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The Effect of Sample Edge Conditions on Standing Wave Tube Measurements of Absorption and Transmission Loss

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1. Introduction Summary

- Observation: Frequently when samples are measured in small and large standing wave tubes, the results do not overlap.
- Question: What is the origin of this discrepancy?
- Conclusion: Not always possible to model samples in standing wave tubes using a single set of parameters due to edge effects (damage at edge of sample).

1. Introduction
Outline

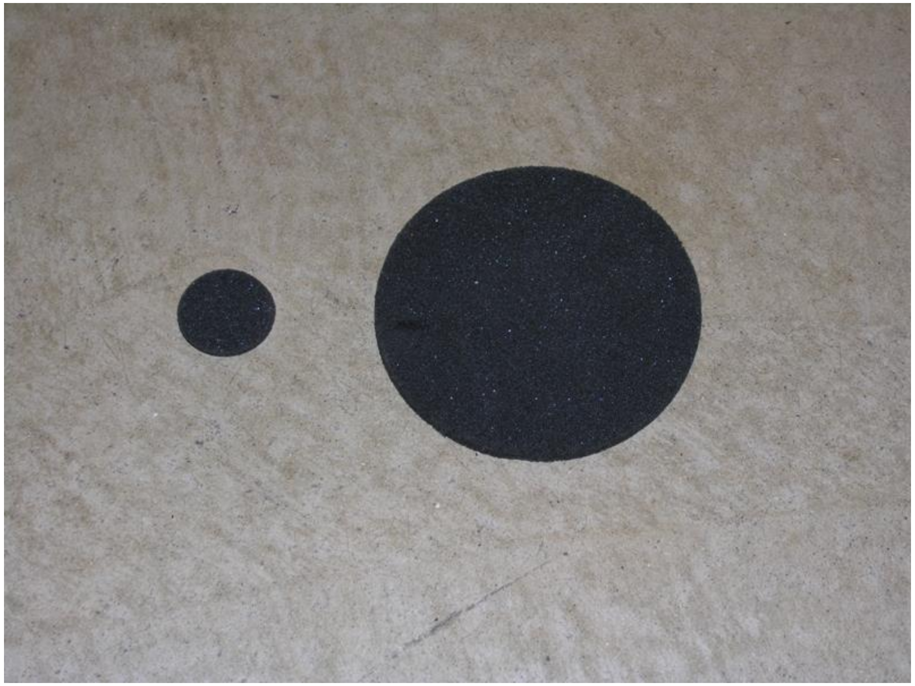
- Verify the effect of sample edge conditions on standing wave tube measurements

1. The acoustical measurement of the samples in two, and four-microphone standing wave tube
2. Sensitivity analysis based on finite element model
3. Inverse characterization by using finite element models
4. Inhomogeneous finite element model to predict the effect of sample edge conditions

1. Introduction
Sample foam

Polyurethane DO5 foam (Bridgestone)

Good sound absorbing performance in certain frequency range with relatively thin thickness

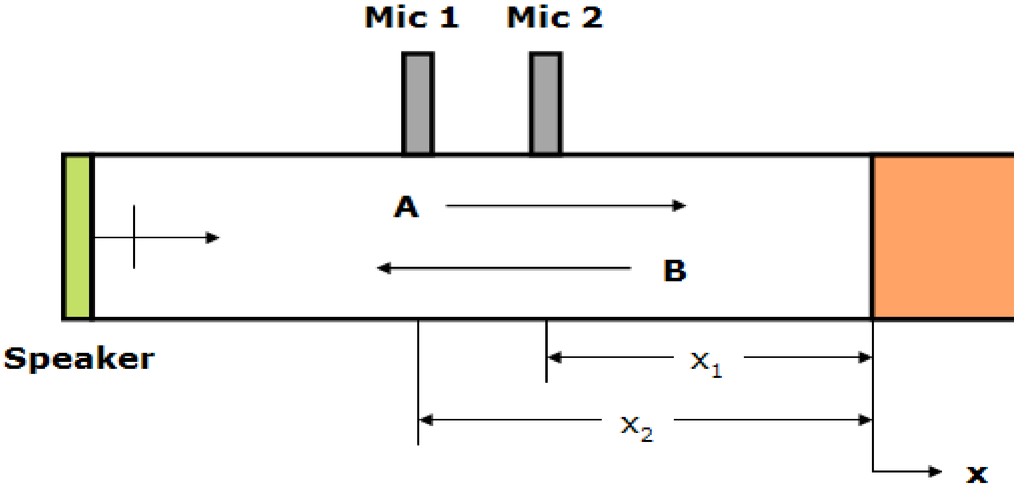


Thickness : 5 mm

Density : 64.7 kg/m^3

Measured absorption and TL of 10 different small and large samples

2. Measurement Procedures Absorption Coefficient (ASTM E1050)



1. Sound pressures

$$P_1 = \left(Ae^{-jkx_1} + Be^{jkx_1}\right)e^{j\omega t}$$
$$P_2 = \left(Ae^{-jkx_2} + Be^{jkx_2}\right)e^{j\omega t}$$

