

Texas Tech University

Acoustic Metamaterial Composite Panel (AMP) for Spacecraft Noise Suppression

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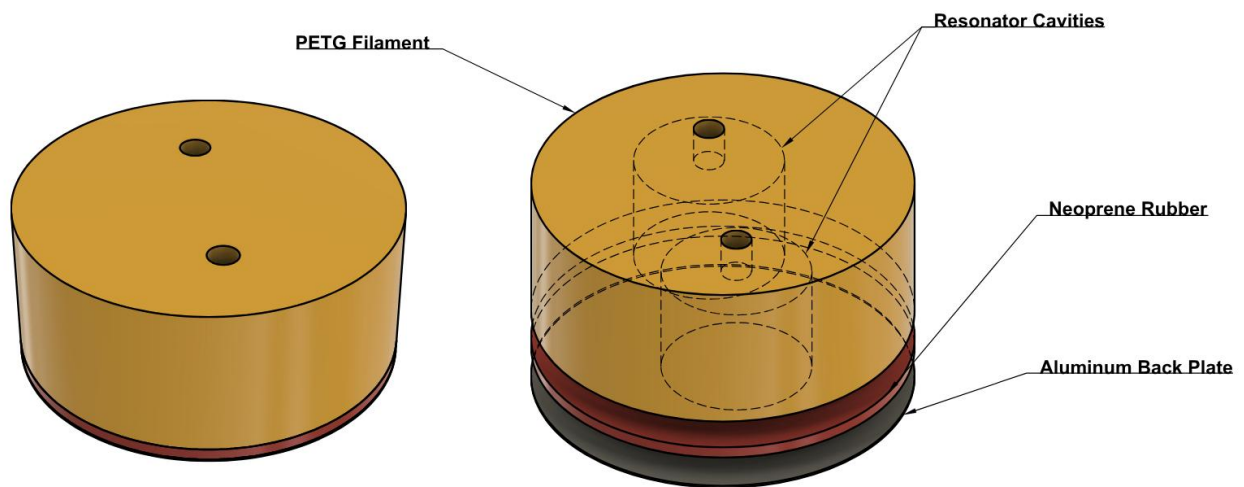
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Acoustic Metamaterial Panel (AMP) Unit Cell Architecture



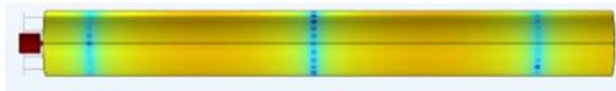
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Acoustic Metamaterial Composite Panel (AMP) for Spacecraft Noise Suppression Texas Tech University

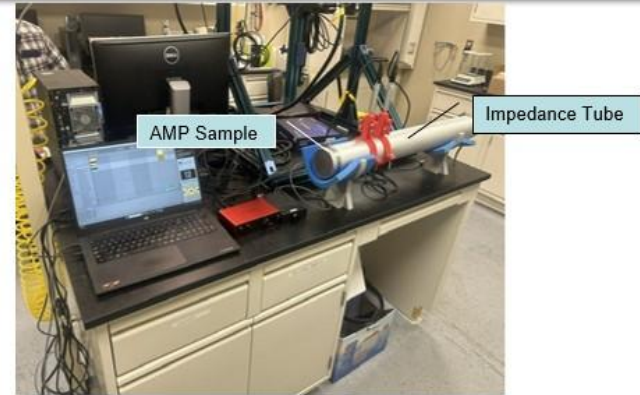


Theme Subtopic, Major Objectives & Technical Approach

- **Theme Subtopic:** Noise Suppression & Control
- **Major Objectives:** Passive reduction of ECLSS-generated spacecraft noise
- **Technical Approach:** Acoustic metamaterial resonator panel validated through simulation and experimental testing

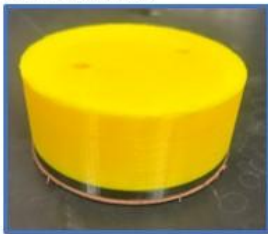


COMSOL Sound Pressure Level Simulation



Key Design Details & Innovations of the Concept

- **Design Details:** Passive sandwich composite panel combining resonators, damping layers, and structural backing
- **Innovations:** Frequency-targeted acoustic metamaterials enabling compact, low-power noise suppression



500 Hz Resonator AMP Sample

Projected Technology Maturation Costs	Suggested Years	Projected Cost
1.1 Resonator Development	2026–2027	\$25,000
1.2 Aluminum Backing Structure	2026–2027	\$15,000
1.3 Neoprene Isolation/Gasket Layer	2026–2027	\$7,500
1.4 Acoustic Testing Infrastructure	2026–2028	\$35,000
1.5 Grazing Flow Mini-Duct Testing	2028–2029	\$45,000
1.6 Manufacturing Scale-Up Studies	2029–2030	\$60,000
1.7 Habitat Integration Studies	2030–2033	\$85,000
Total Projected Maturation Cost		\$354,250

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Summary Statement / Executive Summary

Texas Tech University's HuLC Noise Suppression Team proposes an acoustic metamaterial composite panel (AMP) to reduce Environmental Control and Life Support System (ECLSS) noise in the Human Landing System and future spacecraft habitat environments. ECLSS hardware, including fans, pumps, compressors, ducts, and ventilation components, must operate continuously to maintain a safe crew environment. However, these systems can generate tonal, broadband, and structure-borne noise that affects crew communication, concentration, comfort, sleep quality, and long-duration habitability [1]-[6].

The proposed solution is a passive sandwich-style acoustic panel that combines tuned resonator cavities, a damping layer, and a rigid backing layer. The resonator layer provides frequency-targeted acoustic attenuation, the damping layer dissipates vibration and acoustic energy, and the aluminum backing layer provides stiffness, sealing support, and mounting capability. The design targets low-to-mid-frequency ECLSS-related noise bands, with the current proof-of-concept focused on the 500 Hz region and future expansion toward 1000 Hz, 1500 Hz, and 2000 Hz.

