Lightweight Absorption and Barrier Systems Comprising N-Layer Microperforates

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The Effect of Flexibility on the Acoustical Performance of Microperforated Materials

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With thanks to: Jinho Song (Otis Elevator), Taewook Yoo (3M/EAR), Ryan Schultz (Sandia) and Yangfan Liu (Purdue)

ASA Fall meeting, Kansas City, 10/22/12
Computational Investigation of Microperforated Materials: End Corrections, Thermal Effects and Fluid–Structure Interaction

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INTRODUCTION

• Traditional Uses of MPP’s
  • Absorptive surface treatments
OBJECTIVES

• Proposed Alternative Uses

(i) Functional Absorbers

→ Lightweight, multi-layer, highly dissipative systems
• Proposed Alternative Uses

(ii) Absorbing barriers

➔ Lightweight, multi-layer, repositionable highly dissipative barrier
**INTRODUCTION**

- **Microperforated material**
  - Thin film with 100 microns scale holes
  - Clean, light → one alternative to fibrous sound absorbing materials

- **Viscous Dissipation**
  - In hole
  - Within shearing fluid exterior to the hole

- **Objective**
  - Multilayer panels to control sound level in speech interference range (500 Hz to 4 KHz)

- Expand bandwidth
• Procedure

✓ MPP’s modeled as flexible

✓ Locally reacting

✓ Bounded properties

✓ Arbitrary number of layers up to 10

✓ Arbitrary spacing of layers

✓ Genetic Algorithm used to optimize properties over the Speech Interference Range (500 Hz to 4 kHz)

✓ Objective function depends on application
MULTI-LAYER OF MICROPERFORATED PANELS

- **Assumptions**
  - Hole in the MPP are cylindrical and sharp edged
  - Flexural stiffness of the panel can be ignored
  - Only locally reacting case considered
  - Infinite panels

\[ \begin{array}{c}
\text{Incident} \\
Z_{p1} \quad Z_{p2} \quad Z_{p3} \\
\vdots \\
Z_{pn} \\
\text{Reflected} \\
\text{Transmitted}
\end{array} \]
TRANSFER MATRIX METHOD

\[
\begin{bmatrix}
P_1 \\
U_1
\end{bmatrix} =
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}
\begin{bmatrix}
P_2 \\
U_2
\end{bmatrix}
\]

- **Transfer Matrix**

- **Reflection Coefficient**

\[
R = \frac{T_{11} + T_{11} \cos \theta / (\rho c) - T_{21} (\rho c)/\cos \theta - T_{22}}{T_{11} + T_{11} \cos \theta / (\rho c) + T_{21} (\rho c)/\cos \theta + T_{22}}
\]

- **Transmission Coefficient**

\[
\tau = \frac{2 e^{jk \cos \theta L}}{T_{11} + T_{11} \cos \theta / (\rho c) + T_{21} (\rho c)/\cos \theta + T_{22}}
\]

- **Dissipation Coefficient**

\[
\alpha_d = 1 - |R|^2 - |\tau|^2
\]
• Random Incidence
  
  • Absorption Coefficient
  \[ \overline{\alpha} = \frac{\int_0^{\pi/2} \alpha(\theta) \sin(\theta) \cos(\theta) \, d\theta}{\int_0^{\pi/2} \sin(\theta) \cos(\theta) \, d\theta} \]

  • Dissipation Coefficient
  \[ \overline{\alpha_d} = \frac{\int_0^{\pi/2} \alpha_d(\theta) \sin(\theta) \cos(\theta) \, d\theta}{\int_0^{\pi/2} \sin(\theta) \cos(\theta) \, d\theta} \]

  • Transmission Loss
  \[ \overline{\tau} = \frac{\int_0^{\pi/2} |\tau(\theta)|^2 \sin(\theta) \cos(\theta) \, d\theta}{\int_0^{\pi/2} \sin(\theta) \cos(\theta) \, d\theta} \]

  \[ TL = 10\log_{10} \frac{1}{\overline{\tau}} \]
TRANSFER MATRIX METHOD

INTRODUCTION

OBJECTIVE

TMM

OPTIMIZATION

RESULTS

CONC.

