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The Use of a Four-Microphone Standing Wave Tube to Estimate the Anisotropic Properties of Fibrous Noise Control Materials

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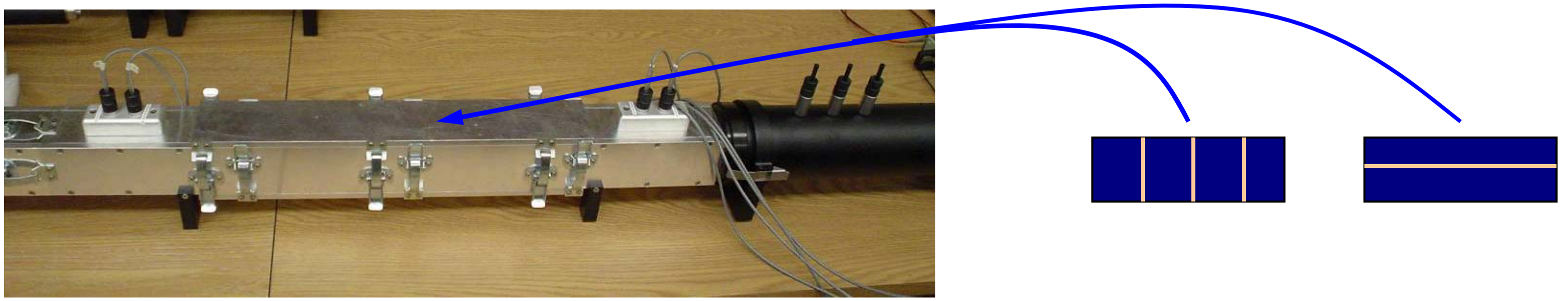
Overall Approach

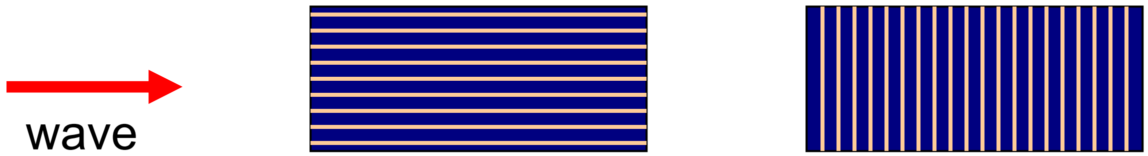
1. Measuring TL and absorption coefficient in square tube



2. Estimating material properties (COMET/Trim)
    - Flow resistivity, Characteristic lengths, tortuosity, porosity, bulk density, Young's modulus, Poisson's ratio, loss factor
3. Predicting performance using FEM (COMET/SAFE)
    - Partially filled cases

Introduction & Objectives

- Fibrous material
  - Blown in certain direction: Thus are anisotropic
  - Level of anisotropy depends on density of fiber, fiber’s material and physical dimensions



- Anisotropy
  - Performance differs with respect to wave direction with respect to fiber orientation
  - When is the performance better?
  - Estimation of material properties in different fiber orientations
  - Prediction of performance with the estimated properties

Material Properties I

- Nine properties represent a material

1. Flow resistivity
   - Pressure drop from low velocity flow in material
   - One of the most sensitive properties to performance
2. Viscous characteristic length
   - Depth of viscous boundary layer
   - Sensitive properties
   - Range: $1\text{x}10^{-5}\sim9.99\text{x}10^{-4}$ m
3. Thermal characteristic length
   - Depth of thermal boundary layer
   - Sensitive properties
   - Range: $1\text{x}10^{-5}\sim9.99\text{x}10^{-4}$ m

Material properties II

4. Tortuosity
   - Complexity in structure (usually 1.1 for fibrous material)
5. Porosity
   - Ratio of open to closed volume in bulk material
   - Usually 0.99 for fibrous material
6. Bulk density
   - Weight per unit volume
7. Young’s modulus
   - Axial stiffness of bulk material (usually less than 20 kPa for fibrous media)
8. Poisson’s ratio
   - Ratio of change in dimension in two different directions
9. Loss factor
   - Energy dissipation in solid material

