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Reducing Cavity Response in Strongly Coupled Acoustic-Structure Systems

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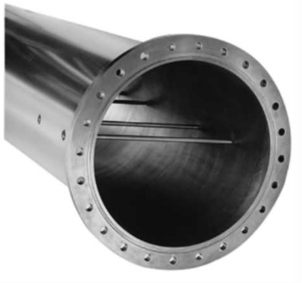
Acoustic-Structure Coupling

Basics

- Hollow structures can dynamically couple to internal acoustic cavities

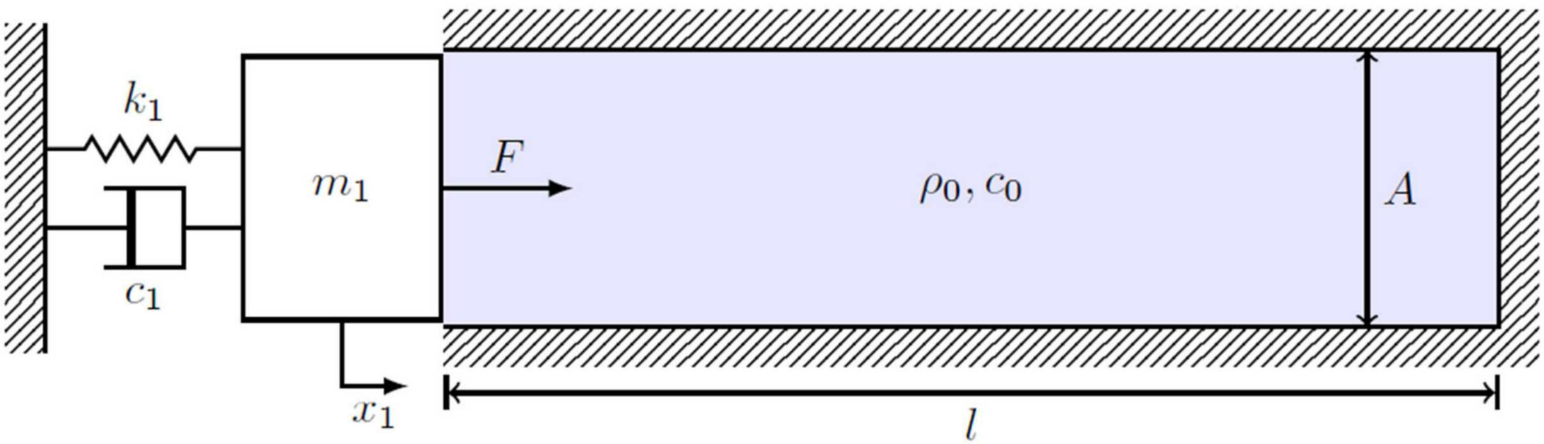
- Strong coupling requires:
  - Near coincidence of uncoupled natural frequencies
  - Mode shape similarity



Acoustic-Structure Coupling

Piston/Duct

- SDOF piston coupled to a 1D acoustic duct
- Coupled behavior determined by:
  - Piston-to-fluid mass ratio
  - Uncoupled natural frequency ratio



