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Design of an Acoustic Silencer with Microperforated Elements Considering Flow Effects

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INTER-NOISE 15, SAN FRANCISCO, USA
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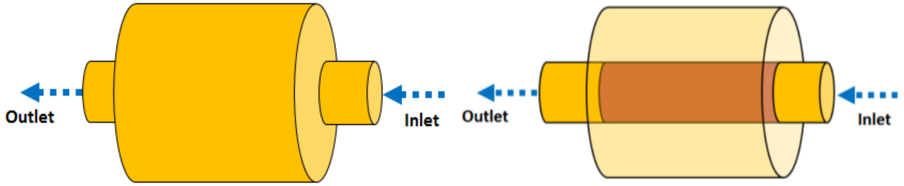
Acknowledgement

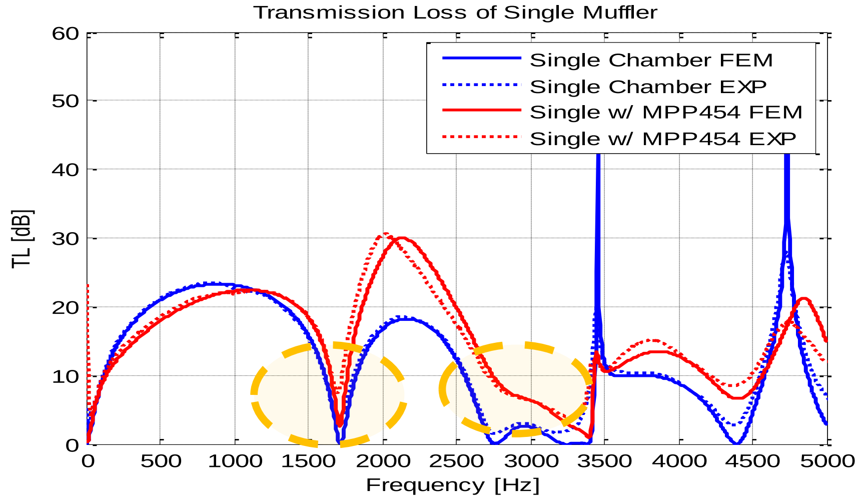
- **3M Company, USA**

  - **The authors acknowledge the support of 3M Corporation through the provision of materials for the fan noise experiments and for the financial support of this work.**

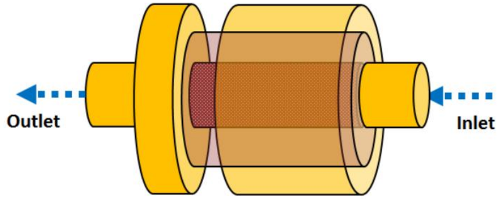
Previous work (Presented at Noise Con 2014)

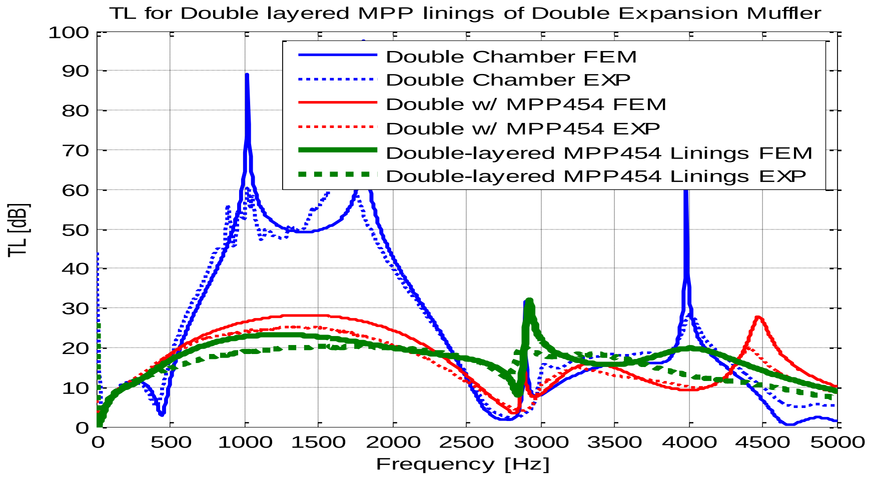
- A cylindrical MPP lining has beneficial effects in reducing the minima in the transmission loss of an expansion muffler.





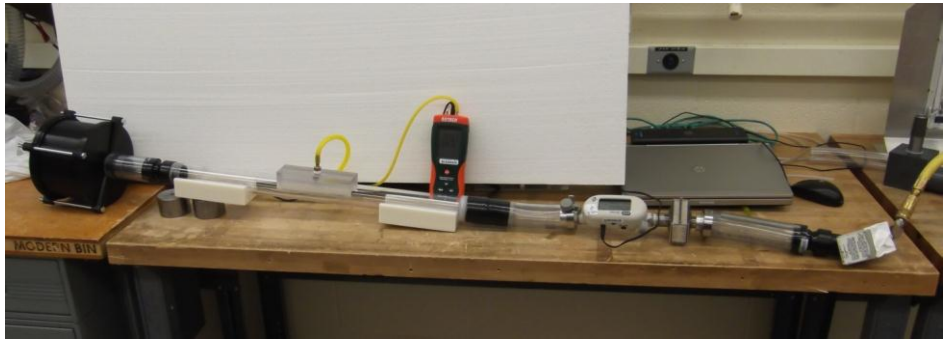
- Dual chamber muffler with double-MPP lining showed flat TL curve of the muffler over the speech interference range.

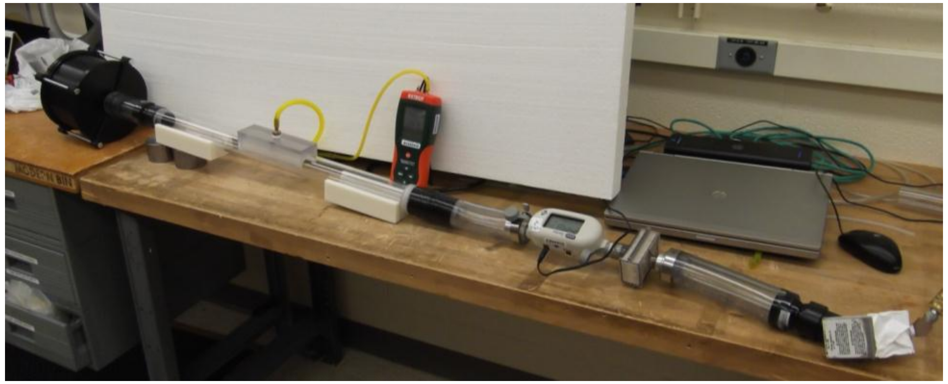


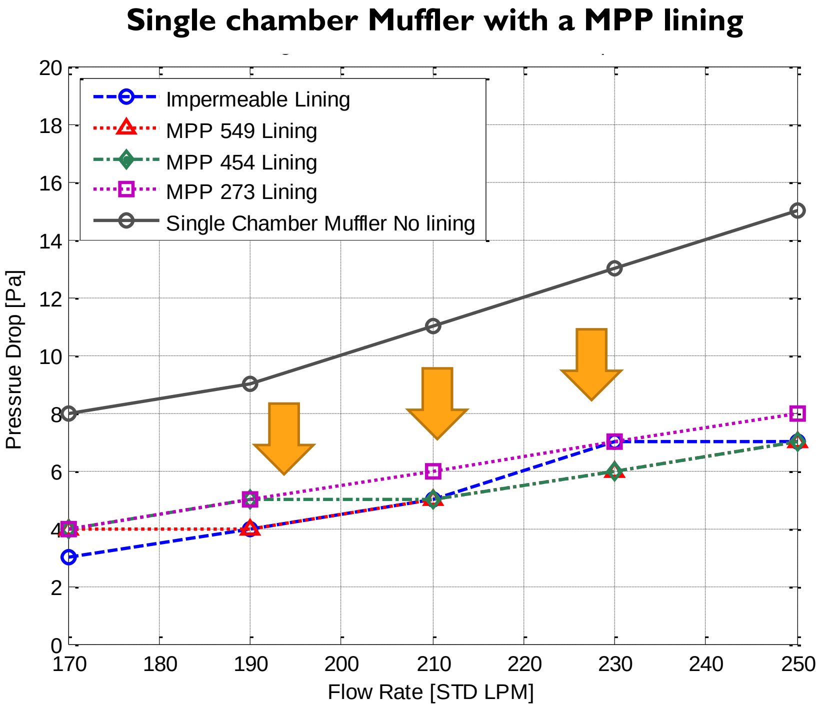


Previous work (Presented at Noise Con 2014)

- MPP linings in the muffler system were not only advantageous in reduction of minima in the transmission loss curve but also have beneficial effects in improvement of pressure drop.







