TEXAS TECH UNIVERSITY

Acoustic Metamaterial Panel (AMP) for Spacecraft Noise Suppression

NASA 2026 Human Lander Challenge

Biomedical Acoustics Research Lab

Department of Mechanical Engineering

Texas Tech University

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Content

Meet the team!

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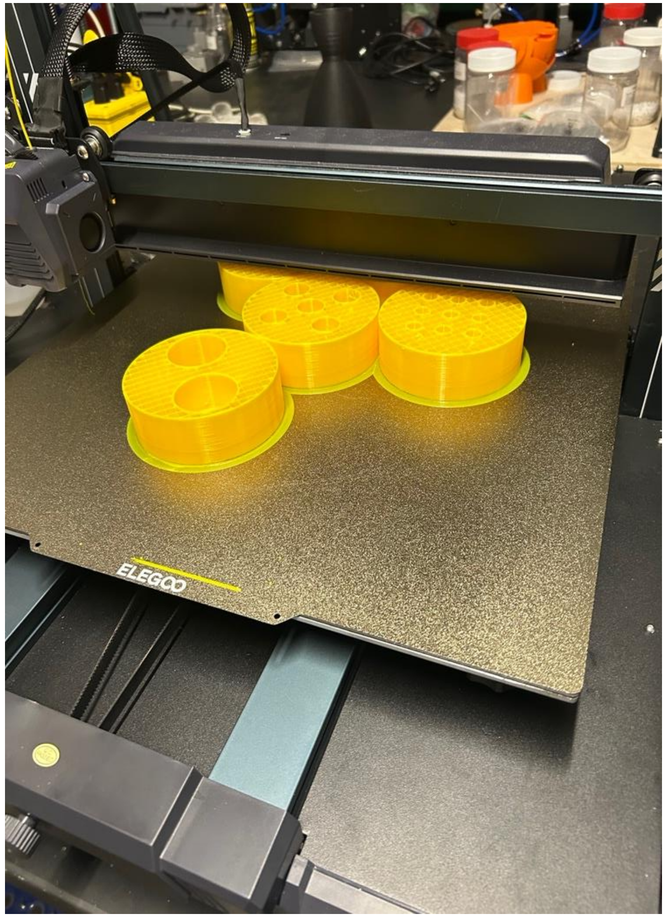


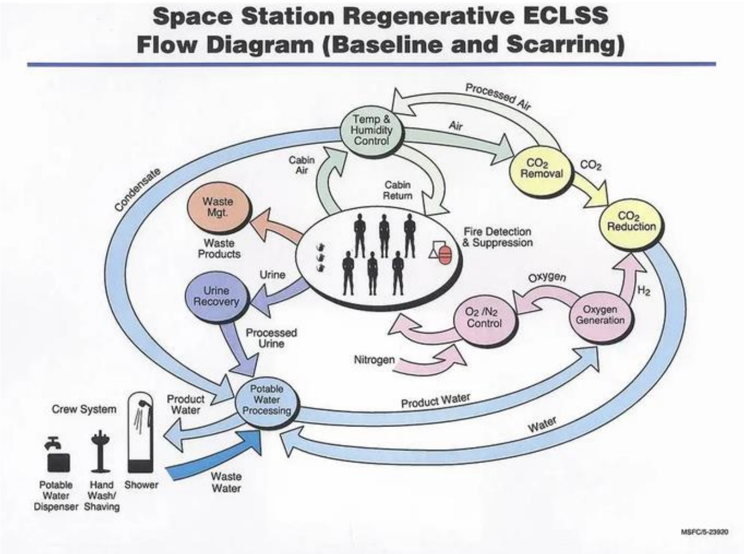
TTU Mechanical Engineering

NASA HuLC 2026 Problem Statement: Noise Suppression and Control

- NASA Identifies fans and other ECLSS (**Environment Control and Life Support Systems**) as sources of loud pervasive background noises in current spacecrafts.

➢ Future long duration missions require improved concepts to:
- Reduce noise generated by the ECLSS
- Isolate equipment noise from crew spaces
- Manage acoustic propagation within confined spaces
- Improve crew long-term health, communication, mission performance

- The Human Landing System is part of NASA's Artemis architecture for transporting crews to and from the lunar surface.
- As missions progress toward longer lunar stays and eventual Mars exploration, **acoustic control becomes a habitability and human-performance requirement rather than a comfort consideration.**



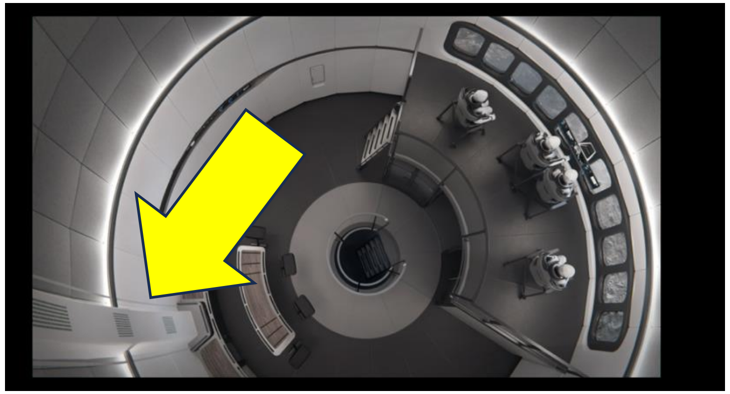
NASA Acoustic Limits and Expected Spacecraft Noise Sources

- **Continuous Sources**
  - ventilation and circulation fans
  - pumps and fluid-flow systems
  - air-handling and ventilation ducts
  - avionics cooling equipment
  - compressors and rotating machinery

- **Noise Mechanisms**
  - blade-passing and motor tones
  - turbulent airflow
  - pump and water-flow noise
  - duct-borne propagation
  - structure-borne vibration
  - equipment harmonics and narrow-band tones

- **Operational Evidence**
  - NASA identifies ECLSS fans and airflow, together with thermal-control pumps and water flow, as primary persistent noise sources aboard the International Space Station.

Source: SpaceX, *To the Moon and Beyond*, 2025.



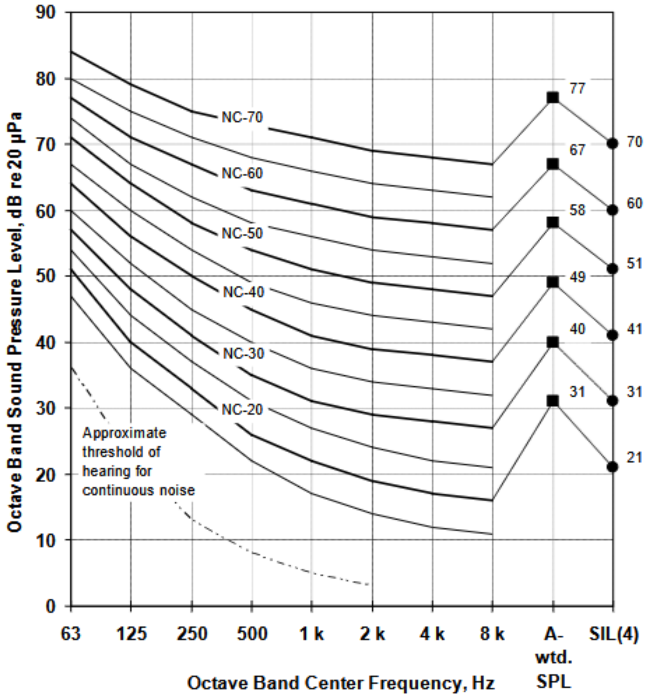


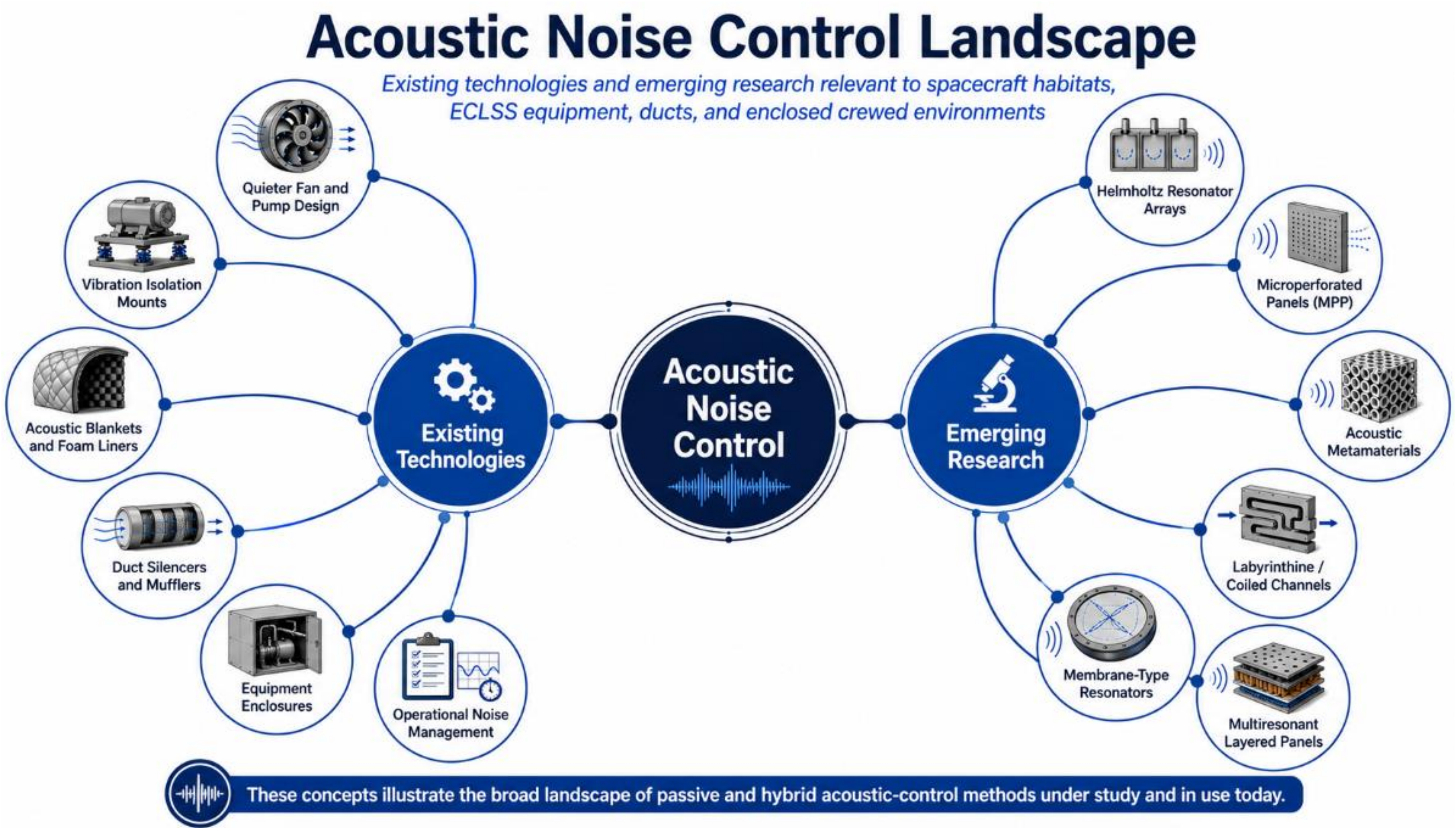
Figure 6.6-1—NC Curves

Literature Review and Existing Noise-Control Solutions

- **Source-Level Control**
  - quieter fan and pump design
  - reduced rotational speed
  - improved blade and motor design
  - vibration isolation mounts

- **Path and Receiver Control**
  - duct silencers and mufflers
  - acoustic enclosures
  - absorptive blankets and foam

- **Emerging Acoustic Metamaterials**
  - Helmholtz-resonator arrays
  - microperforated panels
  - labyrinthine and coiled channels
  - membrane and locally resonant structures
  - multiresonant layered absorbers
  - ventilated acoustic metamaterials



Design Priorities

- Testable through COMSOL and impedance tube methods
- Design should be passive with no added power demand.
- Compact size and low added mass
- Frequency-targeted acoustic response.
- Scalable and modular for future spacecraft applications.
- Our primary goal is to investigate the underlying physics of **acoustic wave propagation, attenuation, absorption, and transmission** through composite, multilayer, and multimodal material systems and geometries.
- This investigation can establish the basis for a **passive, multimodal, broadband acoustic unit cell** and its subsequent development into a **scalable acoustic metamaterial**.

Design Priorities

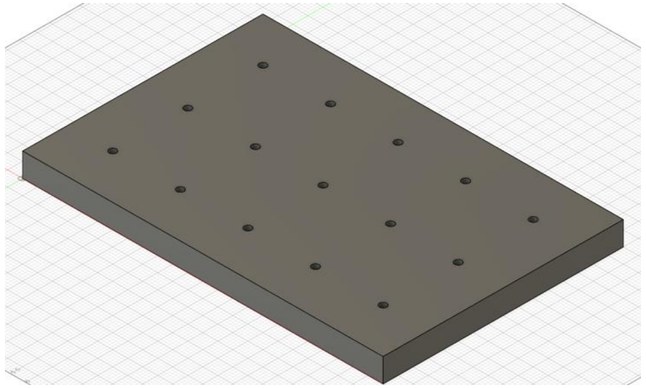
Ranked Selection Criteria for Our Acoustic Panel Concept

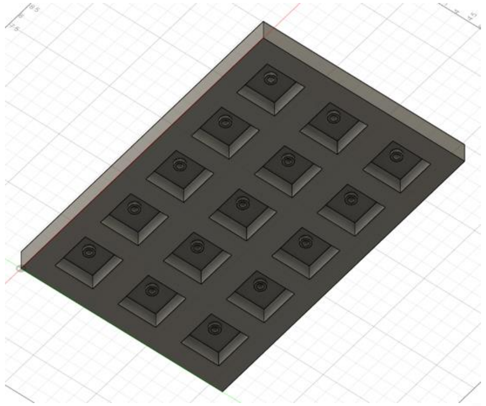
Priority	Criterion	Design Intent
1	**Testability**	Can be fabricated and verified in impedance-tube and grazing-flow testing
2	**Effectiveness**	Produces meaningful attenuation in the target ECLSS frequency range
3	**Innovation**	Advances beyond conventional treatments with a defensible metamaterial concept
4	**Mass**	Minimizes added spacecraft mass and thickness
5	**Electricity**	Requires no continuous electrical power; passive operation preferred
6	**Manufacturability**	Can be produced repeatably with practical fabrication methods
7	**Scalability**	Can grow from lab samples to duct, panel, and habitat-scale implementations
8	**Cost**	Supports low-cost prototyping and iterative development

Primary emphasis: experimentally verifiable performance first, followed by acoustic effectiveness and innovation.

