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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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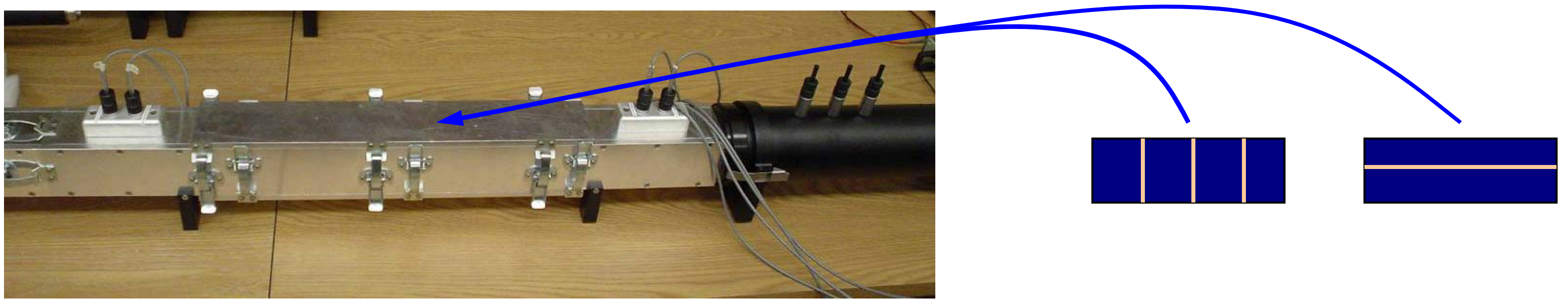
Overall Approach

1. Measuring TL and absorption coefficient in square tube

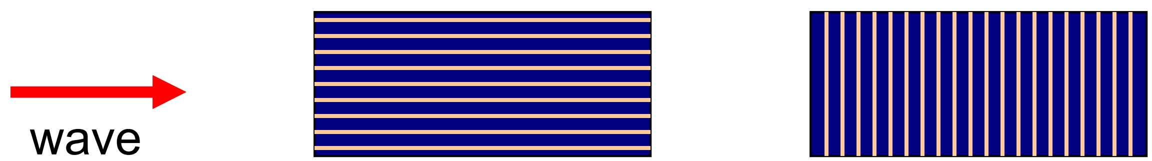


2. Estimating material properties (COMET/Trim)
   - Flow resistivity, Characteristic lengths, tortuosity, porosity, bulk density, Young's modulus, Poisson's ratio, loss factor

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



Parallel fiber direction

Normal fiber direction

- 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: $1x10^{-5}$~$9.99x10^{-4}$ m
3. Thermal characteristic length
   - Depth of thermal boundary layer
   - Sensitive properties
   - Range: $1x10^{-5}$~$9.99x10^{-4}$ 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

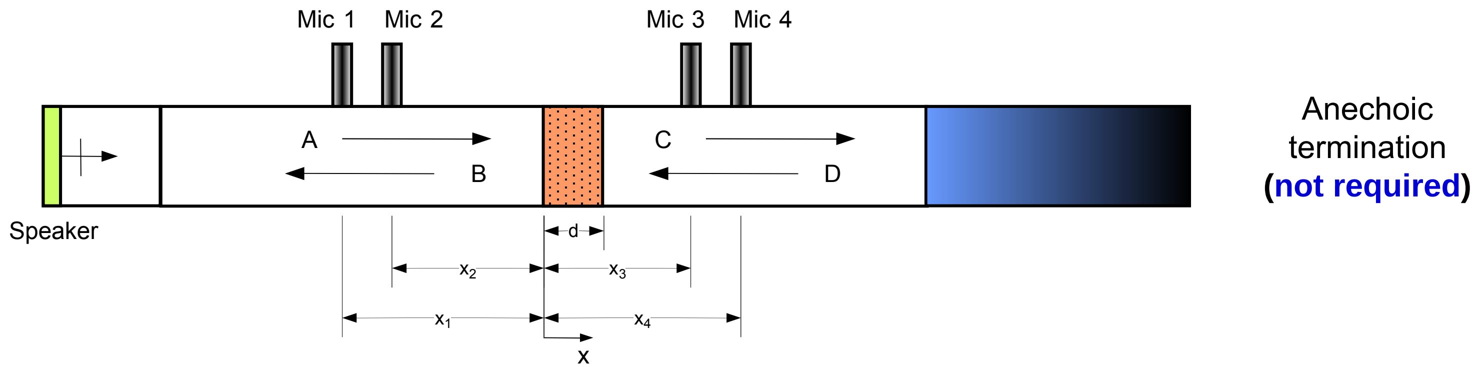
Materials

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:

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

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

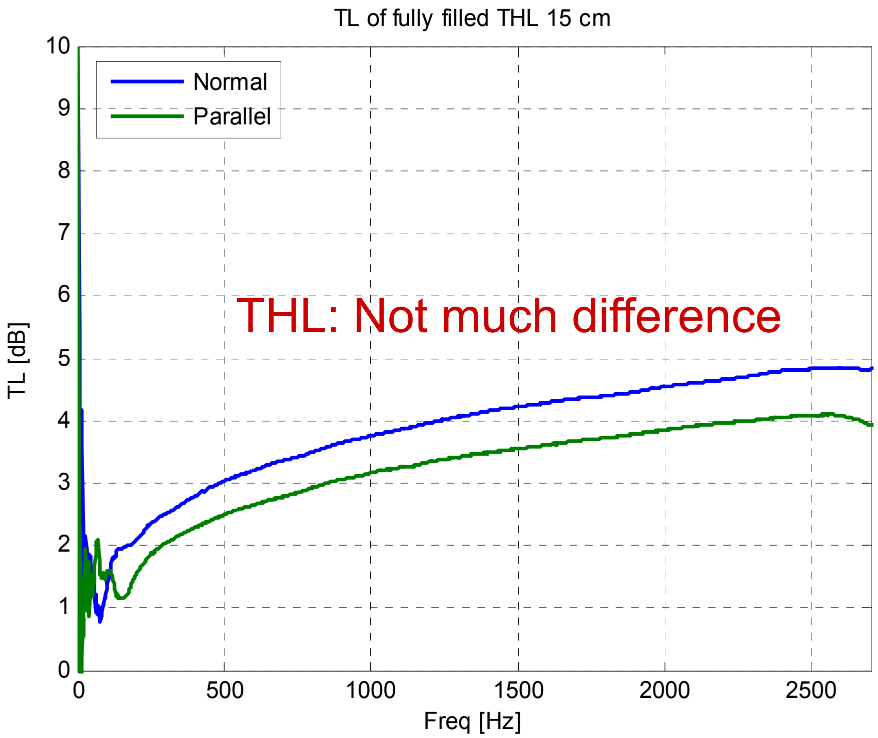
4. Obtain Transmission loss:

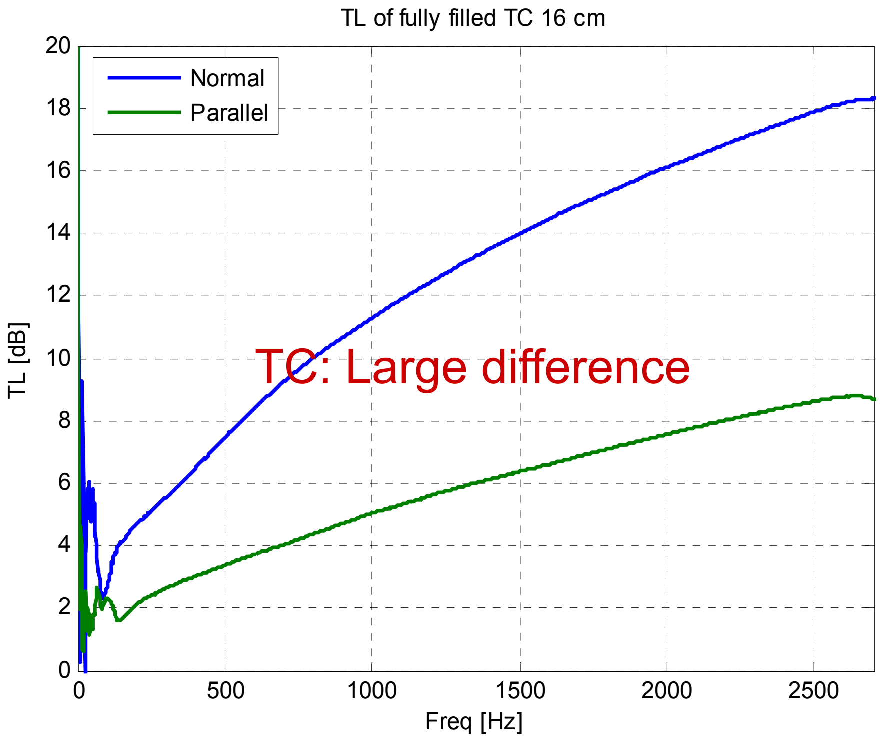
$$\mathrm{TL} = 20\log_{10}\left(1/|T|\right)$$

