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

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Introduction

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]

Surface Normal Impedance

\[ z_n = -jZ_0 \cot (K_0 d) \]

\( d \): 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

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
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

\[
Z = \frac{P_1 - P_2}{v_{y1}} = \frac{R_{tm}\Omega_s(1 - \Omega_s)(\omega_m - j\omega \rho_s(t + 2\delta)) + j\omega \rho_s(t + 2\delta)(\omega_m(1 - \Omega_s) + R_{tm}\rho_s))}{\Omega_s(1 - \Omega_s)(R_{tm} + j\omega_m) + (1 - \Omega_s)^2\rho_s(t + 2\delta)j\omega + \Omega_s^2R_{tm}}
\]

Dynamic macroscopic flow resistance

\[
R_{tm} = \frac{32\eta t}{\sigma \rho_c \epsilon d^2} \left[ \sqrt{1 + \frac{x^2}{32}} + \sqrt{\frac{2xd}{8t}} \right]
\]

End correction factor

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

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

Configuration of local reaction treatment

CORD:

1. Configuration of local reaction treatment

2. Analytical model approaches

Surface Normal Impedance:

\[ \xi_n = \frac{Z - j\rho_0 c \cdot \cot(Kd_a)}{\rho_0 c} \]

where:
- \( Z \) is the characteristic impedance
- \( \rho_0 \) is the density of the fluid
- \( c \) is the speed of sound in the fluid
- \( K \) is the wavenumber
- \( d_a \) is the 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
Measurements

- 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 transmission loss of Glass fiber and Microperforated material against frequency.](image)

Comparison between local and extended reaction case:

- Glass fiber
- Microperforated material

SOUND ATTENUATION OF MICROPERFORATED MATERIAL

Transmission Loss (dB) vs Frequency [Hz]
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><img src="image1.png" alt="Case 1 Diagram" /></td>
<td><img src="image2.png" alt="Case 2 Diagram" /></td>
<td><img src="image3.png" alt="Case 3 Diagram" /></td>
</tr>
</tbody>
</table>

![Graph of Different Backing Segmentations](image4.png)
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 approaches

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

| Flow resistivity | $\varphi = \frac{8\eta}{\sigma r^2}$ |
| Tortuosity       | $\alpha_{\varphi} = 1 + \frac{\varepsilon_e}{t}$ |

- Correction length
  - $\varepsilon_e = 0.48 \sqrt{\pi r^2} (1 - 1.4 \sqrt{\varphi})$

- Surface impedance with a finite-depth air cavity
  - $Z_A = \left(\frac{2t}{r} + 4\right) \frac{R_s}{\varphi} + \frac{1}{\varphi} (2\varepsilon_e + d) j \omega \rho_o - j \rho_o c_o \cot(k_o L)$
  - $R_s = \frac{1}{2} \sqrt{2 \pi \omega \rho_o}$

- 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>
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<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>
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<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/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0004</td>
<td>1.8</td>
<td>0.000152</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](image1)

![Extended reaction case](image2)
Finite element model approaches

- Local and extended reaction treatments for microperforated material

Local reaction case

Extended reaction case
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

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<th>Length (m)</th>
<th>Mass per unit area(kg/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before adjustment</td>
<td>0.0004</td>
<td>1.8</td>
<td>0.000152</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>After adjustment</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