Metamaterial-based acoustic noise mitigation technologies

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Structure-property relationship of materials (mechanical + acoustic)

Nanoindentation

16 processors, 96 physical cores, 256 GB RAM, 1536 GFLOPS. Material studio, LAMMPS, Abaqus FEA

Multiscale FEA Model

MD Simulation
Need and Relevance

A better acoustic noise attenuation/filter technology:

- Less bulky
- Less heavy / Lower frequency attenuation
- Flexible geometry
- Active noise attenuation
- Better filtering (control on frequency bands)
- Multifunctional (eg:- structural + acoustic)
Goals

1. Design, develop and test the prototype of an acoustic noise attenuation panel based on acoustic metamaterial concept

2. Evaluate different types of metamaterial concepts (energy trapping mechanisms)

3. Scalability – Cost effective fabrication methods

Metamaterial membrane

Demonstration application: engine acoustic liner
Potential Benefits

Promising solution for acoustic noise and structural vibration filtering: **Metamaterial**

- An order or more improved performance in acoustic energy absorption for a given weight (/volume)
- Attenuation of the low-frequency (10-1000Hz) sound is hard to achieve for traditional materials
- Weight is a serious constraint in many applications
Approach

Honeycomb structure integrated with acoustic metamaterial membrane ➔ super low-frequency sound wave absorption

- Light-weight
- Higher acoustic energy absorption in the range of 20-60dB (dependent on the frequency) compared to the conventional materials (less than 10dB)
- Multifunctional design capability (eg: mechanical performance, active elements)
Approach: Type #1 - Mass-in-mass

Acoustic meta-materials with negative dynamic mass

**Liu, et al, Science, 2000**

Examples: (A) a structural unit consisting of a spherical metallic core particle with 5 mm radius coated by a layer of silicone rubber, (B) a negative mass density metamaterial assembled in an epoxy matrix for low frequency vibration isolation using internal resonators

Principle of “negative” mass

\[ M_{\text{eff}} = \frac{(m_1 v_1 + M_0 V_0)}{V_{\text{eff}}} < 0 \]
Approach: Type #1 - Mass-in-mass

Acoustic meta-materials with negative dynamic mass

mass-in mass system

equivalent system

Compare equilibrium eqns:

$$\frac{m_{\text{eff}}}{m_{\text{st}}} = 1 + \left(\frac{\theta}{1+\theta}\right) \frac{(\omega/\omega_0)^2}{1 - (\omega/\omega_0)^2}$$

$$\theta = \frac{m_2}{m_1} \quad \omega_0^2 = \frac{k_2}{m_2}$$

$$m_{\text{st}} = m_1 + m_2$$

Negative effective mass for

$$1 < (\omega/\omega_0)^2 < 1 + \theta.$$
Approach: Type #2 – Membrane type
**Approach: Proposed research plan**

**Task 1: Computational model and design of unit cells and acoustic liner**

Acoustic metamaterial slab (1) to negative mass design in broadband frequency range; (2) Snapshot of the deformed shapes of the plates at three frequencies (a) 603Hz, (b) 724Hz, and (c) 916Hz in the metamaterial.
Approach: Proposed prototype for membrane type

Task 2: Fabrication of unit cell, layers and acoustic liner

Honeycomb core, honeycomb core with membrane, membrane attached and trimmed, mass added

Honeycomb core array and membrane (a), after attachment (b), mass added (c)

Membrane type acoustic meta-structure. Please note that a tapered shape is not necessary for this concept

Conventional CCMC based acoustic liner
Approach: Proposed research plan

**Task 3: Acoustic testing of the unit cell, individual layer and the whole liner**

- New 1” impedance tube built by undergraduate senior students + 2 NSF REU students
- Calibrated with the help of UTRC
Preliminary work: Membrane type

Metamaterial sample

Impedance Tube

Membrane with no mass

Metamaterial
Preliminary work: 3D Printed samples

Printing of stacks in progress
Preliminary modeling studies for aircraft cabin noise problem is quite promising
Preliminary work: Membrane type

Membrane-Type

Low-frequency sound reflector

Rubber membrane:
\( r = 10 \text{ mm}, \ t = 0.28 \text{ mm}, \ E = 2.0 \times 10^5 \text{ Pa}, \ \nu = 0.49. \)

Circular steel disk:
\( r = 3 \text{ mm}, \ m = 300 \text{ mg} \)

Low-frequency sound absorber

Rubber membrane:
\( 31 \times 15 \text{ mm}, \ t = 0.2 \text{ mm} , \ E = 1.9 \text{ MPa}, \nu = 0.48. \)

Semi-circular iron platelet:
\( r = 6 \text{ mm}, \ t = 1 \text{ mm} \)


Impact

General Applications

1.0 Protecting at the receiving end  
2.0 Containing at the source

3.0 Selective transmission (filter)  
4.0 Any fluid medium
Impact

Aircraft Noise Issues

Community Noise

ICAO aircraft noise certification (Effective Perceived Noise Level, EPNdB)

Cabin Noise

Community noise footprint (various noise metrics - peak dBA, day/night level, etc)

Engine-related sources of cabin noise
BPF and Buzzsaw noise (forward cabin)
Jet exhaust shock-cell noise (aft cabin)
Structure-borne noise (low frequency)
Impact

**Cabin noise** (The Boeing Co.)

**Aircraft Engine noise** (GE)
Outcomes and Deliverables

Milestone:

• Design of unit cell
• Design of the acoustic liner
• Fabrication of the acoustic liner
• Testing the acoustic liner

Deliverables:

Report on
• Design of unit cell and acoustic liner
• Fabrication details of the prototype
• Testing/performance of the acoustic liner, and recommendations for design improvements

Expected outcome:

A design blueprint of a novel metamaterial-based acoustic liner that has an order or more improvement in performance when compared to conventional liners.
## Duration and Budget

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<td>1.0 Computational model and design of unit cells and acoustic liner</td>
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<td>4.0 Reporting (Monthly)</td>
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### Budget ($40K)

- **Student support:** $30K
- **Material and fabrication:** $7K
- **Travel & Miscellaneous:** $3K
Acknowledgements

James Min, NASA Glenn

Jeff Mendoza, United Technologies (UTRC)
Thank You!