2. Measuring transfer function

$$H_{21} = \frac{Ae^{-jkx_2} + Be^{jkx_2}}{Ae^{-jkx_1} + Be^{jkx_1}}$$
$$H_{21} = \frac{e^{-jkx_2} + \mathrm{R}e^{jkx_2}}{e^{-jkx_1} + \mathrm{R}e^{jkx_1}}$$

3. Solve for R

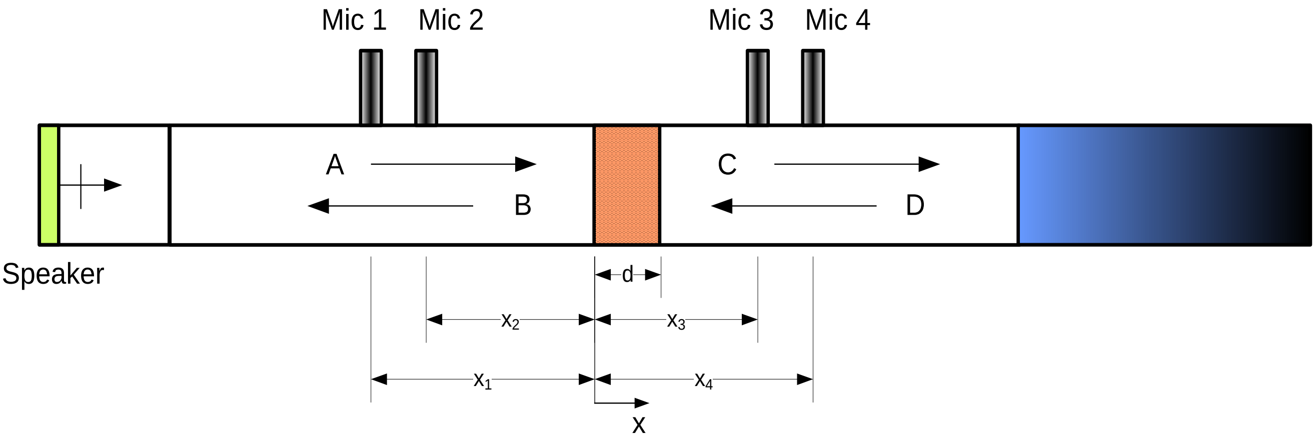
$$R = \frac{-H_{21}e^{-jkx_1} + e^{-jkx_2}}{H_{21}e^{jkx_1} - e^{jkx_2}}$$

4. Absorption coefficient

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

2.9 cm diameter tube: 500 Hz to 6400 Hz
10 cm diameter tube: 100 Hz to 1600 Hz

2. Measurement Procedures Transmission Loss



1. Measuring sound pressure:

$$P_1 = (Ae^{-jkx_1} + Be^{jkx_1})e^{j\omega t} \quad P_3 = (Ce^{-jkx_3} + De^{jkx_3})e^{j\omega t}$$

$$P_2 = (Ae^{-jkx_2} + Be^{jkx_2})e^{j\omega t} \quad P_4 = (Ce^{-jkx_4} + De^{jkx_4})e^{j\omega t}$$

2. Calculate complex amplitude of waves:

$$A = \frac{j(P_1 e^{jkx_2} - P_2 e^{jkx_1})}{2\sin k(x_1 - x_2)} \qquad C = \frac{j(P_3 e^{jkx_4} - P_4 e^{jkx_3})}{2\sin k(x_3 - x_4)}$$

$$B = \frac{j(P_2 e^{-jkx_1} - P_1 e^{-jkx_2})}{2\sin k(x_1 - x_2)} \qquad D = \frac{j(P_4 e^{-jkx_3} - P_3 e^{-jkx_4})}{2\sin k(x_3 - x_4)}$$

3. Estimate transfer matrix elements:

$$T_{11} = \frac{P|_{x=d} V|_{x=d} + P|_{x=0} V|_{x=0}}{P|_{x=0} V|_{x=d} + P|_{x=d} V|_{x=0}} \qquad T_{12} = \frac{P|_{x=0}^2 - P|_{x=d}^2}{P|_{x=0} V|_{x=d} + P|_{x=d} V|_{x=0}}$$