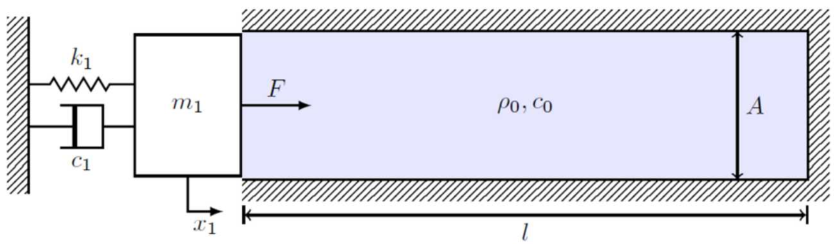
Acoustic-Structure Coupling

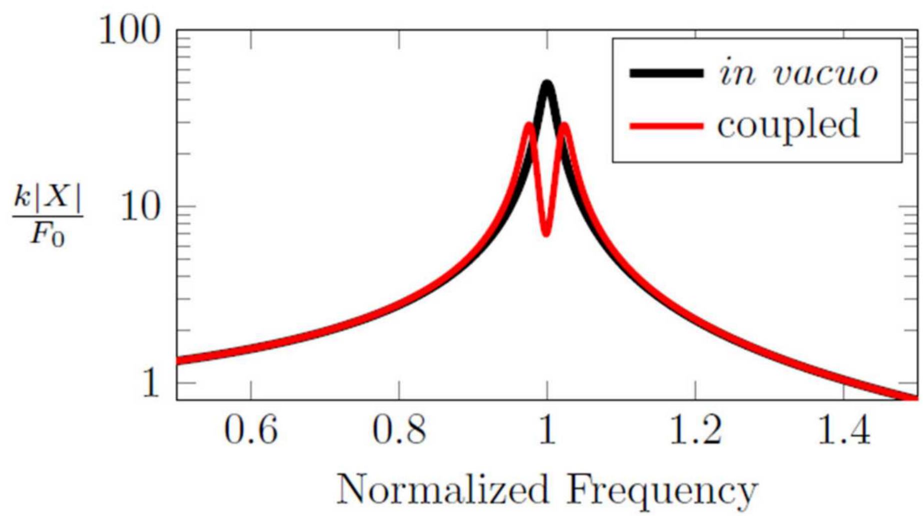
Structural Response

- Coupled structure has resonances above and below *in vacuo* natural frequency

- Coupled resonances are lower than in the uncoupled case

- Analogous to a tuned-mass-damper
  - Cavity acting as the attachment mass