The AMP concept is intended to minimize power demand, system complexity, crew interaction, and operational maintenance. Because the design is passive and modular, it can be placed near localized ECLSS noise sources, equipment enclosures, duct-adjacent surfaces, or interior panels without requiring a full cabin redesign. Computational modeling and preliminary impedance-tube testing indicate that the current 500 Hz resonator configuration produces measurable resonance behavior near the predicted frequency, supporting continued development toward a broader multi-frequency acoustic treatment.

1. Project Description

1.1 Solution

The subtopic challenge addressed in this project is the reduction of noise generated by ECLSS equipment in spacecraft habitat environments. ECLSS hardware must operate continuously to regulate air quality, temperature, pressure, humidity, and other life-support functions. Although these systems are essential, their fans, pumps, compressors, ducts, and rotating machinery can produce persistent acoustic and vibration-related noise. In a confined spacecraft cabin, this noise can affect communication, rest, workload, and long-duration crew health [1]-[6].

The proposed solution is an Acoustic Metamaterial Composite Panel (AMP) designed to reduce selected low-to-mid-frequency noise components associated with ECLSS hardware. The panel uses repeated resonator unit cells inspired by Helmholtz resonator behavior. Each unit cell contains a cavity connected to the incident acoustic field through a neck opening. When acoustic waves interact with the neck and cavity, the air in the neck oscillates against the compressibility of the cavity volume, creating a resonant response. Around the tuned frequency, acoustic energy can be redirected, dissipated, or attenuated through resonance, damping, and impedance mismatch effects [8], [11]-[19].

The initial panel concept uses a modular resonator layout that can be tuned by adjusting cavity volume, neck diameter, neck length, and effective neck correction. The current development effort focuses on a circular prototype constrained by the available test geometry. The broader concept targets ECLSS-related acoustic bands near 500 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. These frequencies are relevant because fan shaft frequencies, pump shaft frequencies, blade-pass frequencies, harmonics, duct modes, turbulence, and structure-borne vibration can shift acoustic energy into the low-to-mid-frequency range [6], [8]-[10].

The updated design uses a sandwich composite architecture instead of a simple single-material resonator plate. The current prototype stack consists of a resonator/metamaterial layer, an intermediate damping or isolation layer, and an aluminum backing layer. The resonator layer provides the primary frequency-targeted acoustic behavior. The damping layer helps dissipate vibrational and acoustic energy while reducing leakage between stacked interfaces. The aluminum backing layer improves stiffness, mounting support, and boundary-condition

control. A future version may add a microperforated panel (MPP) face sheet to improve acoustic resistance and broadband absorption [11], [12], [18].

The objective of this project is not to replace all spacecraft acoustic treatment with a single panel. Instead, the goal is to demonstrate a compact, passive, modular, and frequency-selective treatment that can be placed near dominant ECLSS noise sources or integrated into localized panel surfaces. The current 500 Hz proof-of-concept validates the resonator geometry, COMSOL modeling workflow, and impedance-tube testing method before the design is expanded into a multi-frequency panel.

1.2 Adherence to Design Constraints and Guidelines

The proposed AMP concept was selected to satisfy major NASA adoption constraints, including low mass, compact size, low power demand, low operational complexity, crew safety, launch-load survivability, mission-duration compatibility, and a realistic development path within a 5-to-8-year window.

The first major advantage of the design is passive operation. The AMP does not require electrical power, active control hardware, sensors, actuators, embedded electronics, or crew input during normal operation. This reduces system complexity and avoids adding a continuous power load to an already power-constrained spacecraft environment. Since ECLSS hardware must operate continuously, a passive acoustic treatment is attractive because it can reduce selected noise components without increasing operational burden.

The design also supports low-mass and compact integration goals. Spacecraft systems are constrained by available mass, volume, and installation space. Instead of adding large amounts of traditional acoustic insulation throughout the cabin, the AMP is intended for targeted placement near dominant noise sources such as equipment enclosures, duct-adjacent walls, localized cabin panels, or machinery-adjacent surfaces. This targeted approach can reduce unnecessary added mass while still addressing the most relevant noise-producing regions.

Crew safety is another design constraint. The current concept has no moving parts and does not require crew interaction during nominal operation. Therefore, it is not expected to introduce operational hazards during routine use. However, any future flight-relevant version must use spacecraft-compatible materials that satisfy requirements for flammability, off-gassing, toxicity, particulate release, durability, cleanability, and structural safety [4], [5].

The concept also supports mission-duration requirements. HuLC guidelines identify operational life requirements of at least 30 days for lunar surface missions or 1200 days for Mars-class missions. Because the AMP is passive and does not depend on powered components, software, or active maintenance, it has a credible path toward long-duration operation. Future validation must still confirm long-term durability under launch vibration, thermal cycling, material aging, and spacecraft habitat environmental conditions.

Overall, the AMP aligns with the major design constraints by emphasizing passive operation, low system complexity, modularity, compact installation, and a realistic maturation path.

1.3 Changes Since the Proposal

Several changes have been made since the initial proposal. The original proposal described a passive acoustic metamaterial panel using resonator cavities tuned to reduce dominant ECLSS noise frequencies. The general concept remains the same, but the design has been refined into a sandwich composite acoustic panel.

The updated configuration includes three primary layers: a resonator/metamaterial layer, a damping or isolation layer, and an aluminum backing layer. This change improves the design because it combines frequency-targeted acoustic behavior, vibration damping, and structural support into one compact assembly. The design now more closely resembles aerospace acoustic panel construction while preserving the project's main innovation: the use of tuned metamaterial resonator features within the acoustic core.

The target-frequency strategy was also refined. The proposal identified 125 Hz, 250 Hz, 500 Hz, and 1000 Hz as important spacecraft-related acoustic bands. During prototype development, the team narrowed the initial

experimental focus to the 500 Hz region because this frequency allowed practical fabrication, COMSOL validation, and impedance-tube testing within the available time and hardware constraints. The broader design remains scalable toward 1000 Hz, 1500 Hz, and 2000 Hz resonators.

The verification approach has also become more defined. The current validation strategy combines COMSOL acoustic modeling with impedance-tube testing using a two-microphone transfer-function method. This allows the team to compare predicted and measured acoustic behavior, including resonant frequency, normalized surface impedance, reflection behavior, transfer-function magnitude, and attenuation trends [21].