Present Objective

- ❑ Develop an acoustic silencer that can attenuate sound efficiently over the speech interference range (400 – 4000 Hz) using Microperforated Panels (MPPs) and considering flow effects.
- ❑ Internal structural design: Inlet/outlet extensions, multiple chambers

Muffler Design considering flow effect procedure

1. TL Measurement of MPP liner

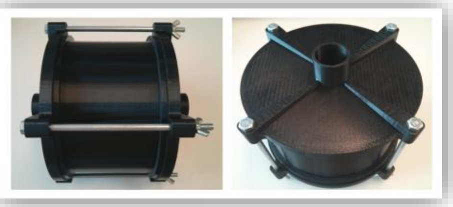
- TL measurement of MPP liner considering flow effect using the standing wave tube.

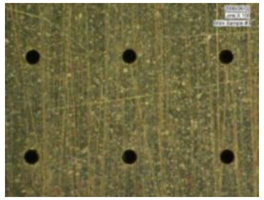
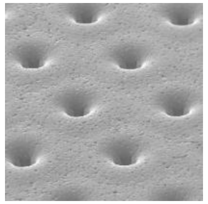
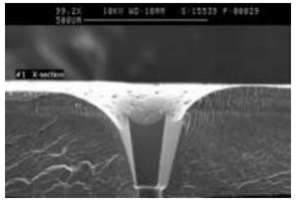
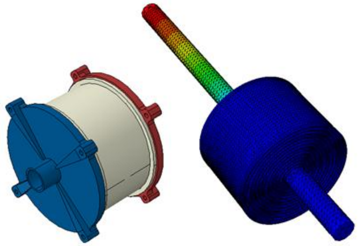
2. Develop FE model of MPP with mean flow effect

- Develop the FE model of MPP and validate with the measured TL

3. Design muffler with validation

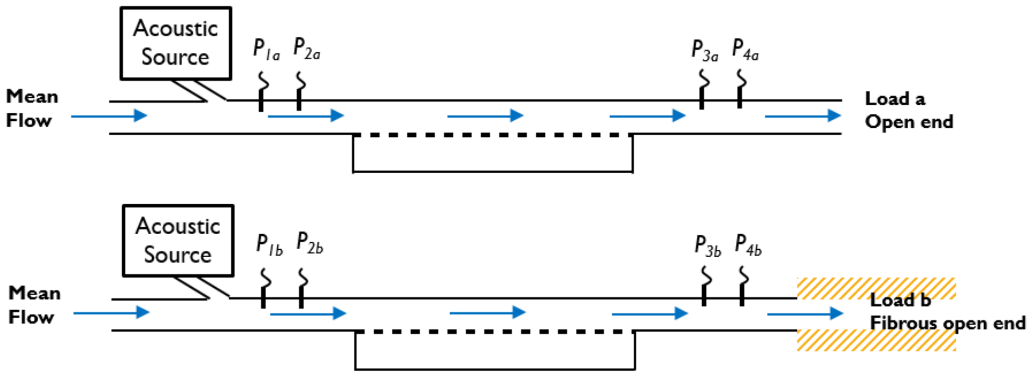
- Create the FE prediction model of muffler and validate with the measured TL



Transmission Loss measurement considering mean flow

❑ 4 – Microphone and 2 – load Method



❑ Transfer Matrix Calculation*

$$\begin{bmatrix} p_{1a} \\ v_{1a} \end{bmatrix} = \begin{bmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{bmatrix} \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} A_{34} & B_{34} \\ C_{34} & D_{34} \end{bmatrix} \begin{bmatrix} p_{4a} \\ p_{4a}/Z_a \end{bmatrix}, \quad \begin{bmatrix} p \\ v \end{bmatrix}_{z=0} = e^{-jMk_c l} \begin{bmatrix} \cos k_c l & jY \sin k_c l \\ (j/Y)\sin k_c l & \cos k_c l \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}_{z=l}$$

$$Y = Y_0 \left\{ 1 - \frac{\alpha(M)}{k_0} + j\frac{\alpha(M)}{k_0} \right\} \qquad k_c = \frac{k_0 - j\alpha(M)}{1 - M^2}$$

$$T_a = \frac{2e^{jkd}}{T_{11} + T_{12}/\rho_0 c + \rho_0 c T_{21} + T_{22}}$$

❑ Transmission Loss

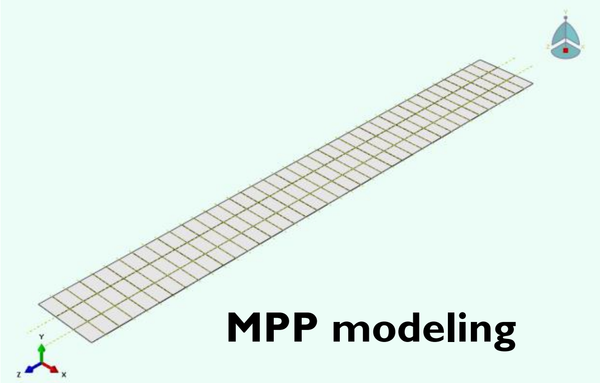
$$TL = 20\log_{10}\left|\frac{1}{T_a}\right|$$

* M. L. Munjal, *Acoustics of Ducts and Mufflers*, WILEY (2014)

Microperforated Panel (MPP) Modeling

❑ Equivalent fluid – JCA model [1,2]

- Complex Density and Bulk Modulus were modeled using following equations
- Calculated properties were implemented in the finite element model of the MPP
- Rigid inclusions to make the MPP locally reacting. *



Complex Density :

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

Complex Bulk Modulus :

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

ϕ: Perforation rate
α: Dynamic Tortuosity
σ: Flow resistivity
η: Dynamic viscosity of air
Λ: Viscous characteristic length
Λ': Thermal characteristic length
$\Lambda = \Lambda' = r$ (radius of perforation)

k: Thermal conductivity
γ: Specific heat ratio of air
P_o: Atmospheric pressure
C_p: Specific heat of air at const. pressure

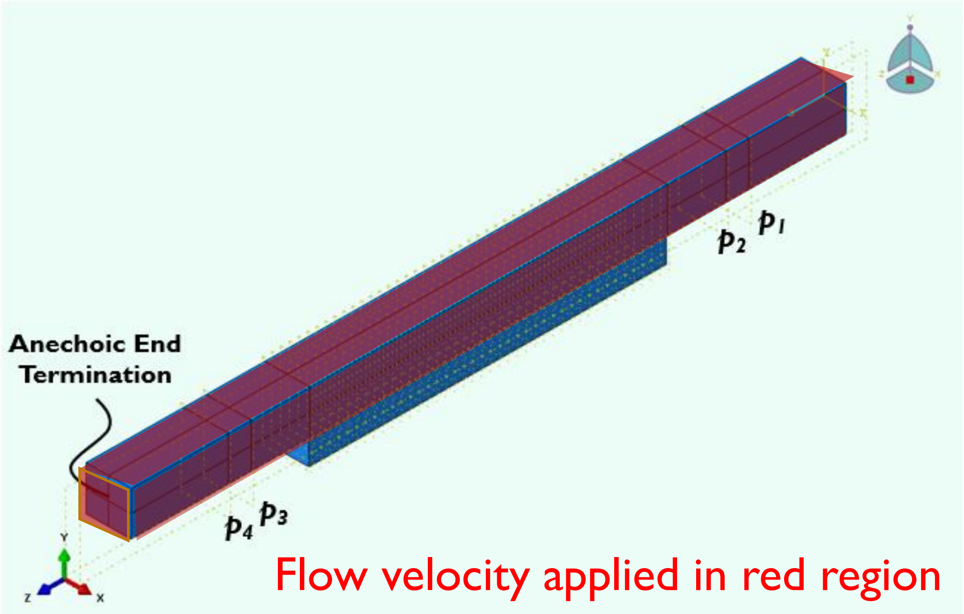
❑ MPP Properties

	MPP 549
Hole diameter [μm]	126.6
Thickness [mm]	0.35
Flow resistance [Rayls]	549

1) Champoux Y. and Allard J.-F., *Dynamic tortuosity and bulk modulus in air-saturated porous media*, J. Appl. Phys. 70, 1991, pp. 1975-1979
2) L. Jaouen and F.-X. Be´cot, "Acoustical characterization of perforated facings", J. Acoust. Soc. Am. 129 (3), March 2011
* S. Lee, J. S. Bolton and P. A. Martinson, "Design of multi-chamber silencers with microperforated elements," NoiseCon 14 Conference Proceedings, Fort Lauderdale, Florida, USA (2014)

