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Study of the Effect of Grazing Flow on the Performance of Microperforated and Perforated Panels

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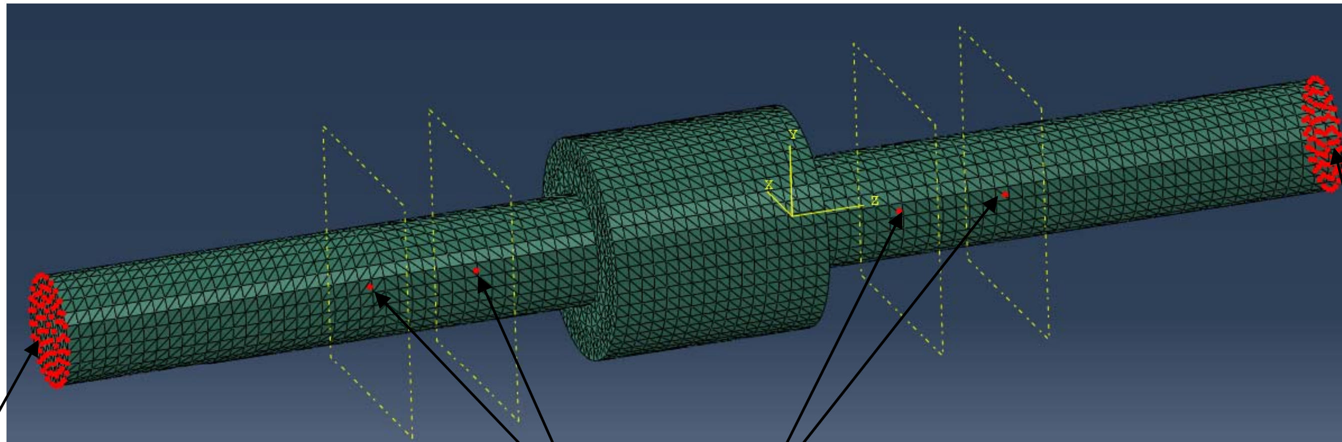
Simple Expansion Chamber FEM model



Inlet (unit pressure)

Microphone positions

Anechoic termination
(Characteristic Z)

<u>Analysis Details:</u>

- Commercial Finite Element code ABAQUS is used.
- Domain discretization with Acoustic Elements (AC3D4)
- Steady State Dynamic analysis with complex response output
- The real and imaginary part of pressure data in the frequency domain is post-processed to obtain the Transmission Loss (TL)

MPP as an equivalent porous material

The perforated facings are modeled as porous media composed of identical cylindrical perforations of circular cross-section. The equivalent acoustical parameters are:

Complex Density (Johnson et al.)

$$\tilde{\rho}_{cs}(\omega) = \frac{\alpha_\infty \rho_0}{\phi}\left[1 - \frac{j\sigma\phi}{\omega\rho_0\alpha_\infty}\sqrt{1 + \frac{j4\alpha_\infty^2\eta\rho_0\omega}{\sigma^2\Lambda^2\phi^2}}\right]$$

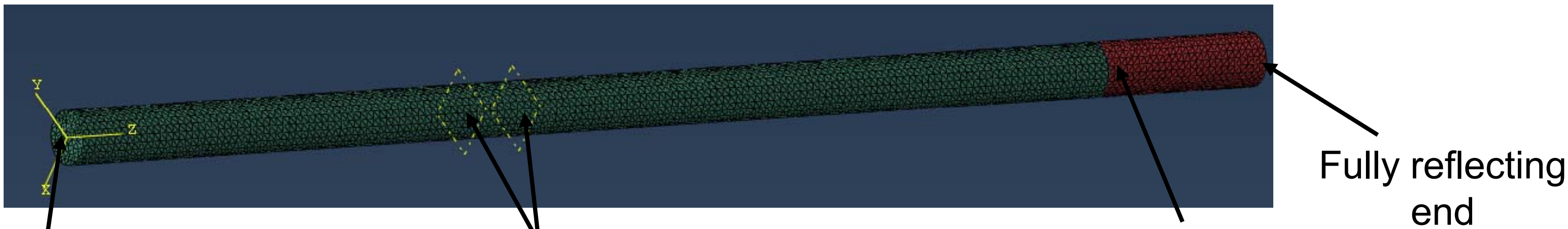
Complex Bulk Modulus (Champoux and Allard)

$$\tilde{K}(\omega) = \frac{\gamma P_0/\phi}{\gamma - (\gamma - 1)\left[1 - \frac{j8\kappa}{\Lambda'^2 C_p \rho_0 \omega}\sqrt{1 + \frac{j\Lambda'^2 C_p \rho_0 \omega}{16\kappa}}\right]^{-1}}$$

Jaouen and Bécot followed this approach by characterizing the radius of the perforations and the perforation rate as the acoustical parameters.

