2011

Microperforated Materials as Duct Liners: Local Reaction vs. Extended Reaction

J Stuart Bolton  
*Purdue University*, bolton@purdue.edu

Hyunjung Shin

Follow this and additional works at: [http://docs.lib.purdue.edu/herrick](http://docs.lib.purdue.edu/herrick)

[http://docs.lib.purdue.edu/herrick/55](http://docs.lib.purdue.edu/herrick/55)

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Microperforated Materials as Duct Liners:
Local Reaction vs. Extended Reaction

Hyunjun Shin and J. Stuart Bolton

Ray. W. Herrick Laboratories
School of Mechanical Engineering Department
Purdue University
Question: Can microperforated materials (MPPs) be used to create duct linings that produce attenuation comparable with that of fibrous duct linings.

- MPP silencers only required an air-cavity in the backing space.
- No problems with fiber erosion
- More easily cleanable than fibrous linings
- Both the local and extended reaction treatments are considered
Analytical model approaches

- Configuration of local reaction treatment
- Use Miki model for fibrous media to represent glass fiber [1]

\[ \zeta_n = -j Z_0 \text{cut} (K_y d) \]

\( d \): Depth of a cavity (3.8 cm)
## Analytical model approaches

- **Basic equations and solution methods**

**Basic equation**

\[ F(W) = W \tan(W) - \frac{jKL}{\xi_n} \]

- \( L \): Width of a duct
- \( K_y = \frac{W}{L} \)

**Solutions**

\[ K_x L = \sqrt{(KL)^2 - (W)^2} \]

- \( K_x = \beta - j\alpha \)
- Complex wave numbers in x-direction
- \( \alpha = -\text{Im}\{K_x\} \)
- Imaginary part of wave number

**Transmission loss in a duct**

\[ TL = 8.685\alpha L_{\text{tube}} \]

- \( L_{\text{tube}} \): Length of a cavity (tube)
Analytical model approaches

- Sound attenuation

Image: Locally reacting case for fibrous material

Imaginary part of wave number determines the magnitude of sound attenuation
Analytical model approaches

- **Extended reaction** treatment for fibrous material
- Miki Model is also applied to calculate characteristic impedance and propagation constant

\[ \rho_p = \frac{Z_0 K_p}{\omega} \quad \text{Complex density of a material} \]
\[ c_p = \frac{\omega}{K_p} \quad \text{Complex speed of a sound of a material} \]
Analytical model approaches

- Sound attenuation

Transmission loss in a duct

\[ TL = 8.685 \alpha L_{\text{tube}} \]

- Peak location shifted to higher frequency
- Overall sound attenuation level decreased
Analytical model approaches

- Local reaction treatment for microperforated material
- Maa-flex Model

Transfer Impedance

\[
Z = \frac{P_1 - P_2}{\nu_{y1}} = \frac{R_{tm} \Omega_s (1 - \Omega_s) (f_{om} - j \omega \rho_v (t + 2 \delta)) + j \omega \rho_v (t + 2 \delta) (f_{om} (1 - \Omega_s) + R_{tm} \Omega_s))}{\Omega_s (1 - \Omega_s) (R_{tm} + f_{om}) + (1 - \Omega_s)^2 \rho_v (t + 2 \delta) j \omega + R_{tm}^2 R_{tm}}
\]

Dynamic macroscopic flow resistance

\[
R_{tm} = \frac{32 \pi t}{\sigma \rho_v \epsilon d^2} \left[ \sqrt{1 + \frac{x^2}{32}} + \sqrt{\frac{8 x d}{16}} \right]
\]

End correction factor

\[
\delta = \frac{1}{2} \left( \frac{t}{9 + \frac{x^2}{2}} + 0.85 d \right)
\]

- \(\nu_{y1}\): Tangential particle velocity on the panel
- \(t\): Thickness of the panel
- \(\Omega_s\): Surface porosity
- \(\omega\): Tangential particle velocity on the panel
- \(m\): mass per unit area
- \(d\): Diameter of holes
Analytical model approaches

- Configuration of local reaction treatment

![Diagram showing configuration of local reaction treatment with labels for DUCT, Length of a duct, Width of a duct, Depth of a cavity, Length of a cavity, Microperforated material, Air, and Surface Normal Impedance with the formula: \( \xi_n = \frac{Z - j\rho_0 c \cot(Kd_e)}{\rho_0 c} \). Depth of a cavity (3.8 cm).]
Analytical model approaches

- Sound attenuation

Transmission loss in a duct

\[ TL = 8.685 \alpha L_{\text{tube}} \]

\( L_{\text{tube}} \): Length of a cavity (panel)
Measurements

- 4-microphone measurements
- Duct-shaped standing wave tube
- Configuration

- Transfer matrix method
Local reaction treatment for fibrous material

- Yellow glass fiber
- 3.8 cm thickness
- Cavity is segmented using 2 mm acrylic pieces
Measurements

- Local and extended reaction treatment for Microperforated materials

- Cavity is segmented using 2 mm acrylic pieces

Locally reacting case

Extended reaction case

Acrylic pieces are all removed for the extended reaction case
Measurements

- Local and extended reaction treatments

![Graphs comparing Glass fiber and Microperforated material](image-url)
Measurements

- Effects of segmentations in the cavity - microperforated

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Case 1 Image]</td>
<td>![Case 2 Image]</td>
<td>![Case 3 Image]</td>
</tr>
</tbody>
</table>

![Graph showing transmission loss vs. frequency for different backing segmentations]
Finite element model approaches

- COMET/VISION is based on finite element implementation of the Biot theory for wave propagation in porous material.
- PATRAN is used as a meshing tool.

