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Numerical Modeling of an Enclosed Cylinder

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NOMAD Research Institute

- NOMAD is six week student research program sponsored by Sandia National Labs with volunteer mentors
- This talk discusses the background work for a project involving structural-acoustic coupling of enclosed cylinders
  - Designing the structure to be tested
  - Preliminary modeling of the structure
  - Design alterations to lessen the coupling (that are difficult to realize in an experiment)

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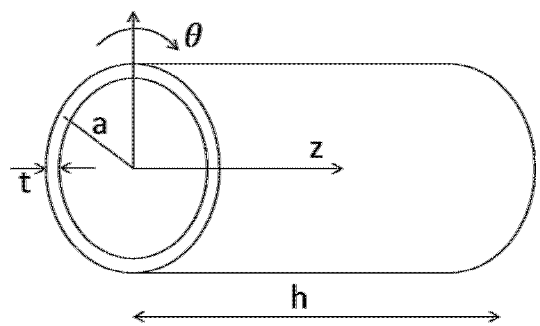
Analytical Model

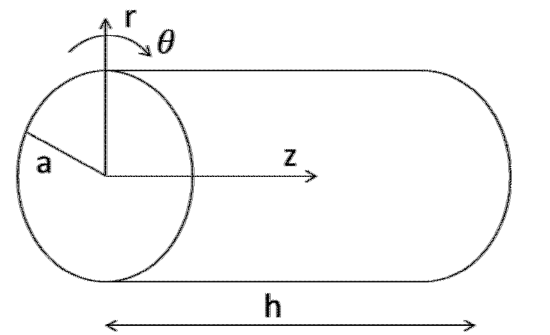
Structural Resonances – Cylinder



$$f_{m,l} = \frac{\lambda_{m,l}}{2\pi a}\sqrt{\frac{E}{\rho(1-v^2)}}$$

*Simply-supported boundaries

Acoustic Resonances – Cylinder



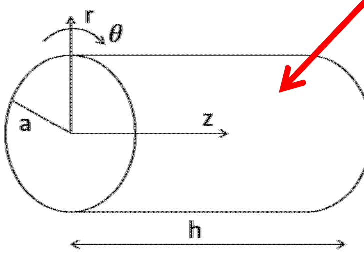
$$f_{l,m,n} = \frac{c_0}{2}\sqrt{\left(\frac{\alpha_{mn}}{\pi a}\right)^2 + \left(\frac{l}{h}\right)^2}$$

*Rigid boundaries

Coupling Coefficient

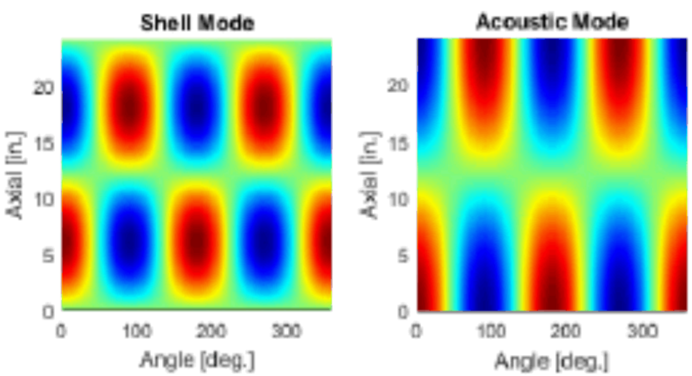
Metric to describe the similarity of the structural and acoustic shapes along the 'wetted' surface

$$L_{ij} = \frac{1}{A_w} \int_{A_w} \Phi_{a,i} \Phi_{s,j} dA_w$$



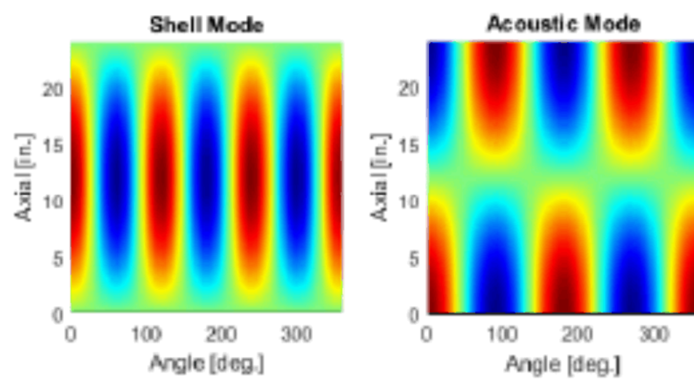
Wetted Surface

Large Coupling



Small Coupling

'unwrapped' mode shapes



Designing the Acoustoelastic Structure

- Need hardware for NOMAD project which exhibits acoustoelastic coupling
- Design Objectives:
  - Simple geometry - cylindrical
  - Simple & cheap to manufacture (stock sizes, little machining)
  - Have coupled modes below 4kHz for straightforward excitation & measurement
  - Thick-walled to demonstrate coupling effects on heavy structures
- Design Process:
  - Compute mode frequencies for various orders of ovaling modes of the cylindrical shell & acoustic cavity
  - Vary the shell dimensions based on stock material sizes, adjust the length
  - Determine which shell sizes provide structure & acoustic modes of the same order with similar frequencies

