8-2015

Microperforated Films as Duct Liners

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9-12 AUGUST 2015
inter.noise 2015
SAN FRANCISCO, CALIFORNIA USA

Microperforated films as duct liners

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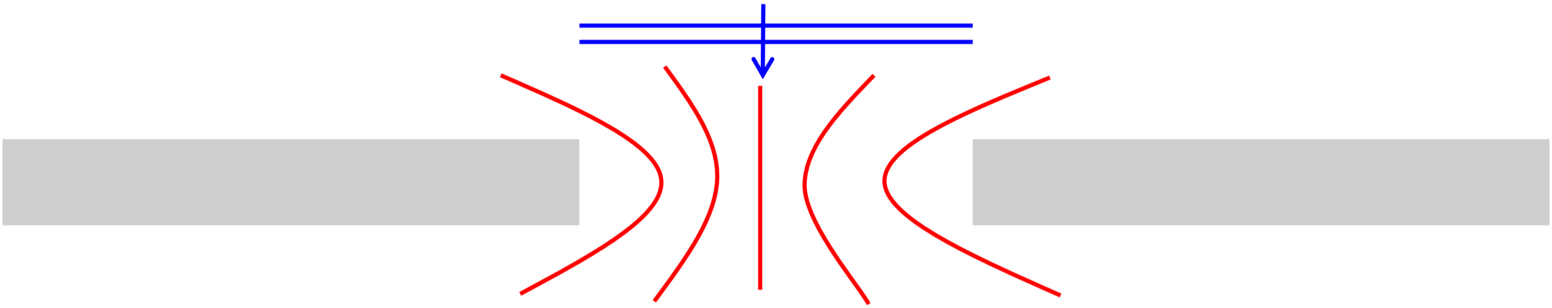
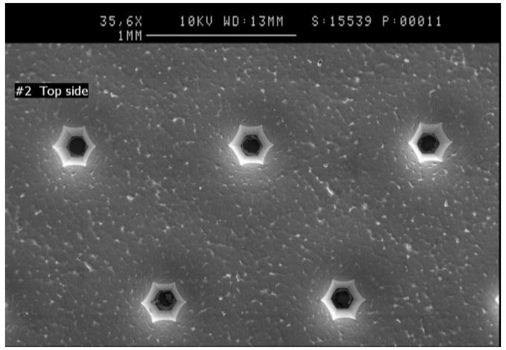
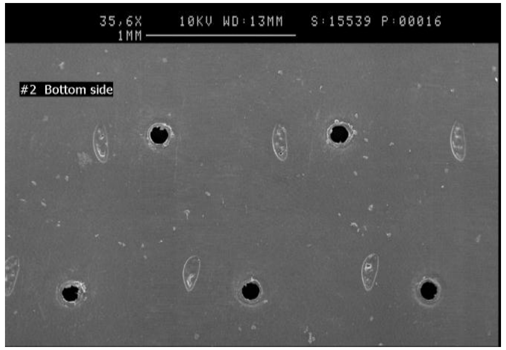
Introduction

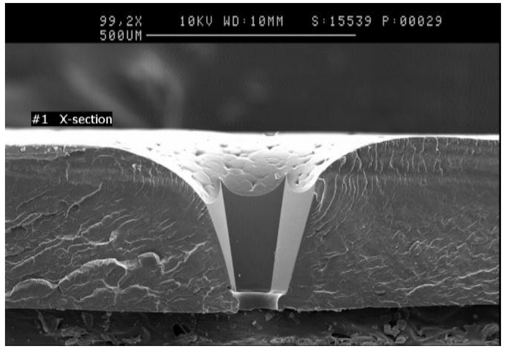
- ❖ Microperforated Panel:
  Thin film with 100 microns scale holes



- ❖ Clean, light → an alternative to fibrous sound absorbing material







Introduction

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inter.noise 2015
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❖ Acoustic Properties are controlled by:

1. Thickness of the panel
2. Diameter of the hole
3. Porosity
4. Mass per unit area
5. Air cavity depth

❖ By appropriate choice of these parameters, single panel can provide good acoustic performance in one or two octave band, but not in broader range.

➡ Multiple-Layer Microperforated Panels are needed to cover broad frequency range

❖ Duct liner composed of multi-layer microperforated panels can be one solution to reduce noise from a duct.

Microperforated Panel

❖ Cylindrical hole (Maa (1975,1987,1998,1999))

$$z = \frac{j\omega t}{\sigma c}\left[1 - \frac{2}{x\sqrt{-j}}\frac{J_1(x\sqrt{-j})}{J_0(x\sqrt{-j})}\right]^{-1}$$

Simplify

$$z = \frac{32\eta t}{d^2}\sqrt{1+\frac{x^2}{32}} + j\omega\rho t\left(1+\frac{1}{\sqrt{3^2+\frac{x^2}{2}}}\right)$$

❑ Resistance End Correction Factor

1975: $\frac{\sqrt{2}}{8}x\frac{d}{t}$ 1987: $\frac{\sqrt{2xd}}{8t}$ 1998, 1999: $\frac{\sqrt{2}}{32}x\frac{d}{t}$

❑ Meant to account for resistance exterior to hole

Microperforated Panel

- Cylindrical hole (Guo *et al.* (2008))
  - Complete Resistance

Cylinder | Surface

$$R = \left(Re\left\{ \frac{j\omega t}{\sigma c}\left[1 - \frac{2}{k\sqrt{-j}}\frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})}\right]^{-1} \right\} + \frac{\alpha 2R_s}{\sigma\rho c} \right) \times \rho c$$

$$k = d\sqrt{\frac{\omega\rho_0}{4\eta}} \qquad R_s = \frac{\sqrt{2\omega\rho_0\eta}}{2}$$