1.4 Innovative Approaches, Capabilities, and Technologies

The main innovation of this project is the application of a sandwich-style acoustic metamaterial composite panel to spacecraft ECLSS noise suppression. Instead of relying only on conventional insulation, porous absorbers, or duct liners, the AMP uses resonator-based acoustic behavior to target specific frequency bands while remaining passive, compact, and modular.

The design combines multiple acoustic and structural functions in a single layered panel. The resonator/metamaterial layer provides frequency-selective acoustic attenuation. The damping layer helps dissipate vibrational and acoustic energy while reducing leakage between stacked components. The aluminum backing layer provides stiffness, structural support, and a more controlled acoustic boundary condition.

The AMP is also innovative because it improves the internal acoustic core rather than simply using a conventional honeycomb or passive backing layer. By embedding tuned resonator cavities into a modular panel, the design can be adjusted to match measured ECLSS noise spectra. A future MPP face layer could further improve broadband absorption by adding acoustic resistance and damping at the front surface [11], [12], [18].

The modular nature of the design is important for spacecraft integration. Individual resonator cells can be tuned to different frequencies and arranged in mixed populations across a panel. This allows the design to target tonal peaks, blade-pass harmonics, pump-related components, and broadband low-frequency regions without requiring a single large resonator.

1.5 Supporting Engineering Analysis and Justification of Assumptions

The engineering basis for the AMP is that ECLSS noise can be reduced by targeting dominant low-to-mid-frequency components produced by fans, pumps, ducts, rotating machinery, and structure-borne vibration. Ventilation fan and pump shaft frequencies can be estimated using rotational speed:

$$f_{shaft} = \frac{RPM}{60}$$

For an assumed fan speed range of 2000 to 6000 RPM, the estimated fan shaft frequency range is approximately 33.3 to 100 Hz. For an assumed pump speed range of 1000 to 3500 RPM, the estimated pump shaft frequency range is approximately 16.7 to 58.3 Hz. Harmonics, blade-pass frequencies, duct effects, structural radiation, and rotating machinery interactions can shift energy into higher low-to-mid-frequency bands [6], [8]-[10].

The resonator tuning is based on first-order Helmholtz resonator theory:

$$f_H = \frac{c}{2\pi} \sqrt{\frac{A}{VL_{eff}}}$$

where f_H is the resonant frequency, c is the speed of sound, A is the neck area, V is the cavity volume, and L_{eff} is the effective neck length including end correction. This relationship provides a practical tuning method for selecting cavity volume, neck diameter, and neck length for target frequencies [8], [13]-[19].

The current proof-of-concept focused on the 500 Hz region. COMSOL modeling predicted resonance near 510 Hz, while impedance-tube measurements identified impedance peaks and reactance transitions between

approximately 511 and 514 Hz. The difference between the predicted and measured resonant frequency was less than 1%, indicating strong agreement between computational and experimental results for the current 500 Hz test article. This does not yet prove full flight readiness, but it supports the validity of the resonator geometry, modeling workflow, and laboratory measurement approach.

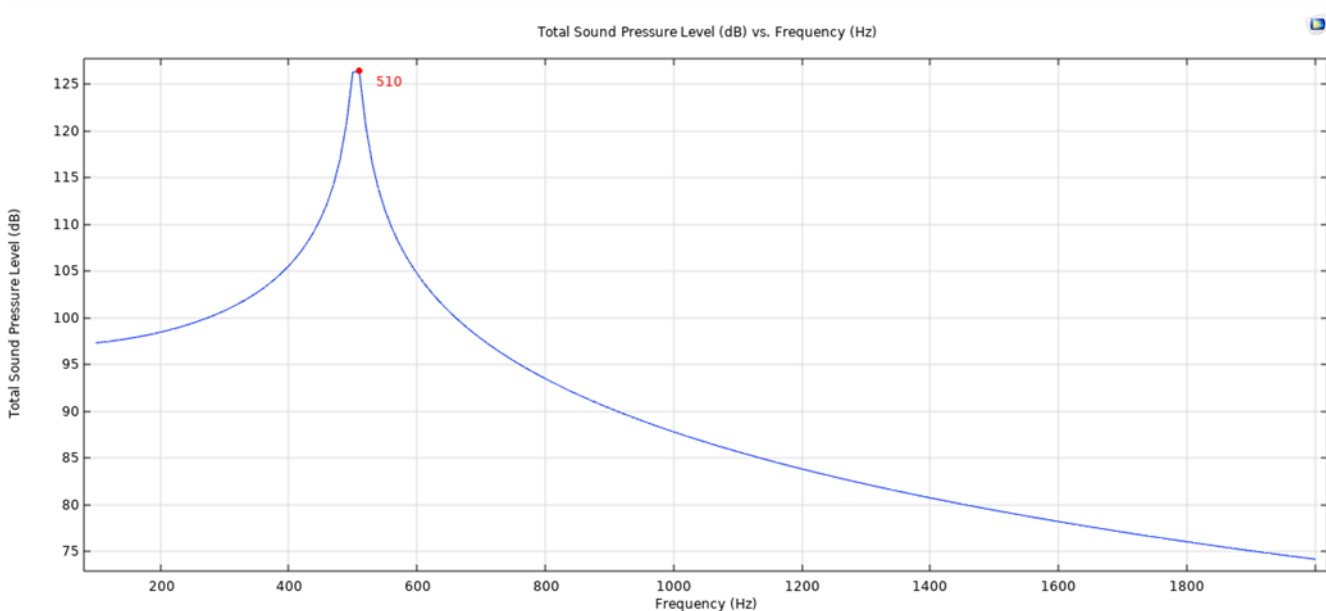
2. Verification and Validation of the Solution

2.1 Verification and Testing Approach

Verification and validation of the AMP were performed using a combined computational and experimental approach. The purpose was to evaluate resonator behavior, compare predicted and measured resonance, and establish confidence in the proposed passive noise-mitigation mechanism.