Finite Element Model – Flow Effect

- Square cross-section standing wave tube model



Flow velocity applied in red region

- Variational form, Helmholtz Equation

$$\int_V \left[\frac{1}{\omega^2 \rho_0} \nabla \delta \tilde{p} \cdot (I - \tilde{\mathbf{v}}\tilde{\mathbf{v}}) \cdot \nabla \tilde{p} - \frac{j}{\omega \rho_0 c} (\nabla \delta \tilde{p} \cdot \tilde{\mathbf{v}} \tilde{p} - \delta \tilde{p} \tilde{\mathbf{v}} \cdot \nabla \tilde{p}) - \frac{1}{K} \delta \tilde{p} \tilde{p} \right] dV$$

$$+ \int_S \frac{1}{\omega^2 \rho_0} \delta \tilde{p} \left[\mathbf{n}^- \cdot (I - \tilde{\mathbf{v}}\tilde{\mathbf{v}}) \cdot \nabla \tilde{p} - \frac{j\omega}{c} \mathbf{n}^- \cdot \tilde{\mathbf{v}} \tilde{p} \right] dS = 0$$

- Sound Pressure along the duct

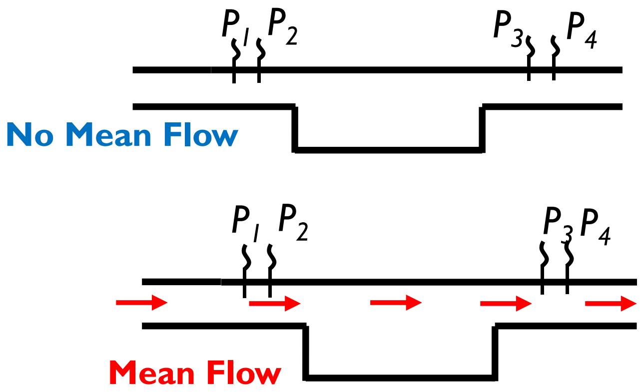
$$\tilde{p} = A e^{-\frac{jkx}{1+M}} + B e^{\frac{jkx}{1-M}}$$

- Anechoic Termination

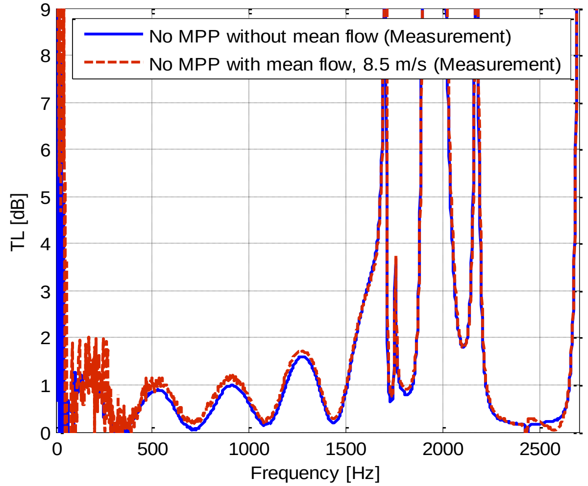
$$\left((1 - M^2) \nabla \tilde{p} - \frac{j\omega}{c} M \tilde{p} \right) \cdot \mathbf{n} = p \frac{i\omega}{Z_{anechoic}} \qquad Z_{anechoic} = \rho_0 c$$

TL Results Comparison

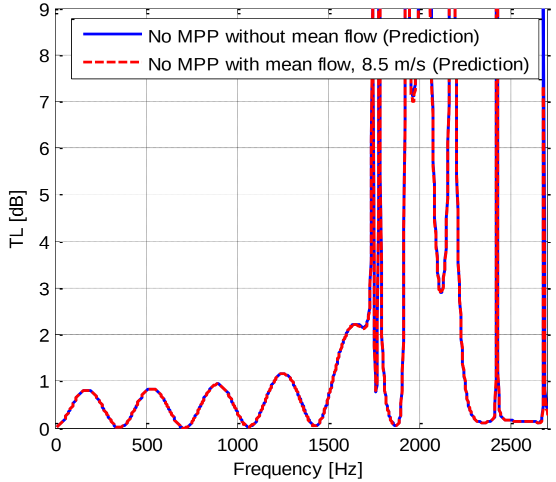
- ❑ **No MPP lining**



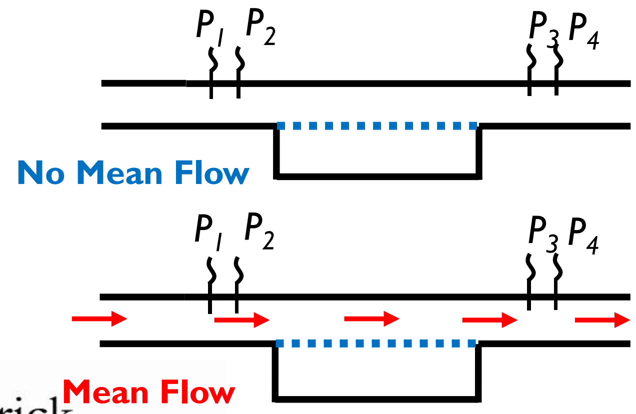
Measurement

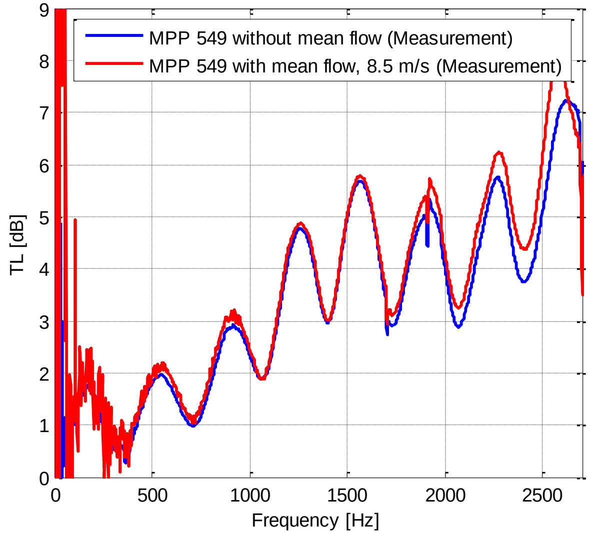


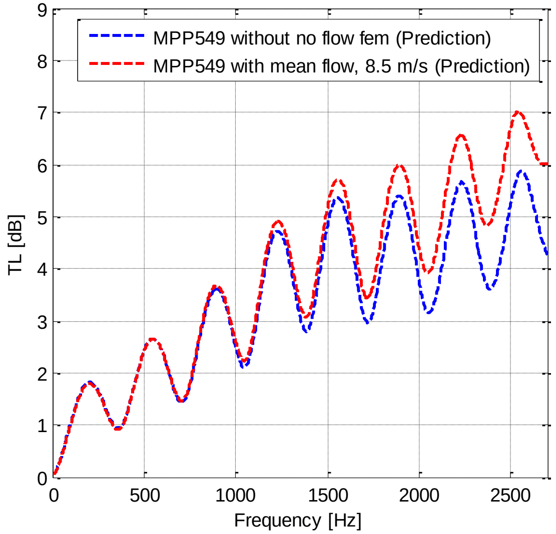
Prediction



- ❑ **MPP lining attached**

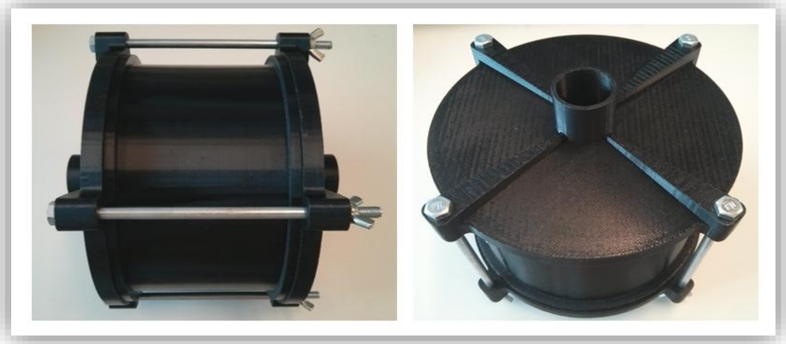


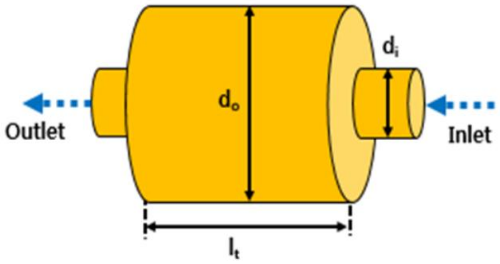




Flow effects in the TL of the muffler

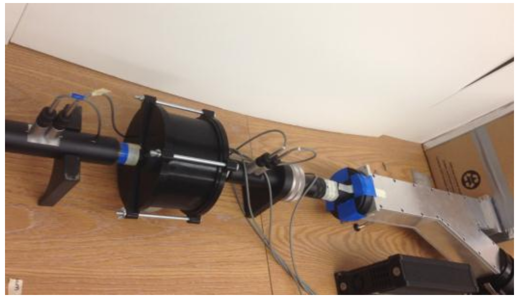
- The prototype muffler used in this study