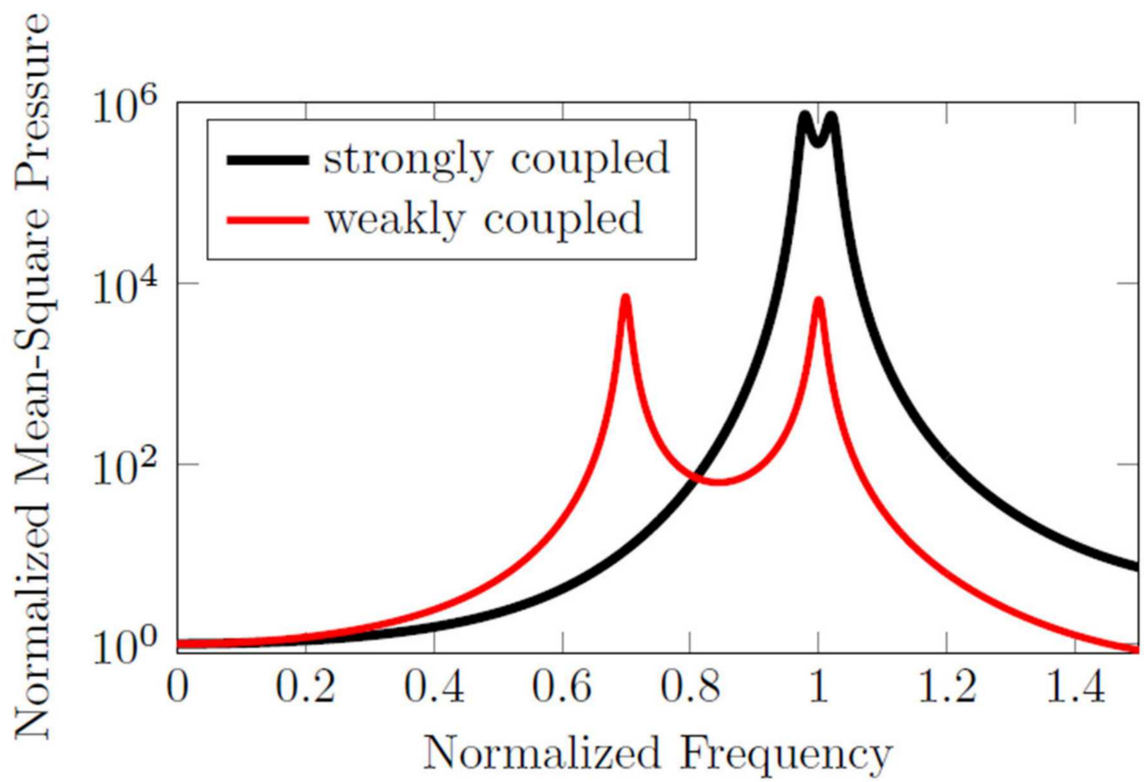


Acoustic-Structure Coupling

Acoustic Response

- Cavity response also exhibits two resonances

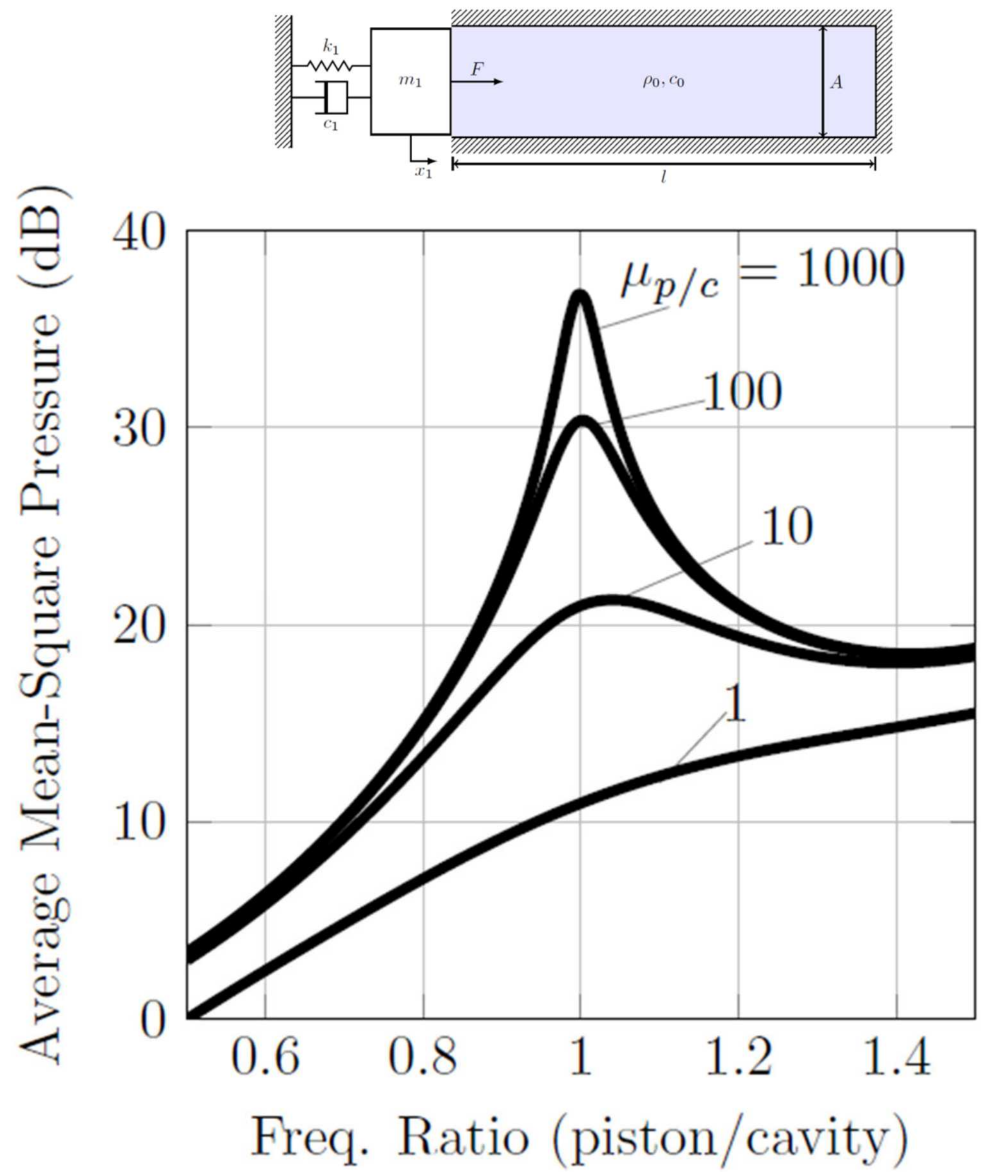
- Coupled resonant amplitudes are much higher than in the weakly coupled case
  - Overall, weakly coupled case is about 20 dB lower