The verification process began with numerical modeling in COMSOL Multiphysics. Frequency-domain acoustic simulations were used to characterize resonant behavior, identify operating frequencies, visualize acoustic pressure fields, and estimate attenuation trends within the target frequency region. The simulation geometry incorporated the resonator cavity and the relevant stacked boundary conditions associated with the prototype design.

Simulation outputs included acoustic pressure distributions, resonant frequency predictions, pressure-field behavior, and frequency-response trends. These results were used to verify that the proposed resonator geometry produced localized resonance behavior near the target low-frequency region before fabrication and testing.



Experimental validation was performed using a custom-built impedance tube based on the two-microphone transfer-function method. Impedance-tube testing was selected because it provides a controlled and repeatable environment for measuring normal-incidence acoustic behavior before larger-scale duct or habitat testing. The method supports measurement of reflection coefficient, absorption coefficient, normalized surface impedance, transfer-function magnitude, and attenuation-related behavior [21].

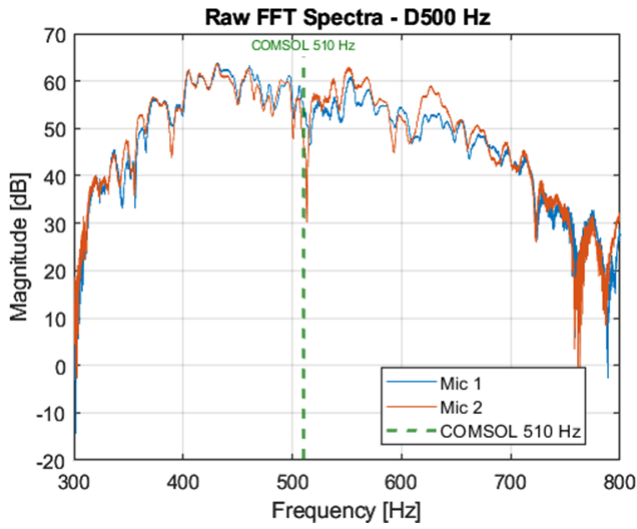
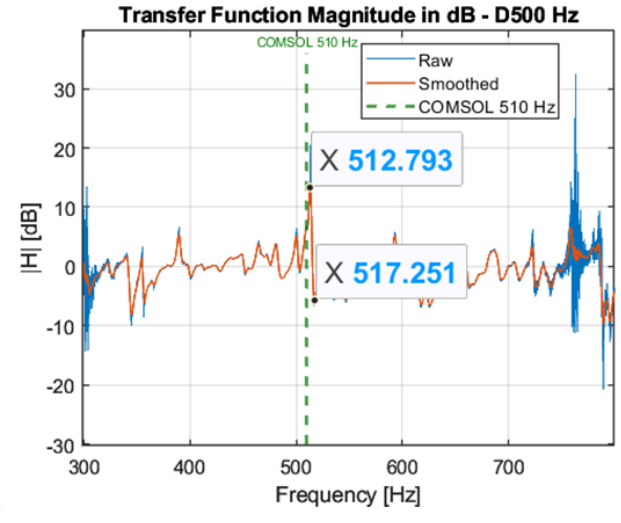
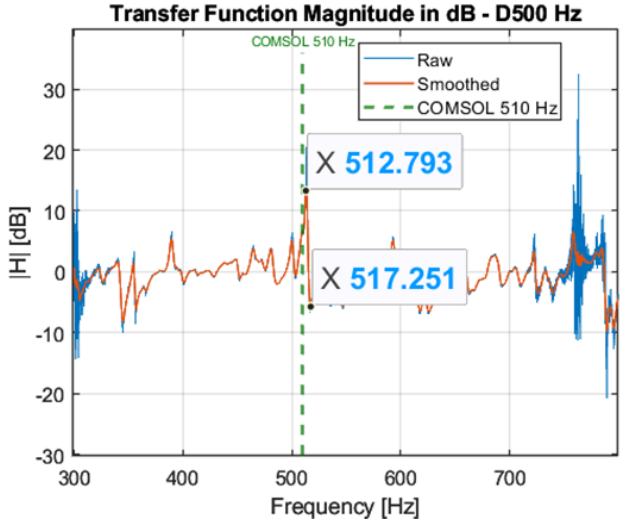
Component	Purpose
Custom impedance tube	Provides controlled acoustic propagation path
Two microphones	Measures pressure response at two locations
Speaker and amplifier	Generates frequency-sweep excitation
Audio interface	Records microphone signals
Test sample holder	Positions the resonator assembly at the tube end

MATLAB post-processing	Computes spectra, transfer functions, and impedance-related metrics
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The absorption coefficient was used to estimate the fraction of incident acoustic energy dissipated by the sample. However, because the AMP operates through resonance-based wave interaction rather than only porous absorption, high absorption values were not expected across the full frequency range. Instead, localized changes near resonance were the most important early indicator.

Reflection coefficient and normalized surface impedance were used to evaluate the acoustic boundary condition created by the resonator. A resonant structure is expected to show rapid changes in reactive impedance near resonance. These transitions are important because they indicate energy storage and release within the resonator system.

The measured experimental data were compared against COMSOL predictions. COMSOL predicted a resonance near 510 Hz. Experimental measurements showed impedance peaks and reactance transitions near 511 to 514 Hz, giving less than 1% deviation from the simulation prediction. Transfer-function measurements also showed localized disturbances near the predicted resonance region. These results indicate successful excitation of the intended resonator mode and support the continued use of the modeling approach.



2.2 Obstacles, Issues, and Mitigation

Several challenges were encountered during development, fabrication, and testing. These challenges involved fabrication constraints, measurement uncertainty, acoustic leakage, and computational modeling limitations.

One significant challenge involved coupling the speaker geometry to the impedance-tube geometry. Speakers capable of low-frequency excitation often have diameters larger than the impedance tube. This mismatch can introduce unwanted reflections and non-ideal acoustic loading. To mitigate this issue, transition geometries, mounting approaches, and sealing methods were evaluated to improve acoustic coupling while maintaining sufficient excitation energy.

