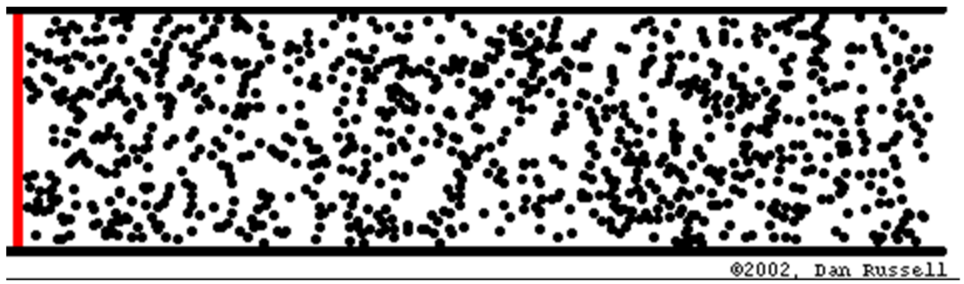
June 11, 2020

Impedance Tube Measurements

Vibro-Acoustics Consortium Web Meeting

University of Kentucky

Plane Waves in a Pipe

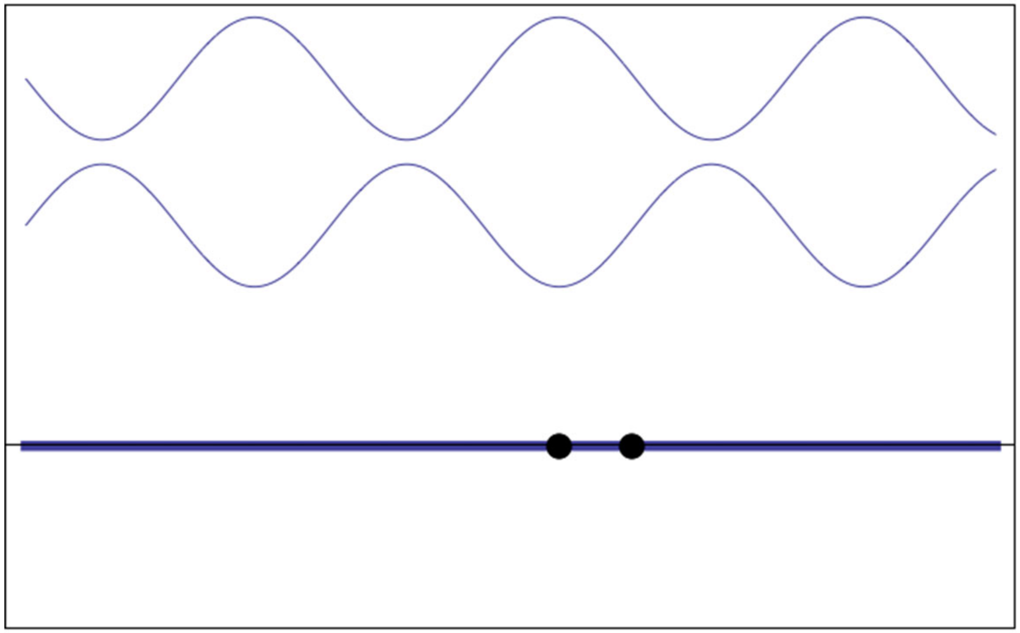


Daniel Russell, Penn State University
https://www.acs.psu.edu/drussell/Demos/waves-intro/waves-intro.html

For a pipe, the cutoff frequency is defined as:

$$f_{cutoff} = \frac{c}{1.71d}$$

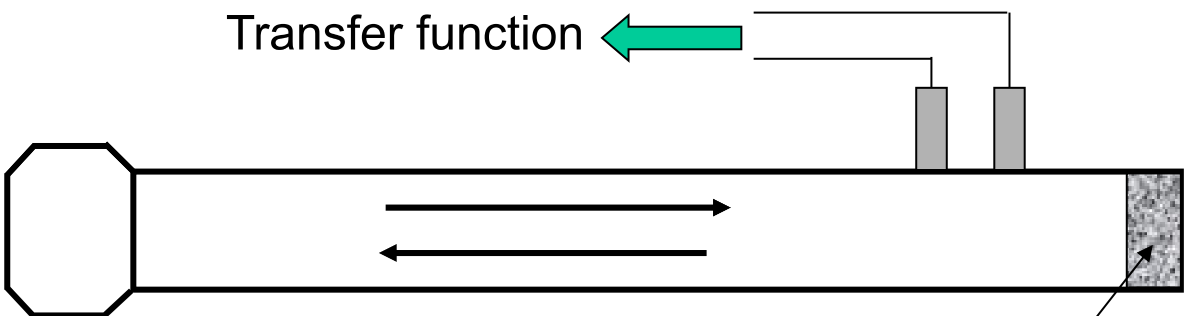
Plane Waves in a Pipe



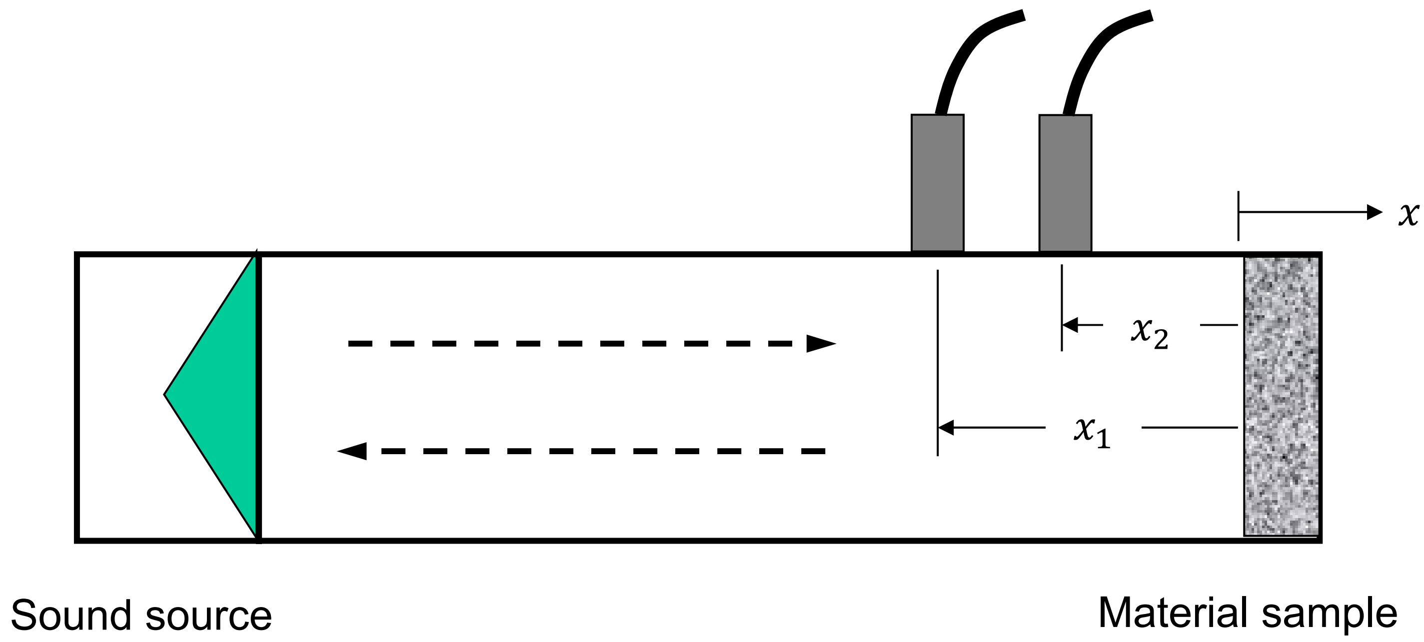
Daniel Russell, Penn State University
https://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

Part 1 Measurement of Sound Impedance

ASTM E1050-95 (ISO 10534-2) Test Method



Coordinate System and Microphone Locations



Plane Wave Theory

Total sound pressure at any point in the tube:

$$P(x) = p_+ e^{-jkx} + p_- e^{jkx}$$

+x traveling wave

-x traveling wave

The transfer function between points 1 and 2:

$$H_{12} = \frac{P(x_2)}{P(x_1)} = \frac{p_+ e^{-jkx_2} + p_- e^{jkx_2}}{p_+ e^{-jkx_1} + p_- e^{jkx_1}} = \frac{e^{-jkx_2} + Re^{jkx_2}}{e^{-jkx_1} + Re^{jkx_1}}$$

$R = \dfrac{p_-}{p_+}$ is the pressure reflection coefficient of the material

Solving for Material Properties

Solving for R:

$$R = \frac{e^{-jkx_2} - H_{12}e^{-jkx_1}}{H_{12}e^{jkx_1} - e^{jkx_2}}$$

Normalized specific boundary impedance:

$$\frac{z}{\rho c} = \frac{1+R}{1-R}$$

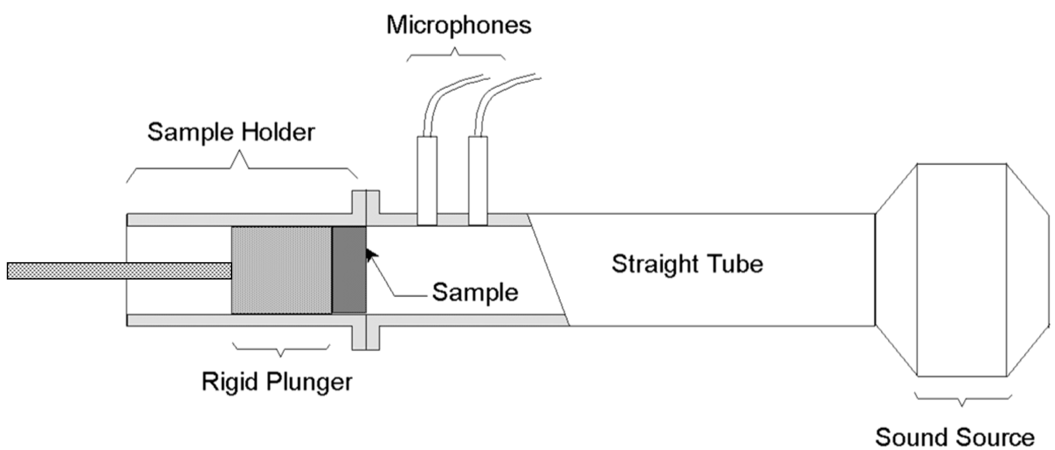
Normal incident sound absorption

$$\alpha = 1 - |R|^2$$

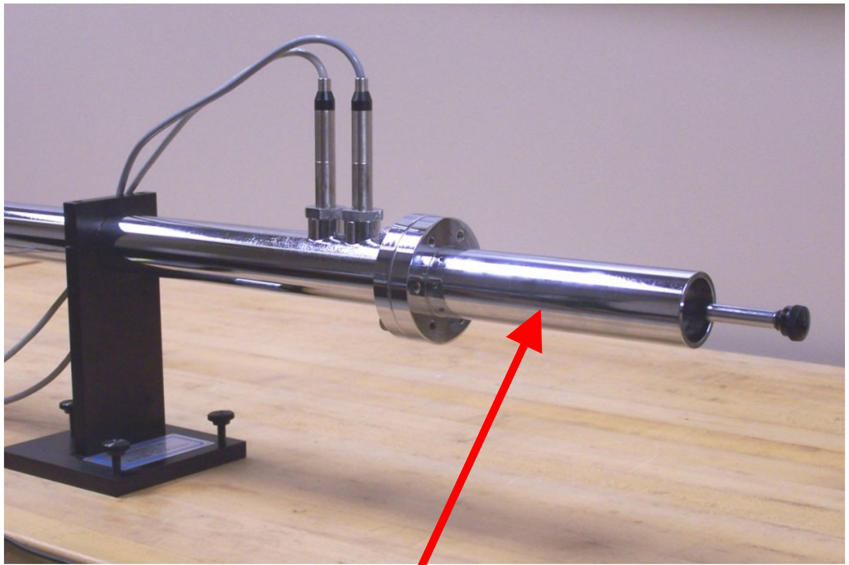
Two-Microphone Standards

1. ISO 10534-2, *Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer-function method*

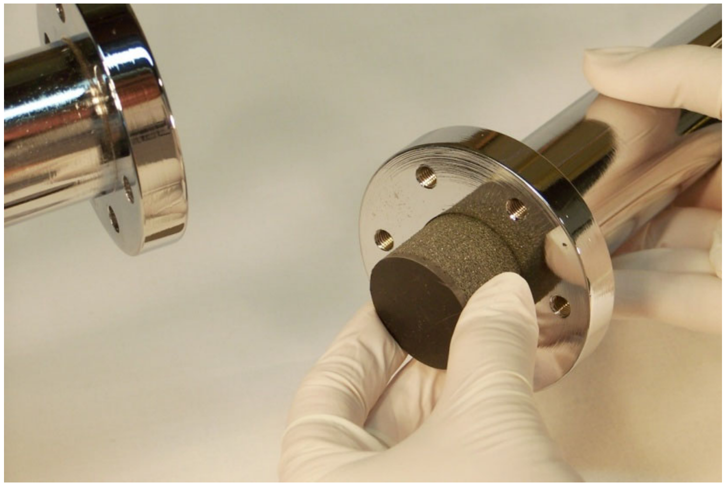
2. ASTM E1050-10, *Standard Test Method for Impedance and Absorption of Acoustical Material Using a Tube, Two Microphones and a Digital Frequency Analysis System*



