The Influence of Boundary Conditions and Constraints on the Performance of Noise Control Treatments: Foams to Metamaterials

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The Influence of Boundary Conditions and Constraints on the Performance of Noise Control Treatments: Foams to Metamaterials

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Introduction

- Effect of front and rear surface boundary conditions on foam sound absorption

- Influence of edge constraints on transmission loss of poroelastic materials including effect of finite mass supports

- “Metamaterial” Barrier
CEDSTRAL TECHNIQUES IN THE MEASUREMENT OF ACOUSTIC REFLECTION
COEFFICIENTS, WITH APPLICATIONS TO THE DETERMINATION OF
ACOUSTIC PROPERTIES OF ELASTIC POROUS MATERIALS

by

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Faculty of Engineering and Applied Science
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Thesis submitted for the degree of

Doctor of Philosophy

July 1984
Normal Incidence Measurement of Reflection

![Diagram of normal incidence measurement of reflection with source, receiver, and image source labels.](image)

Experimental geometry.
Film-faced Polyurethane Foam

Scanning electron micrographs of the foam sample

- 25 mm layer of foam – one side covered with flame-bonded film, the other open.
- Many intact membranes
Reflection Impulse Response

(Film–faced surface up)

(Foam–open surface up)
One-Dimensional Poroelastic Material Theory

Equations of motion:

Fluid:

\[- \frac{\partial p_2}{\partial x} = \rho_2 \frac{\partial v_2}{\partial t} + \rho_2 (\epsilon - 1) \frac{\partial (v_2 - v_1)}{\partial t} + \phi h^2 (v_2 - v_1), \]

Solid:

\[- \frac{\partial p_1}{\partial x} = \rho_1 \frac{\partial v_1}{\partial t} + \rho_2 (\epsilon - 1) \frac{\partial (v_1 - v_2)}{\partial t} + \phi h^2 (v_1 - v_2). \]

- Based on Zwikker and Kosten, plus Rosin with complex density and air stiffness taken from Attenborough.
Boundary Conditions

- Open foam surface
- Foam surface sealed with an imperious membrane
- Foam fixed to a hard backing
Reflection Impulse Response – Predicted

Open Surface Foam

Film–faced Foam

Reflection from rear surface

Disaster!

\[
\rho_1 = 30 \text{ kg/m}^3, t = 25 \text{ mm}, \varphi = 0.9, B_m = 8.125 \times 10^5 \text{ Pa}, \eta = 0.265, \\
\varepsilon = 6.025, \sigma = 130 \times 10^3 \text{ nks Rayls/m}, \nu = 0.485, m_s = 0.045 \text{ kg/m}^2
\]
Film–faced Foam / Thin Air Gap

A finite depth layer of film-faced foam separated from a hard backing surface by an air layer of depth $\Delta$.

At $x = l + \Delta$, $v_a = 0$;

At $x = l$, $P_1 = P_a(1 - h), P_1 = P_a h, v_a = v_1(1 - h) + v_2 h$;

At $x = 0$, $v_1 = v, v_2 = v$, $p - p_1 - p_2 = m_s \frac{dv}{dt}$

Impedance: $j\omega z = -\omega^2 m_s - N'/D'$

The solution of this set of seven equations presents no difficulties in principle, but is algebraically tedious. The complete solution is outlined in Appendix 6.2; only the result is given here. The impedance takes the form

\[ j\omega Z = -\omega^2 m_s - N'/D' \]
Film–forced Foam / Thin Air Gap

Inverted reflection from rear surface

Effect of rear surface boundary condition on Film normal incidence absorption coefficient: model of section 6.4.3.2; model of section 6.4.3.3, air layer depth 0.001m.
Rear Surface Boundary Conditions