Dimension	[cm]
l_t	9.60
d_o	15.2
d_i	2.90

- Muffler attached to the standing wave tube



- Two end terminations

- Flow velocity

21.6 m/s, M = 0.063

Comparison Results – Single chamber muffler

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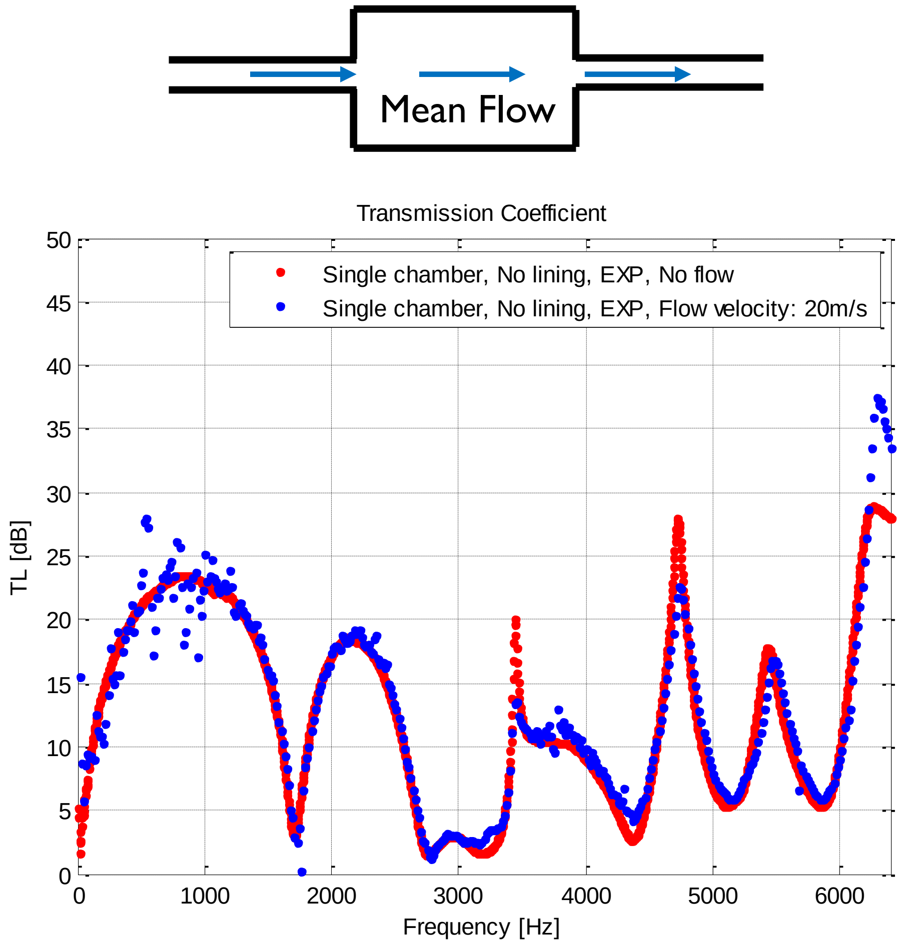
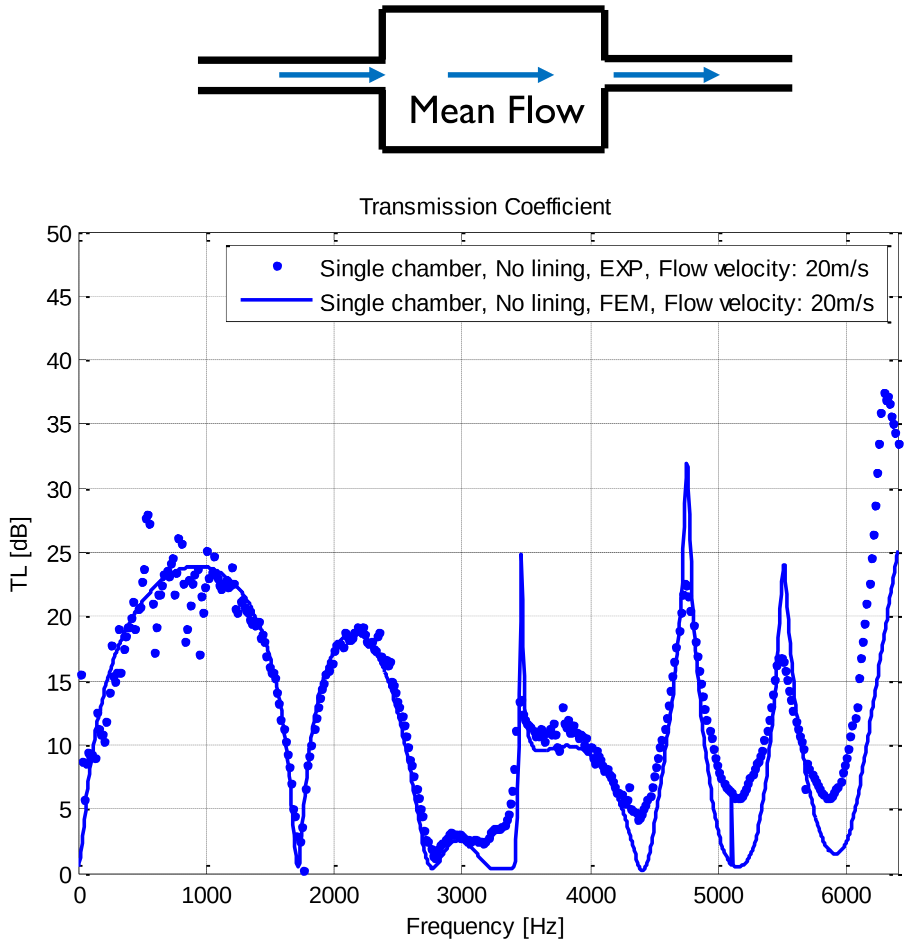
- Measurement: Flow VS No Mean flow

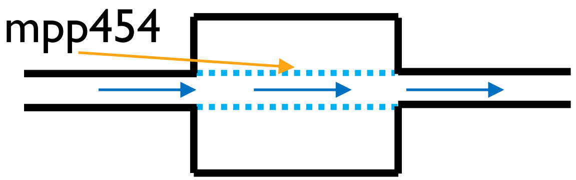


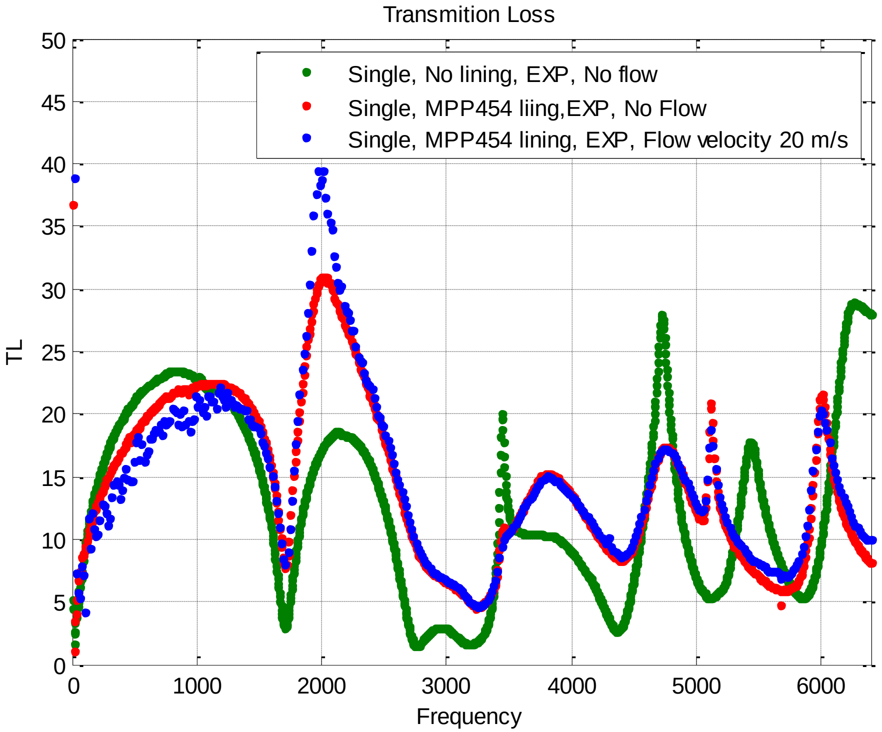
- Measurement VS Prediction



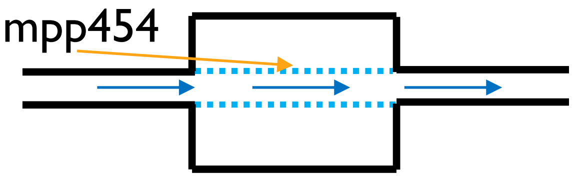
Comparison Results – Single chamber muffler