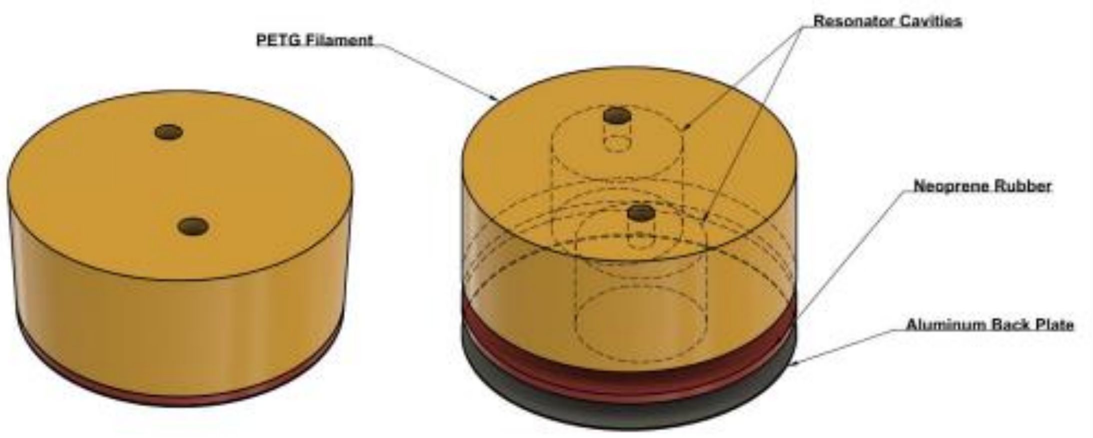
Proposed Solution – Acoustic Metamaterial Architecture

- **Functional Architecture**
  - **Microperforated Surface Layer -**
    Introduces viscous losses and improves broadband acoustic dissipation
  - **Multiresonant Cavity Layer –**
  - Uses independently tuned resonant cavities to target dominant ECLSS frequency bands.
  - **Compliant Damping Layers-**
    Reduce structural vibration transmission and dissipate mechanical energy.
  - **Rigid Backing Layer-**
    Seals the resonant cavities and provides structural support.





Acoustic Metamaterial Panel (AMP) Unit Cell Architecture

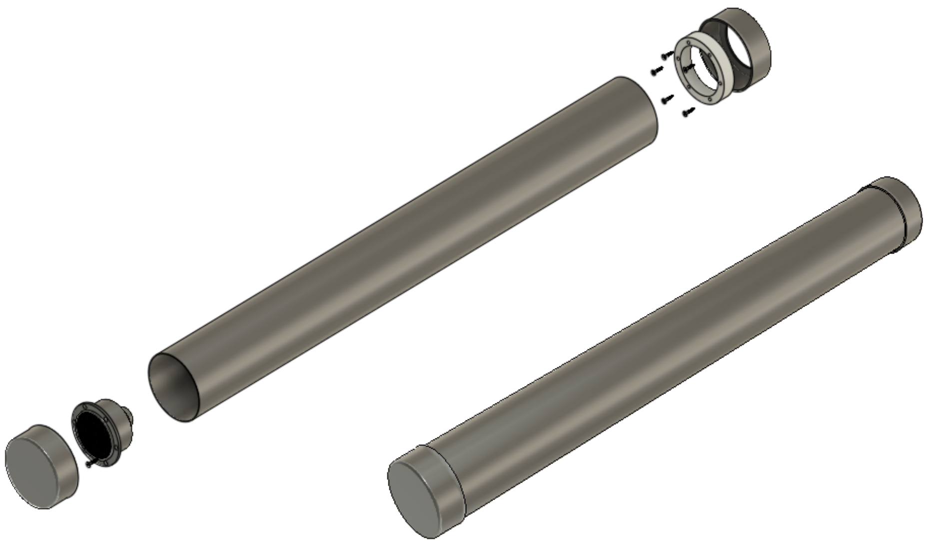


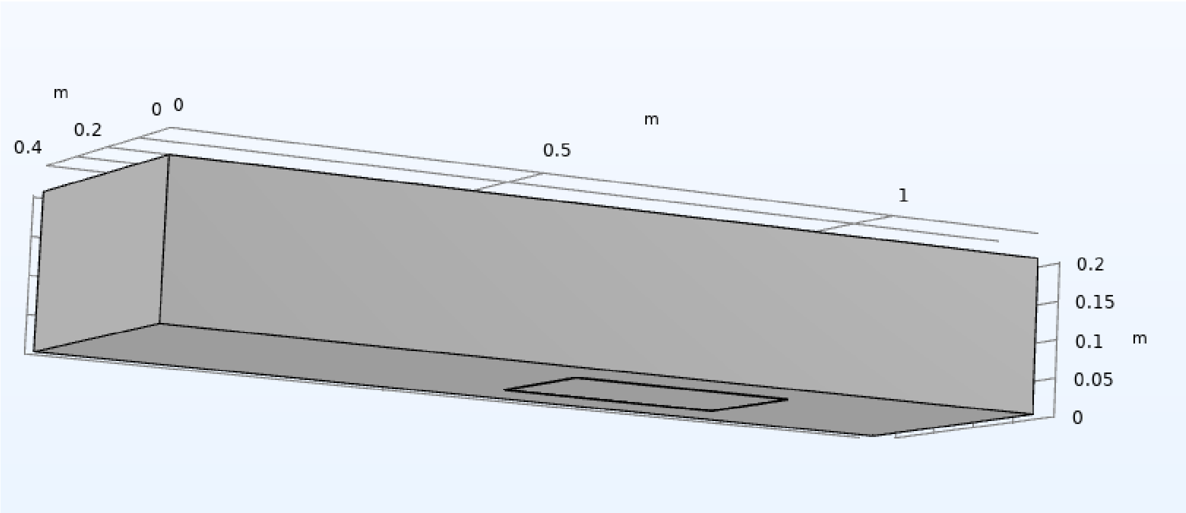
Target Frequency Focus

- Initial project proposal considered 125, 250, 500, and 1000 Hz.
- Current proof-of-concept focuses on 500 Hz.
- 500 Hz was selected for fabrication and testing practicability.
- Lower frequencies need larger resonator volumes.
- Future designs can target additional frequency bands.

Methodology / Test Path

- Research and identify prominent ECLSS-related frequency bands
- Design resonator geometry.
- Simulate acoustic response in COMSOL.
- Fabricate/test prototype using impedance tube setup.
- Compare simulation to experimental resonance behavior.





METHODOLOGY / TEST PATH

FROM RESEARCH TO FINAL COMPARISON

1 RESEARCH

- Literature review
- Acoustic challenges in lunar habitats
- Identify noise sources and requirements
- Define design goals

2 SOLUTION

- Concept development
- Acoustic metamaterial panel design
- Unit cell & resonator configuration
- Design parameters defined

3 IMPEDANCE SIMULATION & TESTING

- COMSOL impedance simulations
- Impedance tube testing (no flow)
- Validate absorption & impedance

4 RESULTS

- Compare simulation vs. experimental data
- Identify resonance behavior
- Refine design parameters

5 SOLUTION MADE FOR DUCT PANEL

- Scale design for duct integration
- Build and assemble duct panel prototype
- Ensure structural and sealing integrity

6 GRAZING FLOW TESTING

- Grazing flow (duct) testing
- Measure transmitted sound under flow
- Evaluate performance in realistic conditions

7 SOLUTION & TESTING RESULTS

- Compare no-flow vs. grazing flow results
- Assess effectivenss of final duct panel solution
- Confirm performance improvements

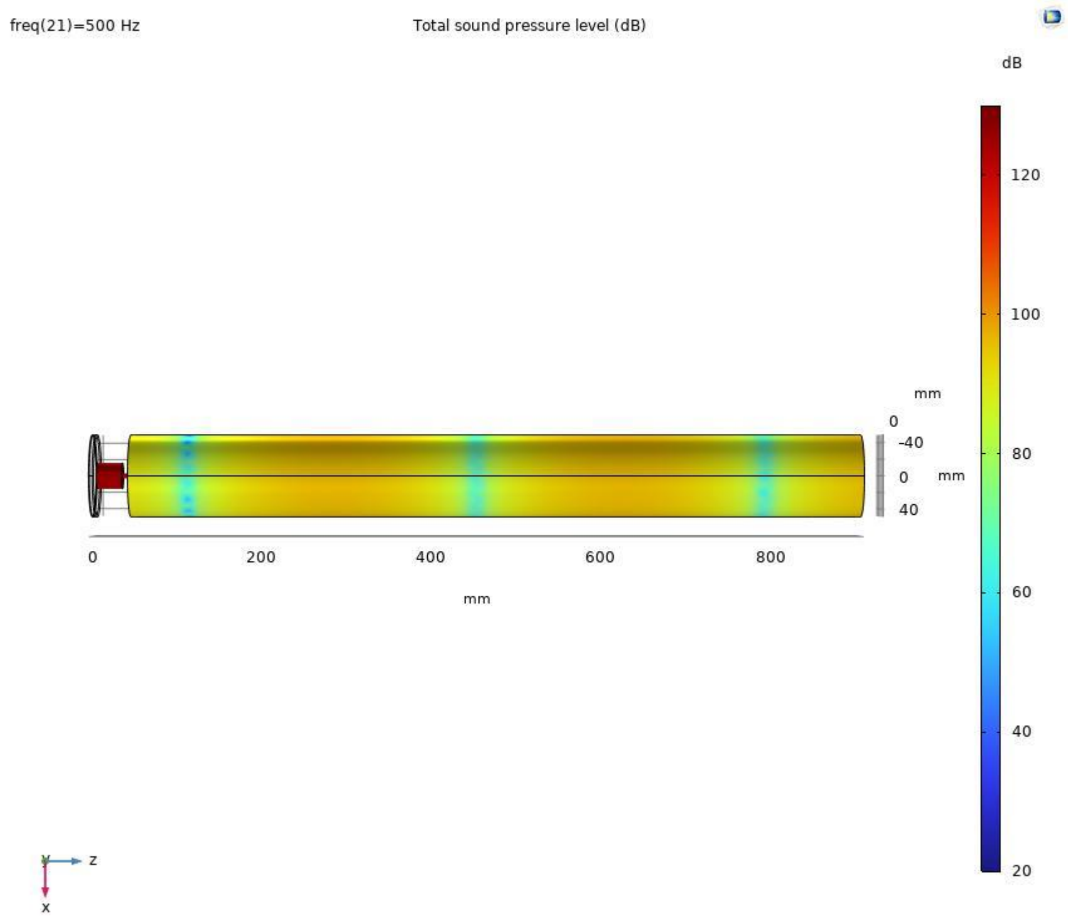
8 FINAL COMPARISON

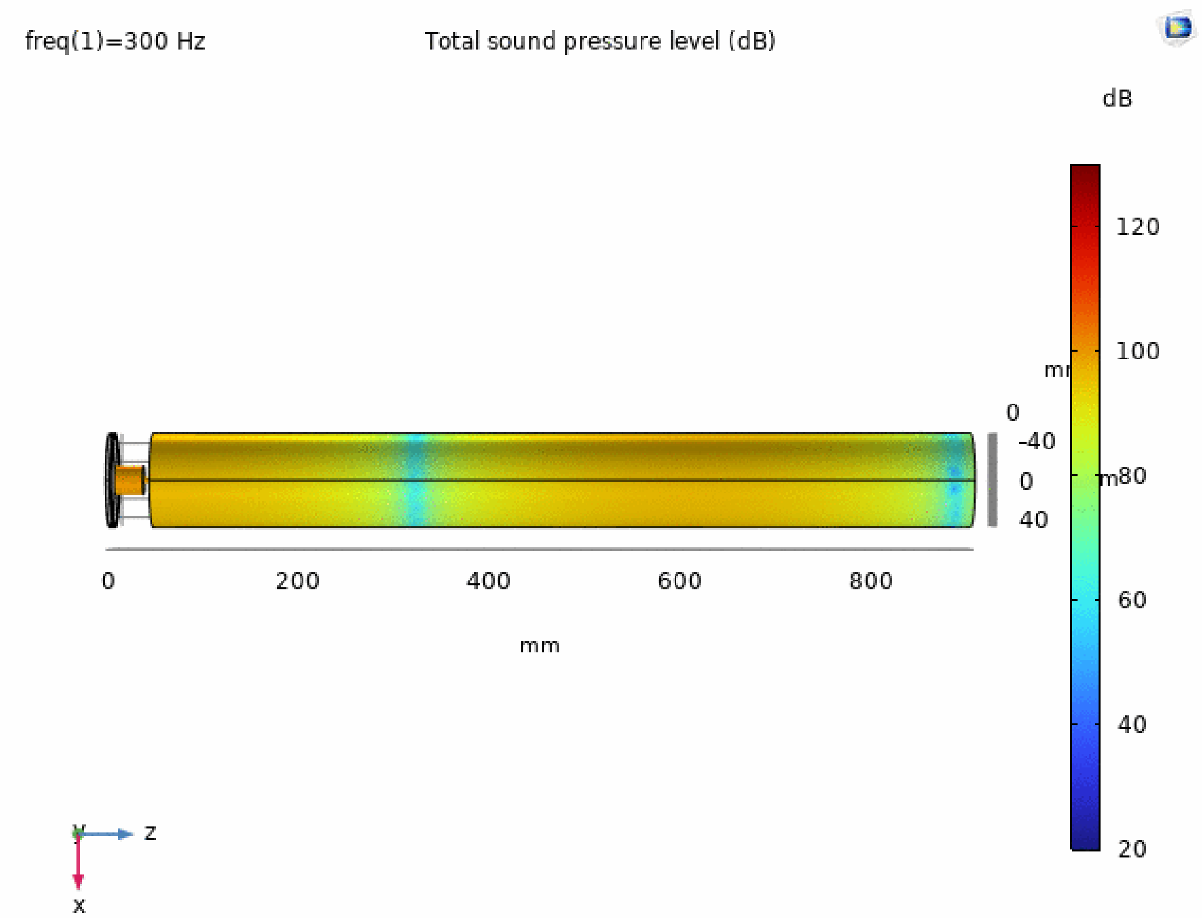
- Compare all panel configurations
- Determine best performing design
- Provide final recommendation

GOAL: Develop and validate an acoustic metamaterial panel that reduces noise in lunar habitat duct systems.