Acoustic-Structure Coupling

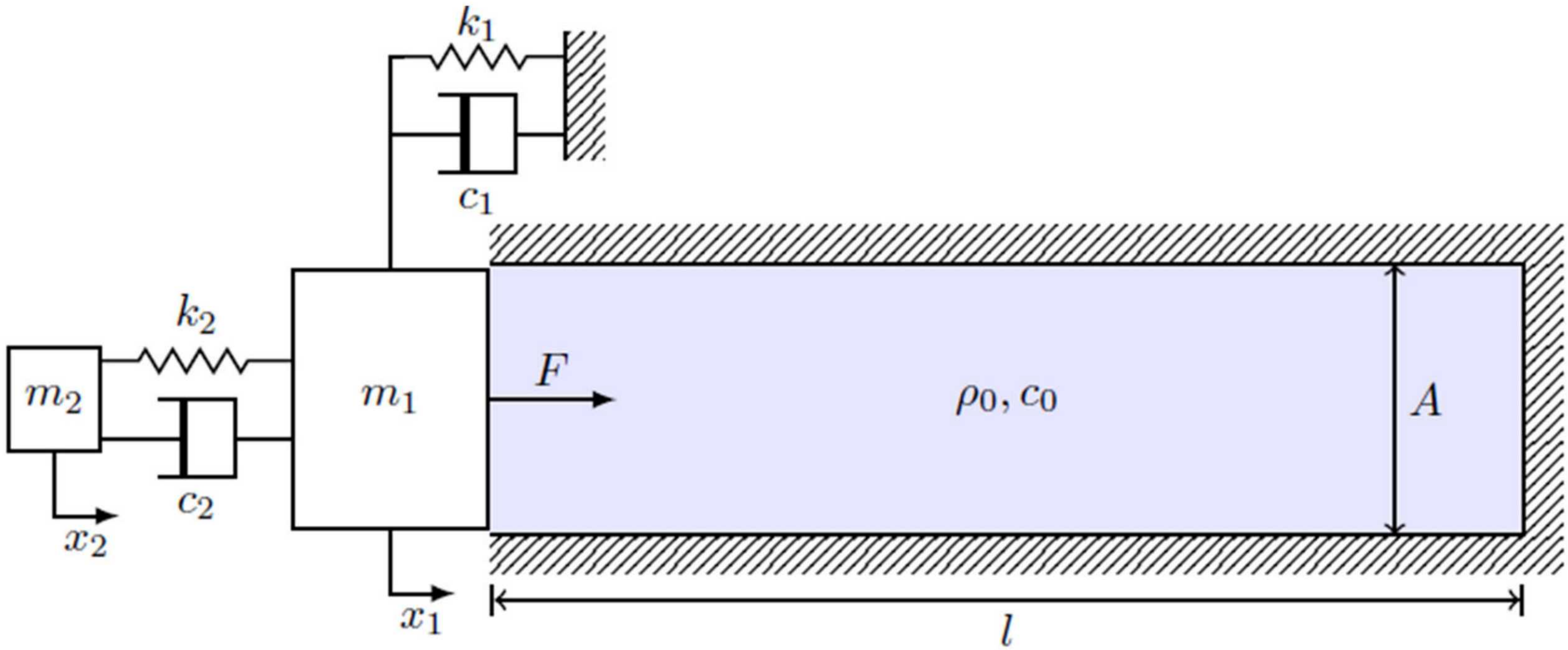
Acoustic Response across Parameter Space

- Cavity pressure amplification most pronounced when uncoupled frequencies are nearly coincident and piston-to-cavity mass ratio is high



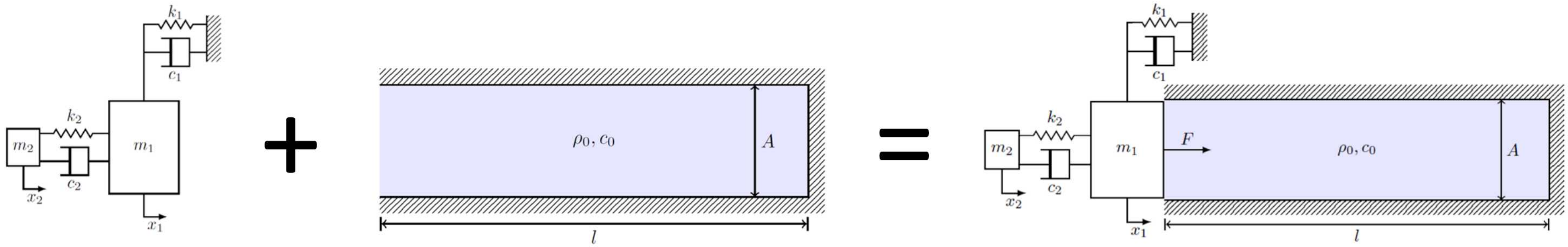
Idea

- Attach tunable attachment mass to primary structure to reduce cavity response



Modeling Approach

- Acoustic-Structure Dynamic Substructuring†



Modeling Steps

1. Find natural frequencies and modes of uncoupled cavity
   - Use mixed basis of rigid wall and pressure-release modes
   - Use gradient of pressure modes to cast problem in terms of fluid displacement
2. Find natural frequencies and modes of undamped, uncoupled structure
3. Calculate modal damping for structural subsystem
4. Assemble disjoint problem in generalized coordinates with subsystem modal damping
5. Build constraint matrix and compute its null space
6. Use null space to transform disjoint EOMs
7. Solve eigenvalue problem associated with transformed EOMs
8. Perform forced response analysis using a complex modal analysis procedure
9. Transform system back into physical coordinates

† Davis, R. B., Schultz, R. (2019). "Using a Dynamic Substructuring Approach to Model the Effects of Acoustic Damping in Coupled Acoustic-Structure Systems", *Journal of Vibration and Acoustics*, 141(2), 021019.