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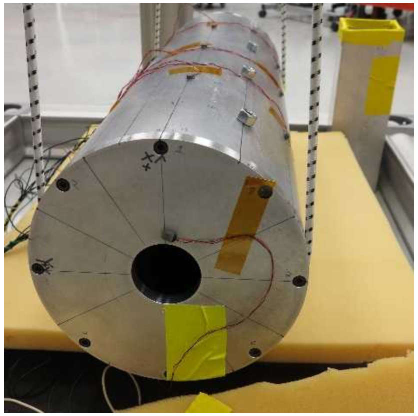
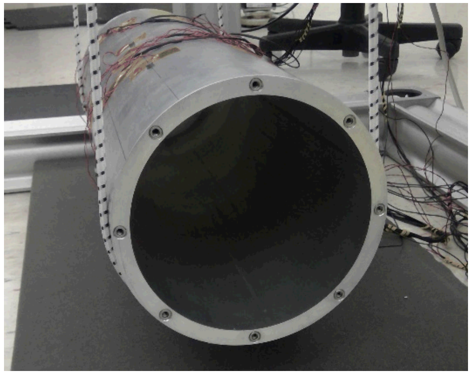
Comparison of Frequencies

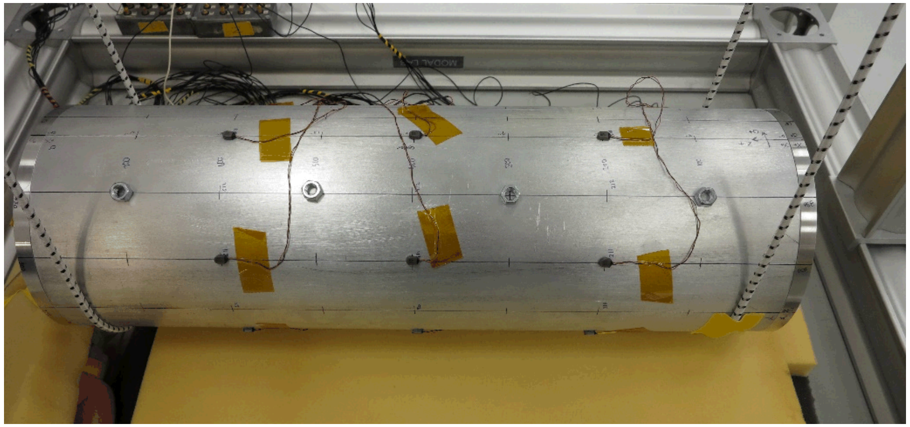
O.D. [in.]	Wall [in.]	Length [in.]	Shell 2,0	Shell 2,1	Shell 3,0	Shell 3,1	Shell 4,0	Shell 4,1	Acs. 2,0	Acs. 2,1	Acs. 3,0	Acs. 3,1	Acs. 4,0	Acs. 4,1
6	0.50	10	**2574**	5316	5229	6868	9347	-	**2622**	2708	3611	3673	4574	4623
6	0.25	12	1525	3777	2512	3605	4530	5176	2384	2449	3282	3330	4158	4196
6	0.50	12	2264	4359	5085	6182	-	-	2622	2682	3611	3654	4574	4608
8	0.25	24	650	1586	1304	1620	2432	2596	1748	1771	2407	2424	3049	3062
8	0.50	20	1177	2292	2728	3196	5046	5381	1873	1903	2579	2601	3267	3284
8	0.50	24	1077	**1857**	**2690**	2988	-	-	1873	**1894**	**2579**	2594	3267	3279
10	0.25	24	618	1704	873	1348	1559	1780	1380	1408	1900	1921	2407	2424
10	0.50	24	824	1815	1730	2140	3191	3454	1457	1484	2006	2026	2541	2556

Acoustoelastic Structure

- Best Design:
  - 8” Diameter x 24” Long, ½” Wall Cylinder with End Caps (20 cm x 61 cm)
  - All aluminum
  - One end cap has a 2” (5 cm) hole to allow for accessing the cavity







Combined Structure / Fluid Model

- The structure can be modeled with finite elements using either 2-D plate or 3-D solid elements, which can have linear or quadratic shape functions
- The internal and external fluid can be modeled using either finite elements (FE) or boundary element (BE)
- Acoustic mesh requires approximately six elements per wavelength at the highest analysis frequency of interest

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BE vs FE

Boundary Element

- Sound radiation computed by solving the Helmholtz Integral equation
- Only surface mesh is required
- Farfield radiation is inherently enforced
- Interior fluids are more difficult

Finite Element

- Fluid is modeled explicitly using solid elements
- Mesh of the entire fluid domain of interest is required
- Boundary condition is required for radiation problems
- Interior fluids use structure as boundary

Acoustic Mesh with Boundary Elements

Advantages

- Meshing is relatively simple for external meshes
- Can utilize interpolation schemes to reduce computation time
- Fits easily into mode-based analyses
- Easily parallelizable

Disadvantages

- Matrices are full making direct solutions expensive
- Large number of modes or acoustic elements leads to large computation times
  - Soft materials or large structures
  - Mid to high frequencies (analysis requires modes to 2x highest frequency)
- Fluid media cannot be inhomogeneous or lossy
- Analysis must be linear
- Can have singularity problems
  - May be reduced or eliminated depending on your formulation

