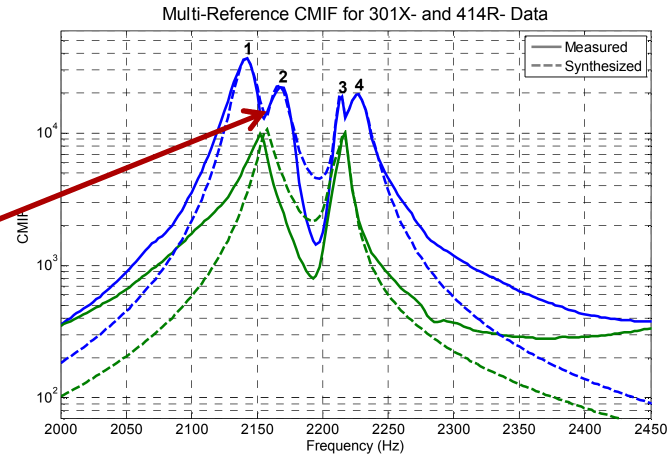
Effect of air on the structure looks like a simple 2-DOF tuned vibration absorber



- Addition of 2nd mass causes a split in the FRF peak of the 1st mass
- Effect on the FRF depends on:
  - Natural frequencies of the two masses
  - Relative mass
  - Damping



Split peaks observed in modal test

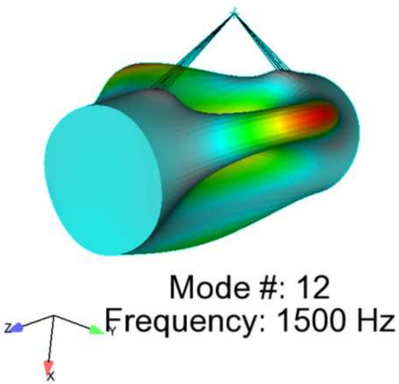


Effect of Proximity of ω_{n1} and ω_{n2}:

- *FRF affected if ω_{n2} near ω_{n1}*
- *Single resonance peak split into two peaks*
- *Max response is reduced*

Investigate how coupling could affect response prediction with a simulation study

- Simple cylinder with force input to 2 points on side
  - Like a store on a wing subject to a base excitation
- Dimensions: 32” long, 12” diameter
- Shell elements allow for varying the wall thickness to align structure and acoustic modes
  - Determine wall thickness to match the (3,1,0) acoustic mode