TOTAL

\[
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{Total}
= \begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{\text{MPP1}} \begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{\text{Air1}} \ldots \begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{\text{MPPn}}
\]

AIR

\[
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{\text{Air}} = \begin{bmatrix}
\cos(kL) & jpc \sin(kL) \\
j \sin(kL) / \rho c & \cos(kL)
\end{bmatrix}
\]

(Local Reaction) \quad k = \frac{\omega}{c}

MPP

\[
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix}_{\text{MPP}} = \begin{bmatrix} 1 & Z_{\text{MPP}} \\ 0 & 1 \end{bmatrix}
\]

\(Z_{\text{MPP}}\) : Transfer Impedance of each MPP

\(L\): Panel separation [m]
MICROPERFORATED PANEL

• Guo et al. Model

\[ R = \left( Re \left( \frac{j\omega t}{\alpha c} \right) \left[ 1 - \frac{2}{k\sqrt{-j} J_1(k\sqrt{-j})} \right]^{-1} \right) + \frac{\alpha 2R_s}{\sigma \rho c} \times \rho c \]

\[ k = \frac{\omega \rho_0}{4\eta} \quad R_s = \frac{\sqrt{2\omega \rho_0 \eta}}{2} \quad \alpha = 4 \quad \text{when sharp end} \]

• Previous work

• adjusted \( \alpha \) by CFD calculation

\[ \alpha = (16.9 \frac{t}{d} + 152.8)f^{-0.5} \]

• Note that this equation was formulated in specific range of hole diameter, thickness of the panel, and porosity
MICROPERFORATED PANEL

• Continuity and Force equilibrium – fully coupled

\[ v_y = (1 - \sigma)v_s + \sigma v_f \]

\[ P_1 - P_2 + (v_f - v_s)R \frac{\sigma^2}{1 - \sigma} = j\omega m v_s \]

\[ P_1 - P_2 + (v_f - v_s)R\sigma = \rho h_p j\omega v_f \]

where \( h_p = t + 2\delta \), \( \delta = 8d/3\pi \)

• Fully coupled transfer impedance of MPP*

\[ Z_{MPP} = \frac{R\sigma(1 - \sigma)(j\omega m - j\omega \rho(t + 2\delta)) + j\omega \rho(t + 2\delta)(j\omega m(1 - \sigma) + R\sigma)}{\sigma(1 - \sigma)(R + j\omega m) + (1 - \sigma)^2 \rho(t + 2\delta)j\omega + \sigma^2 R} \]

\* Taewook Yoo, Ph.D Thesis, Purdue University (2008)
**OPTIMIZATION ALGORITHM**

- **GA [GENETIC ALGORITHM]**

  Initial population (initial point) generated at random.

  Replication is the process of choosing the best individuals to participate in the production of offspring.

  Crossover is to reconstruct points by mixing from the pool. Each solution is split in two by the crossover point, which is chosen at random.

  Mutation is a random change of some individuals.
• Genetic Algorithm was used for optimization: function for optimization is not differentiable and also is not continuous at some points

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N)</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Thickness of MPP: (t) [mm]</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>MPP hole diameter: (d) [mm]</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Surface porosity: (\sigma)</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Panel mass: (m) [kg/m(^2)]</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Panel separation: (l) [m]</td>
<td>0.001</td>
<td>0.2</td>
</tr>
<tr>
<td>Total mass: (M) [kg/m(^2)]</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Total depth: (L) [m]</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

Varied in optimization process
FUNCTIONAL ABSORBER

• Used for dissipating energy

• Both directions were considered

• Maximize dissipation coefficient, $\bar{\alpha}_d$
• Optimization for Dissipation Coefficient

Result by number of panel (error function: $\Sigma(1-\bar{\alpha}_d)$)

Fractional error in panel dissipation coefficient for different numbers of panels.