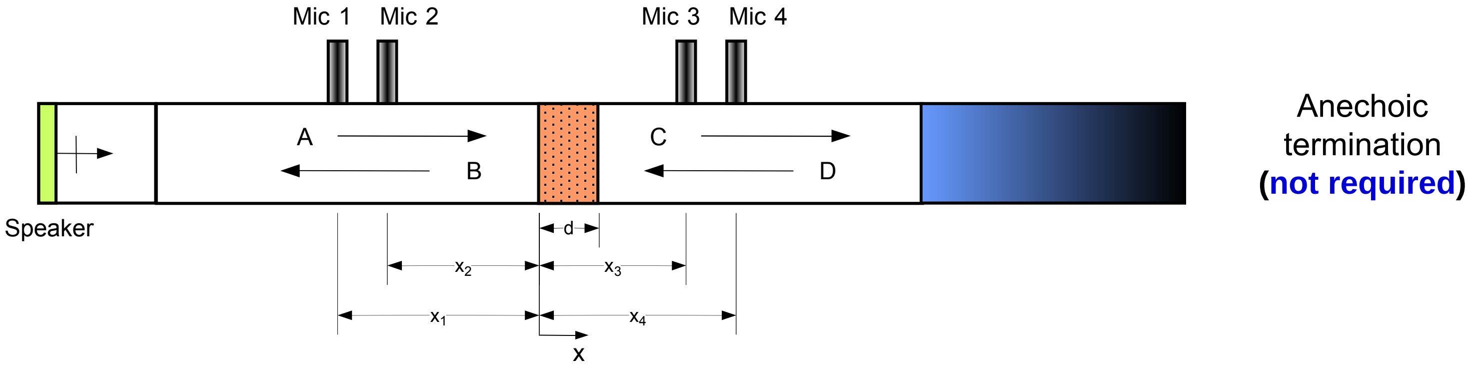
Materials

THL

TC

	THL	TC
Thickness [cm]	3.7	4
Mass per unit area [g/m^2]	156	376
Material	Polyester	Polypropylene + Polyester
Fiber size	Normal	Fine

Measurements of TL – square or round



1. Measuring sound pressure:

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

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

2. Calculate complex amplitude of waves:

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

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

* Measurements are averaged over 10 sets of samples

3. Estimate transfer matrix elements:

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

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

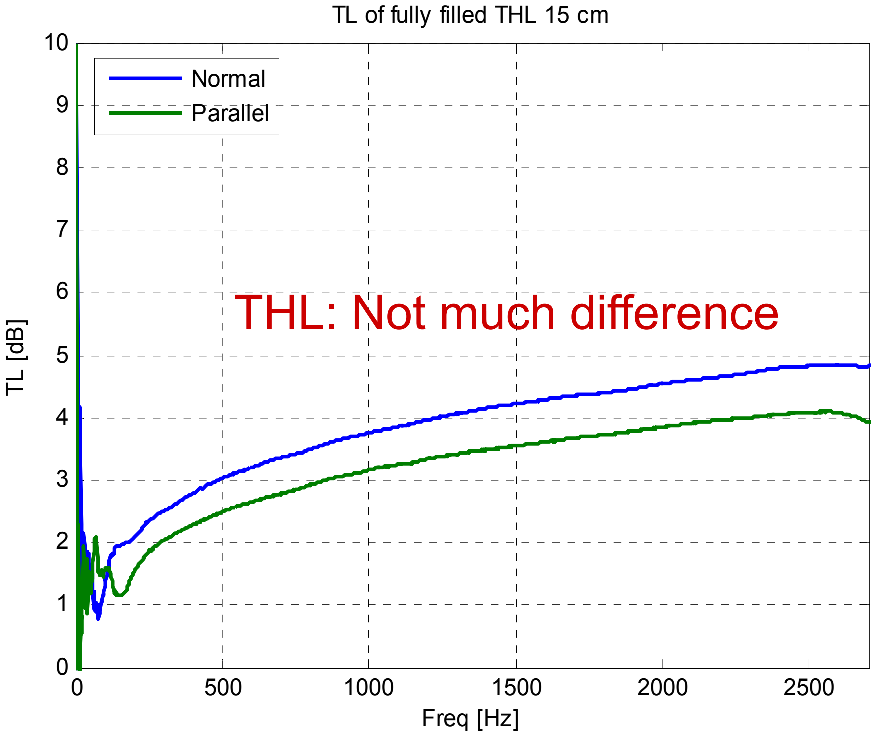
4. Obtain Transmission loss:

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

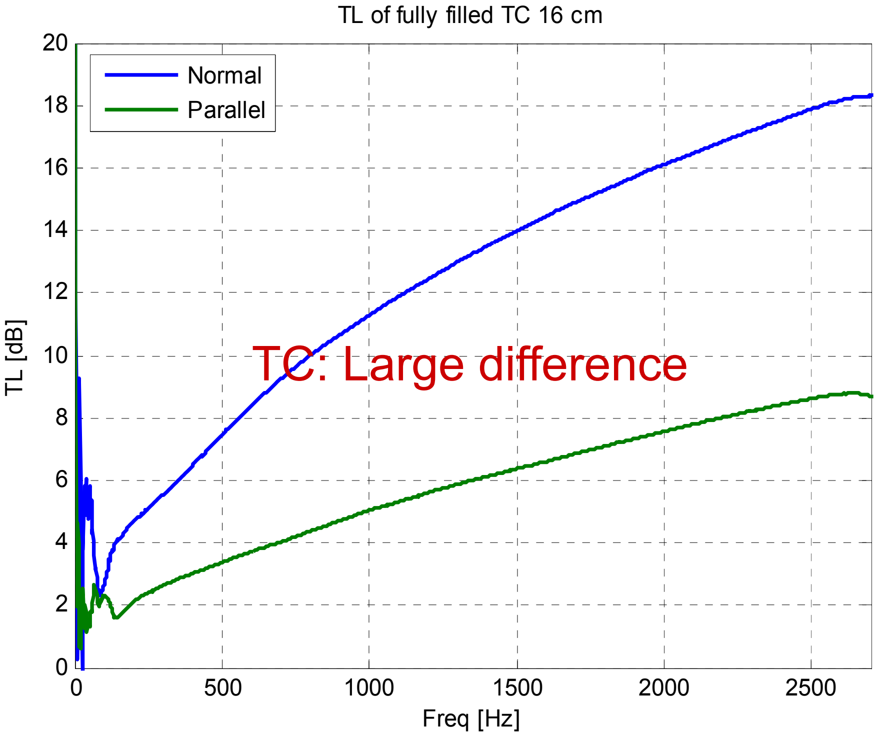
Where, $T = \dfrac{2e^{jkd}}{T_{11} + (T_{12}/\rho_0 c) + \rho_0 c T_{21} + T_{22}}$

TL’s in Two Orientations

- Averaged over ten measurements
  - Normal: using 4 layers
  - Parallel: samples were cut to have same weight as normal cases

