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Design of Multi-Chamber Silencers with Microperforated Elements

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Advancing the Technology and Practice of Noise Control Engineering

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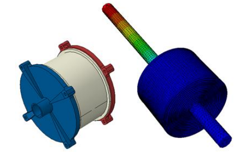
Purdue University **3M**

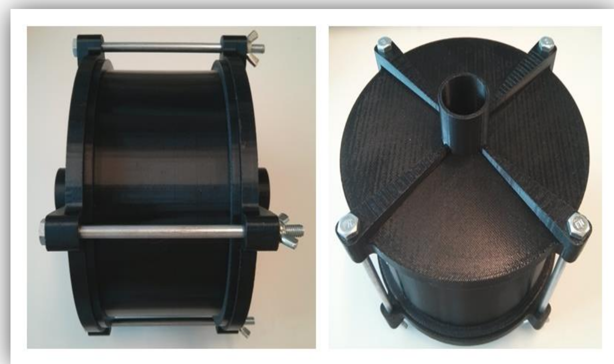
Acknowledgement

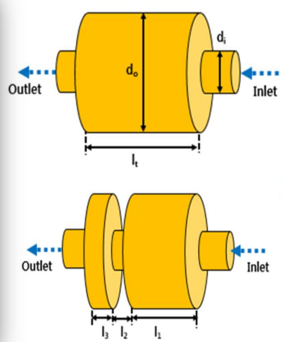


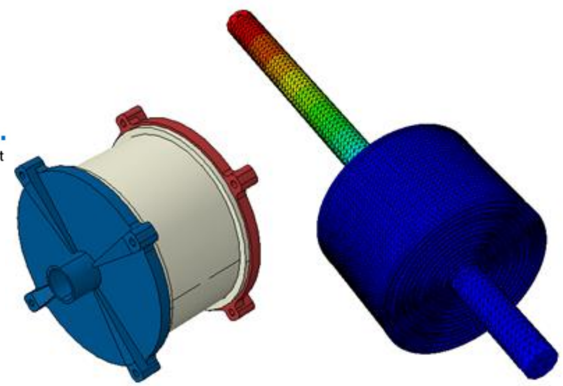
❖ The authors acknowledge the support of 3M Corporation through the provision of materials for the acoustical silencer experiments and for the financial support of this work.

Objective

- Develop the acoustic silencer that could attenuated 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.

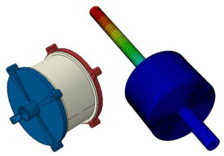






* Muffler figures from “www.suncourt.com/DuctMuffler.html”

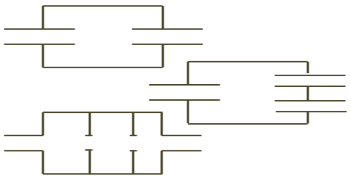
Literature Review –Acoustic Silencer Design



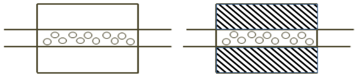
❖ Muffler Design

- ▶ **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)

Dimension Design



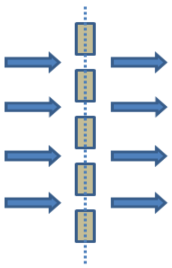
Material implementation



❖ Microperforated Panel Modeling

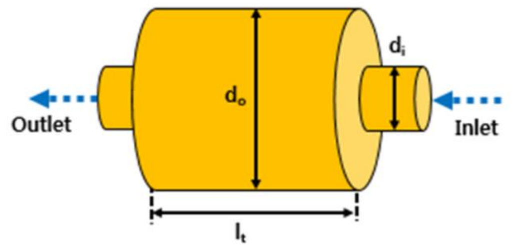
- ▶ **Equivalent fluid model - dynamic permeability, tortuosity and bulk modulus**
  - ✓ Johson and Koplik (1987), Champoux and Allard (1991)
- ▶ **Rigid and motionless skeletons with identical cylinder perforation**
  - ✓ Atalla and Sgard (2007)
- ▶ **Rigid porous model verification**
  - ✓ Jaouen and Bècot (2011)