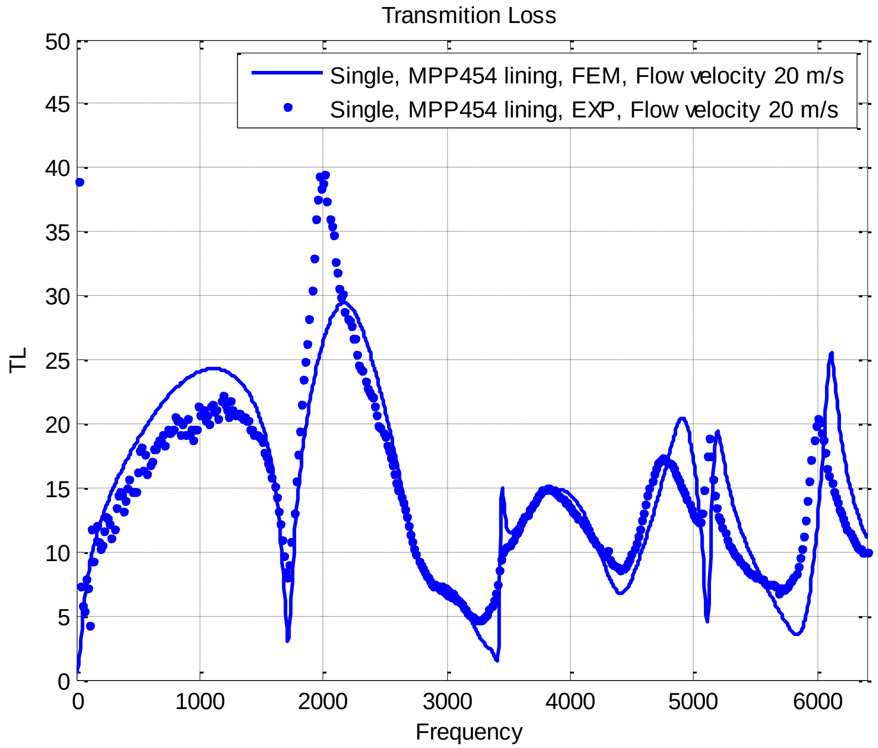
- Measurement: Flow VS No Mean flow





- Measurement VS Prediction

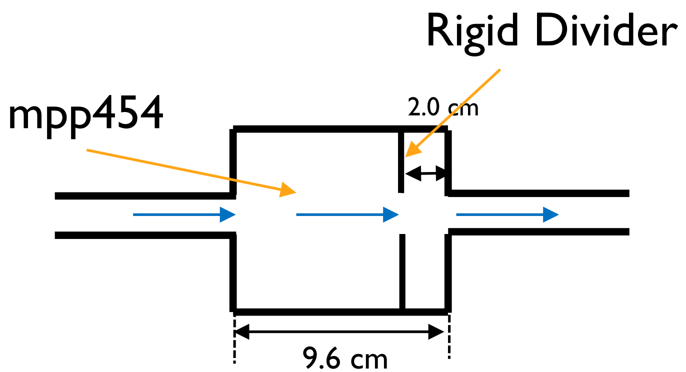




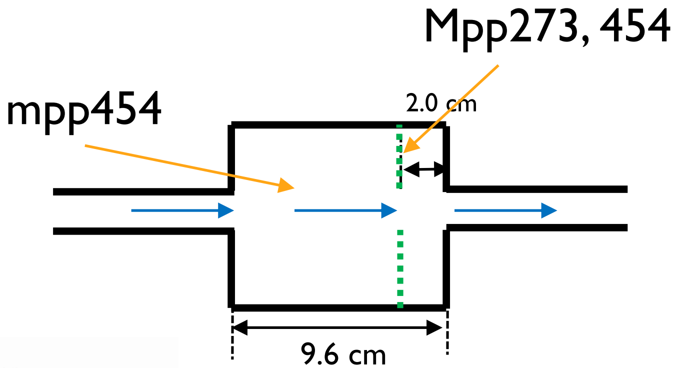
1. Internal design: Dual Muffler using MPP divider

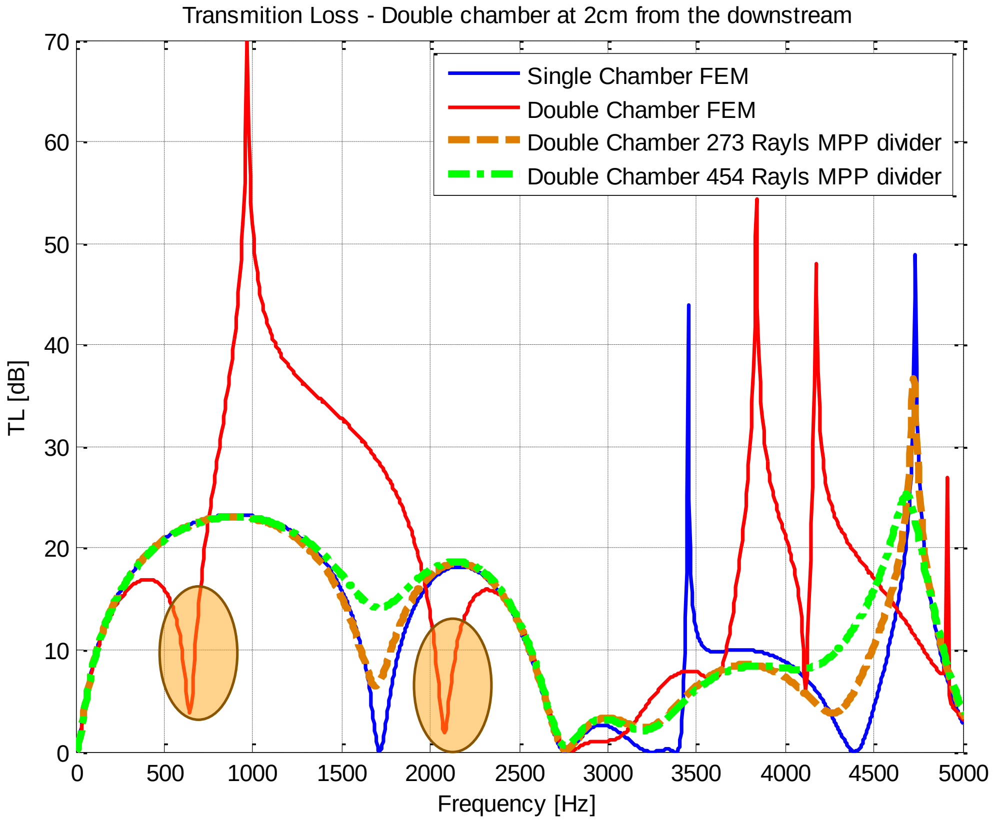
- MPP was used to divide the chamber into two instead of using a rigid divider

Dual chamber using rigid divider



Dual chamber using MPP divider





MPP Dual chamber with MPP lining (No mean flow)