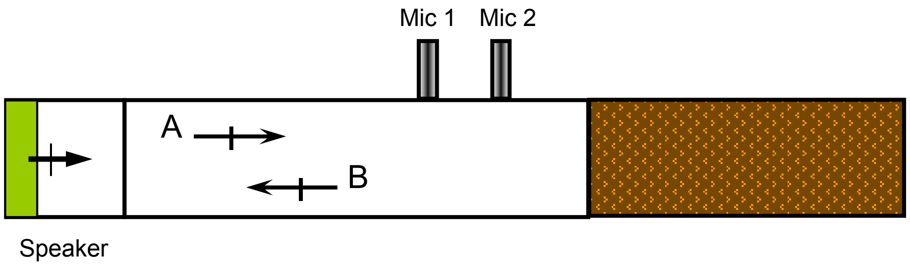

TL of fully filled THL 15 cm

THL: Not much difference


TL of fully filled TC 16 cm

TC: Large difference

Measurement of Absorption coefficient



Normal Incidence
Absorption coefficient

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

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

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

3. Solve for R

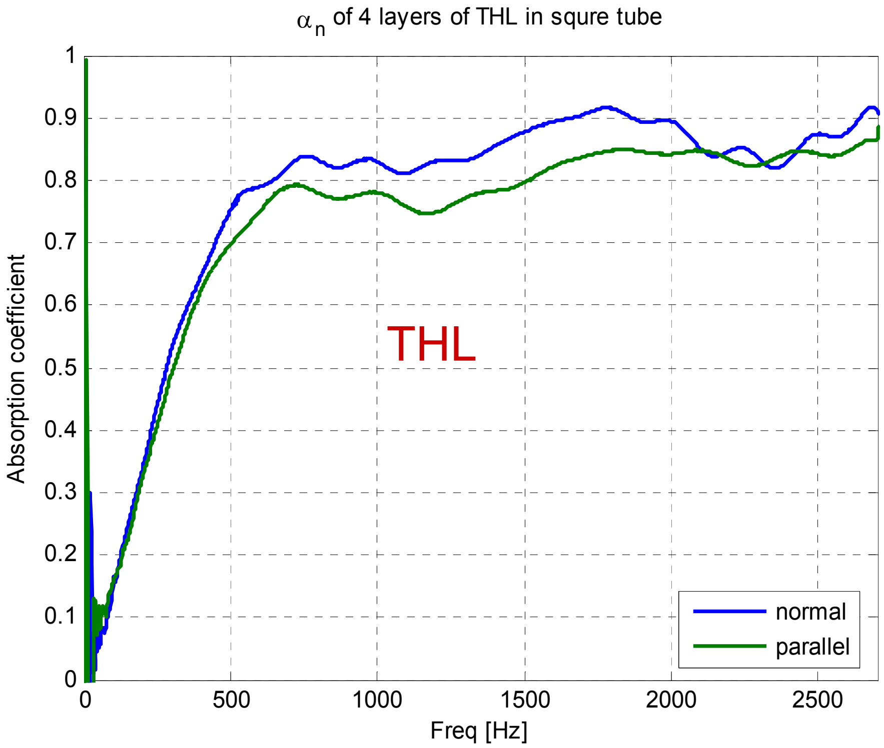
4. Absorption coefficient

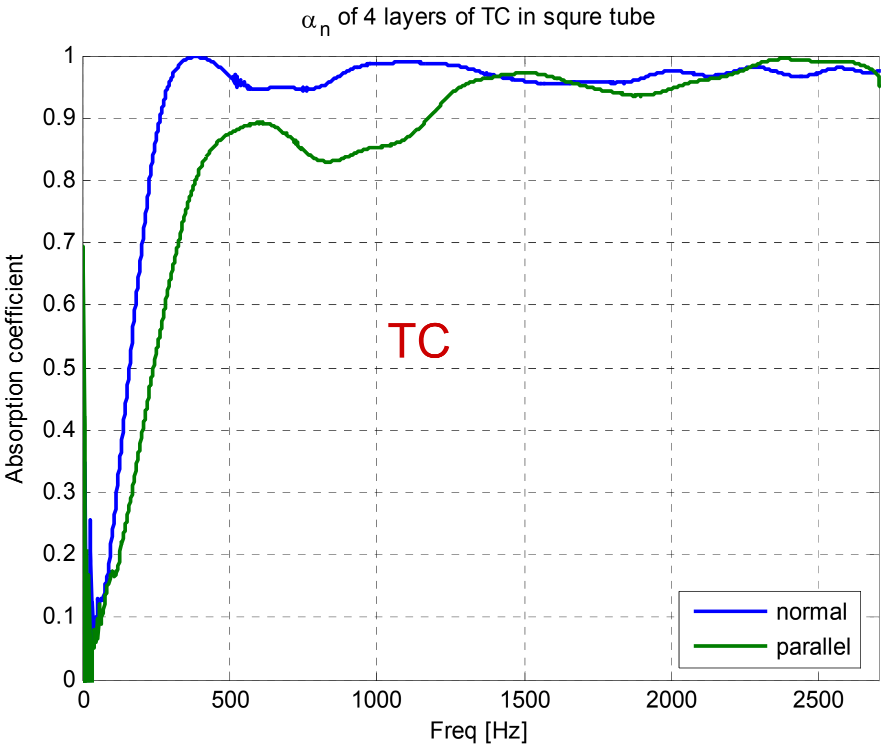
$$\alpha = 1 - |R|^2$$

* Measurements are averaged over 10 sets of samples

Absorptions in Two Orientations

- Averaged over ten measurements
  - Normal: using 4 layers
  - Parallel: samples were cut to have same weight as normal cases