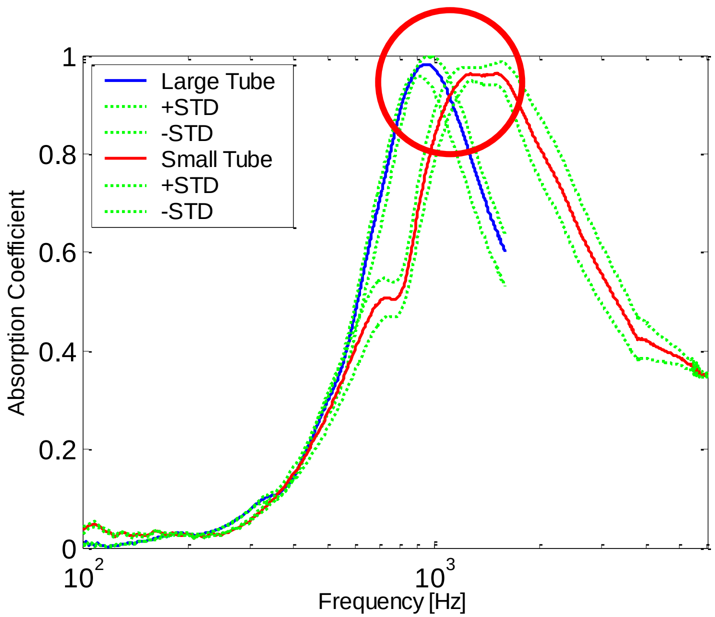
$$T_{21} = \frac{V|_{x=0}^2 - V|_{x=d}^2}{P|_{x=0} V|_{x=d} + P|_{x=d} V|_{x=0}} \qquad T_{22} = \frac{P|_{x=d} V|_{x=d} + P|_{x=0} V|_{x=0}}{P|_{x=0} V|_{x=d} + P|_{x=d} V|_{x=0}}$$

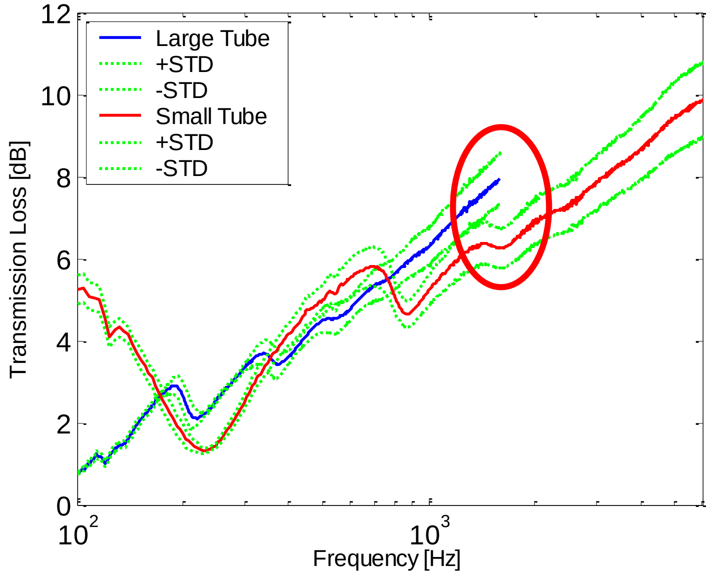
4. Obtain Transmission loss:

$$\mathrm{TL} = 20\log_{10}\left(1/|T|\right)$$

Where, $$T = \frac{2e^{jkd}}{T_{11} + (T_{12}/\rho_0 c) + \rho_0 c T_{21} + T_{22}}$$

2. Measurement Procedures Absorption and TL Results





Note that the first absorption peak appears at a lower frequency when measured in large tube than it does when measured in small tube

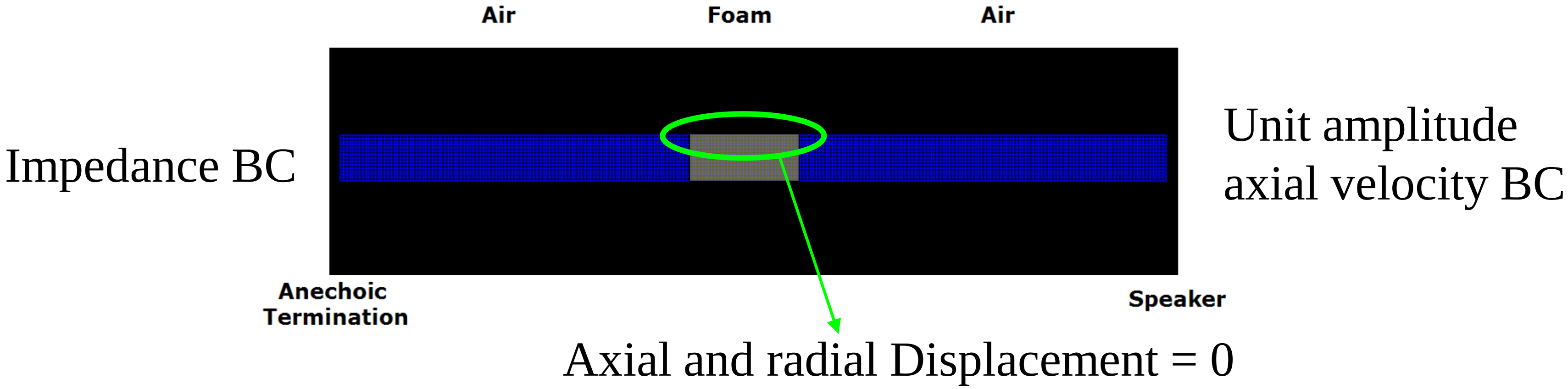
Note that the transmission loss measured in the large tube is larger (about 2 dB) than the small tube result in the region above 800 Hz

3. Finite Element Models COMET/SAFE

- The software COMET/SAFE is used to model and compute the absorption and transmission loss of a finite depth and finite size layer of porous material.
- A finite element based program that allows for the analysis of sound traveling through various media including fluids, solids and foam-like substances.
- Finite element implementation is based on *u-U* and *p-U* versions of Biot theory.
- All models used in this work involved axisymmetric elements.
- It does not support automated inverse characterization capability.