Sound Absorption Measurement



Sample holder
with rigid piston

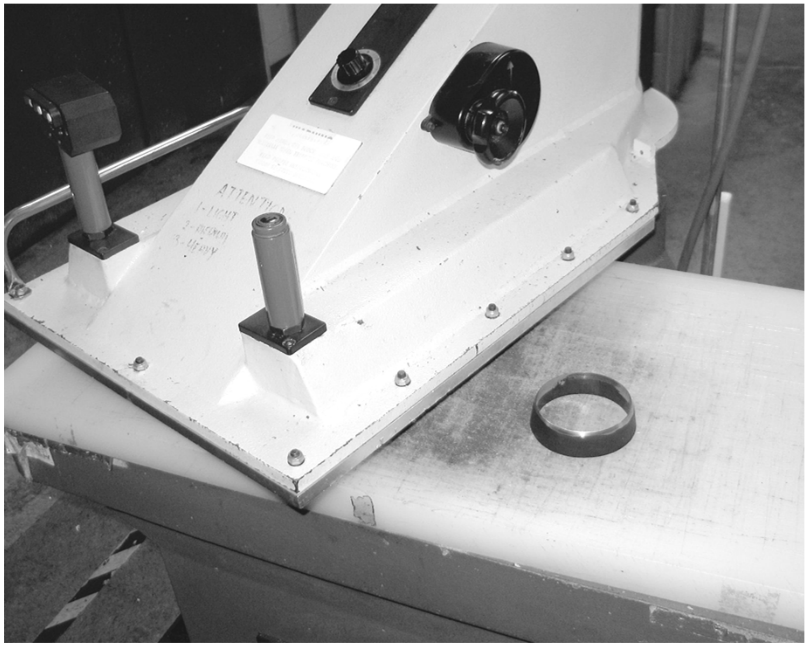


Cutting with Rotating Blade

Inexpensive and accurate if kept sharpened

Stanley, Internoise 2012

Stamping Press System

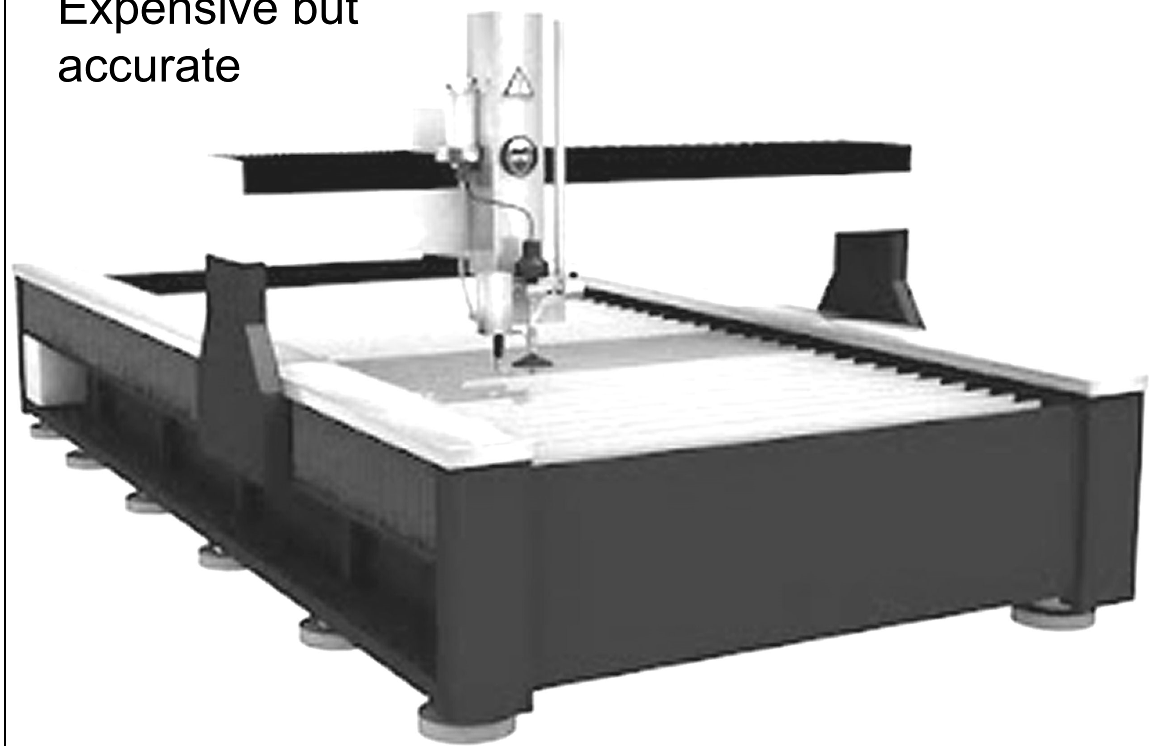


Used for low-density fibrous materials

Stanley, Internoise 2012

Water Jet Cutting

Expensive but accurate



Stanley, Internoise 2012

“Not so Good” and “Good” Specimens

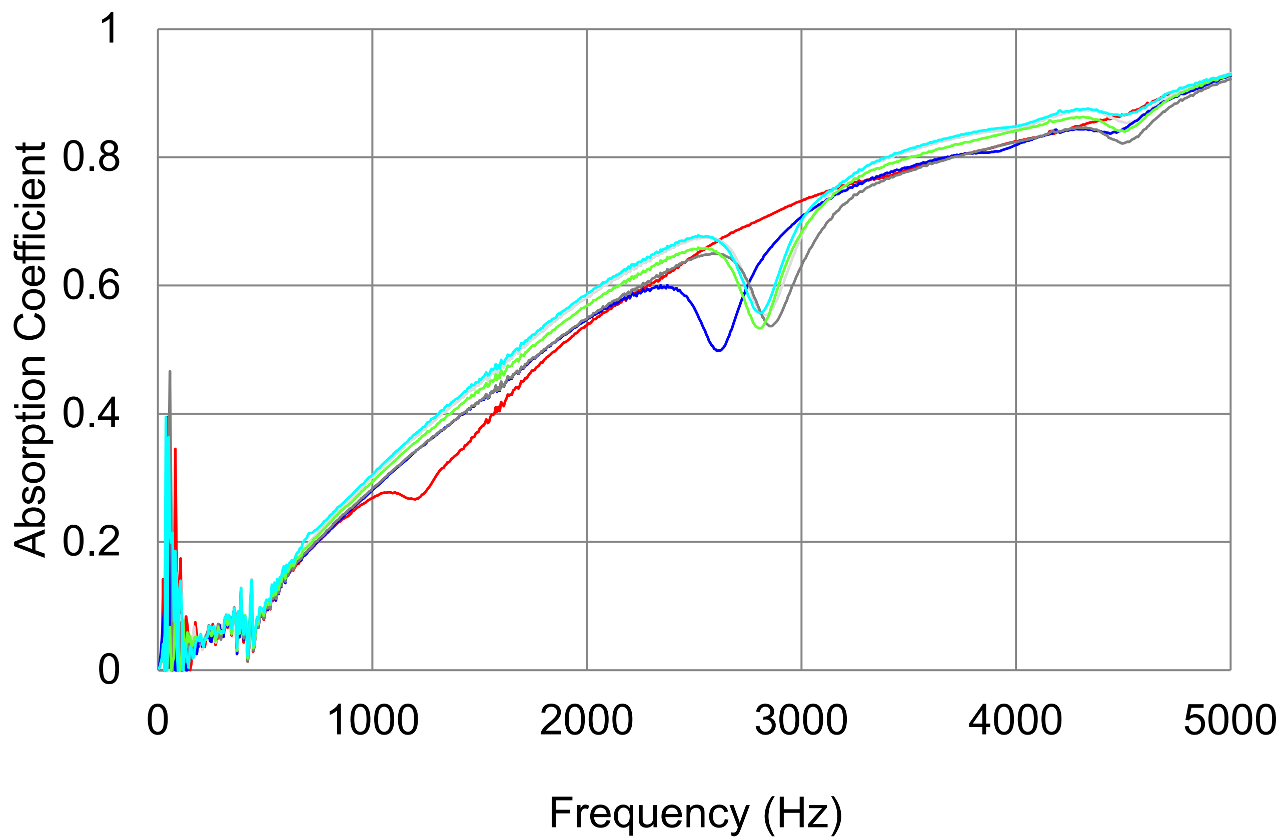
Stanley, Internoise 2012

Stanley, 2012 Specimen Preparation

- Face uniformly flush with cell lip
- Front surface even across lip of sample holder
- Extremely small (at most) and consistent gap between specimen and sample holder
- No specimen compression in the holder

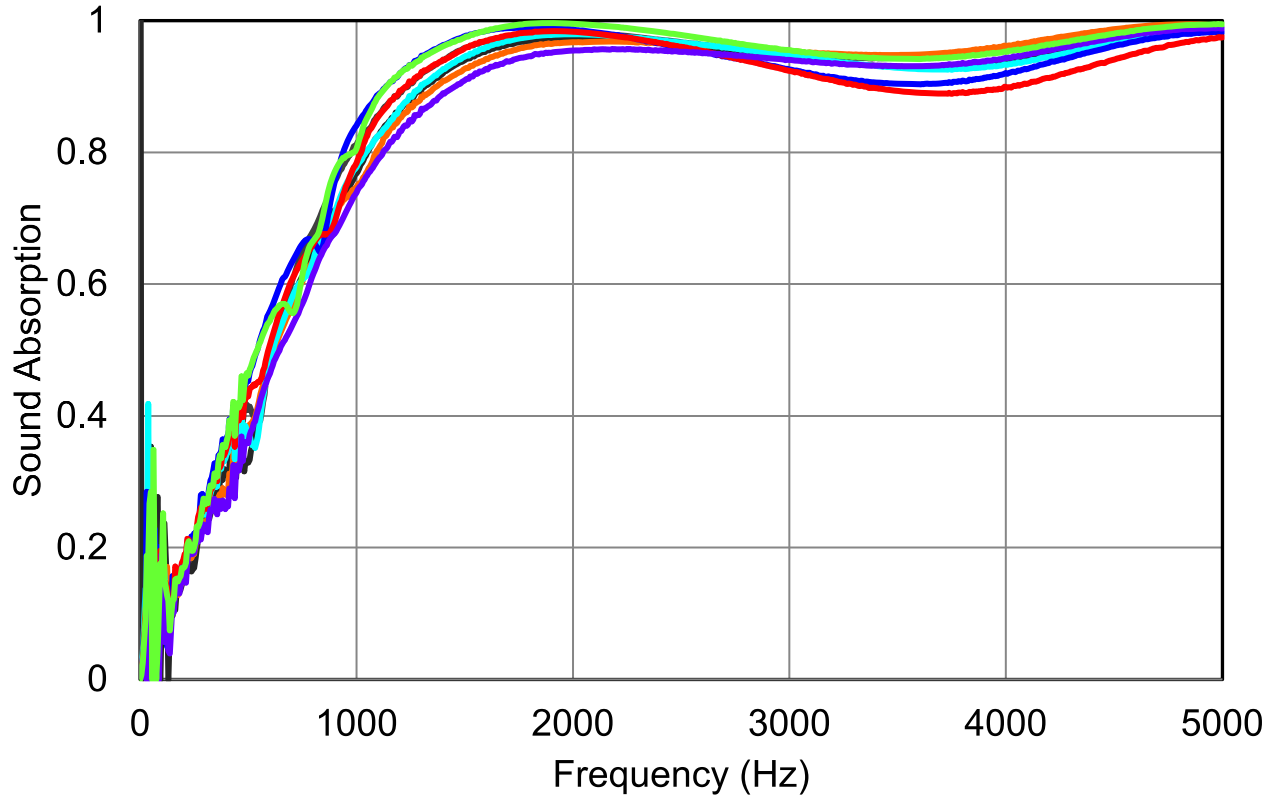
Variability of Melamine

6 Samples of 1.91 cm Melamine

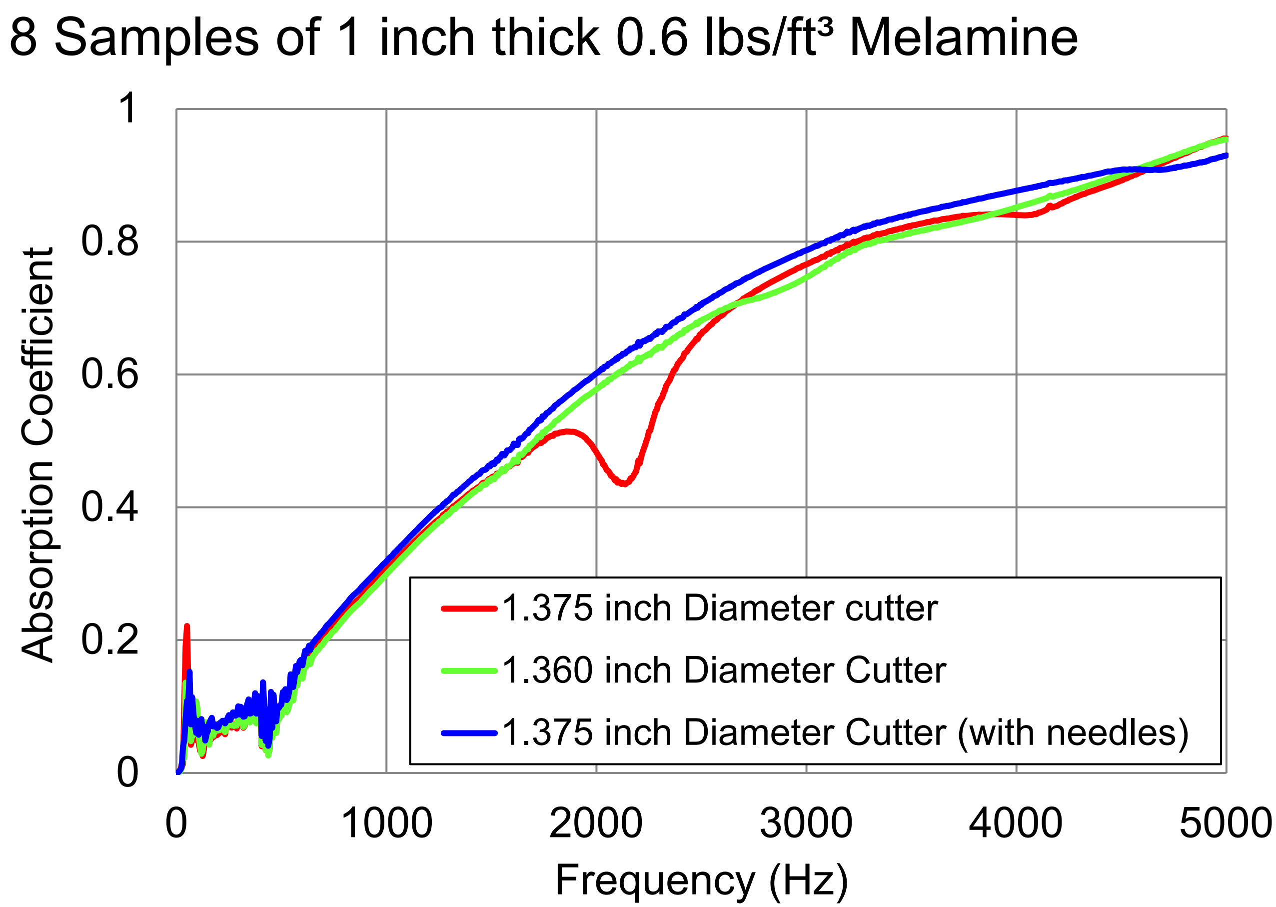


Variability Glass Fiber

8 Samples of 5 cm Glass Fiber

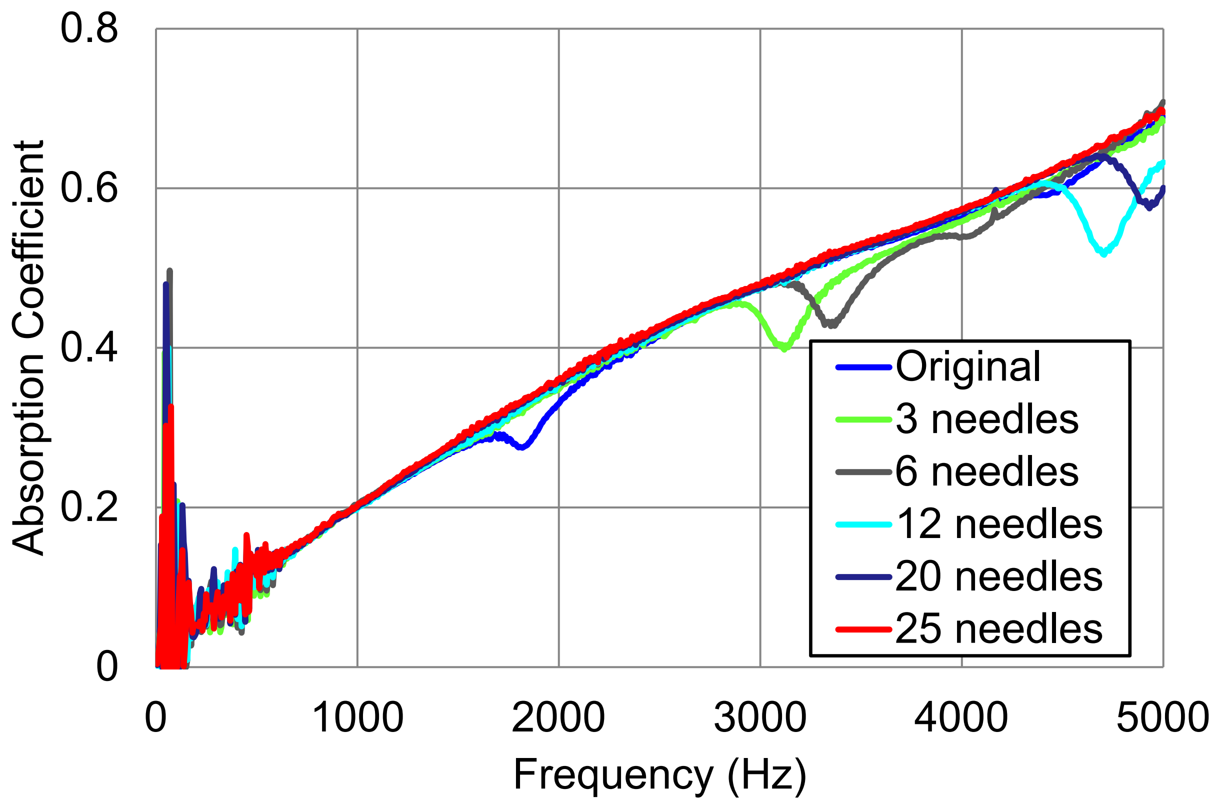


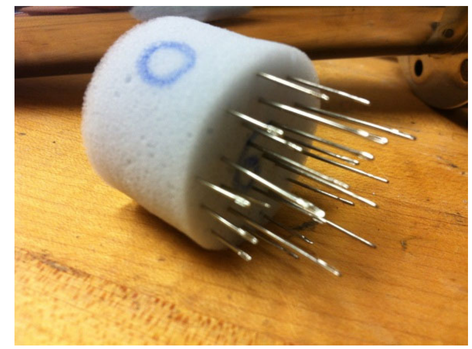
Effect of Cutter Size



Effect of Adding Needles

1.25 cm thick Melamine





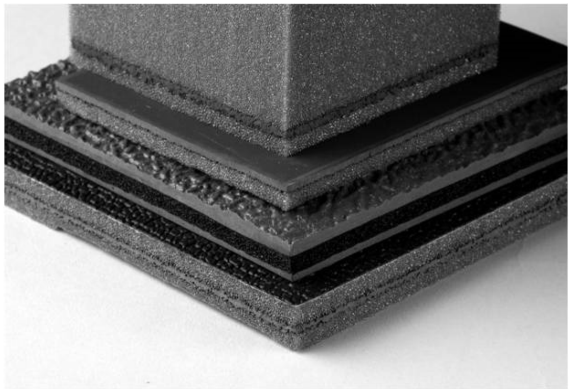
Summary

"While the use of an impedance tube system to measure acoustic absorption is not an extremely precise and repeatable process due to unavoidable variations of specimen cutting and cell fit, the disciplined use of the guidelines stated in this paper will help to insure that test results maintain a consistent level of accuracy and validity. The *experience gained with repeated preparation and testing* will also contribute to a better feel for more subtle aspects of preparation and specimen fitting for testing."