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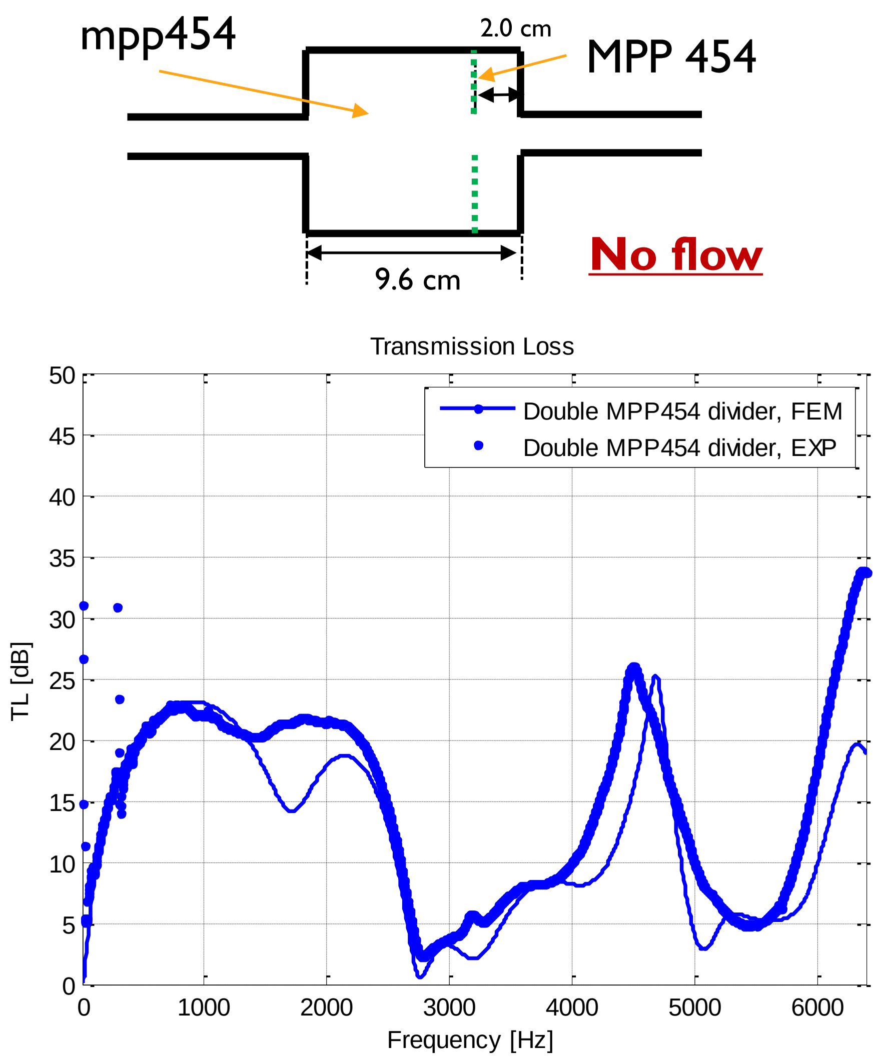
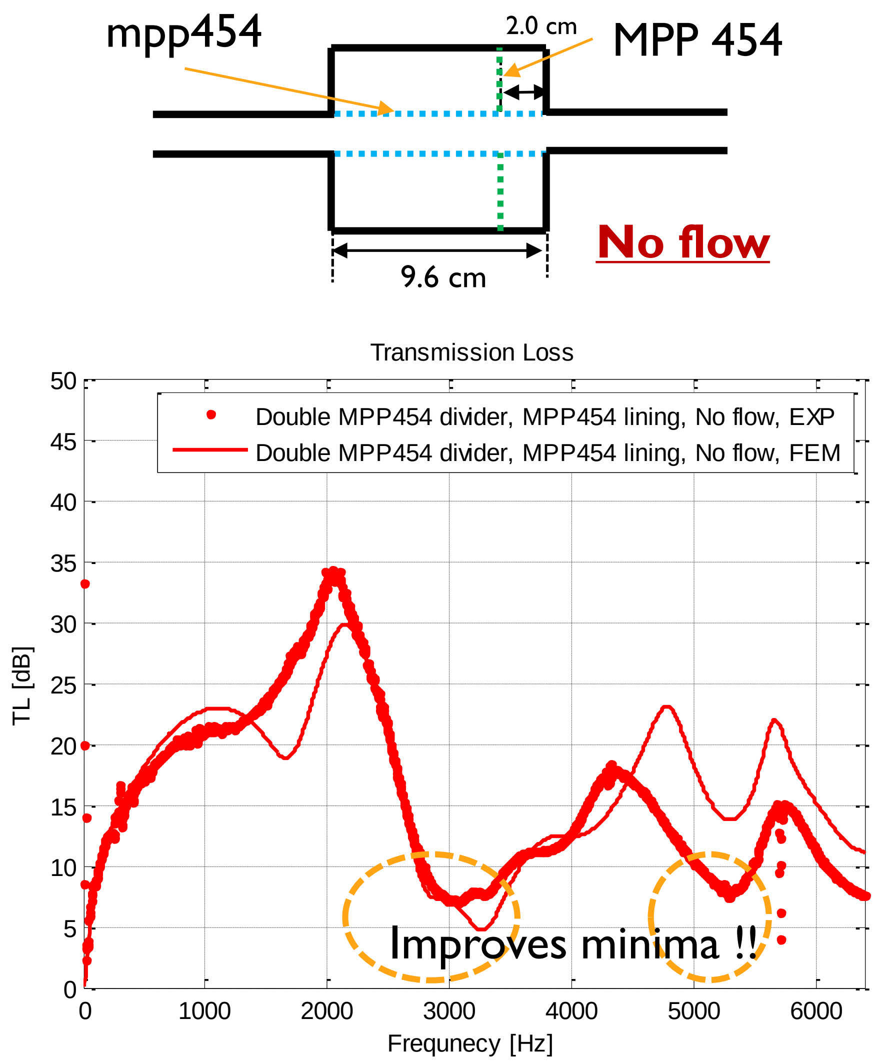
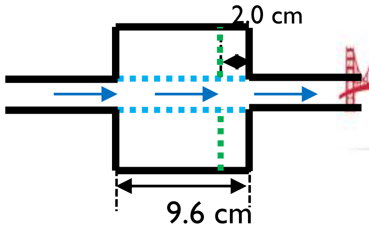
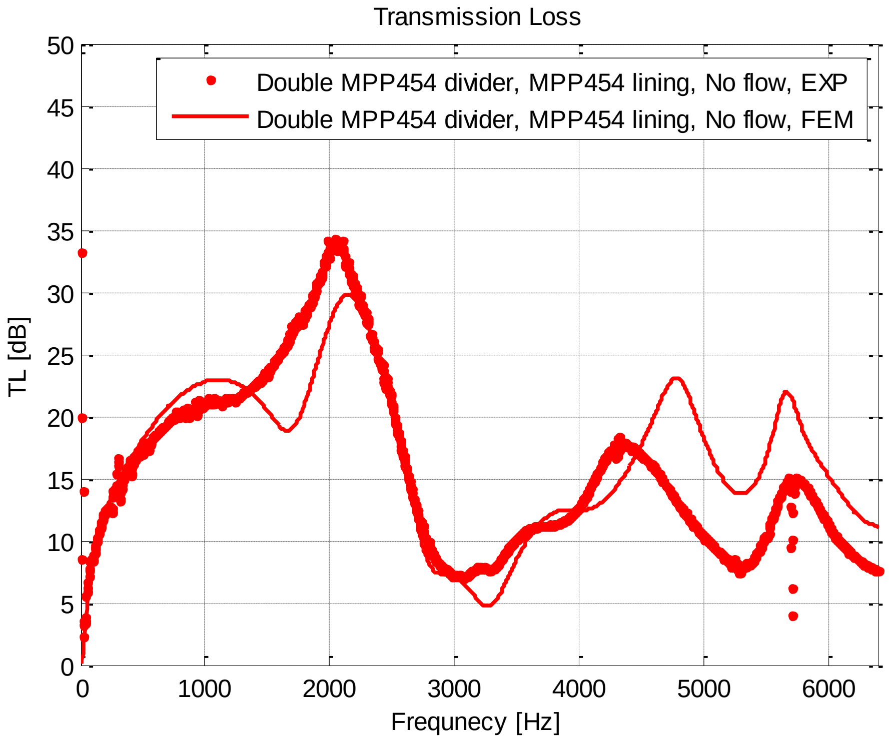