Acoustic Mesh with Finite Elements

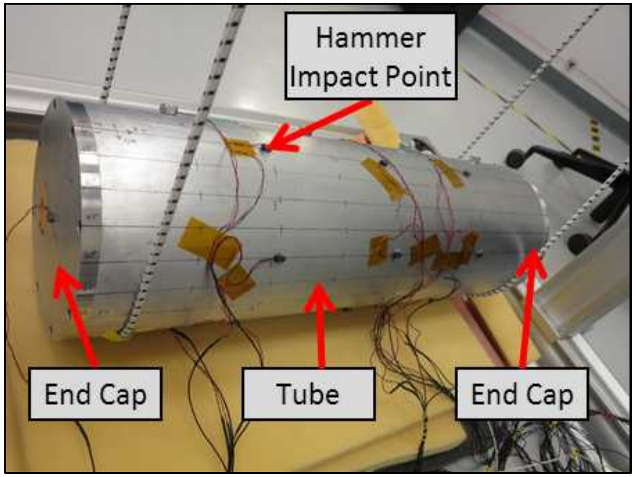
Advantages

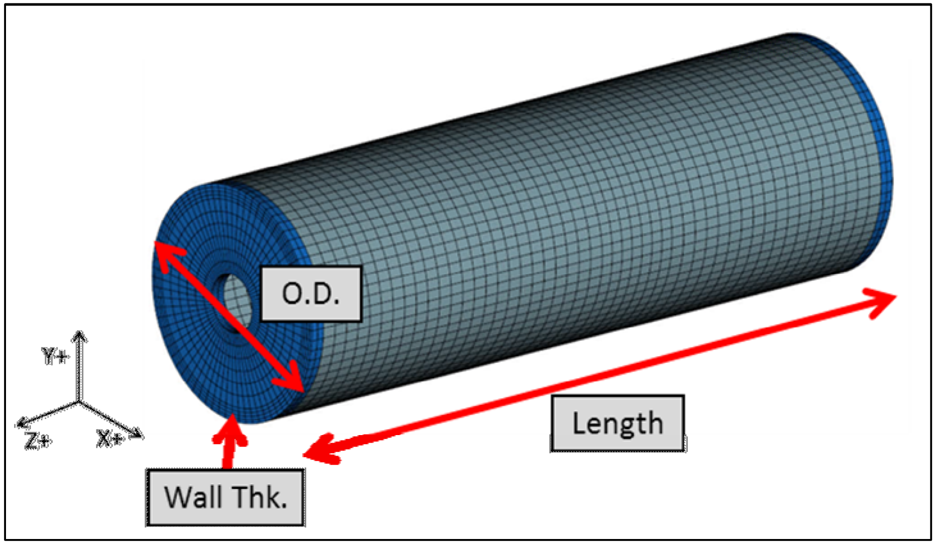
- Matrices are sparse and direct solutions are relatively simple
  - Nonlinear solutions in time or frequency
  - Solution times scale well with model size
- Can utilize interpolation schemes to reduce computation time
- Easily parallelizable
- Fluid media can be inhomogeneous and/or lossy

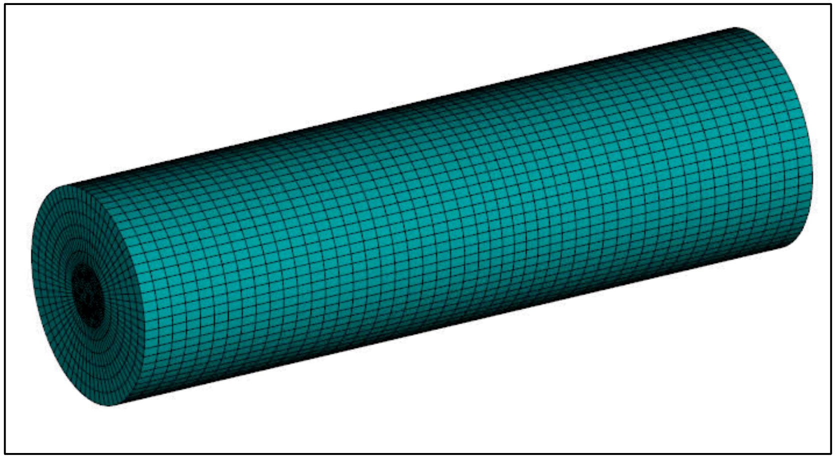
Disadvantages

- Meshes are often large and difficult to create
  - Matching with complicated structures
  - Farfield radiation condition must be met
  - Matrix size increases with model size
- Difficult to accurately model thermo-viscous or relaxation losses in the fluid
- Can have convergence problems with low damping or heavy fluids