Another challenge involved measurement repeatability. Small leaks, microphone placement differences, sample mounting variation, and layer-interface gaps can affect measured acoustic response. These issues were mitigated through improved sealing, fixed microphone positioning, repeated measurements, consistent assembly procedures, and comparison against baseline configurations.

Computational challenges were also encountered in COMSOL modeling. Solver convergence, mesh sensitivity, and acoustic-structural coupling can affect simulation reliability. These issues were addressed by starting with simplified acoustic models, refining the mesh, using parameter sweeps, and gradually increasing model complexity.

Low-frequency testing also presented practical limitations. Generating sufficient acoustic energy near 500 Hz while avoiding distortion, structural vibration, and background noise required iterative test refinement. The team adjusted excitation signals, sample mounting, and damping integration to improve measurement quality.

These mitigation strategies allowed the project to complete proof-of-concept validation while identifying the main areas requiring improvement in future testing.

3. Technology Readiness Level and Realistic Technology Assumptions

3.1 Purpose of the Technology Readiness Assessment

The AMP was evaluated using NASA Technology Readiness Level (TRL) logic to identify its current maturity and the development steps required before possible Human Landing System or habitat adoption. This assessment is important because the underlying acoustic mechanisms are established, but the specific AMP configuration for spacecraft ECLSS noise suppression is still in early development [4], [5].

Helmholtz resonance, acoustic damping, microperforated-panel absorption, and rigid-backed cavity behavior are established acoustic concepts [8], [11]-[19]. However, the proposed integrated AMP has not yet been tested in a representative ECLSS environment, environmentally screened, structurally qualified, or integrated with flight-relevant materials. Therefore, the project should be described as an early-stage technology with promising laboratory evidence rather than a flight-ready system.

3.2 Current Technology Readiness Level

The current AMP is best classified as approximately TRL 4 for the 500 Hz component-level breadboard because the team has completed analytical modeling, fabricated a prototype, and obtained preliminary laboratory validation using impedance-tube testing. COMSOL predicted resonance near 510 Hz, and experimental impedance-tube results showed resonance-related behavior near 511 to 514 Hz. This supports laboratory validation of the basic resonator concept.

The technology should not be classified as TRL 5 because it has not yet been tested in a relevant environment with representative ECLSS hardware, airflow conditions, mounting constraints, thermal cycling, vibration exposure, or flight-relevant material requirements. It should also not be described as flight-ready because material qualification, environmental testing, launch-load survivability, and integrated habitat testing remain incomplete.

A conservative description is that the AMP has advanced from TRL 3 analytical proof-of-concept toward TRL 4 laboratory validation for the 500 Hz prototype. Future work must demonstrate repeatability, multi-frequency behavior, MPP integration, material compatibility, and relevant-environment performance before higher TRL claims are justified.

3.3 Justification for TRL Classification

The project has moved beyond a basic scientific idea because it has a defined mission application, an analytical tuning method, a CAD-based geometry, a fabricated prototype, COMSOL simulation results, and preliminary laboratory test data. The specific use case is passive reduction of ECLSS-related noise in Human Landing System or lunar habitat environments.

The current 500 Hz test article supports TRL 4-level laboratory evidence because the resonator response was predicted computationally and then observed experimentally. The measured resonance region agrees closely with the COMSOL prediction. This provides evidence that the resonator geometry can be designed, fabricated, and tested in a controlled laboratory setting.

However, the project remains below TRL 5 because the test environment is not yet representative of actual spacecraft operation. The design has not been tested with realistic ECLSS fan or pump noise, mean airflow, duct boundary conditions, launch vibration, thermal cycling, material aging, flammability limits, off-gassing limits, or long-duration exposure. These gaps define the next maturation steps.

3.4 Realistic Technology Assumptions

The current design is based on several realistic early-stage assumptions. First, the cabin acoustic field is approximated using linear acoustics. This is appropriate for preliminary modeling because expected crewed-cabin noise levels are within a range where first-order acoustic analysis is useful.

Second, the resonant frequency can be estimated using the Helmholtz relationship between neck area, cavity volume, and effective neck length. This assumption is appropriate when the resonator dimensions are small compared with the acoustic wavelength [8]. Third, the resonator walls are initially treated as acoustically rigid boundaries. If future testing shows significant wall compliance, panel vibration, or backing-layer motion, acoustic-structural coupling must be included.

Fourth, early testing neglects mean airflow. This is acceptable because the current test article is intended for panel-mounted or equipment-adjacent use rather than direct placement inside an active ventilation duct. If the design is later adapted for duct installation, pressure drop, flow noise, contamination, and maintainability must be evaluated.

Fifth, prototype materials such as PETG or resin are acceptable for geometry validation and benchtop testing. They are not flight-qualified materials. Future versions must use flight-relevant material candidates that satisfy spacecraft requirements for flammability, off-gassing, toxicity, durability, cleanability, and mechanical stability [4], [5].

Sixth, internal damping is expected to broaden the resonator response. This is technically reasonable because damping increases acoustic losses and reduces overly sharp resonance. However, this must be verified by comparing damped and undamped cavity configurations. Seventh, an MPP layer can be added after the base resonator response is validated. This staged approach is reasonable because it isolates the resonator behavior before introducing an additional acoustic-resistance layer [11], [12], [18].

3.5 Technology Maturation Path

The next step is to strengthen the TRL 4 evidence by improving repeatability and expanding testing beyond the current 500 Hz configuration. Individual resonators should be fabricated and tested for 500 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. Each resonator should be tested separately before the full multi-frequency panel is tested.

A stronger TRL 4 demonstration would require repeatable impedance-tube measurements showing consistent resonance behavior, absorption or impedance trends, and comparison against baseline samples. Useful baselines include a rigid backing plate, undamped resonator cavities, damped resonator cavities, and future MPP-covered resonator configurations.

Advancement toward TRL 5 would require testing in a relevant environment. For this project, that means exposing the panel to representative fan, pump, or duct noise sources similar to ECLSS hardware. Testing should include realistic mounting, boundary conditions, airflow effects, insertion loss, pressure drop, and durability.

