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CFD Modeling of Tapered Hole Microperforated Panels

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Purdue University

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Introduction

- **Microperforated material**
- **Dissipation**
  - In hole
  - Along outer surface
  - Within shearing fluid
- **Analytical models**
  - Maa (1975) and Guo et al. (2008) account for first two
Real materials do not have regular hole shapes and so are not suitable for analytical treatment.
Objective

By using computational fluid dynamics approach, calculate dynamic flow resistance for tapered hole microperforated panel considering flow through one hole and compare with existing formulation.

\[ R_f = \frac{P_1 - P_2}{v_{in}} \]
Guo’s Model

\[ R = \left( \frac{Re}{\sigma} \right) \left[ \frac{j\omega t}{\sigma} \left( 1 - \frac{2}{k\sqrt{-j}J_0(k\sqrt{-j})} \right)^{-1} \right] \left( 1 + \frac{\alpha^2 R_s}{\sigma \rho c} \right) \times \rho c \]

\[ k = \sqrt{\frac{\omega \rho_0}{4\eta}} \]

\[ R_s = \frac{\sqrt{2\omega \rho_0 \eta}}{2} \]

\[ \alpha = 2 \quad \text{when smooth end} \]
\[ \alpha = 4 \quad \text{when sharp end} \]

Properties
- \( t \): thickness of panel
- \( d \): diameter of hole
- \( \sigma \): porosity
- \( \omega \): frequency
- \( R_s \): surface resistance

Dynamic Flow resistance (R) is function of \( t, d, \sigma \)

Note that \( R_s \to 0 \) as \( \omega \to 0 \)
Analytical Solution (Randeberg, 2000)

Based on Guo’s model, Randeberg used integration method. (used $\alpha = 4$ for sharp edged)

$$r = \text{Re} \left\{ \sum_{n=1}^{N} \frac{j \omega \Delta z}{\sigma_n c} [1 - \frac{2}{k_n \sqrt{-j}} J_1(k_n \sqrt{-j})]^{-1} \right\} + \frac{\alpha R_s}{\sigma_1 \rho c} + \frac{\alpha R_s}{\sigma_N \rho c}$$
The value of $\alpha$ vs. Frequency

In these graphs, it is shown that $\alpha$ is a function of frequency, thickness, and hole diameter.
Flow resistance computed by Fluent vs. $\beta$

$\alpha$, end correction coefficient in Guo model, is dependent on frequency.

$$\alpha = \beta f^{-0.5}$$

$\beta$ is function of thickness, hole diameter, and porosity.

$$\beta = 16.9 \frac{t}{d} + 152.8$$

(at $t = 0.4064$ mm, $d = 0.2032$ mm, $\sigma = 0.02$)
Geometry of CFD model

Mesh size: 0.005 mm, calculating time: 3-8 hours
# CFD Parameters

## 36 Cases with 9 different thicknesses

(t = 0.1016 mm – 0.9144 mm)

<table>
<thead>
<tr>
<th>Case</th>
<th>d₁ [mm]</th>
<th>d₂ [mm]</th>
<th>Case</th>
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<th>d₂ [mm]</th>
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<th>d₁ [mm]</th>
<th>d₂ [mm]</th>
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<tr>
<td>Case1</td>
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<td>0.127</td>
<td>Case13</td>
<td>0.127</td>
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<td>Case25</td>
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<td>Case27</td>
<td>0.2032</td>
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<td>Case36</td>
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</table>
Inlet velocity was chosen to be a Hann windowed, 5 kHz half-sine wave having a maximum value of 1 mm/s in order to cover the frequency range up to 10 kHz.
\[ t = 0.4064 \text{ mm}, \quad d_1 = 0.1016 \text{ mm}, \quad d_2 = 0.2032 \text{ mm}, \quad \sigma = 0.02 \]
Flow resistance & reactance

$t = 0.4064 \text{ mm}, \sigma = 0.02, d_1 = 0.1016 \text{ mm}, d_2 = 0.2032 \text{ mm}$

Flow direction does not affect resistance or reactance.
Dynamic flow resistance and reactance

Fixed diameter of inlet hole

\( t = 0.4064 \text{ mm}, \sigma = 0.02, d_1 = 0.1016 \text{ mm} \)
Dynamic flow resistance and reactance

**Fixed diameter of outlet hole**

\( t = 0.4064 \text{ mm}, \sigma = 0.02, d_1 = 0.3.48 \text{ mm} \)
Compared CFD Result with Guo Model

Flow resistance & reactance

\( t = 0.4064 \text{ mm}, \ \sigma = 0.02, \ d_1 = 0.1016 \text{ mm}, \ d_2 = 0.2032 \text{ mm} \)

Make \( \alpha \), which is defined by Guo et al., function of frequency to fit with CFD results
Error correction factor $\alpha$

In the previous work (sharp-edged cylindrical hole)

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

$$\alpha = \beta f^{-0.5}$$

Make $\beta$ a function as thickness, inlet diameter, and outlet diameter.

$$\beta = \left(16.9 \frac{t}{d_1} + 153\right)f(t,d_1,d_2)$$
Define \( f(t, d_1, d_2) \)

(left is fixed by \( d_1 = 0.1016 \) mm, and right is fixed by \( d_2 = 0.3048 \) mm)

Inversely proportional to thickness and almost linear

\[
f(t, d_1, d_2) = a \left(1 - \frac{d_2}{d_1}\right) t + 1
\]
The value of $a$ vs. Frequency

Define slope $a$

By second order Newton interpolation

$$a = \left(6.66 \left(\frac{d_1}{d_2}\right)^2 - 7.07 \left(\frac{d_1}{d_2}\right) + 3.06\right) \times 10^4$$
The value of $\alpha$ vs. Frequency

$d_1 = 0.1016 \text{ mm}, \ d_2 = 0.2032 \text{ mm}, \ \sigma = 0.02$
The value of $\alpha$ vs. Frequency

$t = 0.4064\, \text{mm}, \ d_2 = 0.2032\, \text{mm}, \ \sigma = 0.02$
The value of $\alpha$ vs. Frequency

$t = 0.4064$ mm, $d_1 = 0.1016$ mm, $\sigma = 0.02$
By changing the definition of $\alpha$, which is defined by Guo et al., accuracy can be improved.

By making $\beta$ a function of thickness, inlet hole diameter, and outlet hole diameter (as below), we can define dynamic flow resistance for any tapered hole.

$$\beta = \left\{ 6.66 \left( \frac{d_1}{d_2} \right)^2 - 7.07 \left( \frac{d_1}{d_2} \right) + 3.06 \right\} \times 10^4 \times \left( 1 - \frac{d_2}{d_1} \right) t + 1 \right\} \left( 16.9 \frac{t}{d_1} + 152.8 \right)$$

Future: Make complete definition of $\alpha$ and an examination of the effect of square or slit hole geometry.
Thanks to:

- Thomas Herdtle of 3M Corporation, St. Paul, Minnesota, for his useful, practical advice at an early stage of this work.