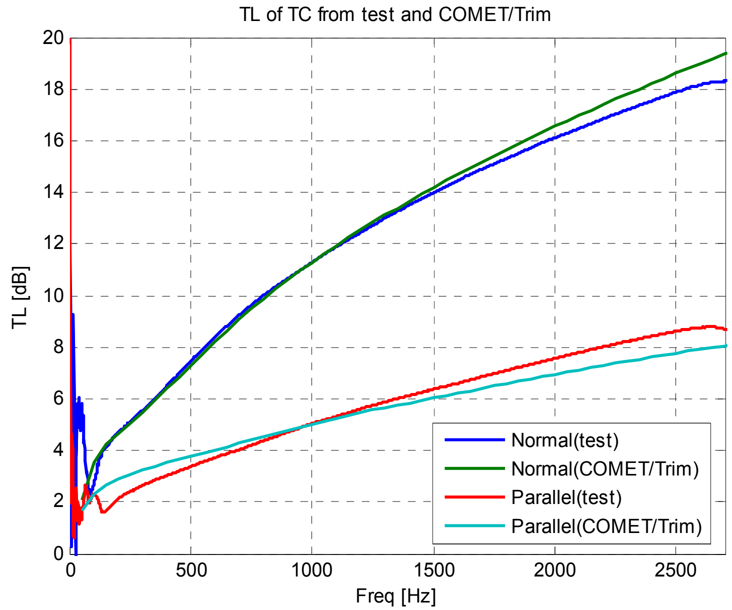

α_n of 4 layers of THL in squre tube

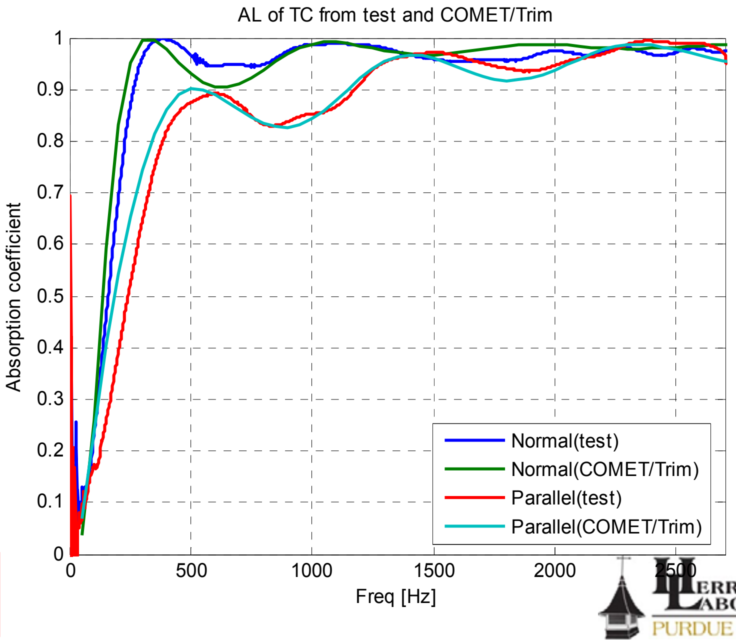

α_n of 4 layers of TC in squre tube

Estimation of TC Properties

Using inverse characterization in COMET/Trim

Material	TC	
Fiber direction	Normal	Parallel
Thickness [mm]	40	40
Porosity	0.99	0.99
Flow resistivity [Rayls/m]	**5500**	**1200**
Tortuosity	1.1	1.1
Viscous characteristic length [m]	7.90E-05	1.90E-04
Thermal characteristic length [m]	1.52E-04	3.55E-04
Bulk density [kg/m3]	9.4	9.4
Young's modulus [Pa]	2000	2000
Poisson's ratio	0.3	0.3
Loss factor	0.3	0.3





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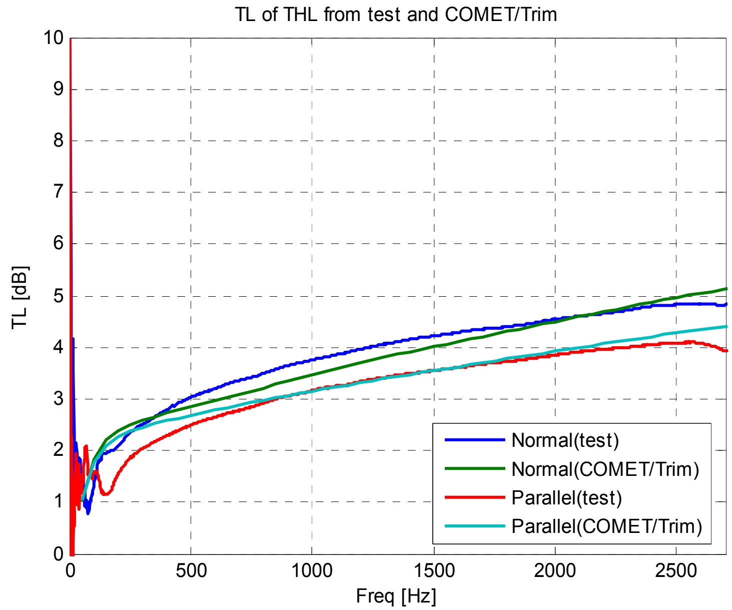
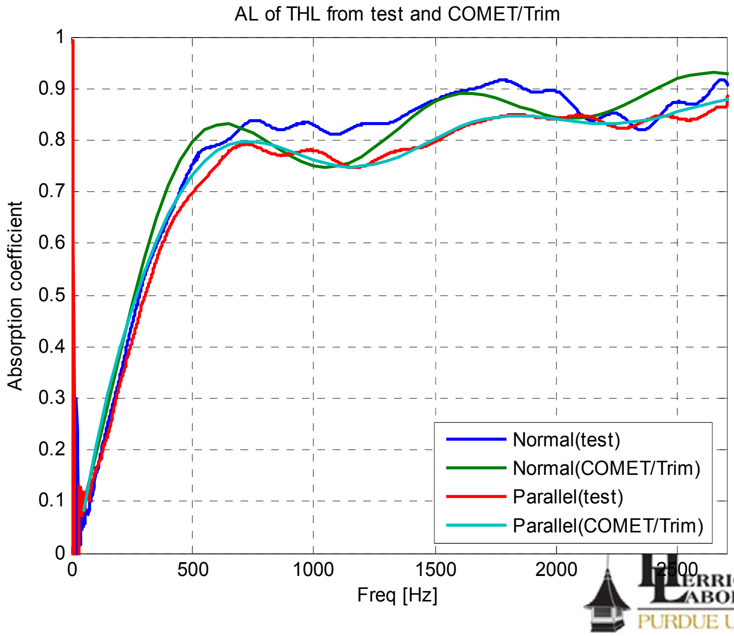
Estimation of THL Properties