Advancement toward TRL 6 would require system-level demonstration in a representative HLS or habitat mockup. At that stage, the design would need to show acoustic benefit, mounting feasibility, maintainability, crew safety, material compatibility, and integration with surrounding vehicle structures.

3.6 Required Future Work

Future maturation requires several specific tasks. The first task is to fabricate individual resonator test articles for 500 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. The second task is to measure the acoustic response of each resonator and compare the measured values with analytical and COMSOL predictions. The third task is to evaluate internal damping by comparing empty cavities with damped cavities. The fourth task is to test the effect of an MPP face layer by comparing open-neck resonators with MPP-covered configurations.

After individual testing, the full multi-frequency panel should be tested to determine whether the integrated design produces broader acoustic attenuation than a single-frequency resonator. Prototype materials should then be replaced with flight-relevant candidates such as aluminum, PEI, PEEK, qualified composites, or other spacecraft-compatible materials.

Later testing should evaluate flammability, off-gassing, particulate release, cleanability, thermal cycling, vibration resistance, long-term material stability, and compatibility with representative ECLSS hardware. The final design should also be optimized for mass, geometry, manufacturability, acoustic sealing, and maintainability.

4. Mass and Size Estimates

The AMP is intended to remain compact, lightweight, and modular so that it can be integrated into Human Landing System, lunar habitat, or ECLSS-adjacent structures without requiring major vehicle redesign. The current prototype should be treated as a small-scale acoustic test article rather than a final flight unit. Its purpose is to validate resonator tuning, acoustic behavior, damping effects, and stacked-panel feasibility.

The current testing configuration does not include an MPP layer. Although an MPP face sheet remains part of the intended future architecture, it was not included in the current prototype because of manufacturing limitations, material availability, and the need to isolate the base resonator behavior first.

The prototype uses a compact circular geometry with a maximum working diameter of approximately 3.9 in., or 99 mm. This size is appropriate for benchtop validation because it is large enough to contain resonator chambers while remaining compatible with fabrication, dimensional inspection, mass measurement, and impedance-tube testing.

4.1 Prototype Size and Mass Estimate

The current prototype panel is based on a circular footprint containing tuned resonator chambers. The broader design targets 500 Hz, 1000 Hz, 1500 Hz, and 2000 Hz. The measured stacked assembly reported here uses the two-500 Hz resonator puck configuration. The present tested assembly includes the resonator puck, a 1 mm intermediate panel, and a 1 mm aluminum panel.

Component Configuration	Measured Mass	Description	Notes
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Primary resonator puck	86.780 g	Circular resonator body prototype	General puck mass reference
Two-500 Hz resonator puck	82.780 g	Resonator puck containing two 500 Hz chambers	Used in measured stacked assembly
1 mm aluminum panel	9.968 g	Thin aluminum backing panel	Rigid metallic layer
1 mm intermediate panel	40.251 g	Intermediate layer between resonator puck and aluminum panel	Included in final stacked mass
Full three-layer stacked assembly	132.992 g	Two-500 Hz puck plus intermediate panel plus aluminum panel	Measured total mass

The measured stacked assembly mass of 132.992 g is the current prototype mass and should not be reported as the final flight-like panel mass. The MPP layer, seals, mounting hardware, damping inserts, and final flight-material substitutions are not yet included.

4.2 Prototype Size Estimate

Parameter	Assumed or Measured Value	Basis for Estimate
Overall prototype diameter	3.90 in., approximately 99 mm	Current circular design and testing constraint
Overall prototype radius	1.95 in., approximately 49.5 mm	Half of prototype diameter
Overall footprint area	Approximately 7700 mm ²	Based on 99 mm circular footprint
Number of target design frequencies	4	500, 1000, 1500, and 2000 Hz
Current measured configuration	Two-500 Hz resonator puck	Fabricated and weighed test article
Current tested stacked assembly mass	132.992 g	Measured mass of puck, intermediate panel, and aluminum panel
MPP layer	Not included in current testing	Planned future acoustic face layer
Future MPP layer thickness	Approximately 1 mm	Intended future face sheet thickness
Aluminum panel thickness	1 mm	Measured backing layer
Intermediate panel thickness	1 mm	Layer between resonator puck and aluminum panel

4.3 Prototype Size Justification

The 3.9 in. circular prototype is a reasonable development size because it allows several acoustic design variables to be evaluated in a single test article. The panel is large enough to contain tuned resonator cavities while remaining small enough for rapid fabrication, weighing, dimensional inspection, and impedance-tube testing.

The current prototype intentionally prioritizes resonator validation before adding the MPP layer. This reduces uncertainty because the base acoustic response of the resonator chambers can be measured first. Once resonator frequency and damping behavior are verified, the MPP face layer can be added as a separate controlled design variable.

For HLS or lunar habitat use, the final design would not necessarily remain a circular puck. The same unit-cell architecture could be repeated across larger rectangular, curved, or modular panels depending on available mounting area. Candidate installation locations include equipment enclosure panels, removable acoustic tiles, cabin wall panels, duct-adjacent surfaces, or machinery-adjacent structures.

4.4 Preliminary Mass Discussion

At the current prototype stage, the most important mass result is the measured three-layer assembly mass of 132.992 g. This value includes the two-500 Hz resonator puck, the 1 mm intermediate panel, and the 1 mm aluminum panel. Since the MPP layer was not included, this value should be reported only as the current tested configuration.

The difference between the measured stacked assembly and the summed component mass is approximately 0.007 g, which confirms consistent mass accounting. Future mass estimates can therefore be built by measuring each added layer separately and checking the final stacked assembly mass.

A future flight-relevant design requires more complete mass accounting. The final mass should include the acoustic resonator body, MPP face sheet, backing layer, damping inserts, seals, mounting hardware, and protective features required for crew safety and cleanability. The design should be optimized to remove unnecessary material while preserving cavity volume, neck geometry, acoustic sealing, stiffness, and launch-load survivability.

4.5 Size and Mass Optimization Strategy

Future iterations should reduce mass while preserving acoustic performance. The most important optimization variables are cavity volume, neck diameter, neck length, wall thickness, resonator spacing, backing-plate stiffness, damping placement, intermediate-layer thickness, sealing method, and MPP geometry.