Result by number of panels ($\bar{\alpha}_d$)

Variation of fractional dissipation coefficient with frequency for different panels.
Random Incidence Case

- Optimization for Dissipation coefficient

Parameters for 9 panels

<table>
<thead>
<tr>
<th>Panel</th>
<th>$t$ Thickness [mm]</th>
<th>$d$ Diameter [mm]</th>
<th>$\sigma$ Porosity</th>
<th>$m$ Mass per unit area [kg/m$^2$]</th>
<th>$l$ Distance to next panel [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>0.3411</td>
<td>0.2831</td>
<td>0.0635</td>
<td>0.6974</td>
<td>0.0368</td>
</tr>
<tr>
<td>Panel 2</td>
<td>0.7350</td>
<td>0.1191</td>
<td>0.0614</td>
<td>0.1181</td>
<td>0.0401</td>
</tr>
<tr>
<td>Panel 3</td>
<td>0.7531</td>
<td>0.1000</td>
<td>0.0648</td>
<td>0.2289</td>
<td>0.0372</td>
</tr>
<tr>
<td>Panel 4</td>
<td>0.6777</td>
<td>0.1000</td>
<td>0.0240</td>
<td>0.7085</td>
<td>0.0053</td>
</tr>
<tr>
<td>Panel 5</td>
<td>0.7493</td>
<td>0.3000</td>
<td>0.0438</td>
<td>0.7308</td>
<td>0.0368</td>
</tr>
<tr>
<td>Panel 6</td>
<td>0.7960</td>
<td>0.1000</td>
<td>0.0437</td>
<td>0.1880</td>
<td>0.0176</td>
</tr>
<tr>
<td>Panel 7</td>
<td>0.4441</td>
<td>0.3000</td>
<td>0.0125</td>
<td>0.1115</td>
<td>0.0395</td>
</tr>
<tr>
<td>Panel 8</td>
<td>0.7960</td>
<td>0.1610</td>
<td>0.1219</td>
<td>0.1051</td>
<td>0.0286</td>
</tr>
<tr>
<td>Panel 9</td>
<td>0.7493</td>
<td>0.3000</td>
<td>0.0725</td>
<td>0.1000</td>
<td>-</td>
</tr>
</tbody>
</table>

$M = 2.9883 \text{ kg/m}^2$, $L = 0.2479 \text{ m}$
• Optimization for Dissipation coefficient

• Finite size wall alters performance \((L = 0.25 \, \text{m}, \:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\:\\...

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    height=\textwidth,
    xlabel={frequency [Hz]},
    ylabel={Dissipation Coefficient \(\alpha_d\)},
    xmin=1000, xmax=4000,
    ymin=0, ymax=1,
    xtick={1000,2000,3000,4000},
    ytick={0,0.2,0.4,0.6,0.8,1},
    legend pos=north west
]\end{axis}
\end{tikzpicture}
\end{center}

9 layers of MPP

• Suspended multilayer systems can dissipate almost all incident acoustic energy

• Finite size will impact performance
ABSORPTIVE BARRIER (I): Maximize TL

- Use for blocking noise propagating from one side to other
- One direction was considered
- Maximizing transmission loss
- Remove the valley point (eliminate minima in TL, which does not guarantee high peak TL)
RANDOM INCIDENCE CASE

- Optimization for Transmission Loss

Result by number of panel (error function: $\Sigma(1/TL)$)
### Parameters for 6 panels