Using inverse characterization in COMET/Trim

Material	THL	
Fiber direction	Normal	Parallel
Thickness [mm]	37	37
Porosity	0.99	0.99
Flow resistivity [Rayls/m]	**2300**	**1560**
Tortuosity	1.1	1.1
Viscous characteristic length [m]	3.00E-04	4.67E-04
Thermal characteristic length [m]	8.29E-04	4.67E-04
Bulk density [kg/m3]	4.16	4.16
Young's modulus [Pa]	3000	3000
Poisson's ratio	0.3	0.3
Loss factor	0.3	0.3





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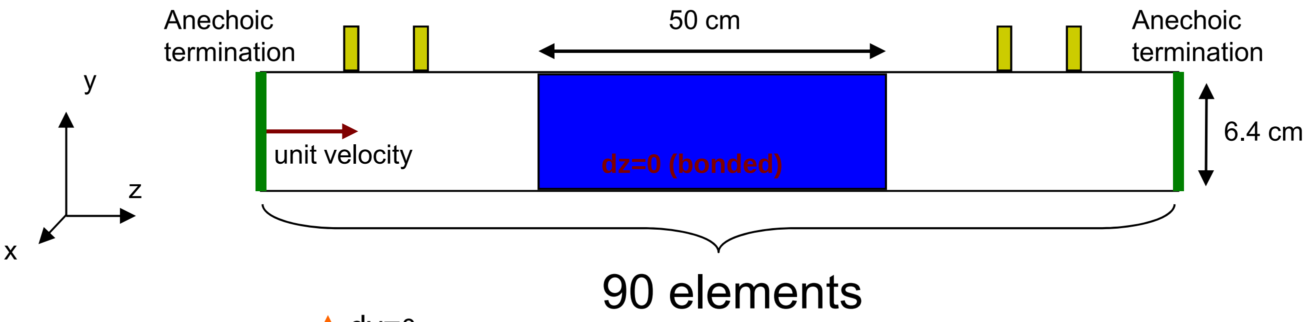
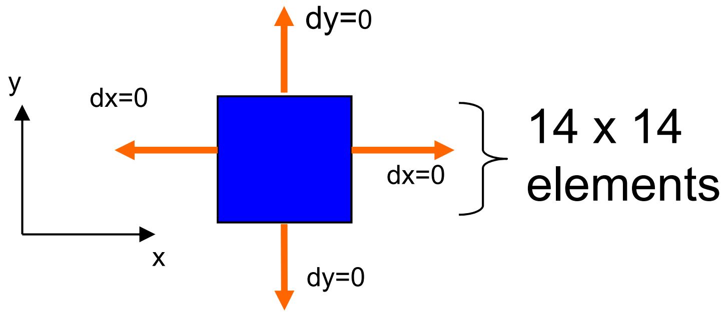
Finite Element Method

- Dimensions are same as experiment setup

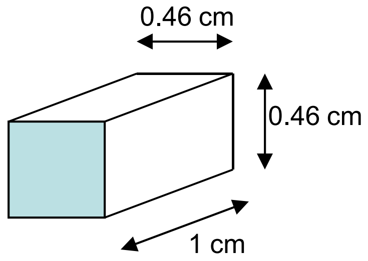
Side view



Front view



Element

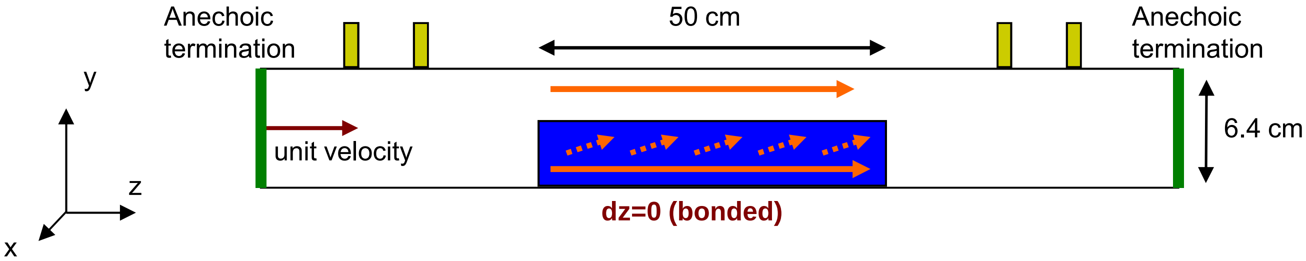


$$\frac{\lambda}{4} = \frac{c}{4 \cdot f} = \frac{340}{4 \cdot 2700} = 0.0315 \quad > 0.01$$