The final geometry should be optimized at two levels. At the unit-cell level, each resonator should be refined to maintain its desired frequency while minimizing unnecessary material. At the panel level, the full layout should balance acoustic bandwidth, total mass, manufacturability, installation space, and integration constraints.

4.6 NASA Relevance of Mass and Size Estimate

The compact and modular nature of the AMP supports NASA adoption because the design can be applied locally near dominant ECLSS noise sources instead of requiring full cabin coverage. This reduces mass impact and allows acoustic treatment to be placed only where it provides the highest value. The passive architecture also avoids power and electronics mass penalties associated with active noise-control systems.

The current prototype should be described as a small-scale demonstration article. A flight-relevant version should be mass-optimized, structurally verified, and expanded to include the intended MPP acoustic face sheet. The final version must satisfy HLS and ECLSS integration expectations, including low mass, compact size, crew safety, launch-load survivability, long-duration material stability, manufacturability, and maintainability.

5. Proposed Path-to-Flight DT&E Timeline

5.1 Scaling Requirements and Methodology for Full-Scale Application

The AMP is intended to mature through a phased Development, Test, and Evaluation (DT&E) pathway over the next 5 to 8 years. The long-term goal is integration into future NASA habitat, HLS, and ECLSS acoustic suppression applications. The system is currently at an early laboratory-validation stage and requires progressive validation through simulation, laboratory testing, relevant-environment testing, and larger-scale habitat studies.

Initial development focuses on COMSOL modeling to predict resonant behavior, acoustic pressure distributions, insertion loss trends, and absorption characteristics. These simulations are used to optimize resonator geometry before fabrication and testing. Early laboratory validation uses circular puck-style samples in impedance-tube testing to characterize normal-incidence acoustic behavior.

Following impedance-tube validation, the project should transition toward grazing-flow and mini-duct testing environments. These tests would better represent spacecraft ventilation conditions and would allow evaluation of insertion loss, pressure drop, flow-acoustic interaction, broadband attenuation behavior, and structural durability under more operationally relevant conditions.

Scaling from laboratory puck testing to full-scale habitat application is a critical challenge. Lower target frequencies require larger cavity volumes. For example, a 500 Hz resonator may require relatively deep cavities in a compact circular puck. Future habitat implementations will likely require thinner and more packaging-efficient panel geometries.

To address this challenge, future development should redistribute resonator volume laterally across the panel surface. By increasing the in-plane footprint of each resonator, the required depth can be reduced while preserving equivalent acoustic volume and target resonance behavior. This allows the design to transition from tall puck-like geometries toward flatter modular panel cells.

Scaling should preserve acoustic equivalence rather than direct geometric similarity. Important parameters include cavity volume, neck area, effective neck length, acoustic impedance, damping, wavelength-to-cell-size ratio, and boundary condition. Experimentally validated impedance-tube data should be incorporated into larger COMSOL models to predict full-scale performance.

5.2 DT&E Pathway

Phase	Activity	Objective
Phase I	COMSOL simulation and resonator optimization	Predict resonance behavior, optimize cavity geometry, and identify target operating frequencies
Phase II	Impedance-tube validation	Experimentally validate resonance, impedance behavior, and attenuation trends
Phase III	Grazing-flow mini-duct testing	Evaluate resonator performance under airflow and duct-relevant conditions
Phase IV	Flat modular panel development	Reduce thickness and transition from individual pucks to scalable panel architecture
Phase V	Habitat integration studies	Evaluate subsystem-level performance and spacecraft installation feasibility

6. Budget Assessment

The budget assessment reflects the current low-to-mid TRL maturity of the AMP and emphasizes subsystem validation, prototype iteration, scalable manufacturing studies, and progressive environmental realism. Several elements, including flattened resonator geometry, MPP integration, and flight-material substitution, remain under development and contribute to reserve-margin requirements.

6.1 Current Prototype and Demonstration Costs

Expense Category	Cost
Design and experimental supplies	\$1,152.19
Travel and forum costs	\$4,030.55
Total	\$5,182.74

The total project expenditure for development, fabrication, testing, and demonstration was \$5,182.74 out of the allocated \$9,000 project budget. Design and experimental supply costs included materials required for prototype fabrication, resonator development, impedance-tube construction, acoustic testing integration, and experimental setup development.

Travel and forum-related expenses supported project presentation, competition participation, and team engagement activities. Maintaining total expenditures below the allocated budget provided financial margin while still enabling simulation, fabrication, testing, and validation activities.

6.2 AMP System Work Breakdown Structure

WBS	Subsystem
1.0	Acoustic Metamaterial Panel System
1.1	Resonator development
1.2	Aluminum backing structure
1.3	Neoprene isolation/gasket layer
1.4	Acoustic testing infrastructure

1.5	Grazing-flow mini-duct testing
1.6	Manufacturing scale-up studies
1.7	Habitat integration studies

6.3 Projected Technology Maturation and Mission Infusion Costs

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

Projected technology maturation costs were estimated using the AMP work breakdown structure, analogy-based subsystem costing, and simplified lifecycle-oriented cost-estimating assumptions. Because the AMP is currently an early laboratory-scale proof-of-concept, these values should be interpreted as order-of-magnitude estimates rather than precise flight-hardware costs.

A 30% reserve margin was included to account for uncertainty associated with prototype iteration, acoustic performance refinement, manufacturing repeatability, testing expansion, material substitution, and subsystem integration. The largest expected cost drivers are grazing-flow mini-duct testing, manufacturing scale-up, and habitat integration studies because these activities require larger test articles, expanded instrumentation, controlled testing environments, and more complex validation.

7. Full Concept / Mission Architecture Timeline

The mission architecture timeline reflects a progressive maturation pathway from laboratory acoustic characterization toward mission-relevant habitat integration. Development phases incrementally increase environmental realism, scalability, manufacturability, and integration readiness.