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

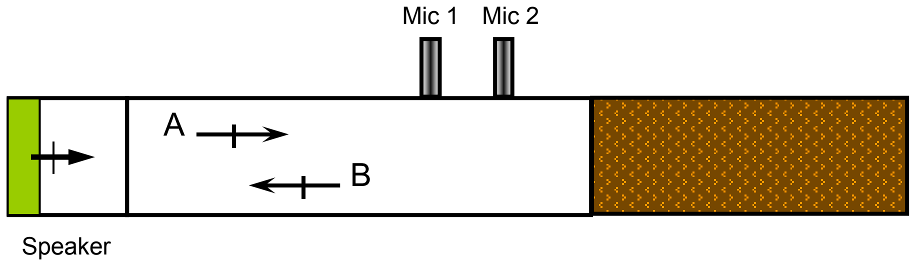
TL's in Two Orientations

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





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

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

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

3. Solve for R

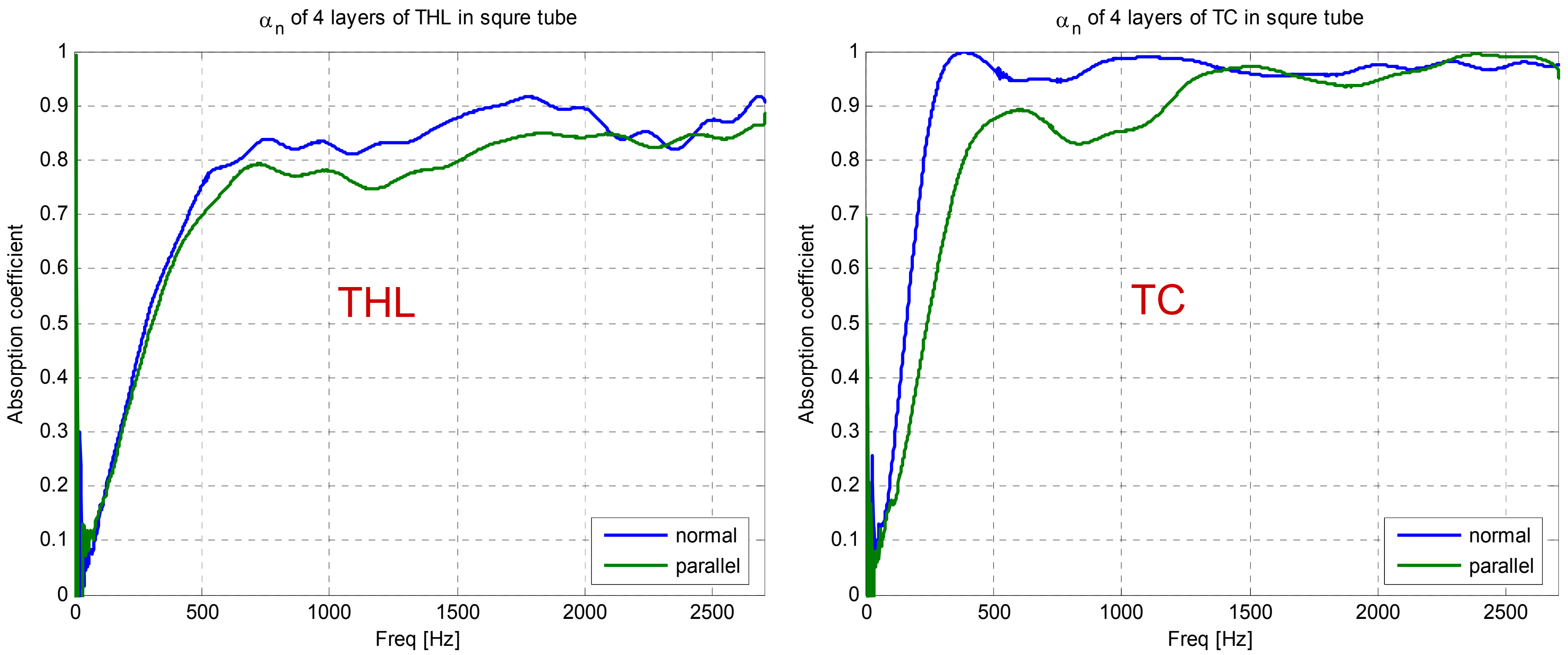
4. Absorption coefficient

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

* Measurements are averaged over 10 sets of samples

Absorptions in Two Orientations

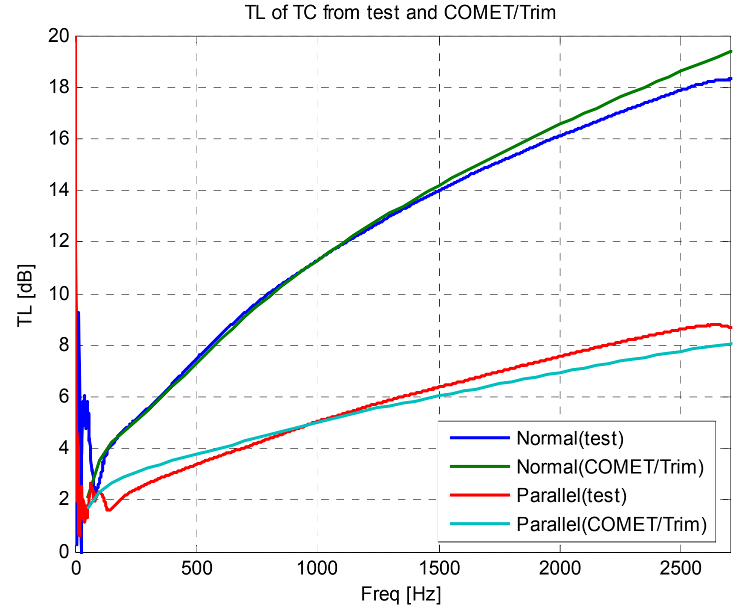
- •Averaged over ten measurements
  - •Normal: using 4 layers
  - •Parallel: samples were cut to have same weight as normal cases