Analytically-calculated Acoustic Modes

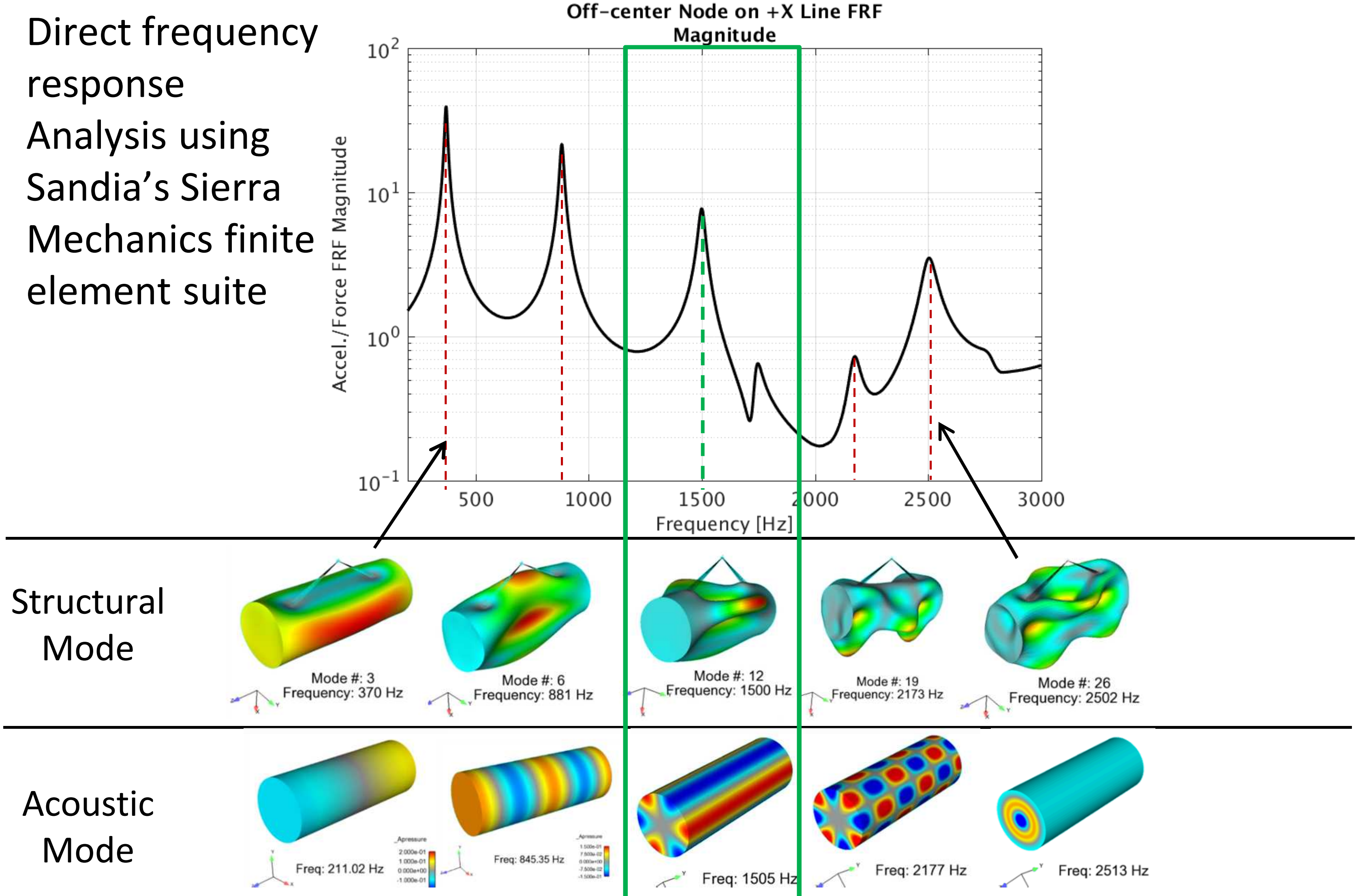
Shape	Freq. [Hz]
Axial 1	211.0
Slosh 1	659.1
Ovaling 2 lobe	1092.5
Ovaling 3 lobe	1504.5
Ovaling 2 + Axial 1	1112.7
Radial 1 (bullseye)	1371.9