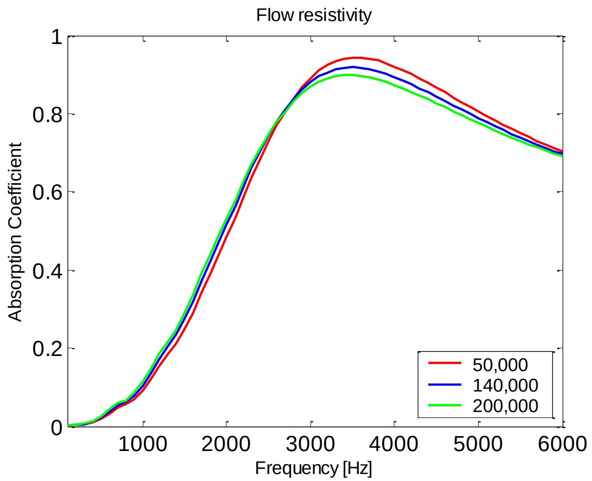
3. Finite Element Models
Mesh and Boundary Conditions

- Four different types of standing wave tubes are modeled.
  1. 2.9 cm two-microphone setup ⇨ high frequency absorption
  2. 10 cm two-microphone setup ⇨ low frequency absorption
  3. 2.9 cm four-microphone setup ⇨ high frequency transmission loss
  4. 10 cm four-microphone setup ⇨ low frequency transmission loss
- For example, 2.9 cm four-microphone setup with polyurethane foam

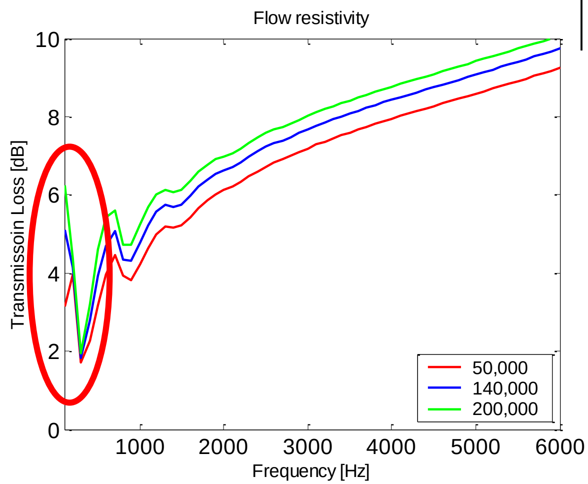


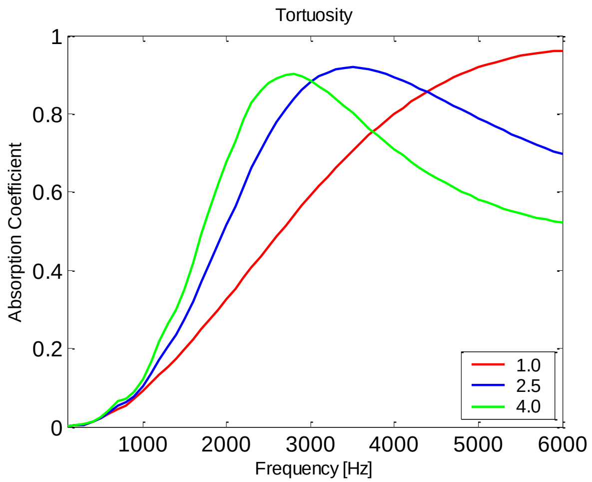
All elements are linear, four-node, quadrilateral and mesh size is 1 mm in the axial and radial direction