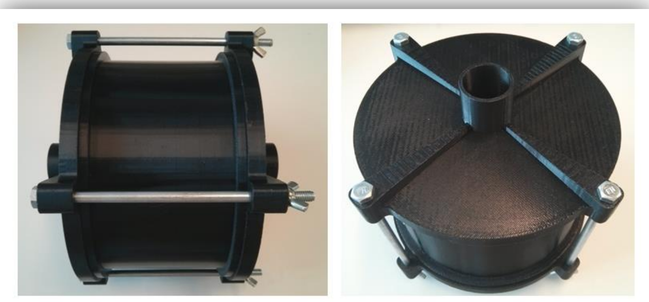
Microperforated Screen modeling



Configuration of mufflers

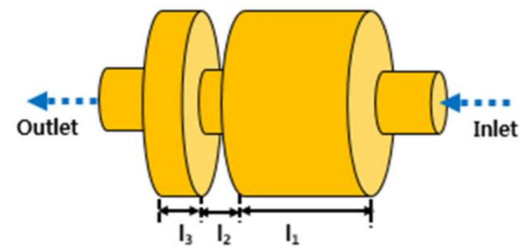
Single Chamber





Dimension	[cm]
l_t	9.60
d_o	15.2
d_i	2.90

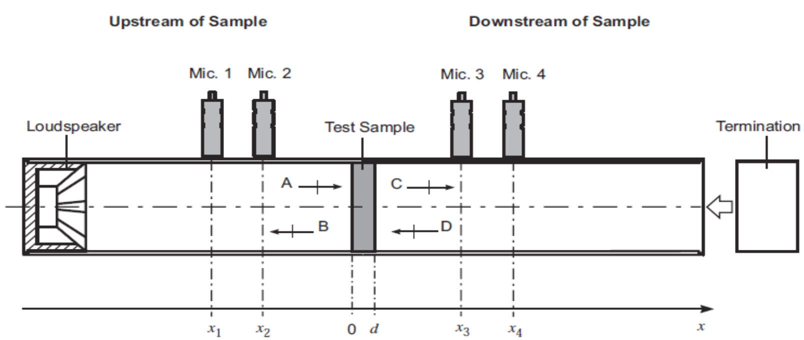
Double Chamber



Dimension	[cm]
l_1	5.6
l_2	2.0
l_3	2.0

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

Experimental Setup



Sound Transmission Loss measurement

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

$$A = \frac{j(p_1 e^{jkx_2} - p_2 e^{jkx_1})}{2\sin k(x_1 - x_2)},$$

$$B = \frac{j(p_2 e^{-jkx_1} - p_1 e^{-jkx_2})}{2\sin k(x_1 - x_2)},$$

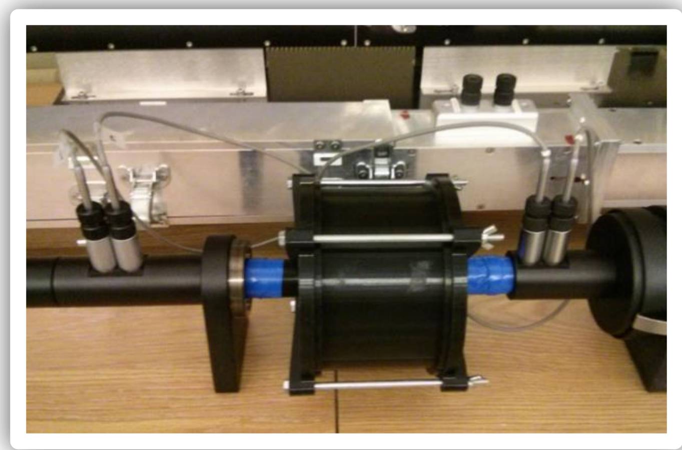
$$C = \frac{j(p_3 e^{jkx_4} - p_4 e^{jkx_3})}{2\sin k(x_3 - x_4)},$$

$$D = \frac{j(p_4 e^{-jkx_3} - p_3 e^{-jkx_4})}{2\sin k(x_3 - x_4)}.$$

$$H_{12} = p_2/p_1$$

$$H_{34} = p_4/p_3$$

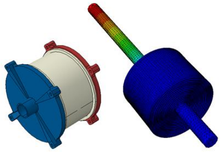
$$s = |x_1 - x_2| = |x_3 - x_4|$$



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

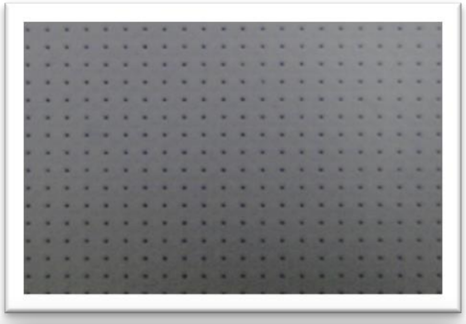
J. S. Bolton, T. Yoo and O. Olivieri, "Measurement of Normal Incidence Transmission Loss and Other Acoustical Properties of Materials Placed in a Standing Wave Tube," *Bruüel & Kjær Techincal Review*, No. 1-2007

Introduction to MPP

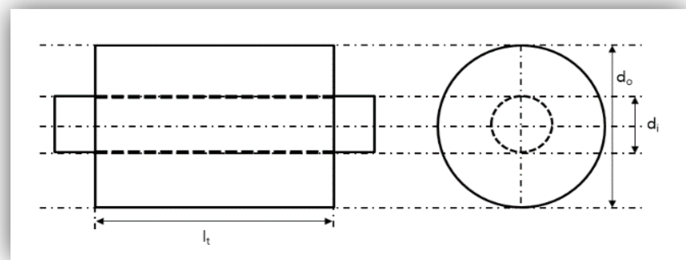


Microperforated material used in the muffler

	Hole Diameter [μm]	Thickness [m]	Flow Resistance [Rayl]
MPP 454	103.6	0.0003	454



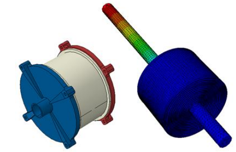
The configuration of microperforated panel lining in the muffler



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

MPP lining Implementation !!

Microperforated Panel Modeling



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

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

Complex Bulkmodulus

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

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

Champoux Y. and Allard J.-F., *Dynamic tortuosity and bulk modulus in air-saturated porous media*, J. Appl. Phys. 70, 1991, pp. 1975-1979

L. Jaouen and F.-X. Be´cot, "Acoustical characterization of perforated facings", J. Acoust. Soc. Am. 129 (3), March 2011

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)