$\alpha = 2$ when round-edged

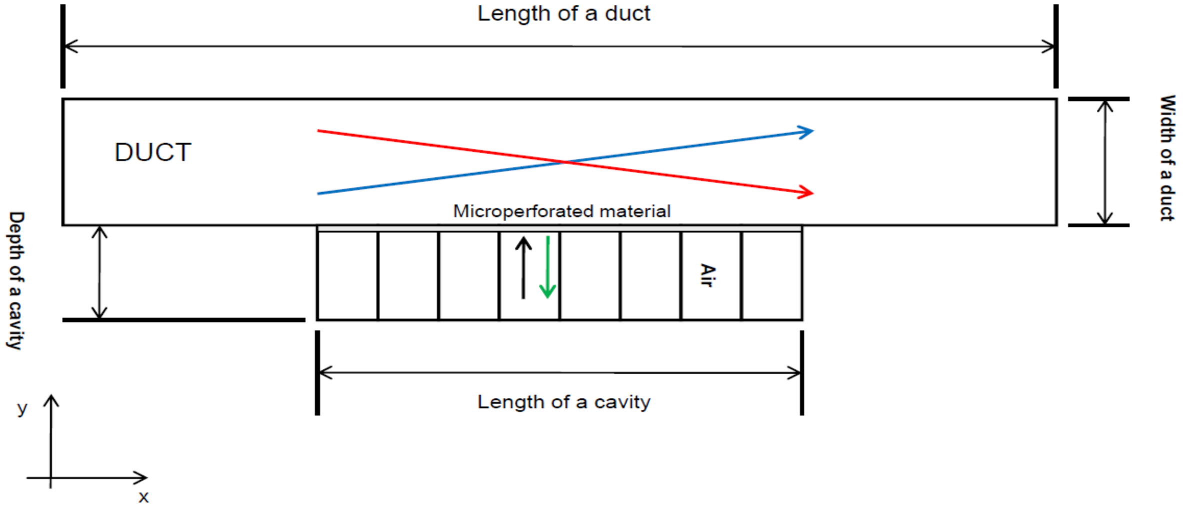
$\alpha = 4$ when sharp-edged

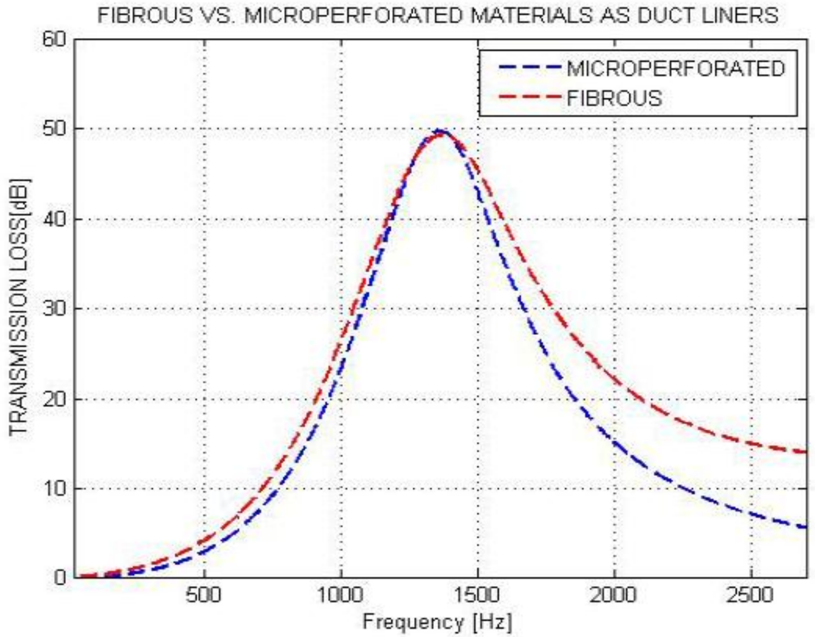
- Previous work (Kim *et al.* (2012))

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

Duct Liner

❖ Square duct(Shin(2011))





- ❑ Desired parameters of microperforated material were obtained to match the impedance of the fibrous material.
- ❑ Locally reacting case outperforms extended reacting case.
- ❑ Microperforated duct liner could be used as an alternative absorbing lining whenever fibrous duct lining is not desired

H. Shin and J. S. Bolton, "Microperforated materials as duct liners: Local reaction versus extended reaction backings", *Proceeding of Noise-Con 2010*, Portland, Oregon, USA, 2010.