3. Finite Element Models Sensitivity Analysis

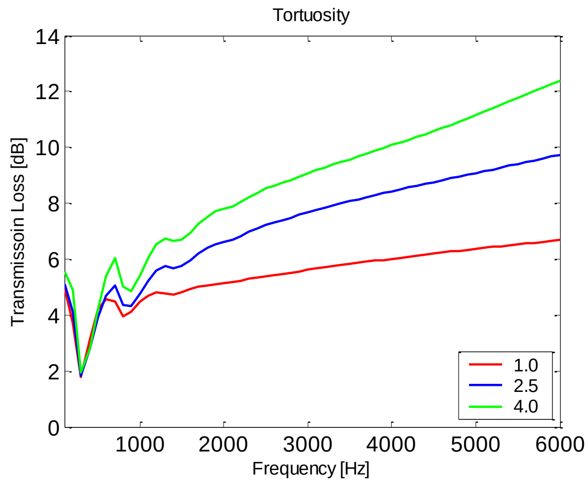


Flow resistivity

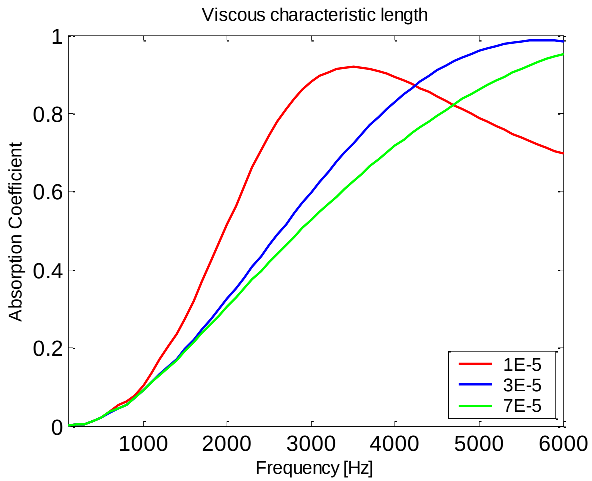




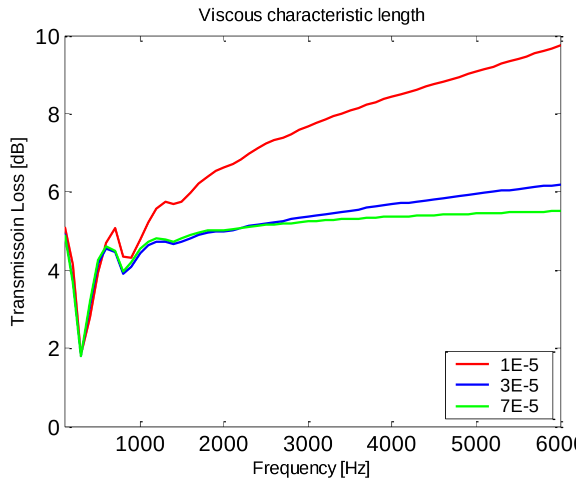
Tortuosity

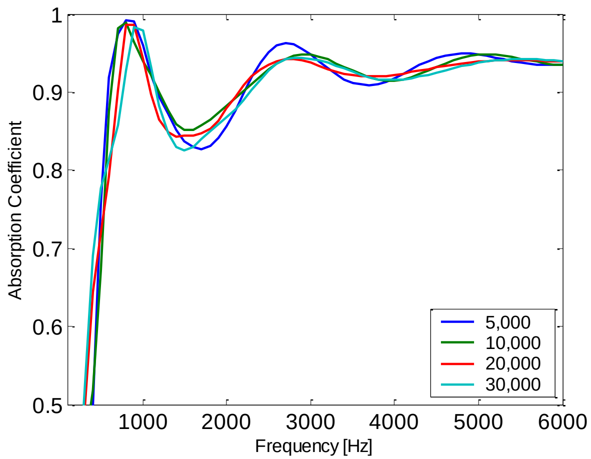


3. Finite Element Models Sensitivity Analysis

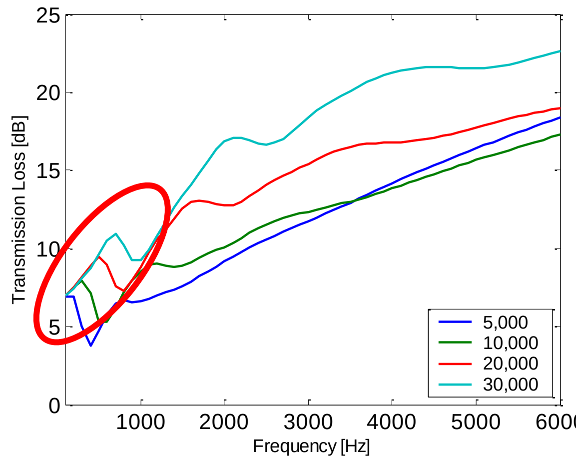


Viscous characteristic length

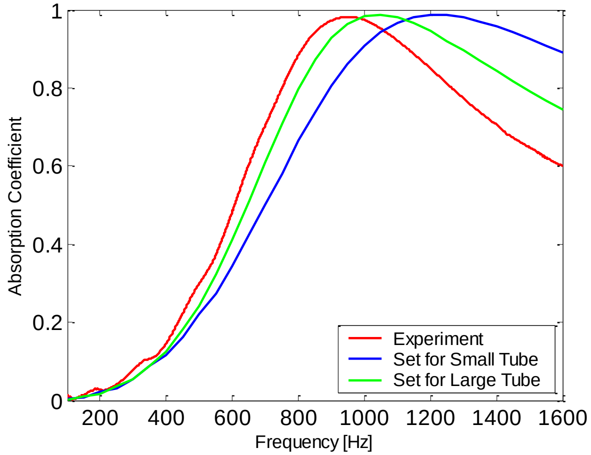




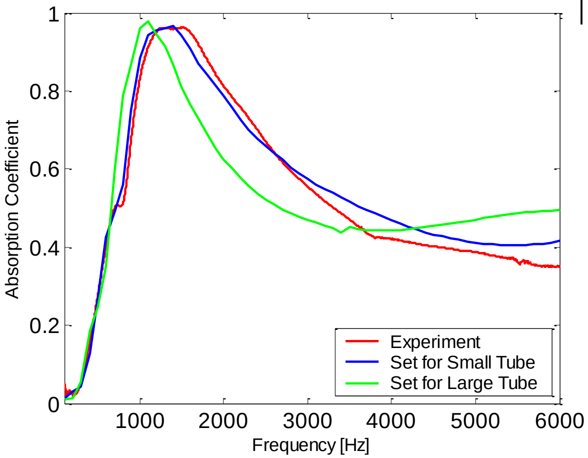
Young's modulus

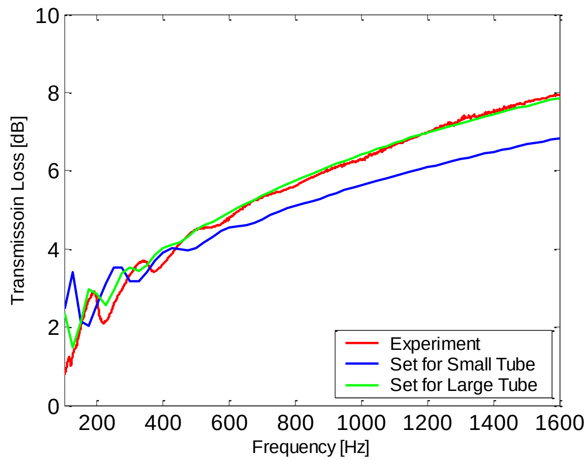


3. Finite Element Models Inverse Characterization