Mesh pictures

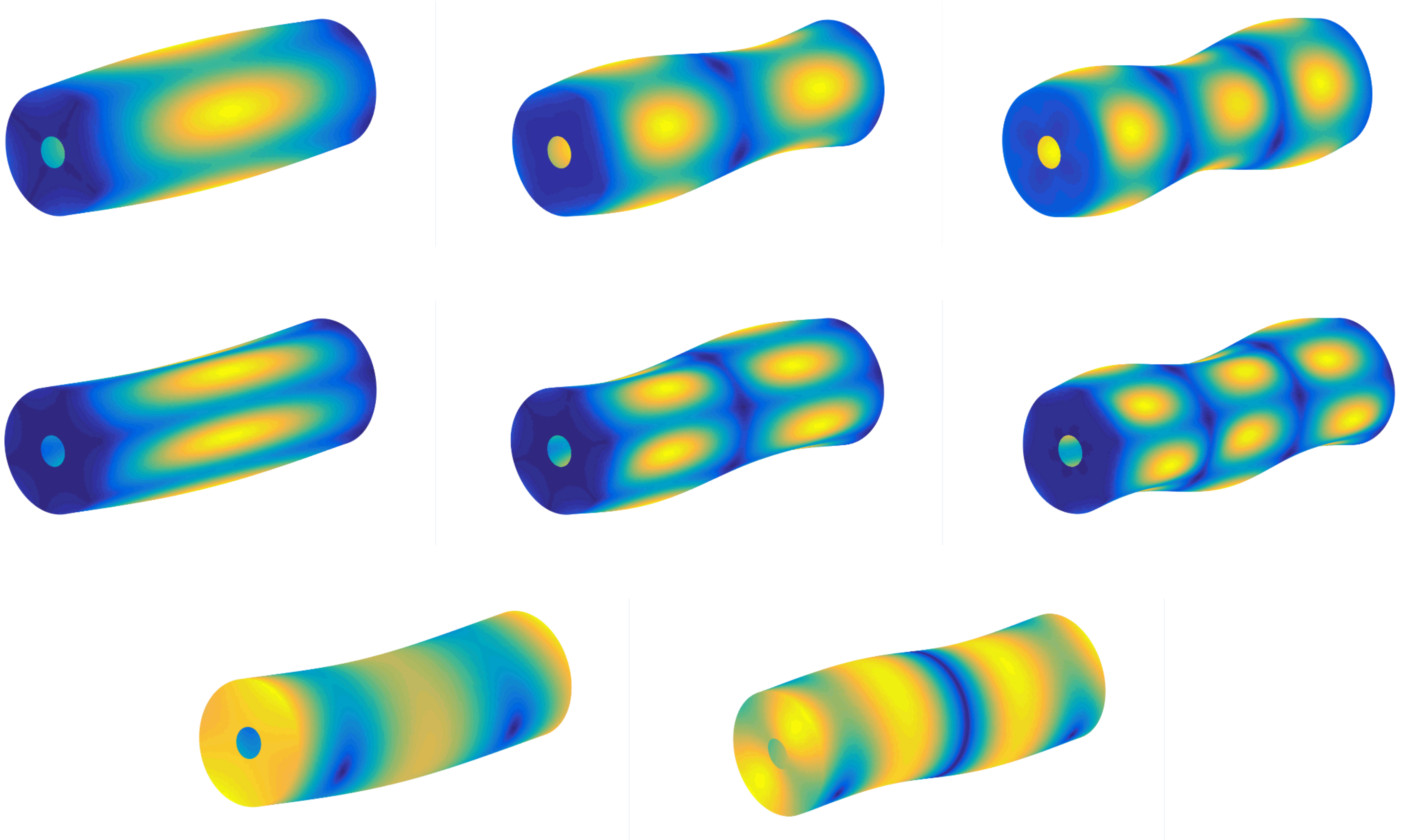






FE Fluid Mesh
Hex20 elements, ½" mesh size, 185k nodes, 44k elements

In-vacuo Mode Shapes



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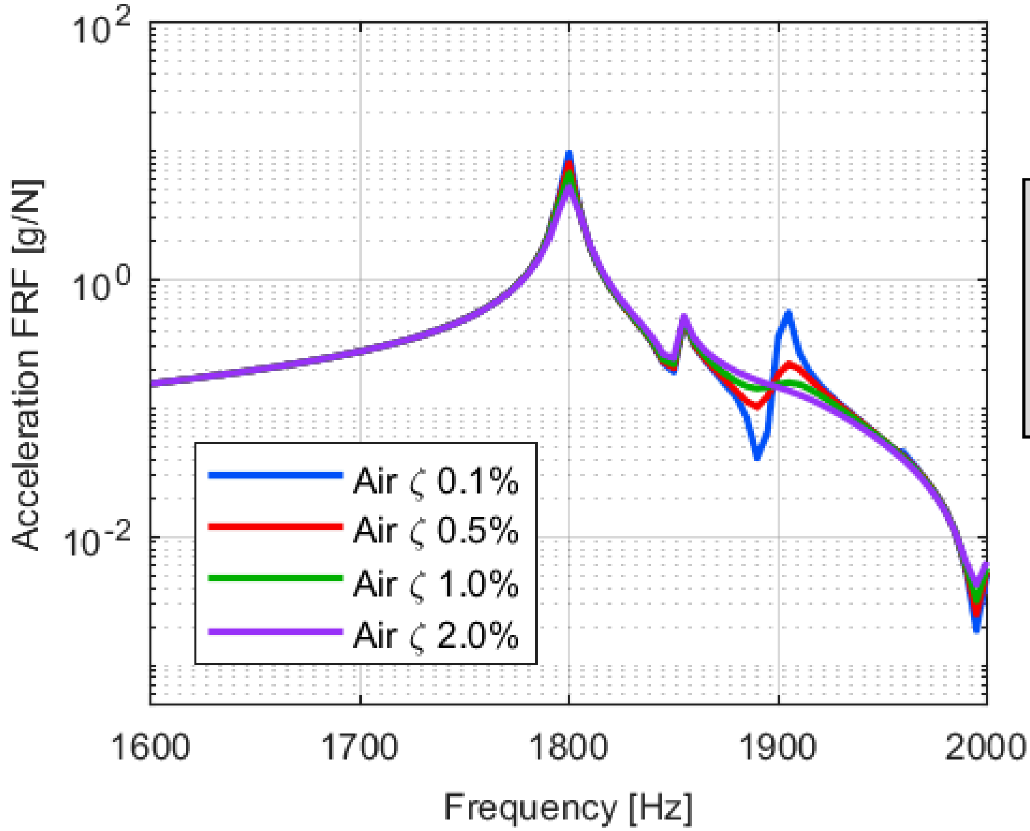
Increase Fluid damping