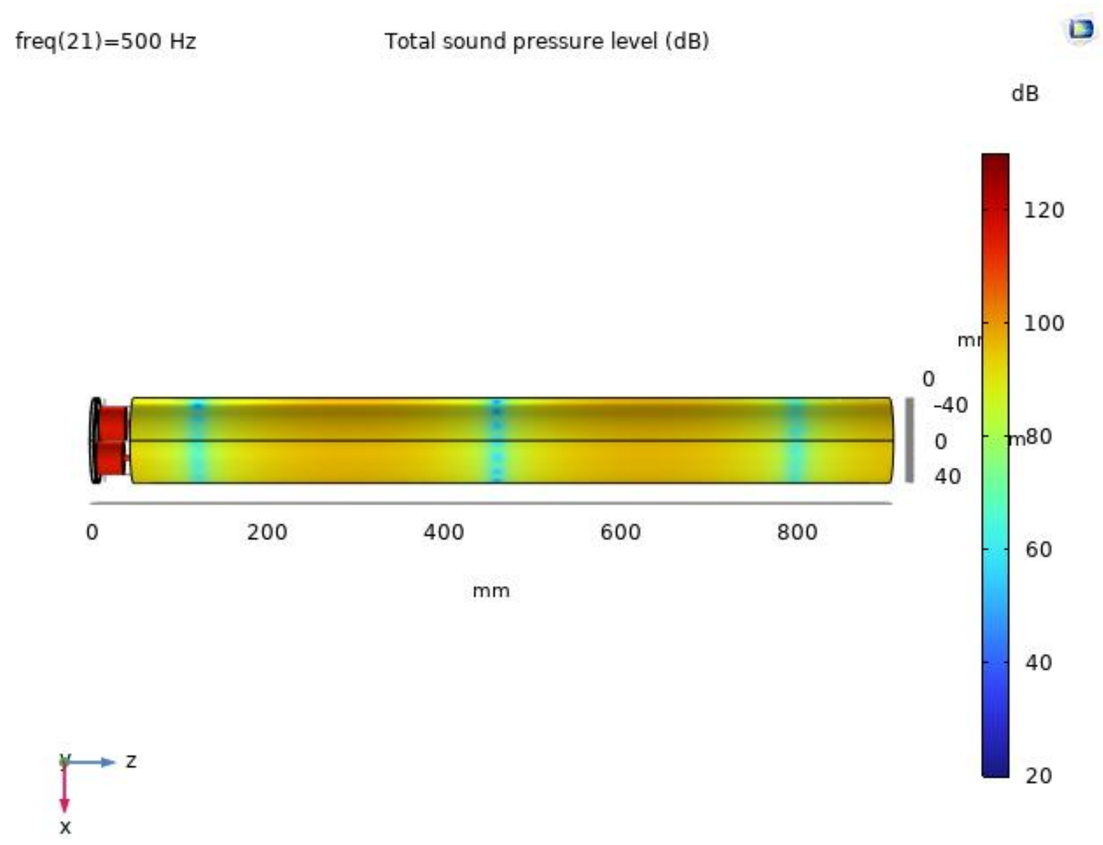
OUTCOME: A tested, validated, and optimized solution for quieter, more comfortable lunar habitats.

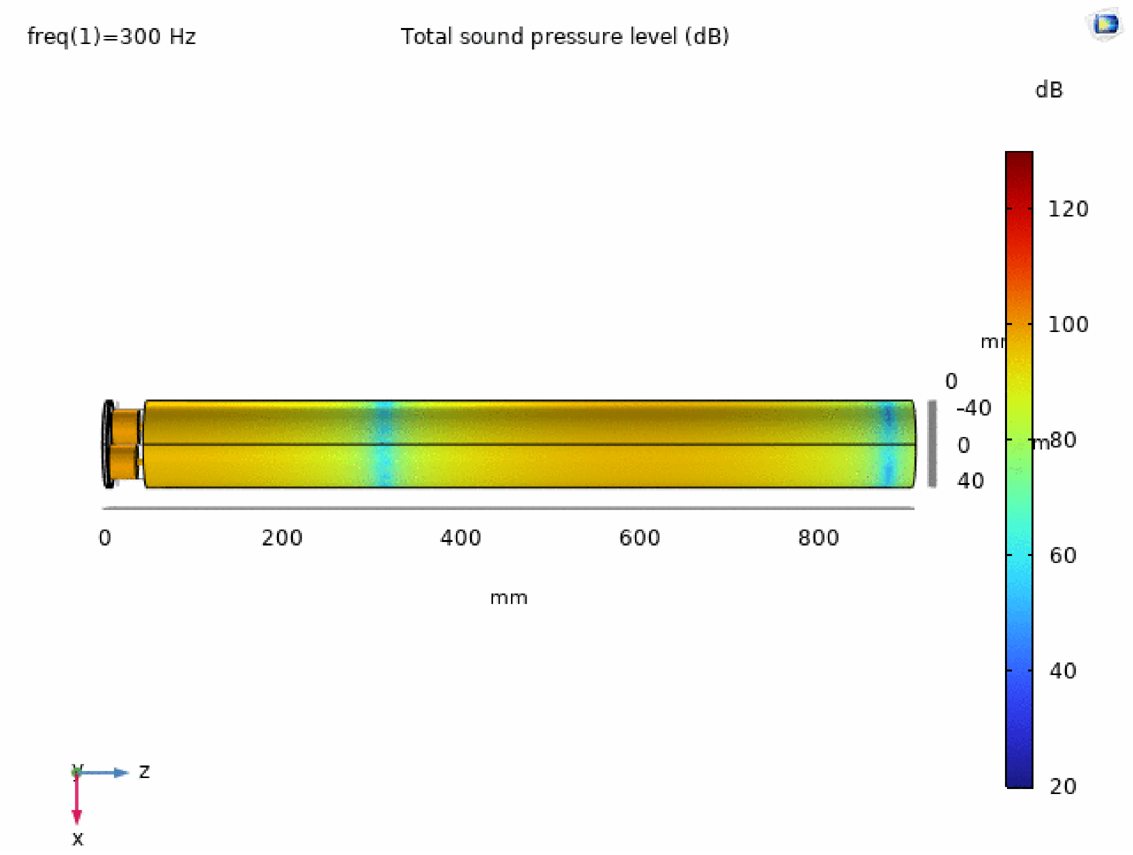
COMSOL Simulation: Impedance Tube Single 500 HZ Resonator



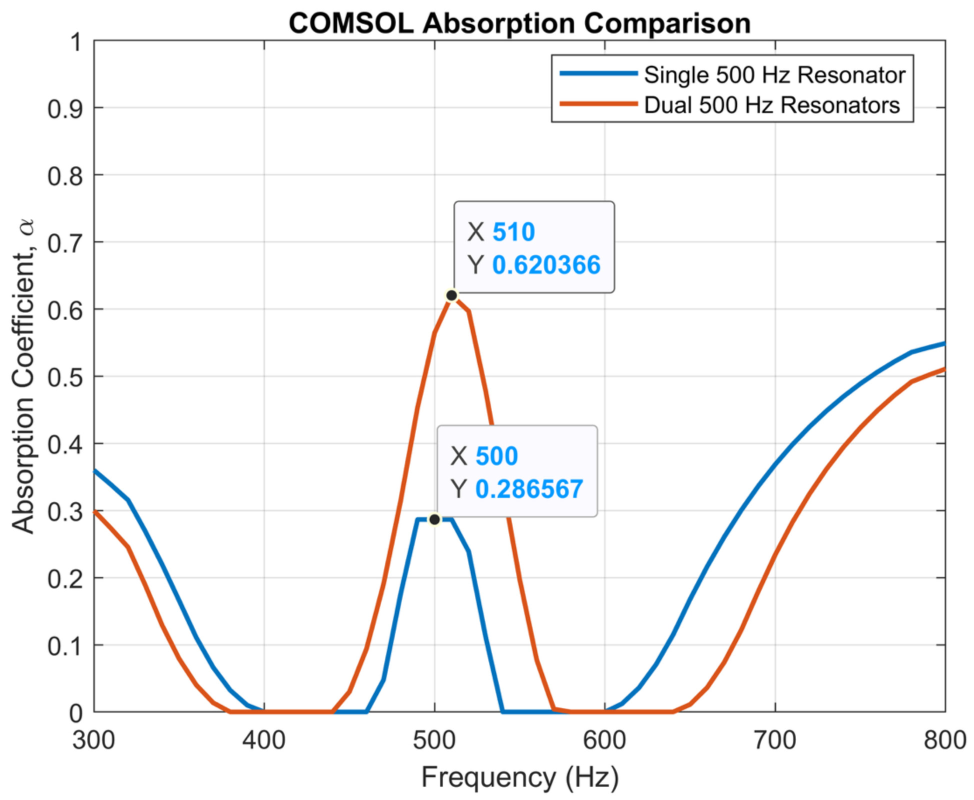


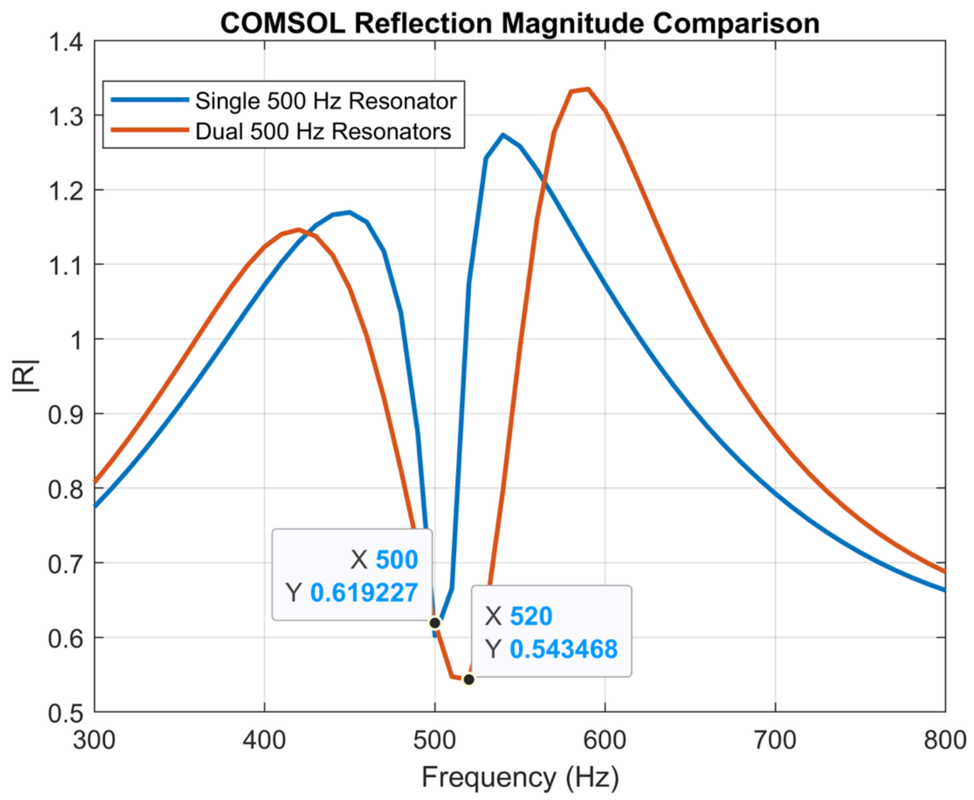
COMSOL Simulation: Impedance Tube Two 500 HZ Resonators