Structural Modes:
0.65” Thick – Aligns with (3,1,0) Acs. Mode

Shape	Freq. [Hz]
2,0 (2nd)	881
3,0	1500
1st bending	1740
3,2	2173

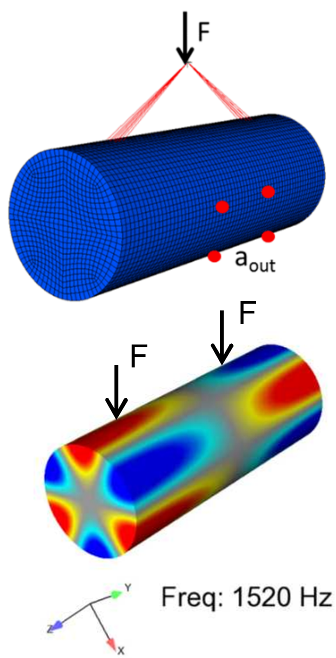
Structural FRFs & Acoustic Modes

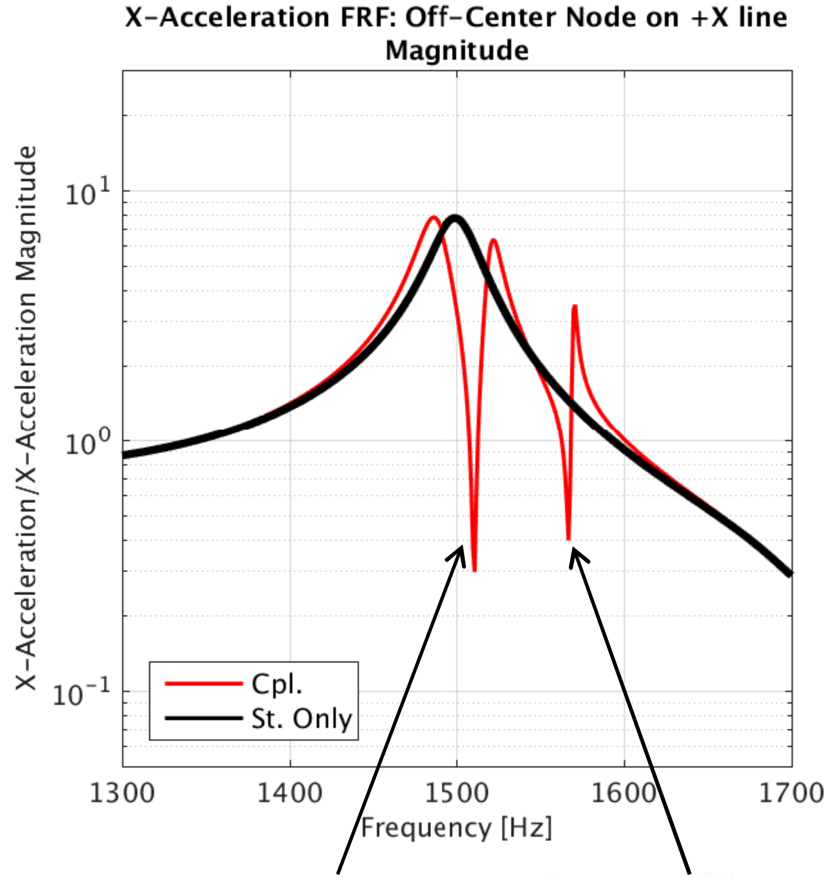
- Direct frequency response Analysis using Sandia's Sierra Mechanics finite element suite



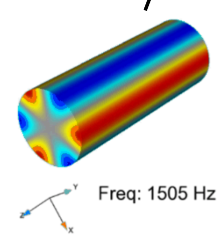
Hollow Cylinder: Effect of Coupling on FRF Peak for the (3,1) Structure Mode

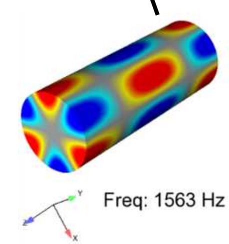
- (3,1,0) and (3,1,2) interact with the structure, but not the (3,1,1) because it is incompatible with the input