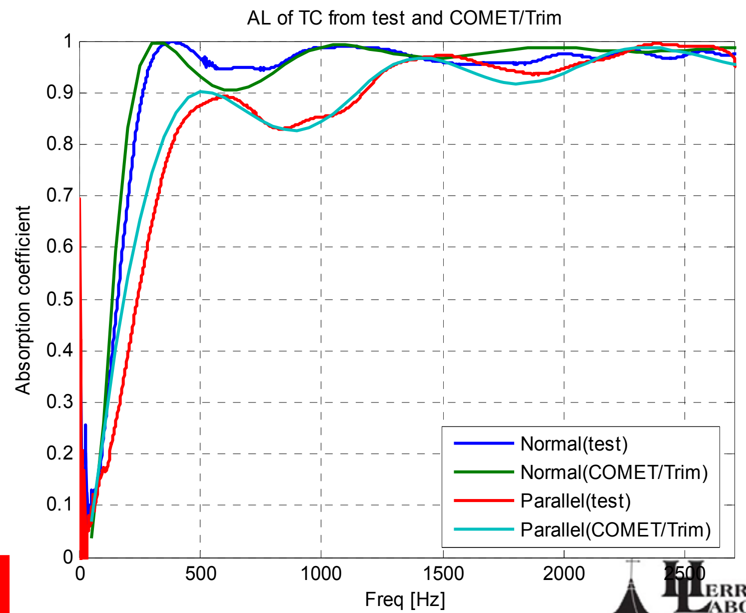


Estimation of TC Properties

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

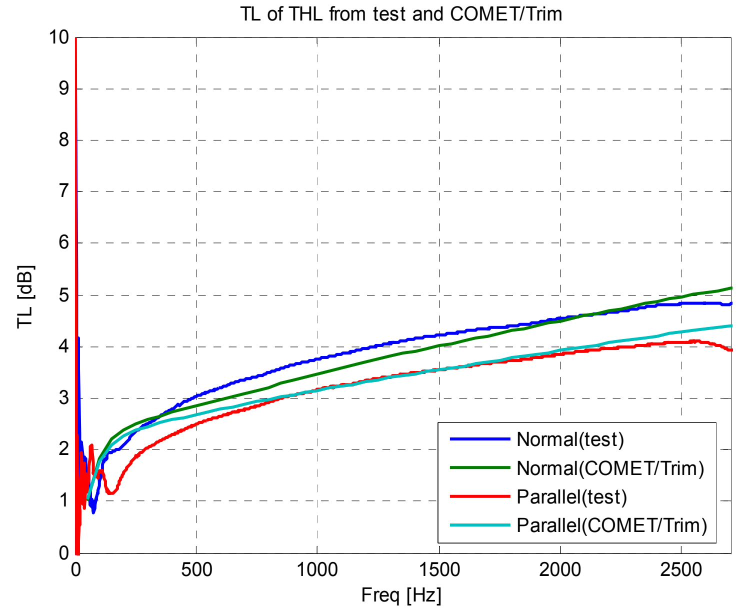


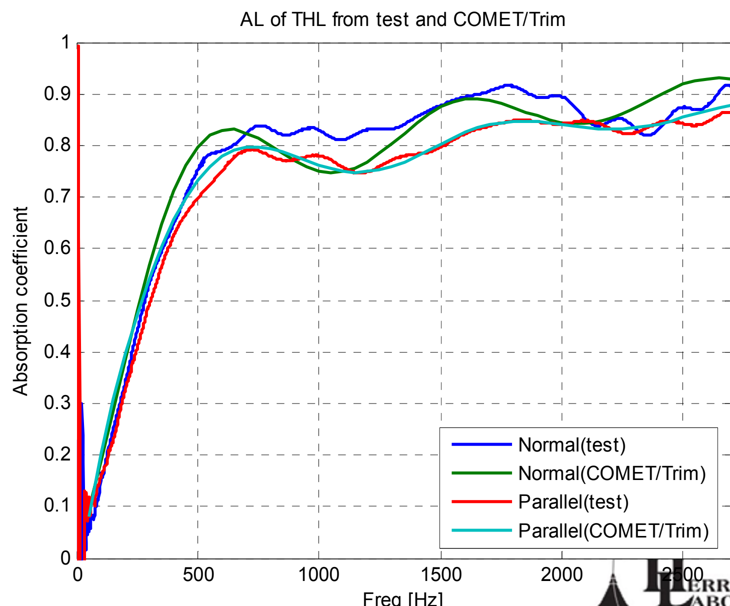


Estimation of THL Properties

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

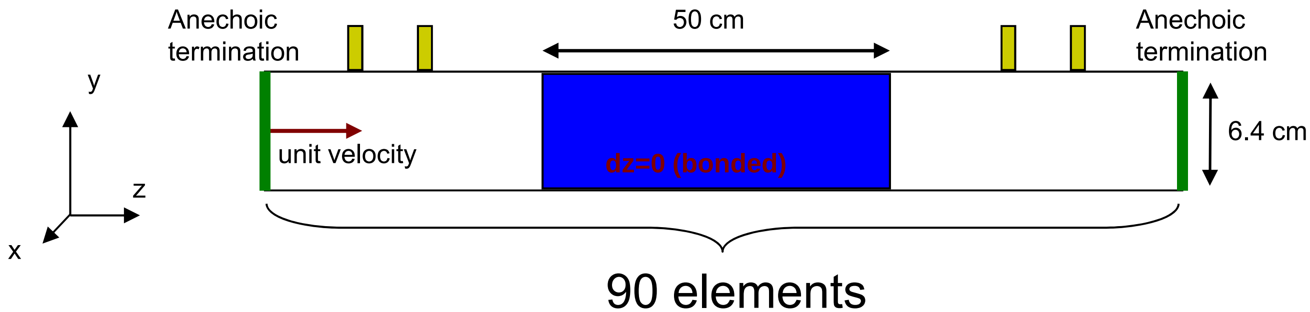




