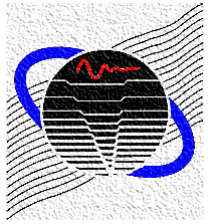
May 28, 2020

Panel Contribution Analysis, Scale Modeling, and a Simple Monopole Source

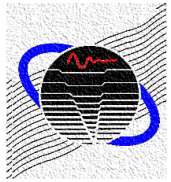
Vibro-Acoustics Consortium Web Meeting

University of Kentucky



Overview

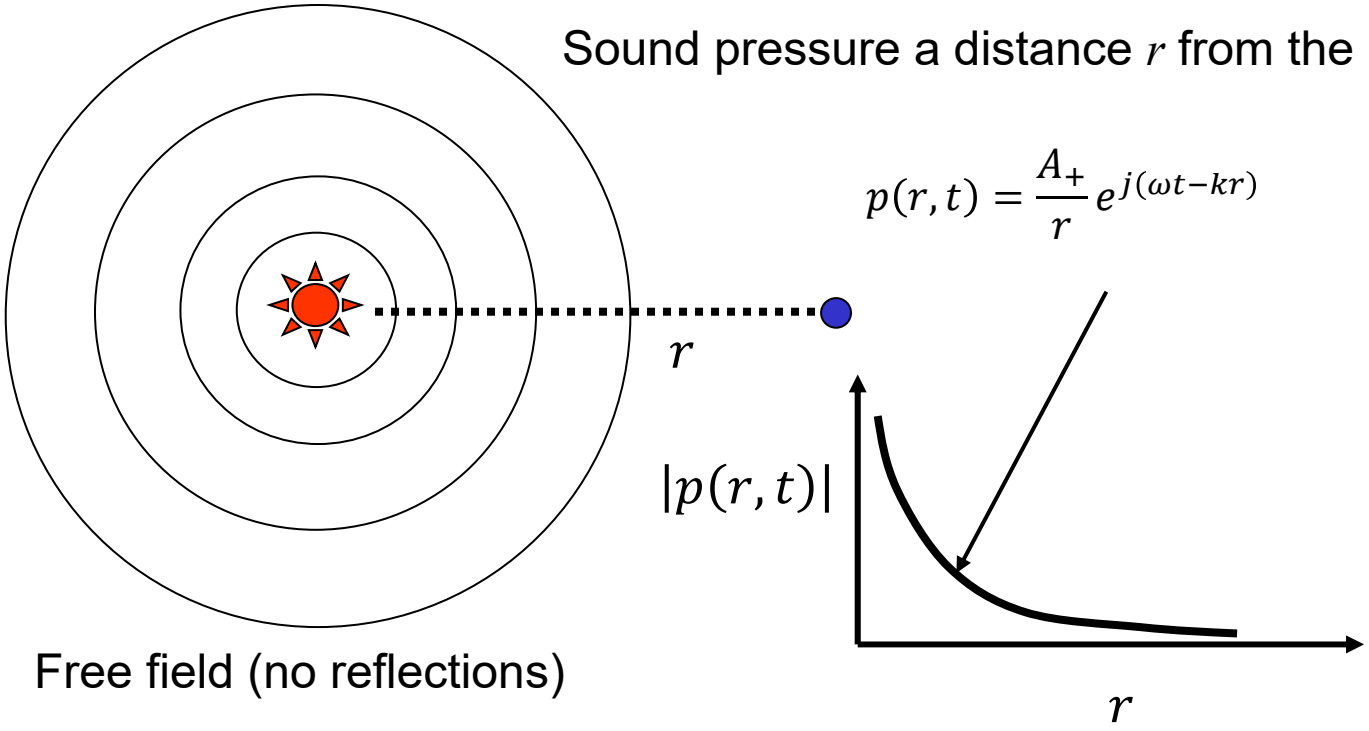
- Acoustic Monopole
- Homemade Acoustic Monopole
- Vibro-Acoustic Scale Modeling
- Vibro-Acoustic Reciprocity
- Panel Contribution Analysis – Engine Noise
- Panel Contribution Analysis – HVAC Noise in Bakery
- Future Directions



Acoustic Monopole

Sound pressure a distance r from the point source:

$$p(r,t) = \frac{A_+}{r} e^{j(\omega t - kr)}$$



Free field (no reflections)

This is similar to a plane wave, but for spherical waves the sound pressure amplitude decreases with distance from the source of sound.

Acoustic Monopole

Sound Pressure

$$p(r,t) = \frac{A_+}{r} e^{j(\omega t - kr)}$$

Volume Velocity

$$Q = \frac{4\pi A_+}{j\rho ck}$$

Derivation of Q

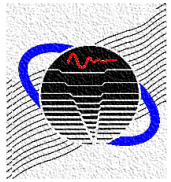
$$\rho_0 \frac{\partial u(r,t)}{\partial t} = -\frac{\partial p(r,t)}{\partial r}$$

$$u_r(r,t) = -\frac{1}{\rho_0}\int \frac{\partial p(r,t)}{\partial r} dt$$

$$u_r(r,t) = -\frac{A_+}{\rho_0}\int \left(\frac{-1}{r^2} + \frac{-jk}{r}\right) e^{j(\omega t - kr)} dt$$

$$u_r(r,t) = \frac{A_+}{\rho_0 cr}\left(1 + \frac{1}{jkr}\right) e^{j(\omega t - kr)}$$

$$Q = \lim_{r\to 0} 4\pi r^2 \frac{A_+}{\rho_0 cr}\left(1 + \frac{1}{jkr}\right) e^{-jkr}$$



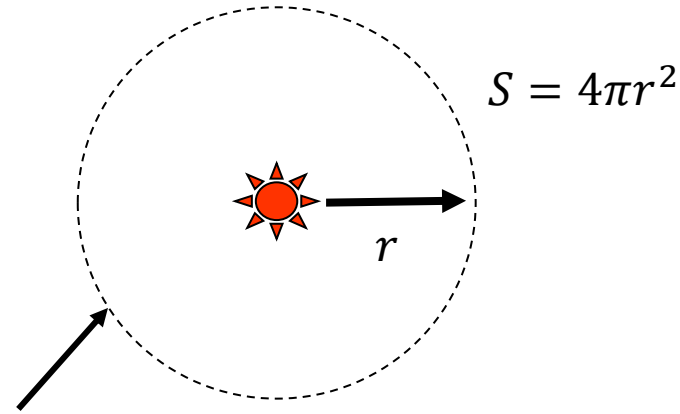
Acoustic Monopole

Sound Intensity

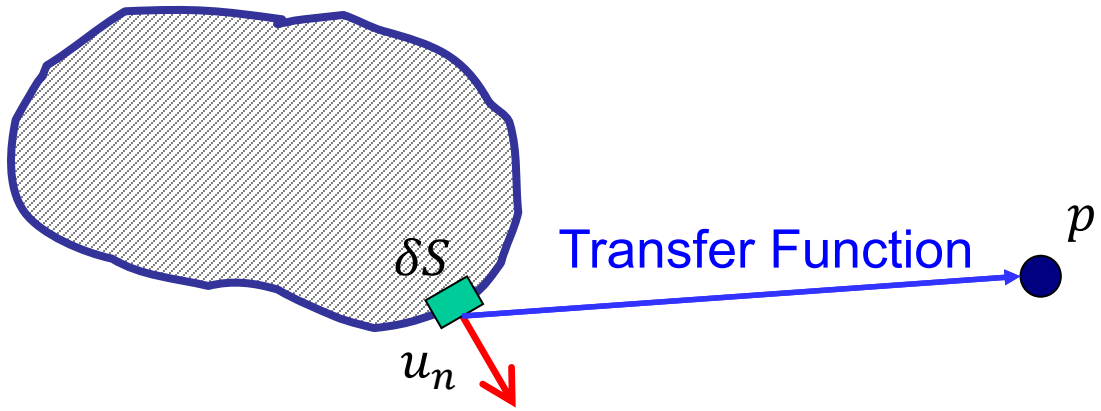
$$I_r(r) = \frac{1}{2}\mathrm{Re}(pu') = \frac{A_+^2}{2\rho_0 c r^2}$$

Sound Power

$$W = I_r(r)4\pi r^2 = 2\pi\frac{A_+^2}{\rho_0 c}$$



Panel Contribution Analysis



Discretized form of Helmholtz Integral Equation

$$p = \sum_{i=1}^{N} ((u_n \delta S)_i \cdot (TF)_i)$$

Transfer Function

$$(TF)_i = \frac{p}{Q_i}$$

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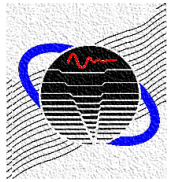
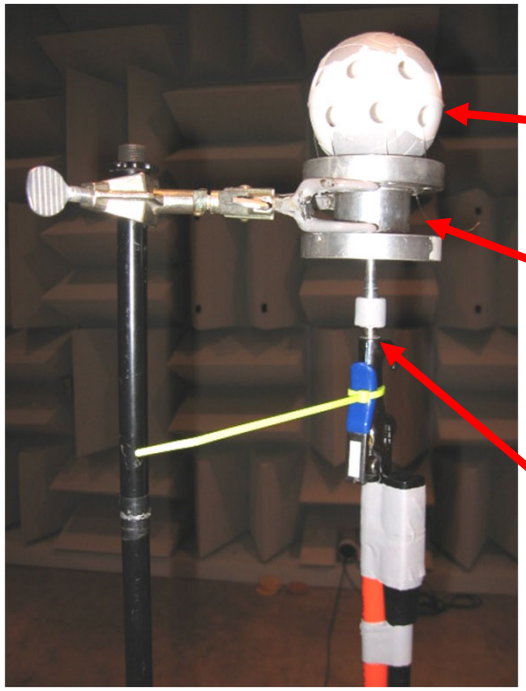


A Simple Acoustic Monopole



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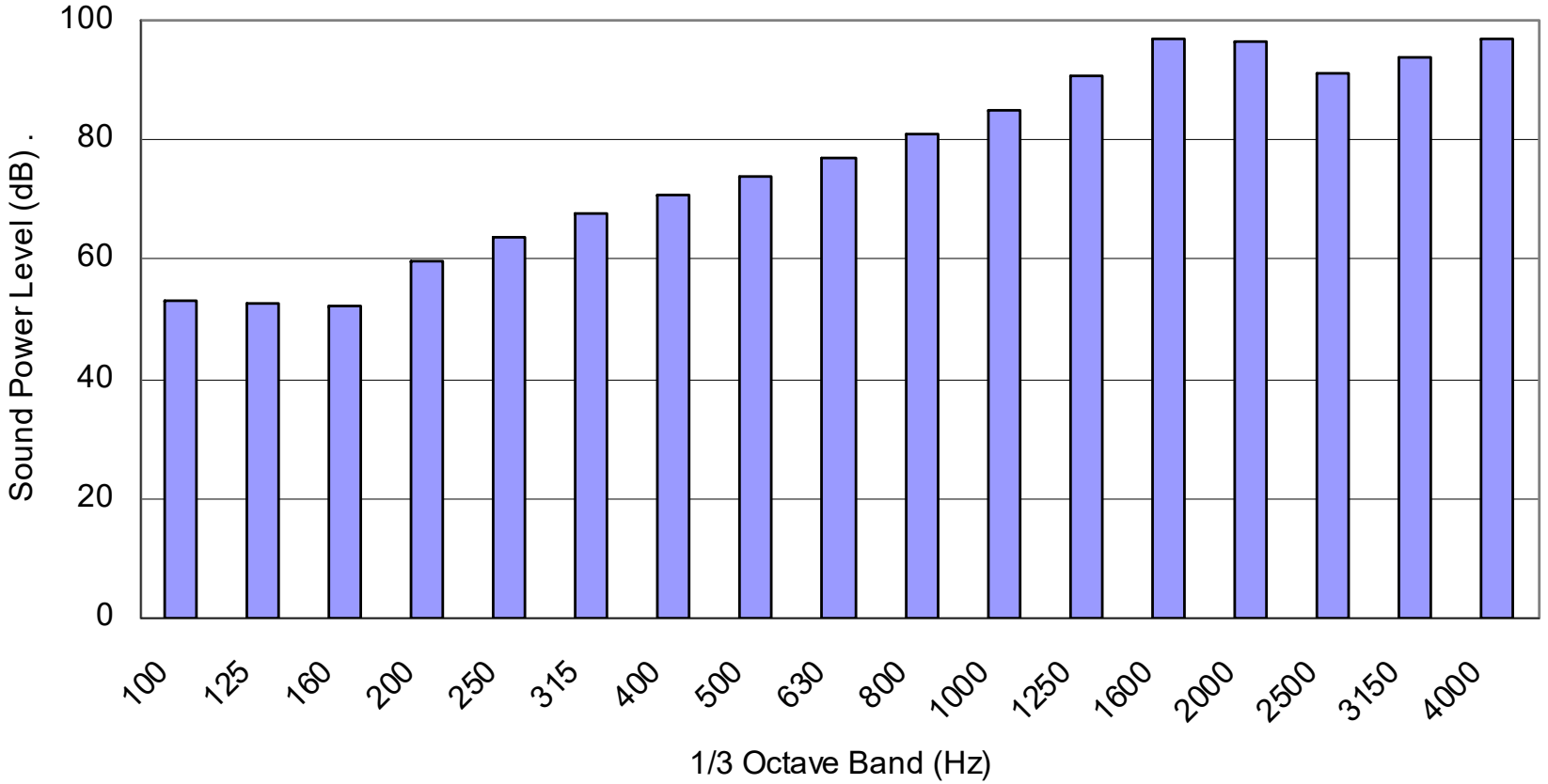
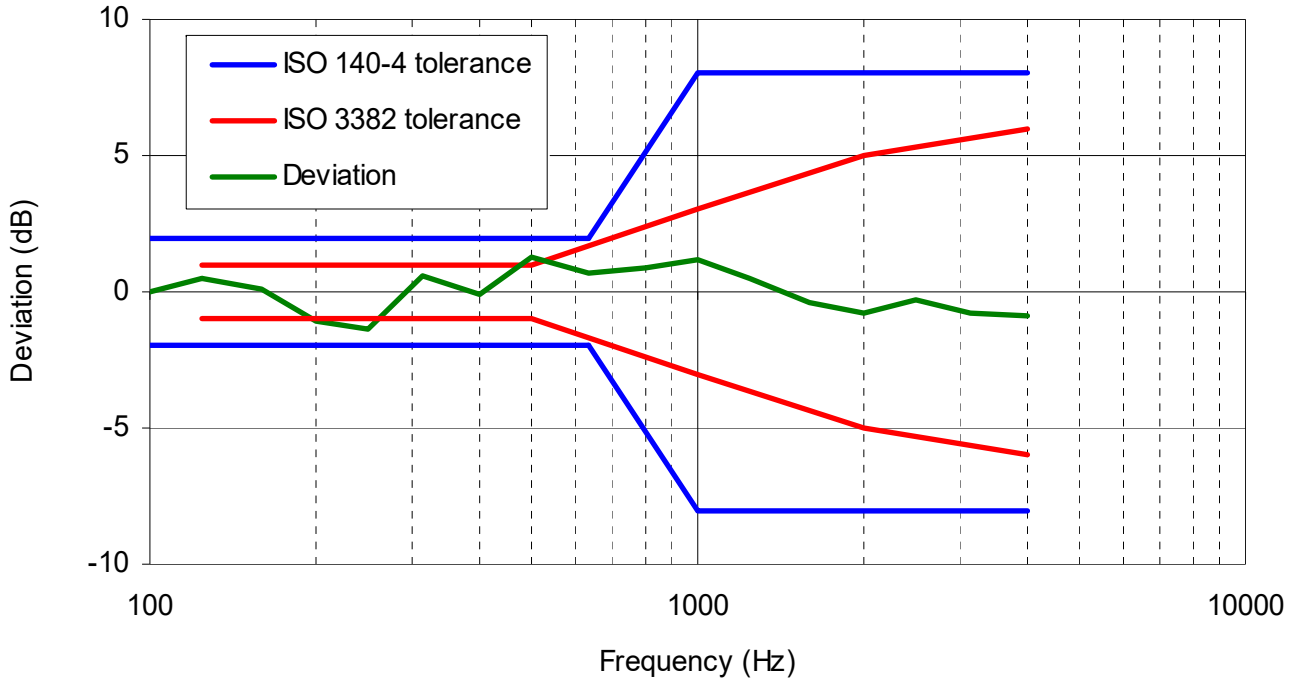
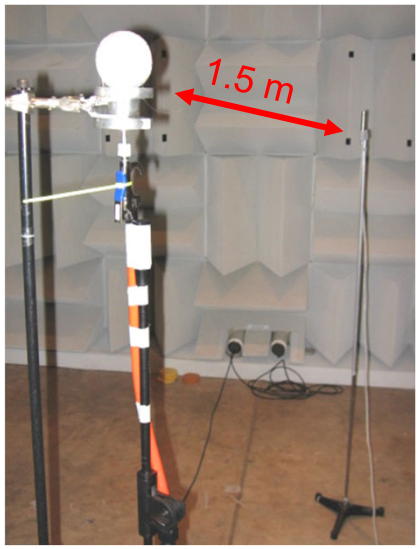