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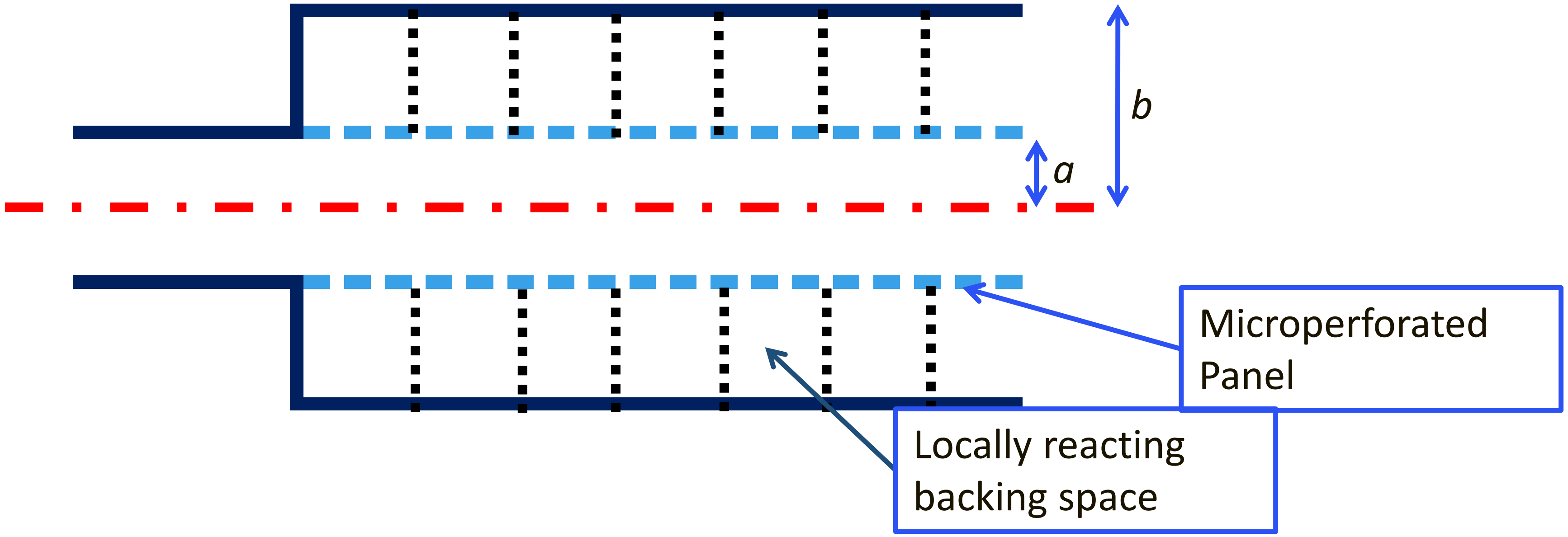
Cylindrical Duct Liner

❖ Microperforated Panel as Duct Liner



- ❑ There is no analytical solution for cylindrical duct liner for microperforated panel.
- ❑ Change to cylindrical coordinate
- ❑ To find surface impedance at the panel, start from Helmholtz equation.

Transfer impedance of flexible microperforated panel

- Resistance of Microperforated panel

$$R = \left(Re\left\{ \frac{j\omega t}{\sigma c}\left[1 - \frac{2}{k\sqrt{-j}}\frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})}\right]^{-1} \right\} + \frac{\alpha 2R_s}{\sigma\rho c} \right) \times \rho c \qquad \alpha = (16.9\frac{t}{d} + 152.8)f^{-0.5}$$

- Continuity and Force equilibrium

$$v_y = (1-\sigma)v_s + \sigma v_f$$

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

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

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

Yoo *et al.*, "Absorption of finite-sized microperforated panels with finite flexural stiffness at normal incidence", *Proceeding of NOISE-CON 2008*, Dearborn, Michigan, USA (2008).

Impedance of air backing space

- Helmholtz Equation

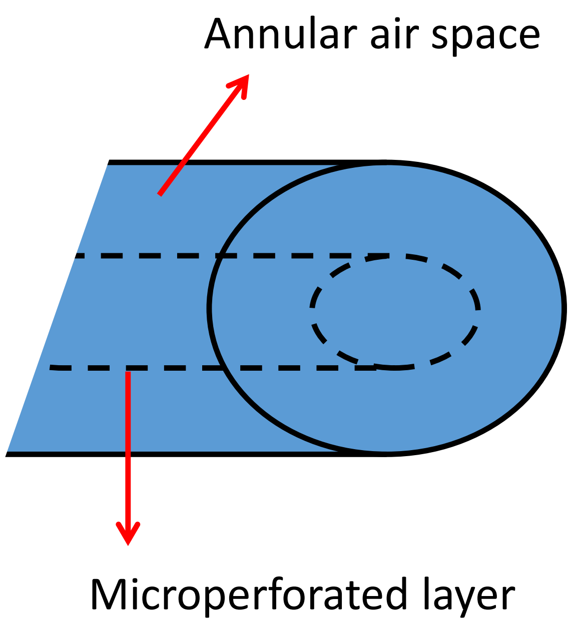
$$(\nabla^2 + k^2)\vec{P}(r,\theta,z) = 0$$

- We can assume that pressure is symmetric in ϑ direction, because we will give plane wave in impedance tube.

$$\vec{P}(\omega,r,z) = \left[AH_0^{(1)}(k_r r) + BH_0^{(2)}(k_r r)\right] e^{j(k_z z-\omega t)}$$

$$\vec{v_r}(\omega,r,z) = \frac{j}{\rho c}\frac{k_r}{k}\left[AH_1^{(1)}(k_r r) + BH_1^{(2)}(k_r r)\right] e^{j(k_z z-\omega t)}$$

$$k^2 = k_r^2 + k_z^2$$

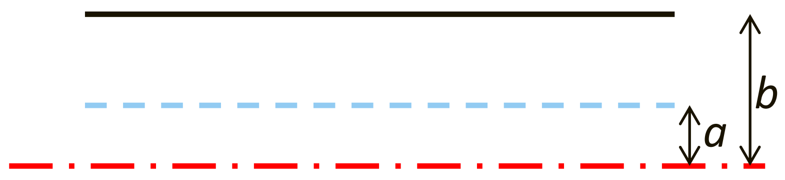


Impedance of air backing space

❖Pressure and Velocity at panel and wall

microperforated panel

duct axis



❖Impedance looking into panel at *r* = *a*

❑at *r* = *a*

$$\overrightarrow{P_a} = \left[AH_0^{(1)}(k_r a) + BH_0^{(2)}(k_r a)\right] e^{j(k_z z - \omega t)}$$

$$\overrightarrow{v_a} = \frac{j}{\rho c}\frac{k_r}{k}\left[AH_1^{(1)}(k_r a) + BH_1^{(2)}(k_r a)\right] e^{j(k_z z - \omega t)}$$

