ASME NCAD WORKSHOP

Noise Control Materials: Characterization and Modeling

Instructors:

Prs Noureddine Atalla and Raymond Panneton
GAUS, Université de Sherbrooke
Mecanum Inc.
www.gaus.ca • www.mecanum.com

raymond.panneton@usherbrooke.ca noureddine.atalla@usherbrooke.ca

GAUS
GROUPE D'ACOUSTIQUE DE L'UNIVERSITÉ DE SHERBROOKE

UNIVERSITÉ DE
SHERBROOKE

ASME
SETTING THE STANDARD

inter.noise
2012
august 19-22
new york city, usa
Quieting the World's Cities

Outline

Part 1

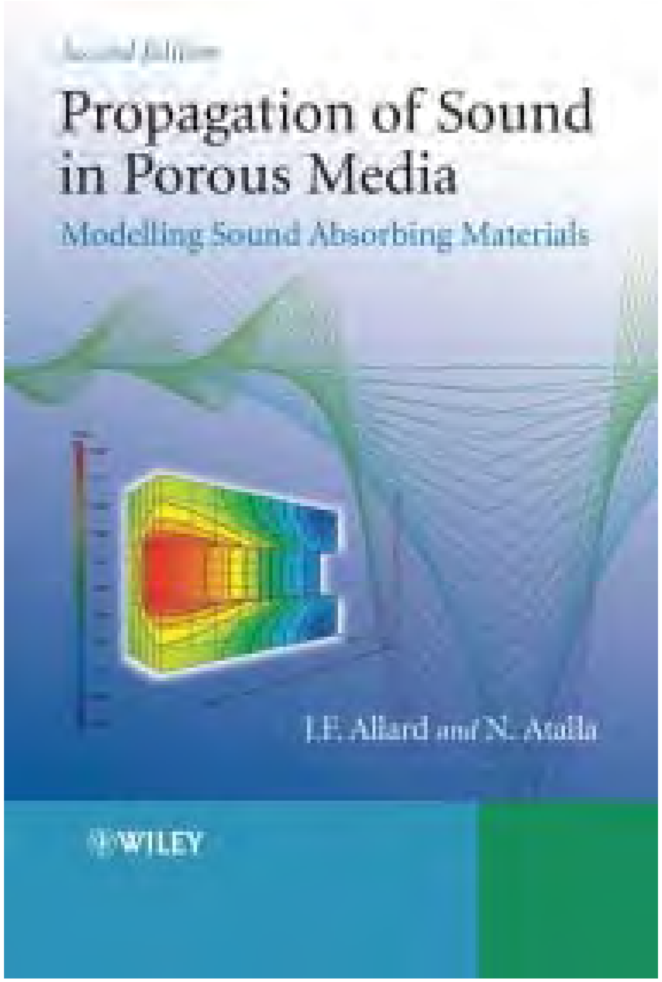
Modeling Noise Control Materials

Pr Noureddine Atalla
GAUS, Université de Sherbrooke
Mecanum Inc.
www.gaus.ca • www.mecanum.com

raymond.panneton@usherbrooke.ca noureddine.atalla@usherbrooke.ca

Main Reference

Propagation of Sound in Porous Media
Modelling Sound Absorbing Materials, 2nd Edition


Second Edition
Propagation of Sound in Porous Media
Modelling Sound Absorbing Materials
J.F. Allard and N. Atalla
WILEY

Contents

1 Plane waves in isotropic fluids and solids.
2 Acoustic impedance at normal incidence of fluids.
3 Acoustic impedance at oblique incidence in fluids.
4 Sound propagation in cylindrical tubes and porous materials having cylindrical pores.
5 Sound propagation in porous materials having a rigid frame.
6 Biot theory of sound propagation in porous materials having an elastic frame.
7 Point source above rigid framed porous layers.
8 Porous frame excitation by point sources in air and by stress circular and line sources
9 Porous materials with perforated facings.
10 Transversally isotropic poroelastic media.
11 Modeling multilayered systems with porous materials using the transfer matrix method.
12 Extensions to the transfer matrix method.
13 Finite element modeling of poroelastic materials.

Outline

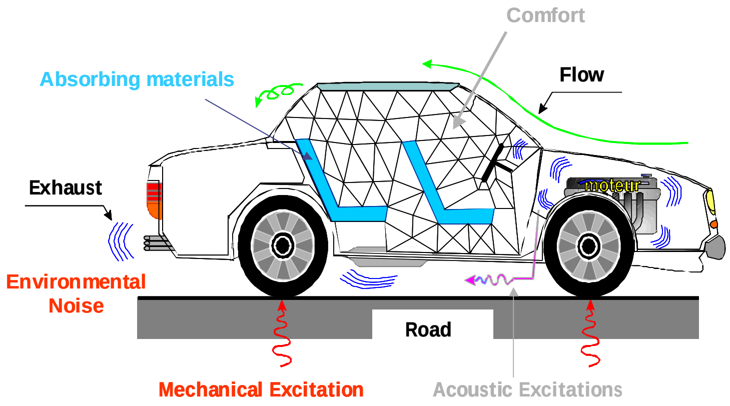
- Motivations and objectives
- Modeling acoustic materials
- Transfer Matrix Method based methodology
- Numerical and experimental validation examples
- Conclusion

MOTIVATIONS

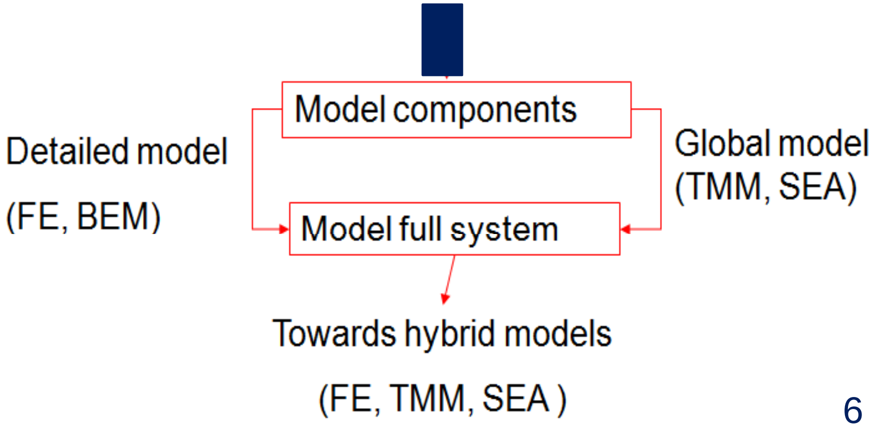
Quick estimation of the vibroacoustic response of structures with added acoustic materials

Classical Modeling:

- Detailed and accurate modeling can be achieved using FEM/BEM based methods
- Various methodologies are used to account efficiently for the sound package
- Detailed Models still computationally expensive and sensitive to uncertainties in input parameters/Boundary conditions



➔ Need for :
  - Approximate and quick methods (to answer what if questions)
  - & Hybrid methods (efficient solutions)



Detailed model

(FE, BEM)

Model components

Global model (TMM, SEA)

Model full system

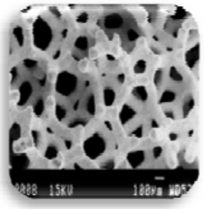
Towards hybrid models

(FE, TMM, SEA)

Objective

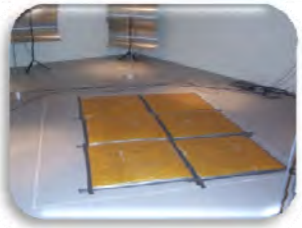
Review computational models to simulate the vibration and acoustic response of sound packages with an emphasis on the Transfer Matrix Method

Materials tests



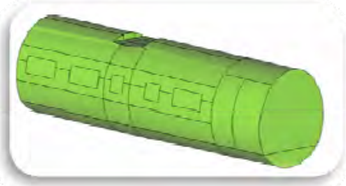
Multi-layers material tests

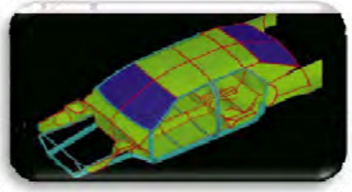
Absorption tests



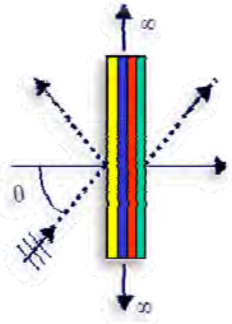
TL tests

SEA Method

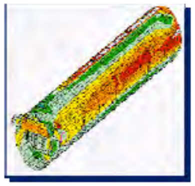


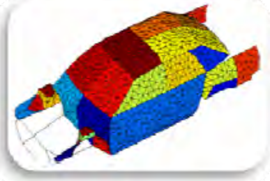


Transfer matrix method



FEM/BEM method





Outline

- Motivations and objectives
- **Modeling Poroelastic materials**
- Transfer Matrix Method based methodology
- Numerical and experimental validation examples
- Conclusion

Porous materials and their characteristics

μ-Structure Types

Granular, fiber, foam, MPP

Material Types

Polymer, metal, textile, …

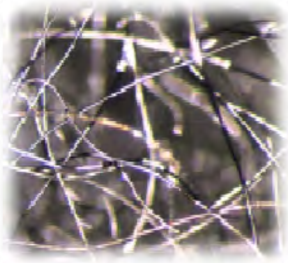
Frame Types

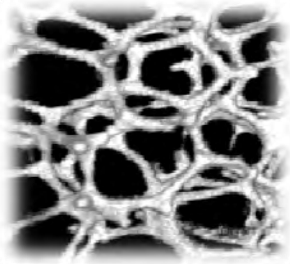
Elastic

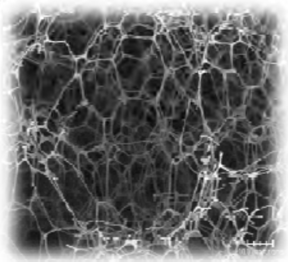
Acoustically rigid or limp

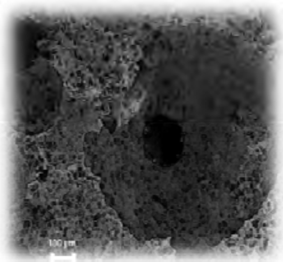
Porous materials and their characteristics

- Porous materials
  - Two phases :solid and fluid
  - Elastic coupling
  - Visco-inertial coupling
- What do they do ?
  - Transform acoustic energy into heat
- How do they dissipate energy ?
  - viscous effect
  - thermal effect
  - structural damping