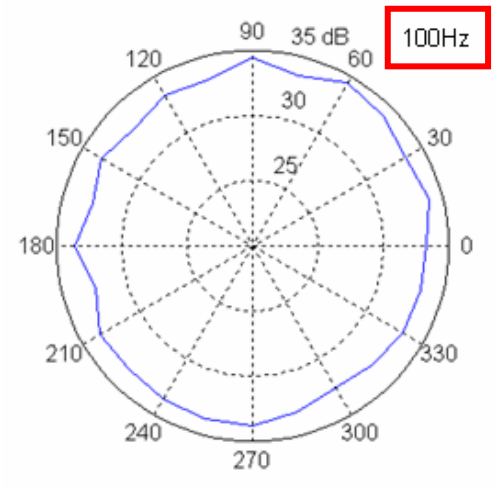
Acoustic Monopole Directivity

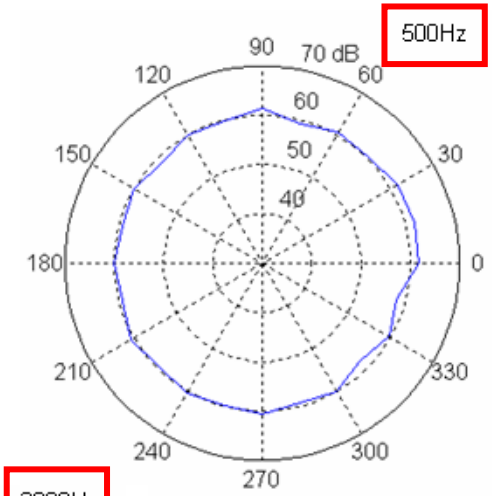


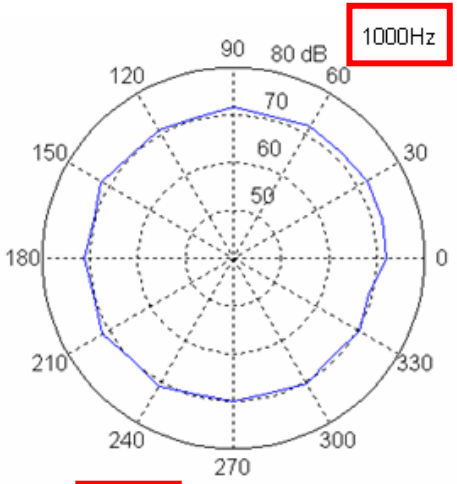


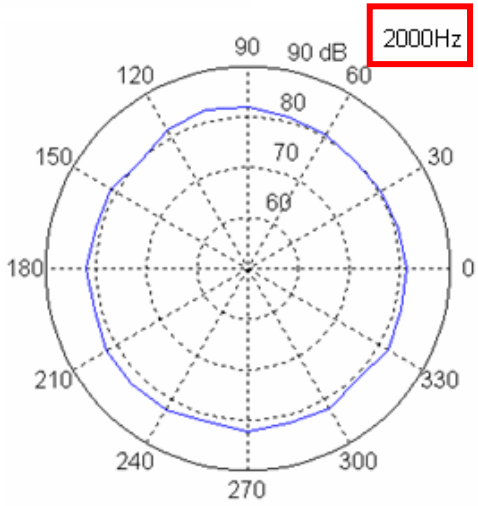
- Distance from the source to the microphone is 1.5 m,
- Deviation is obtained by averaged over “gliding” 30° arc,
- Reference value is 360° energetic average.

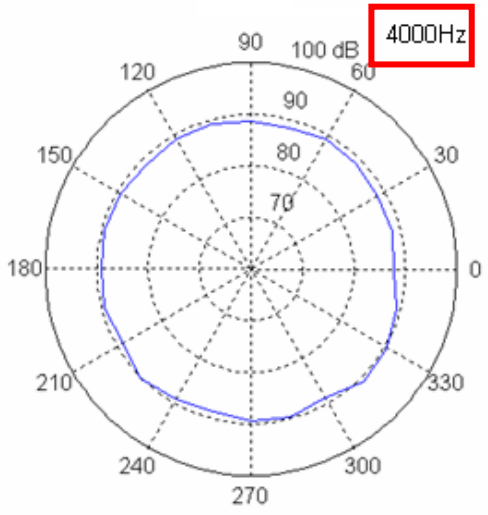
Acoustic Monopole Directivity











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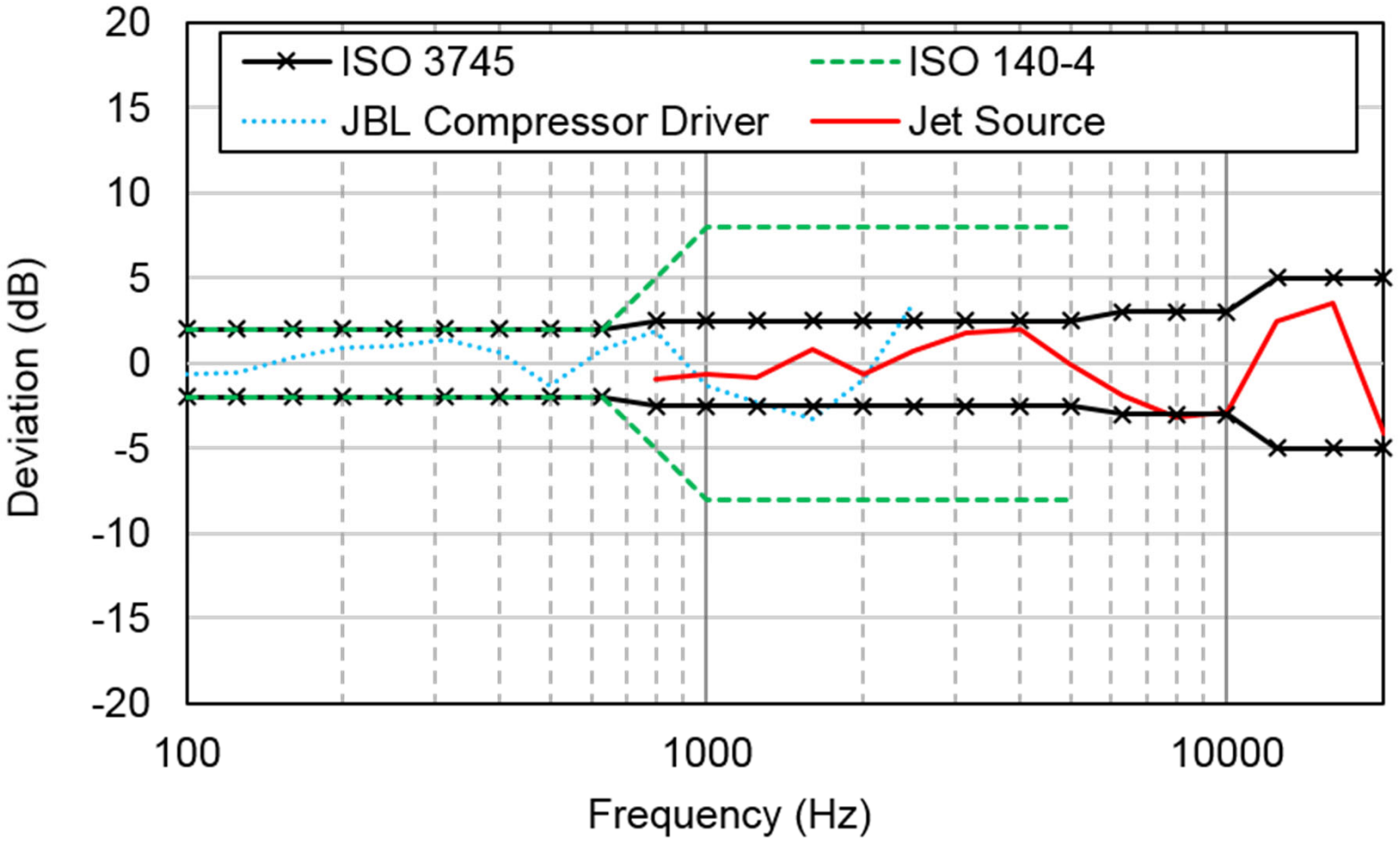

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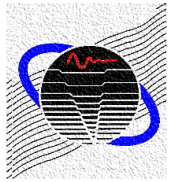
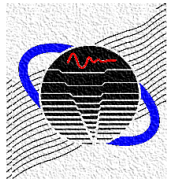


Scaling Rules - Assumptions

- Assume that the gas is air in both full-scale case and scale model.
- Assume panel is constructed out of the same material as full-scale case.
- Assume panel transmission loss is solely dependent on the panel mass.
- Ignore panel mode effects (at low frequencies).