Absorption Coefficient Correlation of FEM results with Jaouen and Bécot results

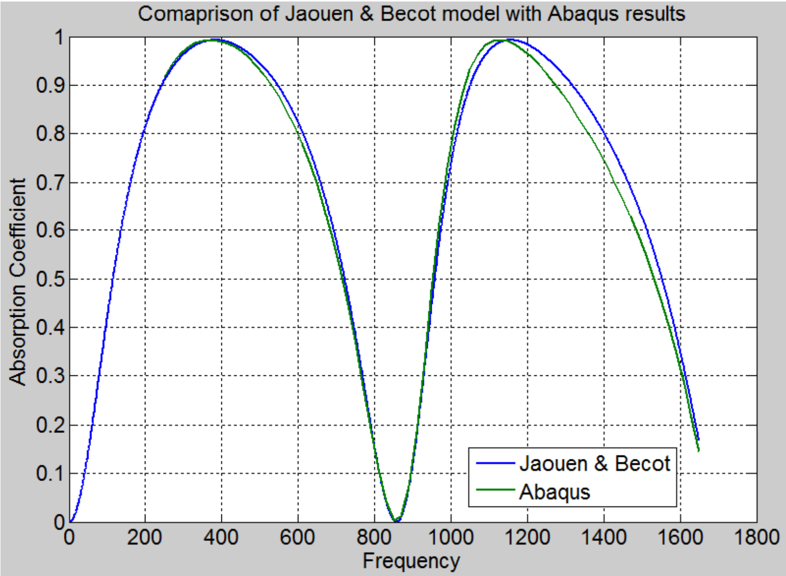
MPP with 200 mm cavity backing



Tie constraints is used to connect the dissimilar MPP and Impedance tube meshes.

<u>MPP properties:</u>

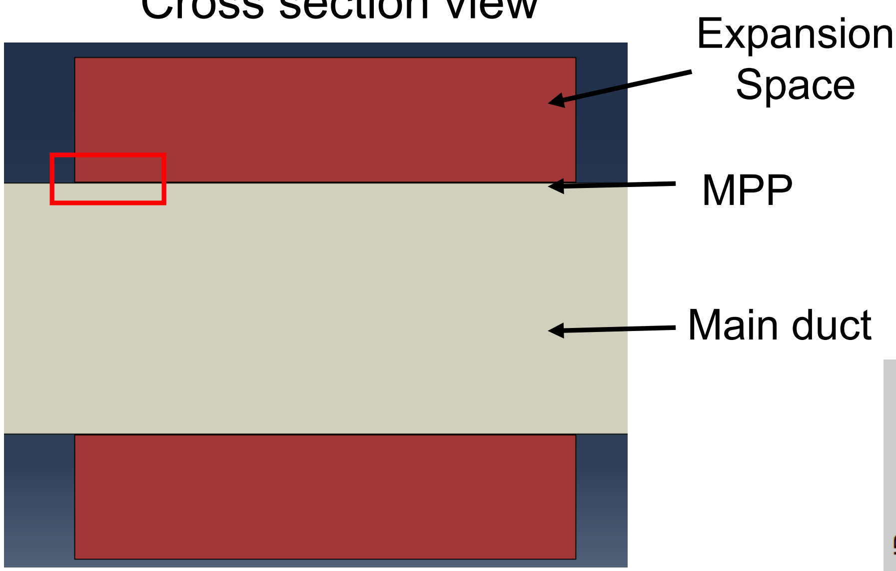
Porosity = 1.8%
Thickness = 0.35 mm
Flow resistivity = 1.41×10^{6} N·s·m^{-3}
Perforation hole radius = 7.61×10^{-5} m