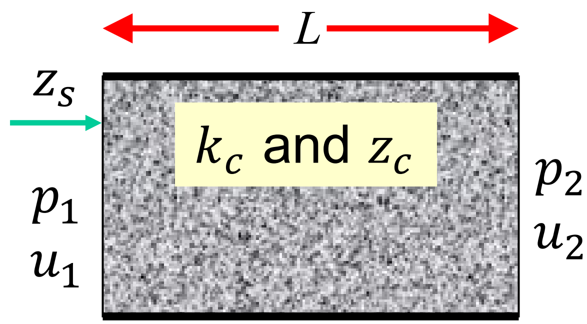
Stanley, Internoise 2012

Part 2 Determination of Bulk Properties

- Determining the bulk properties
  - ✓ Complex wave number and characteristic impedance
  - ✓ Complex speed of sound and density
- Bulk properties are used
  - ✓ For designing layered absorbers
  - ✓ In FEM and BEM models



Porous Absorbers Property Determination



$$k_c = \frac{\omega}{c'} \qquad z_c = \rho' c'$$

Determination of Sound Absorption

$$\begin{Bmatrix} p_1 \\ u_1 \end{Bmatrix} = \begin{bmatrix} \cos(k_c L) & j z_c \sin(k_c L) \\ j/z_c \sin(k_c L) & \cos(k_c L) \end{bmatrix} \begin{Bmatrix} p_2 \\ u_2 \end{Bmatrix}$$

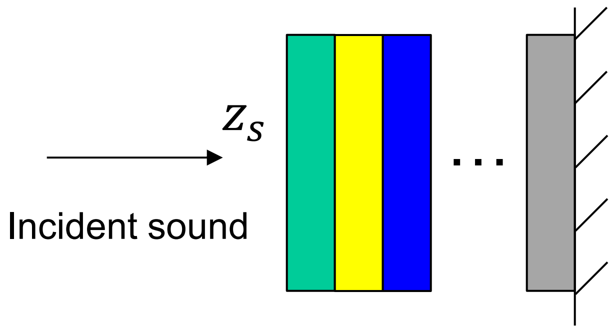
$$z_s = \frac{p_1}{u_1} = -j z_c \cot(k_c L)$$

$$R = \frac{z_s - \rho c}{z_s + \rho c}$$

$$\alpha = 1 - |R|^2$$

Porous Absorbers Layered

$$[T] = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = [T_1][T_2][T_3]\ldots[T_n]$$



$$\longrightarrow z_s = \frac{T_{11}}{T_{21}}$$

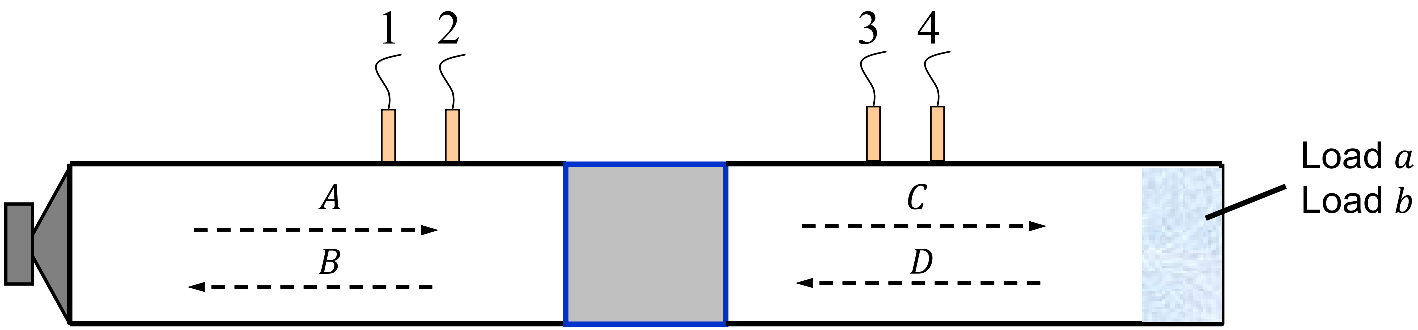
$$R = \frac{z_1 - \rho c}{z_1 + \rho c}$$

$$\longrightarrow \alpha = 1 - |R|^2$$

Overview of Approaches

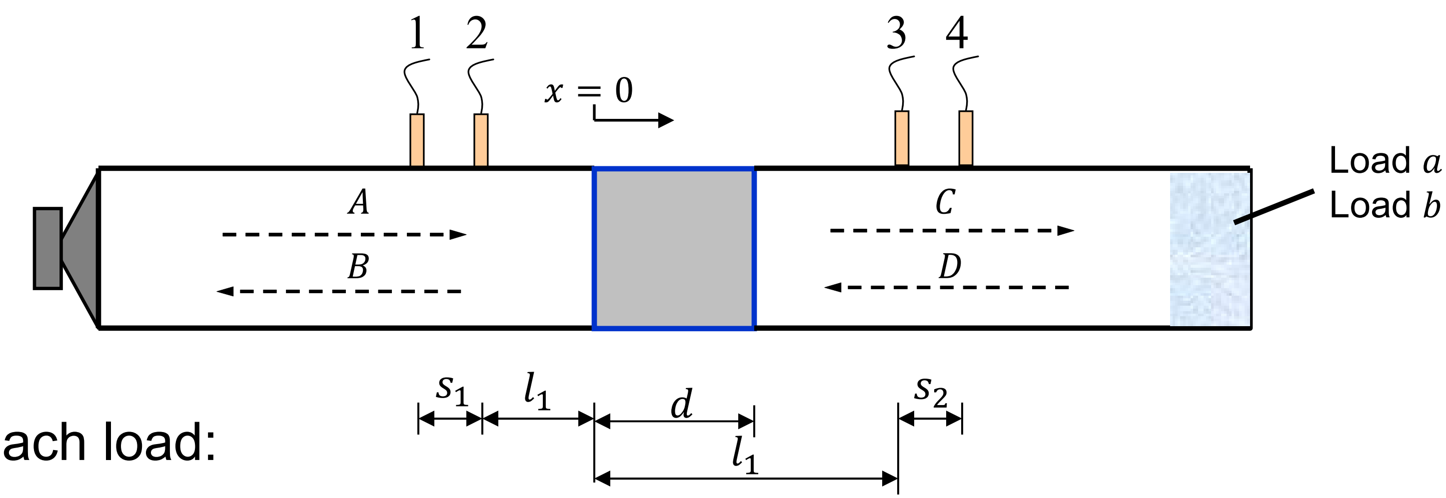
- **Direct Measurement** →
  - Two load method ASTM E 1050
  - Two cavity method Utsuno, 1989
  - Three microphone method Iwase et al., 1998
- **Measure Flow Resistance** → Find bulk properties from measured flow resistivity Wu, 1988; Mechel et al., 2002
- **Measure Sound Absorption** →
  - Curve fit to find flow resistivity based on empirical equations Simón et al., 2006 → Find bulk properties from measured flow resistivity Wu, 1988; Mechel et al., 2002
  - Curve fit to find Biot parameters based on theory → Find bulk properties from fitted Biot parameters Allard, J. F., 1999

Why Two-Loads?



$$\begin{Bmatrix} p_1 \\ u_1 \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} p_2 \\ u_2 \end{Bmatrix}$$

Two-Load Method



For each load:

$$A = j\frac{H_{1,ref}e^{-jkl_1} - H_{2,ref}e^{-jk(l_1+s_1)}}{2\sin k\, s_1}$$

$$C = j\frac{H_{3,ref}e^{jk(l_2+s_2)} - H_{4,ref}e^{jkl_2}}{2\sin k\, s_2}$$

$$B = j\frac{H_{2,ref}e^{jk(l_1+s_1)} - H_{1,ref}e^{jkl_1}}{2\sin k\, s_1}$$

$$D = j\frac{H_{4,ref}e^{-jkl_2} - H_{3,ref}e^{-jk(l_2+s_2)}}{2\sin k\, s_2}$$

Transmission Loss Measurement

Pressures and particle velocities at two ends of the sample:

$$p_0 = A + B \qquad p_d = Ce^{-jkd} + De^{jkd}$$

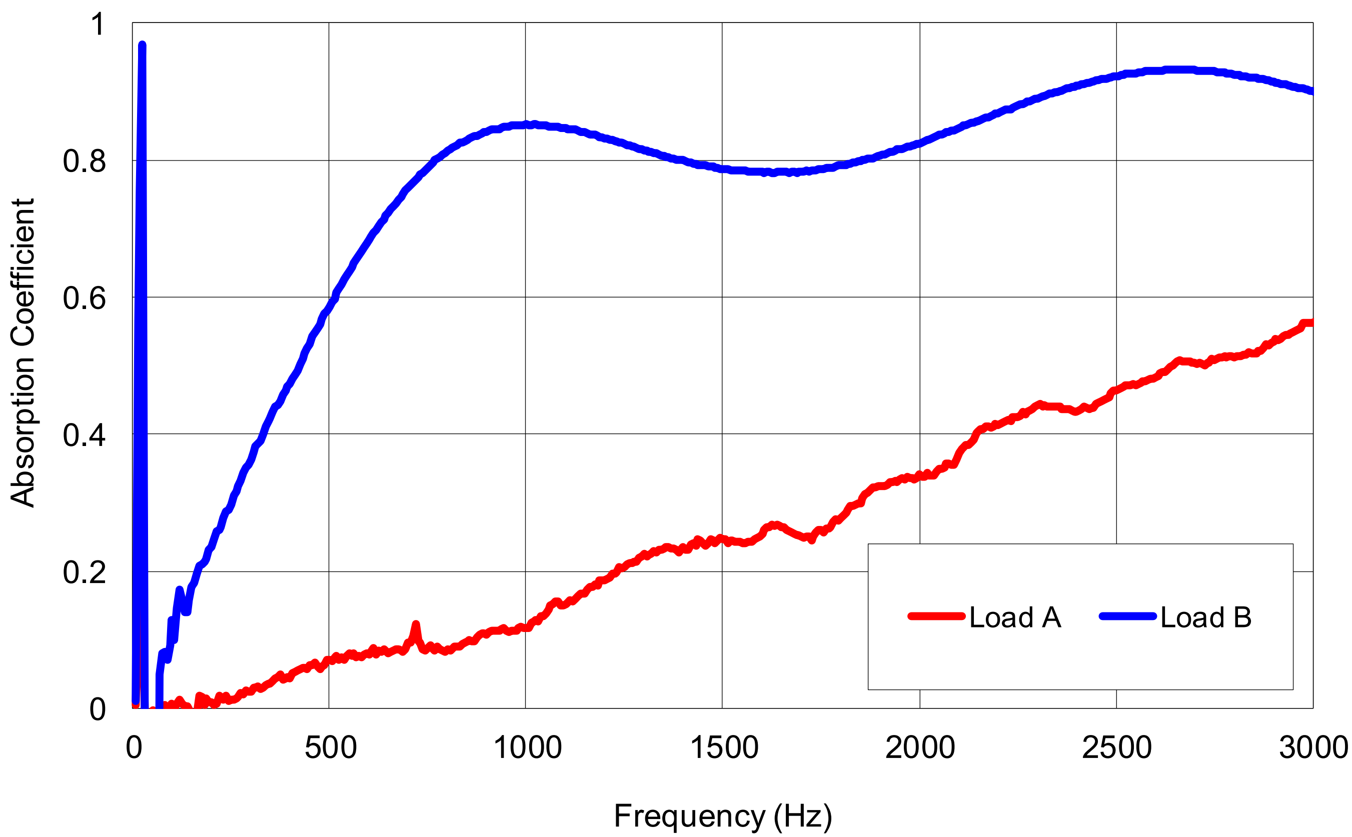
$$u_0 = \frac{(A-B)}{\rho c} \qquad u_d = \frac{\left(Ce^{-jkd} - De^{jkd}\right)}{\rho c}$$

Four-pole matrix (subscripts a and b indicate acoustic loads)

$$T = \begin{bmatrix} \dfrac{p_{0a}u_{db} - p_{0b}u_{da}}{p_{da}u_{db} - p_{db}u_{da}} & \dfrac{p_{0b}p_{da} - p_{0a}p_{db}}{p_{da}u_{db} - p_{db}u_{da}} \\ \dfrac{u_{0a}u_{db} - u_{0b}u_{da}}{p_{da}u_{db} - p_{db}u_{da}} & \dfrac{p_{da}u_{0b} - p_{db}u_{0a}}{p_{da}u_{db} - p_{db}u_{da}} \end{bmatrix}$$

$$TL = 20\log_{10}\left|\frac{1}{2}\left(T_{11} + \frac{T_{12}}{\rho c} + \rho c T_{21} + T_{22}\right)\right|$$

Two Loads



Load A: Open tube. Load B: 10 cm sound absorbing material.

Two Load Method

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(k_c d) & j z_c \sin(k_c d) \\ \dfrac{j \sin(k_c d)}{z_c} & \cos(k_c d) \end{bmatrix}$$

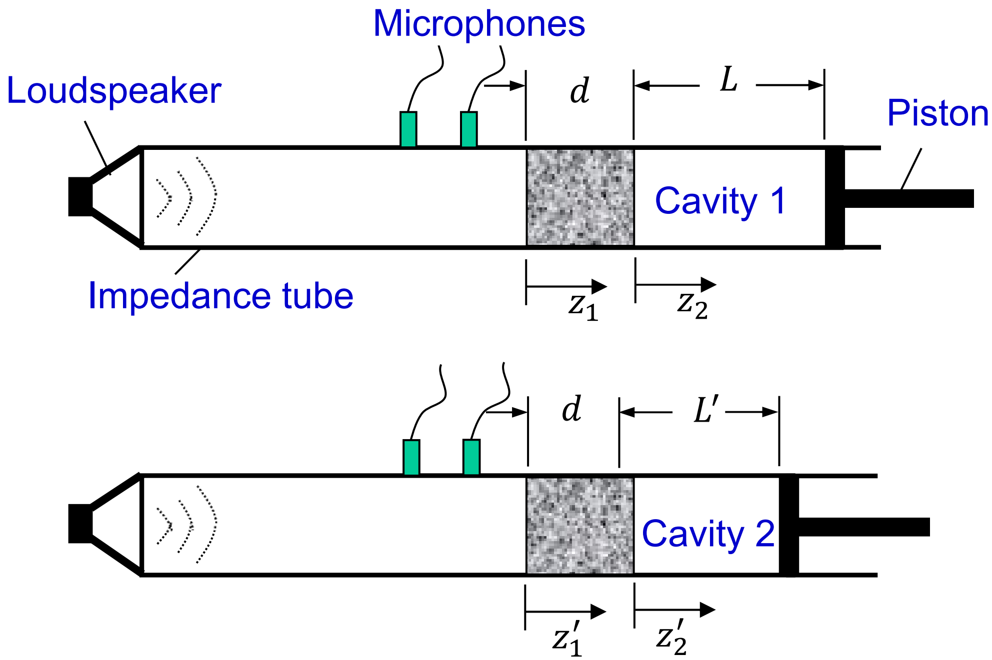
$$\Downarrow$$

$$z_c = \sqrt{\frac{T_{12}}{T_{21}}}$$

$$k_c d = \arctan\left(\frac{T_{12}}{j T_{11} z_c}\right)$$

Utsuno,1989

Two Cavity Method

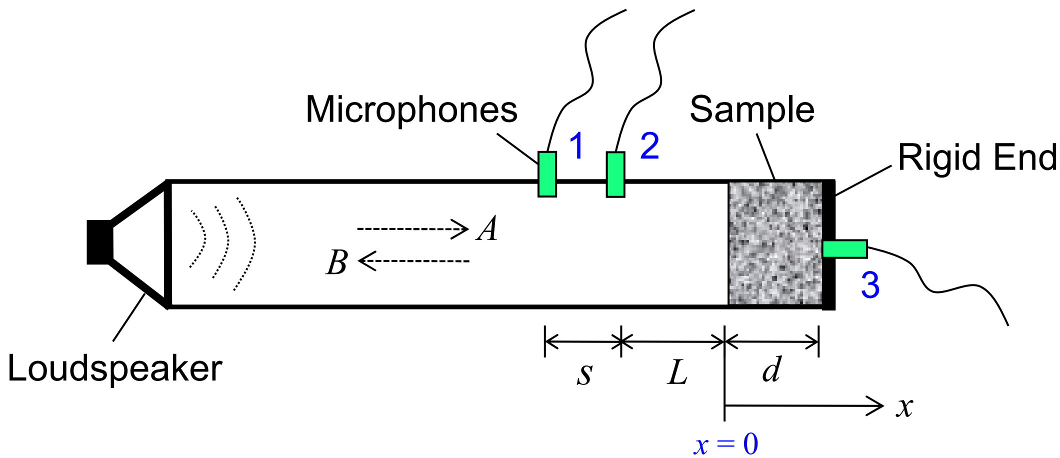


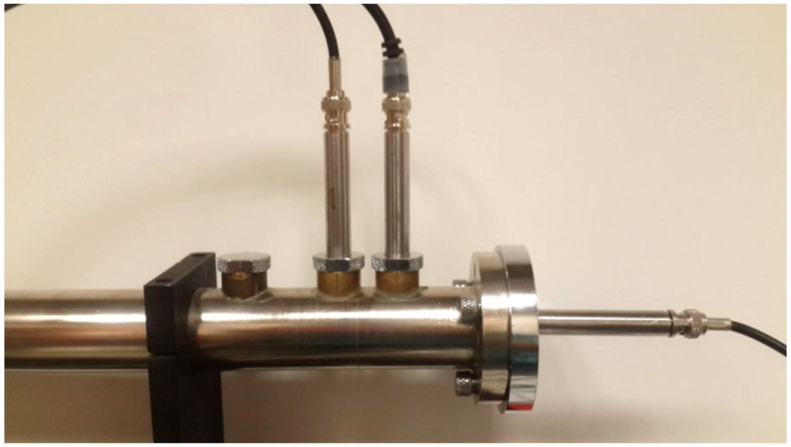
$$z_c = \pm\sqrt{\frac{z_1 z_1'(z_2 - z_2') - z_2 z_2'(z_1 - z_1')}{(z_2 - z_2') - (z_1 - z_1')}}$$

$$k_c = \left(\frac{1}{2jd}\right)\ln\left(\frac{(z_1 + z_c)(z_2 - z_c)}{(z_1 - z_c)(z_2 + z_c)}\right)$$