Scaling Rules

Acoustic Scaling

$$\gamma_L \gamma_f = 1$$

Sound Absorption Scaling

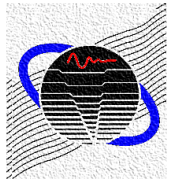
$$\gamma_f \gamma_\sigma^{-1} = 1$$

Panel TL Scaling

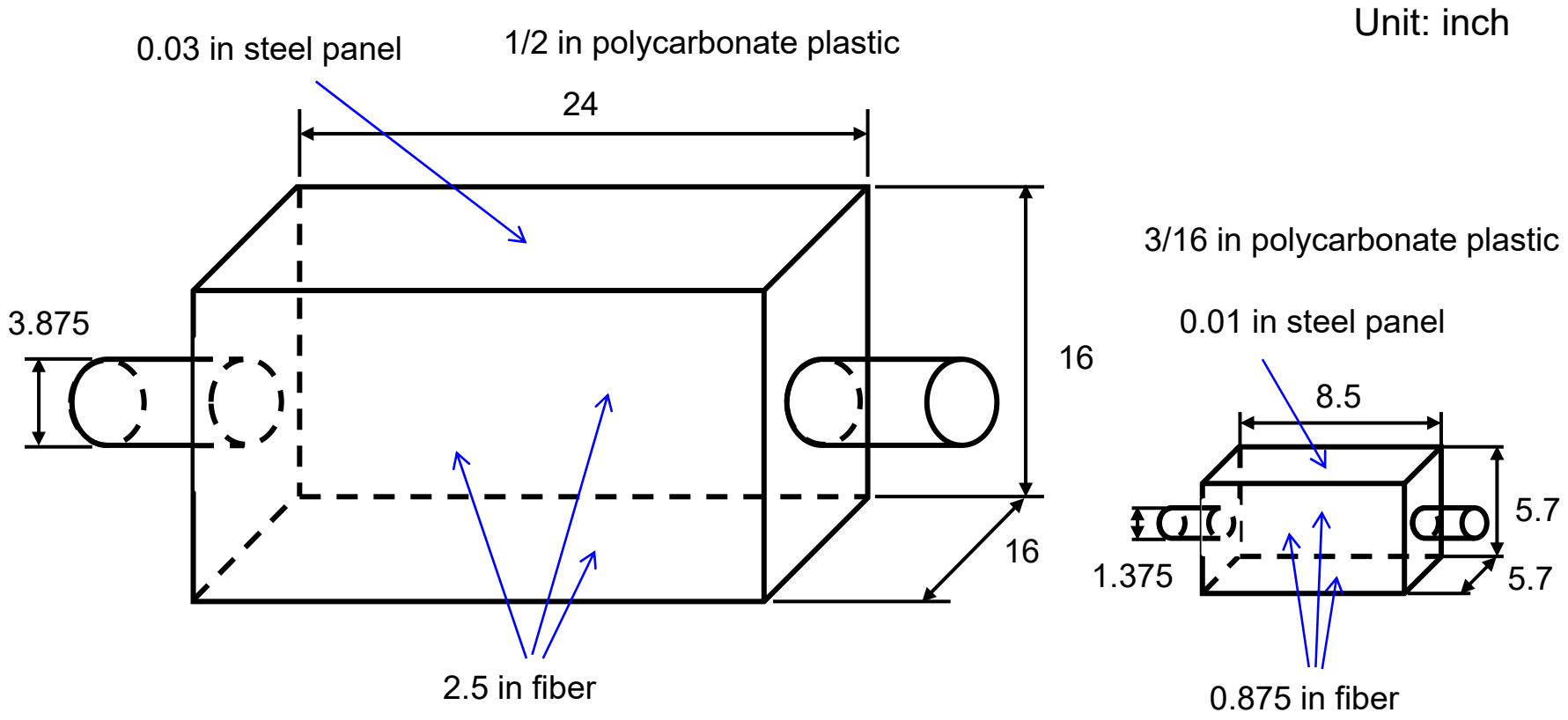
$$\gamma_h \gamma_f = 1$$

$$\gamma_h \gamma_L^{-1} = 1$$

L	Length
f	Frequency
σ	Flow Resistivity
h	Panel Thickness



Example Lined Expansion Chamber



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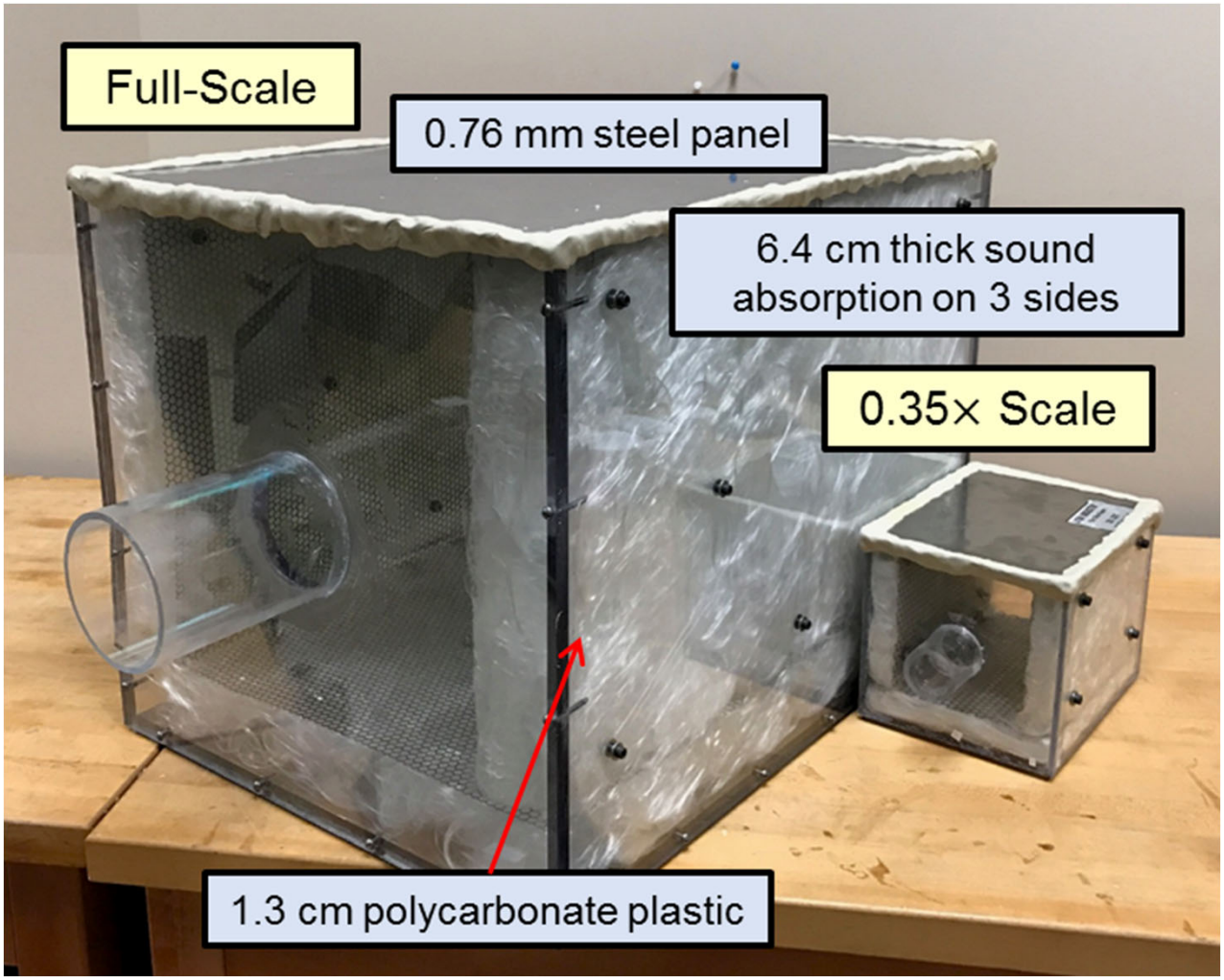

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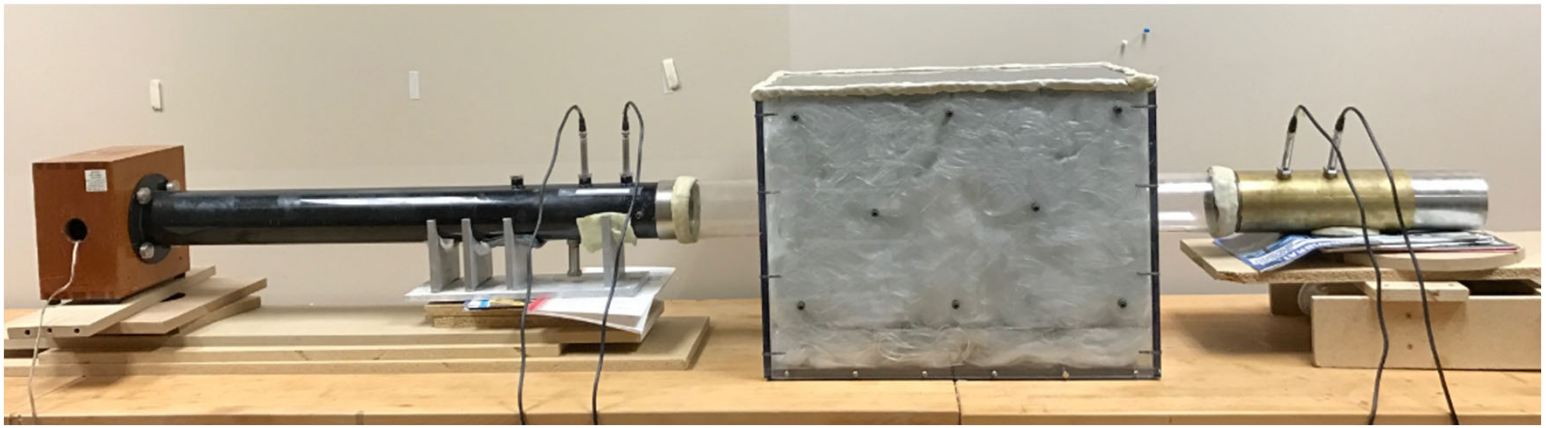

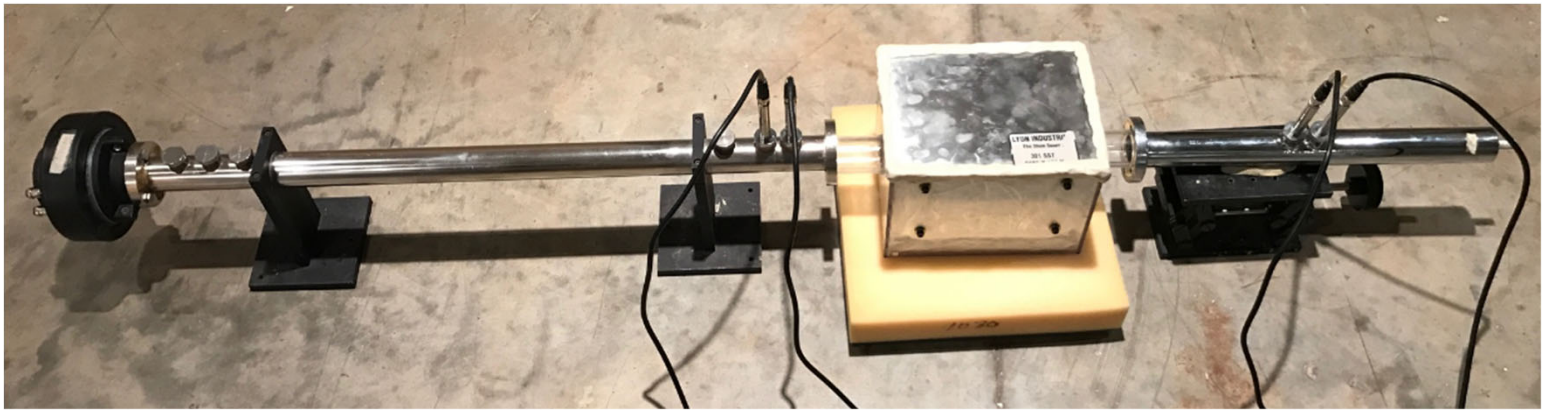

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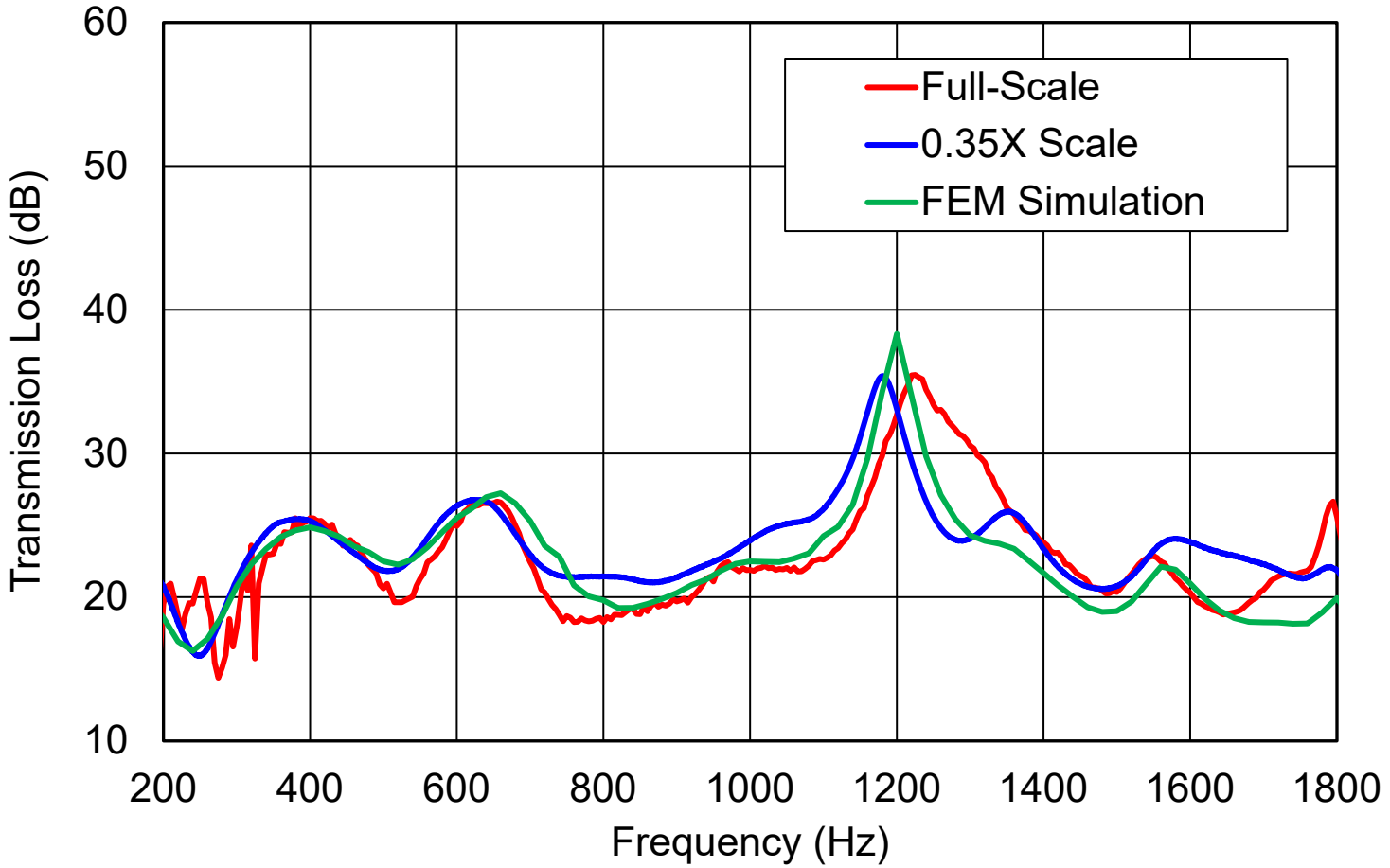

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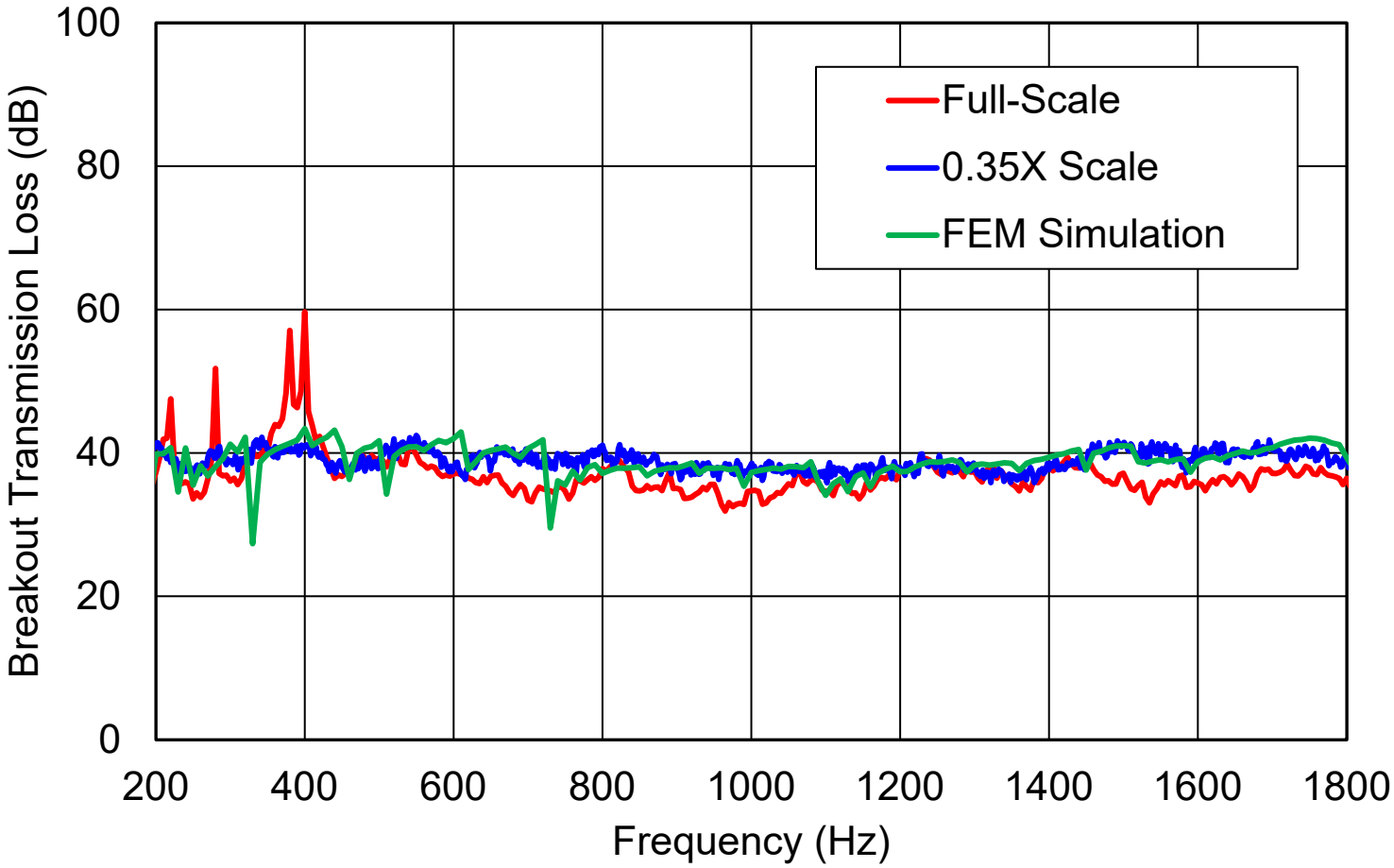