Fiberglass


Urethane


Melamine

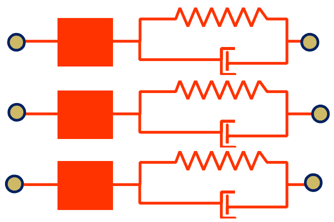

Double porosity

The behavior of porous materials depends on their nature, loads and the coupled structures. The selection of a model/methodology should account for this fact

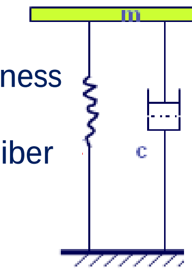
Modeling Porous materials

↳ Mechanical model

(Equivalent mechanical systems)



The membrane mass



K=Stiffness of the foam/Fiber

c = Kinetic viscous coefficient between moving frame and air

↳Empirical models

(limited to certain type of materials and can be inaccurate*; D&B, Miki, … Example Delaney and Basley model for fibrous materials, …)*

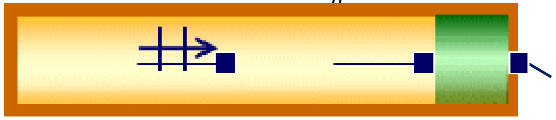
$$Z_C = \rho_0 C_0 \left(1 + 0.0571 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.754} - j\,0.087 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.732} \right),$$

$$k = \frac{\omega}{C_0} \left(1 + 0.0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.700} - j\,0.189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0.595} \right),$$

↳ Admittance model

(Classical codes; …)

$$\frac{\partial P}{\partial n} + j \frac{\rho_o \omega}{\tilde{Z}_n} P = 0$$



$= \text{Rigide}$

$\neq \text{Flexible}$

Microstructural models (Biot)

- Rigid/limp frame

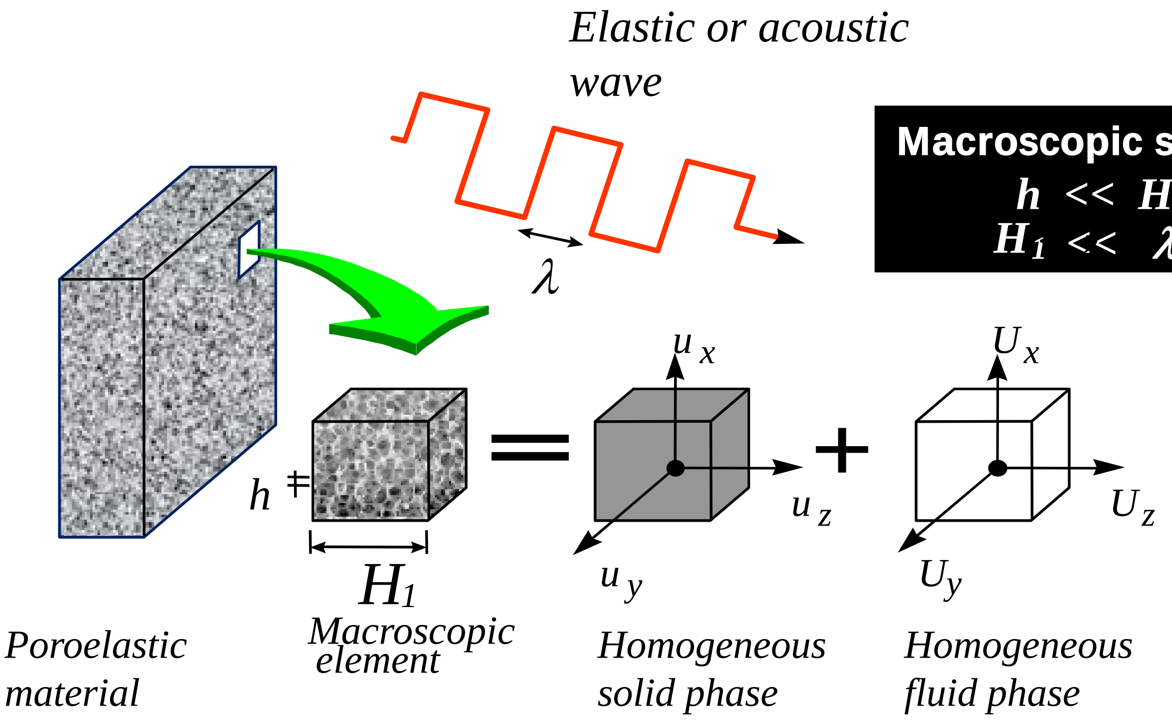
  (Equivalent fluid models)

- Elastic frame.

  Coupled poroelastic models

Modeling of porous materials

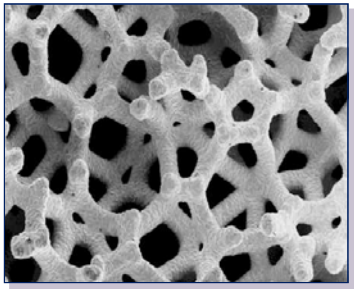
They are modeled at a homogeneous macroscopic scale



Macroscopic scale H_1

$h << H_1$

$H_1 << \lambda$



Biot based models

Example: BIOT (u,p) formulation governs the propagation of the coupled elastic waves (compression and shear) and acoustic wave (compression).

$$\tilde{\mu} u_{i,jj} + \left(\tilde{\lambda} + \tilde{\mu}\right) u_{j,ij} + \omega^2 \tilde{\rho}_s \, u_i = -\tilde{\gamma} \; p_{,i}$$

Elasto-dynamic equation

$$\frac{1}{\omega^2 \tilde{\rho}_f} p_{,ii} + \frac{1}{\tilde{K}_f} p = \tilde{\gamma} \, u_{i,i}$$

Helmholtz equation

Biot's macroscopic parameters

u : solid phase macroscopic displacement vectors
p : fluid phase macroscopic pressure
~: denotes a complex and frequency dependent quantity
λ, μ : Effective solid phase Lamé coefficients
K_f : Effective fluid phase bulk modulus
ρ_s : Effective solid phase density
ρ_f : Effective fluid phase density
γ : Fluid-solid coupling coefficient

Rigid and limp limits

(P)-Rigid frame formulation

- Helmholtz equation with effective density and bulk modulus

$$\Delta p + \omega^2 \frac{\tilde{\rho}_e}{\tilde{K}_e} P = 0$$

Δ : Laplacian operator

(P)-Limp frame formulation

- Helmholtz equation with effective density and bulk modulus
- Added inertia of the solid phase

$$\Delta p + \omega^2 \frac{\tilde{\rho}_{e,l}}{\tilde{K}_e} p = 0$$

$$\tilde{\rho}_{e,l} \rightarrow \frac{\tilde{\rho}_e M - \rho_0^2}{M + \tilde{\rho}_e - 2\rho_0}$$

$$M = \rho_1 + \phi\rho_0$$

Total apparent mass of the bulk volume

Modeling of porous materials

Classical models for the effective density

The ratio $\tilde{\rho}_e/\rho_0$ defined as the dynamic tortuosity is given by: $\alpha(\omega)=\frac{\nu\phi}{j\omega q_0}\{1-b+b[1+\left(\frac{2\alpha_\infty q_0}{b\phi\Lambda}\right)^2\frac{j\omega}{\nu}]^{1/2}\}+\alpha_\infty$

Pride et al. model (1993)	$b=1$	ϕ, $\sigma(q_0=\eta/\sigma)$, α_∞, α_0, Λ	Correct low frequency limit of the real part of the effective density with the extra parameter b. b=3/4 for cylindrical pores.
Johnson et al. model (1987)	$b=\frac{2q_0\alpha_\infty^2}{\phi\Lambda^2(\alpha_0-\alpha_\infty)}$	ϕ, σ, α_∞, Λ	For identical parallel circular cross-sectional shaped pores: - Correct high frequency limit - Correct low frequency limit for the imaginary part - Error in the low frequency limit for the real part - Still excellent surface impedance predictions compared to exact model

➔ widely used model due to the difficulty of measuring the static viscous tortuosity

Given parameters

$j=\sqrt{-1}$

ω: circular frequency

ρ_0 : Saturating fluid density

$\upsilon=\rho_0\eta$: Dynamic viscosity

Needed Macroscopic parameters

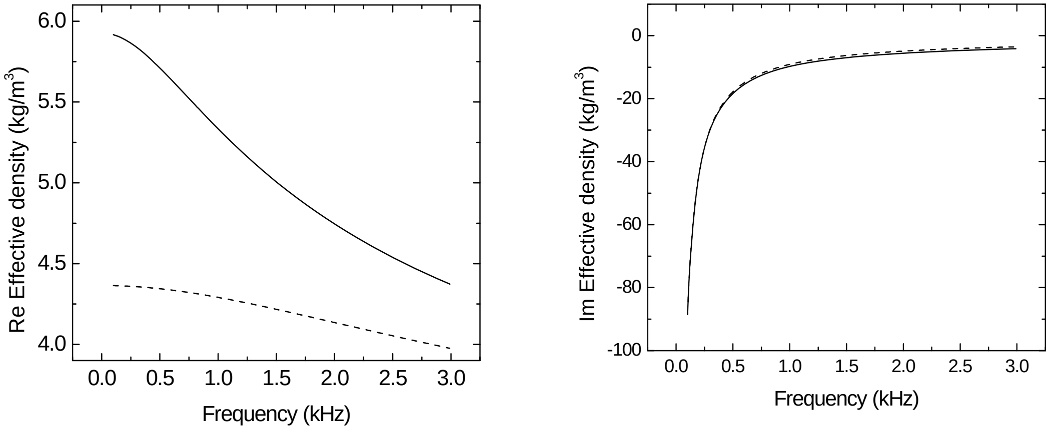
ϕ - Open porosity

α_∞ - Tortuosity

σ - Static airflow resistivity

Λ - Viscous characteristic length

α_0 - Static viscous tortuosity



Example of predicted effective density using Pride et al. model (b=0.6) ——— and Johnson et al. model (b=1) - - - -

Modeling of porous materials

Classical models for the effective bulk modulus

The bulk modulus is given by: $\tilde{K}=P_0/(1-\frac{\gamma-1}{\gamma\alpha'(\omega)})$ with $\alpha'(\omega)=\frac{\nu'\phi}{j\omega q'_0}[1+(\frac{2q'_0}{\phi\Lambda'})^2\frac{j\omega}{\nu'}]^{1/2}+1$

Simplified Lafarge model (1993, 1997)		$\phi\,,\Lambda',q'_0$	- The choice for q'_0 can lead to a large error in the localization of the transition frequency where the imaginary part of the bulk modulus reaches its maximum.
The Champoux-Allard model (1991)	$q'_0=\phi\Lambda'^2/8$	$\phi\,,\ \Lambda'$	- This does not necessarily lead to a large error in the evaluation of a surface impedance because the damping is mainly created by the viscosity via the effective density