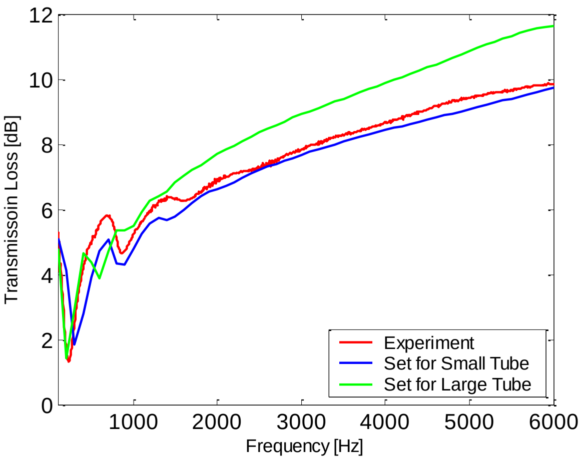


Absorption coefficient

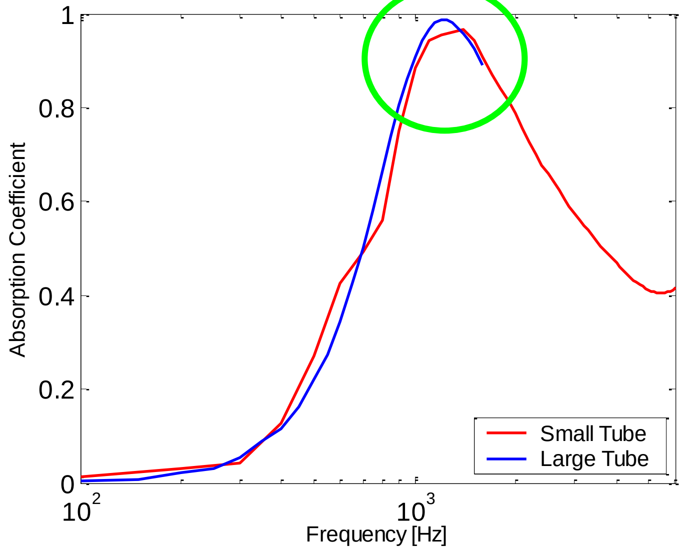




Transmission loss

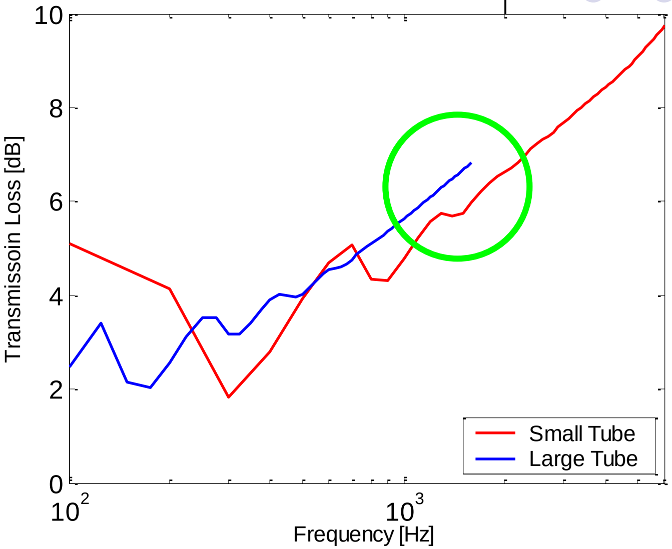


3. Finite Element Models Inverse Characterization



Polyurethane Foam

Density 64.7 Kg/m^3



No discrepancy between large and small tube prediction

Less than 1 dB discrepancy at 1600 Hz

Porosity	Flow Resistivity	Tortuosity	VCL	TCL	Young's modulus	Poisson's ratio	Loss factor
0.99	140,000	2.5	$1.0*10^{-5}$	$8.0*10^{-5}$	50,000	0.48	0.25