25mm foam layer with bonded membrane

1. No Airspace: _________

2. Airspace:

\[ \Delta = 1 \]
Absorption treatments

- Bonded/Bonded

- Bonded/Unbonded

- Unbonded/Bonded

- Unbonded/Unbonded
Normal Incidence Absorption

Effects of Airspace at front and rear

1. Film/Foam/Backin
2. Film/Space/Foam/Backin
3. Film/Foam/Space/Backin
4. Film/Space/Foam/Space/Backin

- Foam – 25 mm, 30kg/m³
- Membrane – 0.045 kg/m²
- Airspaces – 1 mm
Impedance Tube Testing

- Melamine Foam (8.6 kg/m³)
  - 100 mm diameter
  - 25 mm thick

- Each sample fit exactly by trimming the diameter & checking the fit with a TL measurement

- Two Facing & Two Rear Surface Boundary Conditions
  - Multiple trials
  - Multiple samples
Sample Fit: TL Qualification

Non-Zero TL = Sample Constrained

Zero TL = Sample Free to Move

Transmission Loss

As-Cut
1\text{st} \text{Trim}
2\text{nd} \text{Trim}
3\text{rd} \text{Trim}
4\text{th} \text{Trim}

No Leakage
Surface Configurations

Front Surface:

1) Plastic film near, but not adhered to foam
2) Plastic film glued to foam

Rear Surface:

1) Small gap between foam & rigid wall
2) Foam adhered to rigid wall
Absorption vs. Configuration – Test

Absorption Coefficient

\[ l = 25\text{mm}, \Delta_1 = 4.5\text{mm}, \Delta_2 = 1\text{mm}, m_s = 50 \text{g/m}^2, h = 0.99 \]

\[ \sigma = 9.5 \times 10^3 \text{mks Rayls/m}, \quad \varepsilon = 1.4, \]

\[ P – \text{wave modulus} = 6.5 \times 10^5 \text{Pa}, \eta = 0.2 \]
Helmholtz Resonator Effect

**Mechanical Impedance**

\[ z_m = R_r + j(\omega m - s/\omega) \]

**Mass**

\[ m = \rho_0 S L' \]

**Stiffness**

\[ s = \rho_0 c_0^2 S^2 / V \]

**Total Acoustic Impedance**

\[ z = 1/(1/z_H + 1/z_f) \]
Helmholtz Resonator Effect

Combined Foam + Helmholtz Resonator System is Similar to Measured System
Helmholtz Resonator Effect

But is it really due to edge gaps?

Measured Glued Facing + Fixed with Edge Sealed
Sound absorption of elastic framed porous materials in combination with impervious films: effect of bonding

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Abstract

The absorption characteristics of elastic framed absorbers in combination with impervious films has been investigated. The effect of bonding the film to the absorber and the absorbers to their rear surface was examined. The results have been modelled using established methods for predicting the absorption of elastic framed porous materials. The absorption of a foam with a film bonded to its top surface was most sensitive to the rear surface bonding condition. Plain foams and foams with loose-laid surface films were less sensitive to the rear surface bonding condition. The results demonstrate that test data used to predict absorption performance need to reflect the absorber mounting conditions. © 2002 Elsevier Science Ltd. All rights reserved.
### Table 1
Parameters used for the modelled results in Fig. 1

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Tortuosity ($k_s$)</th>
<th>Bulk density ($\rho_1$ kg/m$^3$)</th>
<th>Flow resistivity ($r$ mks rayls/m, or Ns/m$^4$)</th>
<th>Porosity ($h$)</th>
<th>Complex shear modulus ($N$ N/cm$^2$)</th>
<th>Poisson’s ratio ($\nu$)</th>
<th>Form factor ($c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2.85</td>
<td>43</td>
<td>22000</td>
<td>0.98</td>
<td>$20 + 10i$</td>
<td>0.3</td>
<td>4</td>
</tr>
</tbody>
</table>

**Resting on Floor**

- Measured (○) and modelled (--) absorption of film faced foam at 24 mm thickness; foam was placed on rear surface (floor of reverberation room).