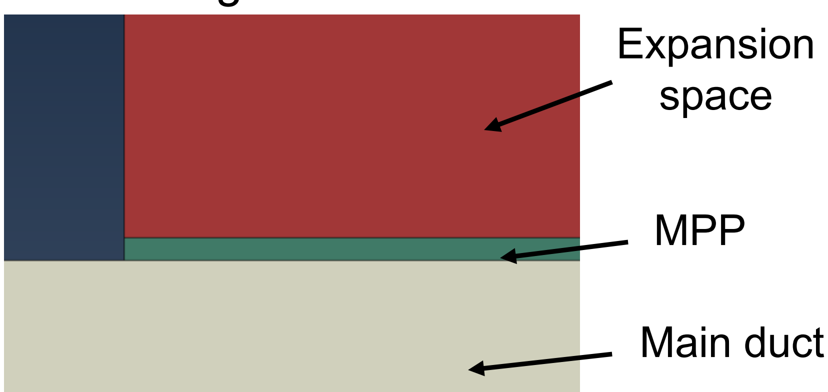
MPP can be modeled effectively in Finite Element Methods by using the equivalent porous material Johnson-Champoux-Allard (JCA) model.

Transmission Loss of Expansion Chamber with MPP

Cross section view

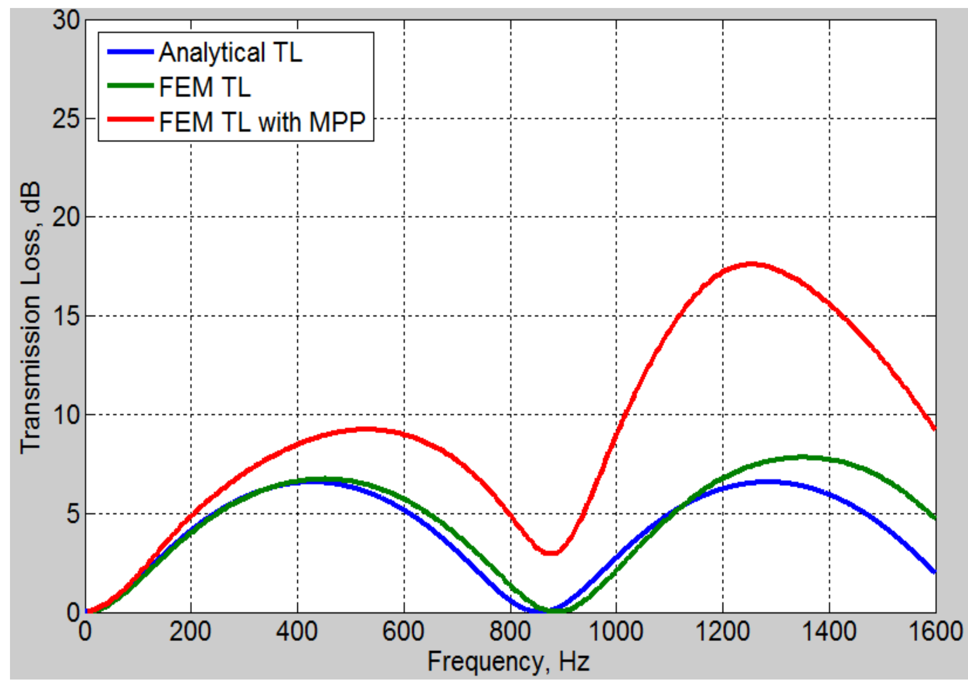


Magnified view



<u>Expansion Chamber:</u>

Expansion ratio = 4
Expansion length = 0.2 m
Inlet & Outlet diameter = 0.1 m



Effect of grazing flow on MPP and PP properties

Resistance and Reactance of MPP with corrections due to grazing flow

The normalized resistance and reactance for circular holed plates (Guo)

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

$$\chi_c = \mathrm{Im}\left(\frac{j\omega t}{\sigma}\left[1-\frac{2}{k\sqrt{-j}}\frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})}\right]^{-1}\right)+\frac{\delta\omega}{\sigma c}$$

where $k = d\sqrt{\omega/4\nu}$ (dimensionless shear wave number)

$R_s = 0.5\sqrt{2\eta\rho\omega}$ (surface resistance)

Corrections due to grazing flow

Resistance additive correction = (constant)(M/ σ)

Rice suggested a value of 0.30 for the constant while Elnady suggests a value of 0.50, and Munjal suggested 0.53. The value suggested by Munjal is used here.