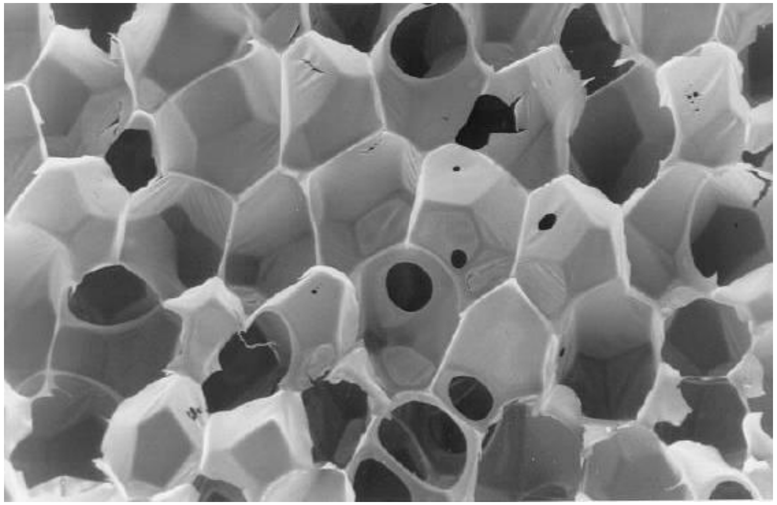
3. Finite Element Models Summary

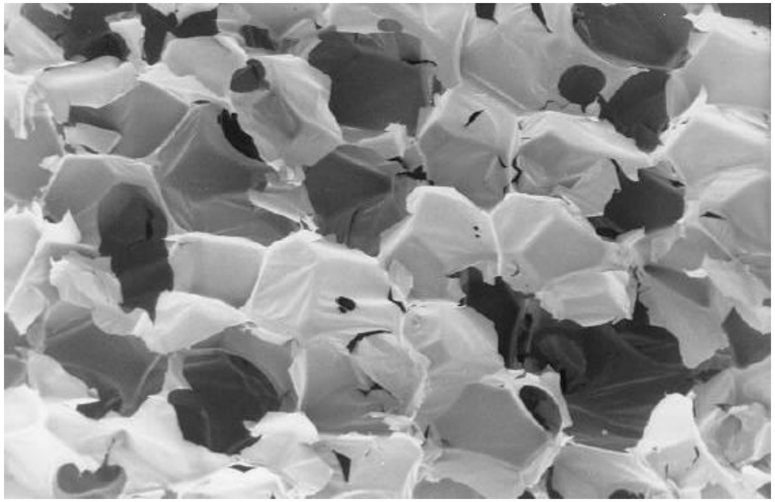
- A single set of material properties could not predict both the small and large tube experimental results simultaneously, thus could not reproduce the discrepancy between small and large tube.

- This discrepancy can be explained if there is a leakage path around the circumferential edge of the sample caused by damage due to the cutting process, that leakage being more significant in the small tube case due to the relatively small sample size.