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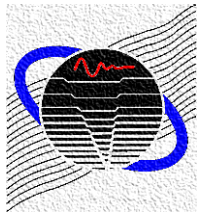
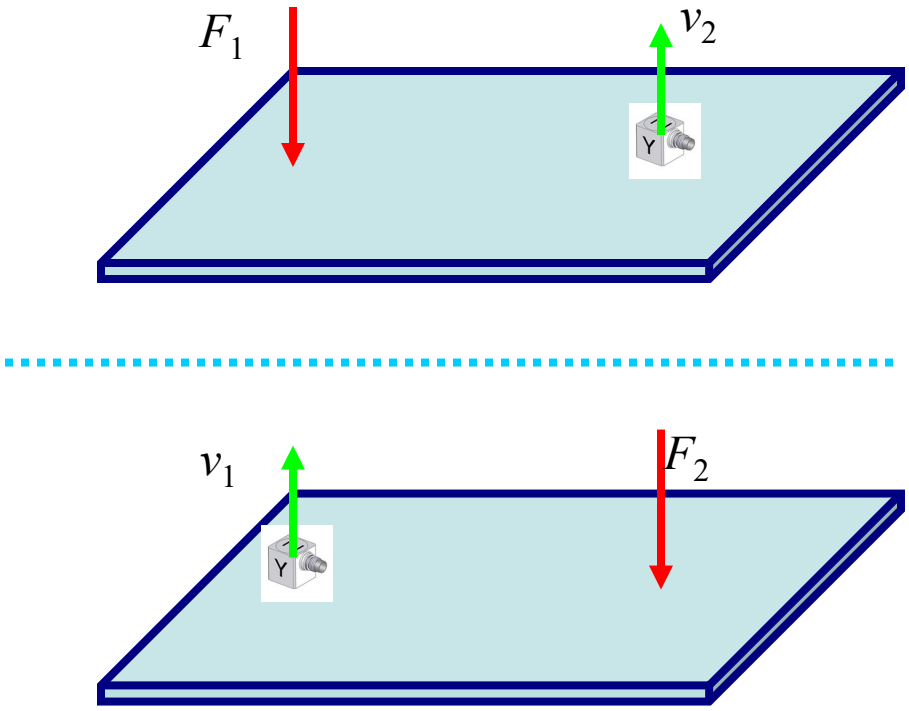


Verheij, 1997

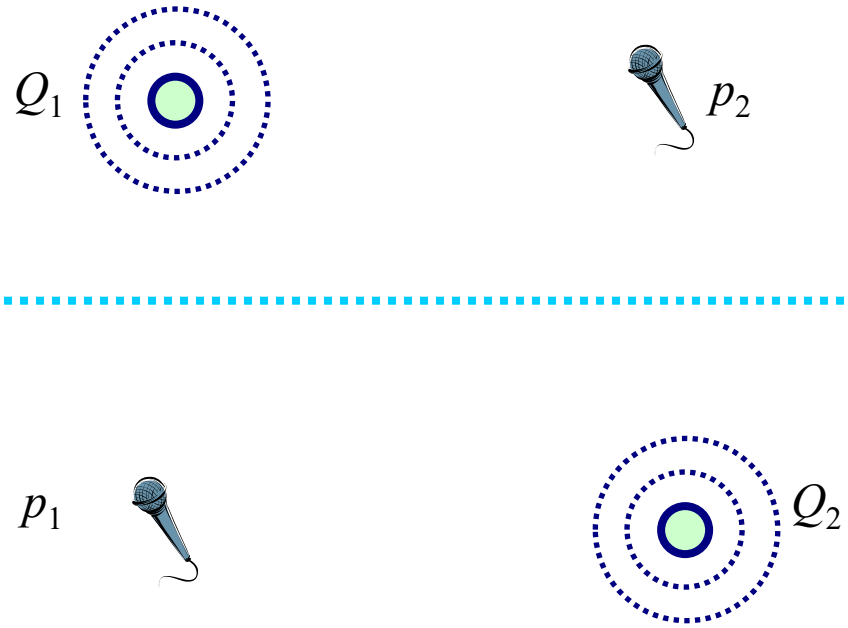
Mechanical-Mechanical Reciprocity



$$\frac{v_2}{F_1} = \frac{v_1}{F_2}$$

Verheij, 1997

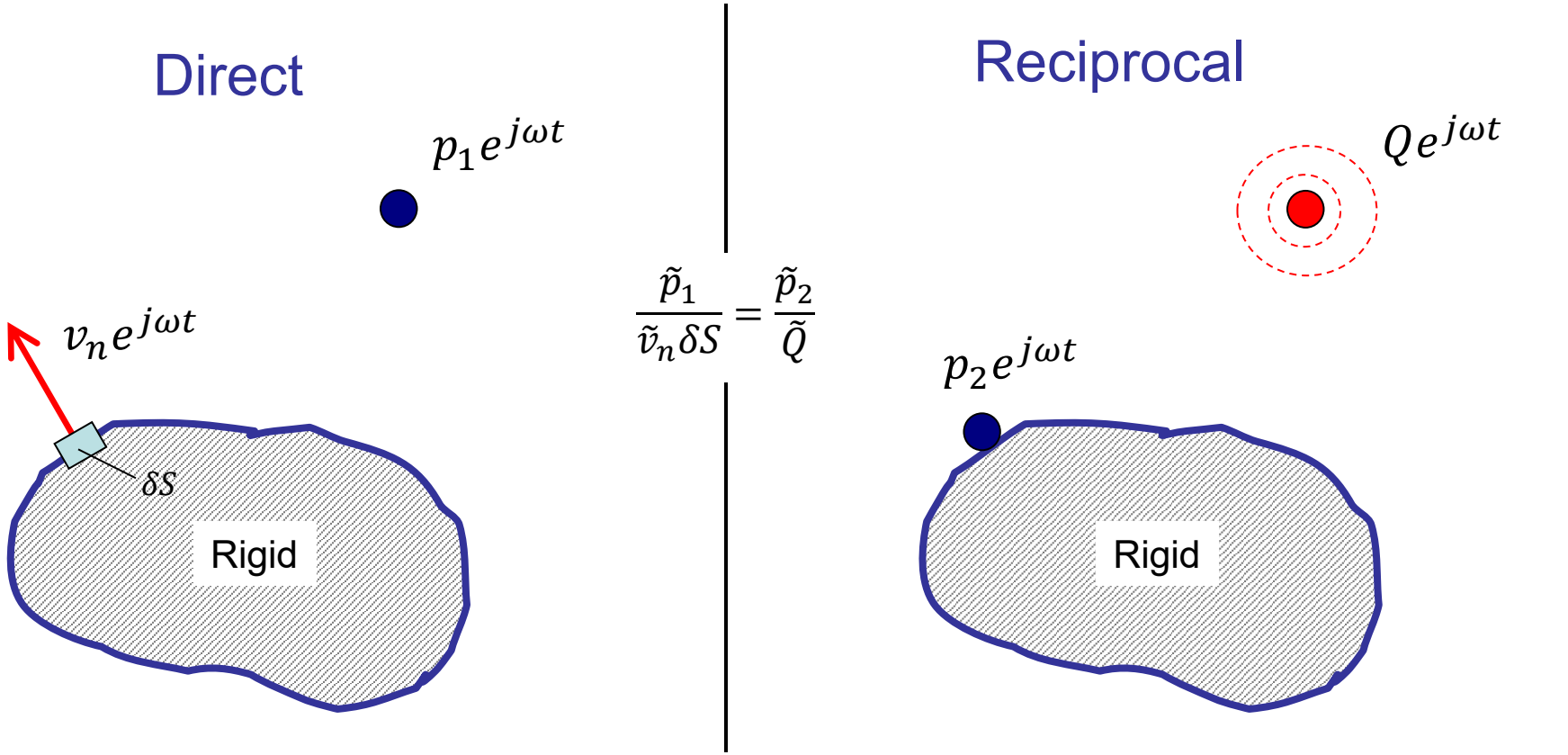
Acoustic-Acoustic Reciprocity



$$\frac{p_2}{Q_1} = \frac{p_1}{Q_2}$$

Fahy, 1995

Mechanical-Acoustic Reciprocity



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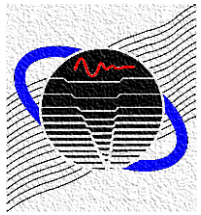
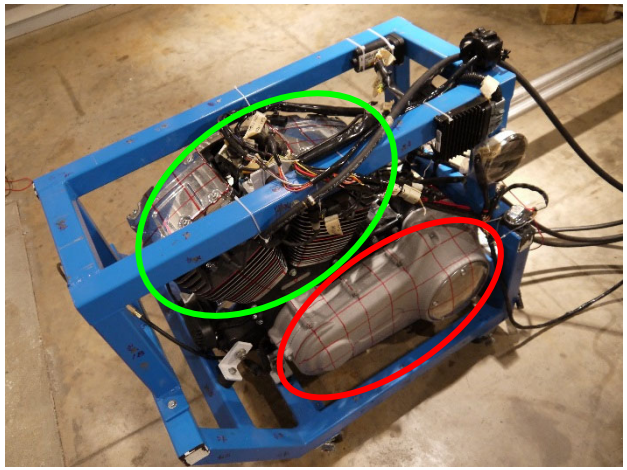
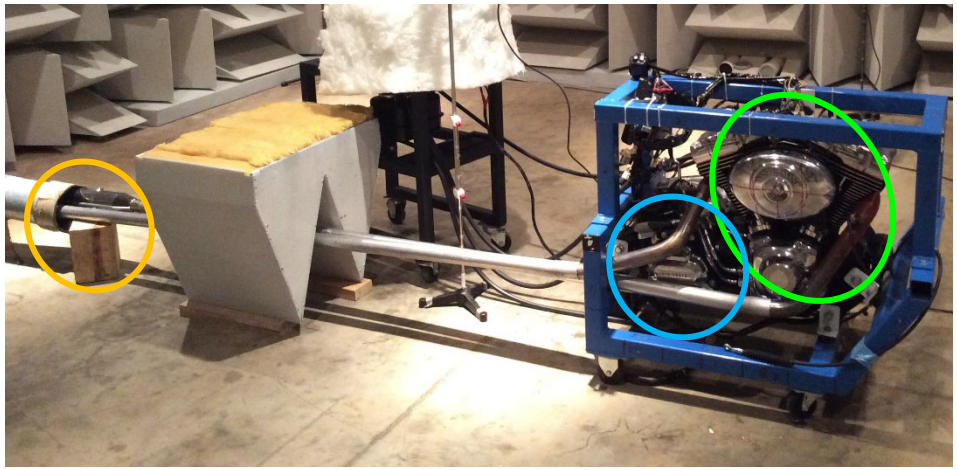