Acs. (3,1,0) coupling at structural mode

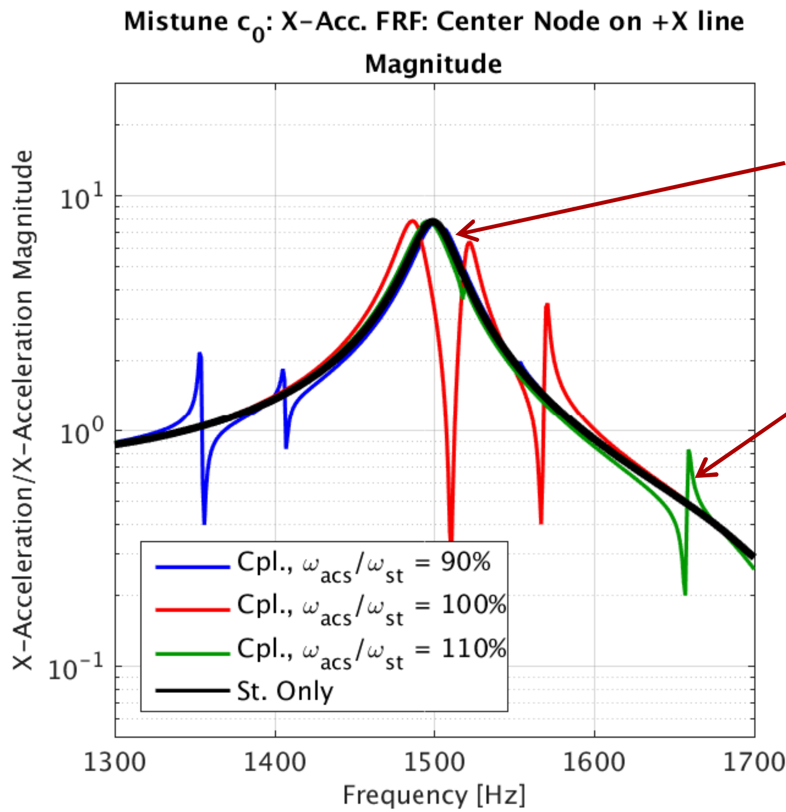




Acs. (3,1,2) mode also couples with same mode

Hollow Cylinder: Effect of Mistuning $(\omega_{n2}/\omega_{n1})$ on (3,0) Structural Response

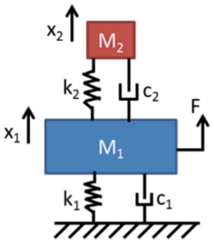
- Mistune the system by adjusting the sound speed of the air
  - 90, 100, 110% of structural mode frequency
- Get strong coupling, peak splitting when $\omega_{st} \approx \omega_{acs}$
  - Peak is not affected when $\omega_{st} \neq \omega_{acs}$

