Design of Multi-Chamber Silencers with Microperforated Elements

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Design of multi-chamber silencers with microperforated elements

Seungkyu Lee and J. Stuart Bolton
Paul A. Martinson
The authors acknowledge the support of 3M Corporation through the provision of materials for the acoustical silencer experiments and for the financial support of this work.
Objective

- Develop the acoustic silencer that could attenuate sound effectively over the speech interference range (400 – 3000 Hz) using Microperforated Panel (MPP).
- Develop a reliable finite element modeling of MPP.
- Multiple MPP linings application in the acoustic silencer to improve the acoustic attenuation performance.
Literature Review – Acoustic Silencer Design

- **Muffler Design**
  - Dimension modification of acoustic silencer
    - Inlet and outlet design of the muffler - Selamet and Ji (2000)
    - Multiple chamber designs – Denia et al. (2008)
  - Perforated Tube lining Application
    - Perofrated Tube lining application/absorbing material – Ji and Selamet (2005)
    - Microperforated panel applicatoin – Allam and Abom (2011)

- **Microperforated Panel Modeling**
  - Equivalent fluid model - dynamic permeability, tortuosity and bulk modulus
  - Rigid and motionless skeletons with identical cylinder perforation
    - Atalla and Sgard (2007)
  - Rigid porous model verification
    - Jaouen and Bècot (2011)
Configuration of mufflers

<table>
<thead>
<tr>
<th>Dimension</th>
<th>[cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_t$</td>
<td>9.60</td>
</tr>
<tr>
<td>$d_o$</td>
<td>15.2</td>
</tr>
<tr>
<td>$d_i$</td>
<td>2.90</td>
</tr>
</tbody>
</table>

$l_t$: chamber total length, $d_o$: outer diameter of chamber, $d_i$: diameter of inlet

<table>
<thead>
<tr>
<th>Dimension</th>
<th>[cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$</td>
<td>5.6</td>
</tr>
<tr>
<td>$l_2$</td>
<td>2.0</td>
</tr>
<tr>
<td>$l_3$</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Experimental Setup

Sound Transmission Loss measurement

- ASTM E2611 4 Mic Measurement
- Two-load method was used
  : Rigid and Anechoic terminations

\[
A = \frac{j(p_1 e^{jkx_2} - p_2 e^{jkx_1})}{2 \sin k(x_1 - x_2)}, \\
B = \frac{j(p_2 e^{-jkx_1} - p_1 e^{-jkx_2})}{2 \sin k(x_1 - x_2)}, \\
C = \frac{j(p_3 e^{jkx_3} - p_4 e^{jkx_4})}{2 \sin k(x_3 - x_4)}, \\
D = \frac{j(p_4 e^{-jkx_3} - p_3 e^{-jkx_4})}{2 \sin k(x_3 - x_4)}.
\]

\[
H_{12} = \frac{p_2}{p_1}, \\
H_{34} = \frac{p_4}{p_3}, \\
s = |x_1 - x_2| = |x_3 - x_4|
\]

\[
TL = 20 \log \left| \frac{e^{jks} - H_{12}}{e^{jks} - H_{34}} \right| - 20 \log |H_t|
\]

Introduction to MPP

Microperforated material used in the muffler

<table>
<thead>
<tr>
<th></th>
<th>Hole Diameter [µm]</th>
<th>Thickness [m]</th>
<th>Flow Resistance [Rayl]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPP 454</td>
<td>103.6</td>
<td>0.0003</td>
<td>454</td>
</tr>
</tbody>
</table>

The configuration of microperforated panel lining in the muffler

- $l_t$: chamber total length
- $d_o$: outer diameter of chamber
- $d_i$: diameter of inlet

MPP lining Implementation!!
The microperforate panel (MPP) was modeled as an equivalent fluid
- Complex Density and Bulk Modulus were modeled using following equations
- Calculated complex Density and bulk modulus were implemented in finite element modeling of the MPP

Complex Density

\[ \tilde{\rho}_{cr}(\omega) = \frac{\alpha_{\infty} \rho_0}{\phi} \left[ 1 - j \frac{\sigma \phi}{\omega \rho_0 \alpha_{\infty}} \sqrt{1 + j \frac{4 \alpha_{\infty}^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}} \right] \]

\( \phi \): Perforation rate
\( \alpha \): Dynamic Tortuosity
\( \sigma \): Flow resistivity
\( \eta \): Dynamic viscosity of air
\( \Lambda \): Viscous characteristic length
\( \Lambda' \): Thermal characteristic length
\( \Lambda = \Lambda' = r \) (radius of perforation)

Complex Bulkmodulus

\[ \tilde{K}(\omega) = \frac{\gamma P_0 / \phi}{\gamma - (\gamma - 1) \left[ 1 - j \frac{8 \kappa}{\Lambda'^2 C_P \rho_0 \omega} \sqrt{1 + j \frac{\Lambda'^2 C_P \rho_0 \omega}{16 \kappa}} \right]^{-1}} \]