FE Direct Solution of the coupled Structural-Acoustic System

Adding acoustic absorption inside the cylinder (ie foam)

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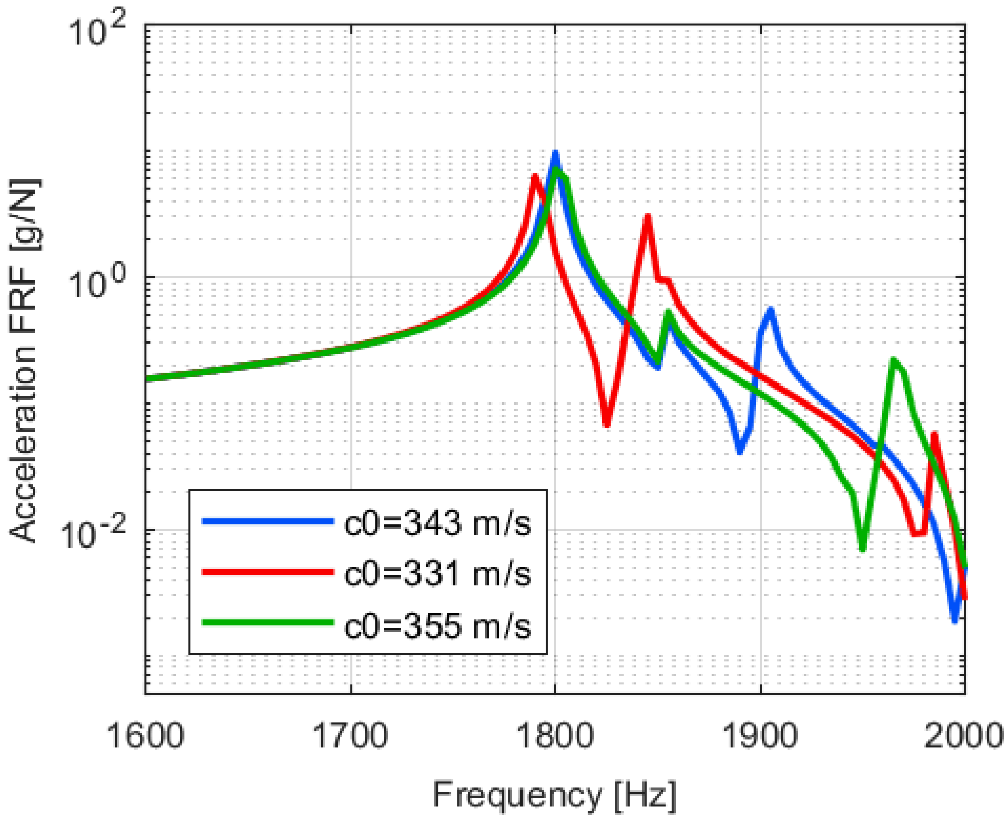
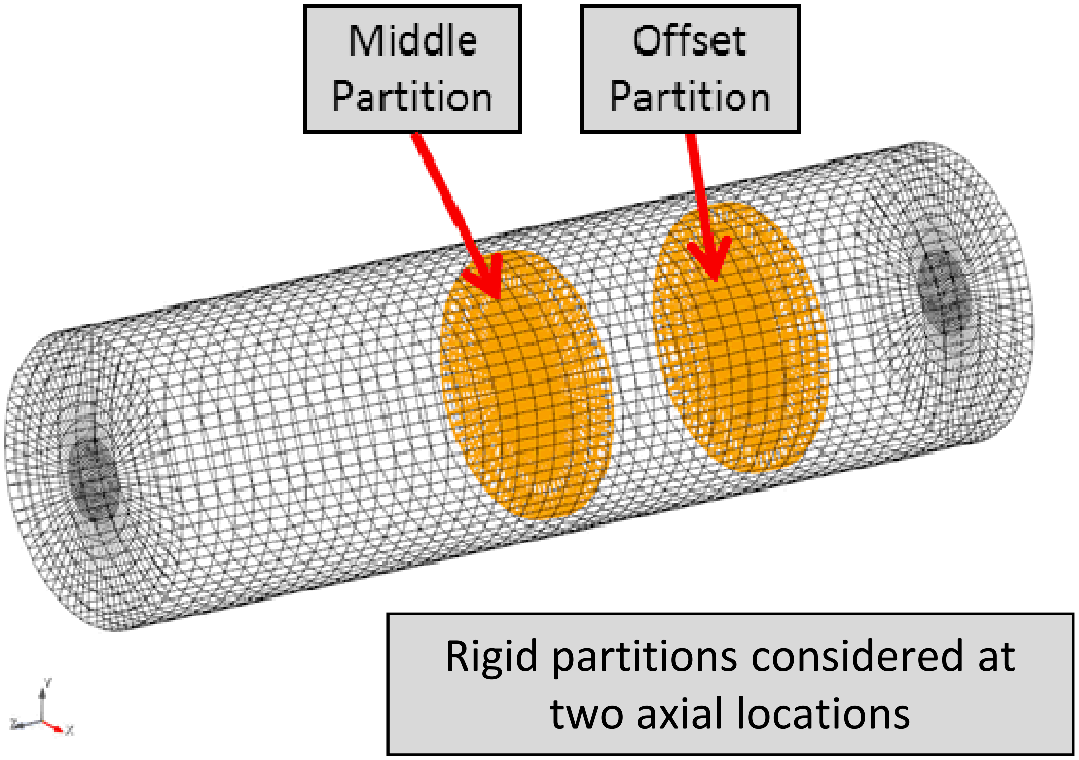
Changing sound speed