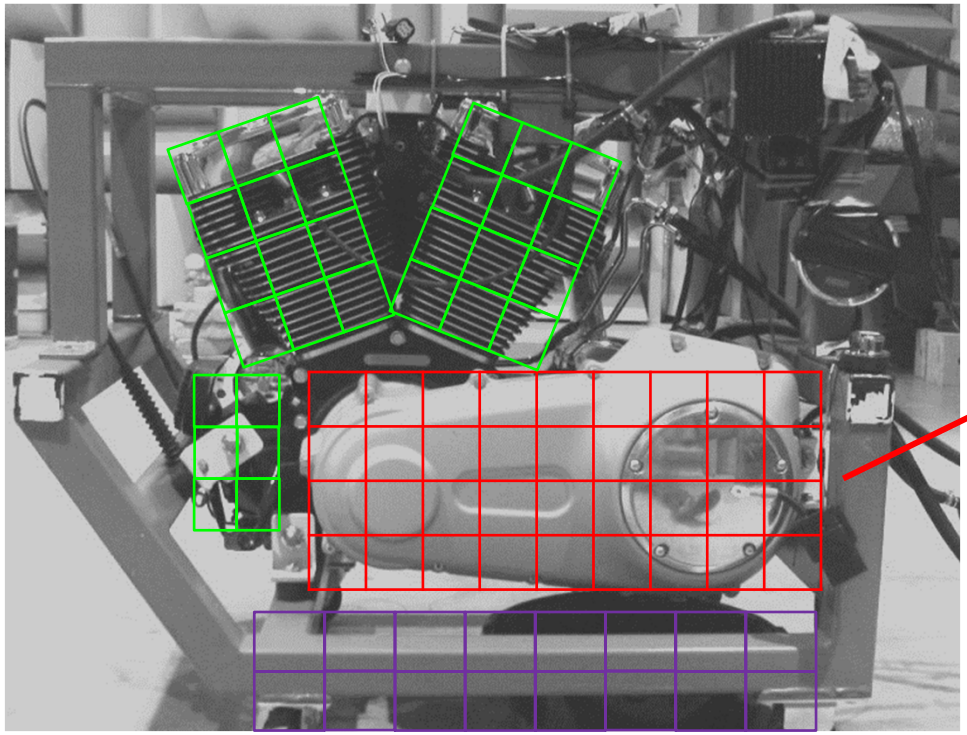
Test Case Motorcycle Engine





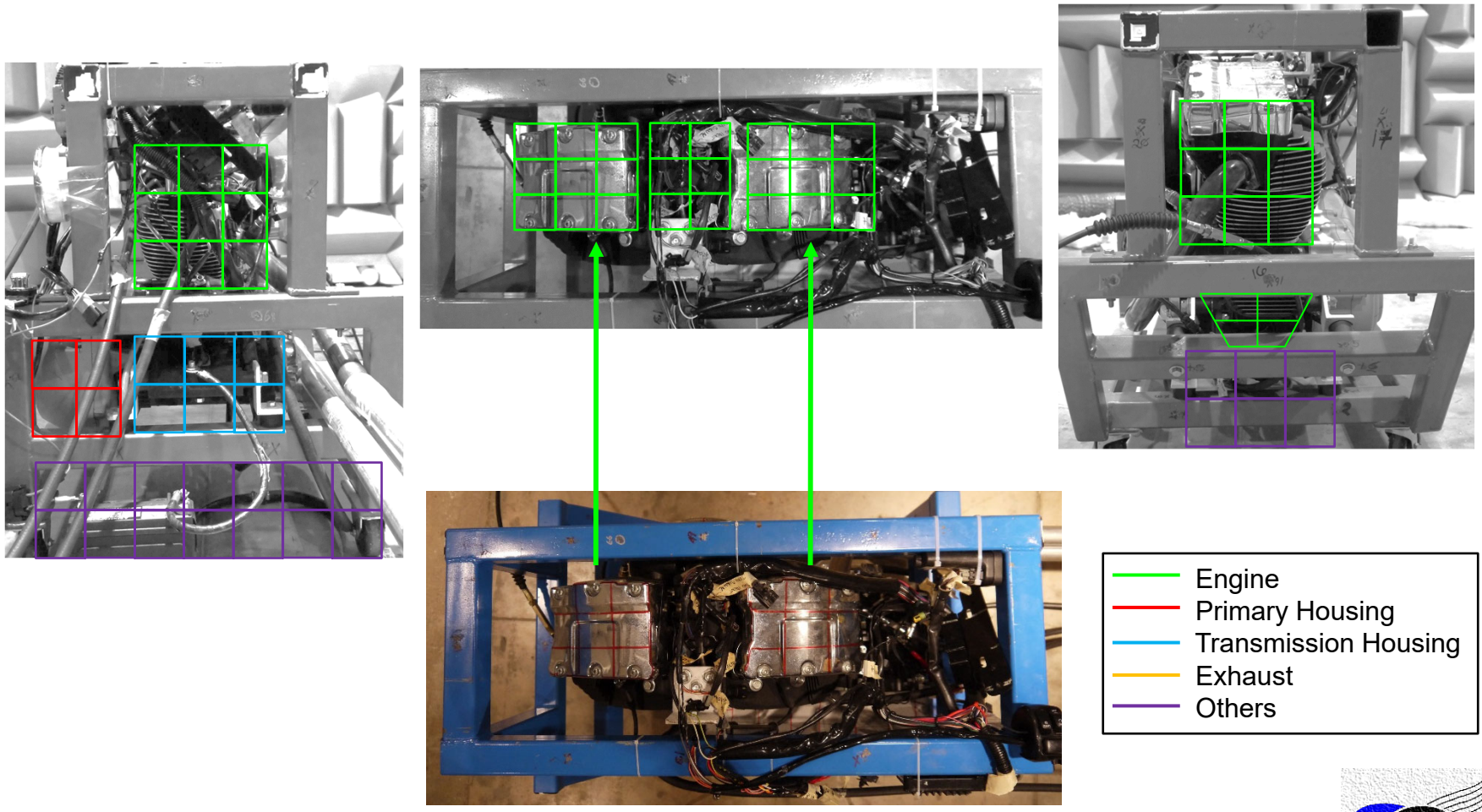
Engine Primary Housing Exhaust Transmission Housing

Step 1 Source Discretization



Engine
Primary Housing
Transmission Housing
Exhaust
Others

Step 1 Source Discretization



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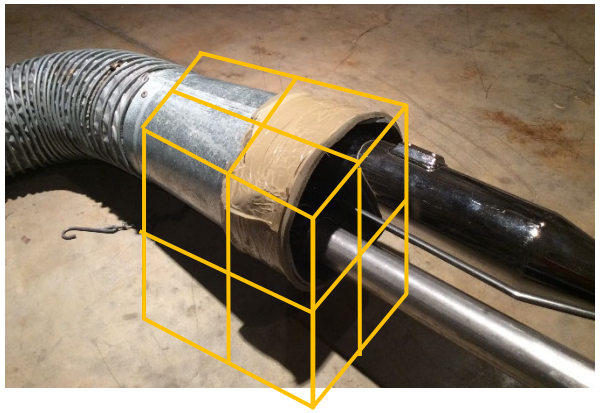
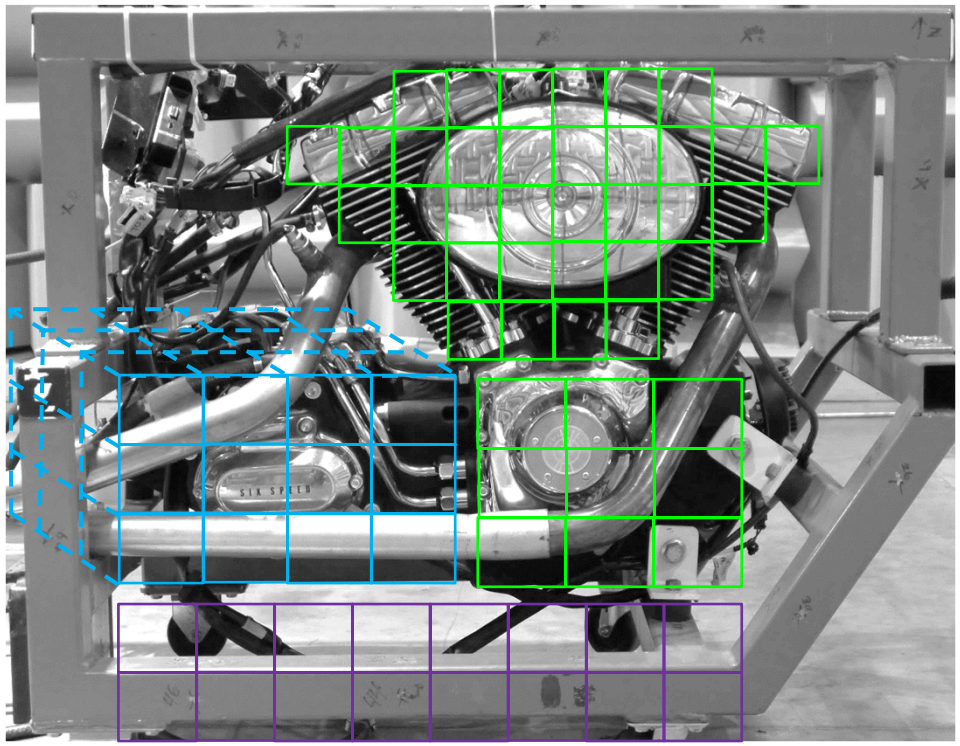
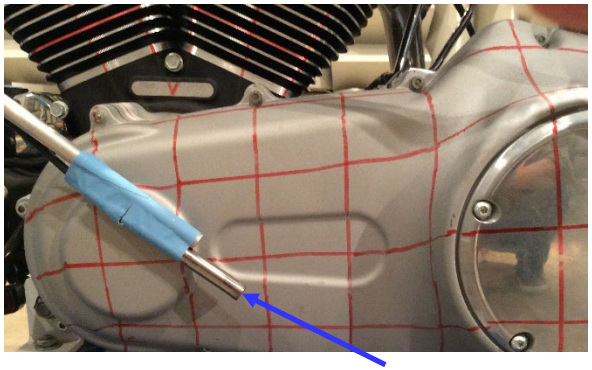


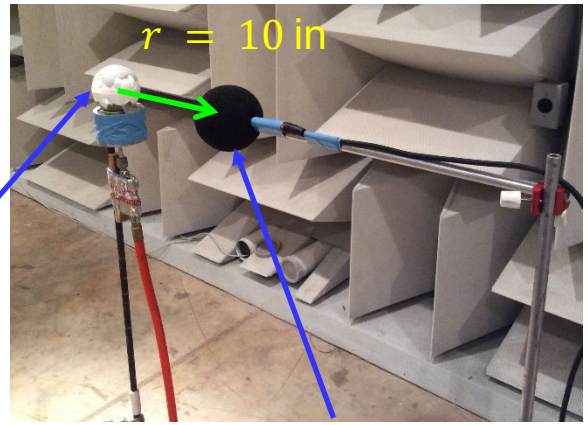


- Engine
- Primary Housing
- Transmission Housing
- Exhaust
- Others

Step 2 Measure Transfer Functions



Mic 2 (p_i)

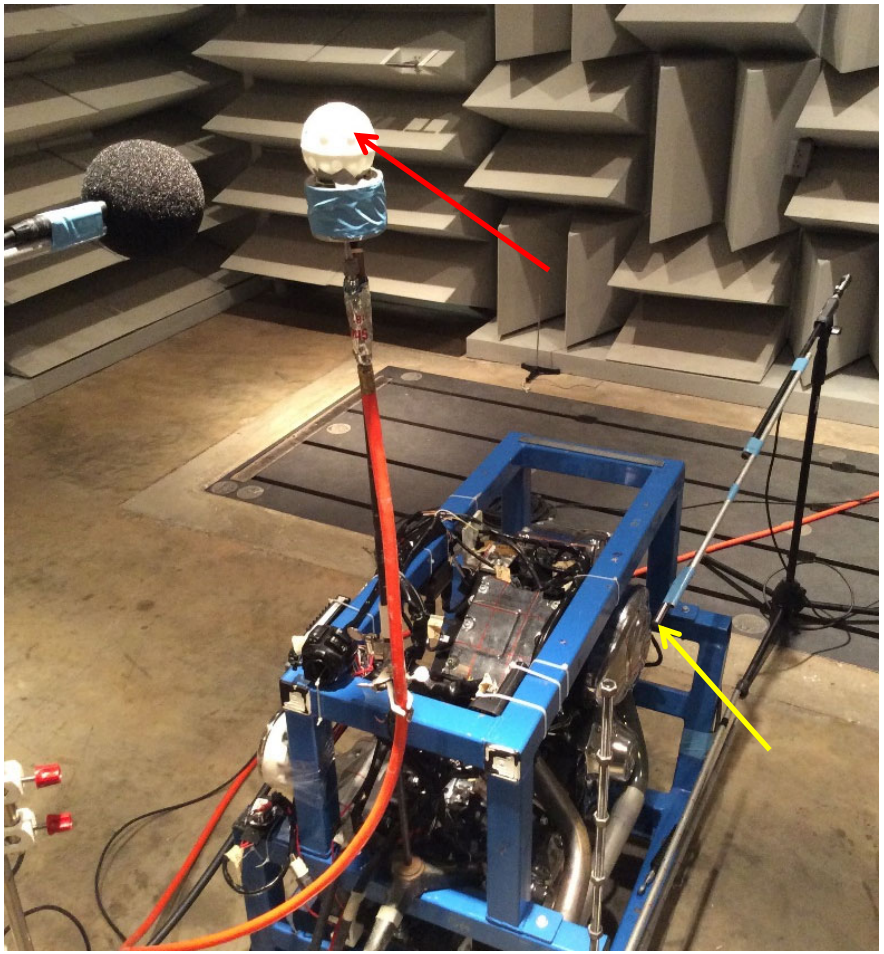


Point Source

Mic 1 (p_o)

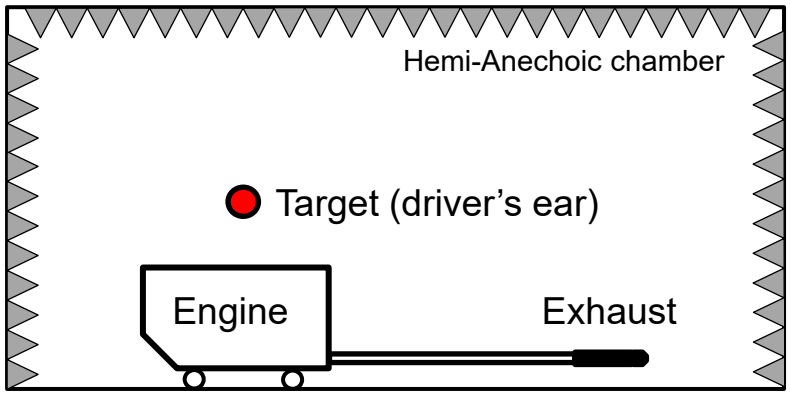
$$TF_i = \frac{p_i}{Q} \quad \text{where} \quad Q = \frac{4\pi r p_o}{\rho_0 i\omega} e^{+ikr}$$

Step 2 Measure Transfer Functions

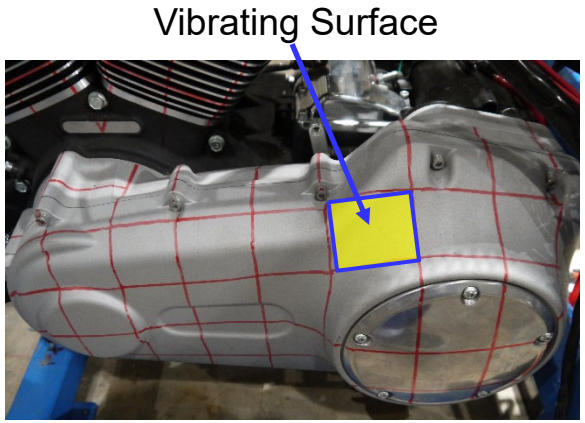


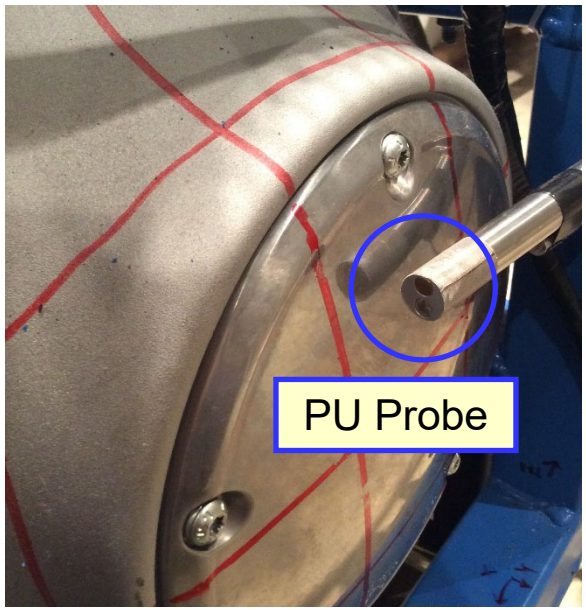
Mechanical-Acoustic Reciprocity

$$TF_i = \frac{p_i}{Q}$$



Step 3 Determine Volume Velocity





- Correlated monopoles (maintains phase)

$$Q_i = v_i \cdot S_i$$

- Uncorrelated monopoles (ignore phase)

$$Q_i^2 = (I_i \cdot S_i)\frac{2\pi c}{\rho\omega^2}$$

Step 4 Predict Sound Pressure Level

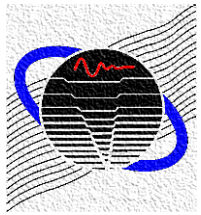
Sound pressure at microphone position can be determined by:

- Correlated monopoles

$$p = \sum_i TF_i \cdot Q_i$$

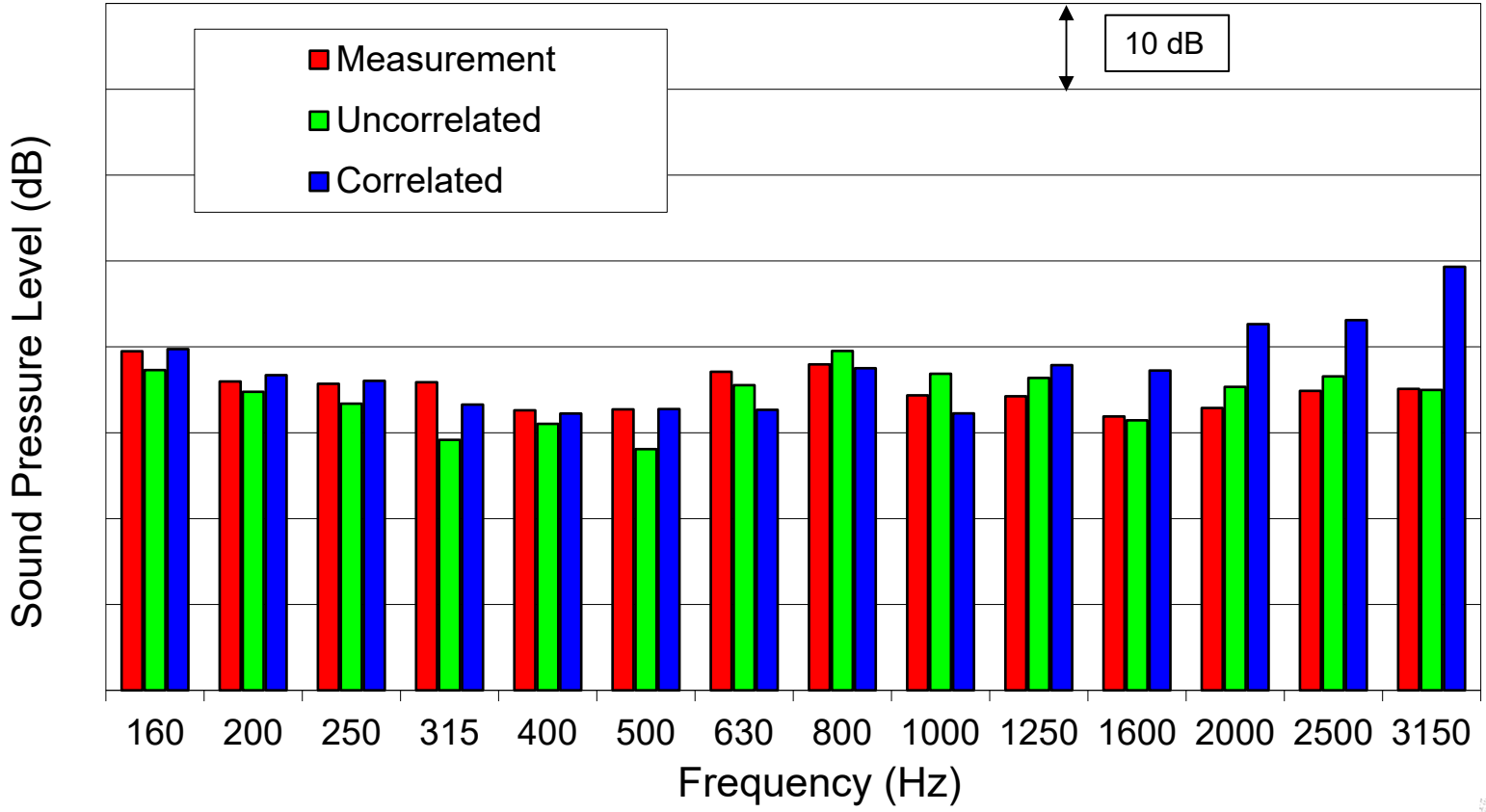
- Uncorrelated monopoles

$$p = \sum_i |TF_i| \cdot |Q_i|$$



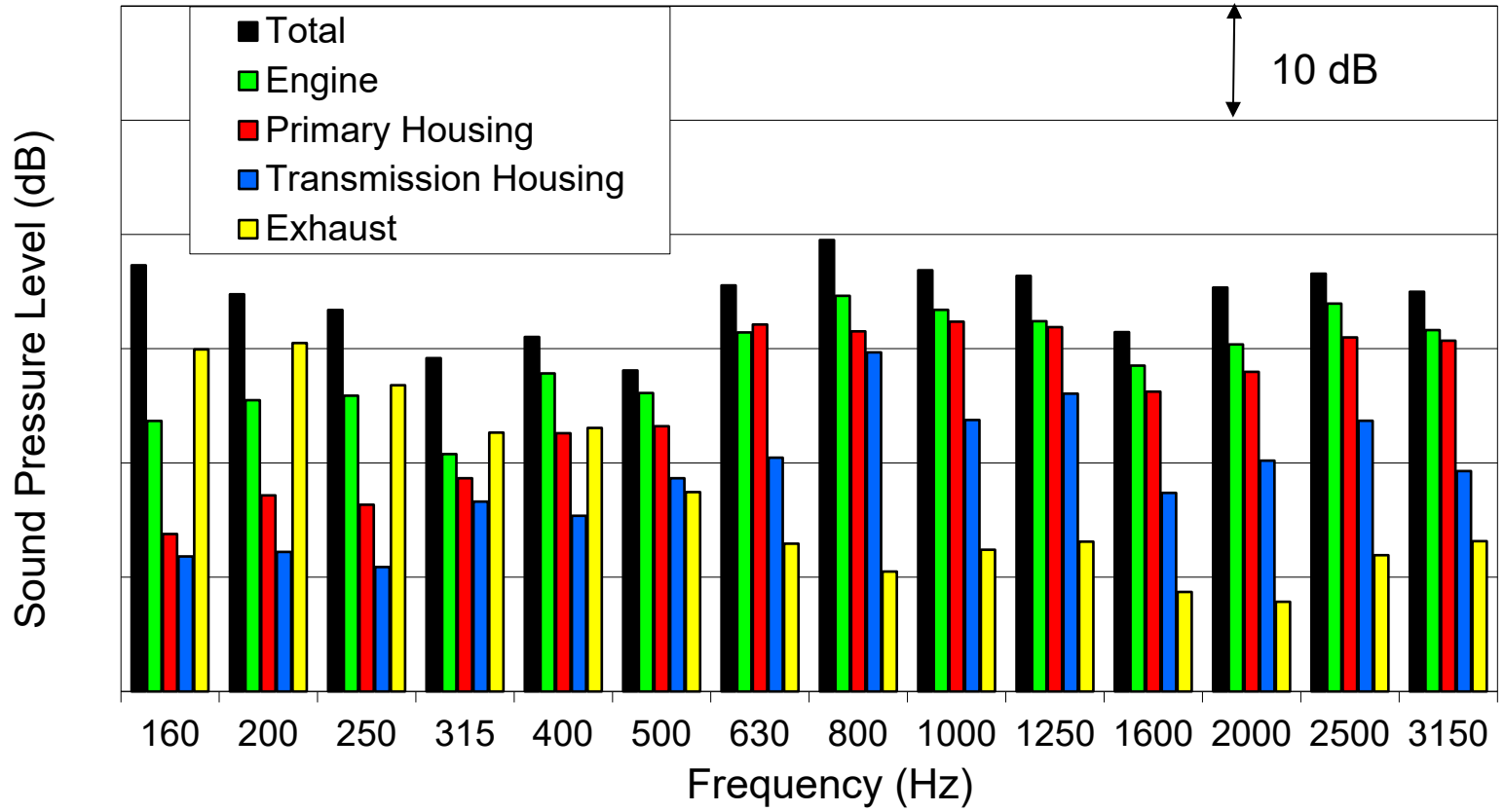
Sound Pressure Level Driver's Ear

Engine Idle (1050 RPM)



Contribution to Sound Pressure Driver's Ear

Engine Idle (1050 RPM)



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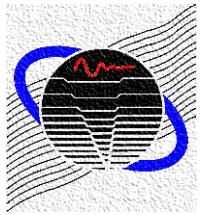
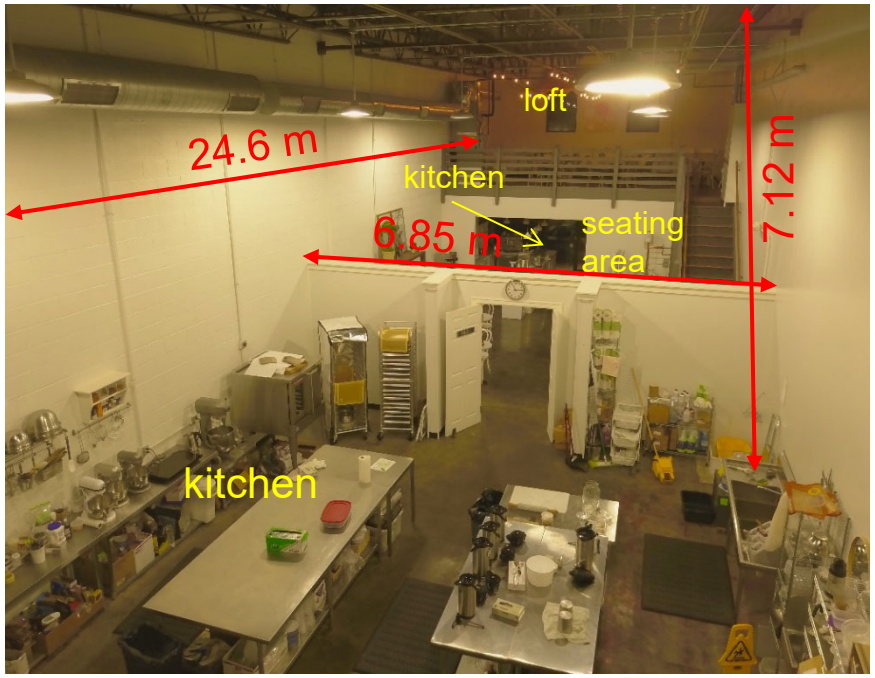
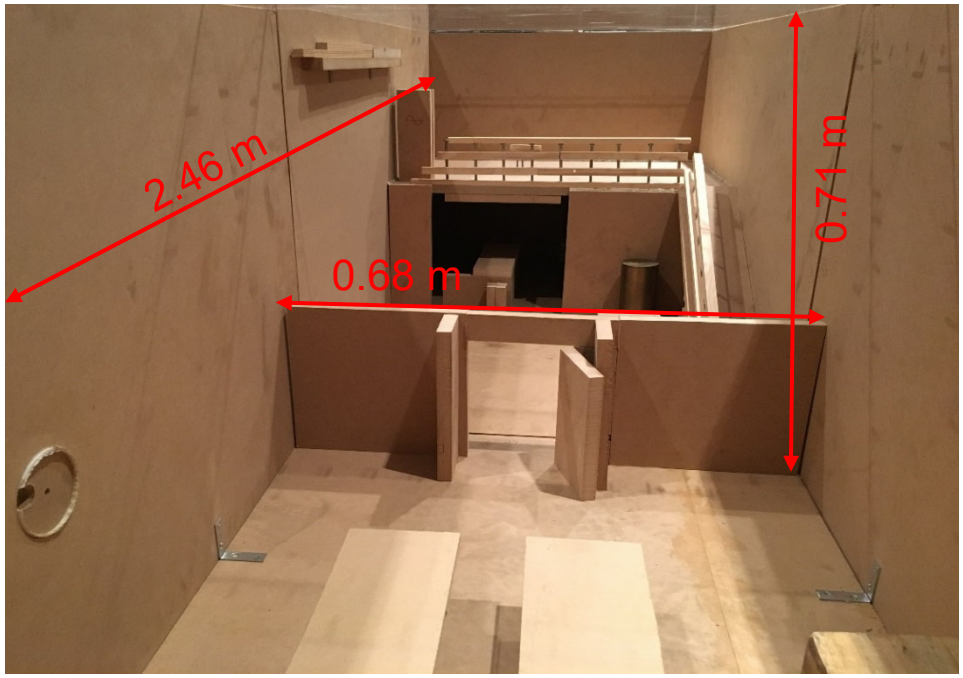


Test Case HVAC Noise in Bakery



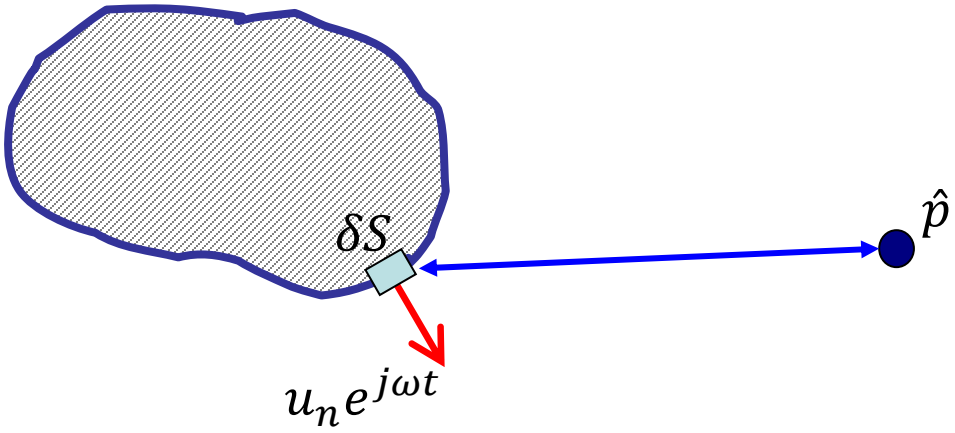
Original Full Model



1/10 Scale Model

All the walls, floors and ceilings are considered rigid.