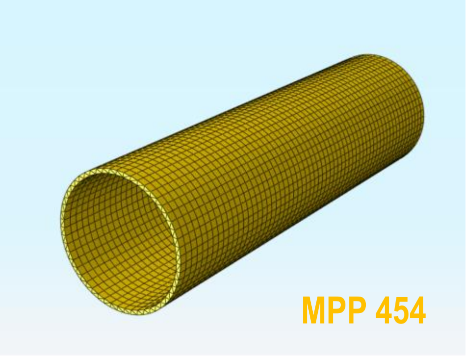
$$\sigma = 8\eta/(\phi r^2)$$

σ : Flow resistivity

η : Dynamic Viscosity

ϕ : Porosity

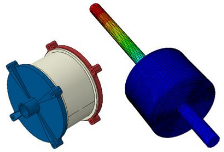
r : Radius



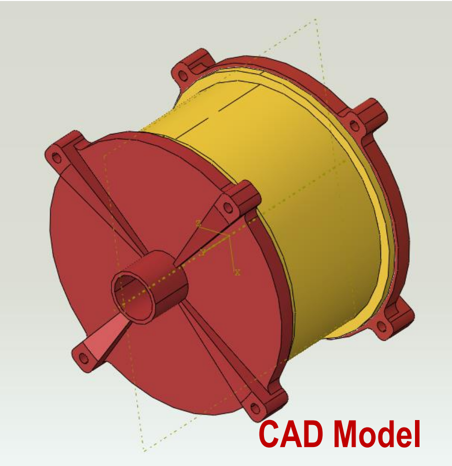
MPP Modeling of ABAQUS

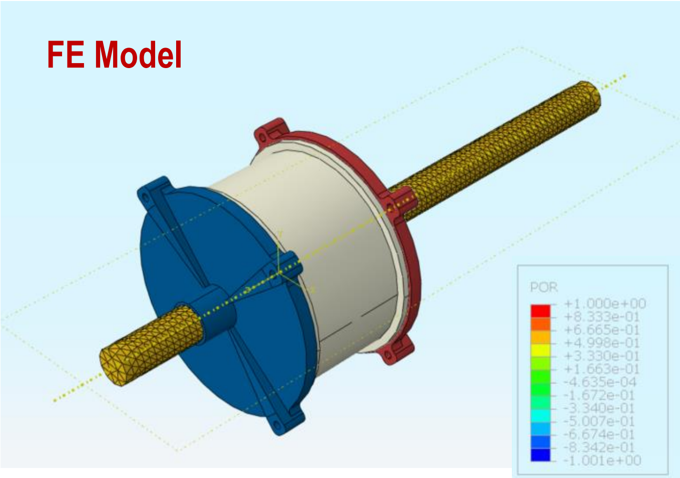
L. Jaouen and F.-X. Be´cot, *"Acoustical characterization of perforated facings"*, J. Acoust. Soc. Am. 129 (3), March 2011

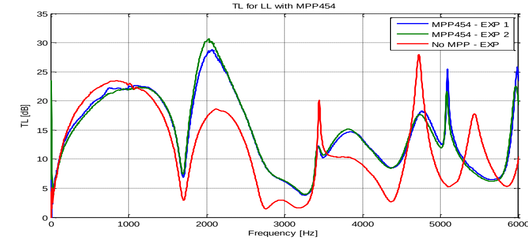
Microperforated Panel Modeling - FE Modeling

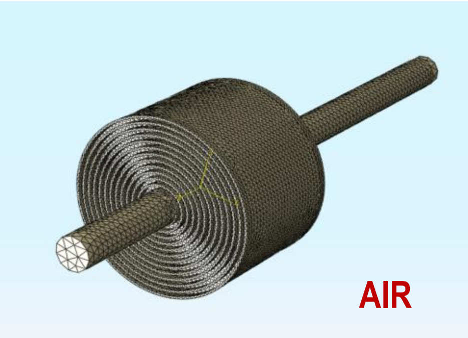


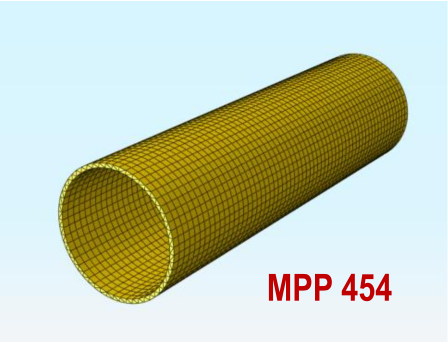
- Commercial Software ABAQUS was used in modeling of muffler with MPP
- Transmission Loss was calculated using 3-point measurement method