FE Direct Solution of the coupled Structural-Acoustic System

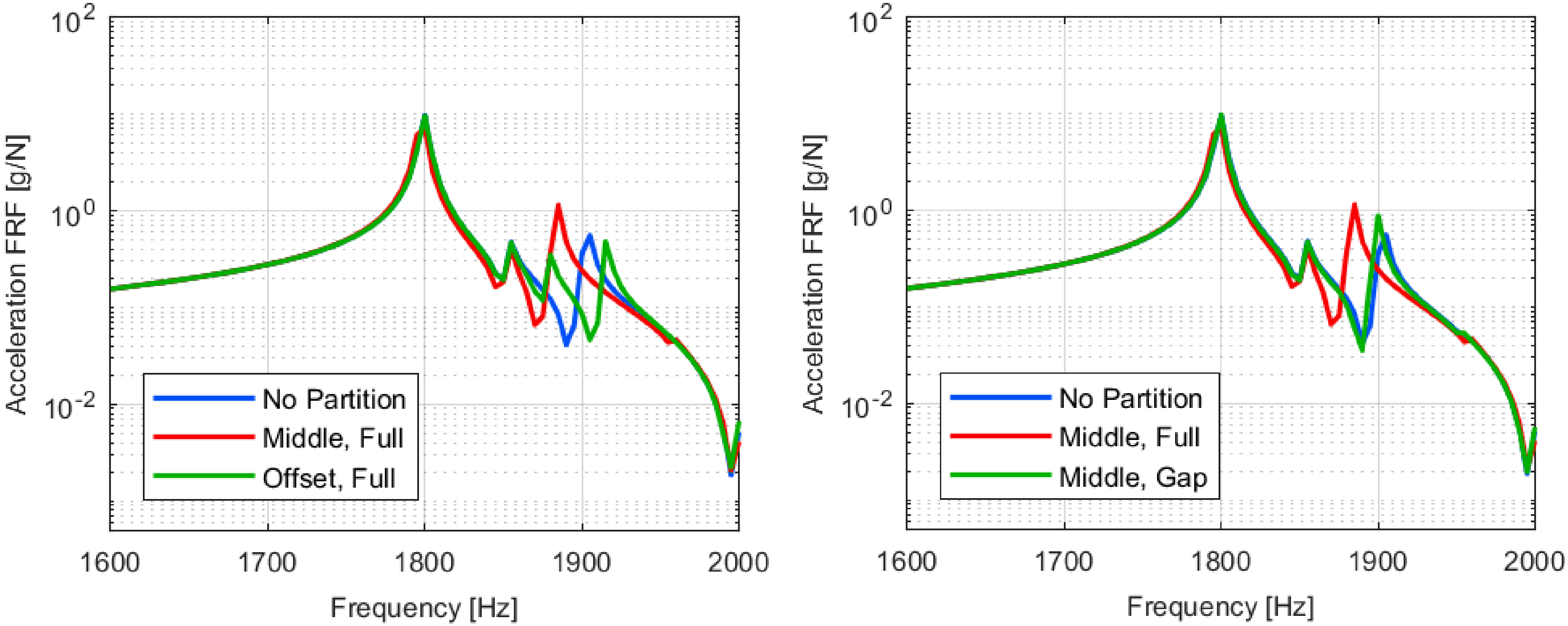
Increase the sound speed by changing the fluid composition