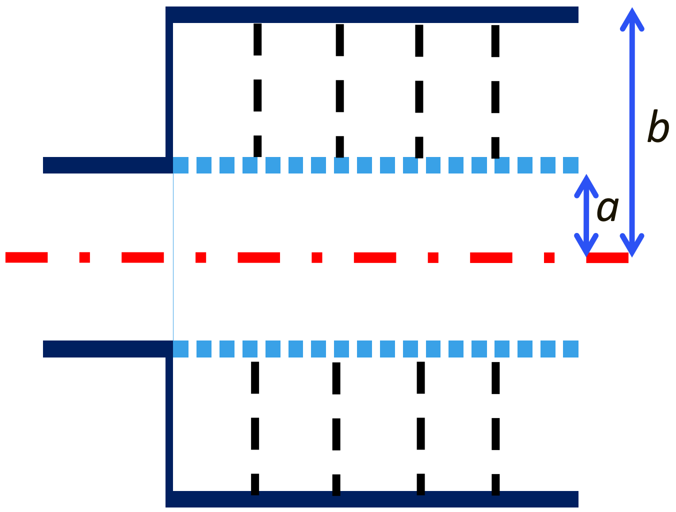
❑at *r* = *b*

$$\overrightarrow{P_b} = \left[AH_0^{(1)}(k_r b) + BH_0^{(2)}(k_r b)\right] e^{j(k_z z - \omega t)}$$

$$\overrightarrow{v_b} = \frac{j}{\rho c}\frac{k_r}{k}\left[AH_1^{(1)}(k_r b) + BH_1^{(2)}(k_r b)\right] e^{j(k_z z - \omega t)}$$

Transfer Matrix Method

❖ Local reaction



$$\begin{bmatrix} P_a \\ v_a \end{bmatrix} = [D] \begin{bmatrix} A \\ B \end{bmatrix} \qquad \begin{bmatrix} P_b \\ v_b \end{bmatrix} = [E] \begin{bmatrix} A \\ B \end{bmatrix} = [E][D]^{-1} \begin{bmatrix} P_a \\ v_a \end{bmatrix}$$

$$[T] = [E][D]^{-1} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}$$

$$T_{11} = -j\frac{\pi}{4} k_r a \left[H_0^{(1)}(k_r b) H_1^{(2)}(k_r a) - H_0^{(2)}(k_r b) H_1^{(1)}(k_r a) \right]$$

$$T_{12} = \frac{\pi}{4} \rho c k a \left[H_0^{(1)}(k_r b) H_0^{(2)}(k_r a) - H_0^{(2)}(k_r b) H_0^{(1)}(k_r a) \right]$$

$$T_{21} = \frac{\pi}{4} \frac{1}{\rho c} \frac{k_r}{k} a \left[H_1^{(1)}(k_r b) H_1^{(2)}(k_r a) - H_1^{(2)}(k_r b) H_1^{(1)}(k_r a) \right]$$

$$T_{22} = -j\frac{\pi}{4} k_r a \left[H_1^{(2)}(k_r b) H_0^{(1)}(k_r a) - H_1^{(1)}(k_r b) H_0^{(2)}(k_r a) \right]$$

Impedance of Duct Liner

❖Impedance of air backing

$$Z_{air} = \frac{T_{11}}{T_{21}} = -j\frac{1}{\rho c}\frac{k_r}{k}\left[\frac{H_0^{(1)}(k_r b)H_1^{(2)}(k_r a) - H_0^{(2)}(k_r b)H_1^{(1)}(k_r a)}{H_1^{(1)}(k_r b)H_1^{(2)}(k_r a) - H_1^{(2)}(k_r b)H_1^{(1)}(k_r a)}\right]$$

❖ Surface Impedance and B.C. at the Panel

$$Z_n = (Z_{air} + Z_{MPP})/\rho c \qquad \frac{jka}{Z_n} = m - \frac{k_r a J_{m-1}(k_r a)}{J_m(k_r a)}$$