Advantages of Substructuring

in Acoustic-Structure Systems

1. In undamped cases, process gives real-valued natural frequencies and modes

2. Ensures continuity at fluid-structure interface
    - Enables recovery of pressures at fluid-structure interface

3. Straightforward application of acoustic subsystem damping

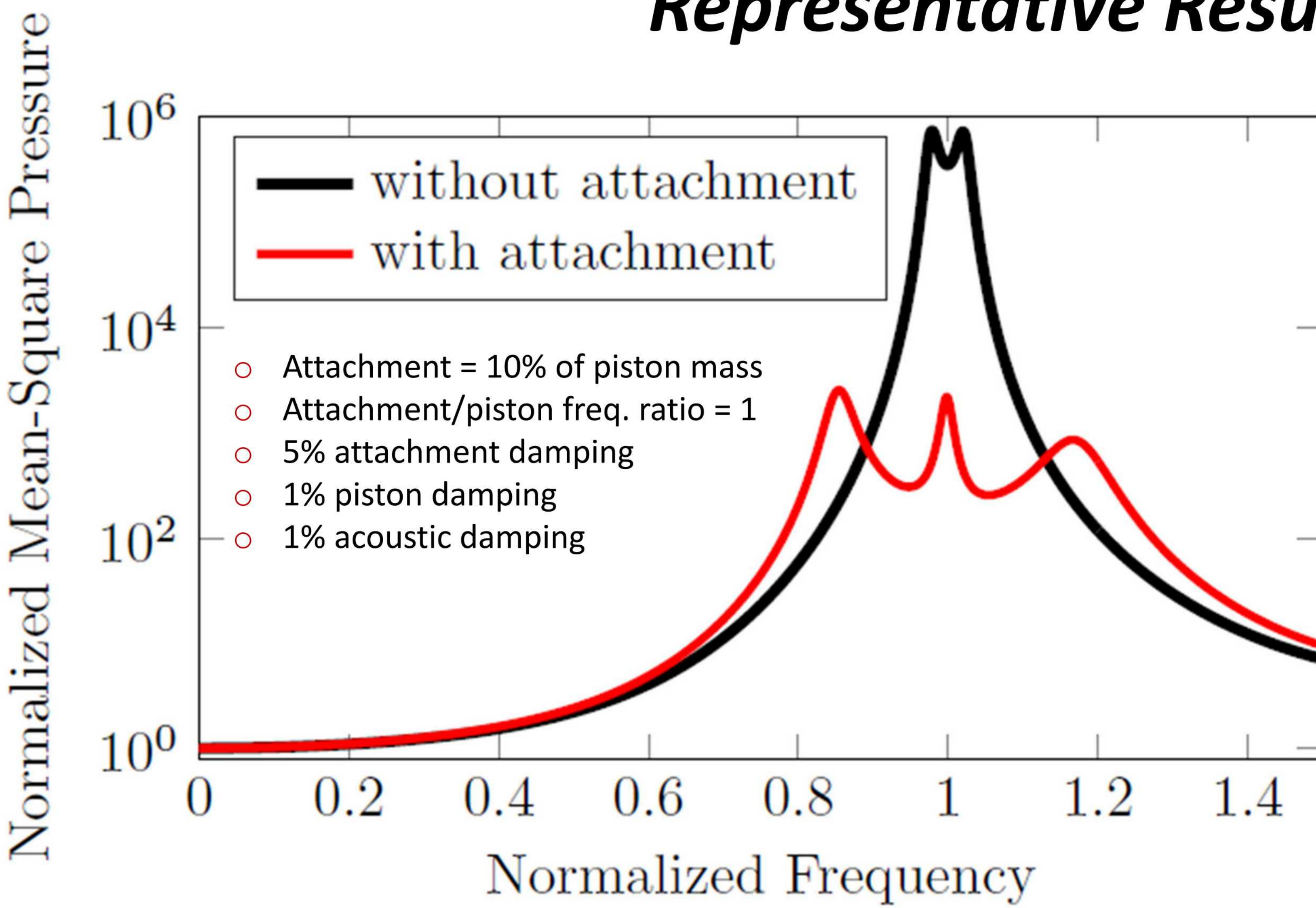
4. No need for explicit knowledge of mass and stiffness matrices