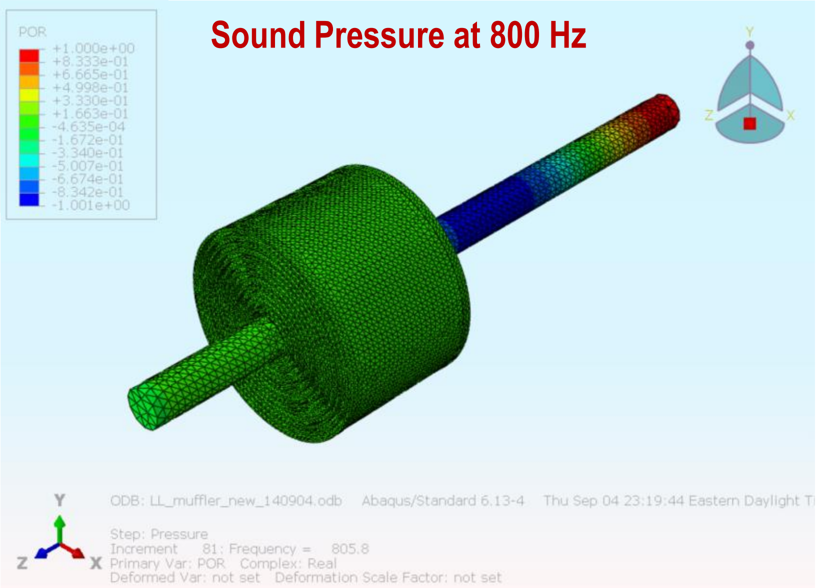


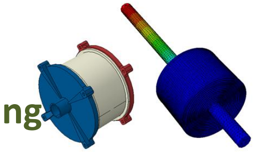




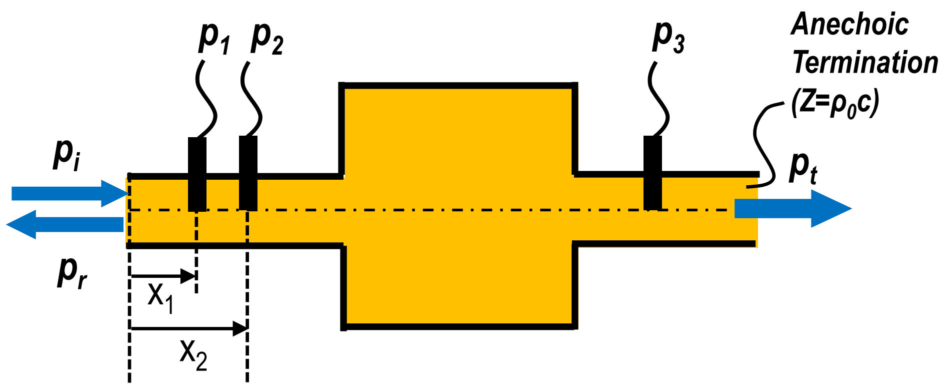


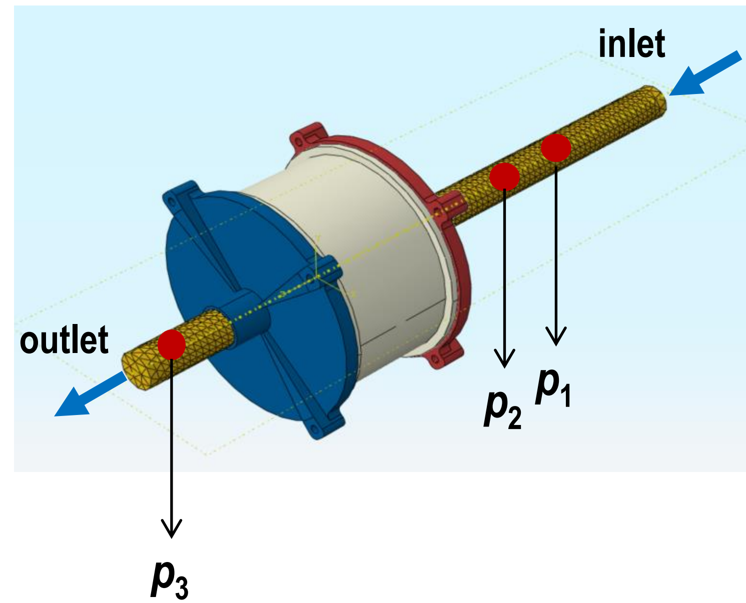






3-Point Measurement Method





$$p_1 = p_i e^{ikx_1} + p_r e^{-ikx_1}$$

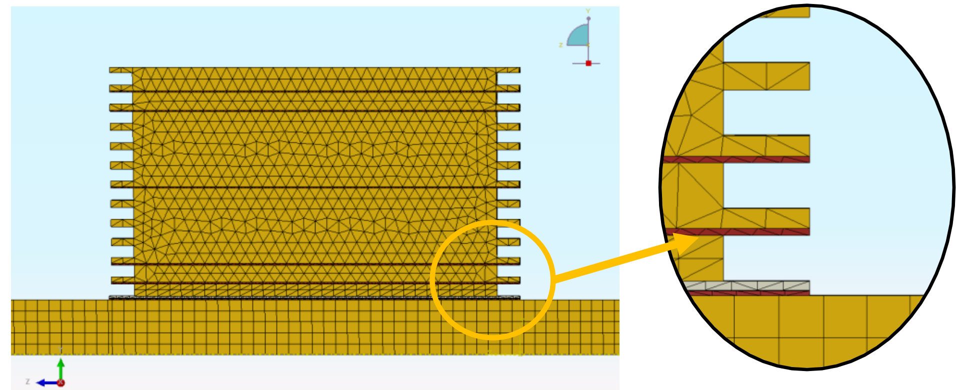
$$p_2 = p_i e^{ikx_2} + p_r e^{-ikx_2}$$

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

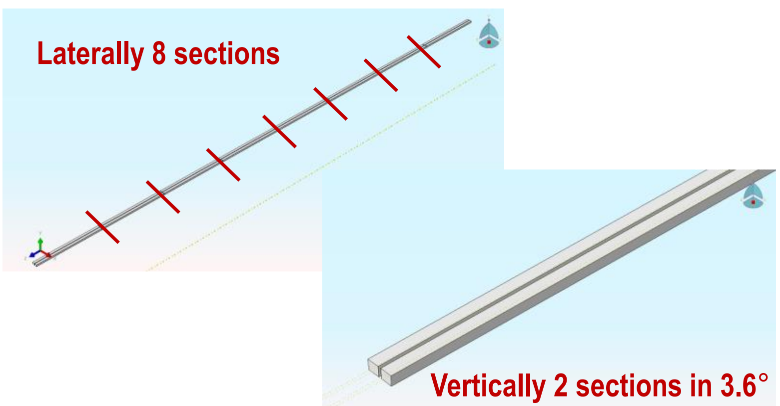
$$\mathrm{TL} = 20\log_{10}\left\{\frac{|p_i|}{|p_3|}\right\} + 10\log_{10}\left(\frac{S_i}{S_o}\right)$$

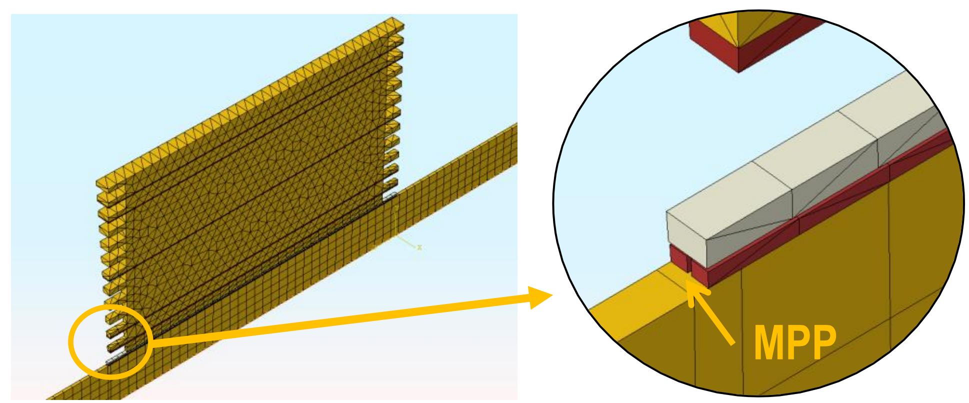
FE modeling of MPP 454

- ❖ **Rigid boundaries modeling**
- ❖ **Implementation of MPP's local reaction**
  - ► **Local reaction of MPP cannot be modeled using fluid modeling of MPP.**