➔ widely used model due to the difficulty of measuring the static thermal permeability

Given parameters

$j=\sqrt{-1}$

ω: circular frequency

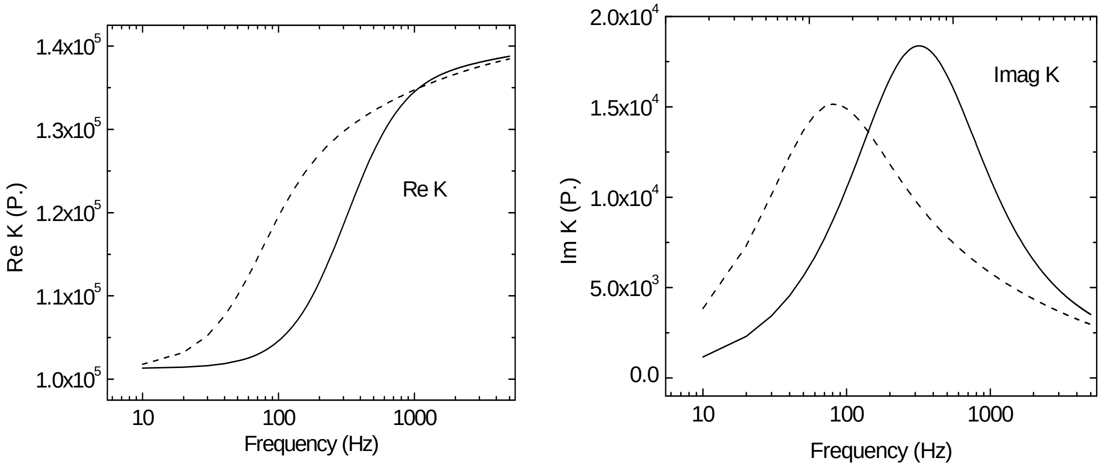
P_0 : ambient mean pressure

$\nu'=\frac{\kappa}{\rho_o c_p}$: κ is the thermal conductivity and c_p the specific heat per unit mass at constant volume

Needed Macroscopic parameters

q'_0 - Static thermal permeability

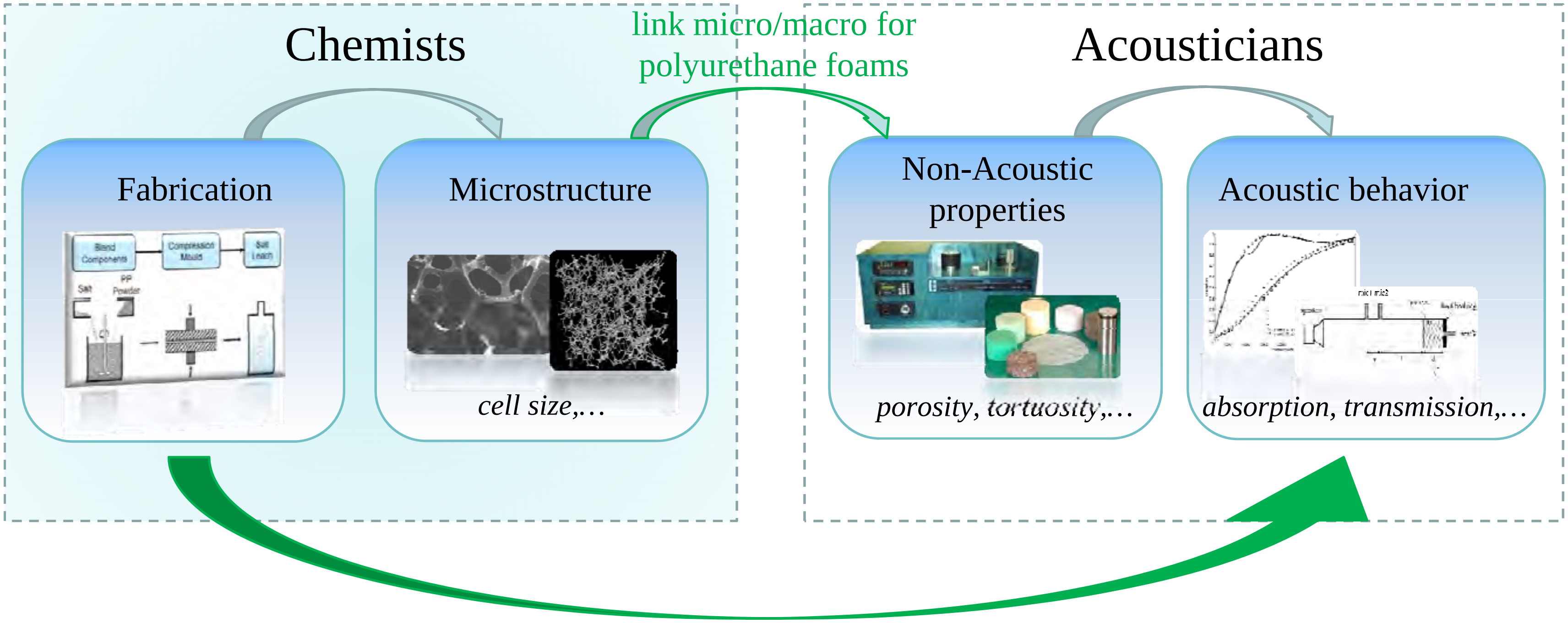
Λ' - Thermal characteristic length



Example of predicted bulk modulus using Lafarge model (measured q'_0) ——— and Champoux-Allard model (set q'_0) - - - -

Microstructure based models

***Alternative models* ➔ microstructure based:** needed to optimize foam's fabrication process to target specific vibroacoustic applications (dash insulator, floor insulator,…)



Chemists

link micro/macro for polyurethane foams

Acousticians

Fabrication

Microstructure

cell size,…

Non-Acoustic properties

porosity, tortuosity,…

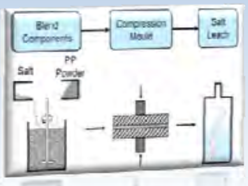
Acoustic behavior

absorption, transmission,…

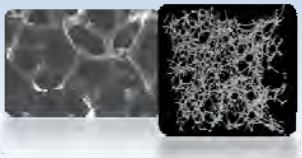
Microstructure based models

An example: semi-empirical model for PU foams

Fabrication



Microstructure

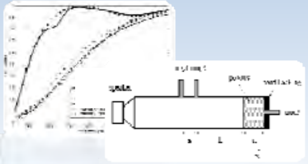


cell size, reticulation rate

Non-Acoustic properties

porosity, tortuosity,…

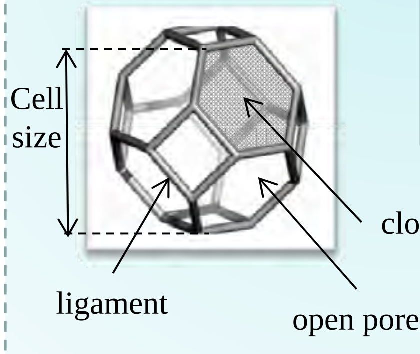
Acoustic behavior



absorption, transmission,…

Polyurethane foam

Tetrakaidecahedra Unit cell



- **Cell size** (C_s)
- **Ligament length** (l)
- **Ligament thickness** (t)
- **Reticulation rate** (R_w)

$$\sigma = C^{\sigma}\left(C^{\rho}\frac{t}{l^2}\right)^2\left(\frac{1}{R_w}\right)^{1.116}$$

$$\alpha_\infty = 1.05\left(\frac{1}{R_w}\right)^{0.380}$$

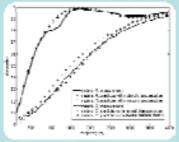
$$\Lambda' = \frac{2V_f}{A_S + (1-R_w)A_w}$$

$$\Lambda = \Lambda'/1.55\left(\frac{1}{R_w}\right)^{0.676}$$

$$\phi = 1 - C^{\rho}\left(\frac{t}{l}\right)^2$$

JCA model

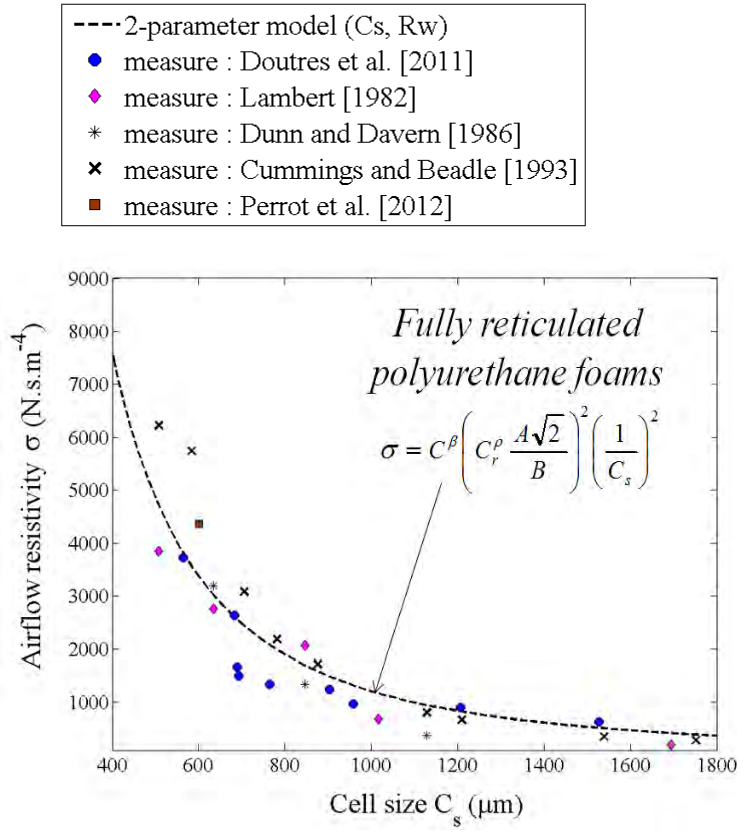
Sound Absorption



Ref. O. Doutres, N. Atalla, “A semi-empirical model to predict the acoustic behavior of fully and partially reticulated polyurethane foams based on microstructure properties” Acoustics 2012

Microstructure based models

Validation



Foam P2:

C_S= 616 ± 36 µm

l = 209 ± 14 µm

t =50 ± 4 µm

R_w= 32 ± 11 %

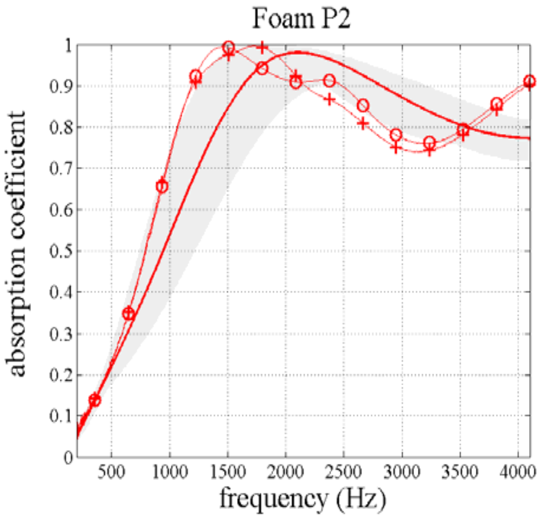
Foam P3:

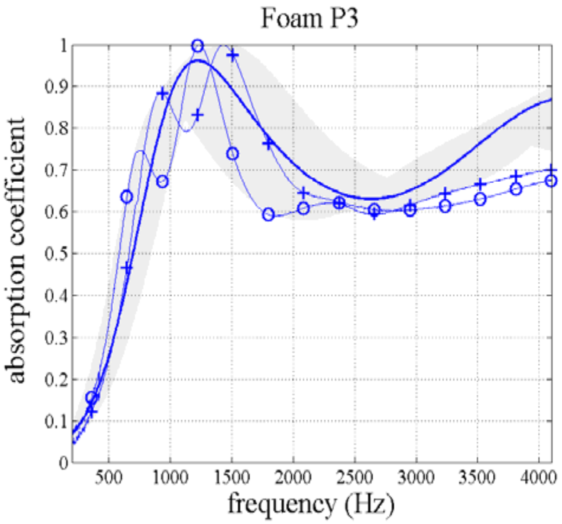
C_S=1710 ± 161 µm

l = 554 ± 39 µm

t =151 ± 8 µm

R_w=5 ± 2 %





▬ simulation

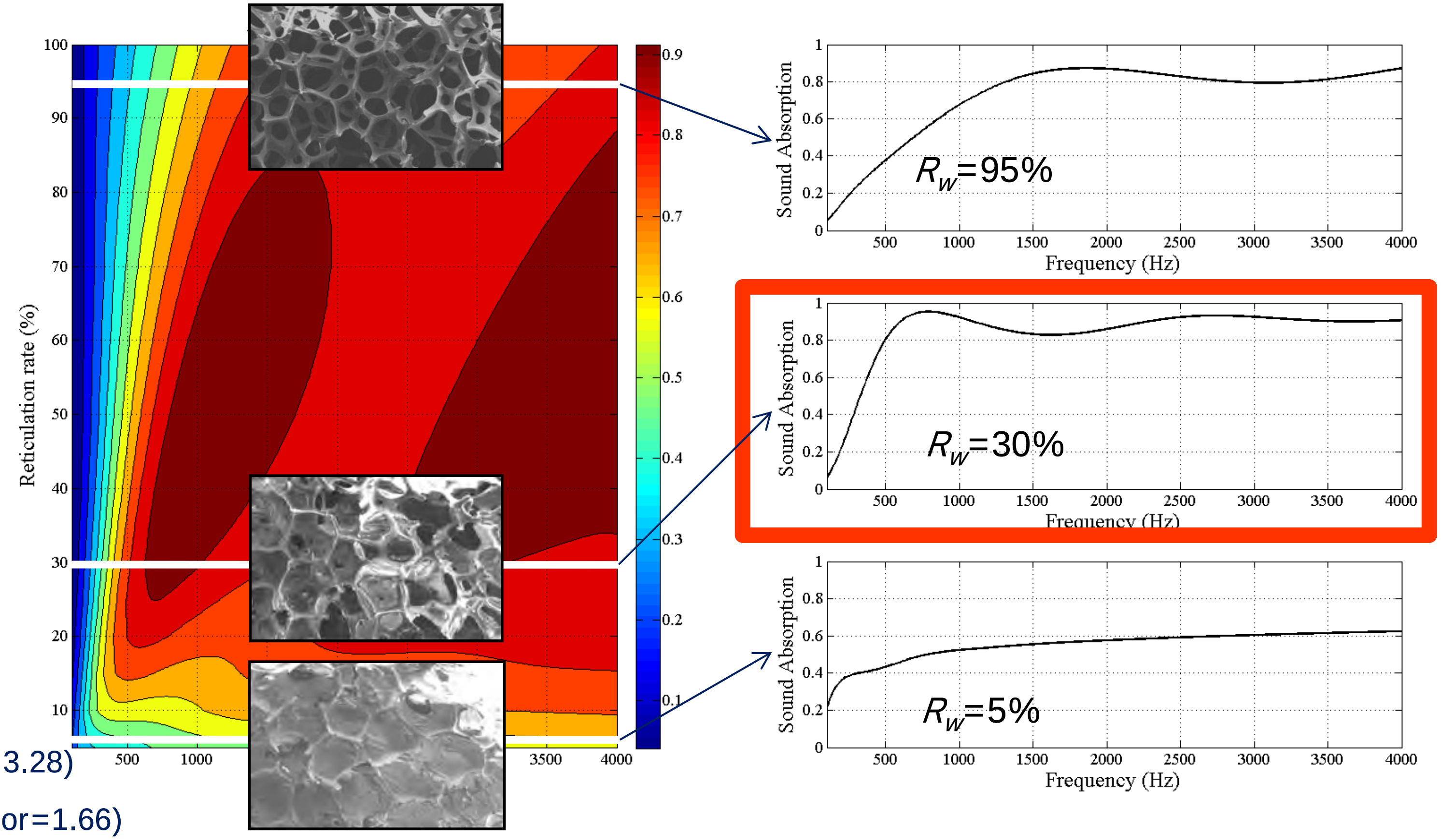
▬ expanded uncertainty

$\ominus$ + measurements

Application (1/2)

Optimum homogeneous foam for sound absorption – importance of reticulation rate

- PU thickness : 2 inches
- The cell size is set to C_s=500 μm and is kept constant within the porous volume
- The reticulation rate can be optimized to get maximum sound absorption



(R_w=5%; RPA=17; tor=3.28)

(R_w=30%; RPA=2.29 ; tor=1.66)

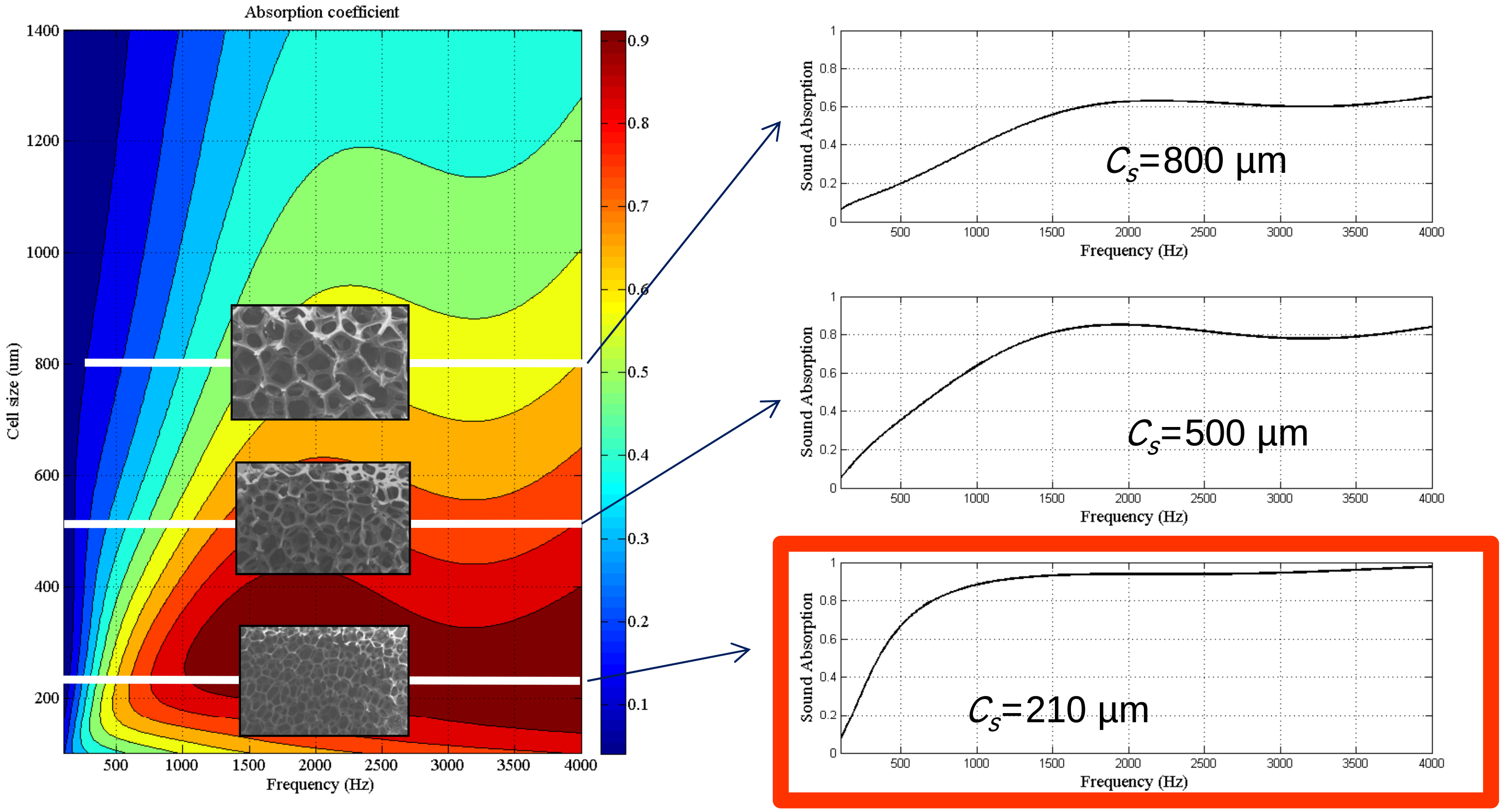
(R_w=95%; RPA=0.63 ; tor=1.07)

Ref. Doutres & Atalla, 2011

Application (2/2)