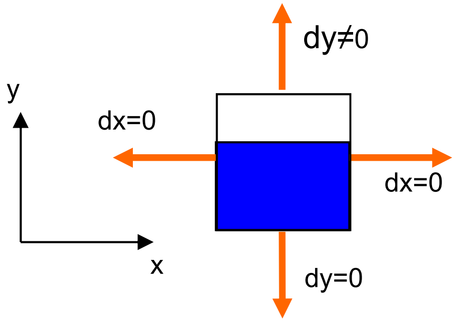
Partially Filled Cases

- Using single layer of TC and THL

Side view

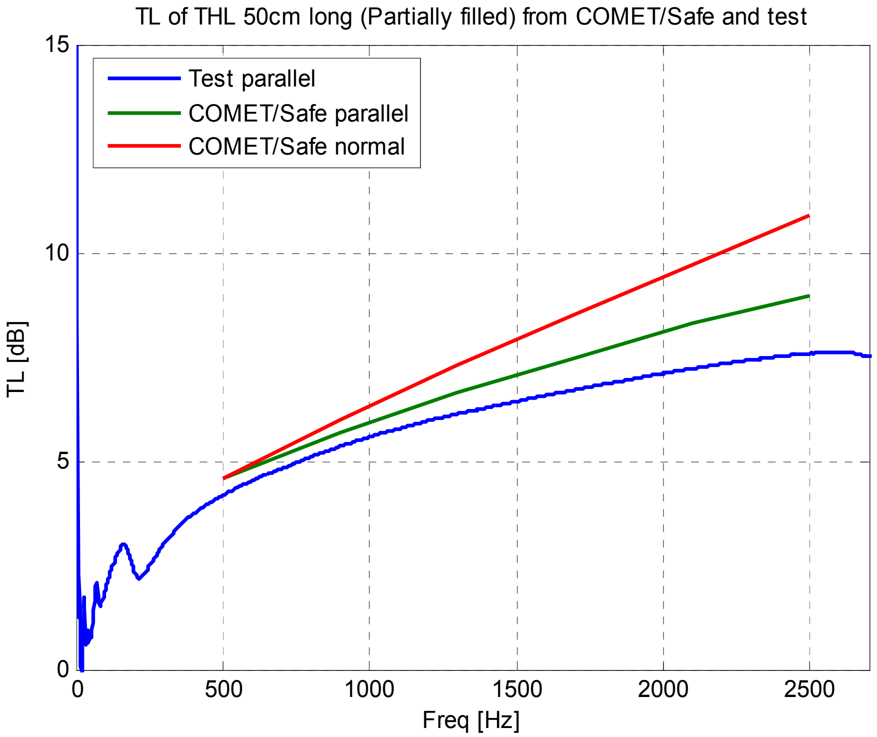


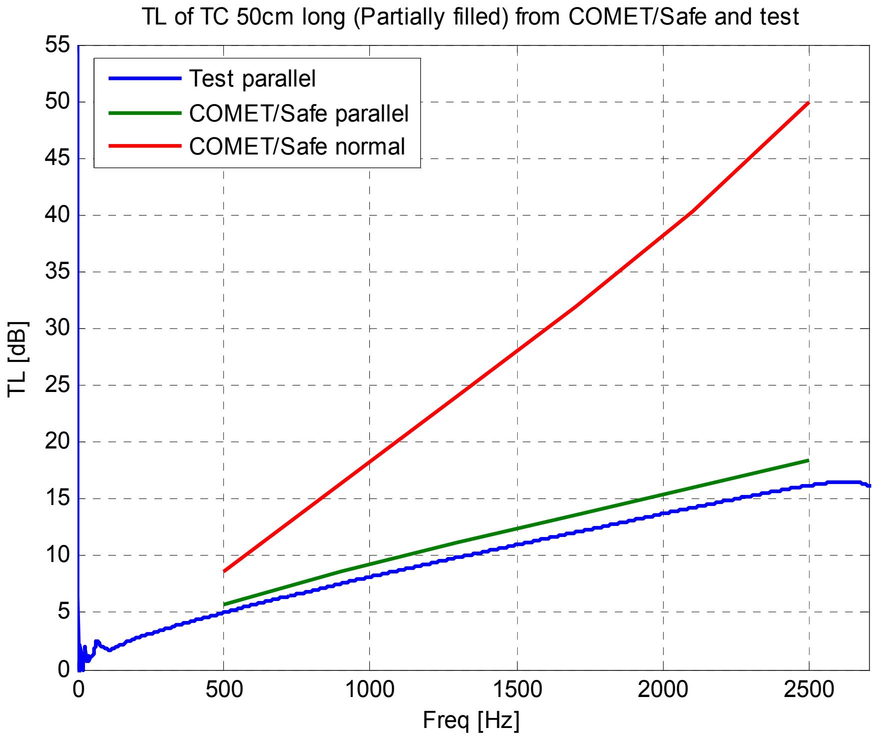
Front view



1. Traveling in empty space
2. Traveling inside the material
    - Wave moves in z and y directions
    - Anisotropy affects the results