Iwase et al., 1998

Three Microphone Method



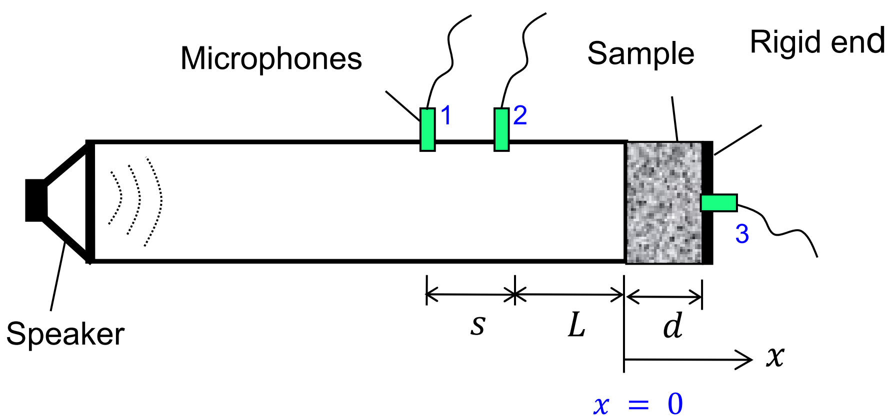


Iwase et al., 1998

Three Microphone Method

Reflection coefficient:

$$R = \frac{e^{jks} - H_{12}}{H_{12} - e^{-jks}} e^{2jkL}$$



Iwase et al., 1998

Three Microphone Method

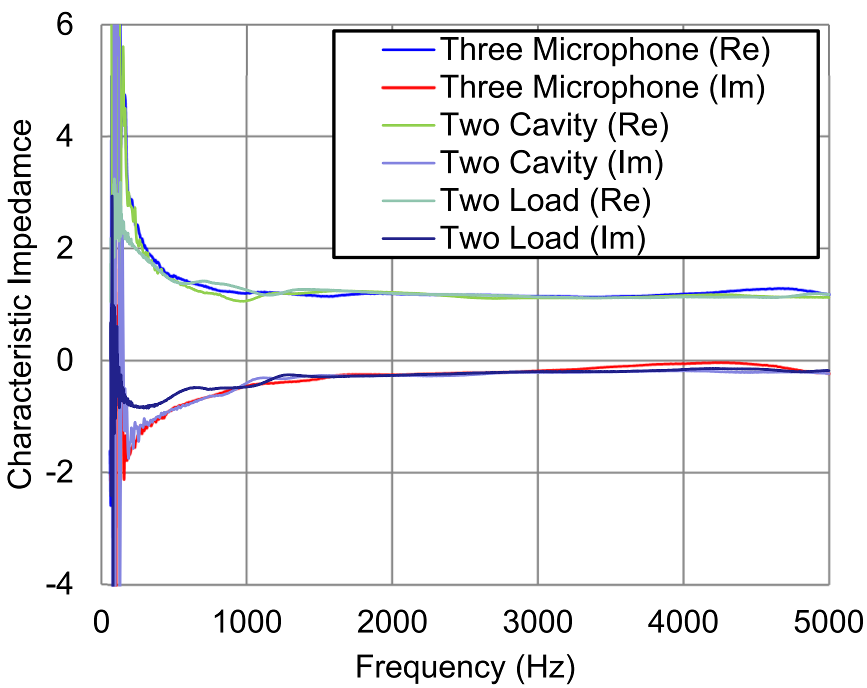
The complex wave number of the sample is:

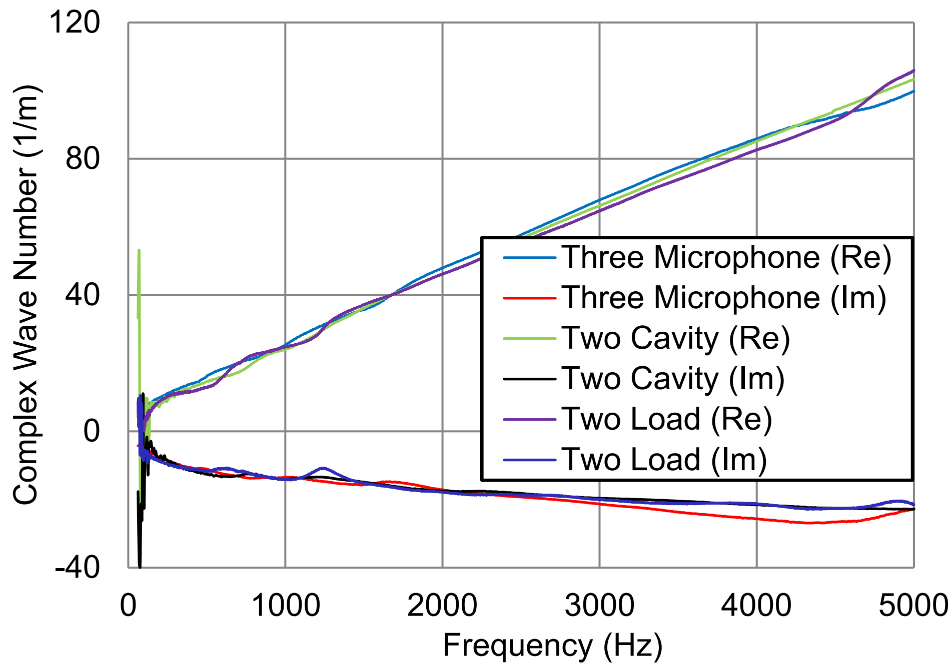
$$k_c = \frac{1}{d}\arccos\left(\left(\frac{1+R}{e^{jkL}+Re^{-jkL}}\right)H_{23}\right)$$

The characteristic impedance of the sample is:

$$z_c = jz_0\frac{1+R}{1-R}\tan(k_c d)$$

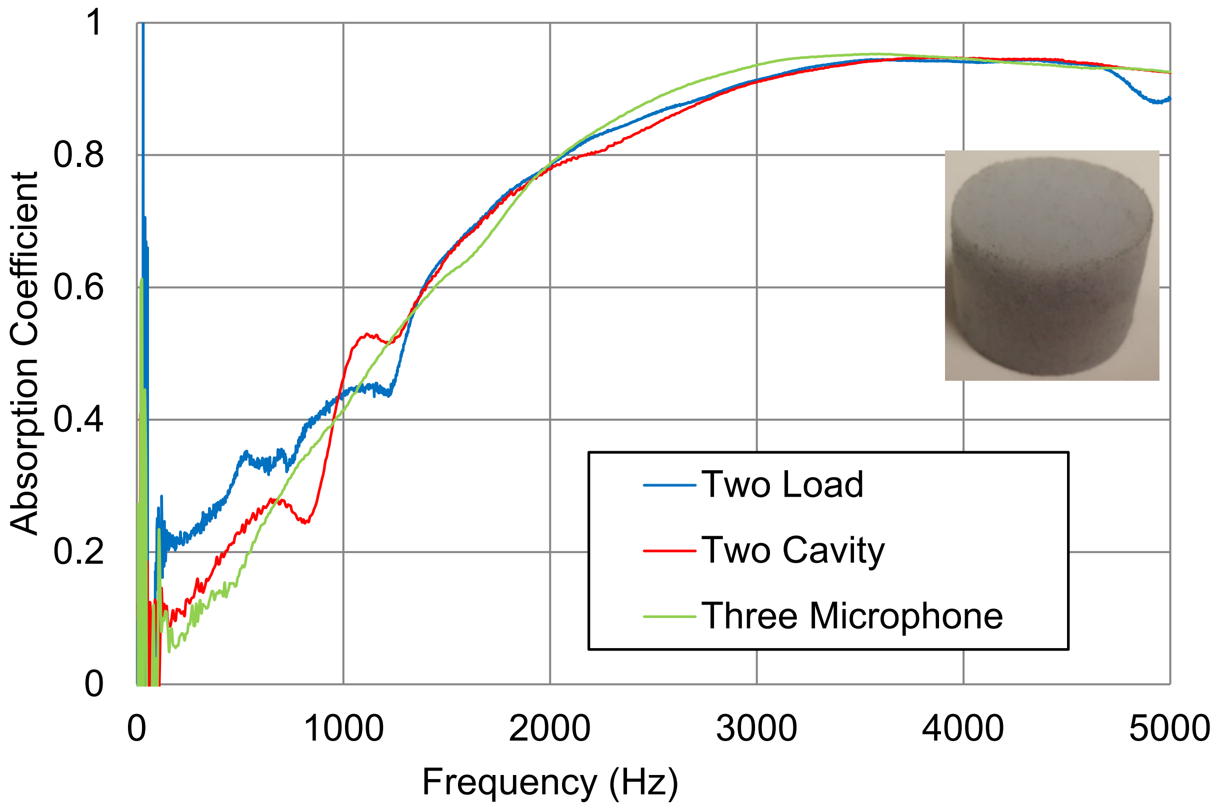
2.5 cm Melamine Bulk Properties





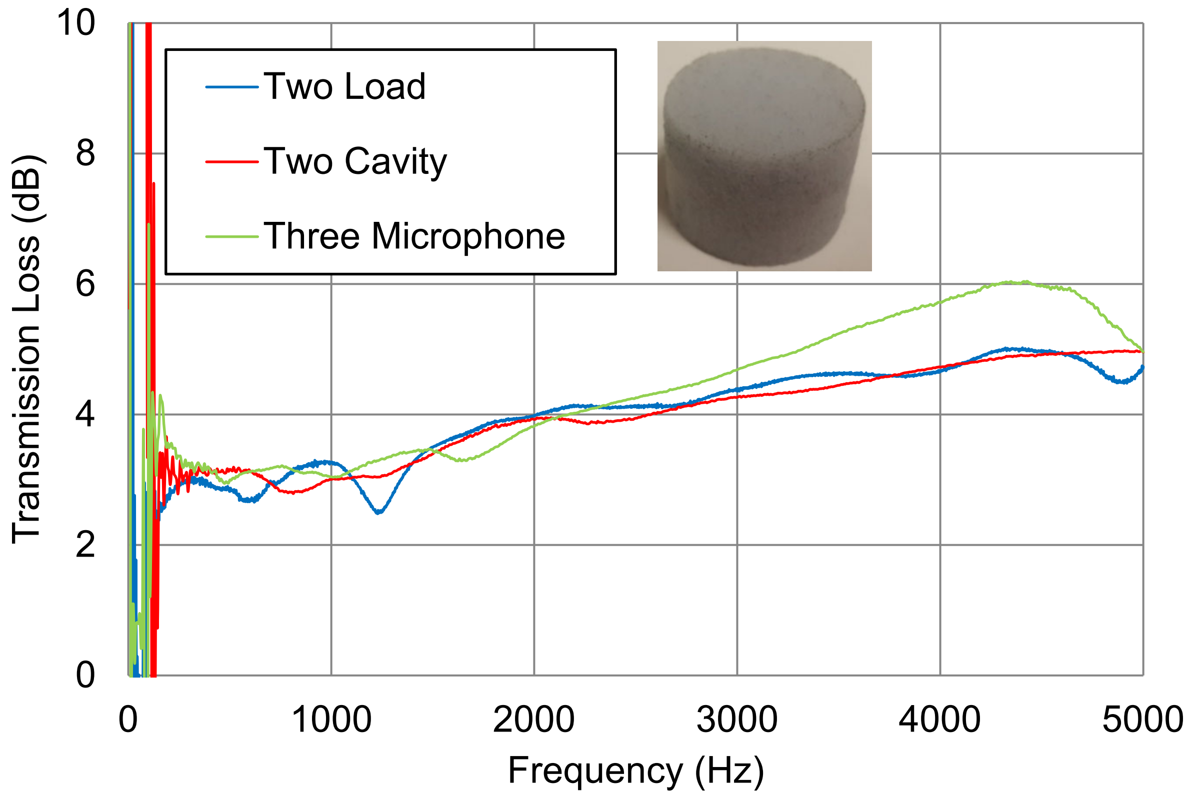
Melamine Sound Absorption Coefficient

2.5 cm Melamine Foam

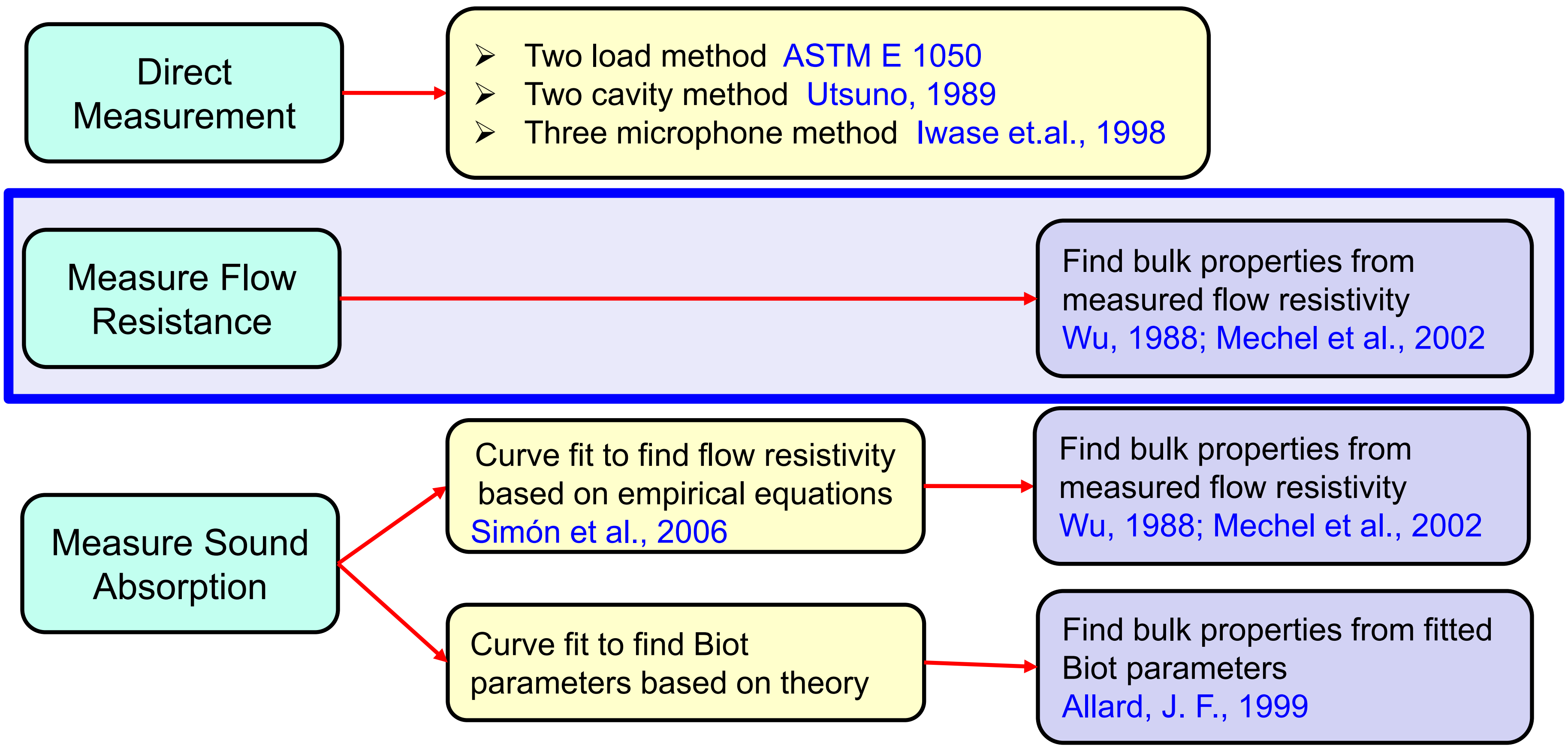


Melamine Transmission Loss

2.5 cm Melamine Foam

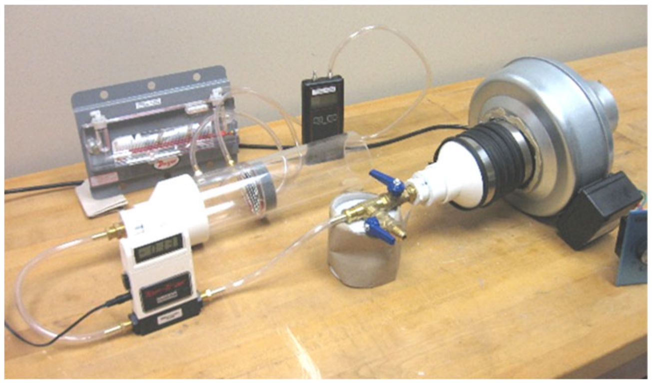


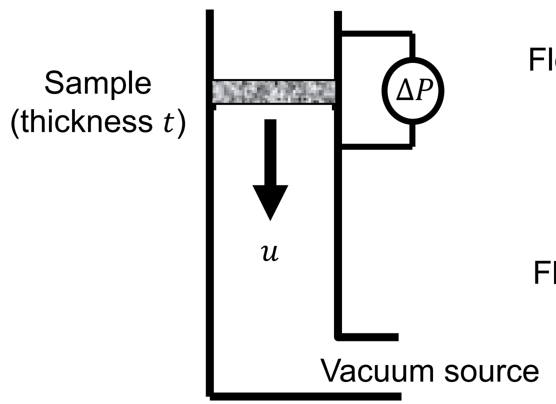
Overview of Approaches



Wu, 1988; Mechel et al., 2002

Measure Flow Resistance





Flow resistance:

$$r_s = \frac{\Delta P}{u}$$

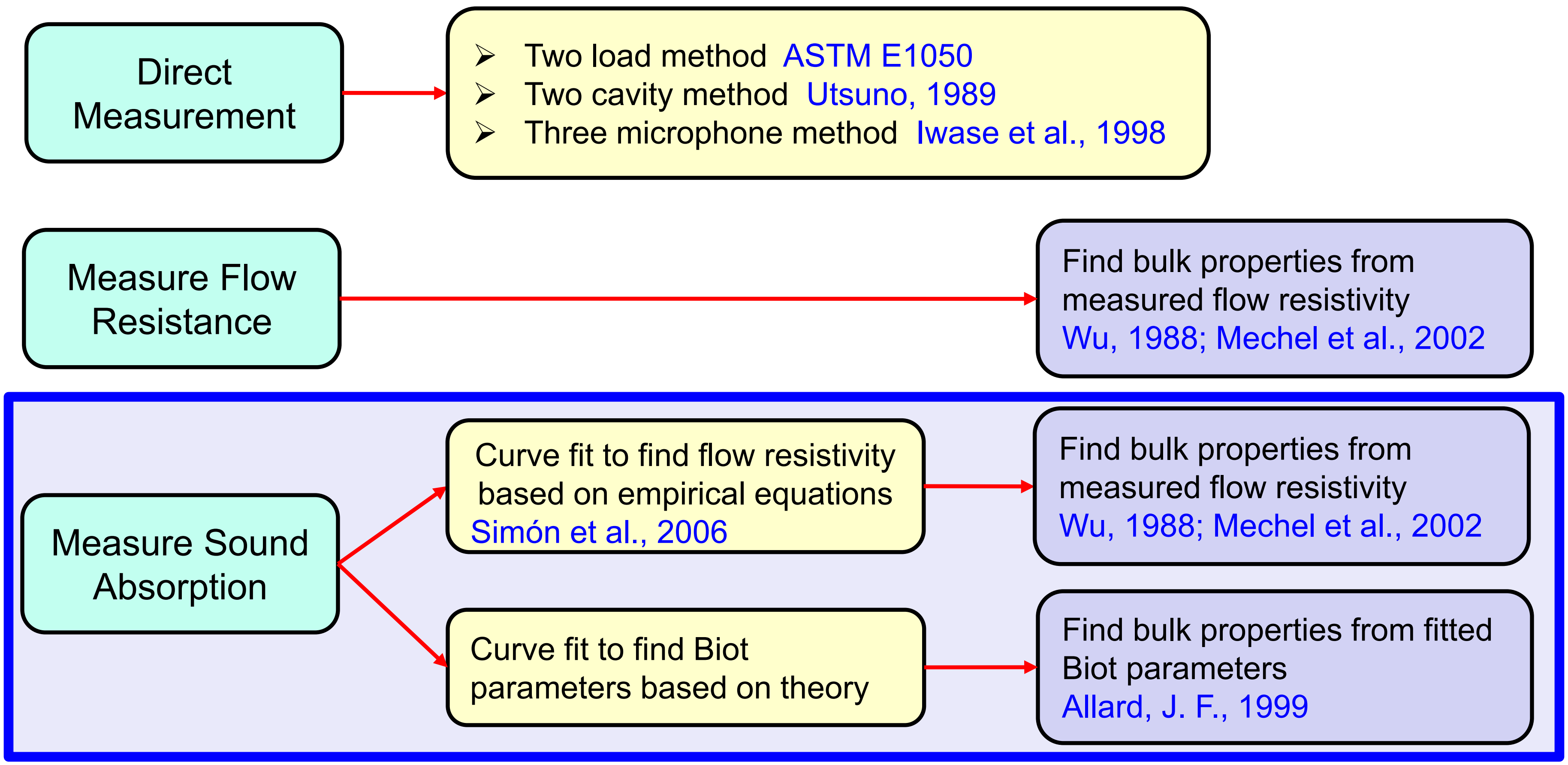
Flow resistivity:

$$\sigma = \frac{r_s}{t}$$

Measure
Flow Resistivity Using
ASTM C522

Plug into Empirical Models
See Sound Absorptive
Material Webinar

Overview of Approaches



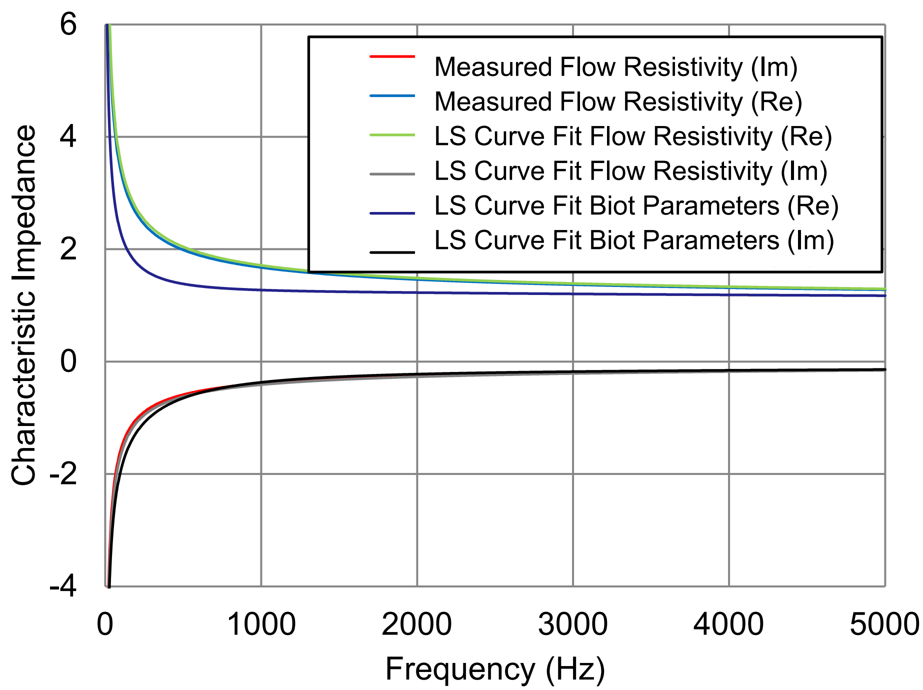
Simon et al., 2006; Allard, J. F., 1999

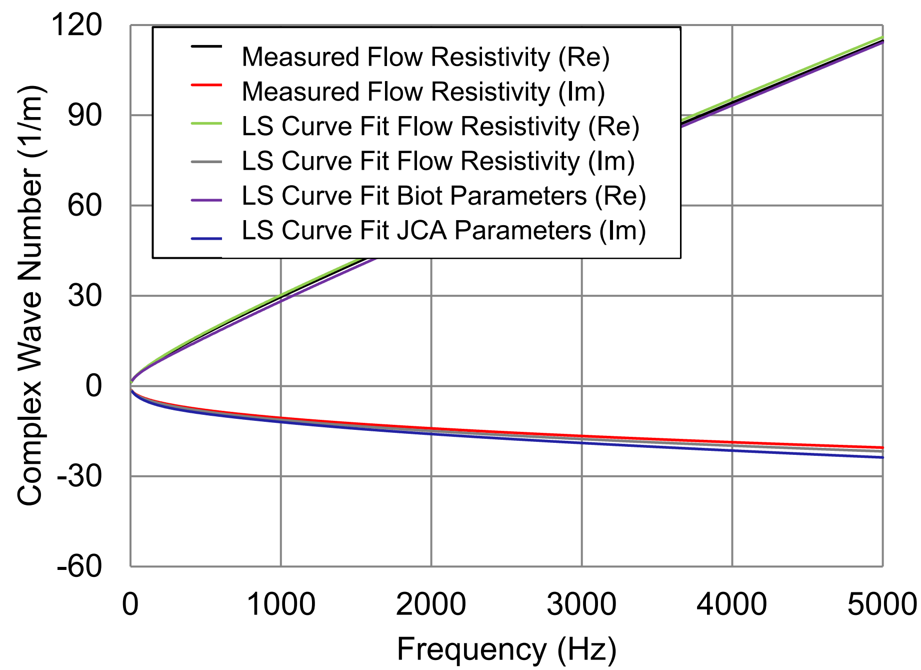
Curve Fitting Methods

Measure sound absorption coefficient
↓
Minimize least squares error with respect to *empirical equations*
↓ Flow Resistivity
Plug into empirical models
Wu (1988) or Mechel et al. (2002)

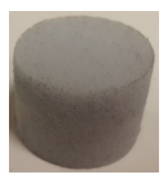
Measure sound absorption coefficient
↓
Minimize least squares error with respect to *analytical equations*
↓ Biot Parameters
Plug into theoretical model
Johnson-Champoux-Allard model

2.5 cm Melamine Bulk Properties





Measured	12,100 Rayls/m
Simón Curve Fitting	11,400 Rayls/m



Summary

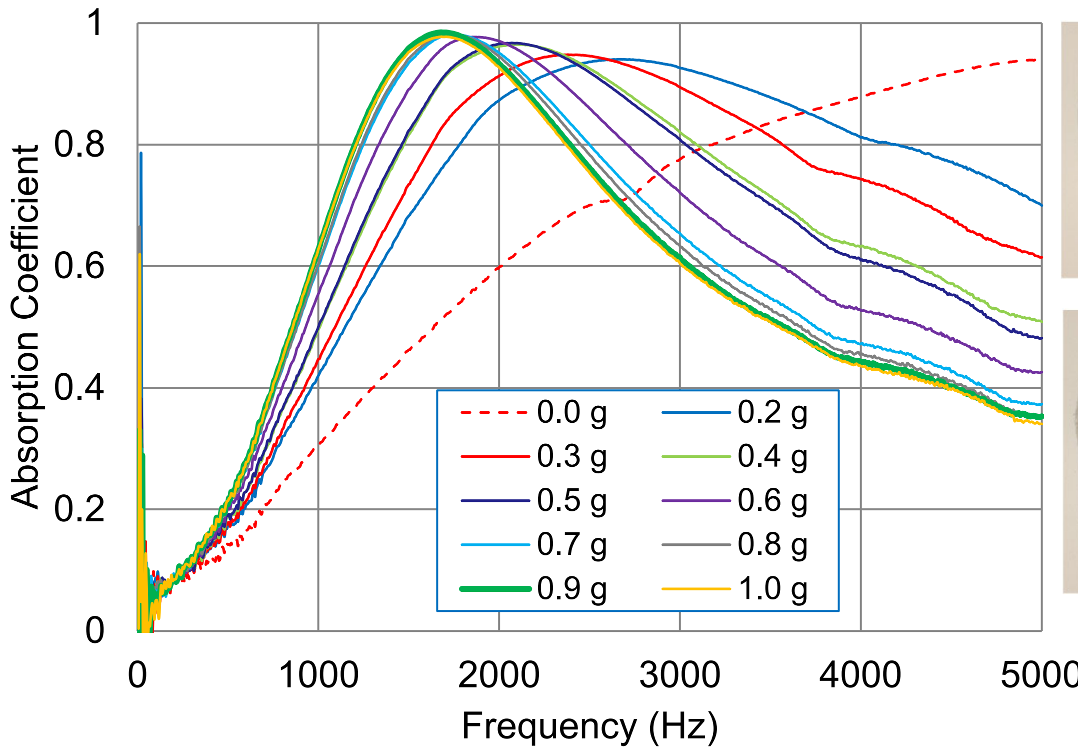
- Compared the various methods for determining the bulk properties of sound absorbers.
- Curve fitting approaches are adequate for common sound absorbing materials.

Part 3 Covers and Adhesives

- How do adhesives and covers between sound absorbing layers affect the overall performance?
- How can we determine the acoustic properties of an adhesive or a cover?

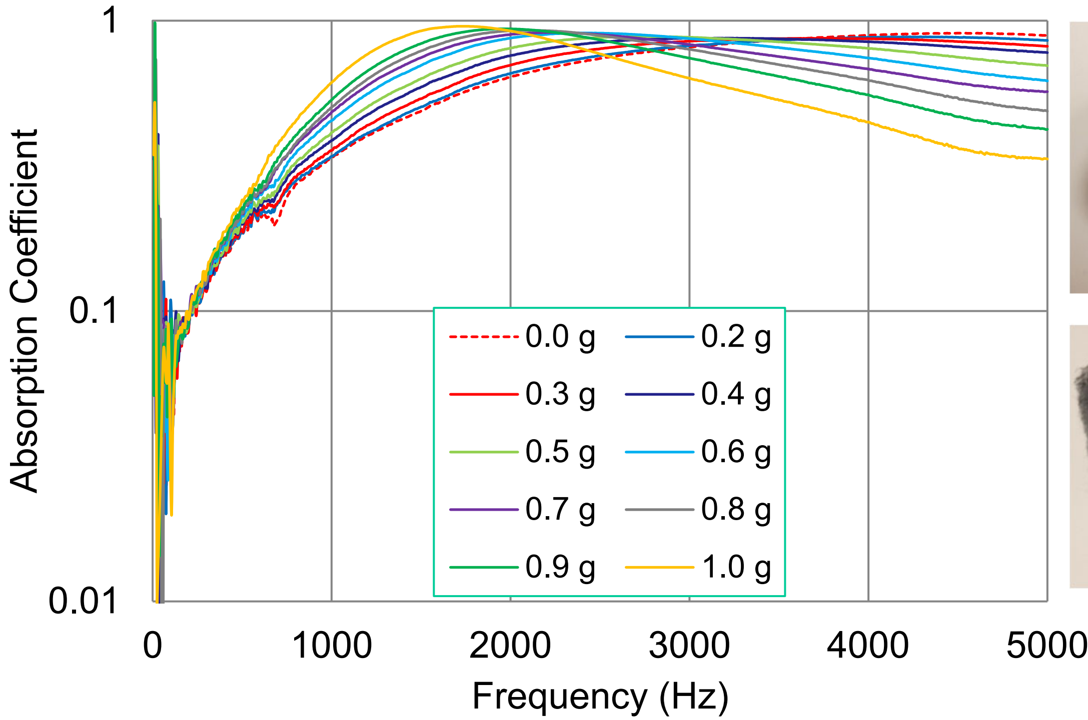
Melamine Effect of Adhesives

1.8 cm thick 9.6 kg/m^3 Melamine Foam



Fiber Effect of Adhesives

2.5 cm thick 19.2 kg/m^3 Fiber

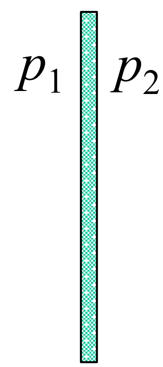


Transfer Impedance

A transfer impedance is commonly used to model perforates, covers and source impedance. Particle velocity is assumed to be continuous across the layer.