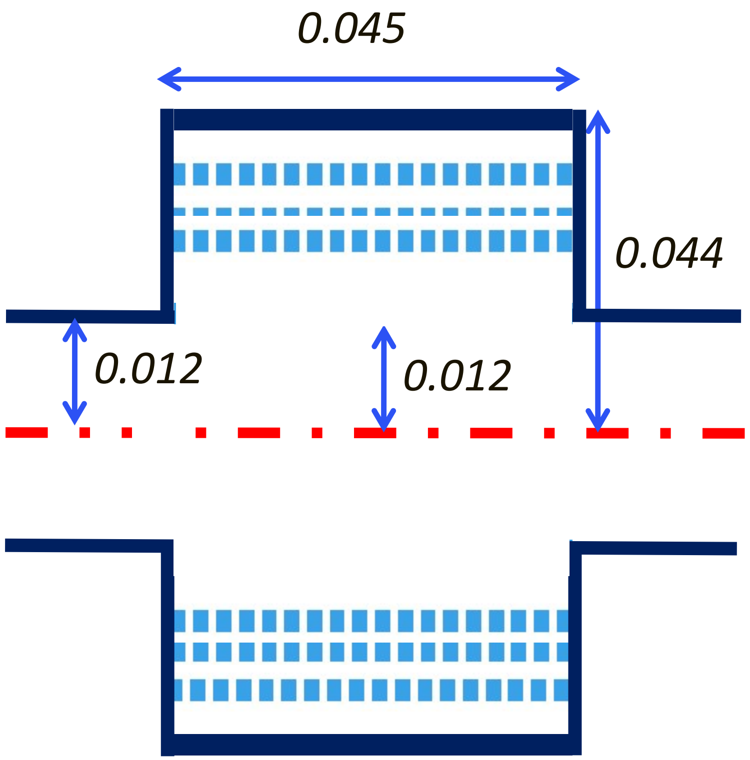
Combine these two equations and solve k_r by secant method

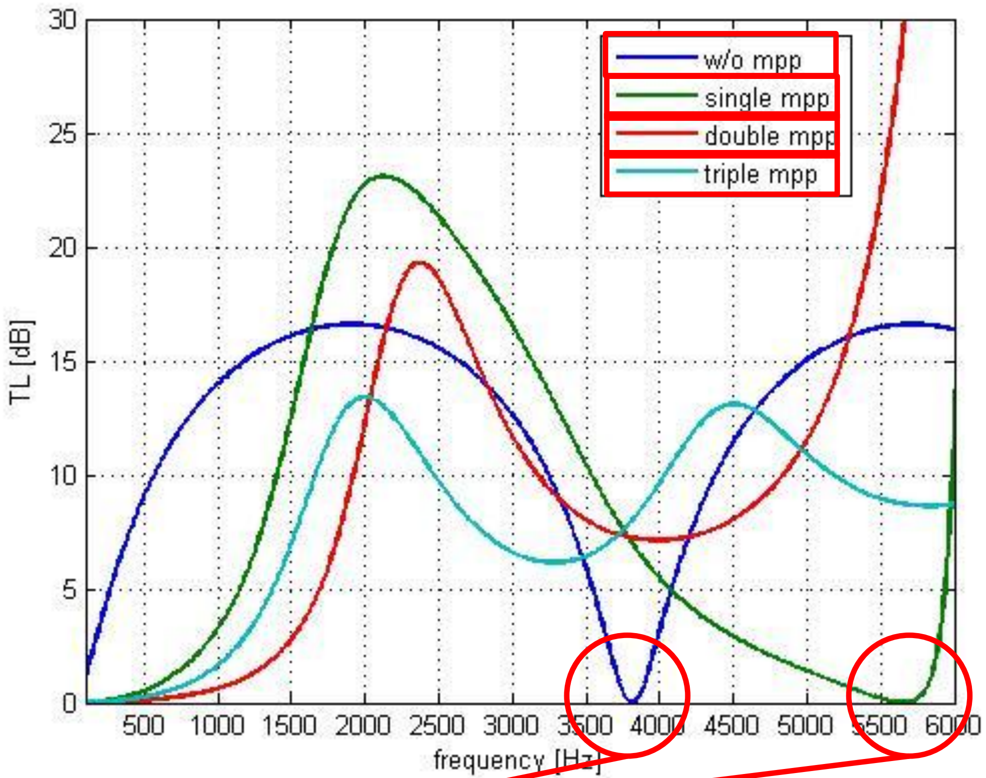
❖ Transmission Loss per meter along duct

$$k_z = \sqrt{k^2 - k_r^2} = \beta - j\alpha \qquad TL = -20\log(1/e^{\alpha})$$

Cylindrical Duct Liner

❖ Microperforated Panel as Duct Liner



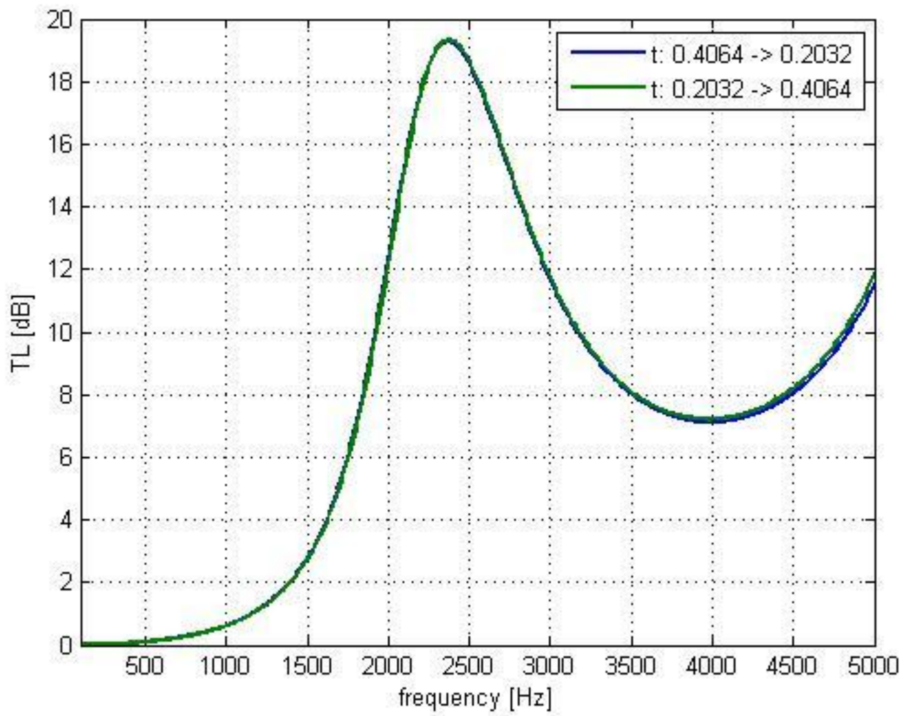


We can avoid critical point by multilayer duct liner without making muffler size bigger.