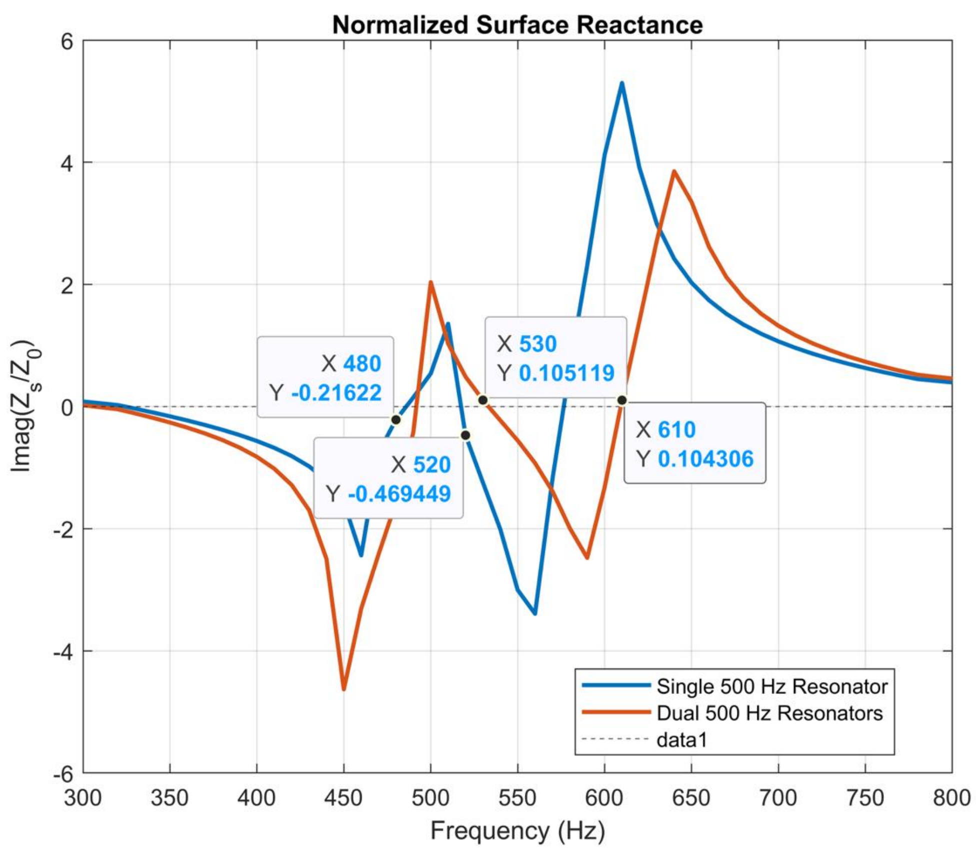


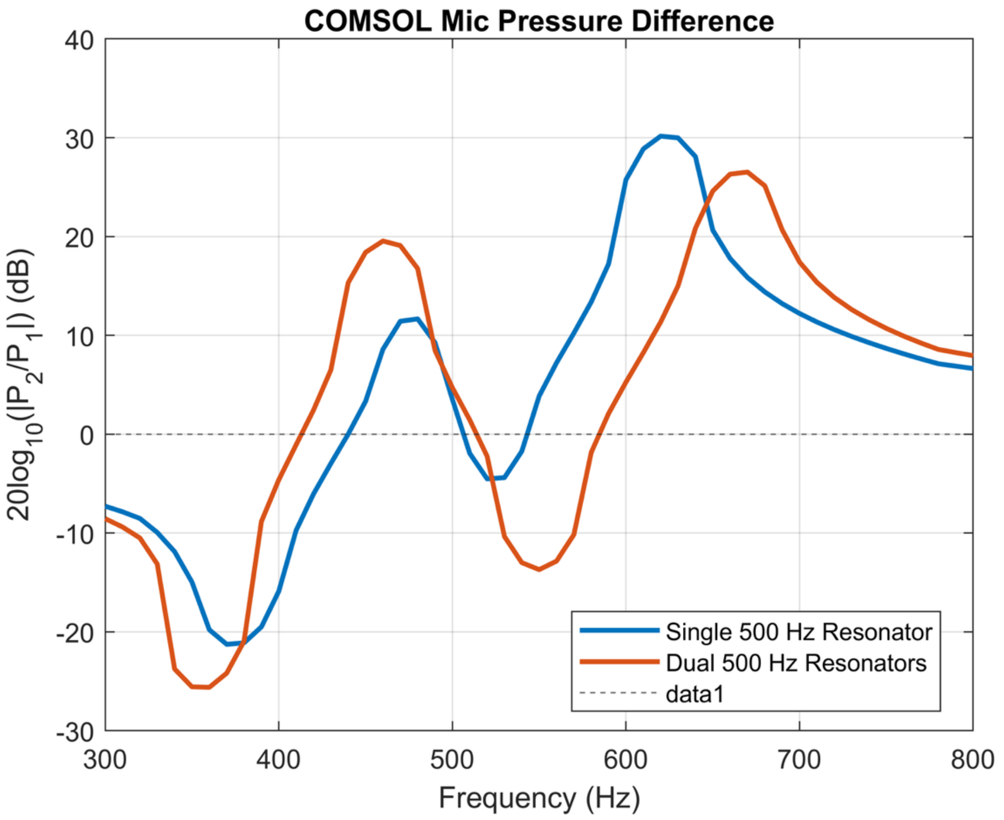
COMSOL Simulation: Results Comparison



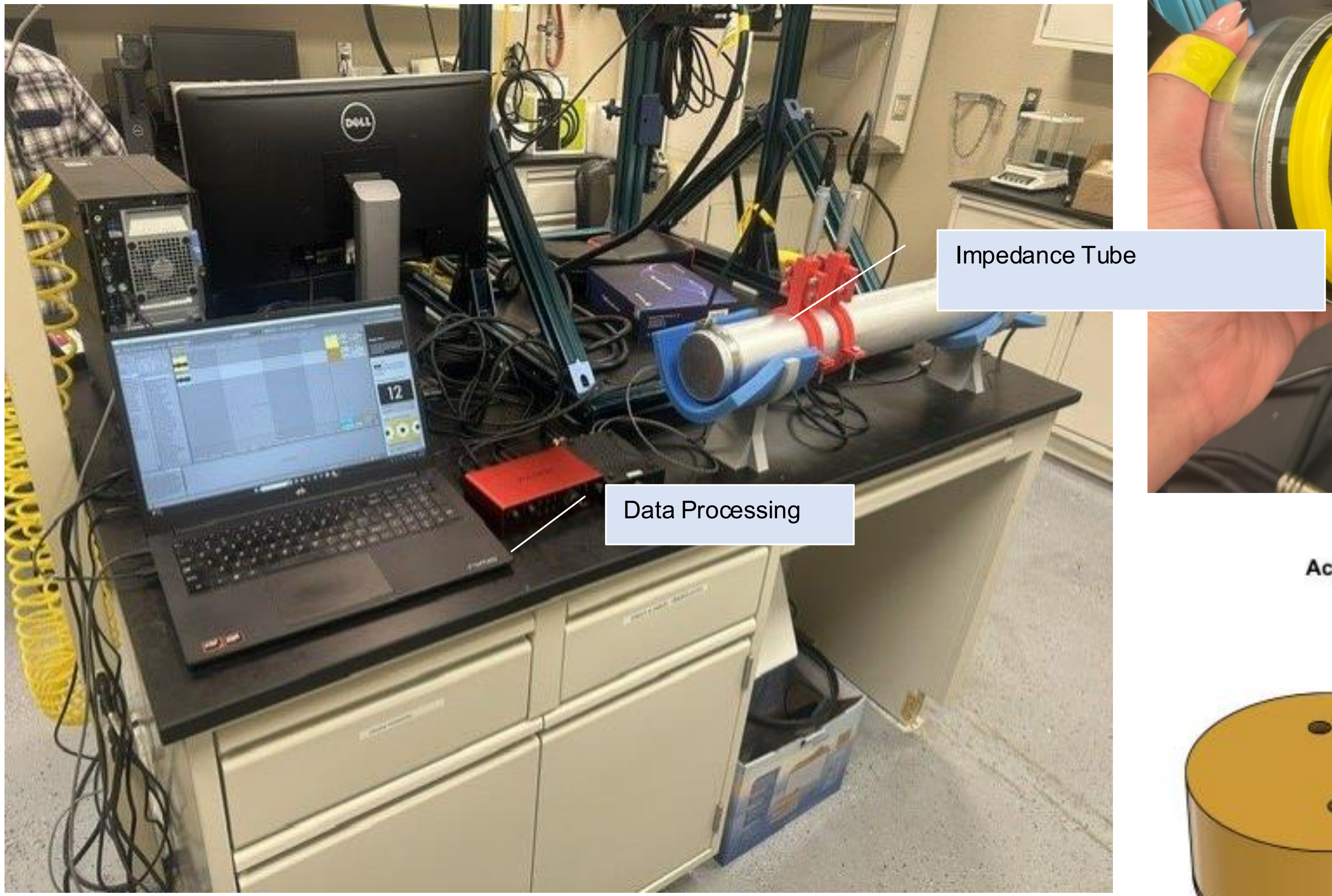


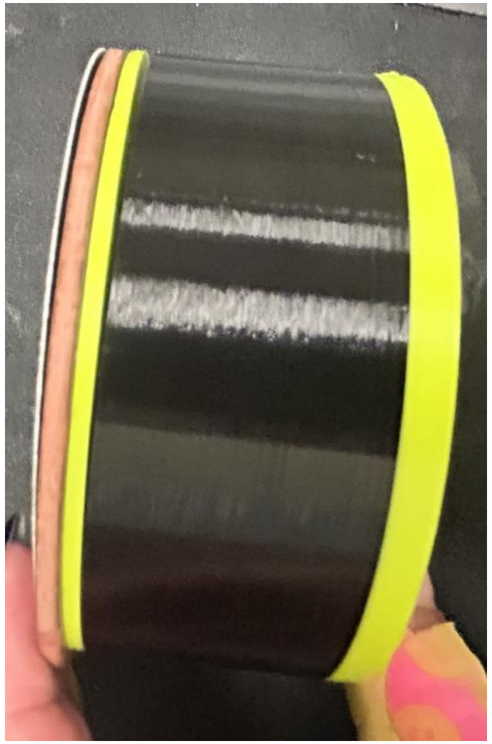
COMSOL Simulation: Results Comparison

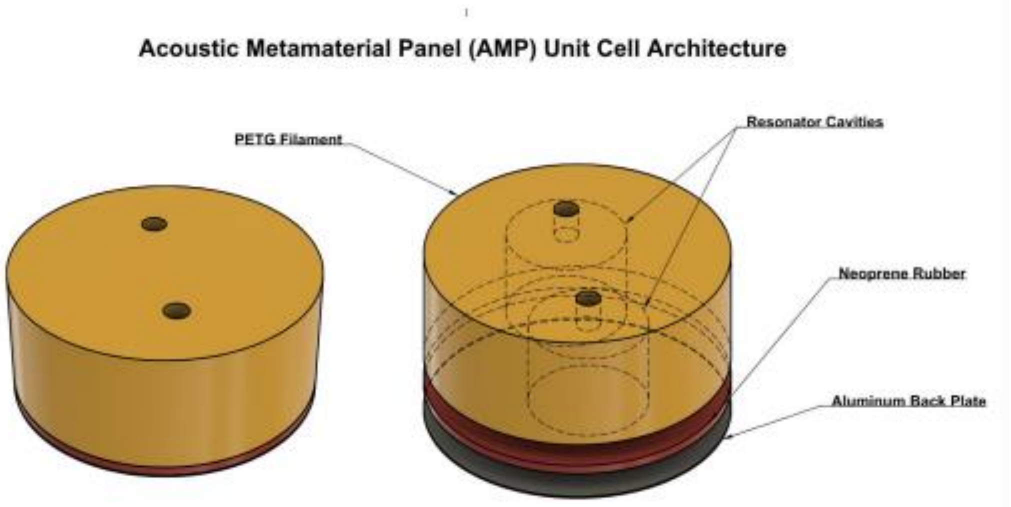




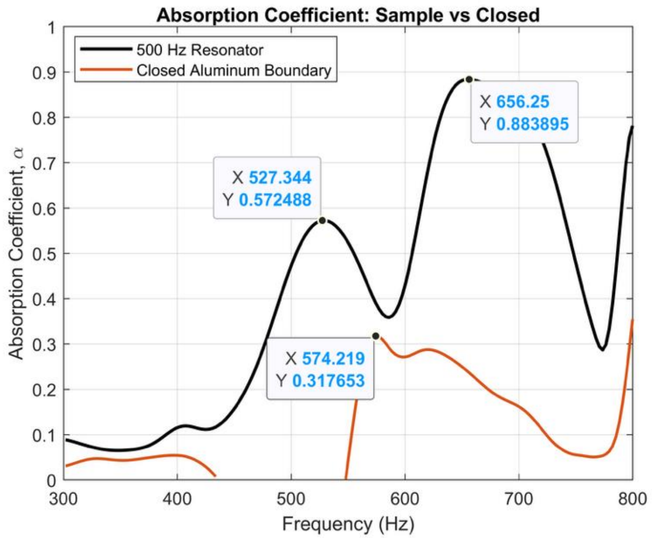
Impedance Tube Testing

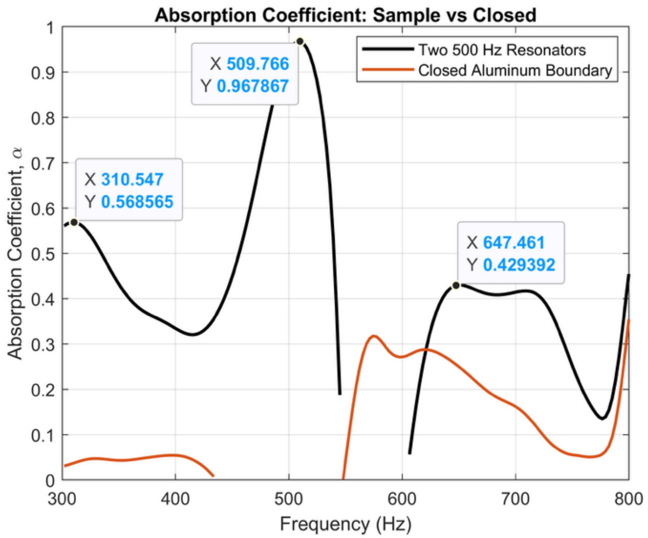


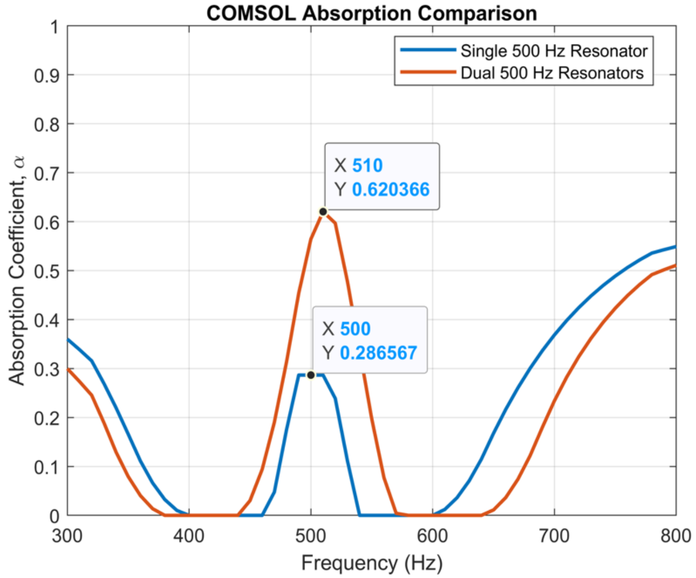




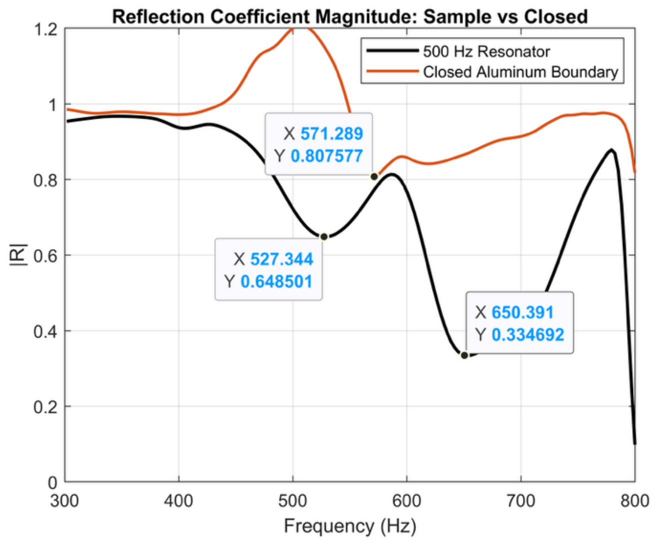
Impedance Test vs COMSOL Simulation: Absorption