Test and FEM results



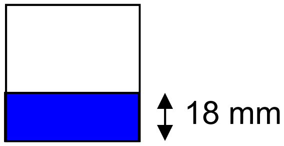


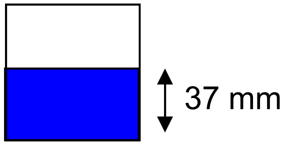
Good agreement between test and prediction with both materials

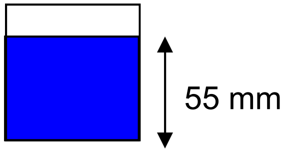
- THL shows a small difference with different fiber orientations

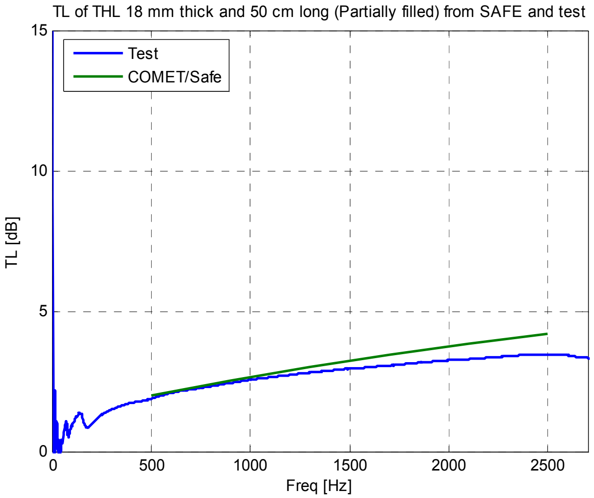
- TC shows large difference with different fiber orientations

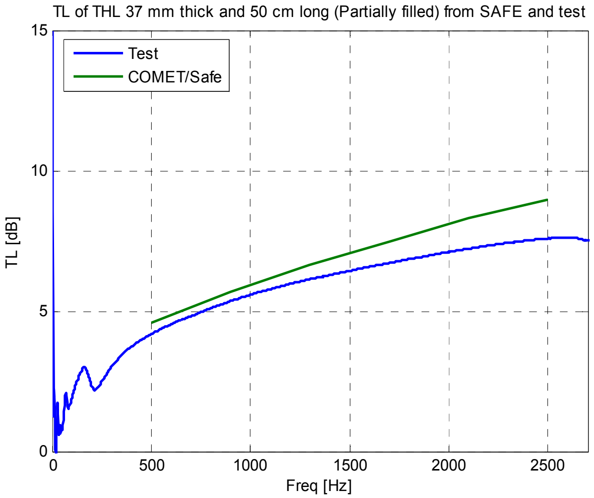
Variation in Lining Thickness

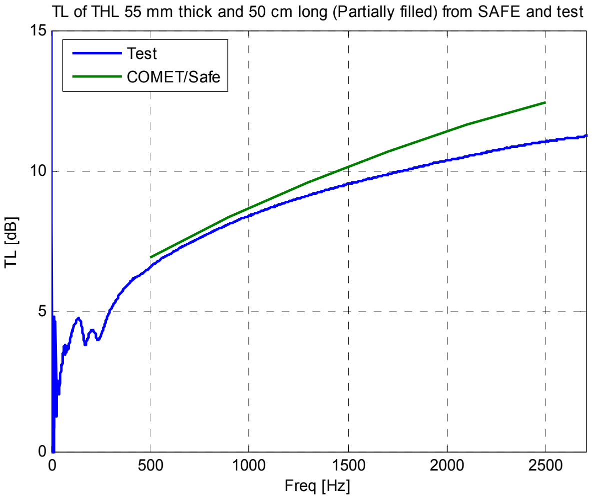







TL of THL 18 mm thick and 50 cm long (Partially filled) from SAFE and test


TL of THL 37 mm thick and 50 cm long (Partially filled) from SAFE and test


TL of THL 55 mm thick and 50 cm long (Partially filled) from SAFE and test

- As the sample fills the duct, TL increases

- The prediction and test show good agreement

Conclusions

- There were large differences in performance and in estimated material properties
  - When the fiber orientation was normal to the wave direction, higher flow resisitvity. Thus higher transmission loss and absorption were found
  - Depending on fiber orientation, TC material has much larger difference in performance than THL because of finer fiber size and scrims

- Homogeneous model predicts anisotropic materials when proper material properties are used
  - Material properties were successfully estimated
  - Performances in partially filled tube were accurately predicted using finite element model