Cylindrical Duct Liner

❖Double MPPs

- ❑ 1st MPP : t=0.4064 mm, d=0.2032 mm, σ=0.02, m=0.5 kg/m^2
- ❑ 2nd MPP: t=0.2032 mm, d=0.2032 mm, σ=0.02, m=0.5 kg/m^2

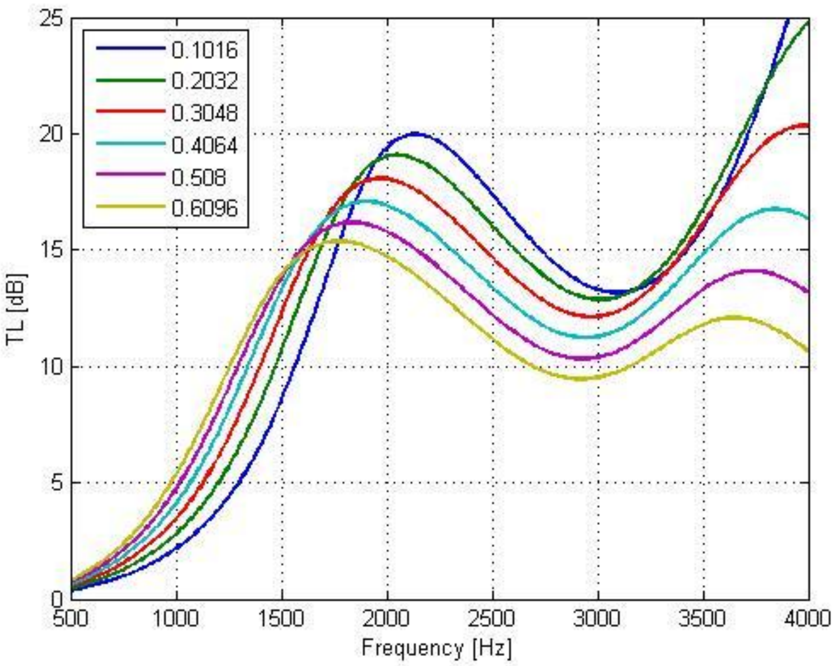


- ❑ Switch the location 1st MPP and 2nd MPP does not give any effect on TL

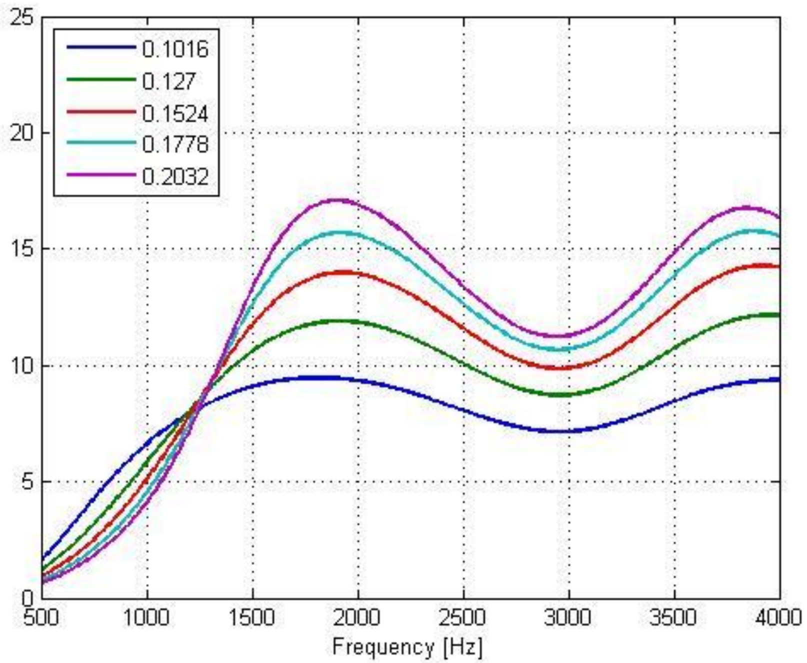
Cylindrical Duct Liner

❖Double MPPs

❖1st MPP : t=0.4064 mm, d=0.2032 mm, σ=0.02, m=0.5 kg/m^2



Change of thickness



Change of diameter

