The Influence of Boundary Conditions and Constraints on the Performance of Noise Control Materials

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The Influence of Boundary Conditions and Constraints on the Performance of Noise Control Materials

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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

John Stuart Bolton

Institute of Sound and Vibration Research
Faculty of Engineering and Applied Science
University of Southampton

Thesis submitted for the degree of

Doctor of Philosophy

July 1984
Normal Incidence Measurement of Reflection

![Diagram showing source, receiver, and image source positions]
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:
\[-\frac{\partial p_2}{\partial x} = \rho_2 \frac{\partial v_2}{\partial t} + \rho_2 (\varepsilon - 1) \frac{\partial (v_2 - v_1)}{\partial t} + \sigma h^2 (v_2 - v_1).\]

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

- 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

\[ \rho_1 = 30 \text{ kg/m}^3, l = 25 \text{ mm}, \varphi = 0.9, B_m = 8.125 \times 10^5 \text{ Pa}, \eta = 0.265, \]
\[ \varepsilon = 6.025, \sigma = 130 \times 10^3 \text{ nks Rayls/m}, \nu = 0.485, m_s = 0.045 \text{ ka/m}^2 \]
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 $\Delta$.

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(— --).
Wave Propagation in Foam

- Semi-Infinite Foam Layer:

- Form of Solutions:

  Expressions for air and frame stresses and velocities:

  \[ V_1 = j\omega(C_2e^{-\gamma_1x} + C_4e^{-\gamma_2x}) \quad \gamma = \alpha + j\beta \]

  \[ e^{-\gamma_1x} : \text{Frame wave} \]
  \[ e^{-\gamma_2x} : \text{Airborne wave} \]
  \[ V_1 : \text{Velocity of the frame} \]
  \[ V_2 : \text{Velocity of air pores} \]
Power Flow in Foam

**Intensity:**

- Division Between Phases

\[ I = \frac{1}{2} \text{Re}\{P_1 V_1^*\} + \frac{1}{2} \text{Re}\{P_2 V_2^*\} \]

(Frame Intensity) (Airborne Intensity)

- Division Between Wave Types

\[ I = F_1 |C_2|^2 e^{-2\alpha_1 x} + F_2 |C_4|^2 e^{-2\alpha_2 x} + (e^{-(\alpha_1+\alpha_2)x}, e^{-(\beta_1+\beta_2)x}) \]

(Frame Wave) (Airborne Wave) (Interaction)

where:

- \( F_{1,2} \) – Material Properties
- \( C_{2,4} \) – Wave Amplitudes.
Power Flow in Foam

Sealed Surface:

- Only frame wave carries significant energy
  (Calculation at 1 kHz for standard foam)
Power Flow in Foam

Sealed Surface:

➢ Conclusion:
   - Most energy conveyed through frame

Total: ____________________
Frame: _____________
Air: _____________
Rear Surface Boundary Conditions

25mm foam layer with bonded membrane

1. No Airspace: 

2. Airspace: \[ \triangle = 1 \]
Absorption treatments

- Bonded/Bonded
- Bonded/Unbonded
- Unbonded/Bonded
- Unbonded/Unbonded
Normal Incidence Absorption

Effects of Airspace at front and rear

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

- 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

Goal: zero gaps & no constraint at the edge

- Zero Gaps = no air leaks at the circumference = no change in flow resistance from the material’s value.
- No Edge Constraint = sample readily slides in tube = zero TL at zero Hz

Procedure:

1. Cut Sample with a Die
2. Measure TL & examine zero-Hz TL
3. Trim with razor blade to reduce diameter & remove axial taper to improve the fit
Sample Fit: TL Qualification

Transmission Loss

Non-Zero TL = Sample Constrained

Zero TL = Sample Free to Move

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

$\begin{align*}
l &= 25 \text{mm}, \Delta_1 = 4.5 \text{mm}, \Delta_2 = 1 \text{mm}, m_s = 50 \text{ g/m}^2, h = 0.99 \\
\sigma &= 9.5 \times 10^3 \text{ mks Rayls/m}, \quad \varepsilon = 1.4, \\
P - \text{wave modulus} &= 6.5 \times 10^5 \text{ Pa}, \eta = 0.2
\end{align*}$
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>Poison’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>

Fig. 1. Measured (○) and modelled (-) absorption of film faced foam at 24 mm thickness; foam was placed on rear surface (floor of reverberation room).

Fig. 2. 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 of a model verification experiment for velocity measurement. The diagram includes:
- Power Amplifier
- Pre-Amplifier
- Signal Analyzer
- Microphone
- Membrane
- Sound Source
- Finite Backing
- Amplifier
- Laser Sensor

In the bottom left corner, there is an image of a membrane-covered cylinder. In the bottom right corner, there is an image of the experimental setup with a laser sensor and acoustic equipment.
Model Verification – Vibrational Modes

1\textsuperscript{st} and 2\textsuperscript{nd} Vibrational Modes

### Theory

- Absolute velocity of membrane - Theory

### Experiment

- Absolute velocity of membrane - Experiment

Graphs show the comparison of theoretical and experimental results for the absolute velocity of a membrane in its vibrational modes.
Model Verification – Experimental Set-up

[Diagram of experimental setup with labeled components: Power Amplifier, Pre-Amplifier, Signal Analyzer, Sound Source, Microphone, Anechoic Termination, Test Sample, B&K Pulse System, Speaker Amplifier, Microphones, B&K Standing Wave Tube, Computer]
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.

\[
T = 82 \, Pa \quad \eta = 0.0040 \quad \rho_s = 0.0870 \, \frac{kg}{m^2}
\]
Glass Fiber Material Inside of Sample Holder
Anechoic Transmission Loss (Green)

Increase in TL due to edge constraint (10dB)

Shearing mode
## 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
(1\textsuperscript{st} and 2\textsuperscript{nd} Modes, Green)

1\textsuperscript{st} (133 Hz)

2\textsuperscript{nd} (422 Hz)
Internal Constraint to Enhance the Sound Transmission Loss
Sound Transmission Loss (Experiment, Green) [Density of Plexiglass = 1717 Kg/m3]
Sound Transmission Loss (FE Prediction, 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
Effect of Varying Constraint Density When the Constraint is Free Move
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 array

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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

$M_{eff} := M_{eff}(f)$

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

$T = \frac{2\rho_0 c}{2\rho_0 c + j2\pi f M_{eff}(f)}$

$STL = -20\log|T|$

$M_{eff}$: Mass per unit area

$STL$: 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.
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

\[
T = \frac{2\rho_0 c}{2\rho_0 c + j2\pi fM_{\text{eff}}(f)}
\]
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
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
Acknowledgements

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  • Bryan H. Song
  • Jinho Song

• Current Students:
  • Ryan Schultz
  • Srinivas Varanasi
  • Yangfan Liu
References


Power Flow in Foam

Open Surface:

- Near Surface: most energy in airborne wave
- Eventually: all energy in frame wave

(Calculation at 1 kHz for standard foam)
Power Flow in Foam

Open Surface:

- At Surface: energy conveyed in air
- Within Material: energy carried by frame

Total:  
Frame:  
Air:  

Conclusion:
Geometry-Based vs. Material-Based

- Material-based approach has a wider benefit region.
- Predicted average STL in the benefit region is better for material-based approach.

Areal mass: 5 kg/m²