Optimum homogeneous foam for sound absorption : Fully reticulated

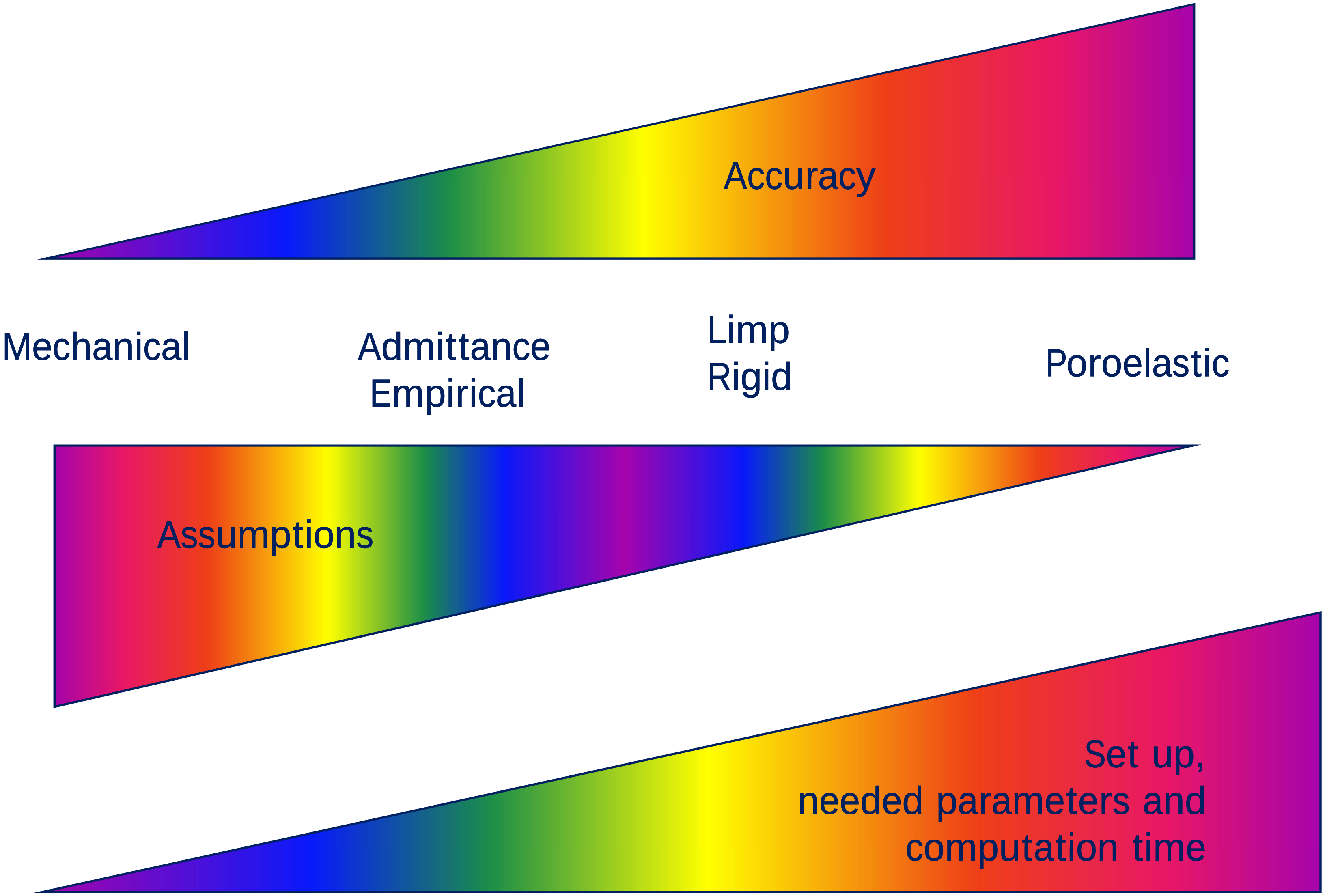
- PU thickness : 2 inches
- The cell size can be optimized to get maximum sound absorption
- The reticulation rate is set to 100% and is kept constant within the porous volume



Optimum sound absorption for C_s=210 µm; but cannot be produced

Ref. Doutres & Atalla, 2011

Predictive methods for porous media



Accuracy

Mechanical

Admittance
Empirical

Limp
Rigid

Poroelastic

Assumptions

Set up,
needed parameters and
computation time

Outline

- Motivations and objectives
- Modeling Poroelastic materials
- **Transfer Matrix Method based methodology**
- Numerical and experimental validation examples

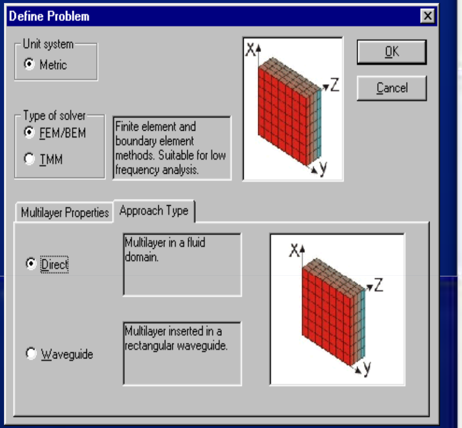
- Conclusion

II Modeling sound packages

Noise control materials models are usually implemented using the Transfer Matrix Method for planar multilayer systems and FE/BEM approach for general configurations

FE module

FEM/BEM



Define Problem

Unit system
● Metric

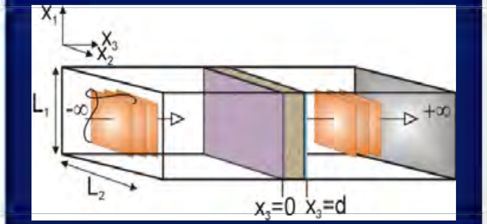
Type of solver
● FEM/BEM
○ TMM

Finite element and boundary element methods. Suitable for low frequency analysis.

Multilayer Properties | Approach Type

● Direct
Multilayer in a fluid domain.

○ Waveguide
Multilayer inserted in a rectangular waveguide.

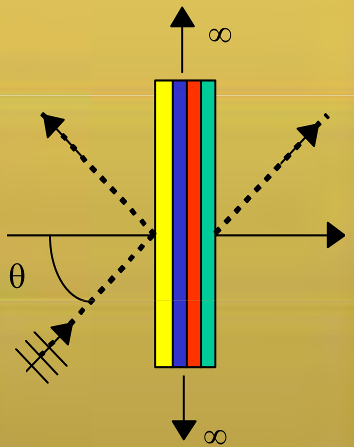


Finite size correction for the transfer matrix method

Hierarchical finite element for speed and accuracy

TMM module

Generalized Transfer matrix method (TMM) with size effects

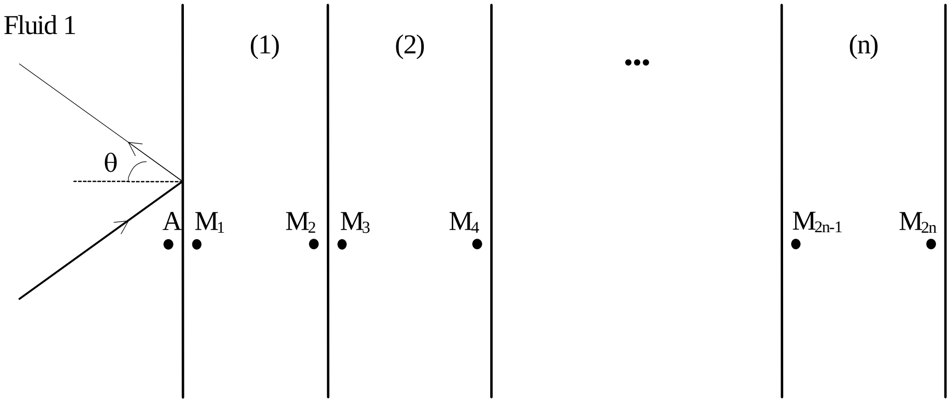


LF MF HF

Principle of Transfer Matrix Method

- Assumes planar infinite systems (1D problems)
- The global matrix is constructed from constituent transfer matrices, the coupling conditions and the termination conditions :

$$[D]V = 0$$



Structure

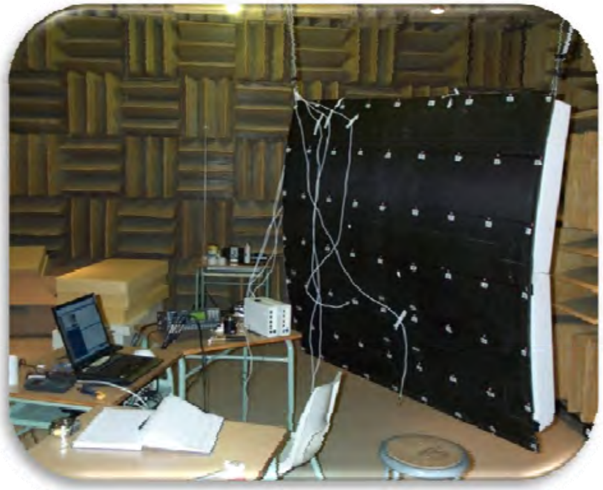
- Thin panel
- Solid
- Septum
- Sandwich
- General laminates
- ...

Porous layer

- Rigid /limp frame
- Porous-elastic
- Perforated plates & screens
- Double porosity
- ...

Principle of Transfer Matrix Method

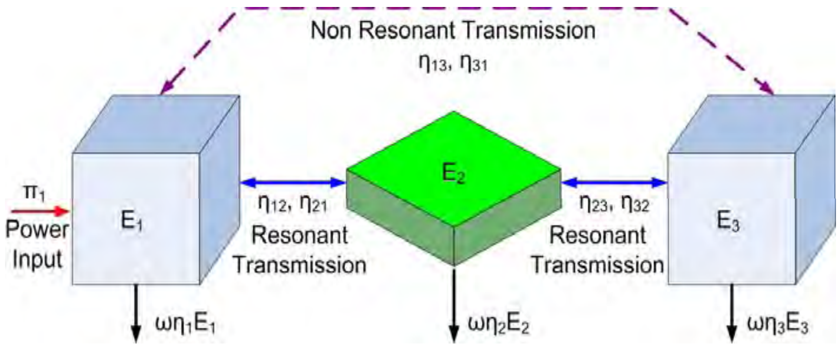
The method allows for the calculation of vibroacoustic indicators under various excitations:



- Impedance / Absorption
- Transmission Loss
- Added damping
- Radiation efficiency
- Acoustic/Vibration transmissibility
- ...