Challenges of Substructuring
in Acoustic-Structure Systems

In 3D configurations with complex geometries, substructuring can present some challenges:

1. Selection of appropriate acoustic basis
2. Employing appropriate interface reduction strategy
3. Numerical calculation of the gradients of pressure mode shapes

Representative Result



- Adding attachment mass results in ≈ 20 dB reduction in overall cavity response

Optimization Study

- Use gradient-based optimizer to minimize the integrated average mean square pressure in the duct

- Optimization tuning parameters
  - Attachment/piston frequency ratio
  - Attachment mass damping

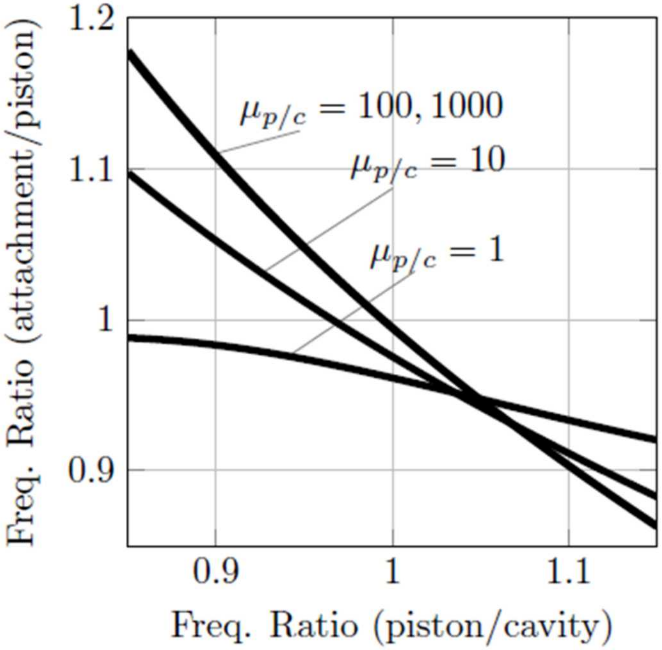
- Solve for different configurations:
  - Vary piston/cavity mass and frequency ratios

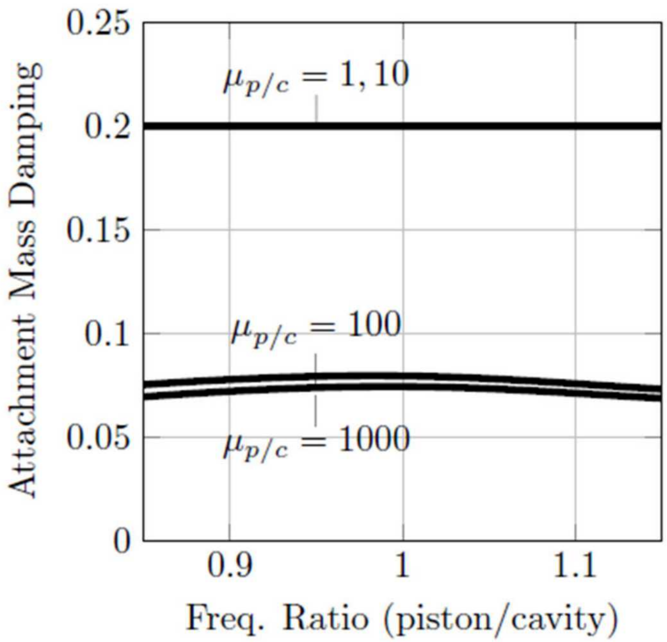
- Blanket assumptions and constraints:
  - 1% damping on piston
  - 1% damping in acoustic cavity
  - Attachment mass damping capped at 20%