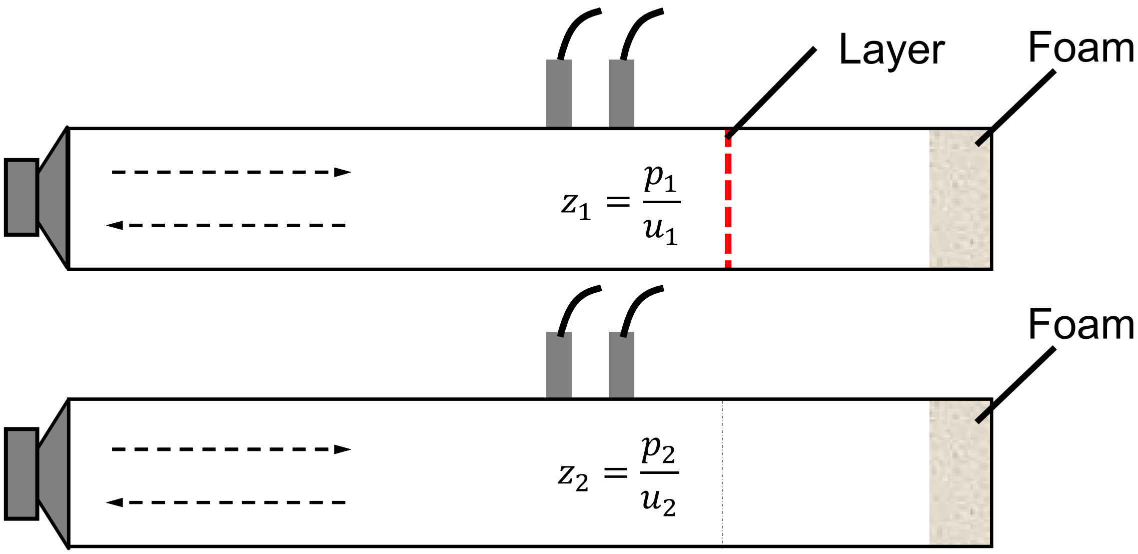
$$z_{tr} = \frac{p_1 - p_2}{u}$$

$$u_1 = u_2 = u$$



Transfer Impedance Measurement

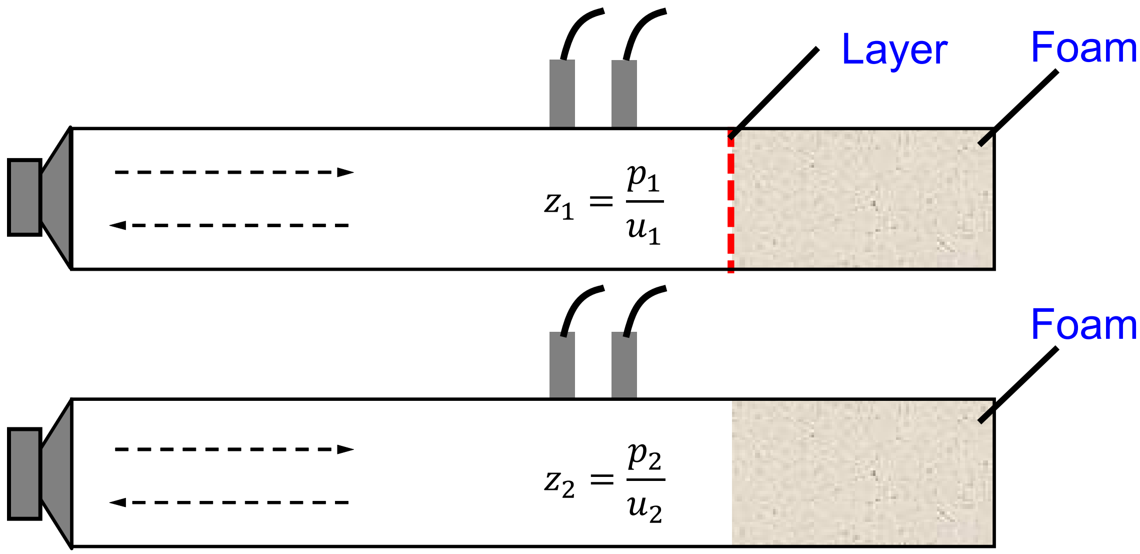
Measurement of perforates or fabrics



$$z_{tr} = z_1 - z_2$$

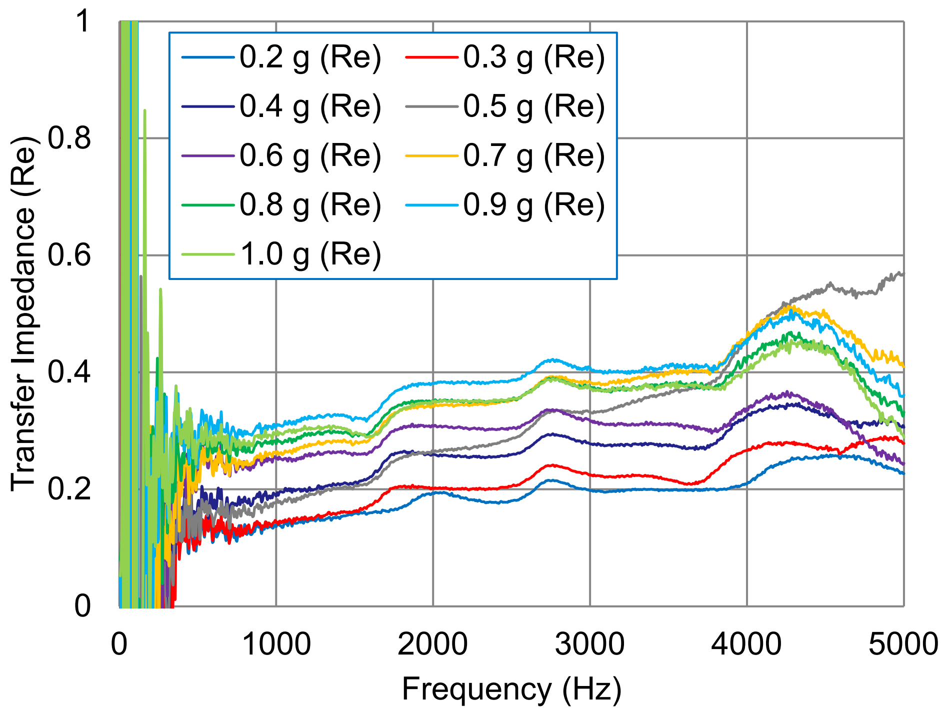
Transfer Impedance Measurement

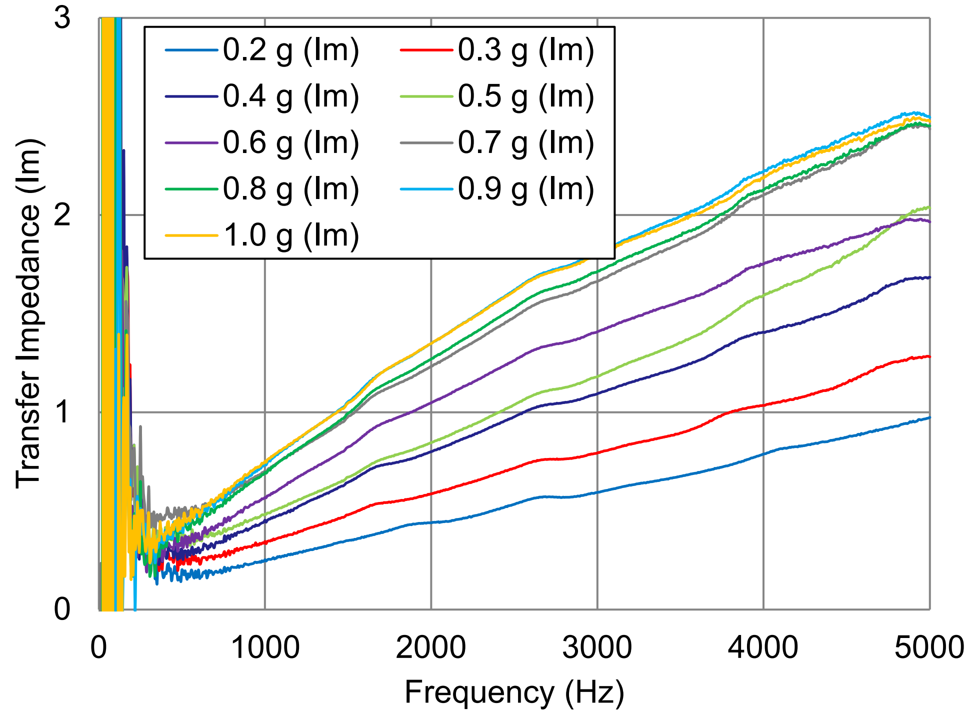
Measurement of adhesive layer or bonded cover



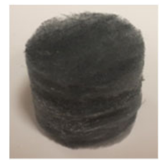
$$z_{tr} = z_1 - z_2$$

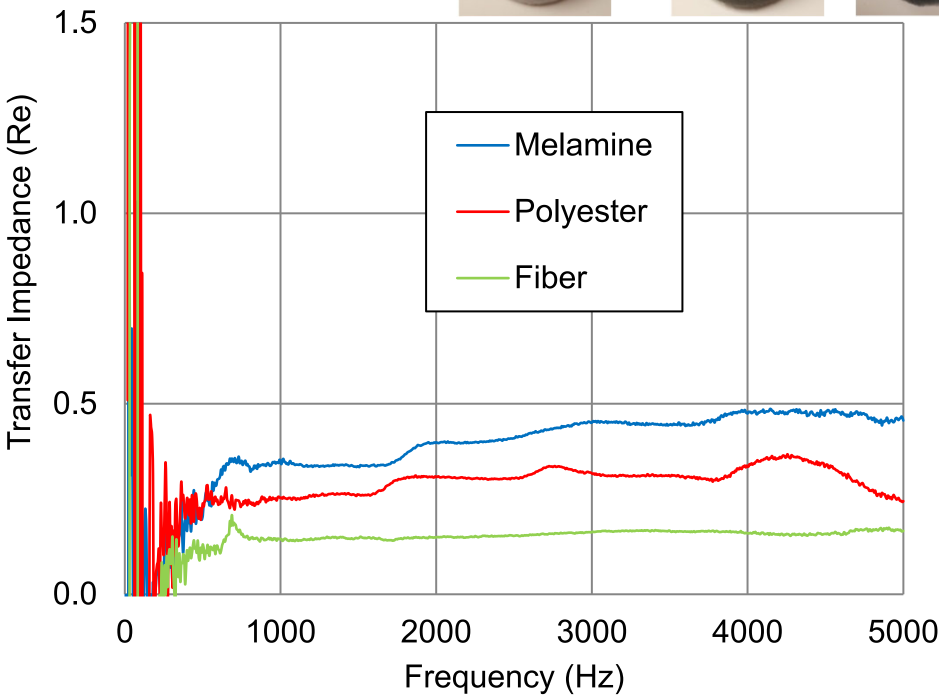
Transfer Impedance Glue

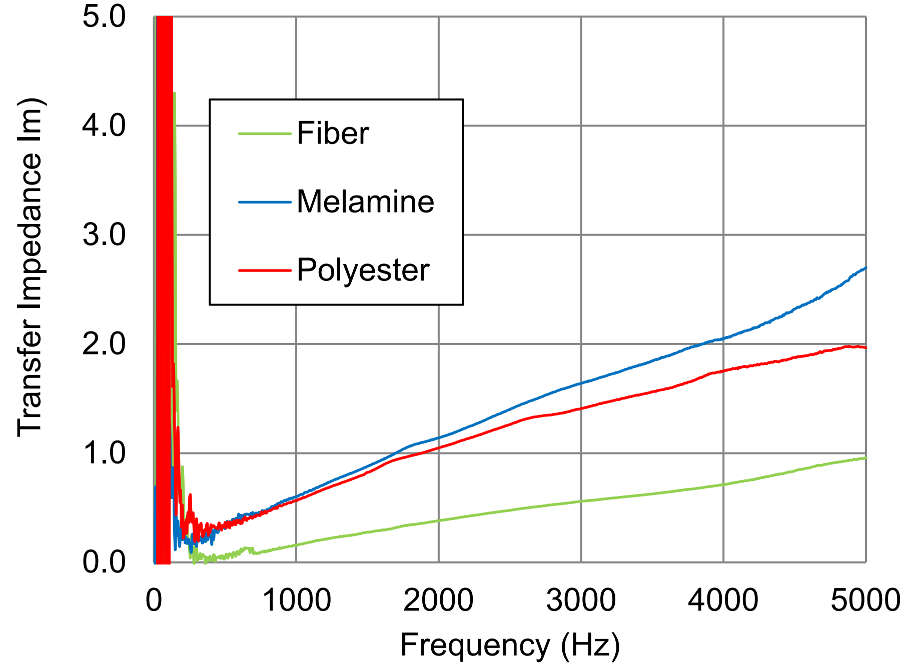




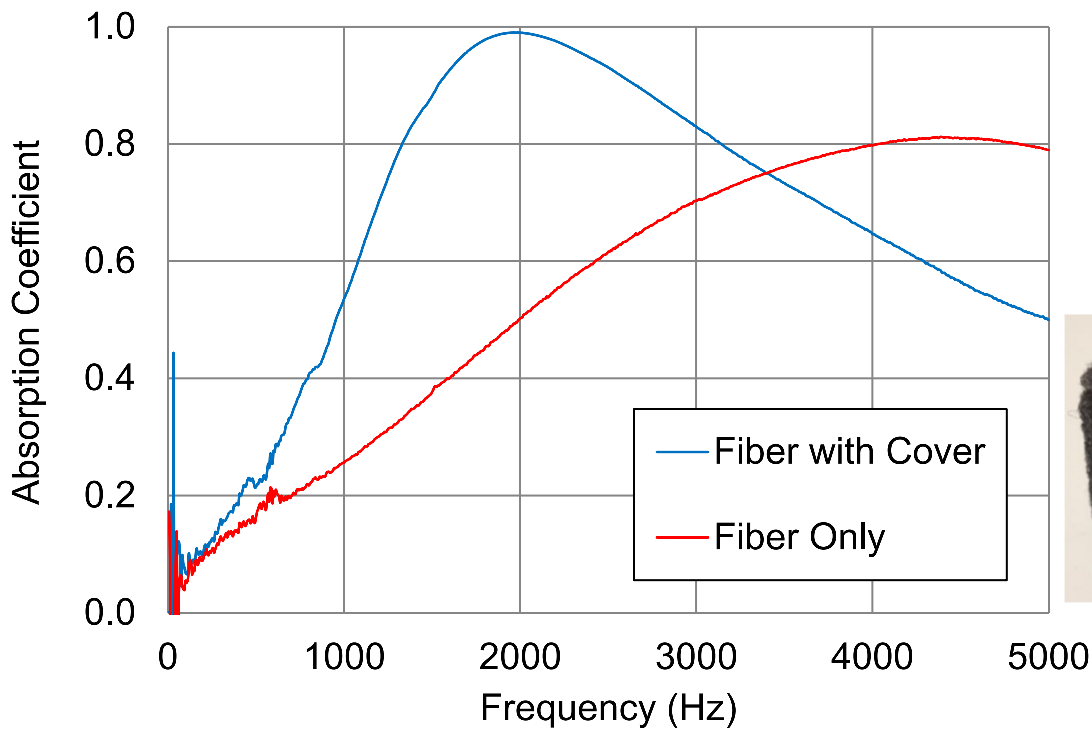
0.6 g of Glue Effect of Different Substrate