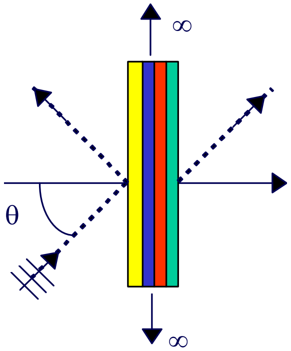
The TMM can also be used within SEA framework to handle, approximately, complicated geometries and systems

Principle: assumes the sound package planar and uses TMM to correct (i) non-resonant path; (ii) radiation efficiency; (iii) absorption and (iv) added damping



Principle of Transfer Matrix Method (…)

Absorption Problem:



$$\alpha_{f,st,avg} = \frac{\displaystyle\int_0^{\theta_{\lim}} \frac{4\Re\left[Z_A\right]}{\left|Z_A + Z_{R,avg}\right|^2}\sin\theta\, d\theta}{\displaystyle\int_0^{\theta_{\lim}} \cos\theta \sin\theta\, d\theta}$$

$$Z_{R,avg}\left(\theta\right) = \frac{1}{2\pi}\int_0^{2\pi} Z_R\left(\theta,\phi\right) d\phi$$

Transmission Problem:

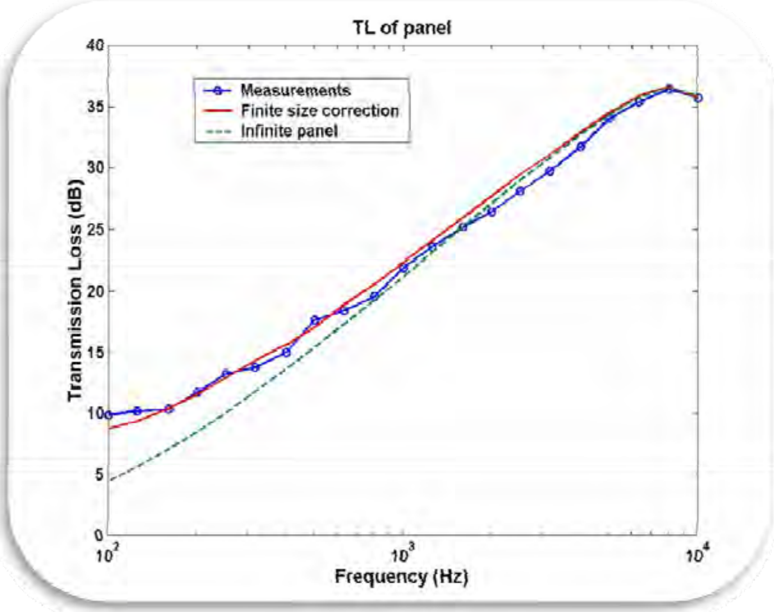
$$\tau_{diffuse} = \frac{\displaystyle\int_0^{2\pi}\int_{\theta_{\min}}^{\theta_{\max}} \tau(\theta,\varphi)\left(\frac{\mathrm{Re}\, Z_R}{\rho_0 c}\cos\theta\right)\sin\theta\cos\theta\, d\theta\, d\varphi}{\displaystyle\int_0^{2\pi}\int_{\theta_{\min}}^{\theta_{\max}} \sin\theta\cos\theta\, d\theta\, d\varphi}$$

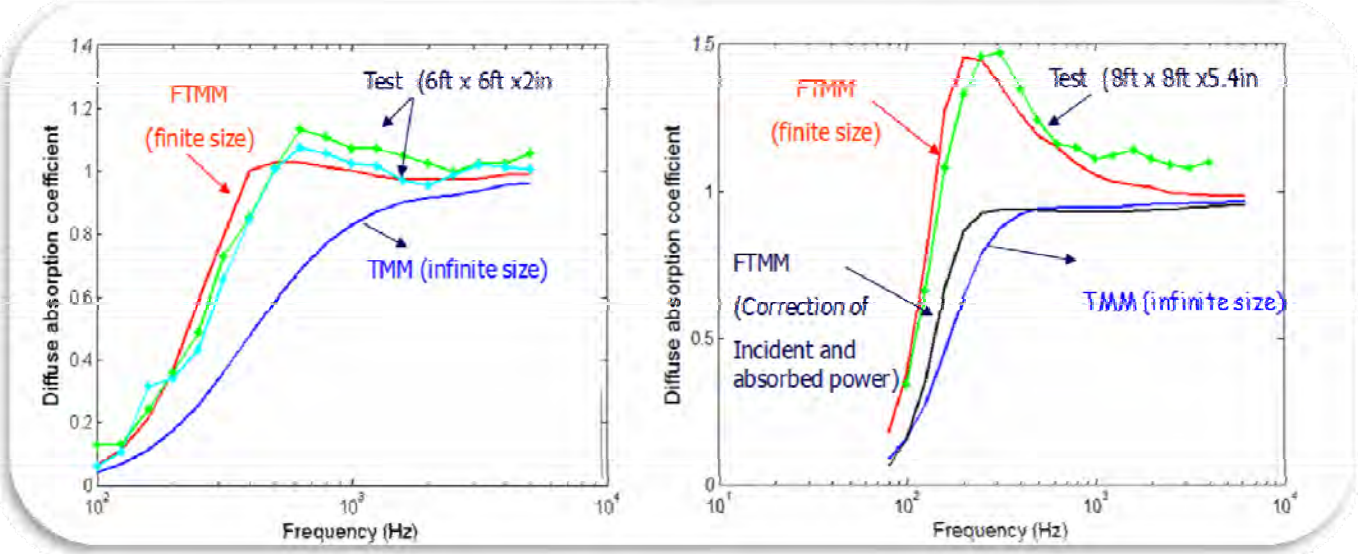
$$Z_R = \frac{ik}{S}\int_S\int_S e^{-jk\sin\theta\left(\cos\phi x_0 + \sin\phi y_0\right)} G(M, M_0) e^{jk\sin\theta\left(\cos\phi x + \sin\phi y\right)} dS\left(M_0\right) dS\left(M\right)$$

$$Z_{R,avg}\left(\theta\right) = \frac{1}{2\pi}\int_0^{2\pi} Z_R\left(\theta,\phi\right) d\phi \qquad \underset{\omega\to\infty}{Z_{R,avg}}\left(\theta\right) = \frac{\rho_0 c_0}{\cos\theta}$$

Double surface Integral to evaluate Z_R is shown to reduce to 1D ➔ quick estimation

Illustration of size correction



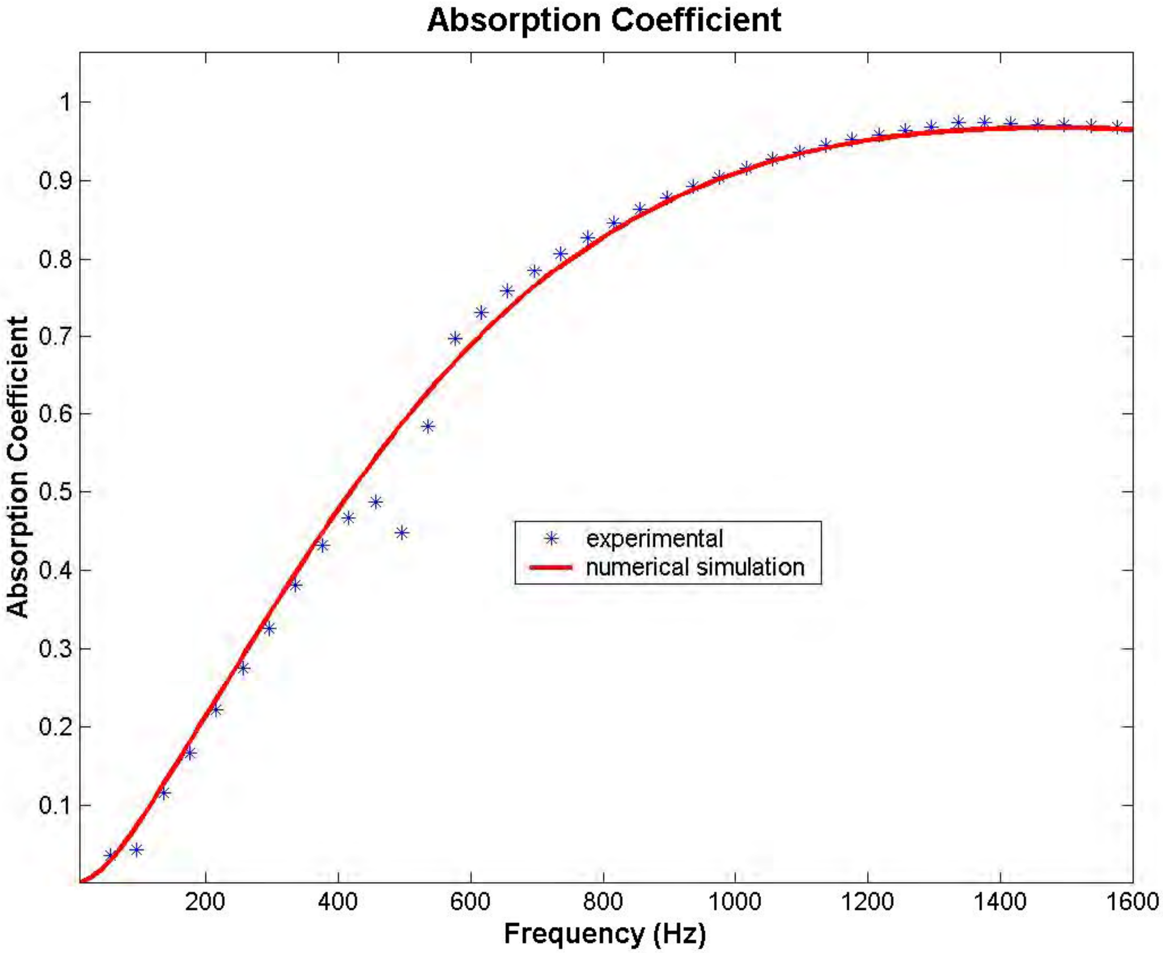


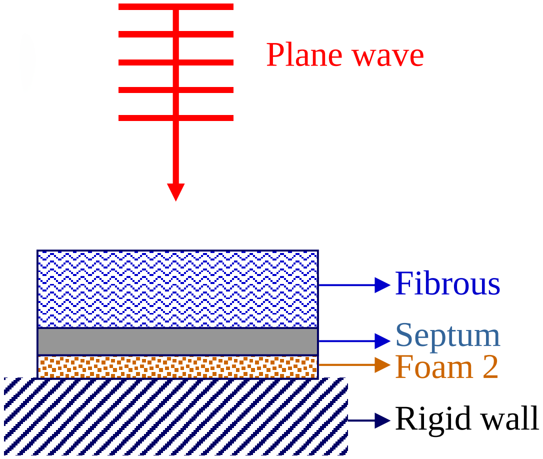
Outline

- Motivations and objectives
- Modeling Poroelastic materials
- Transfer Matrix Method based methodology
- **Numerical and experimental examples**
- Conclusion