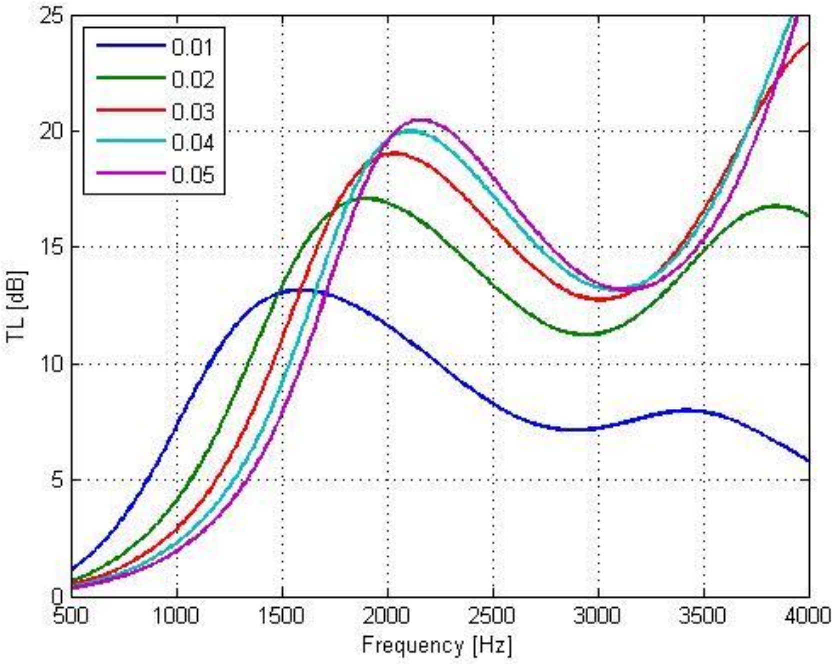
❑As the panel becomes thicker, TL decreases.

❑As diameter of the hole become larger, TL increases.

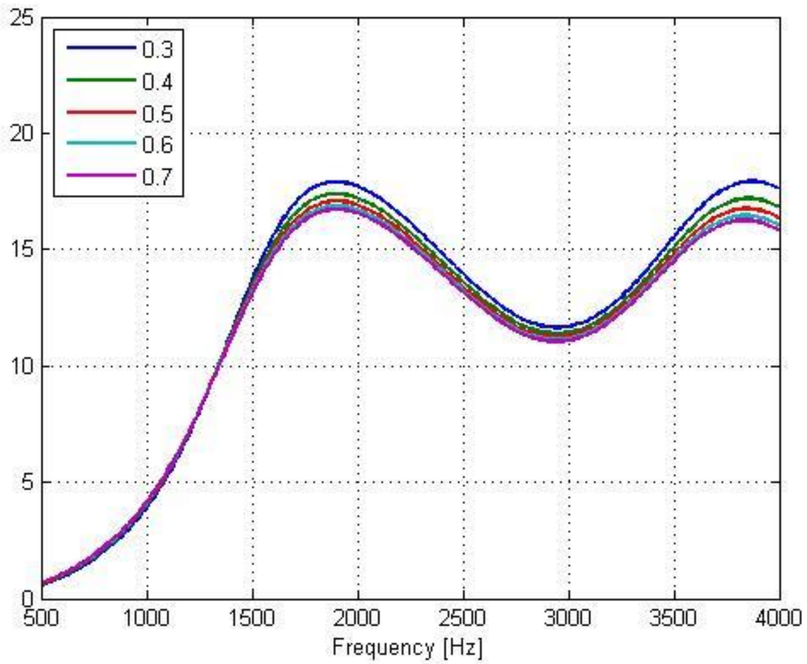
Cylindrical Duct Liner

❖Double MPPs

❖1st MPP : t=0.4064 mm, d=0.2032 mm, σ=0.02, m=0.5 kg/m^2



Change of porosity

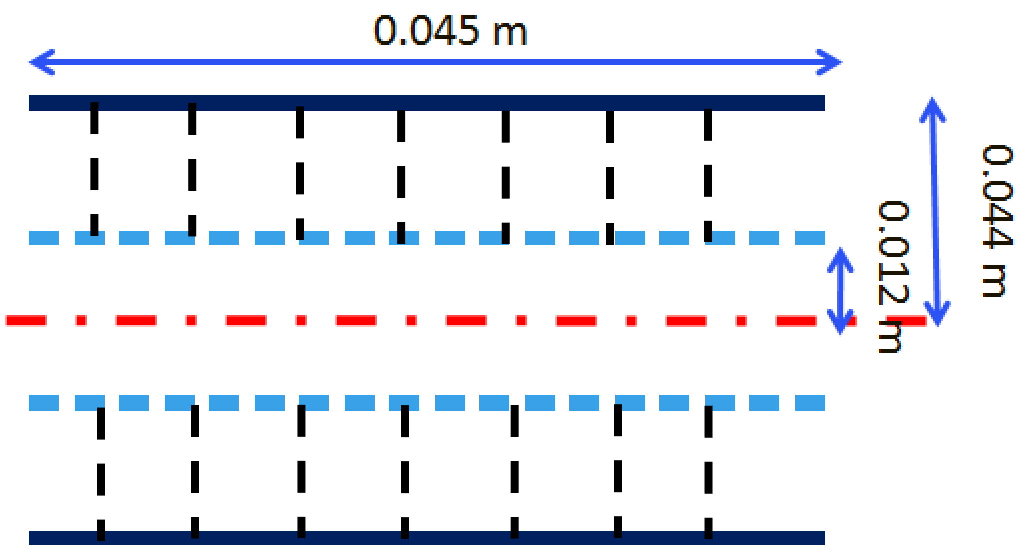


Change of mass per unit area

❑As porosity increase, TL goes increases.

❑As the panel becomes heavier, TL increases.