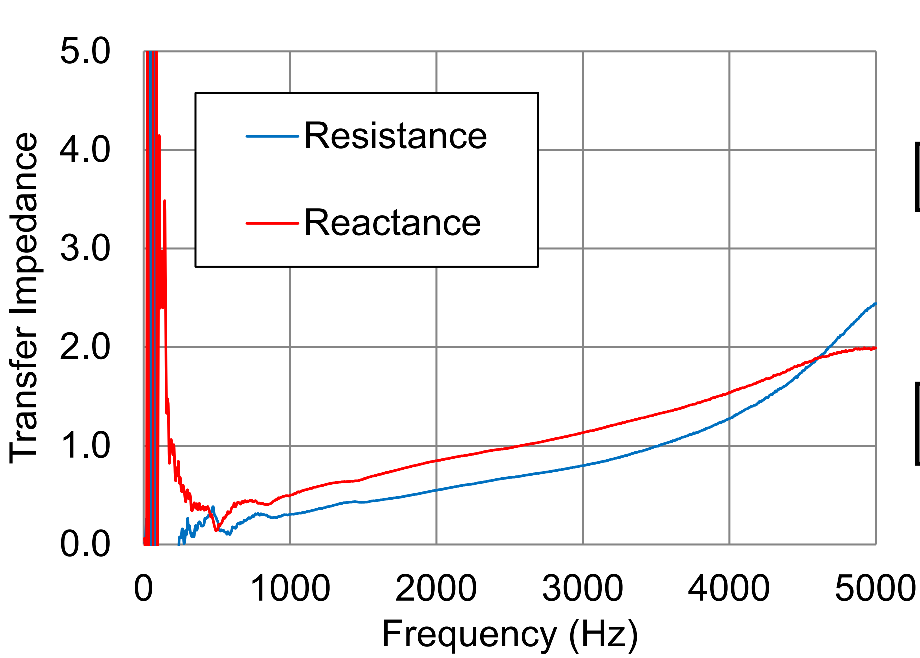


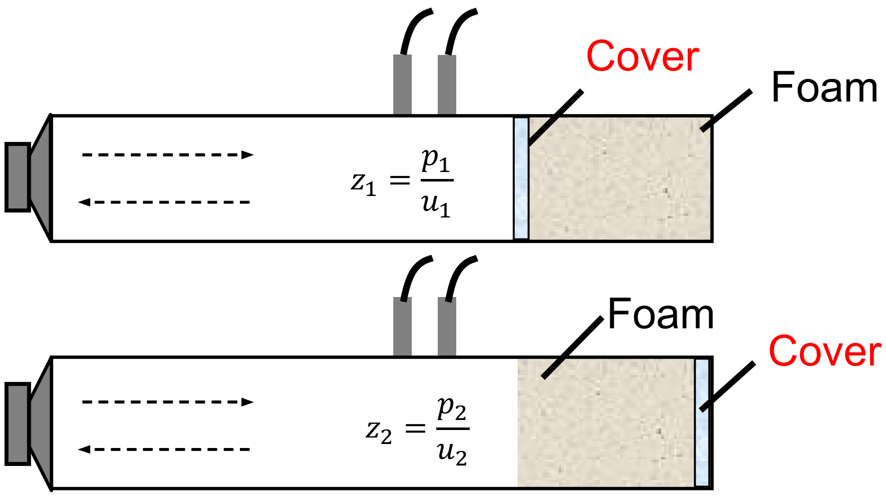


Effect of Covers



Measurement Transfer Impedance

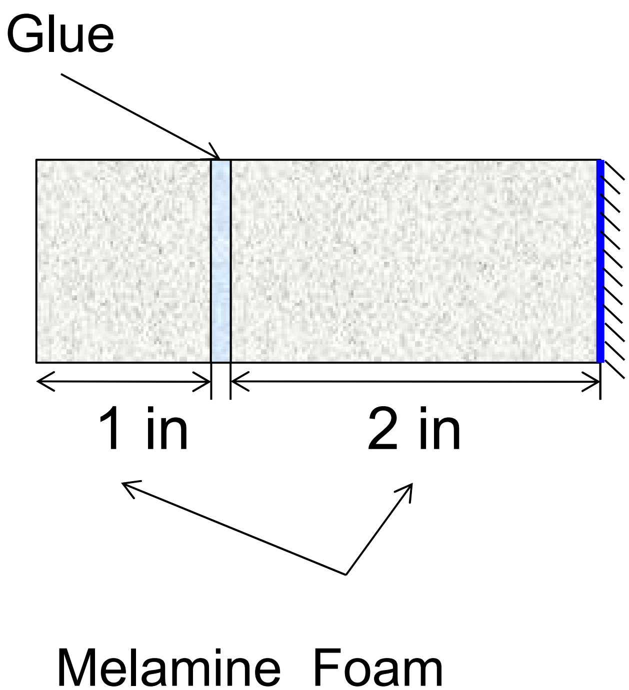


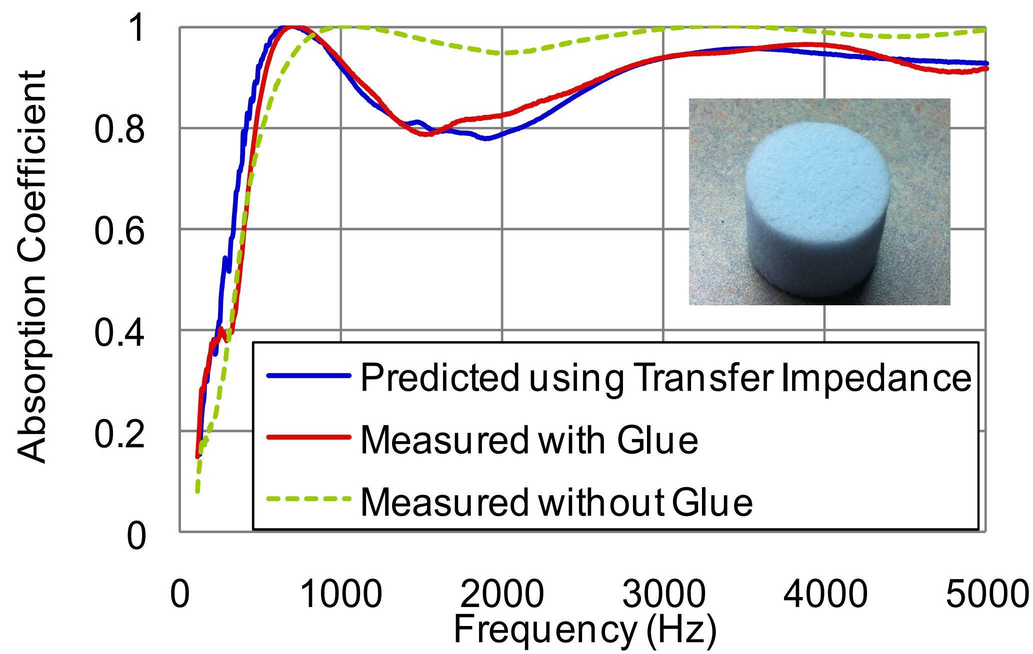


$$z_{tr} = z_1 - z_2$$

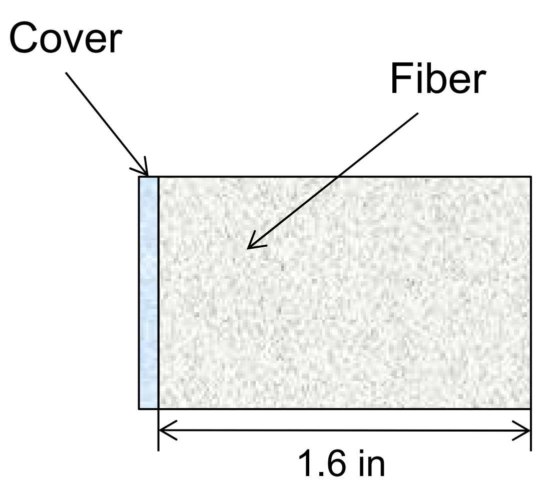
Test Case 1

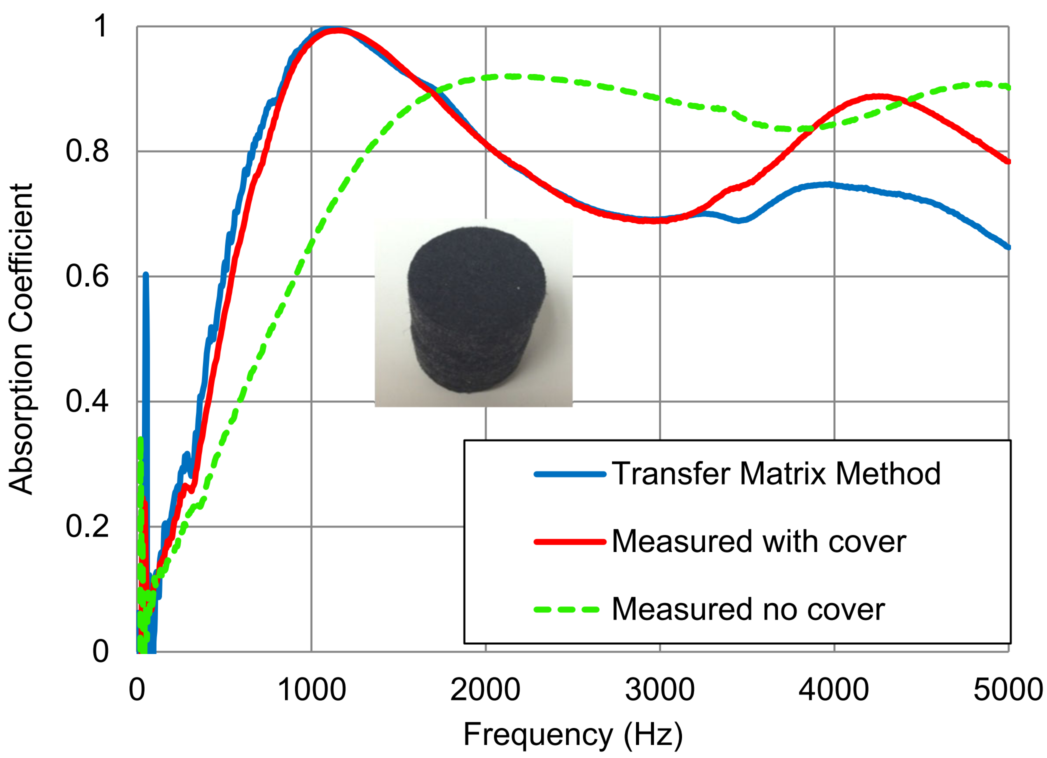
Two Layers of Foam Bonded with Adhesive



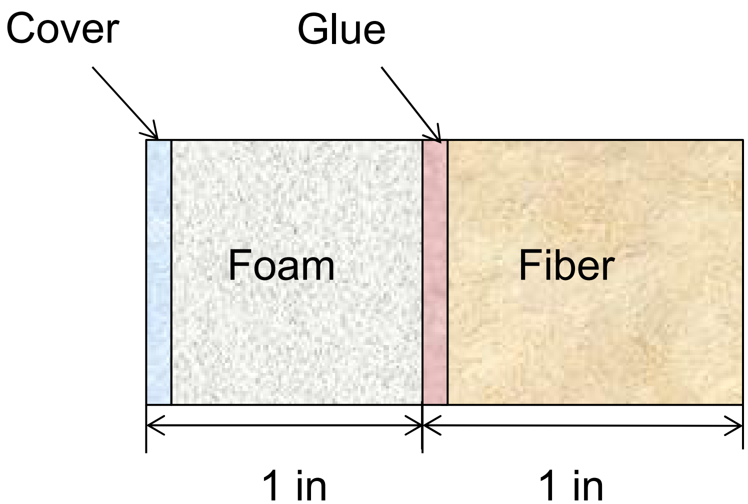


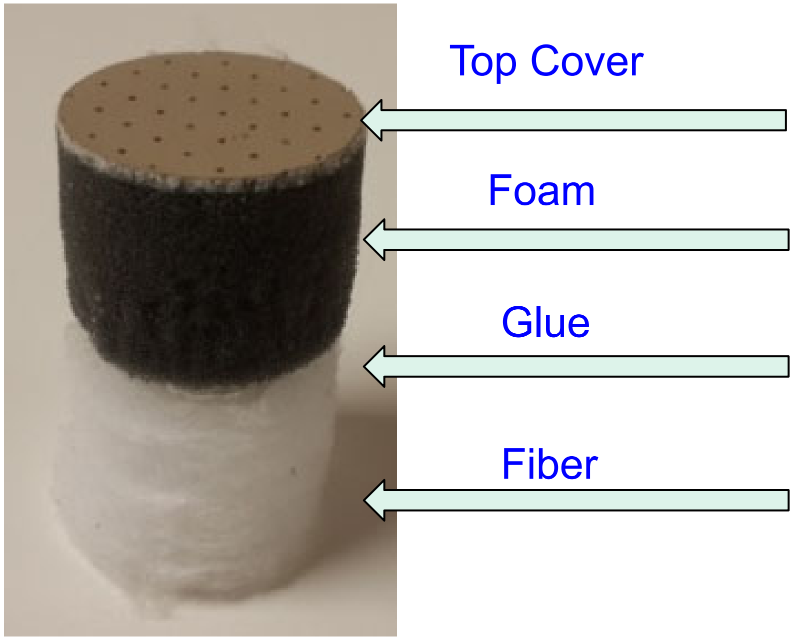
Test Case 2


Cover
Fiber
1.6 in


1
0.8
0.6
0.4
0.2
0
Absorption Coefficient
0
1000
2000
3000
4000
5000
Frequency (Hz)
Transfer Matrix Method
Measured with cover
Measured no cover