**Bonded to Backing**

- Measured (○) and modelled (--) absorption of film faced foam at 24 mm thickness; foam was bonded to rear surface (gypsum board).

$$m_s = 35 \text{ g/m}^2$$
Tensioned Membranes Model Verification – Velocity Measurement

Diagram showing the setup with a sound source, membrane, microphone, pre-amplifier, signal analyzer, and amplifier with a laser sensor.
Model Verification – Vibrational Modes

1st

Absolute velocity of membrane - Theory

Experiment

Absolute velocity of membrane - Experiment

2nd

Absolute velocity of membrane - Theory

Absolute velocity of membrane - Experiment
Model Verification – Experiment Set-up

![Diagram of experiment setup]

- **Power Amplifier**
- **Pre-Amplifier**
- **Signal Analyzer**
- **Sound Source**
- **Microphone**
- **Anechoic Termination**
- **Test Sample**

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![Photo of experiment setup]

- **Computer**
- **B&K Pulse System**
- **Speaker Amplifier**
- **Microphones**
- **B&K Standing Wave Tube**
Model Verification – Model Optimization

- Given experimental results as input, find appropriate material properties \((T_o, \rho_s, \eta)\).

- **Why this behavior?** – Finite size, held at edge, finite stiffness.
Glass Fiber Material Inside of Sample Holder
Anechoic Transmission Loss (Green)

Increase in TL due to edge constraint (10dB)

Shearing mode

- Experiment
- FE Prediction (Edge constrained)
- Prediction (Unconstrained case)
### Poroelastic Material Properties Used in Calculations

<table>
<thead>
<tr>
<th>Material</th>
<th>Bulk density (Kg/m³)</th>
<th>Porosity</th>
<th>Tortuosity</th>
<th>Estimated flow resistivity (MKS Rayls/m)</th>
<th>Shear modulus (Pa)</th>
<th>Loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>6.7</td>
<td>0.99</td>
<td>1.1</td>
<td>21000</td>
<td>1200</td>
<td>0.350</td>
</tr>
<tr>
<td>Green</td>
<td>9.6</td>
<td>0.99</td>
<td>1.1</td>
<td>31000</td>
<td>2800</td>
<td>0.275</td>
</tr>
</tbody>
</table>
Variation of Shear Modulus

- As shear modulus increases, the minimum location of TL moves to higher frequencies
Variation of Flow Resistivity

- Flow resistivity controls TL at low and high frequency limit
Investigation of Vibrational Modes of Glass Fiber Materials
Vibrational Modes of Fiber Glass Materials (1st and 2nd Modes, Green)

1st (133 Hz)

2nd (422 Hz)
Internal Constraint to Enhance the Sound Transmission Loss
Sound Transmission Loss (Experiment, Green) [Density of Plexiglass: 1717 Kg/m3]
Effect of Releasing the Internal Cross–Constraint (Measurement)

- Relatively heavy constraint required to realize low frequency benefit.
Effect of Releasing the Internal Cross–Constraint (FEM Prediction)

Cardboard Constraint

Plexiglass Constraint
Metamaterials

- **Metamaterials** are artificial materials engineered to have properties that may not be found in nature. Metamaterials usually gain their properties from structure rather than composition, using small inhomogeneities to create effective macroscopic behavior.

From: Meta-Material Sound Insulation by E. Wester, X. Bremaud and B. Smith, Building Acoustics, 16 (2009)
Membrane-type metamaterials: Transmission loss of multi-celled arrays

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Acoustic metamaterials with negative dynamic mass density have been shown to demonstrate a five-fold increase in transmission loss (TL) over mass law predictions for a narrowband (100 Hz) at low frequencies (100–1000 Hz). The present work focuses on the scale-up of this effect by examining the behavior of multiple elements arranged in arrays. Single membranes were stretched over rigid frame supports and masses were attached to the center of each divided cell. The TL behavior was measured for multiple configurations with different magnitudes of mass distributed across each of the cell membranes in the array resulting in a multipeak TL profile. To better understand scale-up issues, the effect of the frame structure compliance was evaluated, and more compliant frames resulted in a reduction in the TL peak frequency bandwidth. In addition, displacement measurements of frames and membranes were performed using a laser vibrometer. Finally, the measured TL of the multi-celled structure was compared with the TL behavior predicted by finite element analysis to understand the role of nonuniform mass distribution and frame compliance. © 2011 American Institute of Physics. [doi:10.1063/1.3583656]
Proposed Mass–Neutral Material

Cellular panel

Homogenized mat.