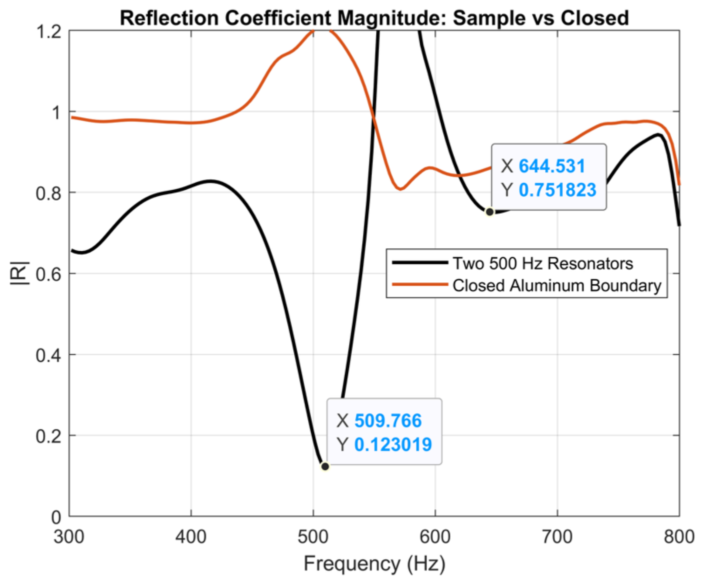


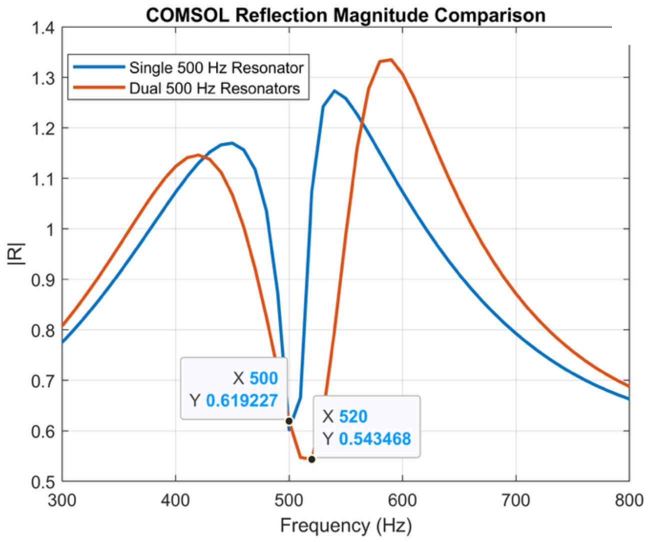




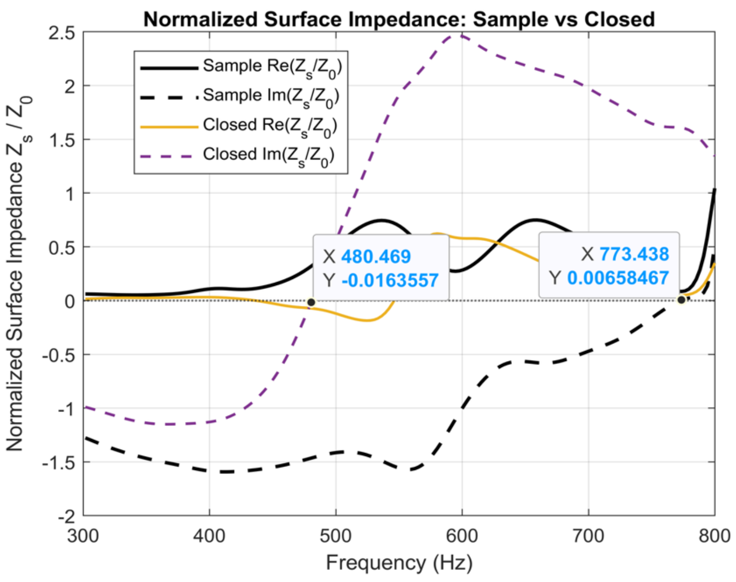
Impedance Test vs COMSOL Simulation: Reflection

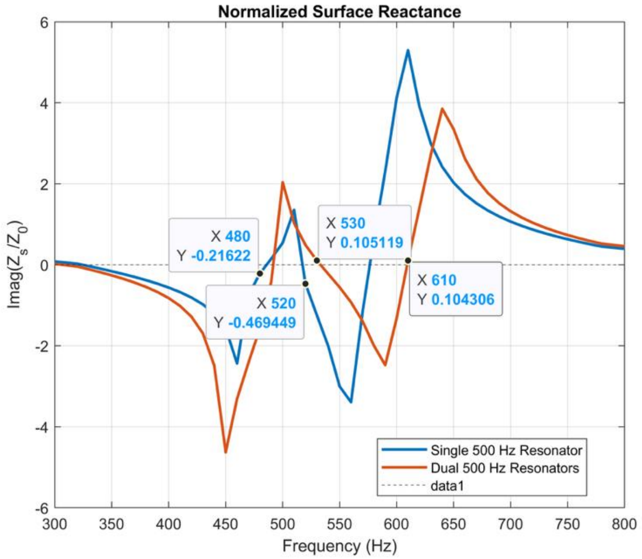


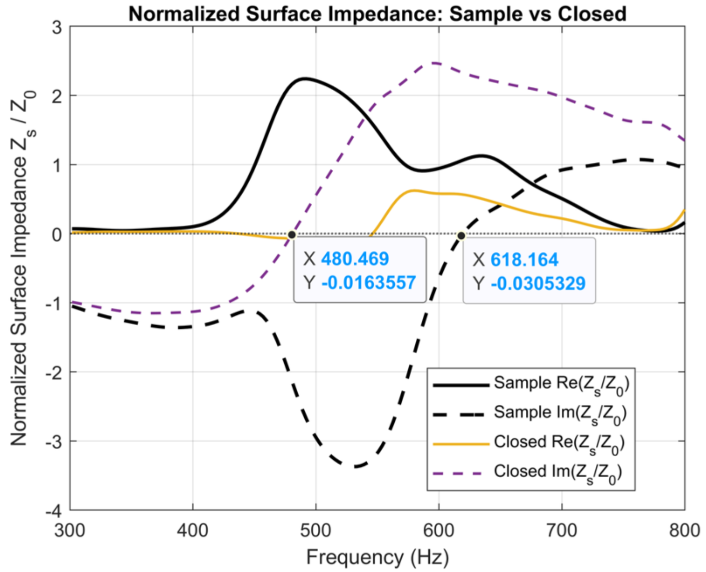




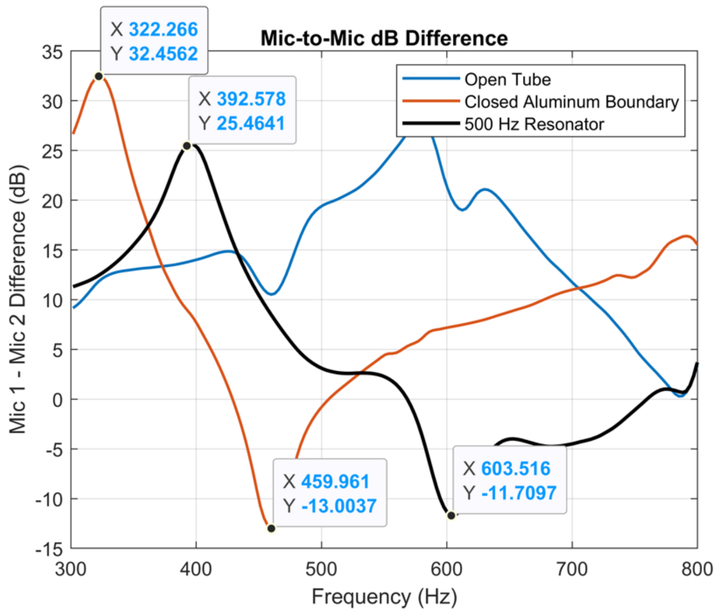
Impedance Test vs COMSOL Simulation: Impedance

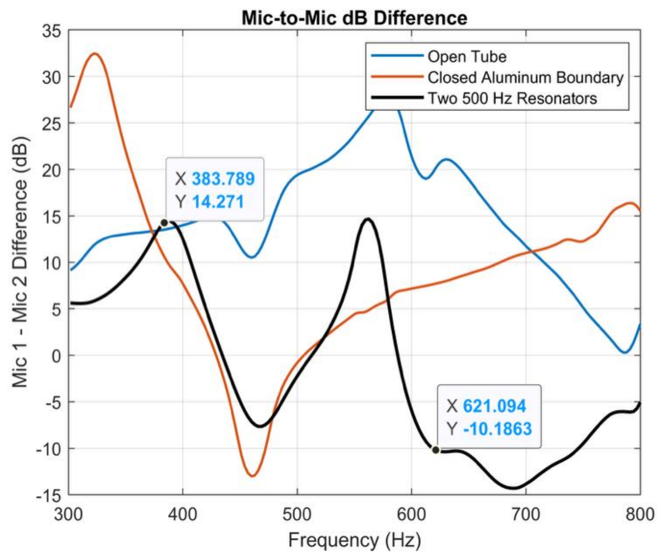


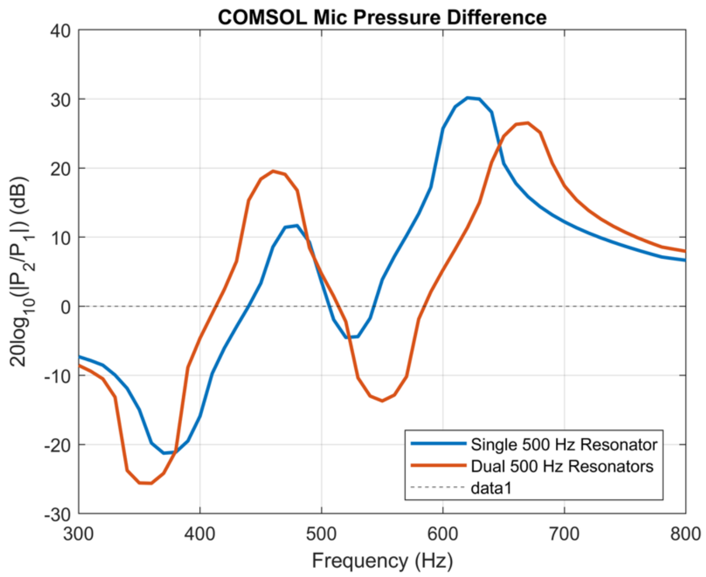




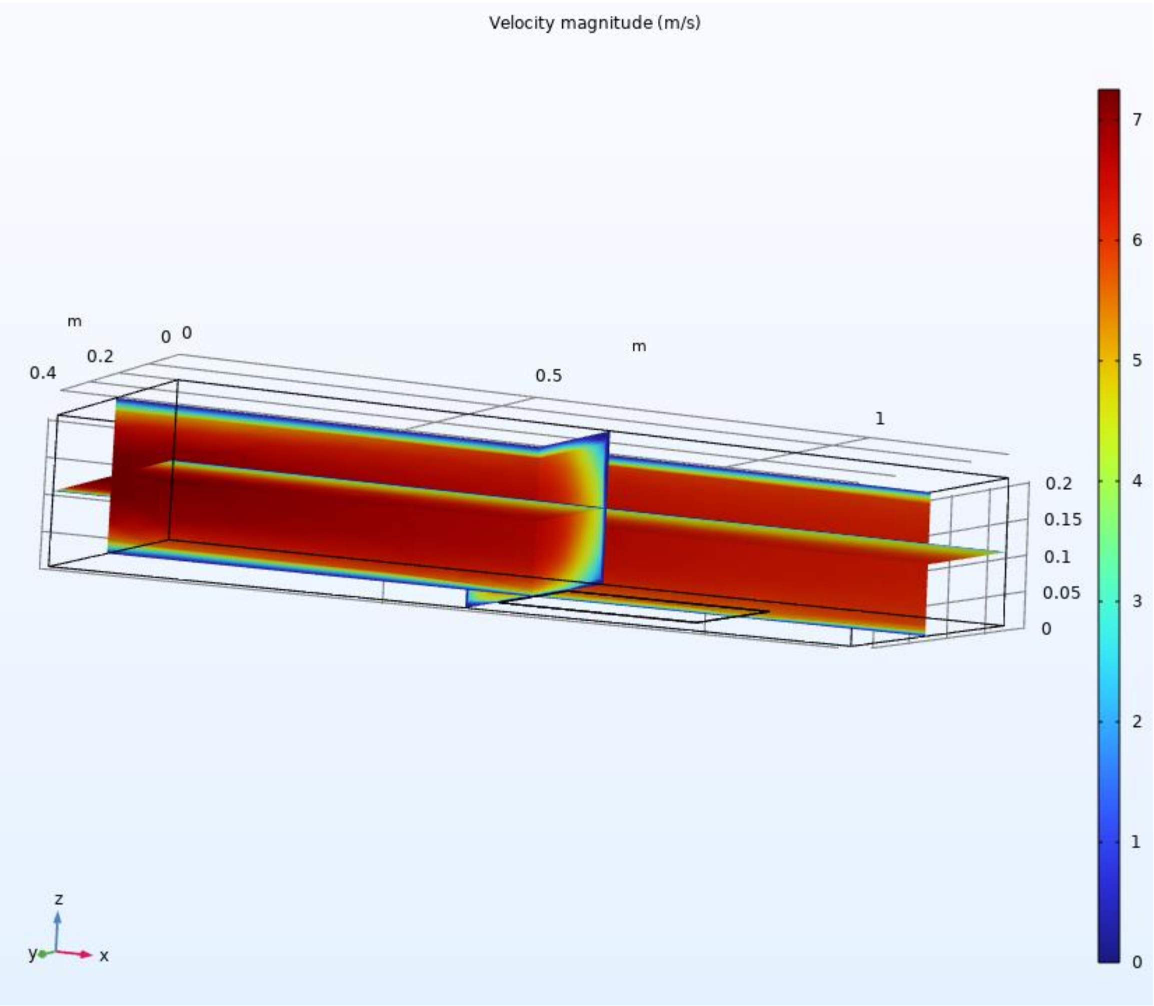
Impedance Test vs COMSOL Simulation: dB Difference