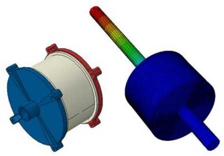


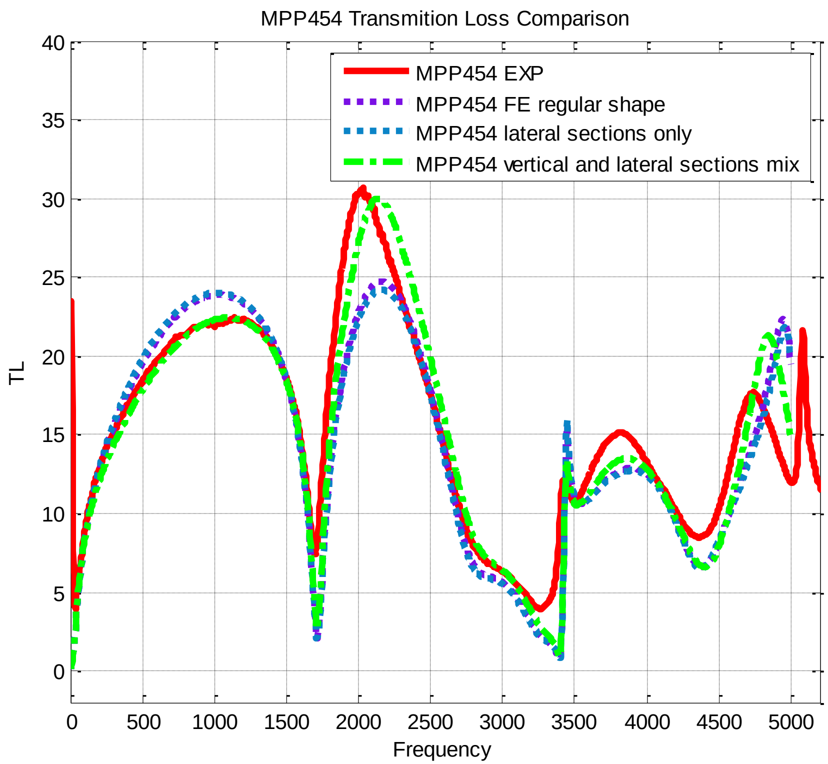
- ❖ **Lateral and Vertical rigid sections were created in MPP modeling.**
  - » **Thickness of rigid cut: 0.00005m**
  - » **Laterally 8 sections were created**
  - » **Divided into 2 sections vertically in 3.6° (total of 360 rigid partition)**