Reactance subtractive correction = $\delta/(1+305M^3)$

δ is the mass end correction given by (0.85*d*) where *d* is the diameter of hole.

Resistance and Reactance of PP with the effect of grazing flow

Munjal proposed the following equations as a general empirical formula for the resistance and reactance terms of the impedance of the perforated panel by including the effects of the thickness, hole diameter, porosity and grazing flow.

$$R = 7.337 \times 10^{-3} (1 + 72.23M) / \sigma$$

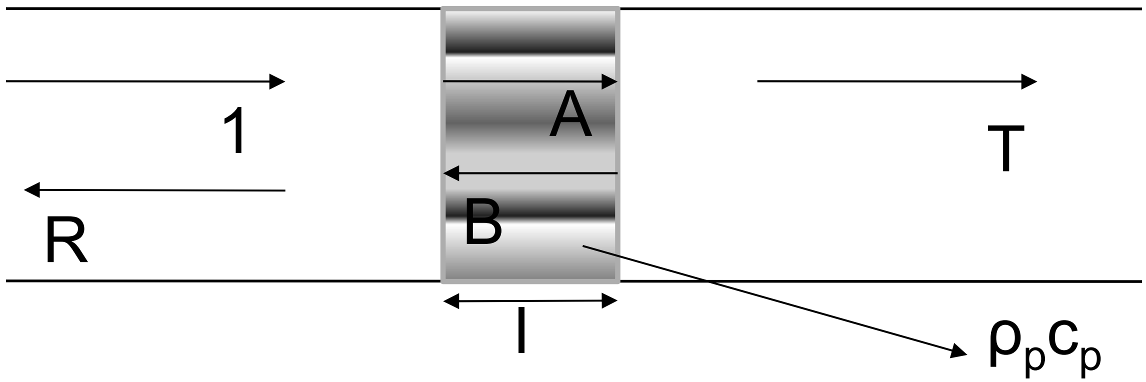
$$X = [2.2245 \times 10^{-5} f (1 + 51.0t)(1.0 + 204.0d_h)] / \sigma$$

where M is the grazing flow Mach number, σ is the porosity, f is the frequency in Hz, t is the thickness of the perforated plate in m, and d_h is the diameter of the holes in m.

<u>Validity range:</u>

$0.05 \le M \le 0.2$; $0.03 \le \sigma \le 0.1$; $1 \le t \le 3$ mm; $1.75 \le d_h \le 7$ mm.

Formulation of MPP and PP properties from impedance data



By using plane wave theory, the Reflection and Transmission Coefficients are:

$$R = \frac{j\left(\frac{\rho_p c_p}{\rho c} - \frac{\rho c}{\rho_p c_p}\right)\sin k_p l}{2\cos k_p l + j\left(\frac{\rho_p c_p}{\rho c} + \frac{\rho c}{\rho_p c_p}\right)\sin k_p l}$$

$$T = \frac{2e^{jkl}}{2\cos k_p l + j\left(\frac{\rho_p c_p}{\rho c} + \frac{\rho c}{\rho_p c_p}\right)\sin k_p l}$$

Four pole parameters in terms of R and T coefficients

For an acoustical element in a duct, the transmission and reflection coefficients in terms of four pole parameters are:

$$T = \frac{2e^{jkd}}{T_{11} + \frac{T_{12}}{\rho_0 c} + \rho_0 c T_{21} + T_{22}} \qquad R = \frac{T_{11} + \frac{T_{12}}{\rho_0 c} - \rho_0 c T_{21} - T_{22}}{T_{11} + \frac{T_{12}}{\rho_0 c} + \rho_0 c T_{21} + T_{22}}$$

Symmetry and reciprocity properties give:

$$\begin{aligned} T_{11} &= T_{22} \\ T_{11}T_{22} - T_{12}T_{21} &= 1 \end{aligned} \quad \Rightarrow T_{11} = T_{22} = \sqrt{1 + T_{12}T_{21}}$$