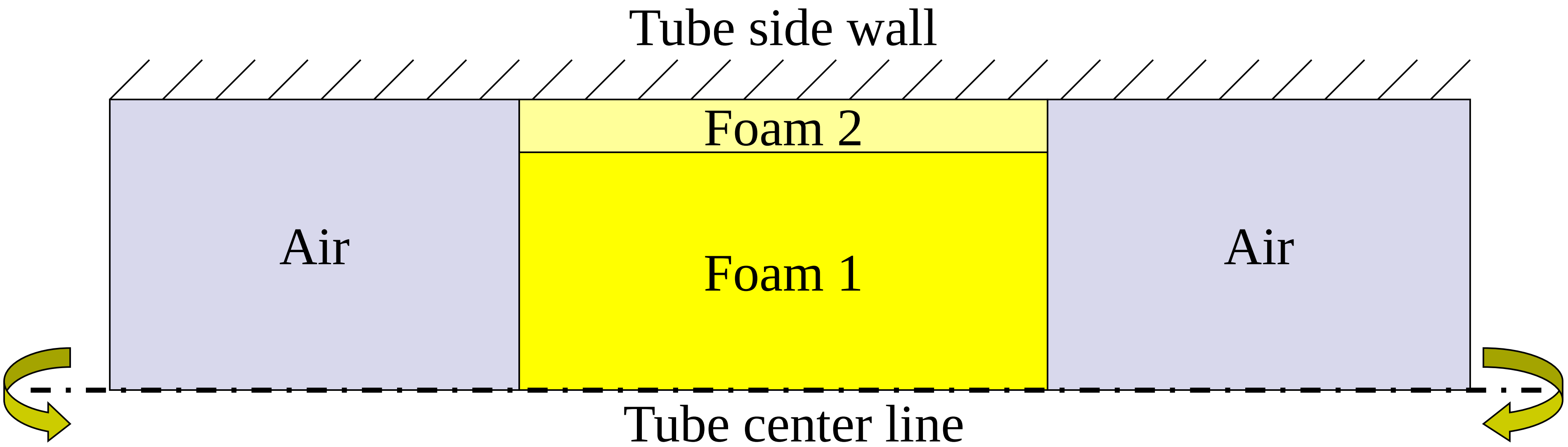
4. Effect of Sample Edge Condition

- The cell structure of the foam can be destroyed by applying external force e.g., damage caused by cutting tool.
- The destroyed cell structure will have different poroelastic material properties



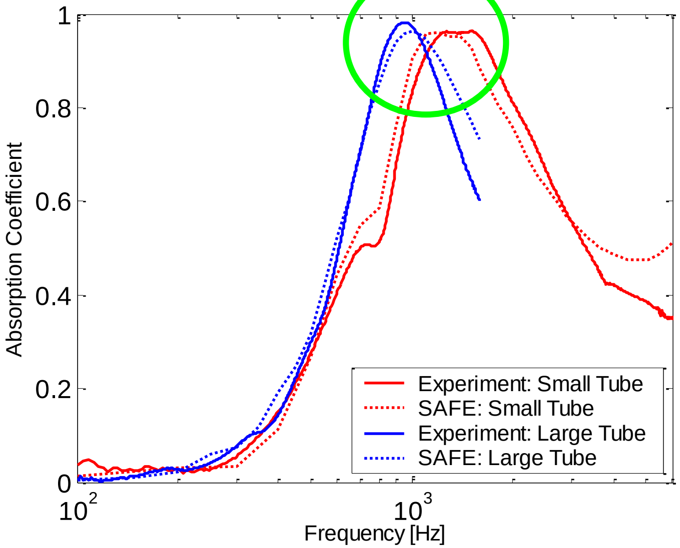


4. Effect of Sample Edge Condition Inhomogeneous Model



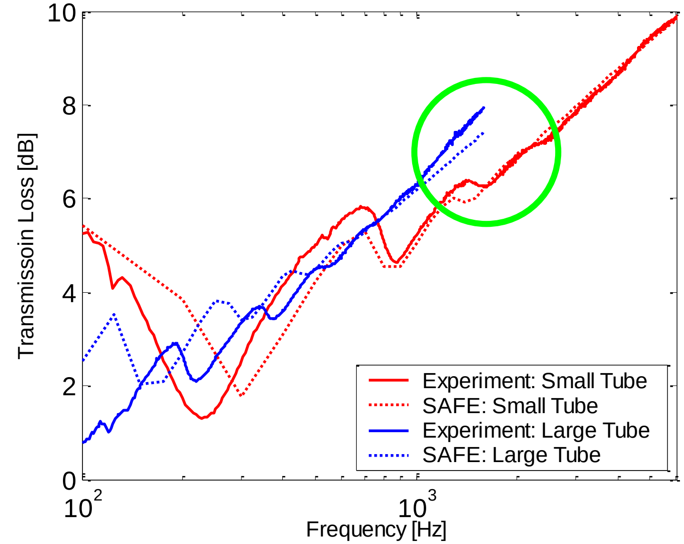
Inhomogeneous model can simulate different material properties at the edge which is caused by cell crushing when a foam is cut.

4. Effect of Sample Edge Condition Inverse Characterization



Polyurethane Foam

Density
64.7 Kg/m^3



A single set of material properties can fit the 4 different experimental results quite closely

Porosity	Flow Resistivity	Tortuosity	VCL	TCL	Young's modulus	Poisson's ratio	Loss factor
0.99	200,000 100,000	3.0 2.0	$1.0*10^{-5}$	$8.0*10^{-5}$	50,000	0.48 0.4	0.25

5. Conclusions

- The discrepancy noted between absorption coefficients and transmission losses measured in large and small tubes may be a consequence of minor damage to the edge of samples during the cutting process which reduces flow resistivity.
- The effect of this damage is relatively more important for small than large diameter samples.
- When this effect is explicitly modeled, a single set of material parameters can be used to predict the performance of multiple sample sizes.