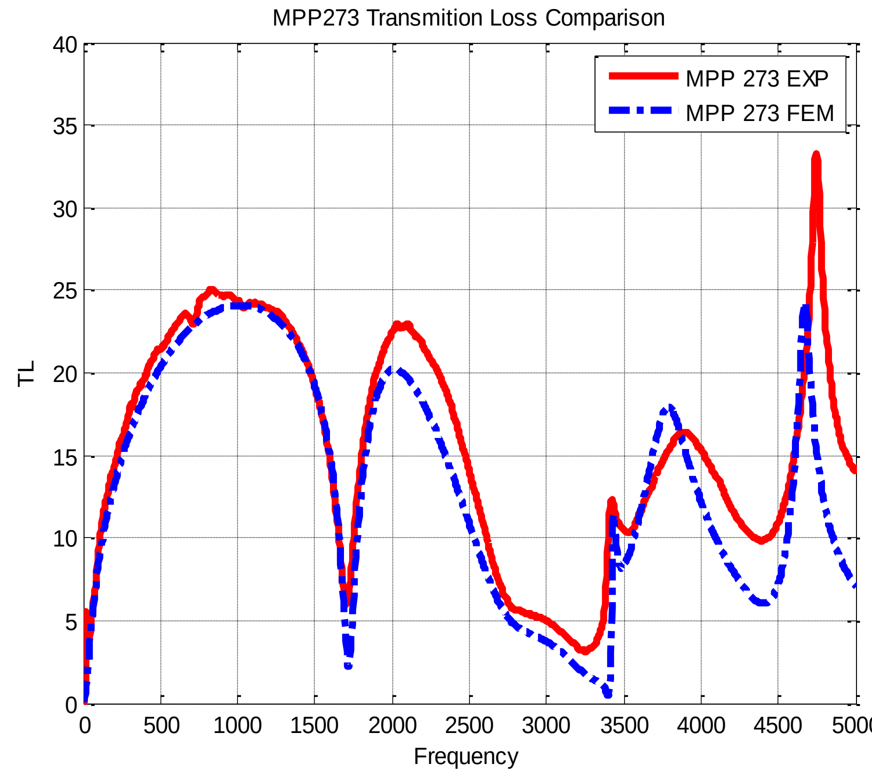




Improved MPP Modeling and Verification



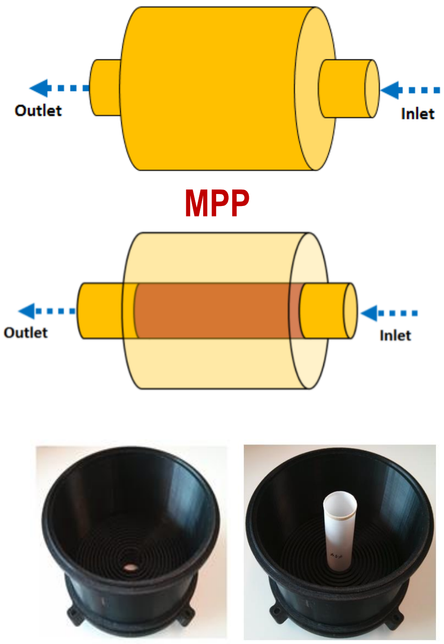




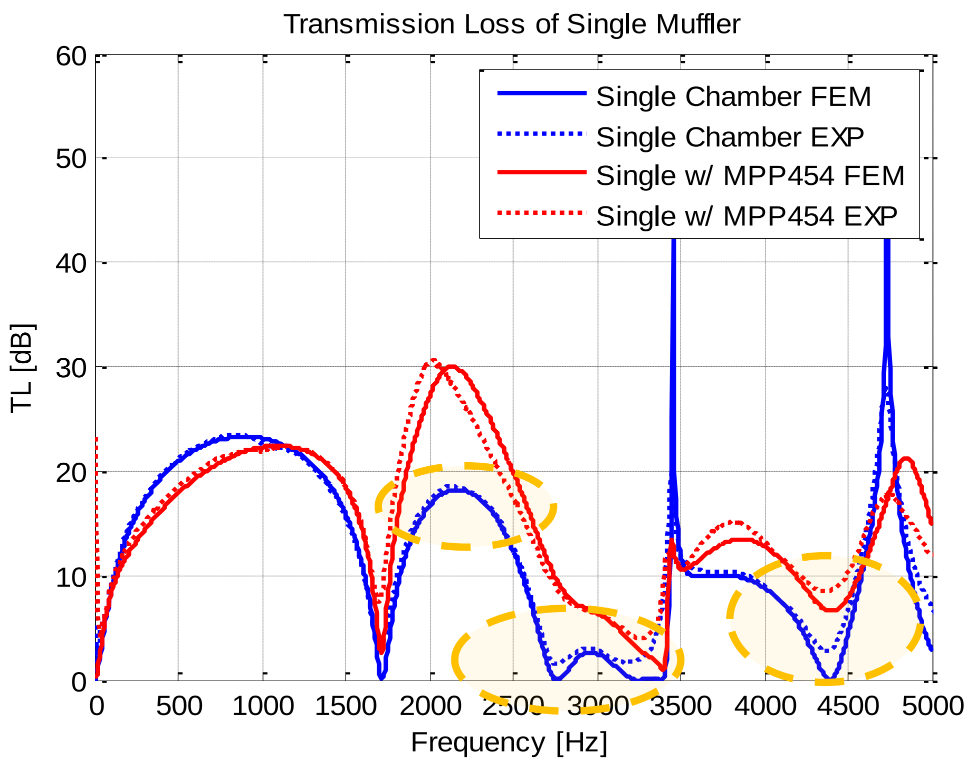
- ***Vertical and lateral rigid sections improved TL in frequency range from 1600 to 2500 Hz for MPP 454 as well as the region below 1600 Hz.***
- ***Developed model shows good agreement with different microperforated material.***

Results comparison – Single Chamber

Muffler Configuration



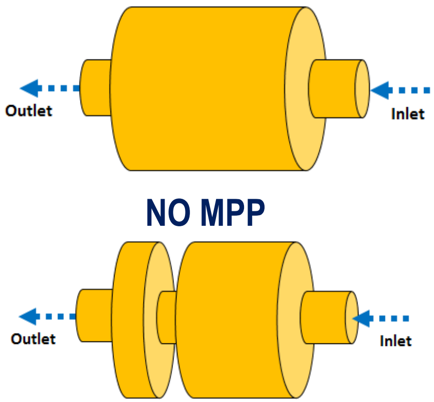
TL Results



- *MPP improved TL performance gradually over 1600 – 3400 Hz*
- *Brought up minima at 1600 Hz, 2700 Hz, 3400 Hz.*

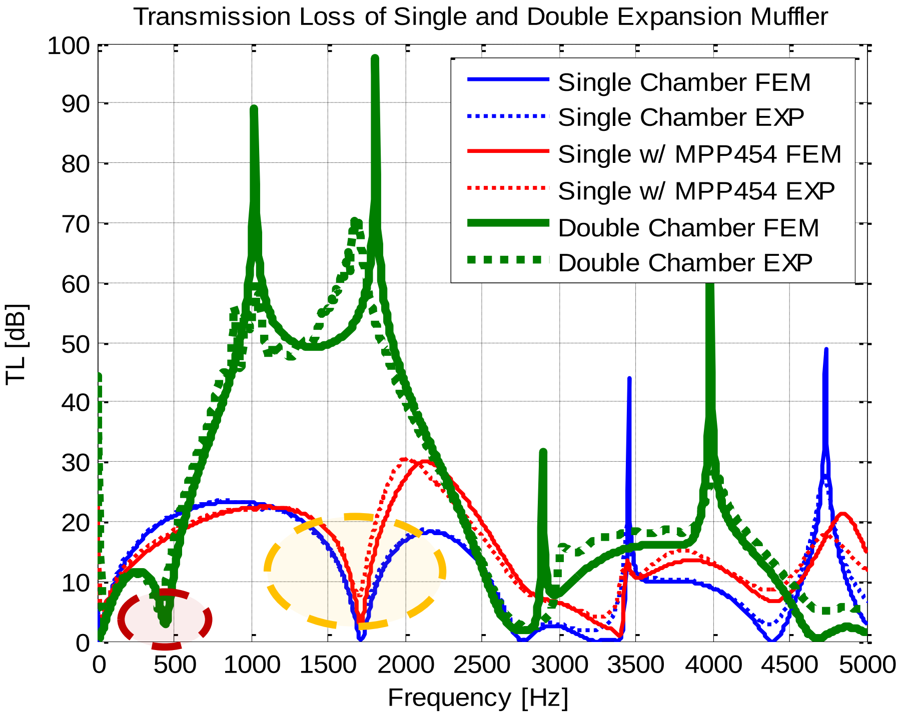
Result comparison – single vs. dual chamber

Muffler Configuration



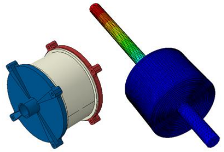
NO MPP MPP

TL Results



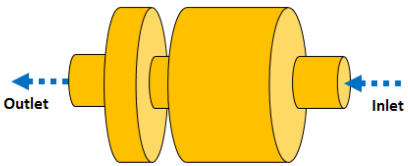
- ***Double chamber configuration improved TL performance at 400 – 2600 Hz***
  - ***Improved speech interference range***
- ***1st peak appeared at single chamber moved to low frequency and created new minima at 480 Hz.***