<table>
<thead>
<tr>
<th></th>
<th>$t$</th>
<th>$d$</th>
<th>$\sigma$</th>
<th>$m$</th>
<th>$l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>0.8000</td>
<td>0.3000</td>
<td>0.0725</td>
<td>0.3755</td>
<td>0.2000</td>
</tr>
<tr>
<td>Panel 2</td>
<td>0.7494</td>
<td>0.1000</td>
<td>0.0100</td>
<td>0.7000</td>
<td>0.2000</td>
</tr>
<tr>
<td>Panel 3</td>
<td>0.8000</td>
<td>0.1000</td>
<td>0.0101</td>
<td>0.7295</td>
<td>0.0363</td>
</tr>
<tr>
<td>Panel 4</td>
<td>0.8000</td>
<td>0.3000</td>
<td>0.2000</td>
<td>0.7014</td>
<td>0.0020</td>
</tr>
<tr>
<td>Panel 5</td>
<td>0.8000</td>
<td>0.3000</td>
<td>0.1375</td>
<td>0.1332</td>
<td>0.0049</td>
</tr>
<tr>
<td>Panel 6</td>
<td>0.7646</td>
<td>0.1000</td>
<td>0.0100</td>
<td>0.3500</td>
<td>-</td>
</tr>
</tbody>
</table>

$M = 2.9896 \text{ kg/m}^2, \quad L = 0.4475 \text{ m}$
Comparison of optimized set and mass law set (Number of panels: 6)

Mass Law: \( m = 3 \, \text{kg/m}^2 \)

- Performance of multilayer system is better than mass law
- Has further advantage of being absorptive on incident side, so does not increase level on source side
• Comparison of optimized set for $\bar{\alpha}_d$ and for $TL (N = 6)$

• Still significant dissipation when optimized for transmission loss
BARRIER TREATMENT

- Impermeable Barrier

- Dissipative Barrier
ABSORPTIVE BARRIER (II): TL and absorption

- Optimization for Partition
  - Result by number of panels (error function: $\Sigma(1-\alpha_d-0.8T)$)

![Graph showing error function vs number of panels](image.png)
RANDOM INCIDENCE CASE

- Optimization for Partition
  - Result by number of panels
**RANDOM INCIDENCE CASE**

- **Optimization for Partition**

  - Parameters for 8 panels

<table>
<thead>
<tr>
<th>Panel</th>
<th>Thickness [mm]</th>
<th>Diameter [mm]</th>
<th>Porosity</th>
<th>Mass per unit area [kg/m²]</th>
<th>Distance to next panel [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel 1</td>
<td>0.800</td>
<td>0.300</td>
<td>0.113</td>
<td>0.100</td>
<td>0.030</td>
</tr>
<tr>
<td>Panel 2</td>
<td>0.800</td>
<td>0.300</td>
<td>0.105</td>
<td>0.140</td>
<td>0.023</td>
</tr>
<tr>
<td>Panel 3</td>
<td>0.800</td>
<td>0.300</td>
<td>0.183</td>
<td>0.382</td>
<td>0.017</td>
</tr>
<tr>
<td>Panel 4</td>
<td>0.800</td>
<td>0.176</td>
<td>0.042</td>
<td>0.100</td>
<td>0.024</td>
</tr>
<tr>
<td>Panel 5</td>
<td>0.780</td>
<td>0.300</td>
<td>0.076</td>
<td>0.112</td>
<td>0.004</td>
</tr>
<tr>
<td>Panel 6</td>
<td>0.234</td>
<td>0.193</td>
<td>0.015</td>
<td>0.631</td>
<td>0.031</td>
</tr>
<tr>
<td>Panel 7</td>
<td>0.800</td>
<td>0.100</td>
<td>0.035</td>
<td>0.644</td>
<td>0.136</td>
</tr>
<tr>
<td>Panel 8</td>
<td>0.800</td>
<td>0.100</td>
<td>0.010</td>
<td>0.618</td>
<td>-</td>
</tr>
</tbody>
</table>
• Comparison optimized result for a functional absorber and for a partition
• Comparison optimized result for a functional absorber and for a partition

![Graphs showing comparison between optimized results for a barrier and a partition.](image-url)
CONCLUSIONS

• Optimization model for a functional absorber and a barrier cases were introduced

• Optimization result for multi-layer panels covers much broader frequency range than single panel

• Future work:
  • To decide number of segments, design optimization model for an extended reacting case
  • To decide size of the system, effects edge scattering and constraint when optimizing the system

• For presentations – search for “Herrick e-Pubs”