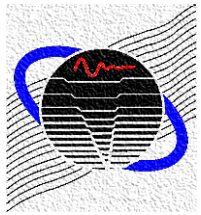
Patch Contribution Analysis



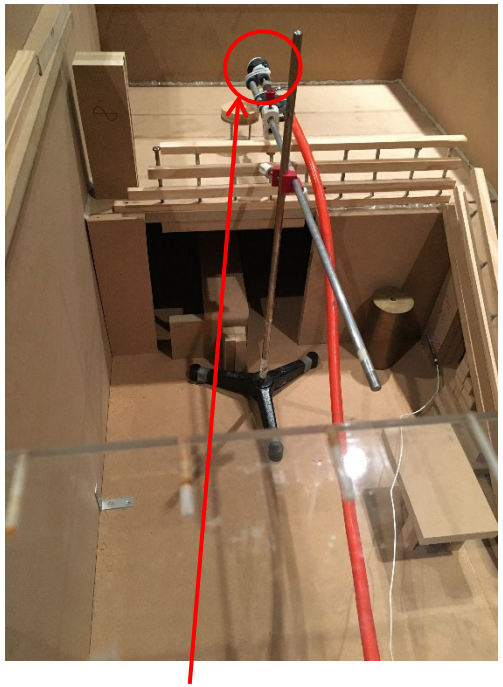
Reciprocal transfer function

$$\hat{p} = \sum_{i=1}^{N} \left((u_n \delta S)_i (TF)_i \right)$$

Measured while running



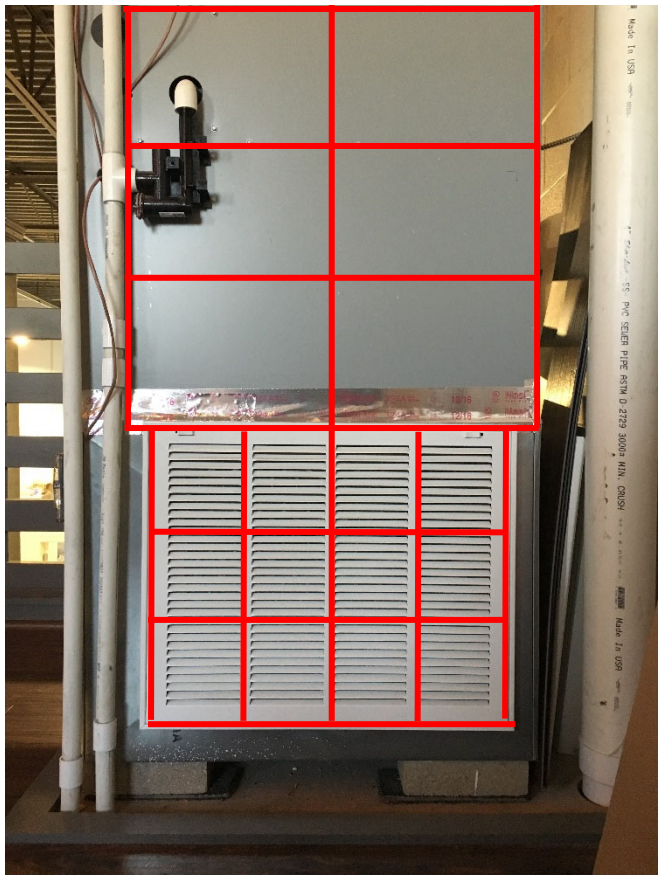
Transfer Functions on Scale Model



Point source located at target position

$$\frac{TF_s}{TF} = \left(\frac{1}{\gamma_L}\right)^2 \text{ with } \frac{f_s}{f} = \frac{1}{\gamma_L}$$

Step 1 Source Discretization

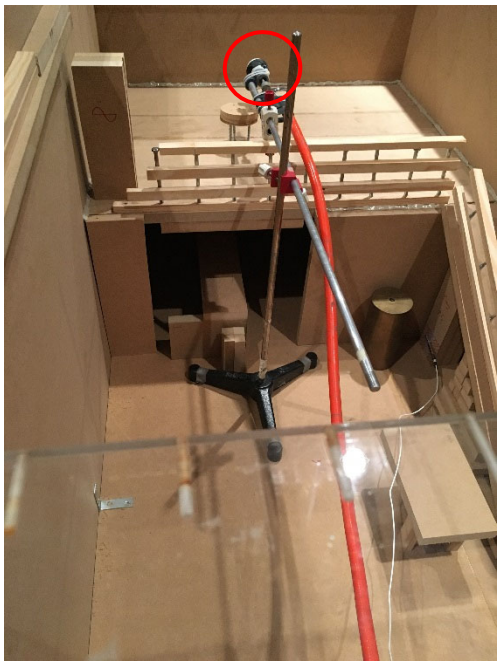


~80 Patches

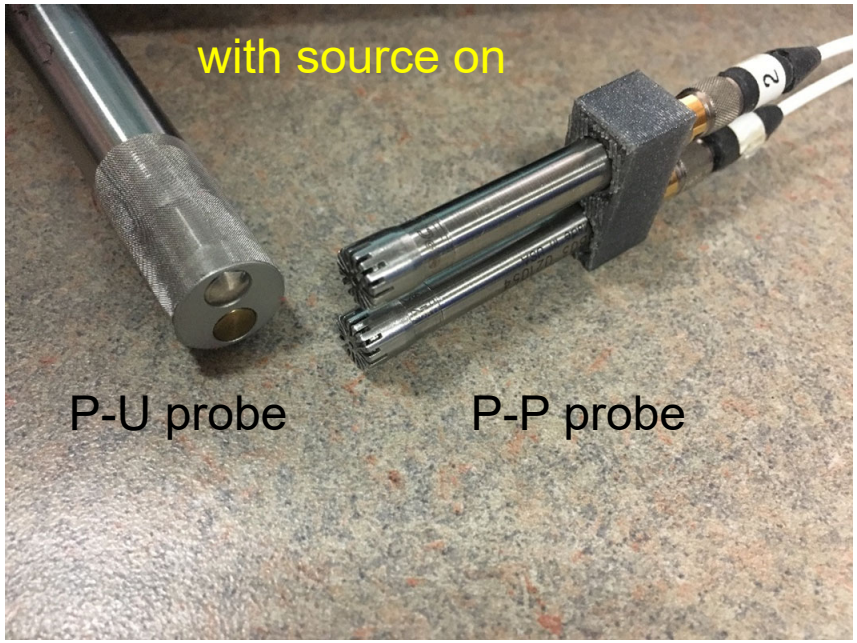
Step 2 Measure Transfer Functions

Full Scale Measurement

1/10th Scale Measurement

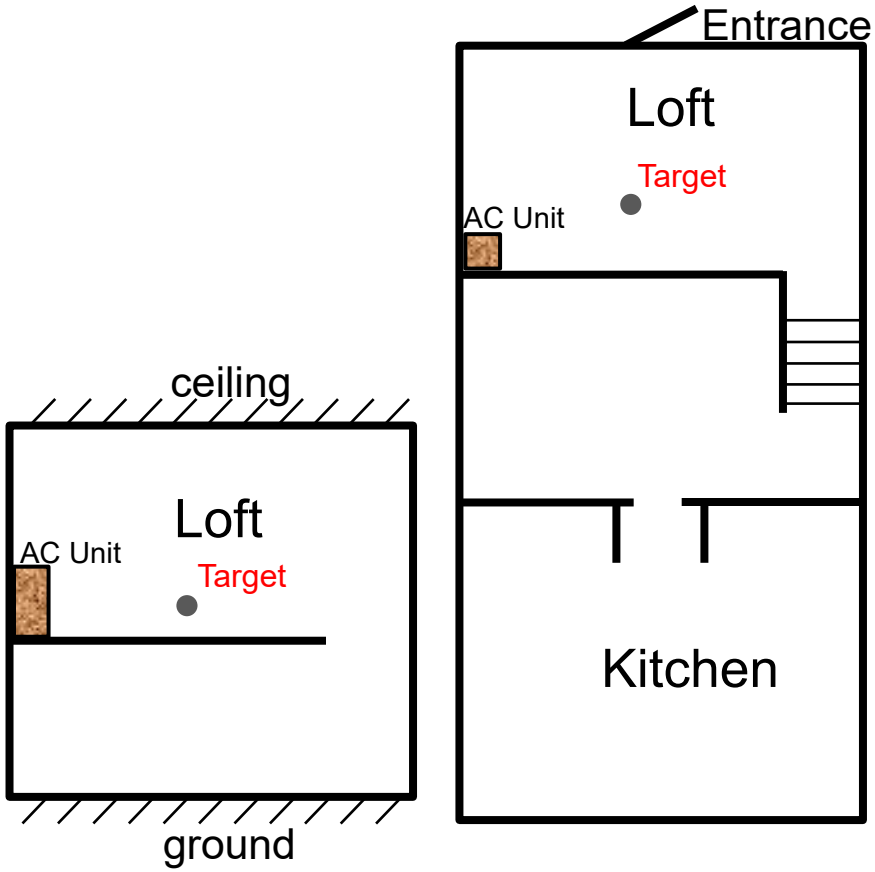


Step 3 Determine Volume Velocity



$$Q_i^2 = \frac{(I_i \cdot S_i)2\pi c}{\rho\omega^2}$$

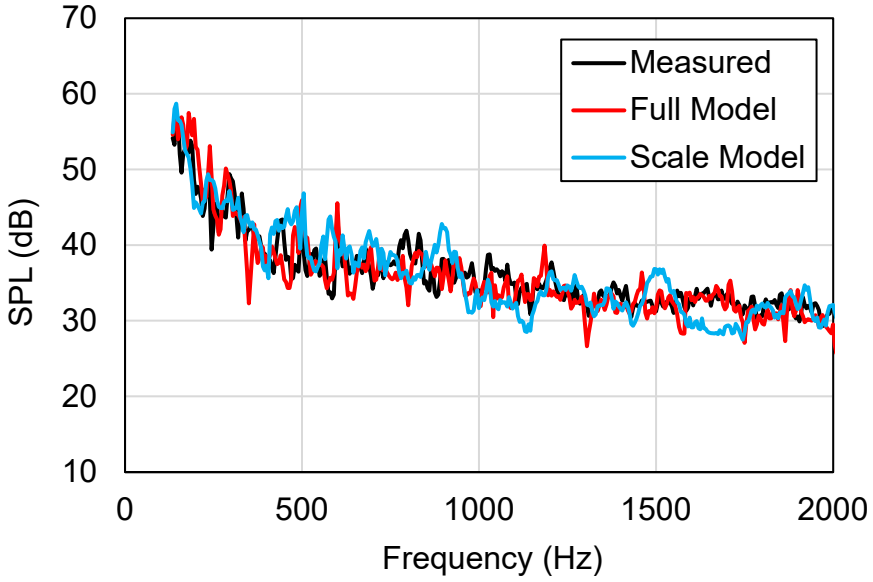
Step 4 Predict Sound Pressure Level

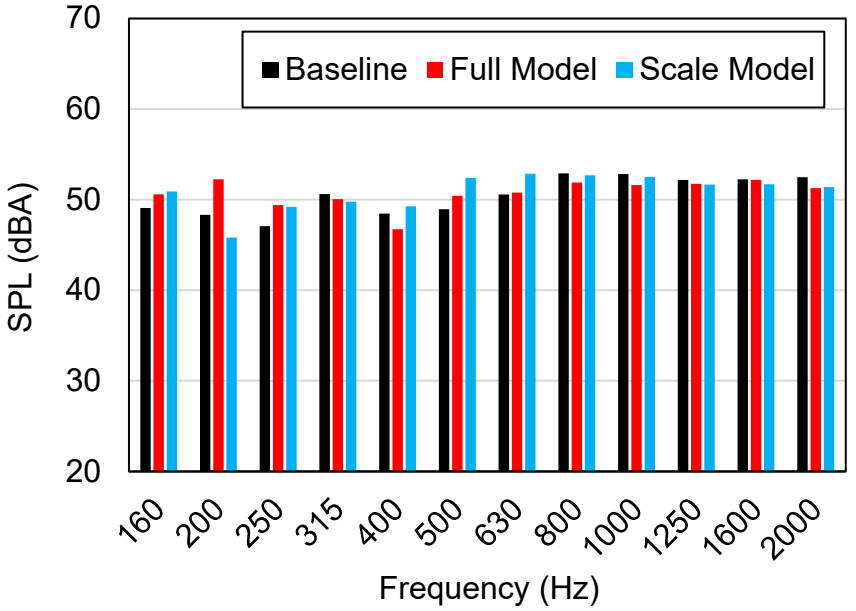


customer table at loft

Step 4 Predict Sound Pressure Level

$$p = \sum_i |TF_i| \cdot |Q_i|$$





The uncorrelated monopole assumption is used during the prediction.