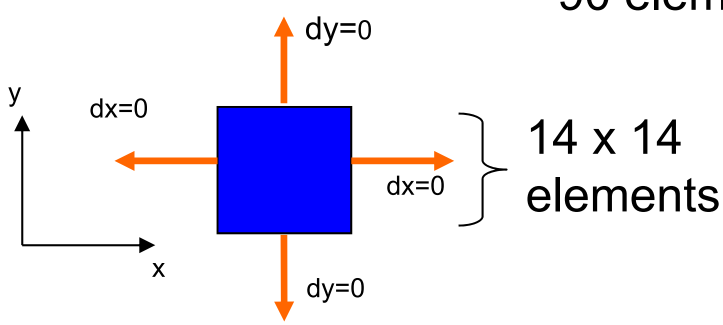
Finite Element Method

- Dimensions are same as experiment setup

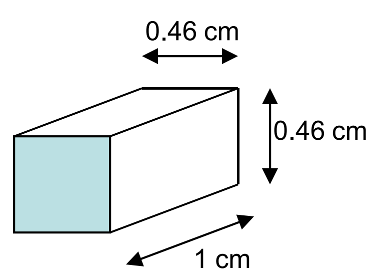
Side view



Front view



Element

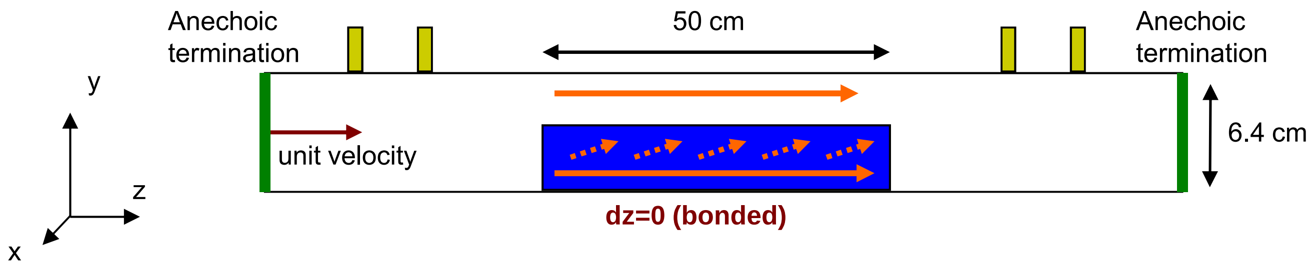


$$\frac{\lambda}{4} = \frac{c}{4 \cdot f} = \frac{340}{4 \cdot 2700} = 0.0315 \quad > 0.01$$