Year	Development Stage	Objective
2026	Modeling and baseline validation	COMSOL optimization, impedance-tube setup, and 500 Hz proof-of-concept validation
2027	Prototype acoustic validation	Multi-frequency puck testing, damping comparisons, and resonance tuning
2028	Grazing-flow evaluation	Mini-duct airflow testing, insertion-loss measurement, and pressure-drop assessment
2029	Scaled panel development	Flatter modular panel architecture and MPP integration
2030	Habitat integration studies	Large-area duct, wall-panel, or equipment-enclosure integration studies
2031-2033	Mission infusion pathway	NASA subsystem maturation, material qualification, and adoption evaluation

This pathway supports a 5-to-8-year maturation window by beginning with controlled laboratory validation and then progressing toward relevant-environment testing, material screening, scaled manufacturing, and system-level integration.

8. Conclusions and Key Findings

8.1 Value of the Design Approach

The proposed AMP addresses a mission-relevant ECLSS noise challenge through a passive, compact, and modular design. The concept is intended to support HLS and lunar habitat operations by reducing selected acoustic effects from fans, pumps, ducts, ventilation hardware, and other continuously operating ECLSS components. In confined crewed environments, persistent acoustic exposure can affect communication, sleep quality, fatigue, workload, and habitability [1]-[6].

At the mission and system level, the AMP could serve as a supplemental acoustic treatment near localized ECLSS noise sources, equipment enclosures, cabin wall panels, or duct-adjacent structures. This approach would not require a full cabin redesign and would not interfere with core ECLSS operation. The modular unit-cell architecture also allows the design to be tuned to measured noise spectra from specific fans, pumps, or duct systems.

The technology has a credible path from early laboratory validation toward higher readiness levels. The underlying acoustic mechanisms are established, including Helmholtz resonance, acoustic damping, and rigid-backed cavity behavior [8], [11]-[19]. The current proof-of-concept results show measurable frequency-dependent behavior and close agreement between COMSOL prediction and experimental impedance-tube measurement near the 500 Hz target. However, the current experiment is not a final validated spacecraft acoustic test. The MPP layer was not included in the current configuration, and the results have not yet been verified under representative ECLSS operating conditions.

Affordability is one of the strengths of the proposed development path. Current test articles can be fabricated using additive manufacturing, stacked components, direct mass measurements, and MATLAB-based acoustic analysis. This allows early design changes before expensive environmental testing, material qualification, or spacecraft integration. The final concept is passive, which may improve reliability and reduce operational cost compared with active noise-control systems.

Programmatic implementation is practical because the concept can mature through staged testing. The first stage is proof-of-concept testing of the resonator and stacked assembly. The next stage should isolate individual resonator behavior, compare damped and undamped cavities, improve sealing, and verify repeatability. After that, the MPP layer should be added as a controlled variable. Once the individual mechanisms are understood, the full multi-frequency metamaterial panel can be tested. Later stages should include mass optimization, flight-material down-selection, ECLSS-relevant acoustic testing, vibration testing, thermal testing, flammability and off-gassing screening, and integration with a habitat-relevant mockup.

The main risks are resonator detuning, leakage between layers, manufacturing tolerance, incomplete damping characterization, material compatibility, launch-load survivability, and the absence of the MPP layer in the current experiment. These risks are manageable through dimensional inspection, improved sealing, repeated measurements, CAD refinement, updated tuning calculations, material substitution, and representative-environment testing.

Overall, the AMP concept has strong value because it combines mission relevance, passive operation, modular scalability, affordable prototype development, measurable proof-of-concept acoustic behavior, and a realistic maturation path. The current results should be framed as promising early evidence rather than final performance validation. With further resonator tuning, damping optimization, MPP integration, mass reduction, flight-relevant material selection, and representative-environment testing, the concept could mature into a practical passive acoustic treatment for HLS and lunar habitat applications.

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Appendix B: Supporting Calculations

B.1 Fan Shaft Frequency

The fan shaft frequency is estimated from the rotational speed. For an assumed ventilation fan speed range of 2000 to 6000 RPM, the estimated fan shaft frequency range is approximately 33.3 Hz to 100 Hz. Fan harmonics and blade-pass frequencies can shift acoustic energy into higher frequency bands.

$$f_{shaft} = \frac{RPM}{60}$$

$$f_{shaftmin} = \frac{2000}{60} = 33.3 \text{ Hz}$$

$$f_{shaftmax} = \frac{6000}{60} = 100 \text{ Hz}$$

B.2 Pump Shaft Frequency

For an assumed pump speed range of 1000 to 3500 RPM, the estimated pump shaft frequency range is approximately 16.7 Hz to 58.3 Hz. Pump harmonics, structural radiation, and duct interactions can contribute to higher low-frequency and mid-frequency acoustic components.

$$f_{shaftmin} = \frac{1000}{60} = 16.7 \text{ Hz}$$

$$f_{shaftmax} = \frac{3500}{60} = 58.3 \text{ Hz}$$

B.3 Blade-Pass Frequency

Blade-pass frequency is estimated using the number of fan blades and shaft frequency. This relationship explains why rotating ECLSS machinery can generate tonal components above the basic shaft frequency.

$$f_{bpf} = N_b f_{shaft}$$

B.4 Helmholtz Resonator Tuning

The first-order Helmholtz resonance frequency relates the target resonance to neck area, cavity volume, and effective neck length. The resonant frequency decreases when cavity volume or effective neck length increases, and it increases when neck area increases.

$$f_H = \left(\frac{c}{2\pi}\right) \sqrt{\frac{A}{VL_{eff}}}$$

$$A = \pi r^2$$

$$L_{eff} = L + \Delta L$$

B.5 Percent Difference Between COMSOL and Experiment

Using a COMSOL prediction of approximately 510 Hz and an experimental value near 513 Hz, the percent difference is less than 1%, supporting strong agreement between simulation and laboratory measurement for the current 500 Hz resonator prototype.

$$\% \text{ difference} = \frac{|f_{\text{measured}} - f_{\text{predicted}}|}{f_{\text{predicted}}} \times 100$$

$$\% \text{ difference} = \frac{|513 \text{ Hz} - 510 \text{ Hz}|}{510 \text{ Hz}} \times 100 = 0.59\%$$