Optimized Results

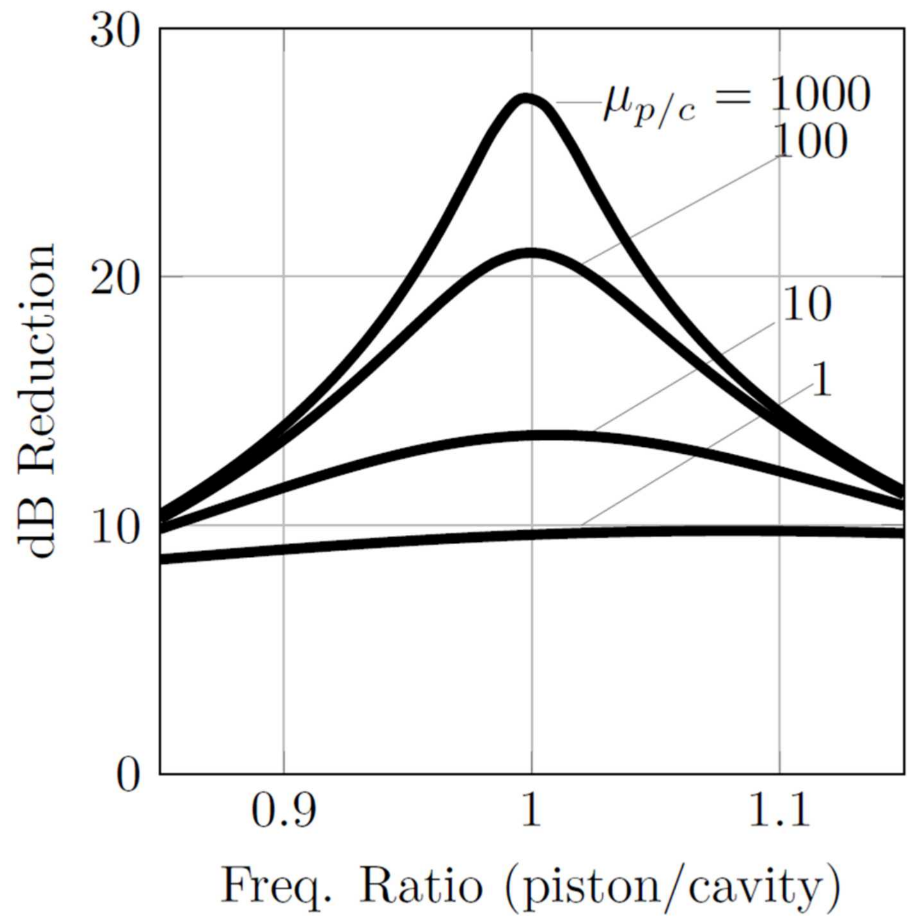
- Attachment mass is 10% of piston mass

Optimal Tuning Parameters





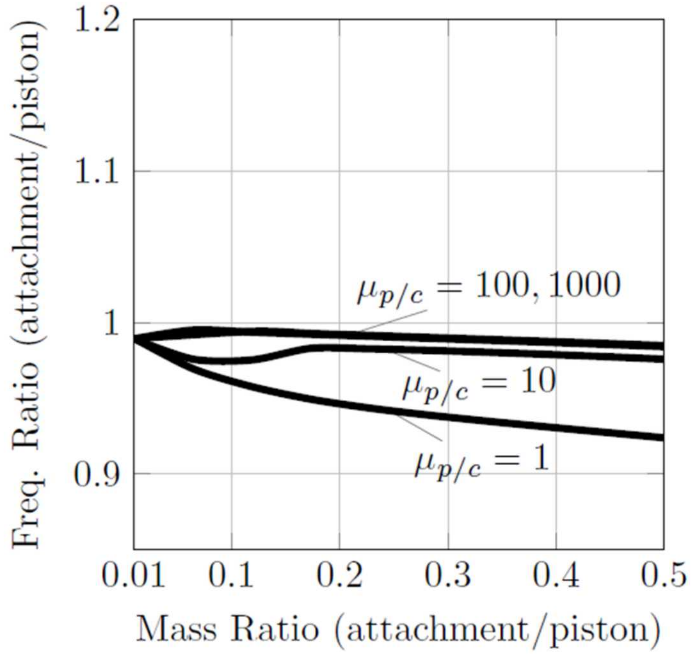
Optimal Reduction in Cavity Response

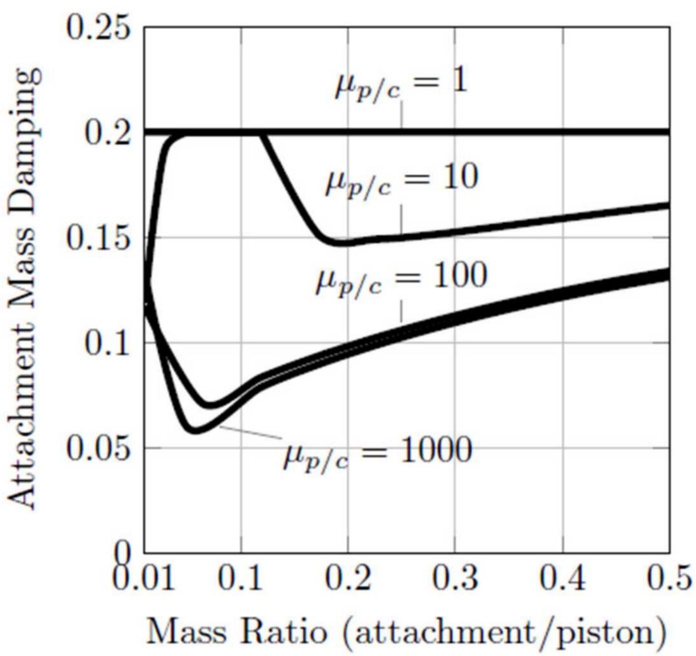


Optimized Results

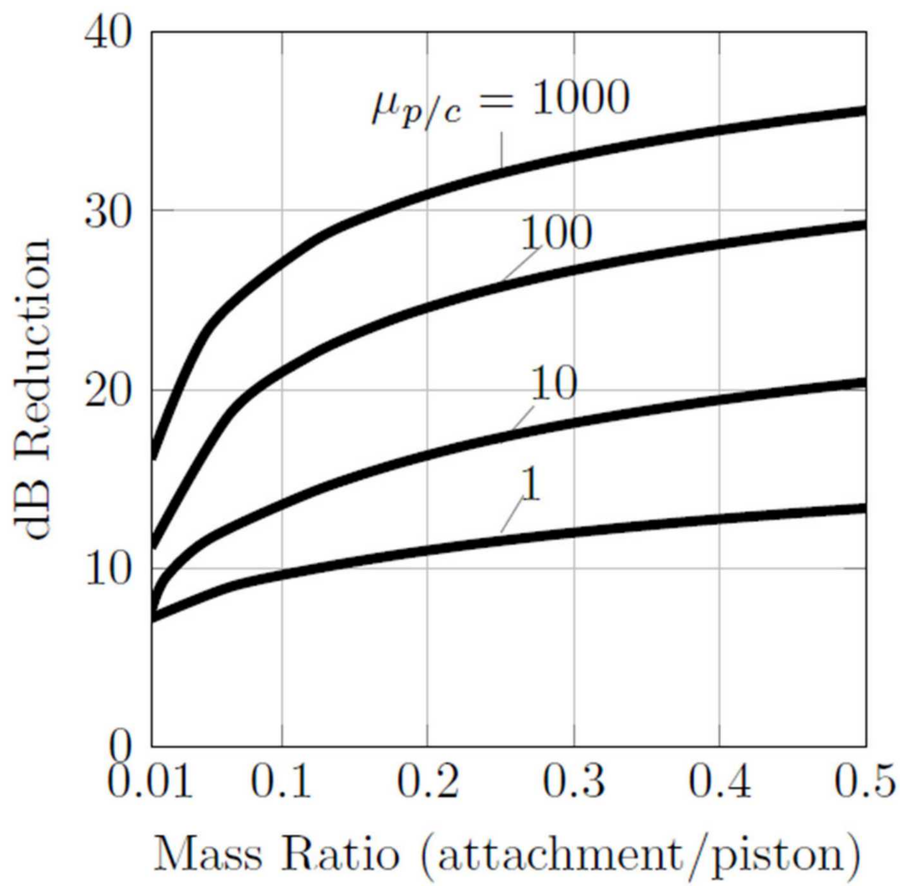
- Piston and cavity natural frequencies coincident

Optimal Tuning Parameters



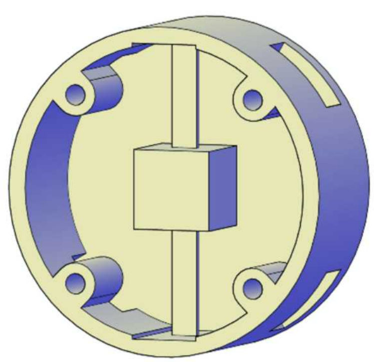


Optimal Reduction in Cavity Response



Experimental Validation

- Wish to show large cavity noise reductions experimentally
- 10 cm diameter pipe with adjustable length
- 3D-printed piston attaches to strongback with springs
- Attachment masses integrated with piston



Conclusions

- Acoustic-Structure coupling can result in large pressure response in the cavity
- Adding an attachment mass to the primary structure shown to be an effective way to reduce cavity response
- Gradient-based optimization used to find optimal frequency ratios and attachment mass damping ratios for a range of configurations
- Additive manufacturing enables the design of attachment masses that are seamlessly integrated with the primary structure