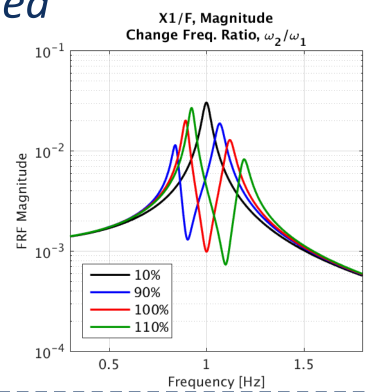


Peak affected only when $\omega_{st} \approx \omega_{acs}$

Minor coupling effects when $\omega_{st} \neq \omega_{acs}$

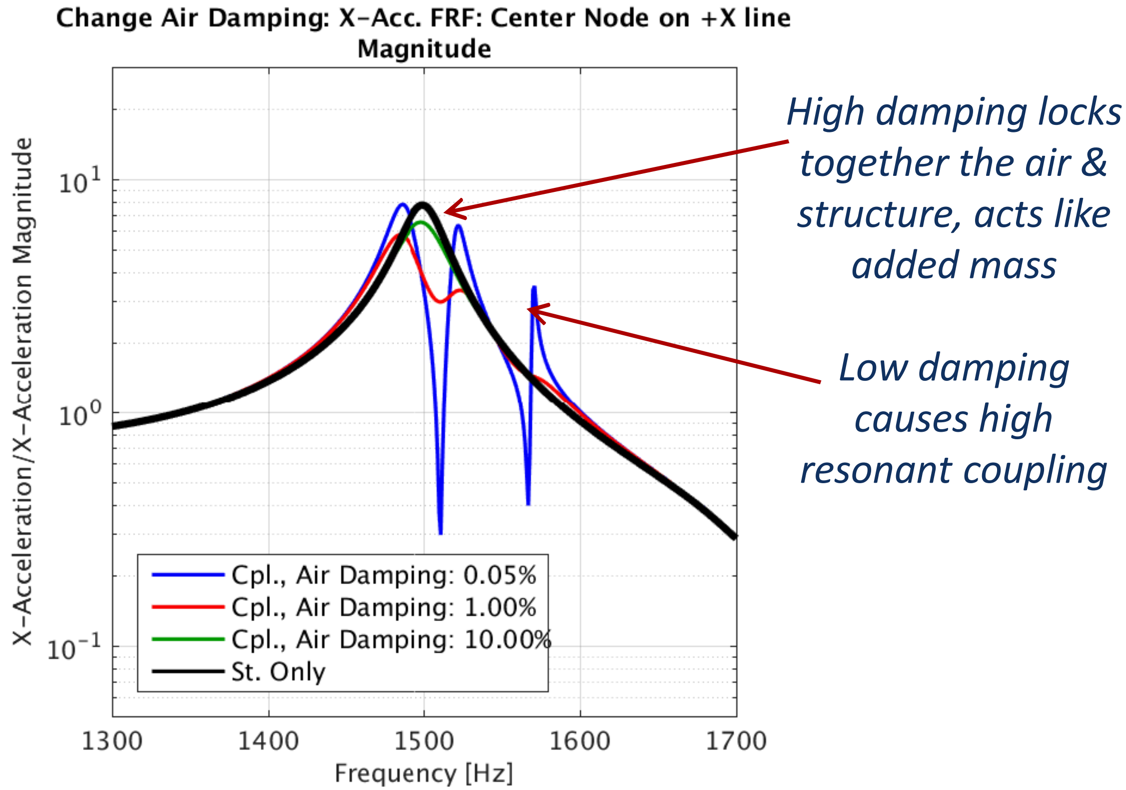
2-DOF Tuned Absorber

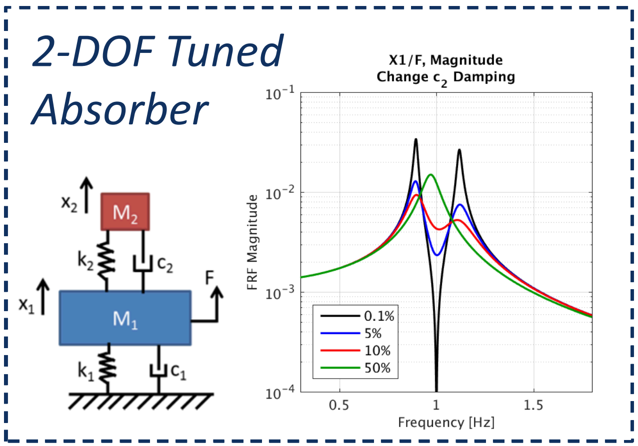




Hollow Cylinder: Effect of Increased Air Damping (c_2) on (3,0) Structural Response