Adding partition



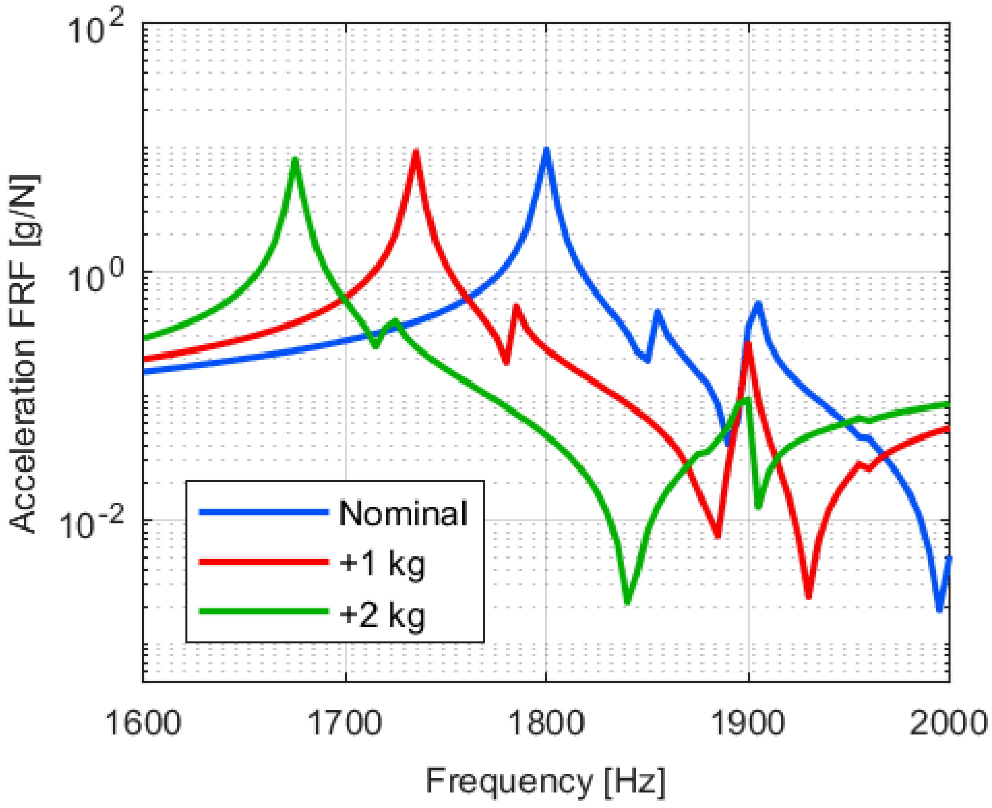
Disrupt the acoustic mode shape by adding a partition

Adding partition



Disrupt the acoustic mode shape by adding a partition

Adding mass to the structure



Added Structural Mass via Density Change

Conclusion

- Simple component simulations were used to design an acoustoelastic structure
- FE was chosen over BE for this work due to the BCs, geometry, and size of the domain
- Coupled, direct simulations were performed to determine the expected structural frequency response of the test structure
- Strong mode coupling effects were observed
- Simulations were performed to examine how changes to the structure and fluid would affect the coupled system response
- These results are similar to the effects observed in the NOMAD group's tests