Absorption of a Multilayer system

Experimental validation for multilayer system with impervious film (septum)





Absorption of a foam-screen system

Perforated screen (h=0.47 mm

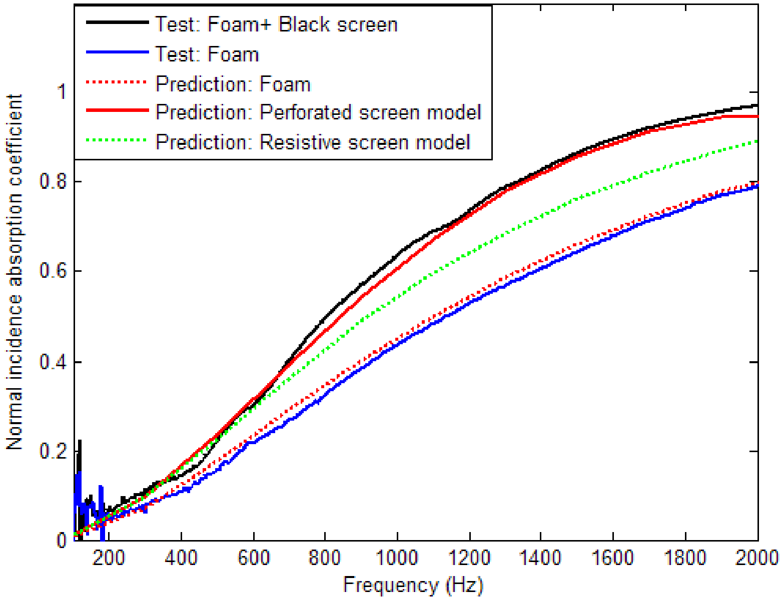
σ=137700 Nsm^{-4} ; ϕ=0.08)

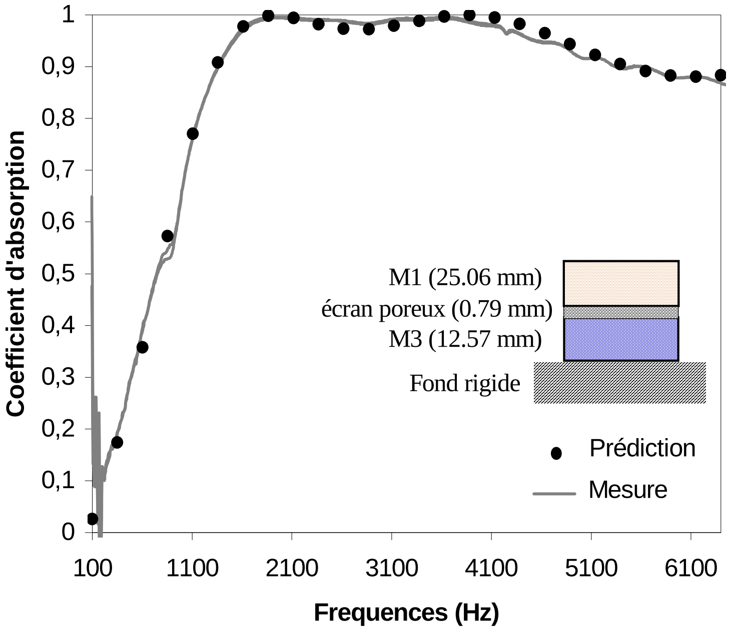
M3

Screen

M1

(σ=17000 Nsm^{-4} ;ϕ=0.059)

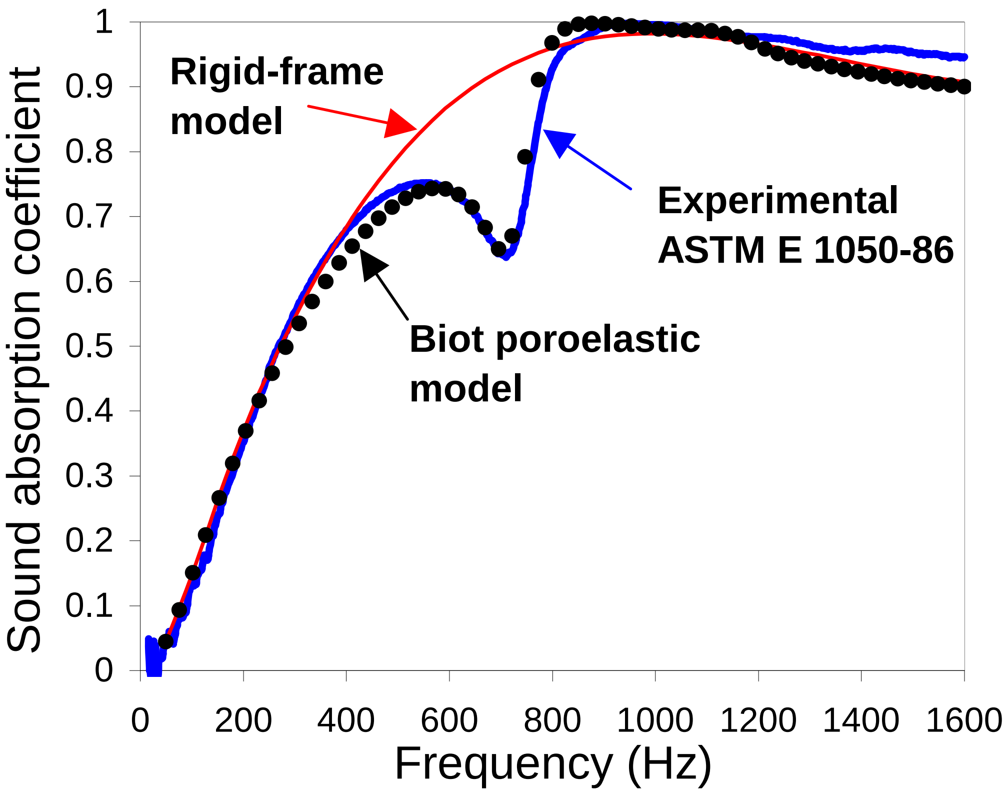




Use of an equivalent fluid model for the perfortaed facing ➔ Good agreement using tortuosity correction formulation (Atalla & Sgard. JSV 2005)