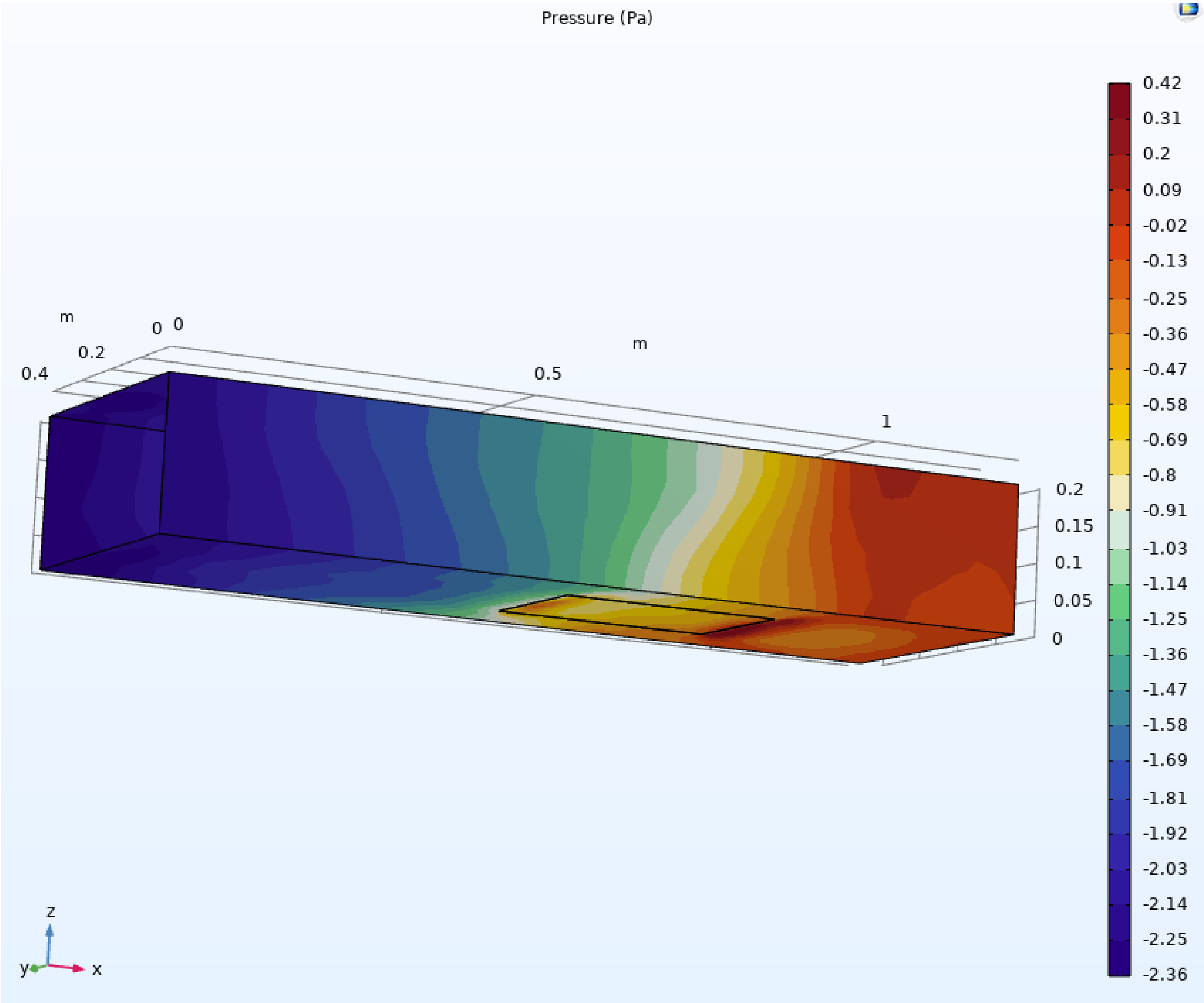




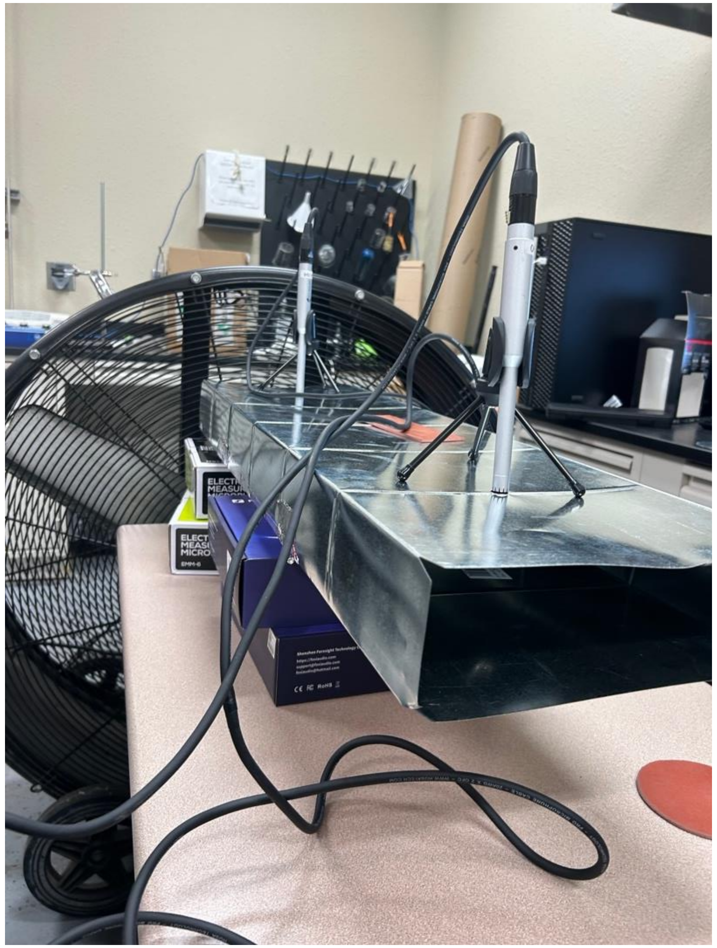


COMSOL Simulation: Grazing Flow Test

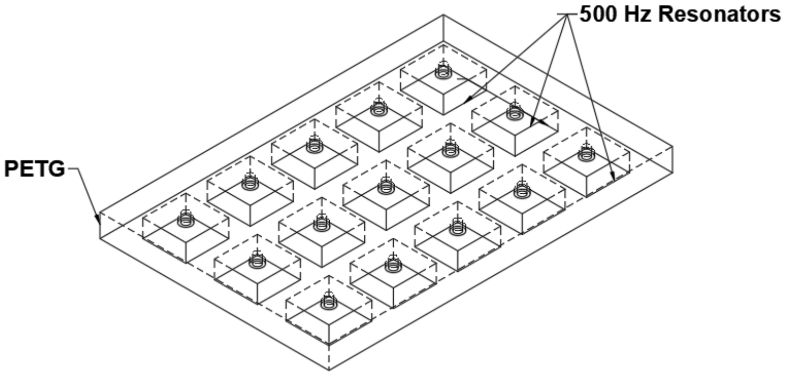




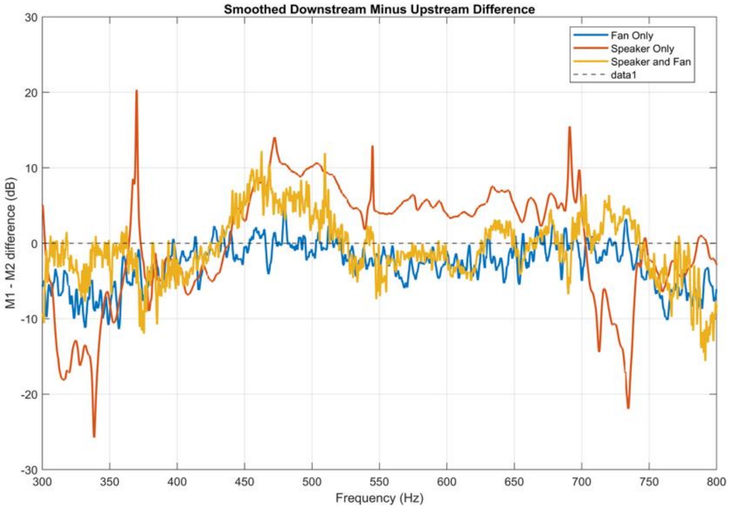
Grazing Flow Testing



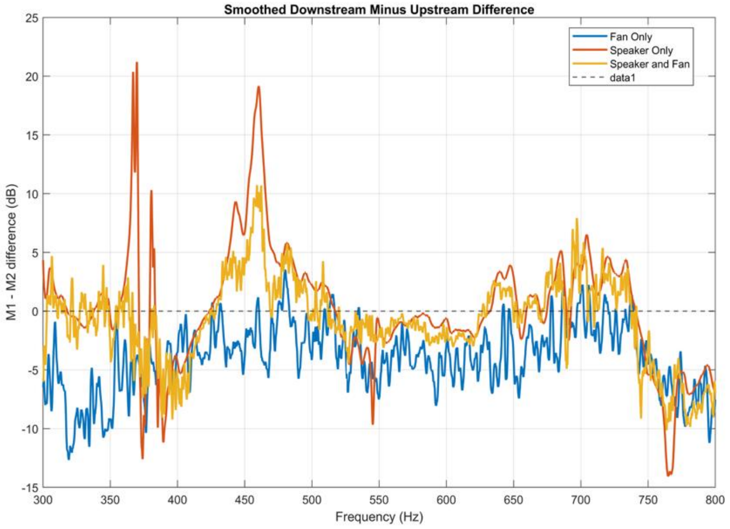
Grazing Flow Testing



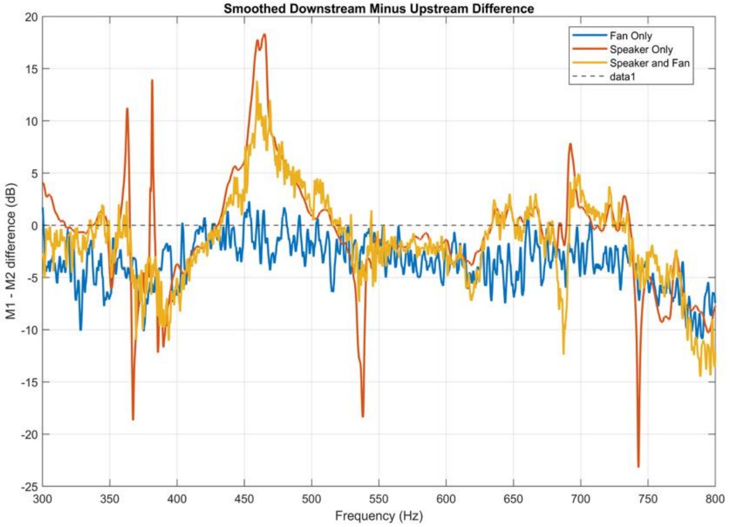
Grazing Flow Test : dB Difference



Control (No Panel)

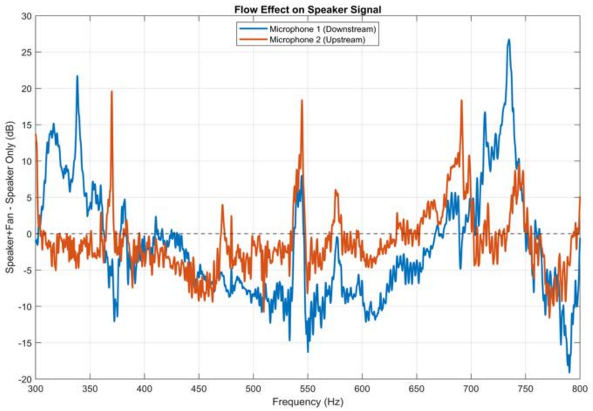


Panel w/ MPP

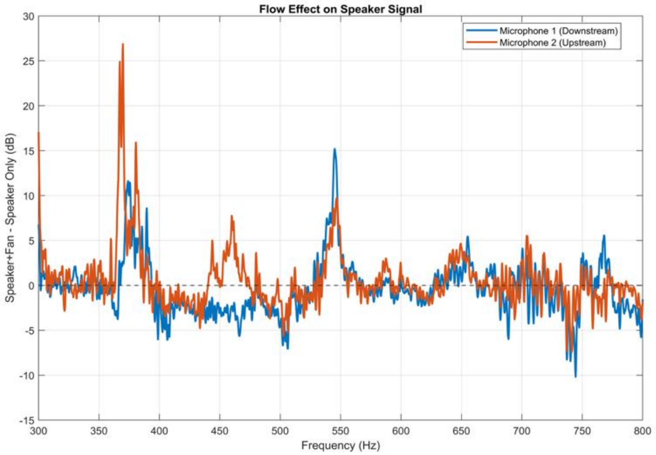


Panel w/o MPP

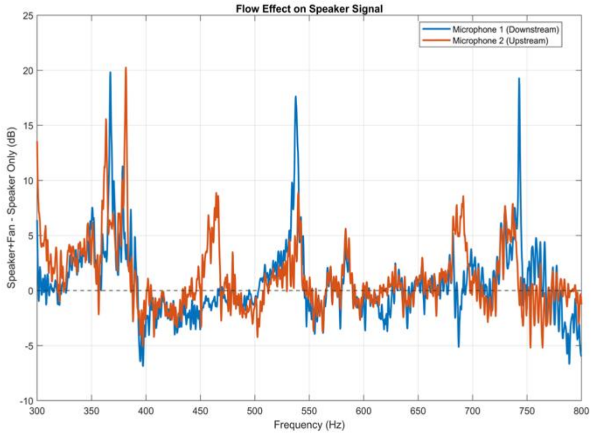
Grazing Flow Test : Flow Impact



Control (No Panel)