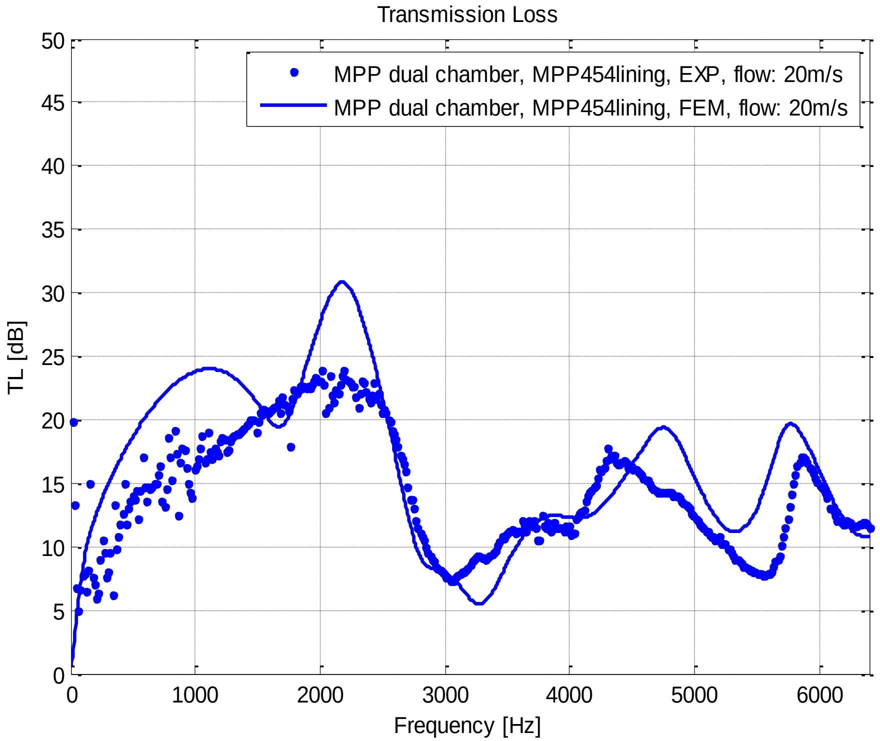
MPP Dual chamber with MPP lining (Mean flow)