\( \gamma \): Specific heat ratio of air
\( \kappa \): Thermal conductivity
\( P_0 \): Atmospheric pressure
\( C_P \): Specific heat of air at const. pressure


Microperforated Panel Modeling – MPP 454

- Relationship between flow resistivity and porosity
- MPP 454 rayls
  - Radius of perforation = 51.8145e-06 m
  - Thickness = 0.0003 m
  - Porosity = 0.0018 (Calculated using the following equation)

\[ \sigma = \frac{8\eta}{(\phi r^2)} \]

- \( \sigma \): Flow resistivity
- \( \eta \): Dynamic Viscosity
- \( \phi \): Porosity
- \( r \): Radius

Microperforated Panel Modeling - FE Modeling

- Commercial Software ABAQUS was used in modeling of muffler with MPP
- Transmission Loss was calculated using 3-point measurement method

Sound Pressure at 800 Hz

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>TL [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>2000</td>
<td>20</td>
</tr>
<tr>
<td>3000</td>
<td>30</td>
</tr>
<tr>
<td>4000</td>
<td>40</td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
</tr>
<tr>
<td>6000</td>
<td>60</td>
</tr>
<tr>
<td>7000</td>
<td>70</td>
</tr>
<tr>
<td>8000</td>
<td>80</td>
</tr>
<tr>
<td>9000</td>
<td>90</td>
</tr>
<tr>
<td>10000</td>
<td>100</td>
</tr>
</tbody>
</table>

TL for LL with MPP454

- MPP454 - EXP 1
- MPP454 - EXP 2
- No MPP - EXP

CAD Model

FE Model

AIR

MPP 454
**3-Point Measurement Method**

\[
p_1 = p_i e^{ikx_1} + p_r e^{-ikx_1}
\]
\[
p_2 = p_i e^{ikx_2} + p_r e^{-ikx_2}
\]
\[
p_i = \frac{1}{2i \sin k(x_2 - x_1)} [p_i e^{-ikx_2} - p_2 e^{-ikx_1}]
\]

Anechoic Termination (Z=\(\rho_0 c\))

\[
\text{TL} = 20 \log_{10} \left| \frac{p_i}{p_3} \right| + 10 \log_{10} \left( \frac{S_i}{S_o} \right)
\]
FE modeling of MPP 454

- Rigid boundaries modeling
- Implementation of MPP’s local reaction
  - Local reaction of MPP cannot be modeled using fluid modeling of MPP.
- Lateral and Vertical rigid sections were created in MPP modeling.
  - Thickness of rigid cut: 0.00005m
  - Laterally 8 sections were created
  - Divided into 2 sections vertically in 3.6° (total of 360 rigid partition)
Improved MPP Modeling and Verification

- Vertical and lateral rigid sections improved TL in frequency range from 1600 to 2500 Hz for MPP 454 as well as the region below 1600 Hz.
- Developed model shows good agreement with different microperforated material.
- **MPP improved TL performance gradually over 1600 – 3400 Hz**
- **Brought up minima at 1600 Hz, 2700 Hz, 3400 Hz.**
Result comparison – single vs. dual chamber

- Double chamber configuration improved TL performance at 400 – 2600 Hz
  - Improved speech interference range
  - 1st peak appeared at single chamber moved to low frequency and created new minima at 480 Hz.
Results comparison – Dual Chamber

- Overall TL peaks were lowered but the lowest TL point at 490 Hz was brought up by MPP.
Multiple MPP linings - Experiment

- Expecting to reduce the minima in TL curves
- Location of Multiple MPP linings were determined using FEM simulation
- Two layers of MPP tube linings were chosen
High peaks were lowered and flat TL curve was created by double-layered MPP
Low TL at 2700 Hz was brought up by using multiple MPP
## Overall A-weighted Sound Pressure Level

<table>
<thead>
<tr>
<th>A-weighted Overall Sound Pressure Level</th>
<th>Sound without muffler treatment</th>
<th>Single Chamber</th>
<th>Single Chamber w/ MPP454</th>
<th>Double Chamber</th>
<th>Double Chamber w/ MPP454</th>
<th>Double Chamber w/ Double MPP454</th>
</tr>
</thead>
<tbody>
<tr>
<td>68.50 dBA</td>
<td>53.98 dBA</td>
<td>52.09 dBA</td>
<td>53.24 dBA</td>
<td>50.49 dBA</td>
<td>51.28 dBA</td>
<td></td>
</tr>
</tbody>
</table>

**Recordings**

- Recorded on 4/10/2014
- Double Layered MPP Cases were Recorded on 4/23/2014
Pressure Drop Experiment

MPP gives beneficial effects in reducing the pressure drop results from the muffler.
Conclusion

- Acoustic silencer for speech interference range was developed.
- Reliable MPP model was developed using FEM and the model was validated with the experimental results.
- Multiple MPP tube linings were introduced to improve the acoustic attenuation and the multiple liners helped in flattening the TL curve.

Future Plans

- Optimized flow resistance of MPP linings and the locations of multiple MPP linings will be studied.
- The modeling of the muffler using MPP liner with flow effect will be studied.