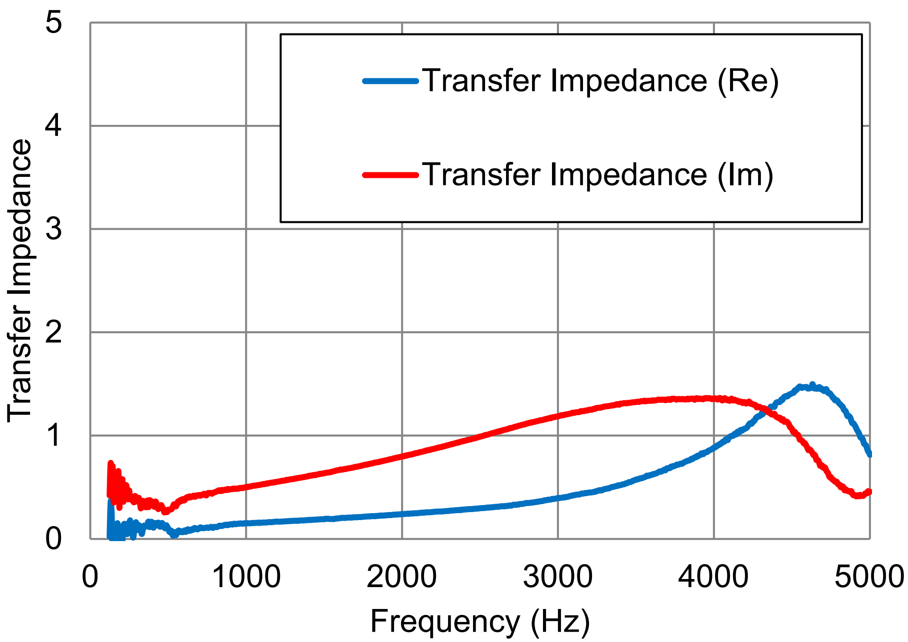
Test Case 3



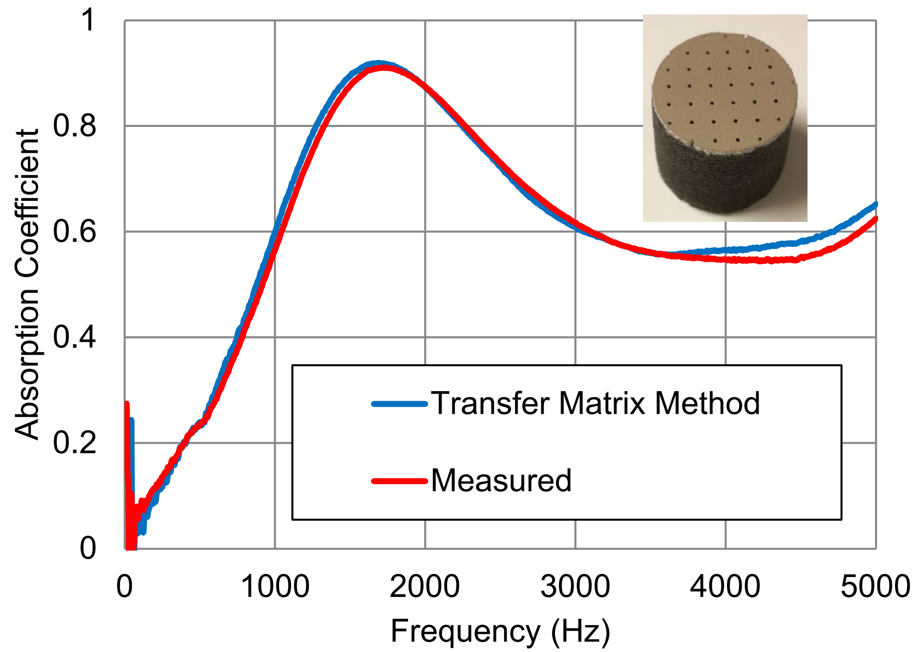


Test Case 3

Top Cover Transfer Impedance

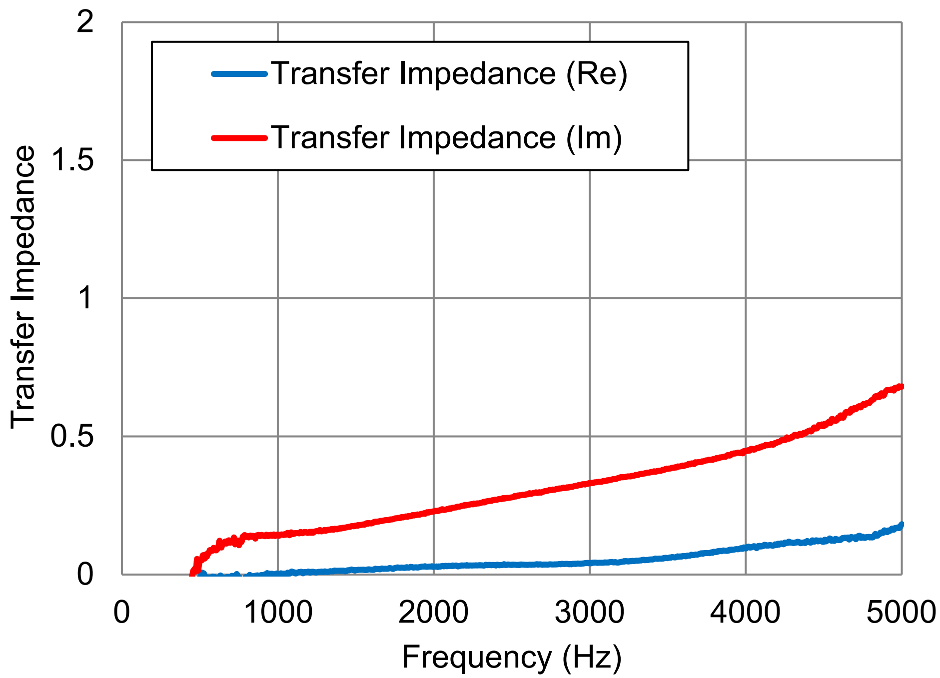


Top Cover + Foam Layer

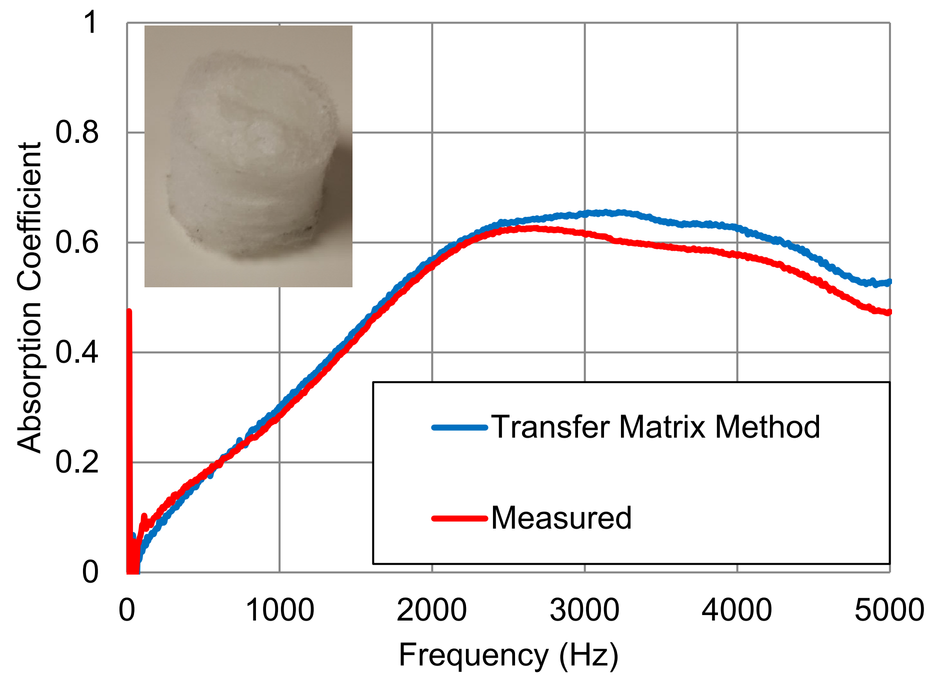


Test Case 3

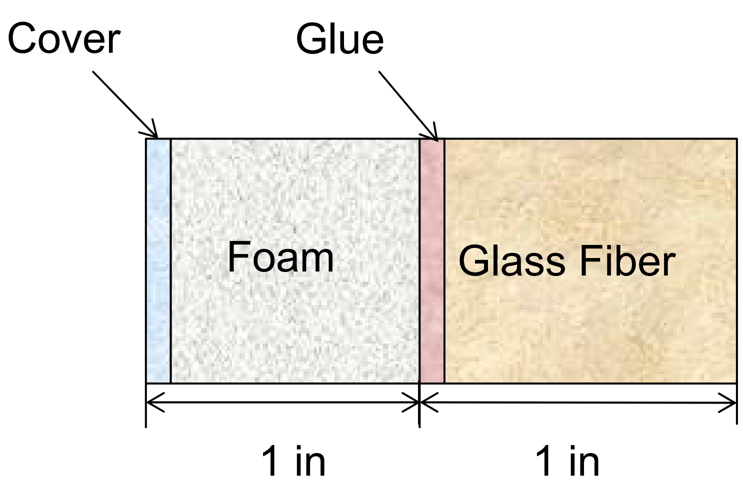
Glue Transfer Impedance



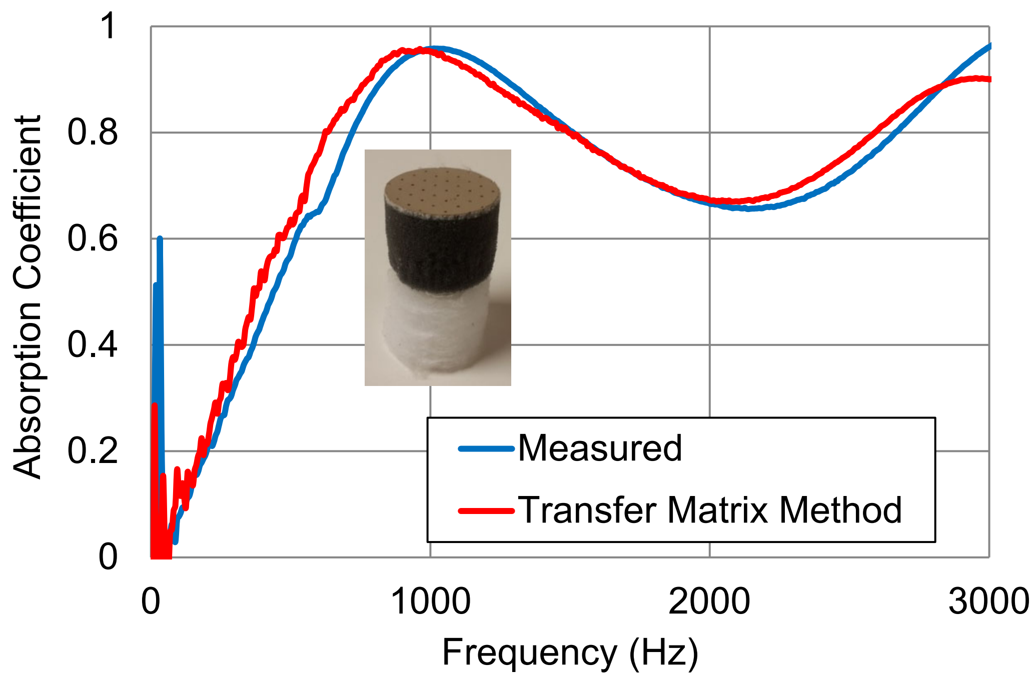
Glue + Fiber Layer



Test Case 3



Cover
Glue
Foam
Glass Fiber
1 in
1 in



1
0.8
0.6
0.4
0.2
0
Absorption Coefficient
0
1000
2000
3000
Frequency (Hz)
Measured
Transfer Matrix Method

Summary

- Transfer impedance is determined using an impedance difference approach.
- Demonstrated capability to predict properties of layered absorbers.

Transmission Loss Standards

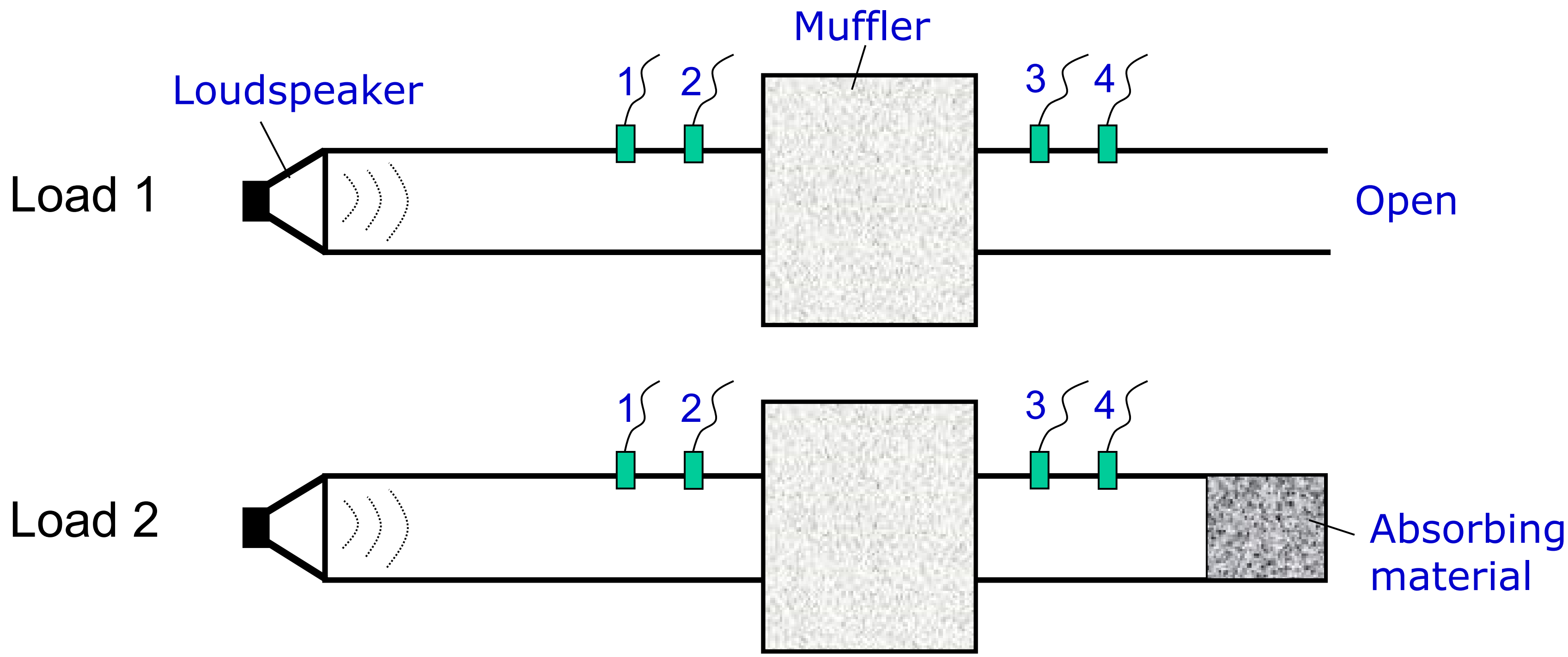
ASTM E2611-09, “Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method,” American Society of Testing and Materials, Philadelphia, 2009.

This standard

- Is designed to measure TL of ‘soft’ barrier materials
- Is not specifically aimed at mufflers
- Only mentions the two-load method*

* Also one-load method for uniform materials

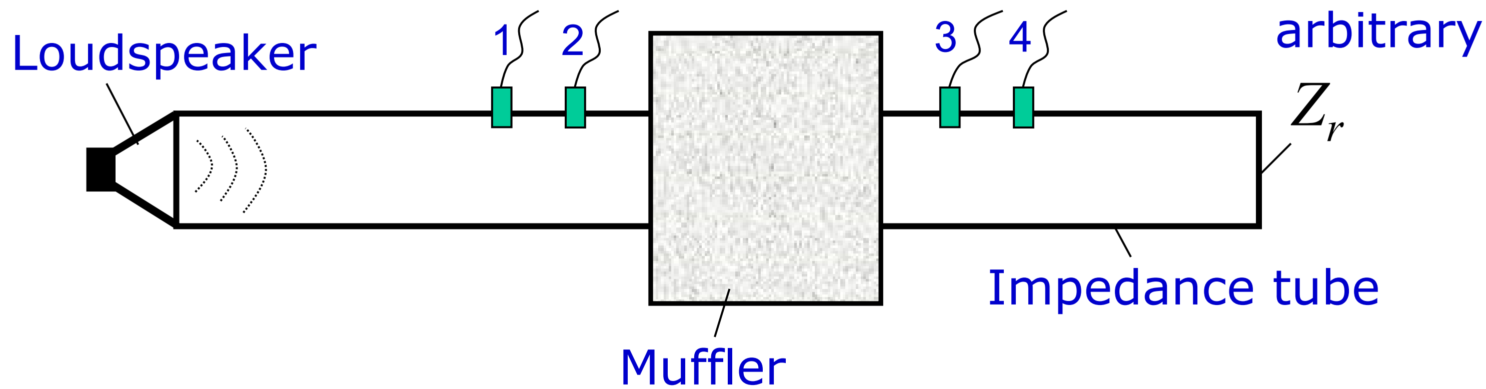
Two-Load Method



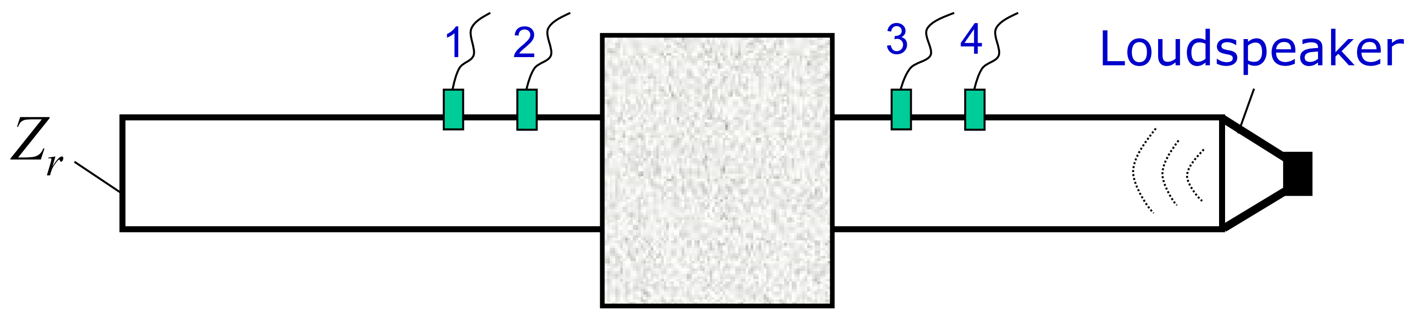
To and Doige, 1979

Two-Source Method

Configuration A



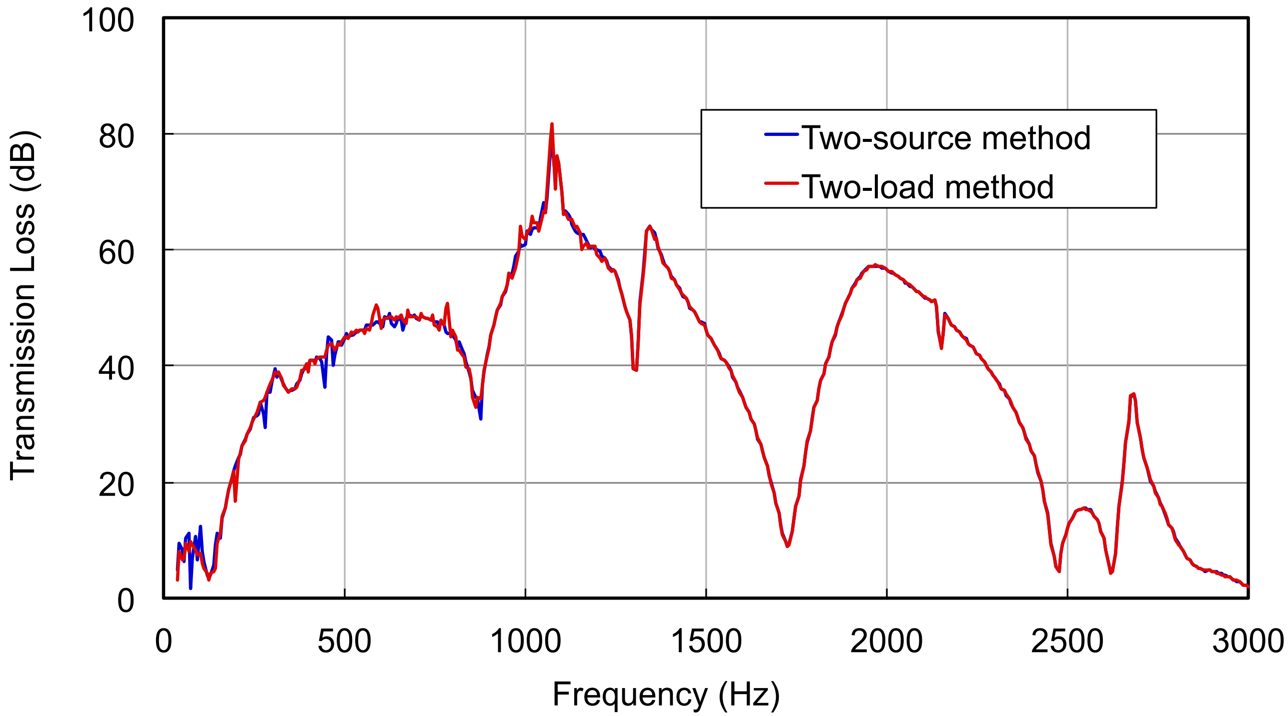
Configuration B



Munjal and Doige, 1990

Transmission Loss Calculation

$$TL = 20\log_{10}\left(\frac{1}{2}\left|T_{11} + \frac{T_{12}}{\rho c} + \rho c T_{21} + T_{22}\right|\right)$$



Future Directions

- Develop a better method (or refine the approach) for determining the transmission loss of hard samples in an impedance tube.
- Explore best practices for cutting samples using the new water jet cutter at the University of Kentucky.

References

- ASTM E1050-19, “Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System”, Philadelphia, 2019.
- ASTM C522-03, “Standard Test Method for Air Flow Resistance of Acoustical Materials,” Philadelphia, 2003.
- ASTM E2611-19, “Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method,” Philadelphia, 2019.
- T. J. Cox and P. D’Antonio, Acoustic Absorbers and Diffusers: Theory, Design and Application, 3rd Edition, CRC Press, Boca Raton, FL (2017).
- W. L. Li, X. Hua, and D. W. Herrin, “A Survey of Methods for Determining the Bulk Properties of Sound Absorbing Materials,” Noise-Con 2014, Fort Lauderdale, FL, September 8-10 (2014).
- W. L. Li, D. W. Herrin, and J. Haylett, “Measurement of the Transfer Impedance of Covers and Adhesives with Application to Multi-Layer Design,” Noise-Con 2014, Fort Lauderdale, FL, September 8-10 (2014).
- Y. Salissou and R. Panneton, “Wideband Characterization of the Complex Wave Number and Characteristic Impedance of Sound Absorbers,” Journal of the Acoustical Society of America, 128(5), 2868-2876 (2010).
- T. W. Wu, C. Y. R. Cheng and Z. Tao, “Boundary Element Analysis of Packed Silencers with Protective Cloth and Embedded Thin Surfaces,” Journal of Sound and Vibration, 261, 1-15 (2003).