By manipulating equations for *T* and *R*, the two unknown four pole parameters T_{12} and T_{21} can be expressed in terms of *T* and *R* as shown:

$$T_{12} = \frac{T(\rho c)}{2e^{jkd}}\left[\frac{(R+1)^2 e^{2jkd}}{T^2} - 1\right] \qquad T_{21} = \frac{1}{2T(\rho c)}\left[(R-1)^2 e^{jkd} - \frac{T^2}{e^{jkd}}\right]$$

FEM Acoustical material properties from four pole parameters

The Complex wave number and Complex characteristic Impedance can be found by:

$$k_p = \frac{1}{t}\cos^{-1}(T_{11}) \qquad Z_p = \sqrt{\frac{T_{12}}{T_{21}}}$$

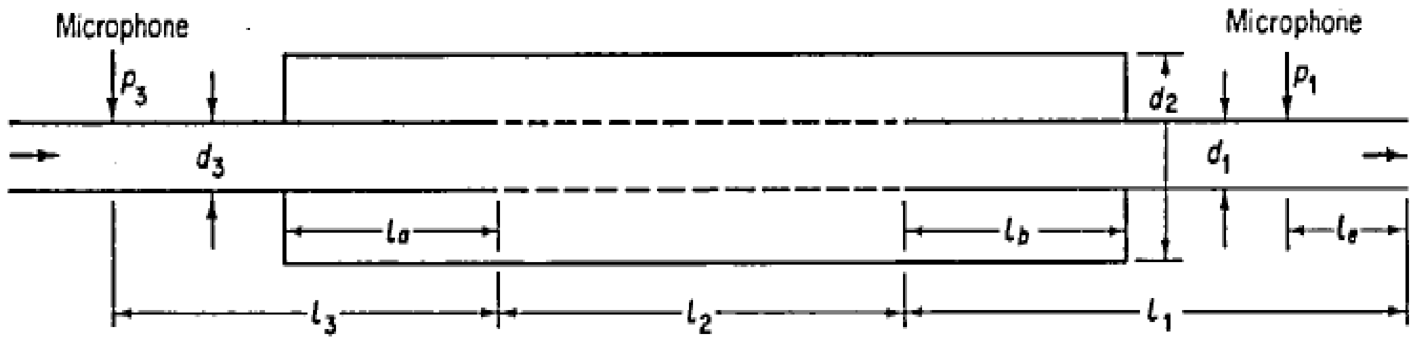
The Complex Density and Complex Bulk Modulus can then be found by:

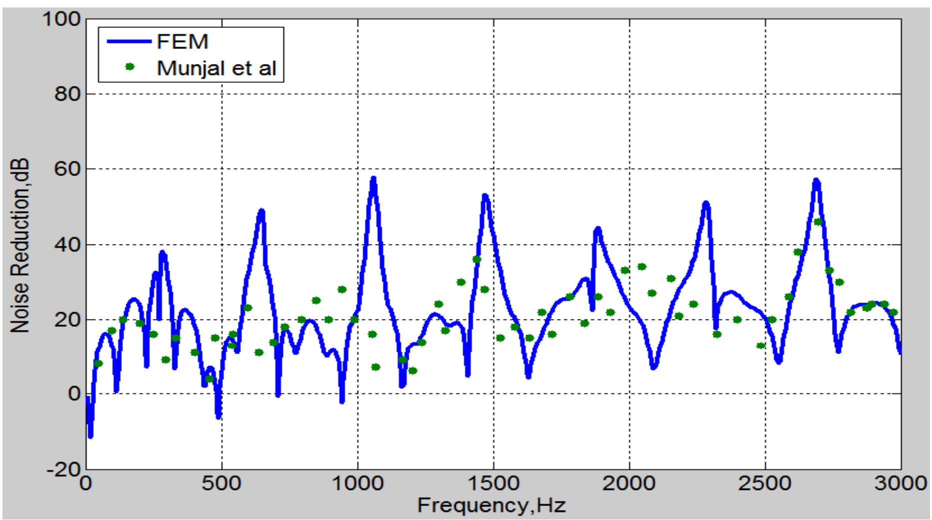
$$\rho_p = \frac{k_p Z_p}{\omega} \qquad \mathrm{K}_p = \frac{\omega Z_p}{k_p}$$

These properties are used to model MPP and PP with grazing flow effects in FEM.

Correlation of Noise Reduction for PP with Grazing flow

Noise reduction of an extended inlet and outlet muffler based on a case described by Munjal. The muffler was tested with a mean flow of $M = 0.2$.