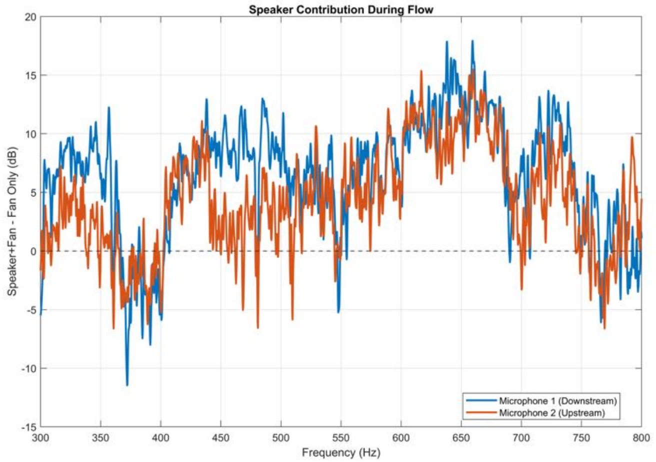


Panel w/ MPP
MPP

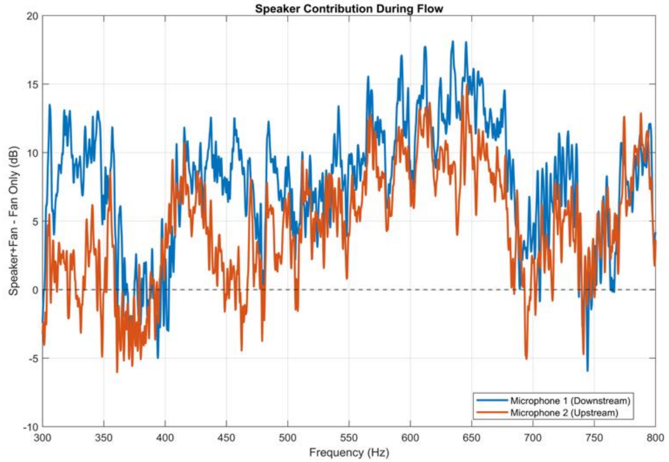


Panel w/o MPP

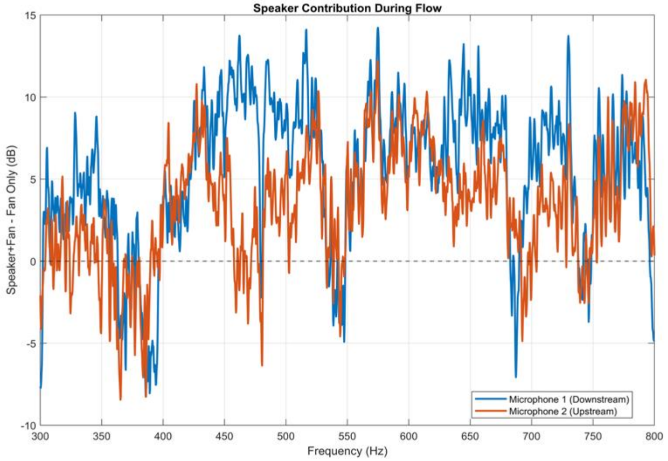
Grazing Flow Test : Speaker Impact



Control (No Panel)

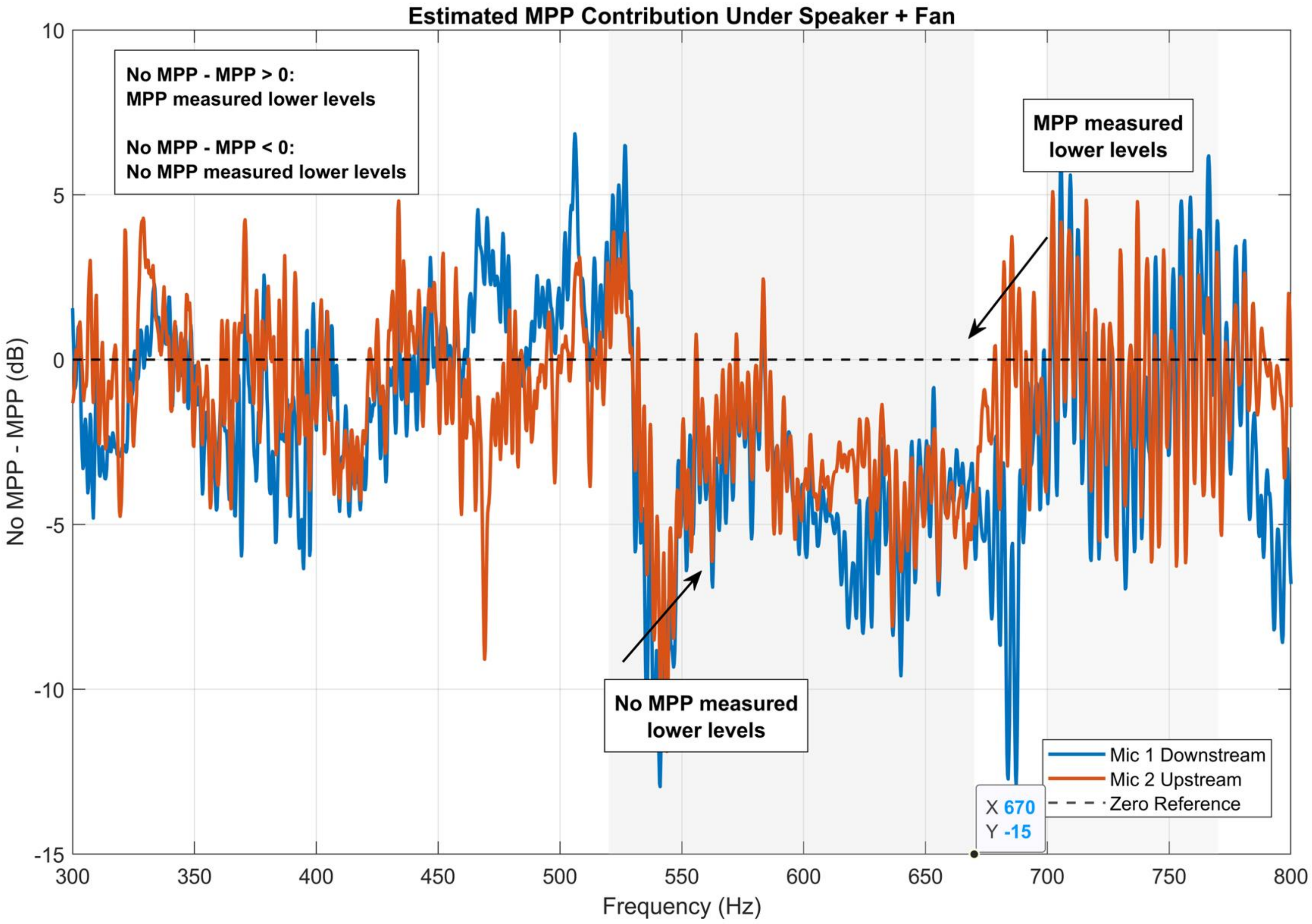


Panel w/ MPP
MPP

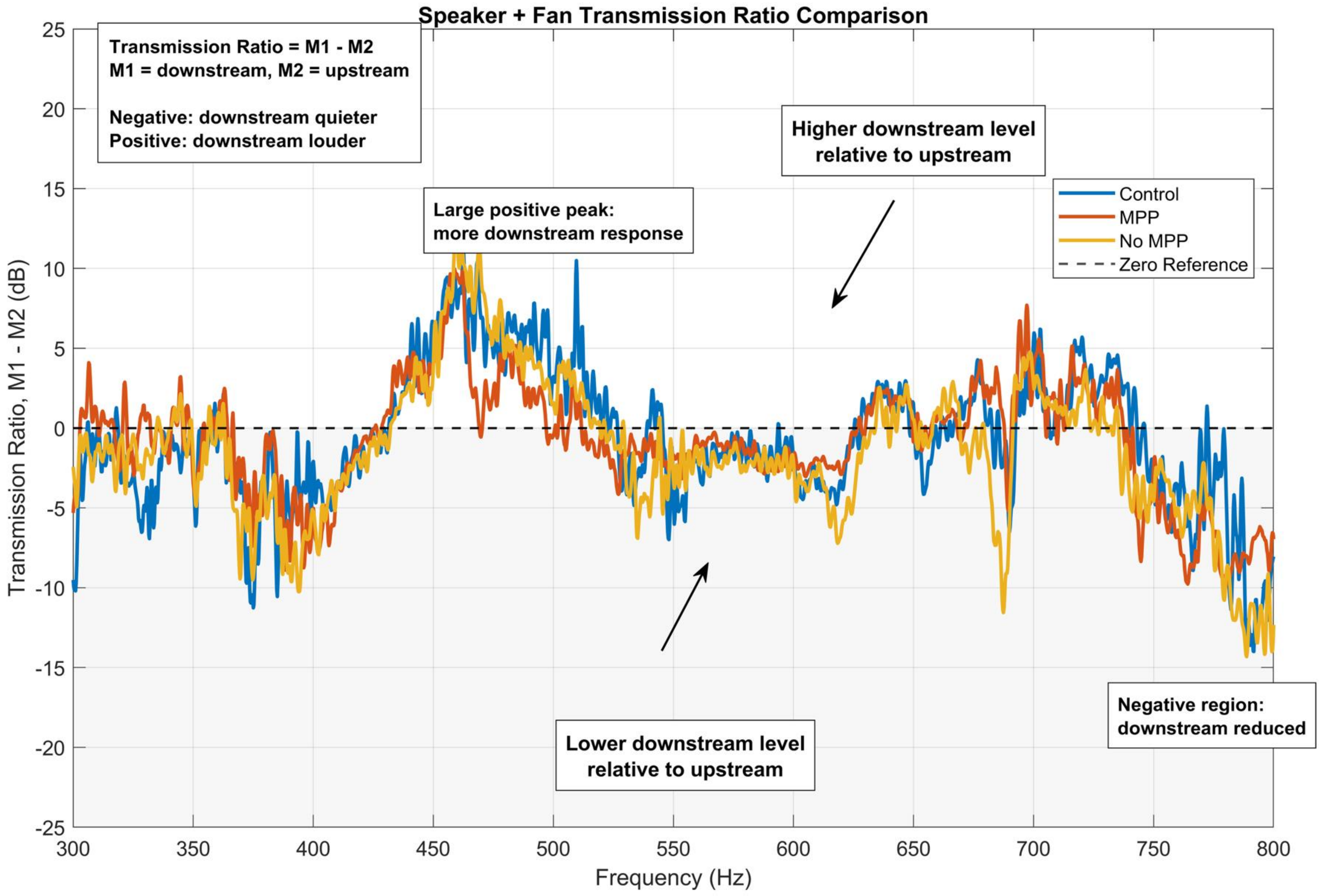


Panel w/o MPP

Grazing Flow Test : MPP w/ or w/o Comparison



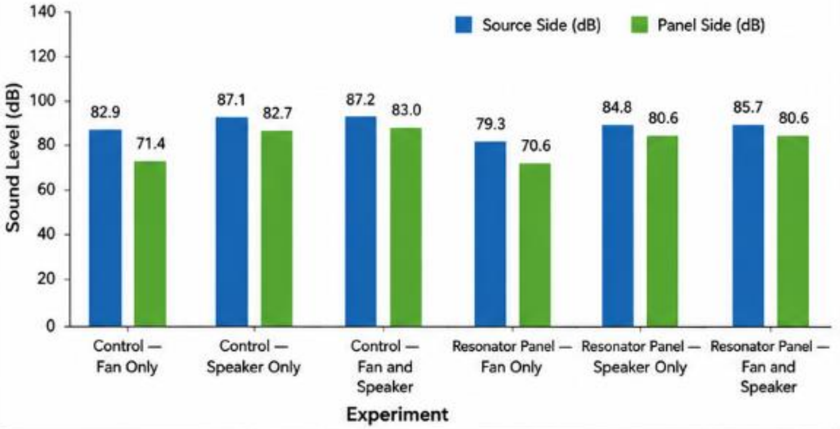
Grazing Flow Test : dB Change Comparison