Finite element model configuration
Finite element model approaches

- Modeling microperforated as a rigid porous material
  - Attala and Sgard model is explicitly used to model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow resistivity</td>
<td>$\varphi = \frac{8\eta}{\sigma r^2}$</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>$\alpha_{\omega} = 1 + \frac{\varepsilon_e}{t}$</td>
</tr>
<tr>
<td>Correction length</td>
<td>$\varepsilon_e = 0.48\sqrt{\frac{n \pi}{2}}(1 - 1.4\sqrt{\varphi})$</td>
</tr>
<tr>
<td>Surface impedance with a finite-depth air cavity</td>
<td>$Z_A = \left(\frac{2t}{r} + 4\right) \frac{R_s}{\varphi} + \frac{1}{\varphi} (2\varepsilon_e + d) j\omega \rho_o - j\rho_o c_o \cot(k_o L)$</td>
</tr>
<tr>
<td>$R_s = \frac{1}{2\sqrt{2\pi\omega\rho_o}}$</td>
<td></td>
</tr>
</tbody>
</table>

Viscous and thermal characteristic lengths $\Lambda = \Lambda' = r$

$\eta$ : dynamic viscosity  
$\sigma$ : porosity  
$r$ : radius  
$t$ : thickness
Finite element model approaches

- Local and extended reaction treatments

- Glass fiber is modeled as an elastic solid

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (%)</td>
<td>9.90e1</td>
</tr>
<tr>
<td>Flow resistivity (Rayls)</td>
<td>1.500e4</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>1.00</td>
</tr>
<tr>
<td>Thermal Characteristic Length (m)</td>
<td>1.00e-4</td>
</tr>
<tr>
<td>Viscous Characteristic Length (m)</td>
<td>5.00e-4</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>6.88</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>1.00e3</td>
</tr>
<tr>
<td>Loss Factor</td>
<td>0.200</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.010</td>
</tr>
</tbody>
</table>

- Microperforated material as a rigid porous material

<table>
<thead>
<tr>
<th>Parameters of Micro-perforated panel</th>
<th>Thickness (m)</th>
<th>Porosity (%)</th>
<th>Hole diameter (m)</th>
<th>Length (m)</th>
<th>Mass per unit area (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0004</td>
<td>1.8</td>
<td>0.0000152</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Finite element model approaches

- Local and extended reaction treatments for fibrous material

Local reaction case

Extended reaction case

![Graphs showing sound attenuation of fibrous material](image)
Finite element model approaches

- Local and extended reaction treatments for microperforated material

![Graphs showing sound attenuation for local and extended reaction cases](image_url)
Matching fibrous performance

To match TL performance, create microperforated treatment having same surface normal impedance as fibrous layer in high performance band.
Comparisons

- Microperforated material matching acoustical performance of fibrous material

NORMALIZED IMPEDANCE

- 3.8 cm air backing depth for microperforated material
- 3.8 cm thick fibrous material

- Least square error method is applied to match the both real and imaginary part of fibrous material by adjusting the parameters of microperforated material.
Comparisons

- Parameters of microperforated material

<table>
<thead>
<tr>
<th>Parameters of Micro-perforated panel</th>
<th>Thickness (m)</th>
<th>Porosity (%)</th>
<th>Hole diameter(m)</th>
<th>Length (m)</th>
<th>Mass per unit area(kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before adjustment</strong></td>
<td>0.0004</td>
<td>1.8</td>
<td>0.000152</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of Micro-perforated panel</th>
<th>Thickness (m)</th>
<th>Porosity (%)</th>
<th>Hole diameter(m)</th>
<th>Length (m)</th>
<th>Mass per unit area(kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>After adjustment</strong></td>
<td>0.0004</td>
<td>5.6</td>
<td>0.000135</td>
<td>0.5</td>
<td>0.365</td>
</tr>
</tbody>
</table>
Comparisons

- Transmission loss of duct linings

Local reaction treatment (Analytical approach)

Local reaction treatment (Finite element approach)
Conclusions

- Analytical predictions provided the reasonable agreement with measurements.
- Microperforated material was successfully modeled as a rigid porous material with equivalent tortuosity.
- Finite element model used in this study was appropriate.
- Desired parameters of microperforated material were obtained to match the impedance of the fibrous material.
- Microperforated duct liner emulated comparable acoustical performance of fibrous material duct liner.
- Microperforated duct liner could be used as an alternative absorbing lining whenever fibrous duct lining is not desired.