Results comparison – Dual Chamber

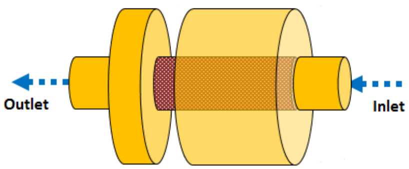


Muffler Configuration

NO MPP

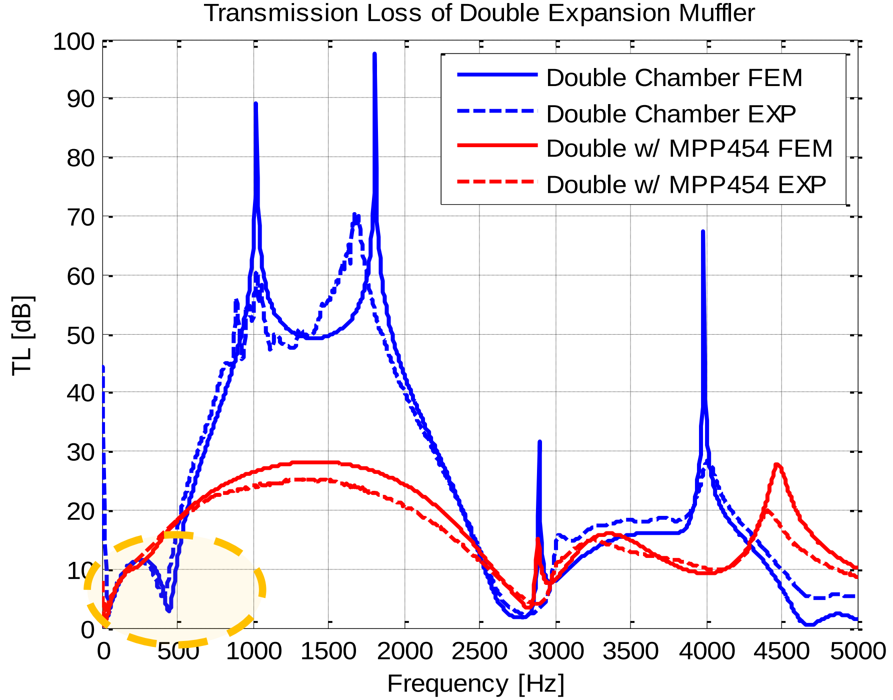


MPP



NO MPP MPP

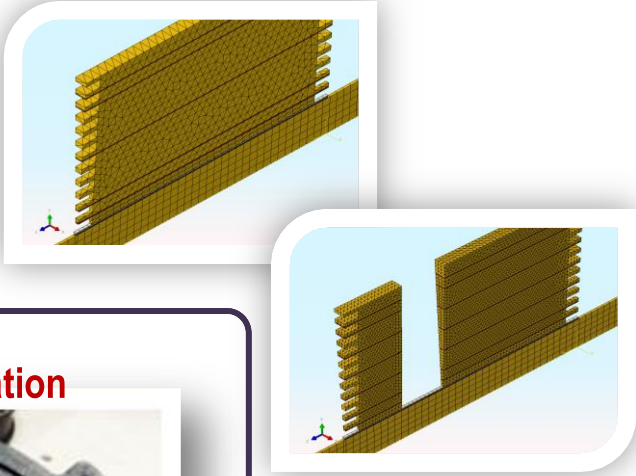
TL Results



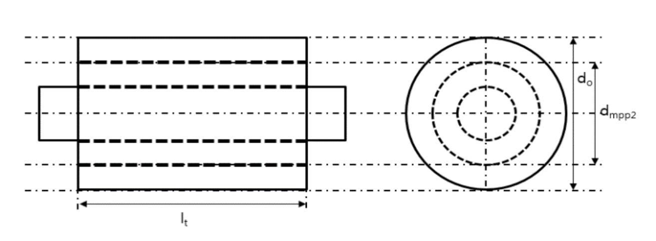
- *Overall TL peaks were lowered but the lowest TL point at 490 Hz was brought up by MPP.*

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

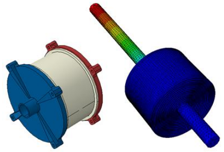


MPP lining Configuration

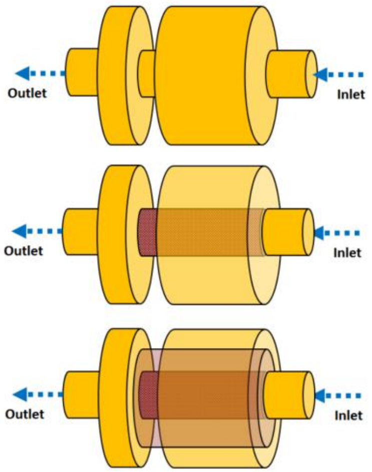


MPP linings location

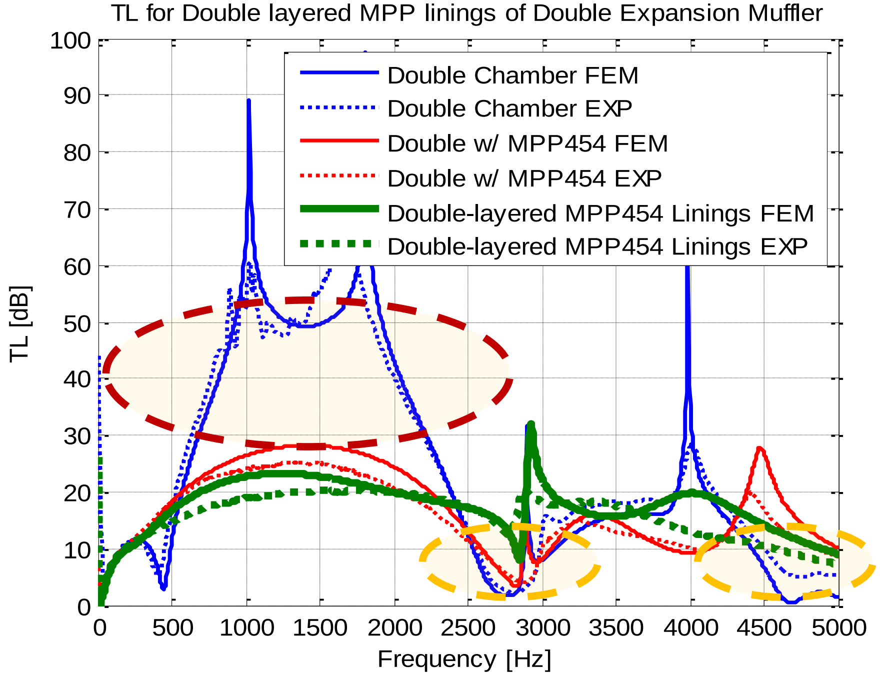
Results comparison - Dual Chamber Double MPP