No mean flow

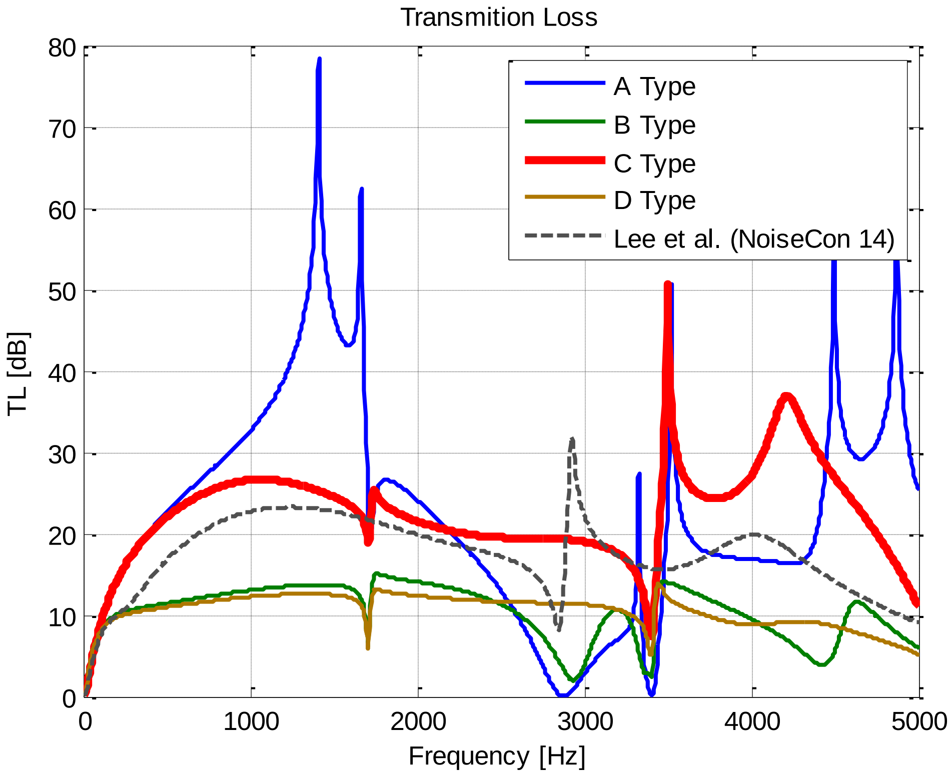


Mean flow

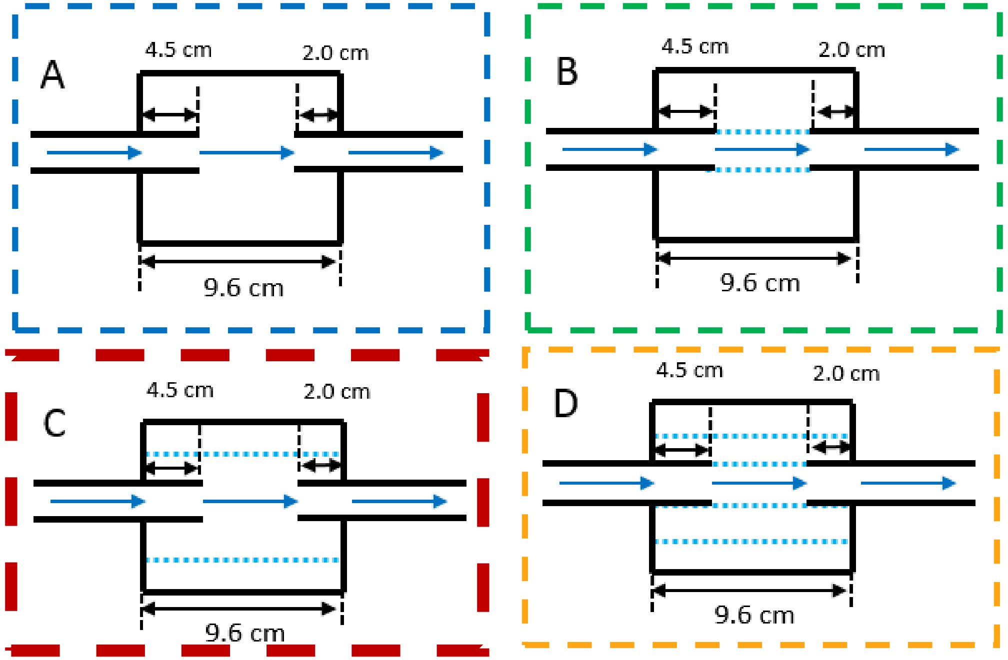


- Measurement: TL at frequency region below 2500 Hz was affected by flow effect

2. Internal design: Inlet and outlet extension

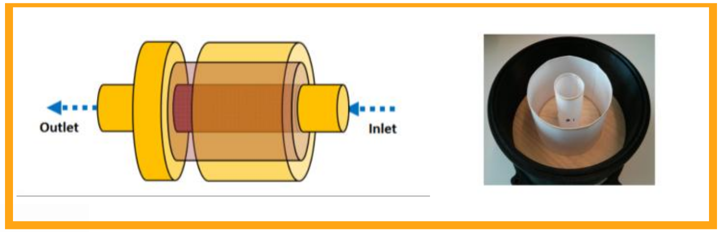


Current work with inlet/outlet extensions

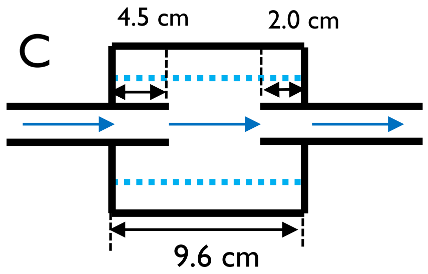


	MPP 454
Hole diameter [μm]	103.6
Thickness [mm]	0.35
Flow resistance [Rayls]	454

Previous Suggested design



Type C muffler with flow effects



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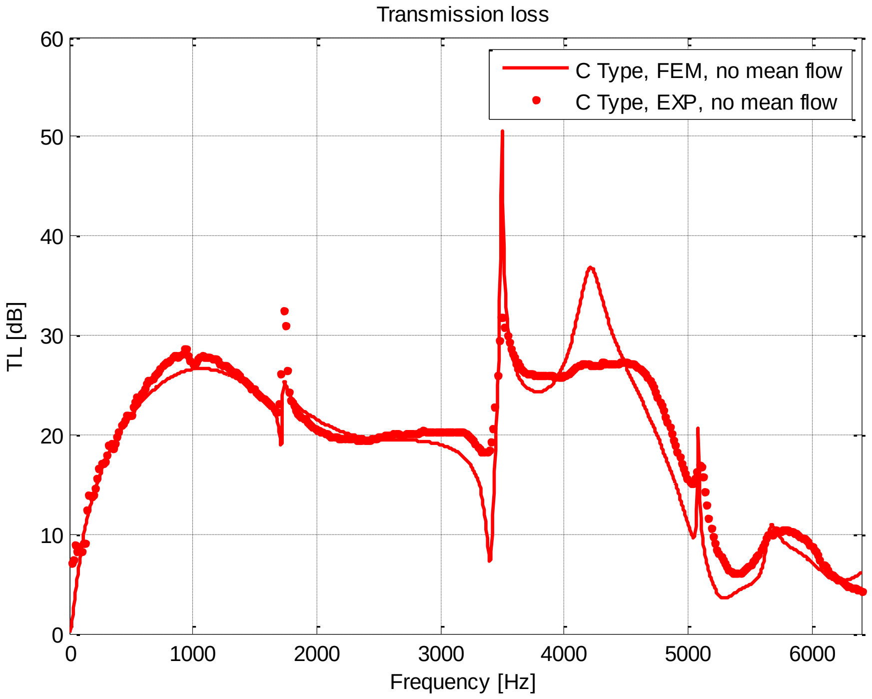
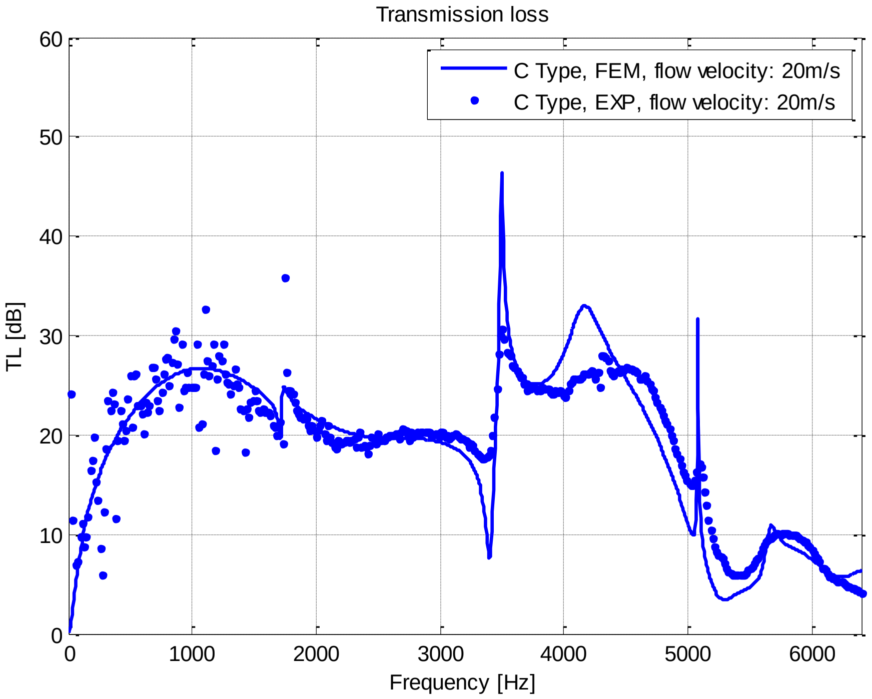
Type C muffler with **No mean flow effect**
Measurement VS Prediction



Type C muffler with Mean flow effect
Measurement VS Prediction



- ❑ NO significant difference in TL at this mean flow velocity with low Mach number

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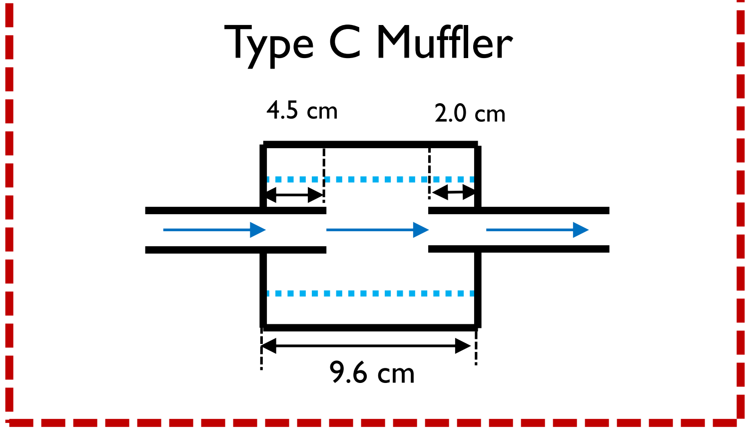
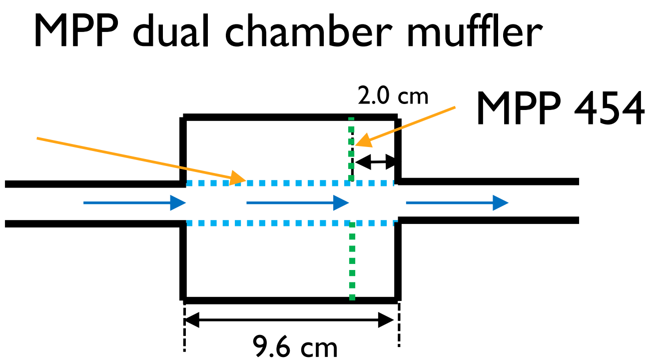
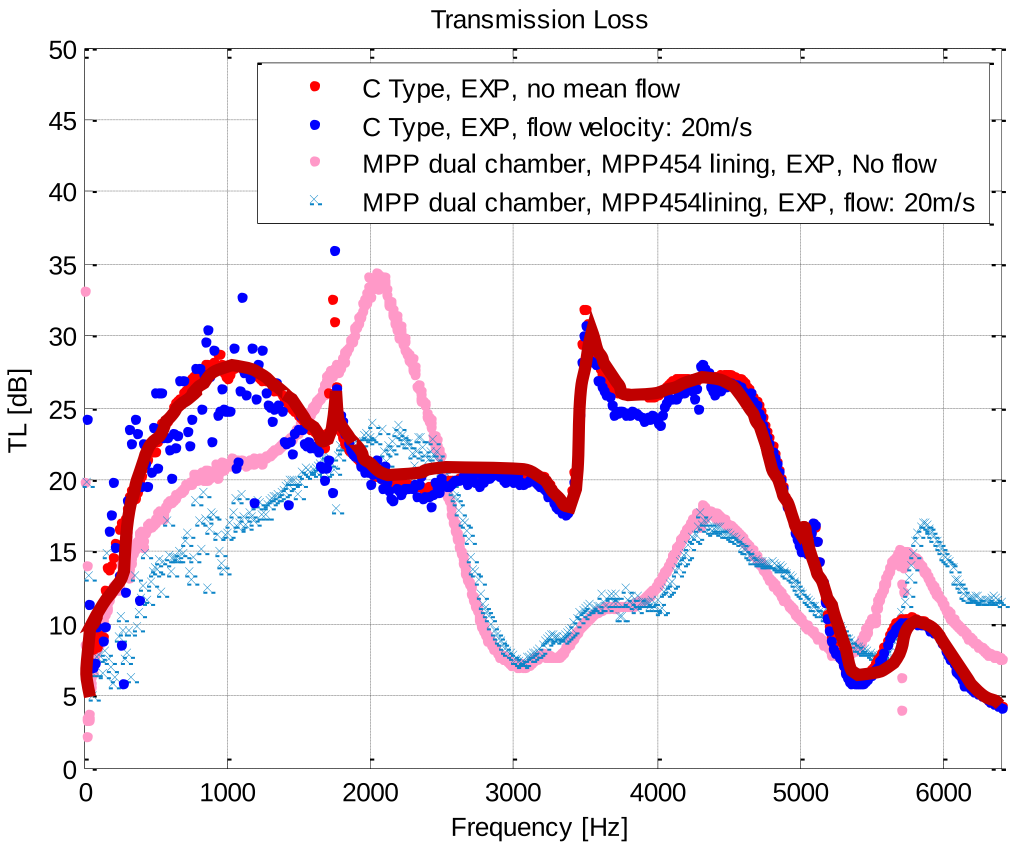
Comparison results (Type C vs MPP dual chamber)



vs.





Conclusion and Future work

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- ❑ Design of acoustic silencers that attenuate noise efficiently over the speech interference range were suggested by FEM and verified experimentally.

- ❑ Internal structure designs such as inlet/outlet extensions and MPP divided chambers were considered.

- ❑ Mean flow effects in the muffler were considered and it was found that the mean flow with relatively low Mach number did not affect the acoustic performance of the mufflers of suggested designs significantly.

- ❑ More optimized internal designs of the muffler will be considered in the future.
  - ✓ Different combinations of inlet and outlet extension lengths combining with MPP lining.
  - ✓ Multi-layer linings will be considered in multi-chamber mufflers.

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