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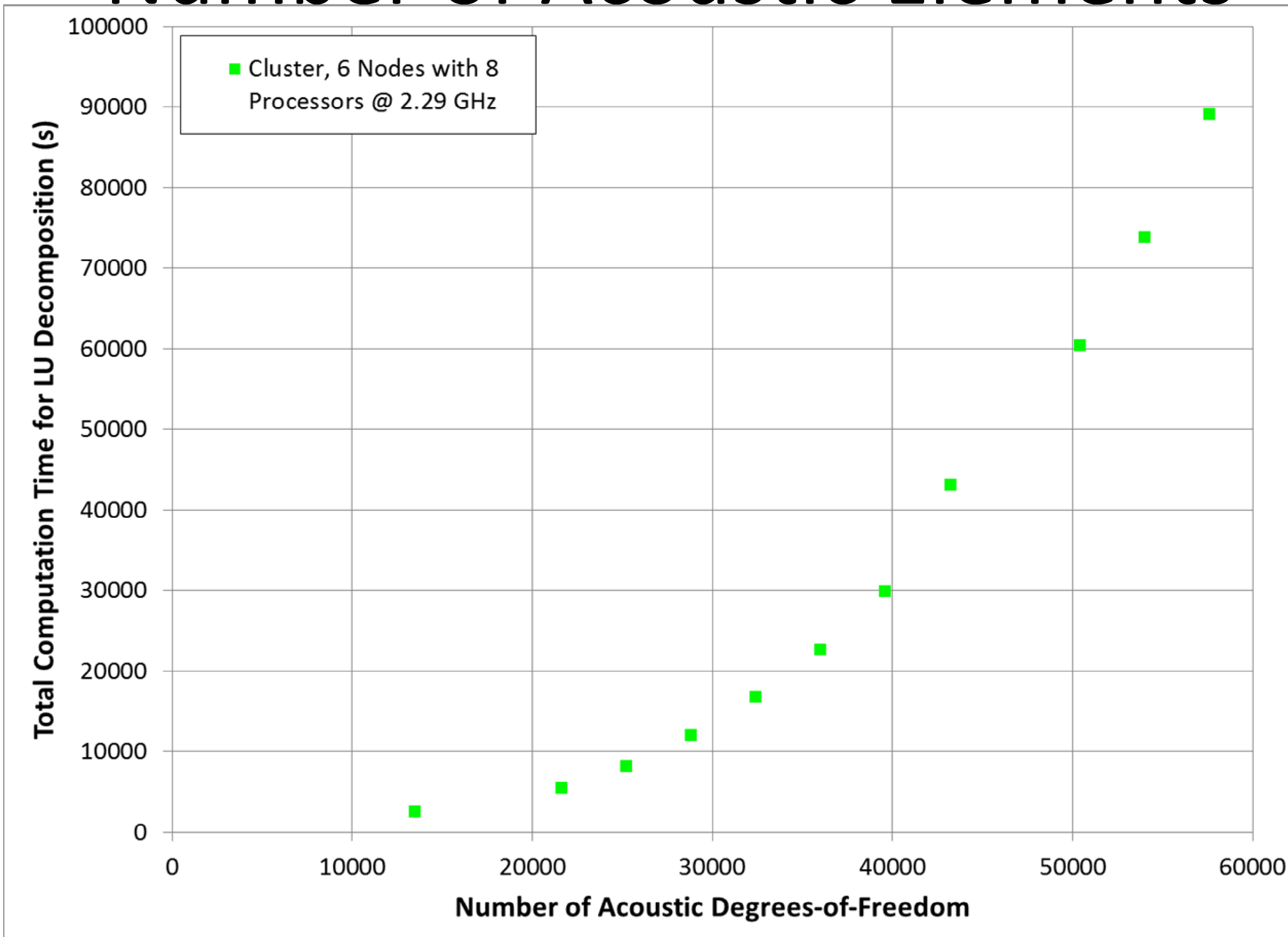
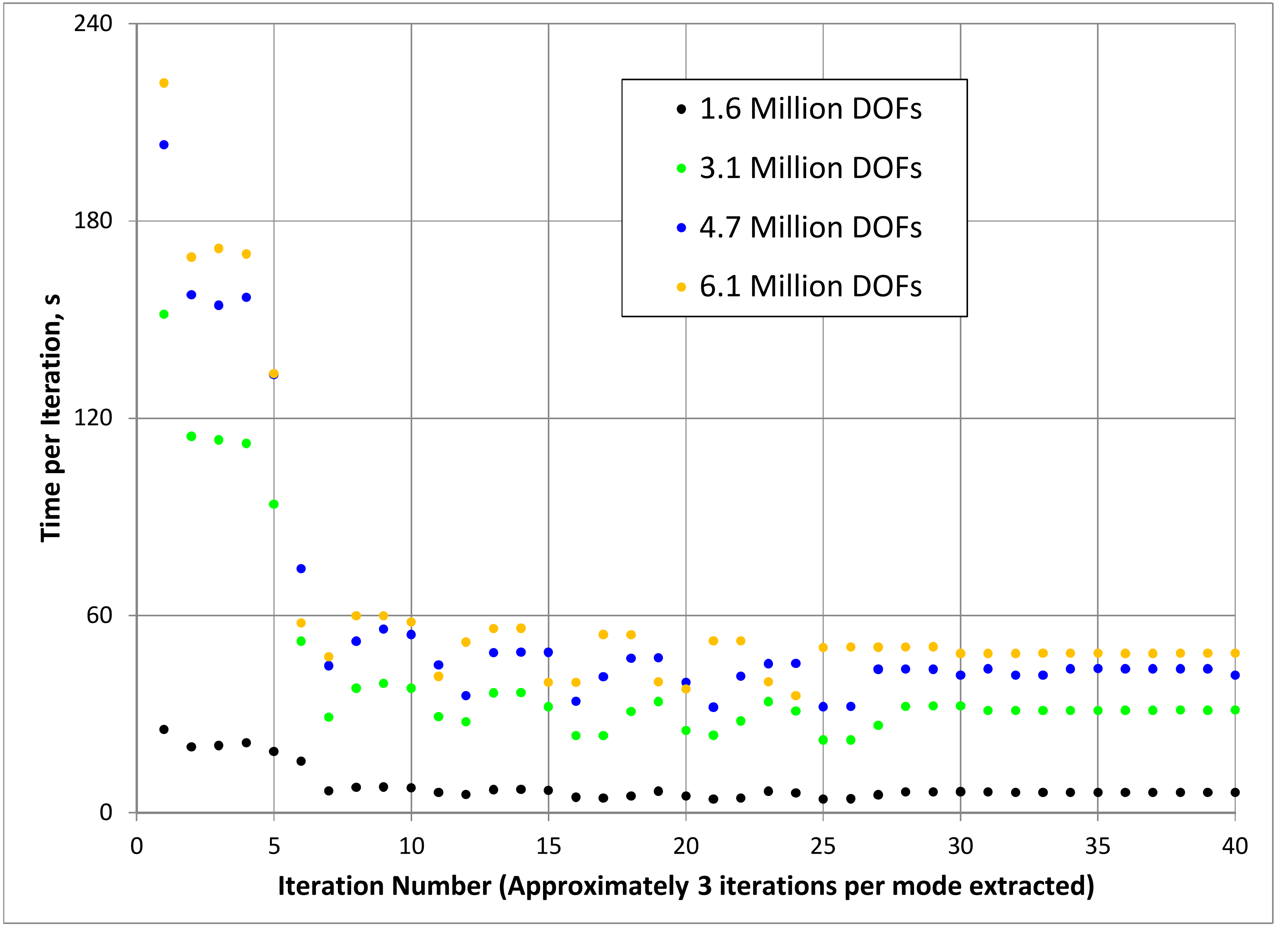
Back up

Number of Acoustic Elements



Number of Modes



Experimental results