Frame (Mat. A)

Plate (Mat. B)

Unit cell

- Cellular material with a periodic array of unit cells
- Unit cell has components with contrasting mass and moduli
- Characteristics of infinite, periodic panel are same as that of a unit cell for normally incident sound

\[ T = \frac{2\rho_0 c}{2\rho_0 c + j2\pi f M_{\text{eff}} f} \]

\[ STL = -20\log|T| \]

\[ M_{\text{eff}} : \text{Mass per unit area} \]

\[ STL : \text{Sound Transmission Loss} \]
A clamped plate has high STL at very low frequencies due to the effect of boundary conditions and finite size and stiffness.
Material–Based Mass Apportioning

- Each unit cell
  - Overall mass constant
  - Different materials for frame and plate

- A series of cases for $\mu$ between 0.1 and 10000
  - $\rho_p$ and $\rho_f$ varied
  - $E_f$ varied keeping $E_p$ constant so that $E_f/E_p = \rho_f/\rho_p$
Experimental Validation

- A good qualitative agreement is observed between measurements and FE predictions.

![Graph showing STL against frequency for different values of Young's modulus and thickness.](image)
Material-Based Mass Apportioning

- As $\mu \uparrow$
  - High STL region broadens in the low frequency regime
  - Region between the first peak and dip is widening
  - The dip – being shifted to the right – desirable

- $\mu \rightarrow O(100) \rightarrow$ saturates

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>Fr.</th>
<th>$E_{fr}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>3910</td>
<td>107</td>
<td>0.055</td>
</tr>
<tr>
<td>0.5</td>
<td>2868</td>
<td>393</td>
<td>0.274</td>
</tr>
<tr>
<td>1</td>
<td>2151</td>
<td>590</td>
<td>0.549</td>
</tr>
<tr>
<td>10</td>
<td>391</td>
<td>1073</td>
<td>5.490</td>
</tr>
<tr>
<td>100</td>
<td>43</td>
<td>1168</td>
<td>54.900</td>
</tr>
</tbody>
</table>

$E_p = 2$ GPa
Effective Mass as a Function of Frequency

- Magnitude of $M_{\text{eff}}$ higher than space-averaged areal mass in the range of 0-1000 Hz
- An order of magnitude higher in 800 – 1000 Hz range
- Shows strong negative mass effect in the peak STL region

$$T = \frac{2\rho_0 c}{2\rho_0 c + j2\pi f M_{\text{eff}} f}$$
Mechanism Behind High STL

- Averaged displacement phase switches from negative to positive value at the STL peak
- Parts of the structure move in opposite directions—similar to observations in LRSMs—resulting in zero averaged displacement
- “Negative mass” observed without locally resonant elements
Hybrid Material

- Cellular structure increases STL at low frequencies
- Lightweight, fine fiber fibrous layer can be used to recover performance at higher frequencies
Hybrid Material

Low Sound Speed Front

- Directs non-normally incident sound to core

Metamaterial Core

- Locally resonant core

Fibrous Cell Filling

- Fibrous cell filling increases STL at high Hz

○ Predicted Sound Transmission Loss in Hybrid System with Fibrous Cell Filling
Conclusions

- Front and rear boundary conditions have a profound effect on the sound absorption offered by poroelastic materials.
- Those effects are predictable and measureable.
- Internal constraint of poroelastic materials can increase their transmission loss, but finite weight of required supports should be accounted for.
- Metamaterials for transmission loss typically depend on the presence of constraints, geometry and flexural stiffness for their performance.
- A proposed mass-neutral “metamaterial” barrier featuring spatially-periodic internal constraints gives low frequency advantage with respect to the mass law, but would require supplementary material to mitigate performance loss at high frequencies.
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  - Yangfan Liu
References