Partially Filled Cases

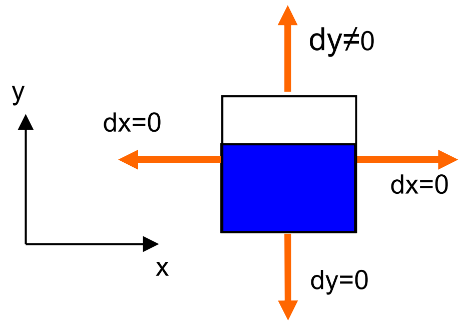
- Using single layer of TC and THL

Side view

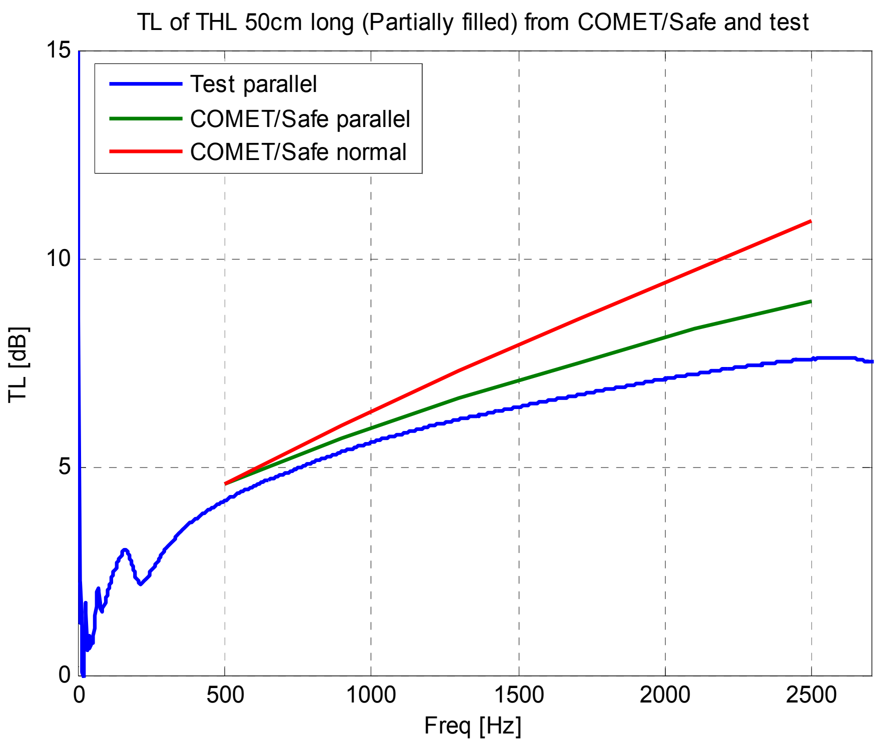


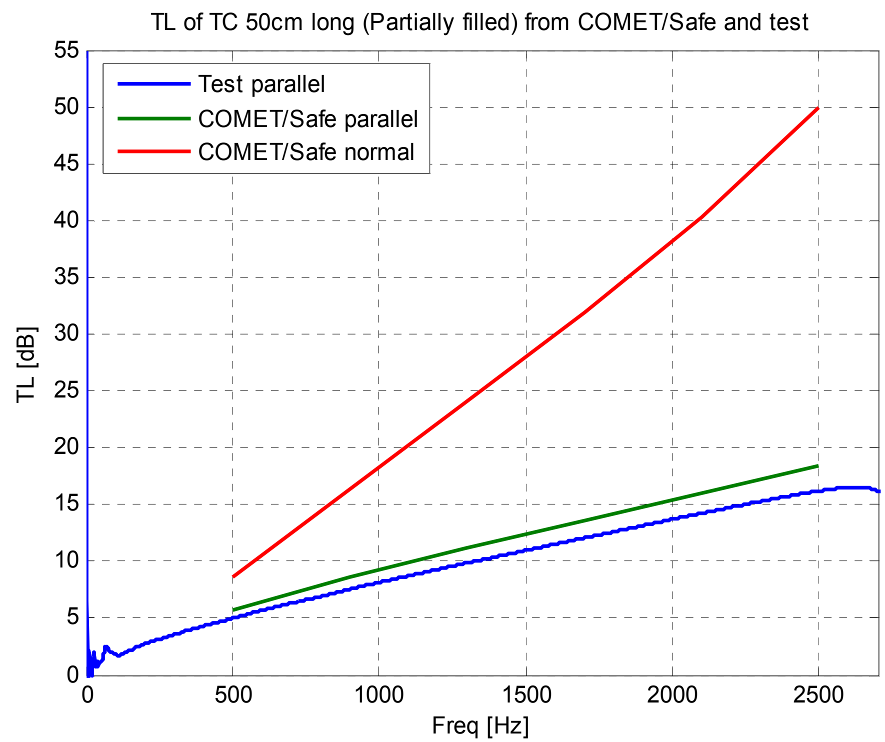
1. Traveling in empty space
2. Traveling inside the material
   - Wave moves in z and y directions
   - Anisotropy affects the results