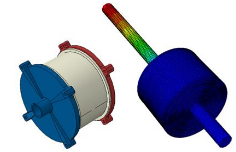
Muffler Configuration



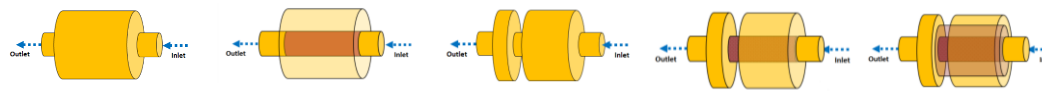
TL Results



- ***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***



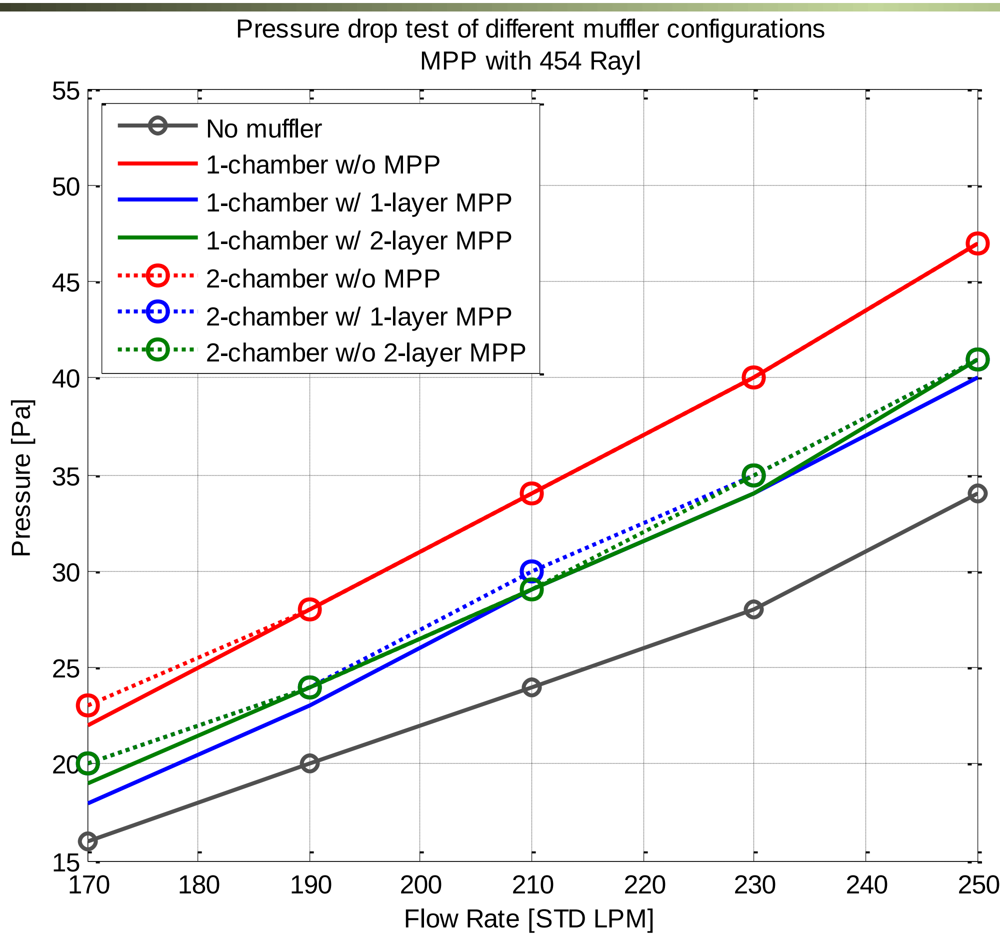
Overall A-weighted Sound Pressure Level

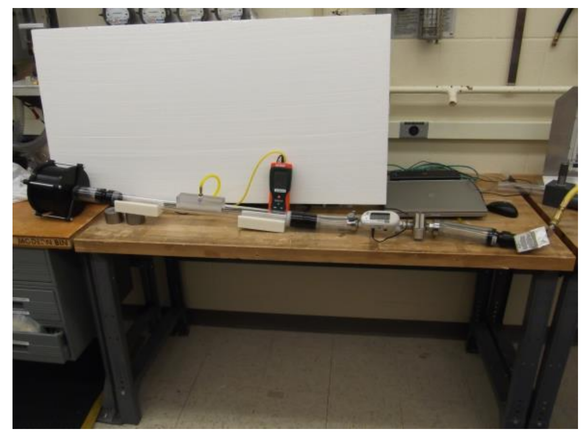


	Sound without muffler treatment	Single Chamber	Single Chamber w/ MPP454	Double Chamber	Double Chamber w/ MPP454	Double Chamber w/ Double MPP454
A-weighted Overall Sound Pressure Level	68.50 dBA	53.98 dBA	52.09 dBA	53.24 dBA	50.49 dBA	51.28 dBA
Recordings						

Recorded on 4/10/2014
Double Layered MPP Cases were Recorded on 4/23/2014

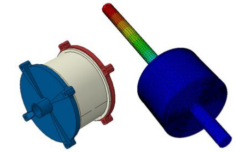
Pressure Drop Experiment





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

Conclusion and Future Plan



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.