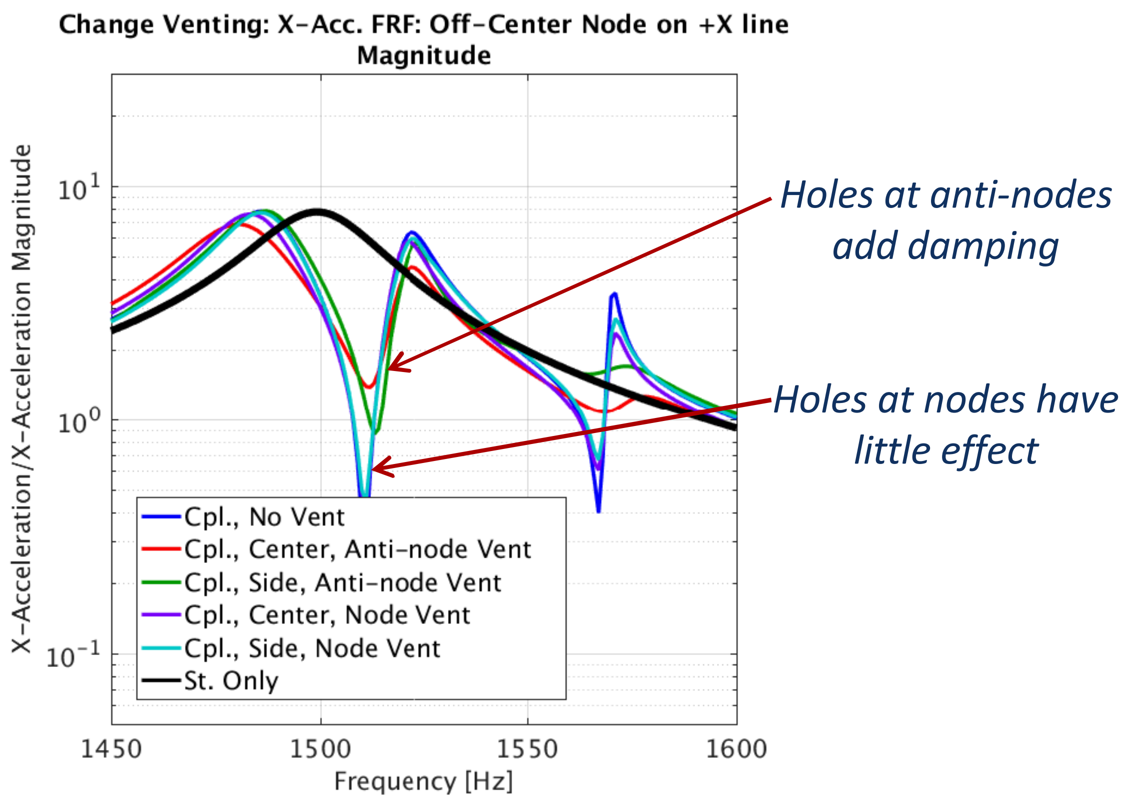
- Add damping to the tuned mass (air) by changing the proportional damping terms
  - 0.05%, 1%, 10% damping
- Added Air Damping could be from:
  - Venting (holes in case)
  - Absorbing material (foam)



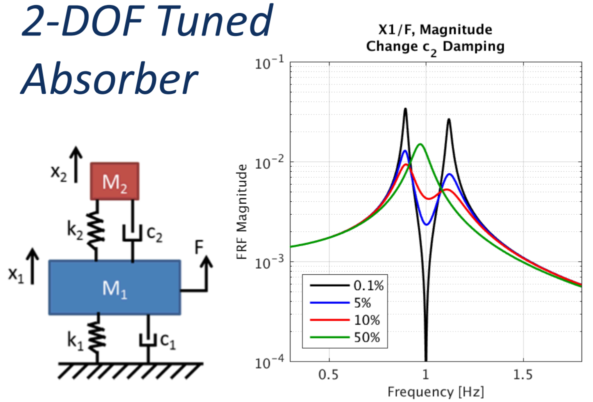


Hollow Cylinder: Effect of Holes on the Coupled Cylinder Response

- Place holes in the casing and add an absorbing (impedance matched) boundary condition on the air at these holes
- Located at pressure nodes, anti-nodes and centered or near the end



2-DOF Tuned Absorber



How Does This Coupling Affect Quantities of Interest?

- Doing a Modal Test:
  - Coupling can add additional modes to the FRF, with repeated shapes which can give parameter estimation algorithms trouble
  - Additional peaks in the FRF would make it seem like more gages are needed on the structure – which isn't necessary
- Making Model Predictions:
  - In-vacuo structural model won't have peak response at same frequency as coupled, physical system
  - Rather than single, narrow peak in response, response may be spread in frequency due to the double peak in the coupled system

Conclusions

- Structural-acoustic coupling can be important for structures we care about
  - Causes a change in the structural response, similar to adding a tuned absorber to the system
  - Observe repeated shapes in the FRF, which can cause problems with parameter estimation algorithms & affect FE model correlation
  - Structure doesn't have to be sealed to exhibit coupling
- **What can you do?**
  - Simple calculations can be used to determine if there are compatible acoustic modes in the vicinity of structural modes
  - In testing, adding absorbing material to the cavity may be enough to reduce the acoustic mode and avoid noticeable coupling
  - For making predictions, add air cavities to finite element models