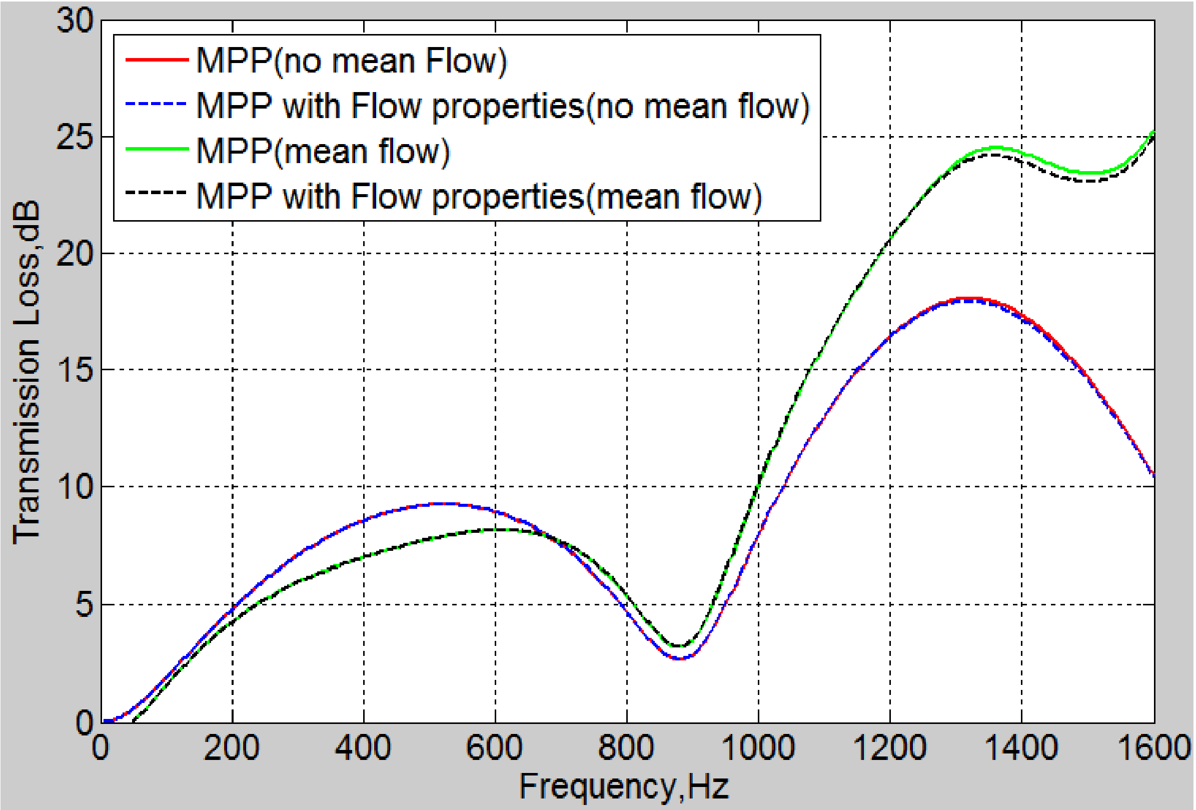


Dimensions:

L_1 = 982 mm
L_2 =750 mm
L_3 = 700 mm
$d_1 = d_3$ =43.5 mm
d_2 = 129.4 mm
$l_a = l_b$ = 400 mm
l_c = 282 mm
Porosity = 3.87%

The deviations may be due to the fact that the FEM model does not take into account the flow noise that occurred during the experiment.

Effect of mean flow and grazing flow on MPP properties



MPP properties:

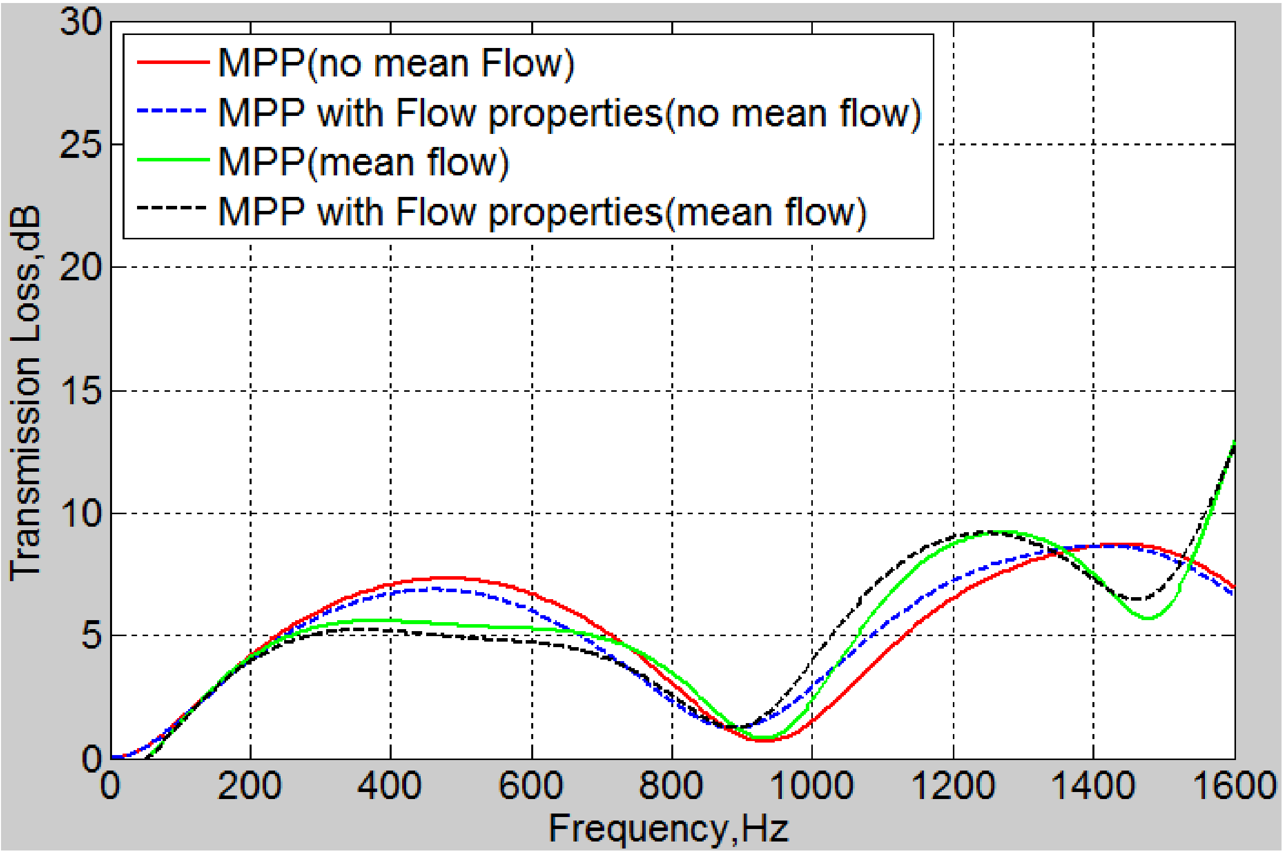
- Porosity = 1.8%
- Thickness = 0.35 mm
- Perforation hole radius = 7.61×10^{-5} m

Flow properties:

- Mach number = 0.2

The effect of grazing flow on MPP properties is negligible. The TL with no flow MPP properties derived from impedance using the relations presented is similar to TL predicted using the JCA model. This corroborates the validity of the formulation.

Effect of mean flow and grazing flow on PP properties



PP properties:

- Porosity = 4.12 %
- Thickness = 1.59 mm
- Perforation hole radius = 1.75 mm

Flow properties:

- Mach number = 0.2

It can be seen that grazing flow has considerable effect on the properties of PP and thereby affects the Transmission Loss performance of PP.

Conclusions

- Perforated and microperforated elements of muffler systems can be modeled as equivalent porous regions
- The effect of grazing flow on perforated sheets is known and can be incorporated into expressions for the transfer impedance of the elements
- From the transfer impedances including flow effects, the characteristic impedance and wave number of the equivalent porous layer can be deduced
- Those values may then be used to model the effect of flow on the performance of perforated muffler elements
- At the low Mach numbers typical of automotive HVAC systems, the effect of flow on the transfer impedance of microperforated elements is negligible
- Flow has some effect on the transfer impedance of perforated elements
- The major effect of flow at low Mach numbers results from the altered wavelengths in the up and downstream directions

Questions?