Decibel and Flow Speed Results

Grazing-Flow Duct Experiments

Sound Levels by Experiment



Sound Level Measurements

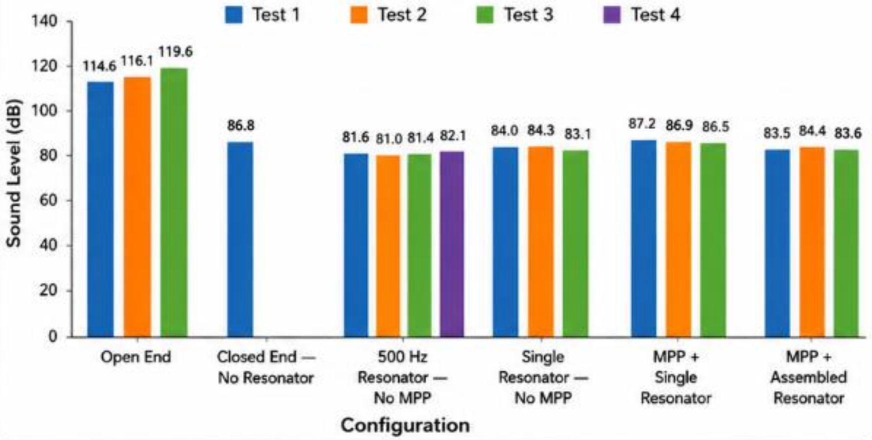
Experiment	Source Side (dB)	Panel Side (dB)
Control — Fan Only	82.9	71.4
Control — Speaker Only	87.1	82.7
Control — Fan and Speaker	87.2	83.0
Resonator Panel — Fan Only	79.3	70.6
Resonator Panel — Speaker Only	84.8	80.6
Resonator Panel — Fan and Speaker	85.7	80.6

Airflow Measurements

Experiment	Source Side (m/s)	Panel Side (m/s)
Overall Fan Control	6.0–6.3	4.0–4.4
Resonator Panel — Fan and Speaker	4.8	3.2

Impedance-Tube Experiments

Sound Levels by Configuration



Sound-Level Testing

Experiment	Configuration	Test 1 (dB)	Test 2 (dB)	Test 3 (dB)	Test 4 (dB)
1	Open End	114.6	116.1	119.6	—
1	Closed End — No Resonator	86.8	—	—	—
2	500 Hz Resonator — No MPP	81.6	81.0	81.4	82.1
3	Single Resonator — No MPP	84.0	84.3	83.1	—
4	MPP + Single Resonator	87.2	86.9	86.5	—
5	MPP + Assembled Resonator	83.5	84.4	83.6	—

Mass Measurements

Component	Mass (g)
Assembled Impedance Puck with MPP	187.73
Assembled Impedance Puck without MPP	163.52
Tested Assembled Resonator Panel	907

Impedance Test Discussion

Rank	Resonator	Why
1	Two MPP 500 Hz	Best overall performance. Highest peak absorption, high average absorption, smoother impedance response, and broader absorption bandwidth.
2	Bare Two 500 Hz	Best tuned to the target frequency. Strong resonance behavior and excellent absorption near 500 Hz.
3	Bare Single 500 Hz	Good absorption performance but lower overall effectiveness than dual-resonator designs.
4	MPP Single 500 Hz	Lowest overall performance. MPP alone did not provide sufficient improvement without the second resonator cavity.

Grazing Flow Test Discussion

Rank	Duct Panel	Why
1	No MPP Resonator	Lowest transmitted levels across much of the measured frequency range.
2	MPP Resonator	Improved over control in some regions but generally not as effective as No MPP.
3	Control	Typically exhibited the highest downstream sound levels.

Discussion

- AMP displayed strong simulation-to-test correlation.
- Passive design avoids added power demand.
- Layered structure offers acoustic and structural function.
- Current design is an early proof-of-concept.
- Additional testing is needed before spacecraft implementation.

DESIGN RISKS, CHALLENGES & MITIGATIONS

RISK / CHALLENGE	IMPACT	MITIGATION
Resonance Frequency Shift Resonance shifted from 500 Hz to ~760 Hz	Reduced agreement with design predictions	Experimental testing and COMSOL model refinement
Manufacturing Tolerances Variations in cavity and neck dimensions	Changed cavity volume and neck tuning	Dimension verification and redesign iterations
Material Property Uncertainty PETG, neoprene, and damping properties not fully known	Reduced simulation accuracy	Literature values and sensitivity studies
Acoustic Leakage Gaps or imperfect sealing reduce absorption	Lower measured absorption	Improved sealing and mounting procedures
Grazing Flow Effects Airflow alters resonator performance	Performance may differ from static (no-flow) testing	Conducted dedicated grazing flow experiments
MPP Fabrication Limitations Small perforations difficult to fabricate consistently	Inconsistent geometry, affects acoustic performance	Evaluated alternative hole sizes and manufacturing methods
COMSOL Multiphytics Complexity Acoustic-structure interaction modeling is complex	Increased development time	Incremental model validation and debugging
Schedule & Hardware Delays Prototype and duct fabrication delays	Limited prototype iterations	Prioritized critical testing milestones

LESSONS LEARNED

TEST EARLY, TEST OFTEN
Experimental validation revealed behavior not predicted by initial theoretical models.

GEOMETRY MATTERS
Small changes in dimensions can cause significant resonance shifts.

SIMULATION ≠ REALITY
Models provide guidance, but physical testing is required to capture real-world effects.

STRUCTURE INFLUENCES ACOUSTICS
Backplates, damping layers, and interfaces impact performance.

FLOW CHANGES EVERYTHING
Performance in a tube may differ under realistic airflow conditions.

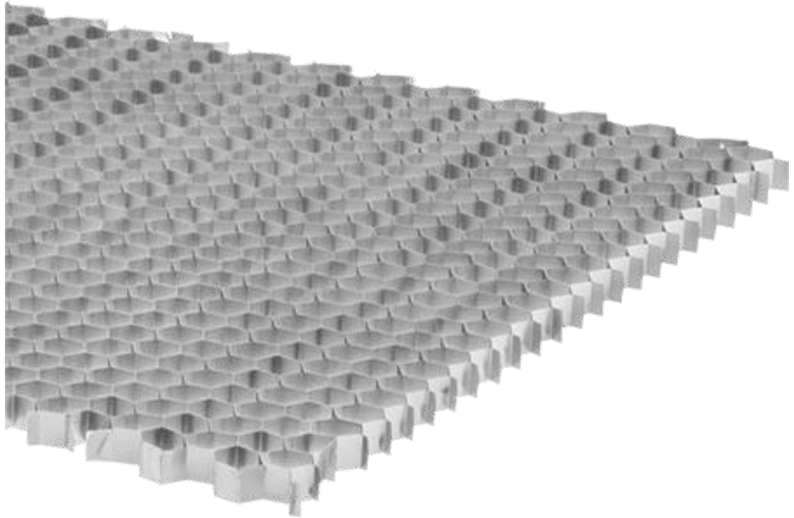
VALIDATION REQUIRES MULTIPLE METRICS
Absorption, impedance, reflection, and transmission each provide unique insight.

MANUFACTURING CONSTRAINTS DRIVE DESIGN
Fabrication limits must be considered alongside acoustic goals.

SYSTEM INTEGRATION MATTERS
Consider airflow, installation, maintenance, and mass constraints from the beginning.

Future tasks

- Expand design to target multiple frequency bands.
- Add full-panel acoustic testing.
- Research flight-relevant material options.
- Perform vibration and thermal cycling tests.
- Test implementation with representative ECLSS hardware.



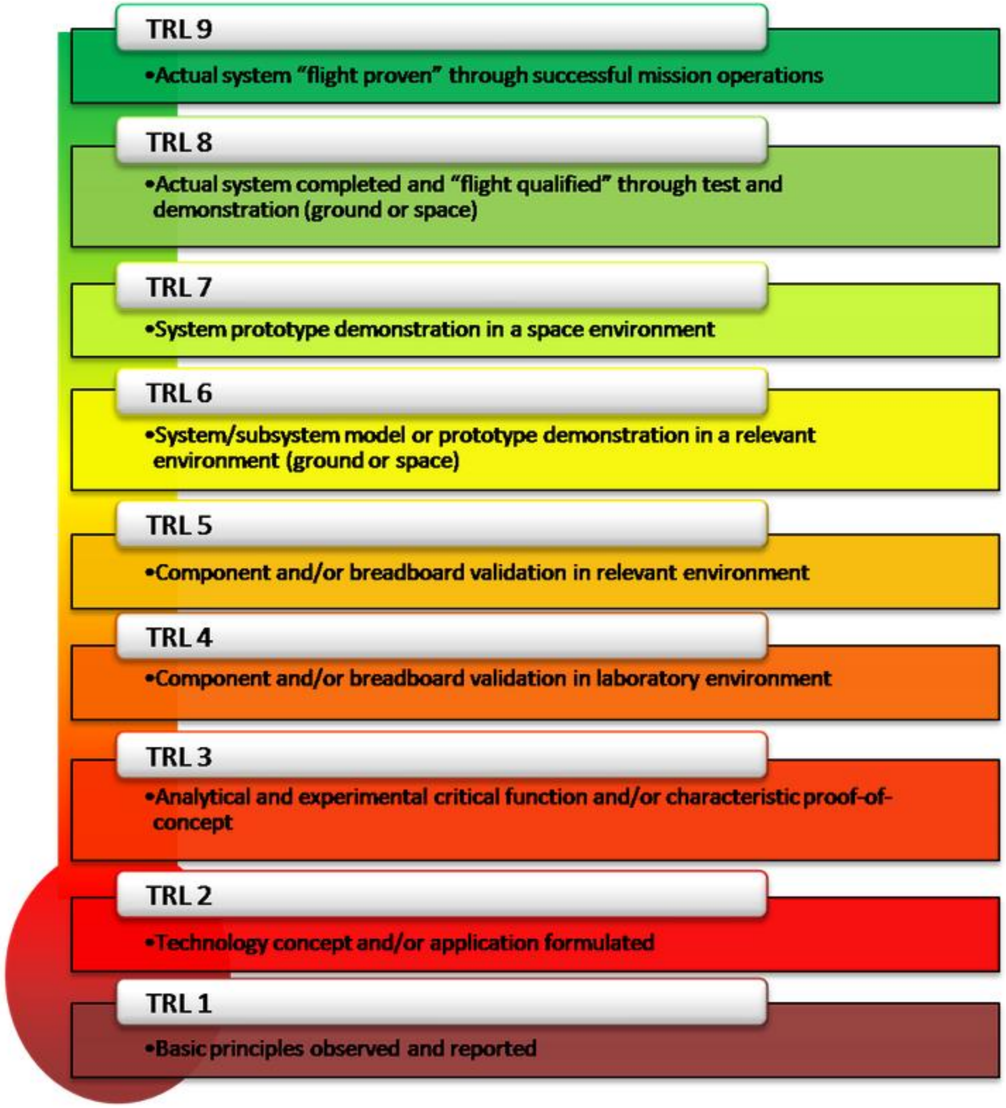
McMaster-Carr Part No. 9635K313

Source: Fibreglast Nomex Honeycomb #1562

Overall Technological Readiness Level

- **TRL 3 — Analytical and Experimental Proof of Concept**
  - The acoustic unit-cell concept has been defined using established resonator, damping, and microperforated-panel physics.
  - COMSOL simulations predict measurable resonant behavior near the 500 Hz design target.
  - Physical prototypes have been fabricated and evaluated in laboratory impedance-tube and grazing-flow experiments
  - Testing demonstrates measurable configuration-dependent acoustic behavior.
  - The current experiments establish feasibility, but do not yet constitute standardized component validation in a controlled, mission-representative environment.

- **Advancement to TRL 4 – Refined Experimental and Computational Validation, and Progressing to Initial Prototype**
  - calibrated and phase-synchronized impedance-tube testing
  - repeated trials with uncertainty bounds
  - standardized absorption and transmission-loss measurements
  - pressure-drop and airflow-impact characterization
  - validation of the complete multilayer panel in a controlled laboratory duct environment



Technology Readiness Levels

Path-to-Flight Timeline

PHASE	FOCUS
PHASE I Literature Review and Conceptual Research	• Review existing research on acoustic metamaterials and spacecraft applications. Identify key noise sources and design requirements in lunar habitats.
PHASE II Concept Development and Design	• Develop and evaluate resonator and panel concepts. Use simulations and analytical models to define and refine design parameters.
PHASE III Simulation, Prototyping, and Initial Testing	• Simulate acoustic performance and validate through impedance tube testing. Assess absorption and impedance characteristics.
PHASE IV Grazing Flow Testing and Performance Validation	• Evaluate panel performance under realistic airflow conditions using grazing flow duct testing and compare results to no-flow data.
PHASE V Final Comparison and Optimization	• Compare all panel configurations to determine the best performing design and provide final recommendations for lunar habitat duct noise reduction.

Project Timeline

Budget/Cost

HuLC Project Budget

Expense Category	Cost
Design and experimental supplies	$1,979.68
Travel and forum costs	$4,030.55
Total	**$6,010.23**

Projected Cost for Path-to-Flight

WBS	Subsystem	Projected Cost
1.1	Resonator development	$25,000
1.2	Aluminum backing structure	$15,000
1.3	Neoprene isolation/gasket layer	$7,500
1.4	Acoustic testing infrastructure	$35,000
1.5	Grazing-flow mini-duct testing	$45,000
1.6	Manufacturing scale-up studies	$60,000
1.7	Habitat integration studies	$85,000
	Subtotal	$272,500
	30% reserve margin	$81,750
	Total projected maturation cost	**$354,250**

Conclusions – Experimental Basis for Passive Multimodal Acoustic Panel

- **Scientific Findings**
  - A passive, multilayer acoustic architecture was designed, simulated, fabricated, and tested using both impedance-tube and grazing-flow configurations.
  - COMSOL and laboratory testing identified resonant behavior near the intended 500 Hz proof-of-concept frequency.
  - The resonator geometry, damping layer, rigid backing, and optional microperforated layer produced distinct and measurable acoustic responses.
  - Grazing-flow testing showed that panel performance depends on both acoustic excitation and airflow conditions.
  - The no-MPP resonator configuration generally produced the lowest transmitted sound levels in the current duct experiments.

- **Engineering Conclusion**
  - The study establishes an experimentally testable foundation for a passive, modular acoustic unit cell capable of combining resonance, structural damping, and viscous-loss mechanisms.

- **Current Maturity**
  - The concept remains an early proof of concept. Additional standardized testing, uncertainty quantification, pressure-drop characterization, material qualification, and multiband optimization are required before spacecraft integration.

- **Final Takeaway**
  - **The principal result is not a flight-ready panel, but a validated research pathway from resonator physics to a scalable multimodal acoustic metamaterial architecture.**