Optimization



❖ Assumptions
- ❑ Geometry of duct: radius = 0.012 m, expanded radius: 0.044 m
- ❑ Hole of the MPP is cylindrical and sharp edged.
- ❑ Flexural stiffness of the panel can be ignored.
- ❑ Only locally reaction case considered.
- ❑ First MPP layer is fixed at 0.012 m from center of duct

Optimization

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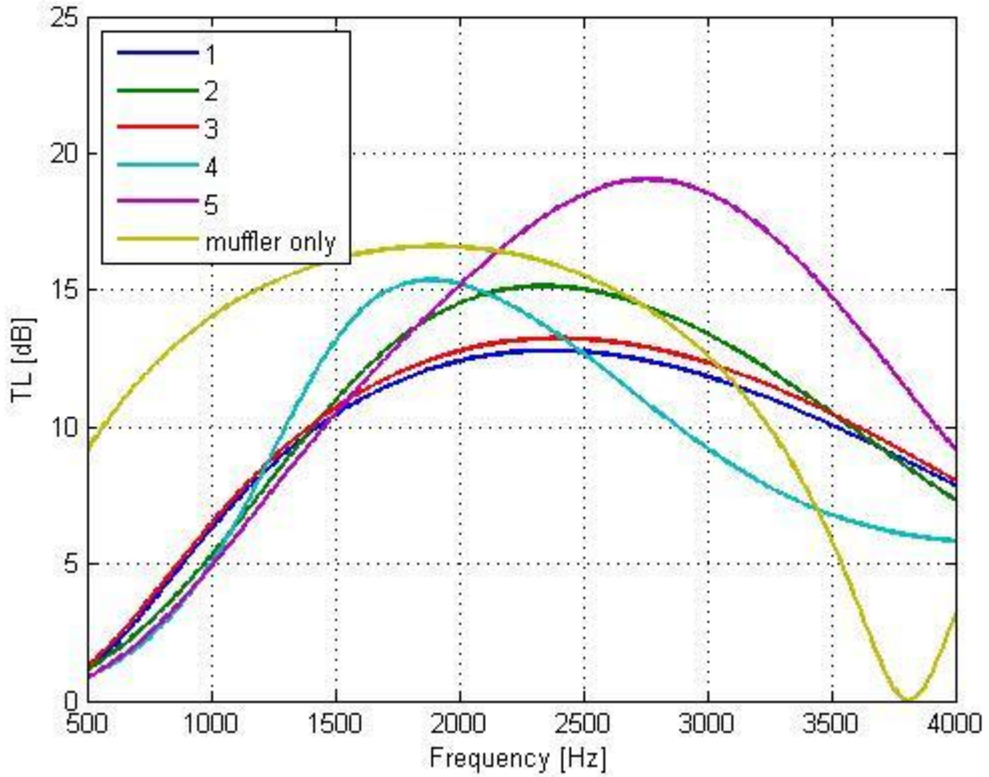
❖ Constraints

	Minimum	**Maximum**
N	1	5
t [mm]	0.2	0.8
d [mm]	0.1	0.3
σ	0.01	0.2
m [kg/m^2]	0.1	0.8
l [m]	0.001	0.2

❖ Genetic Algorithm was used for optimization

Optimization result

❖ Increasing number of layers



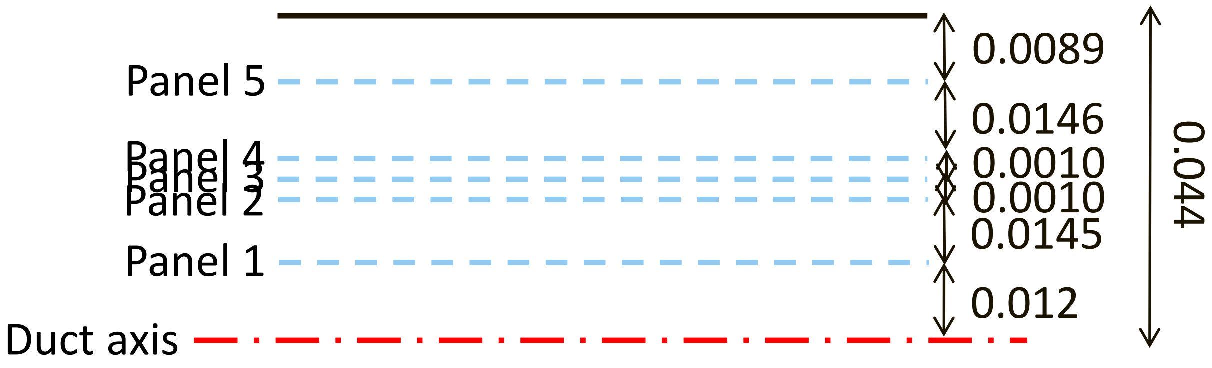
❖ Muffler only case is the best in low frequency range (500 – 2000 Hz) but there is resonance frequency at 3800 Hz.

❖ Duct with duct liner case can remove resonance frequency.

Optimization result

❖ Microperforated panel properties for 5 panel duct liner

	t [mm]	d [mm]	σ	m [kg/m^2]	l [m]
Panel 1	0.2191	0.1000	0.1625	0.31028	0.0145
Panel 2	0.2000	0.1000	0.0101	0.6	0.0010
Panel 3	0.2000	0.3000	0.0842	0.3	0.0010
Panel 4	0.2000	0.3000	0.0110	0.3	0.0146
Panel 5	0.2000	0.3000	0.2000	0.3	0.0089



Conclusion

- The performance of a microperforated panel is determined by the radius of hole, thickness, porosity, mass per unit area, and air cavity depth.

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

- Optimization result shows that appropriate combination of microperforated panel can eliminate the resonance frequency in range of interest

- Optimal design for cylindrical duct liner can help reduce size of muffler

- Future work: extend to extended reaction case