Treatment Barrier

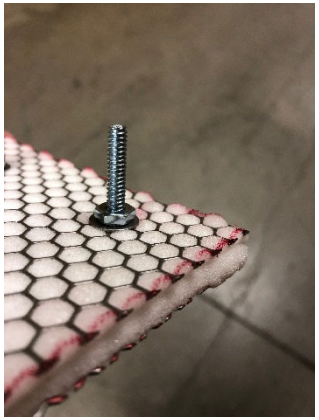
Full model of barrier

Scale model of barrier

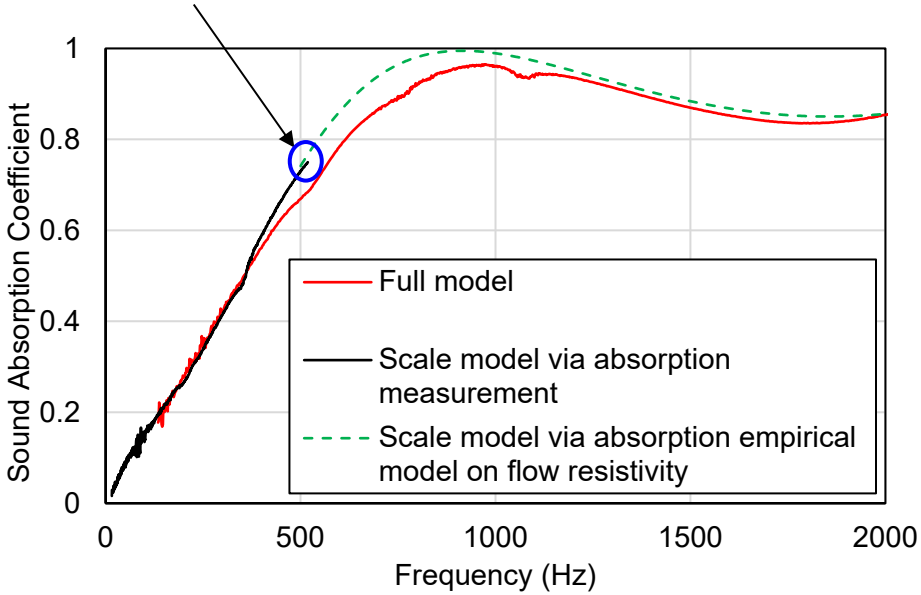
Treatment Sound Absorption

Full model of foam

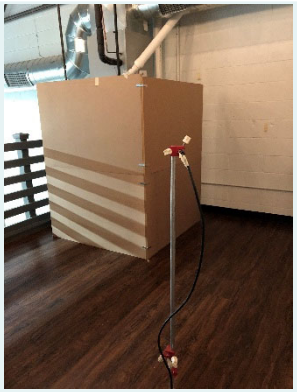
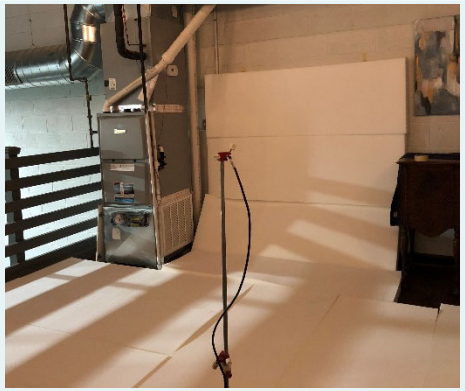
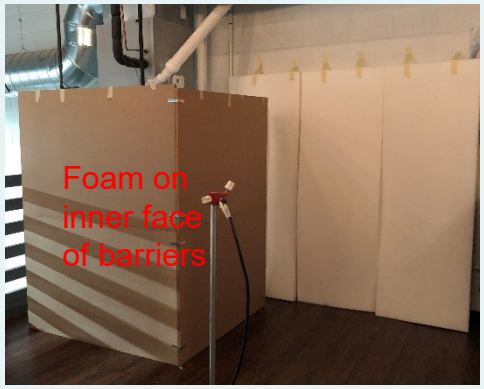
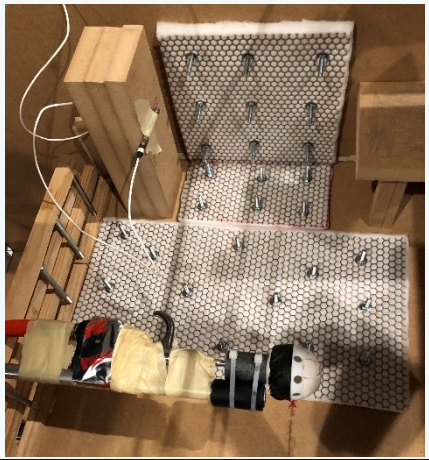
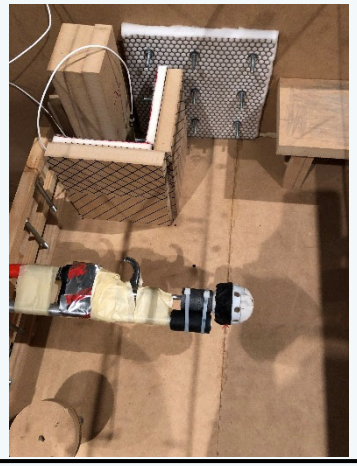
Scale model of foam



Scale model's cut-off frequency via impedance tube measurement

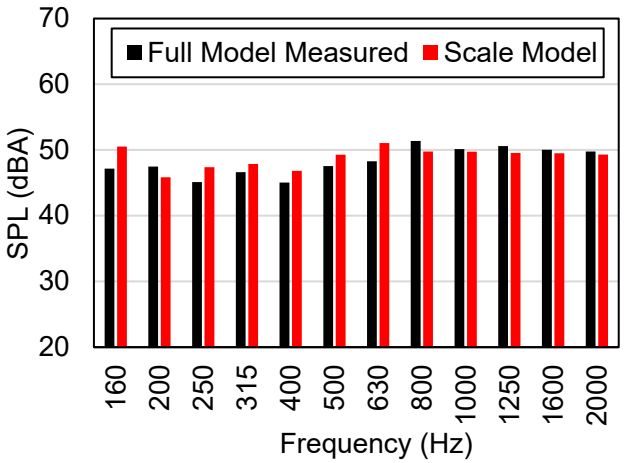


Treatment Configurations

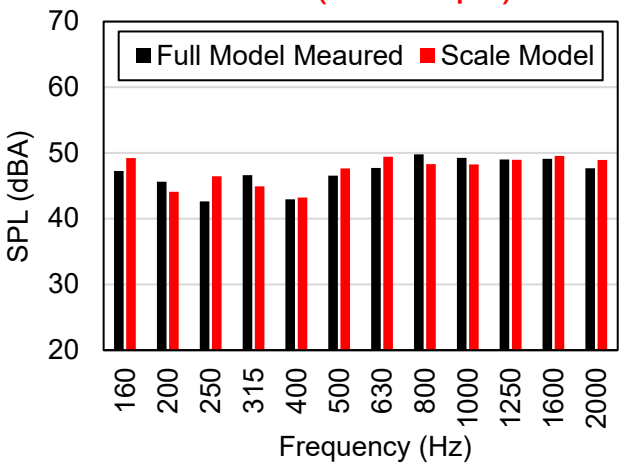
	Barriers	Foam (11.1 sqm)	Barriers + Foam (7.8 sqm)
Full model			
Scale model			

Treatments SPL Prediction

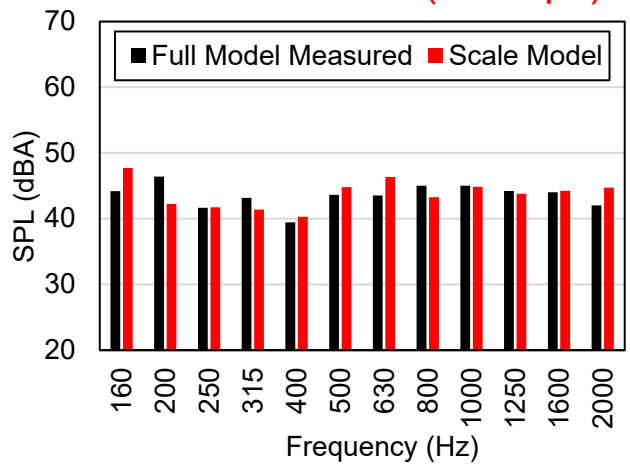
Barriers



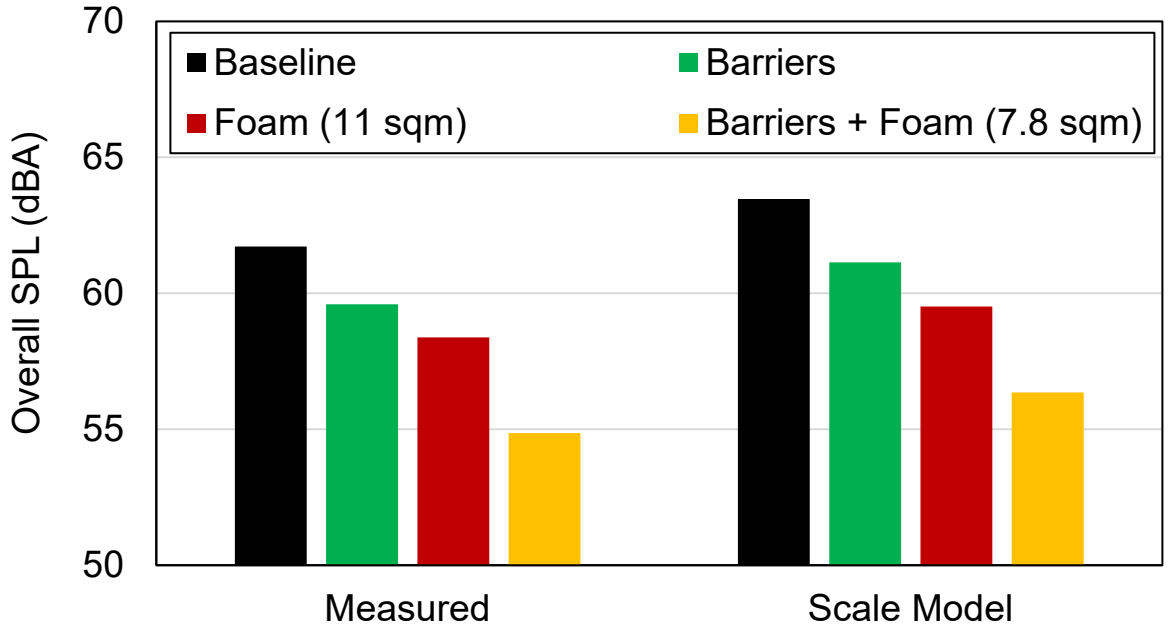
Foam (11.1 sqm)



Barriers + Foam (7.8 sqm)



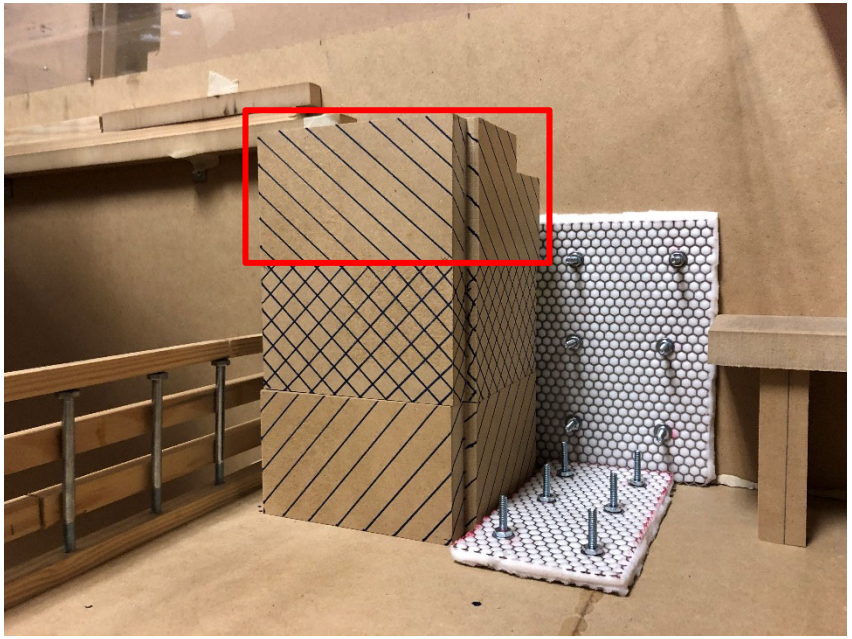
Treatments Overall SPL Prediction



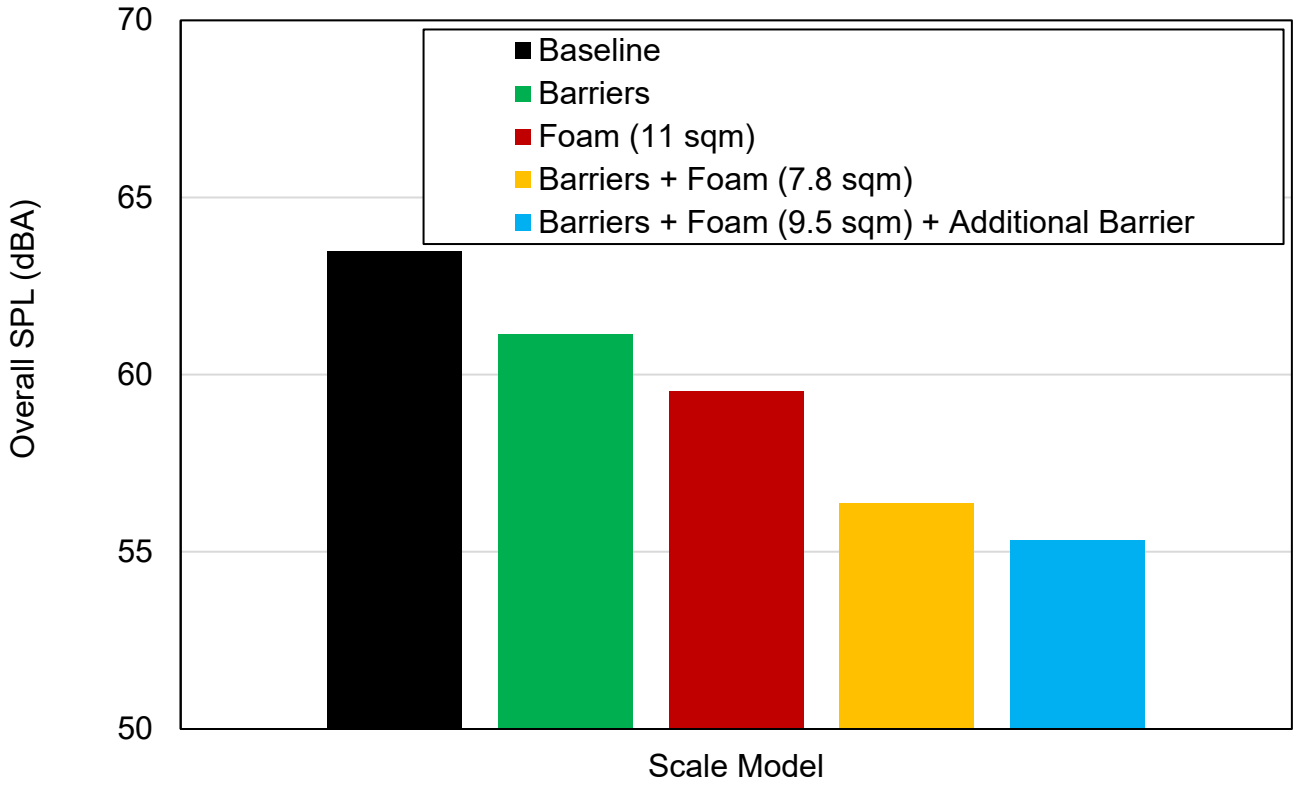
Suggested Modification

Add barrier height (including absorptive backing).

Barriers + Foam (9.5 sqm) + Additional Barrier (including absorption back)

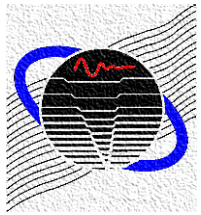


Suggested Modification



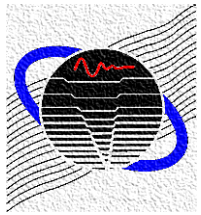
Overview

- Acoustic Monopole
- Homemade Acoustic Monopole
- Vibro-Acoustic Scale Modeling
- Vibro-Acoustic Reciprocity
- Panel Contribution Analysis – Engine Noise
- Panel Contribution Analysis – HVAC Noise in Bakery
- Future Directions



Future Directions

- Interest in investigating panel contribution analysis of transient sources.
- Use of additive manufacturing for creating scale models.
- Investigate methods to speed up the processing.



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