Front view



Test and FEM results



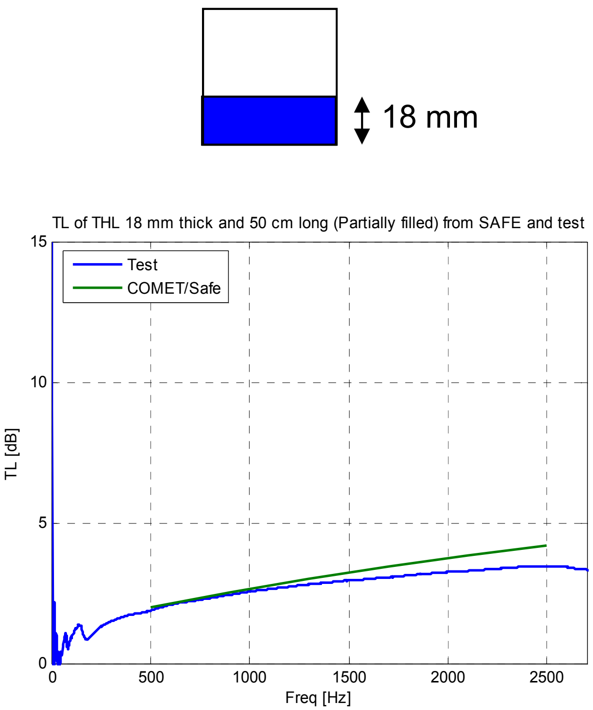


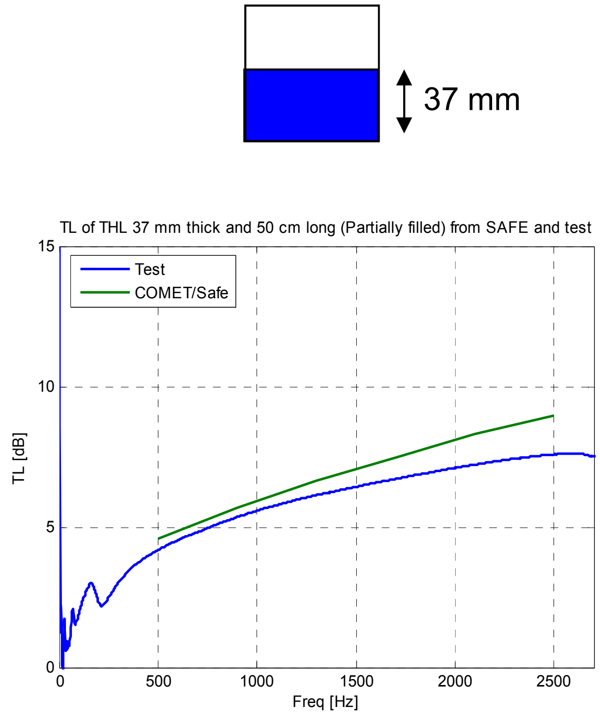
Good agreement between test and prediction with both materials

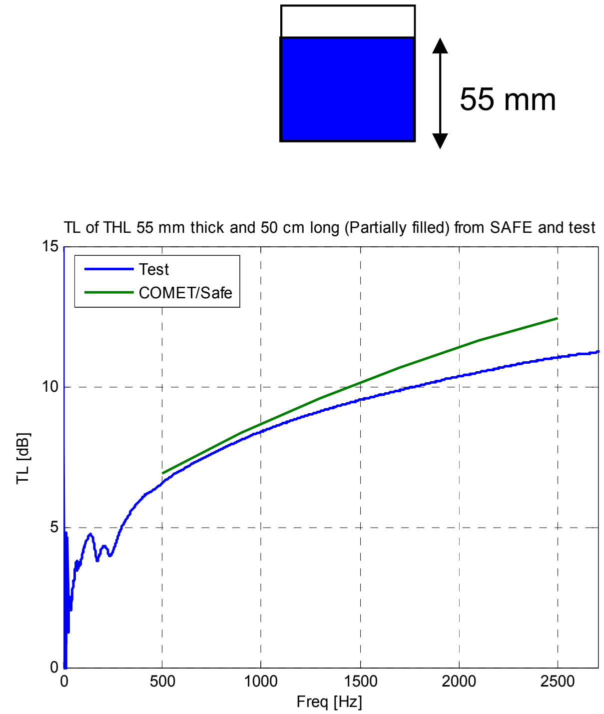
- THL shows a small difference with different fiber orientations

- TC shows large difference with different fiber orientations

Variation in Lining Thickness







- 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