Effect of elastic behavior

Foam is bonded to the tube wall all around its contour



$$f = \frac{1}{4t}\sqrt{\frac{\left(\hat{P} + \gamma P_0\right)}{\rho_f}}$$

$$\hat{P} = \frac{(1-\nu)}{(1+\nu)(1-2\nu)} E$$

t : thickness

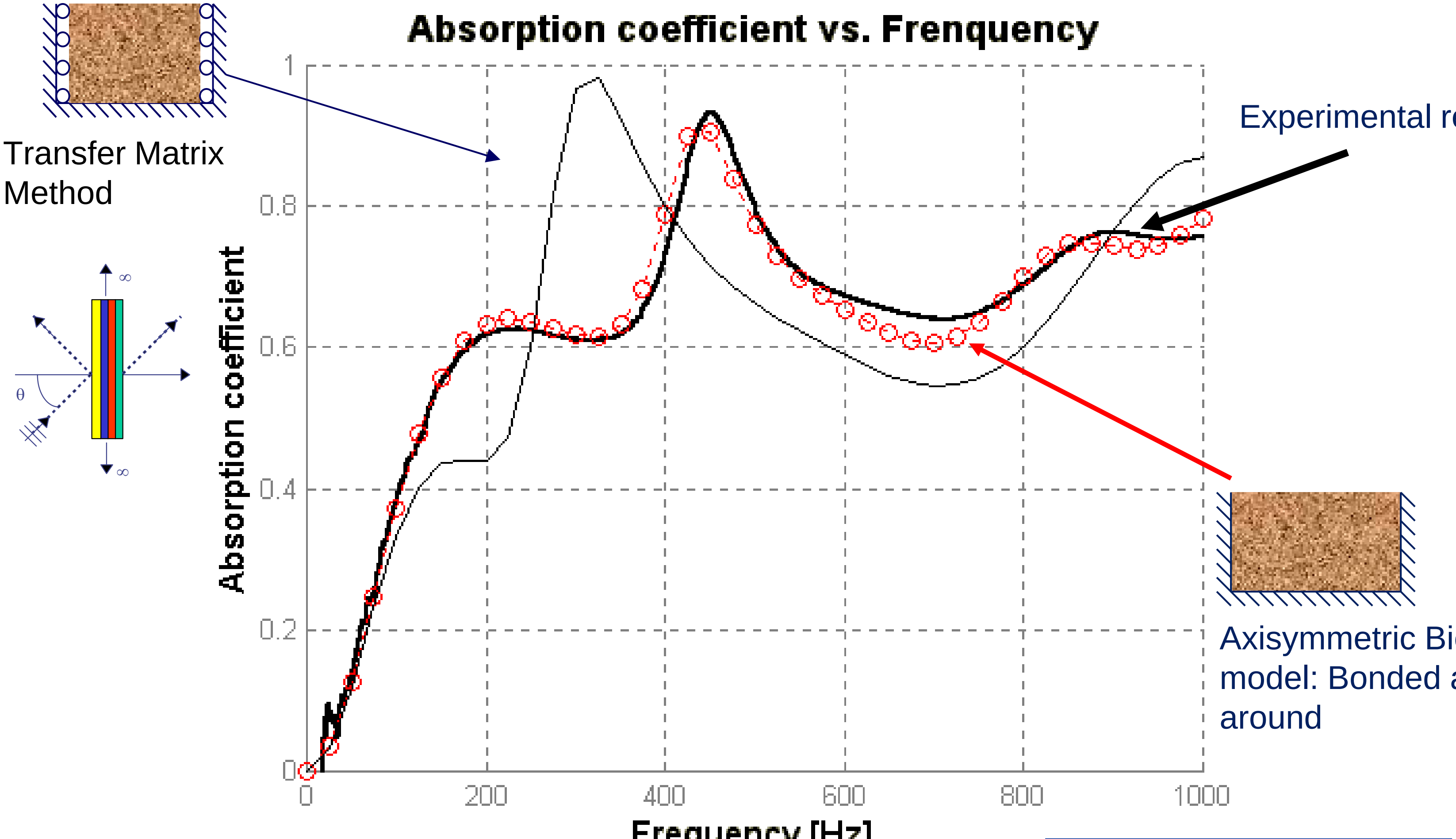
ρ_f : mass desnsity of the foam

γ : specific heat ratio

E: Young's modulus

ν : Poisson ratio

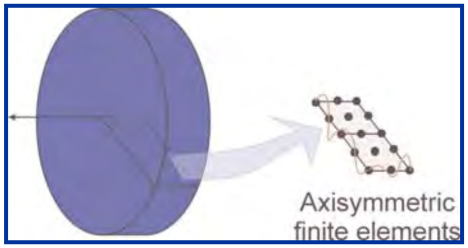
Effects of mounting conditions



Transfer Matrix Method

Experimental results

Axisymmetric Biot (u,P) model: Bonded all around



➔difficulty of Tube based methods to determine mechanical properties

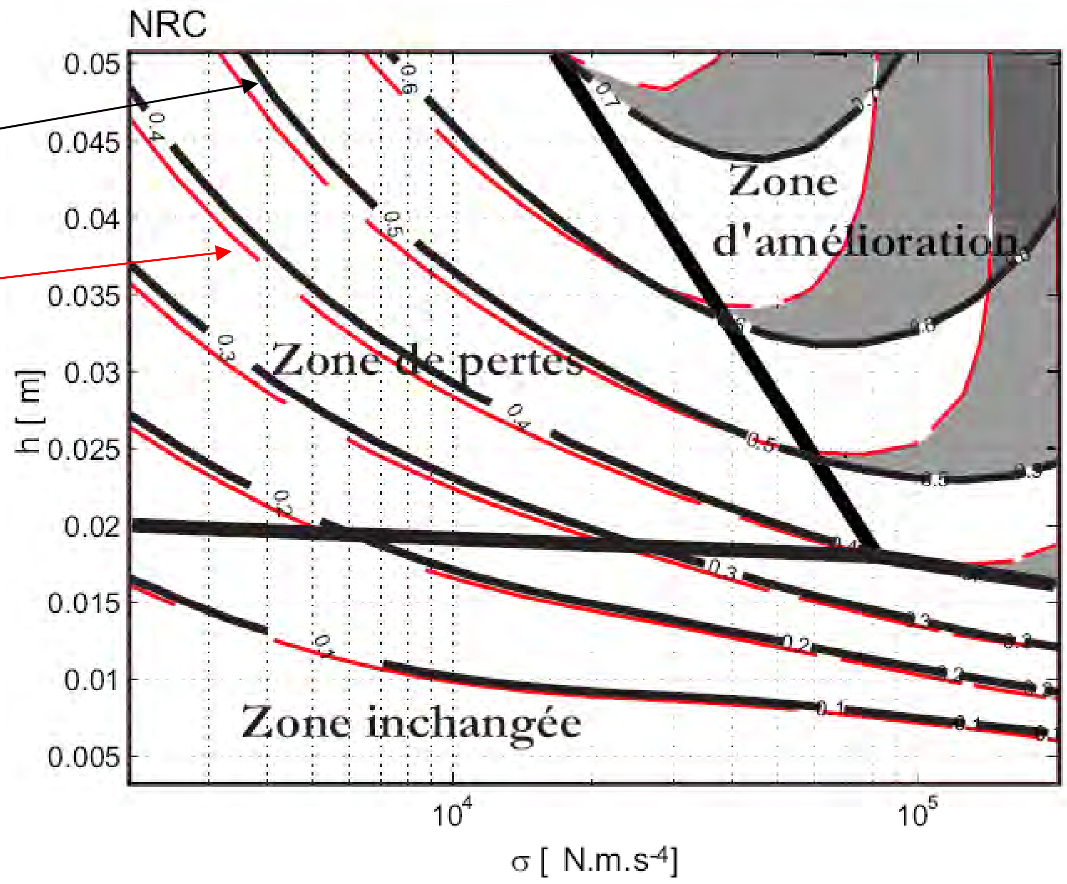
Effects of lateral gaps (leaks)

The effect of lateral air gaps (leaks) are important for thick highly resistive materials

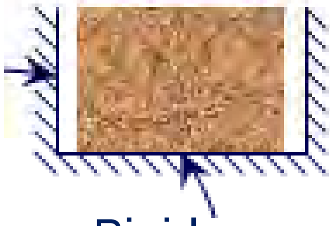
An axisymetric finite element solver helps to verify this effect or used for design.

No leak

With 1% leak



Air gap

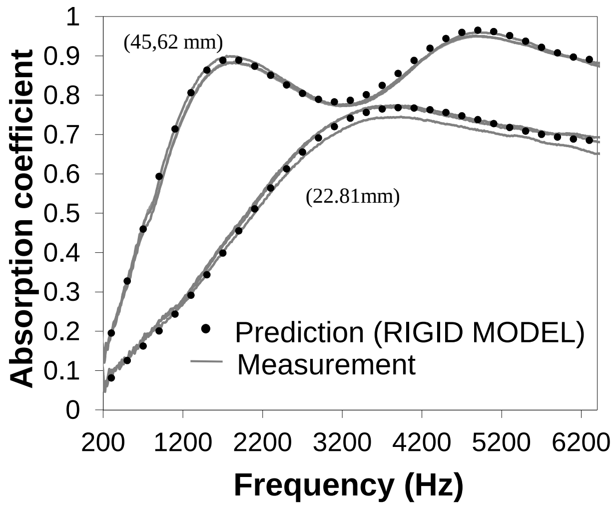


Rigid backing

F. Castel, Ph.D. thesis, Sherbrooke (2005)

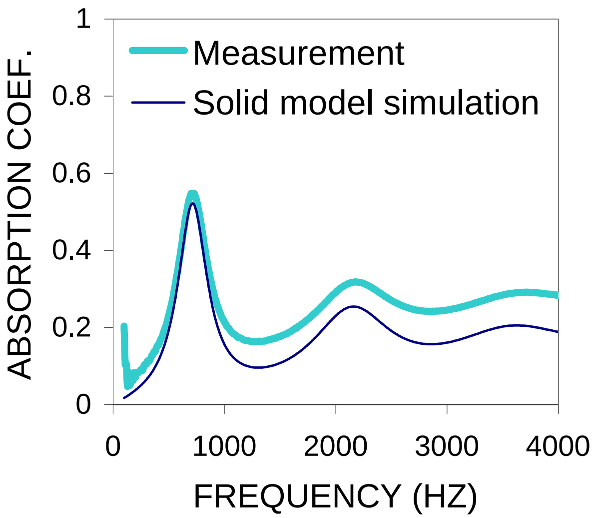
Open cell vs. closed cell foams

- **Porous materials, open cell foams ➔ Usually good absorption**



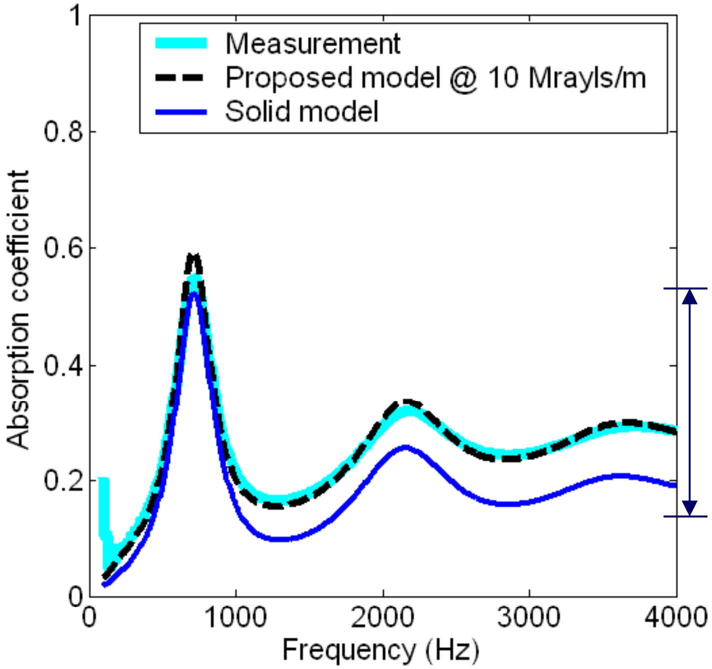
- **Closed cell foams ➔ poor absorption (mechanical behaviour)**

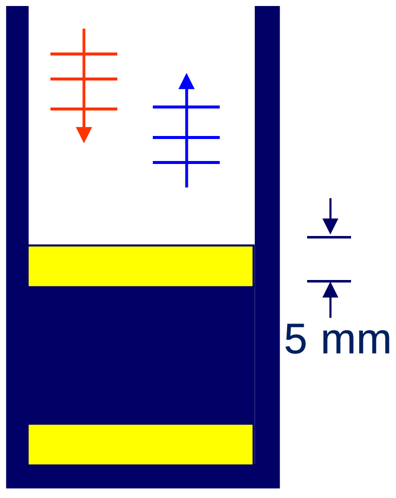
  Closed cell foam & viscoelastic material : used for vibration damping and isolation



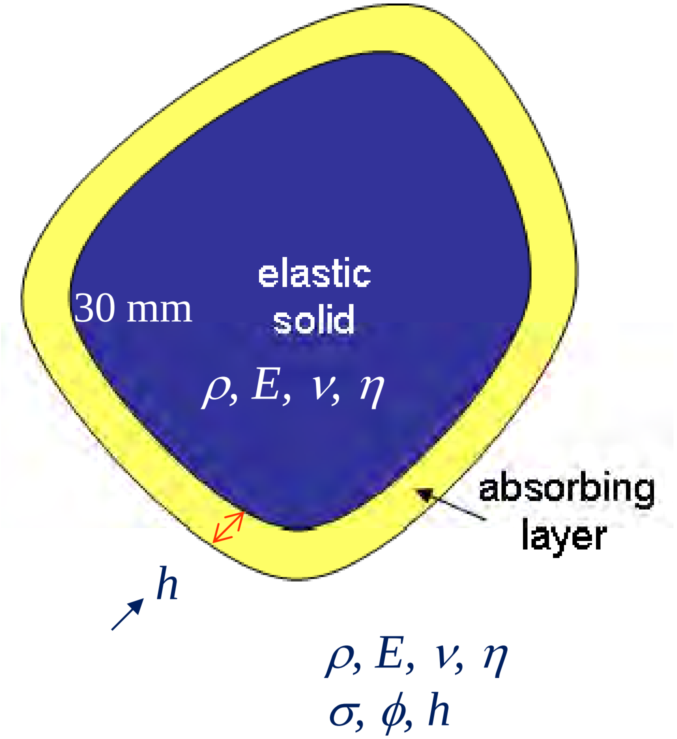
Modeling closed foams

- Two layers model:
  - Elastic core
  - Surrounding absorbing layer





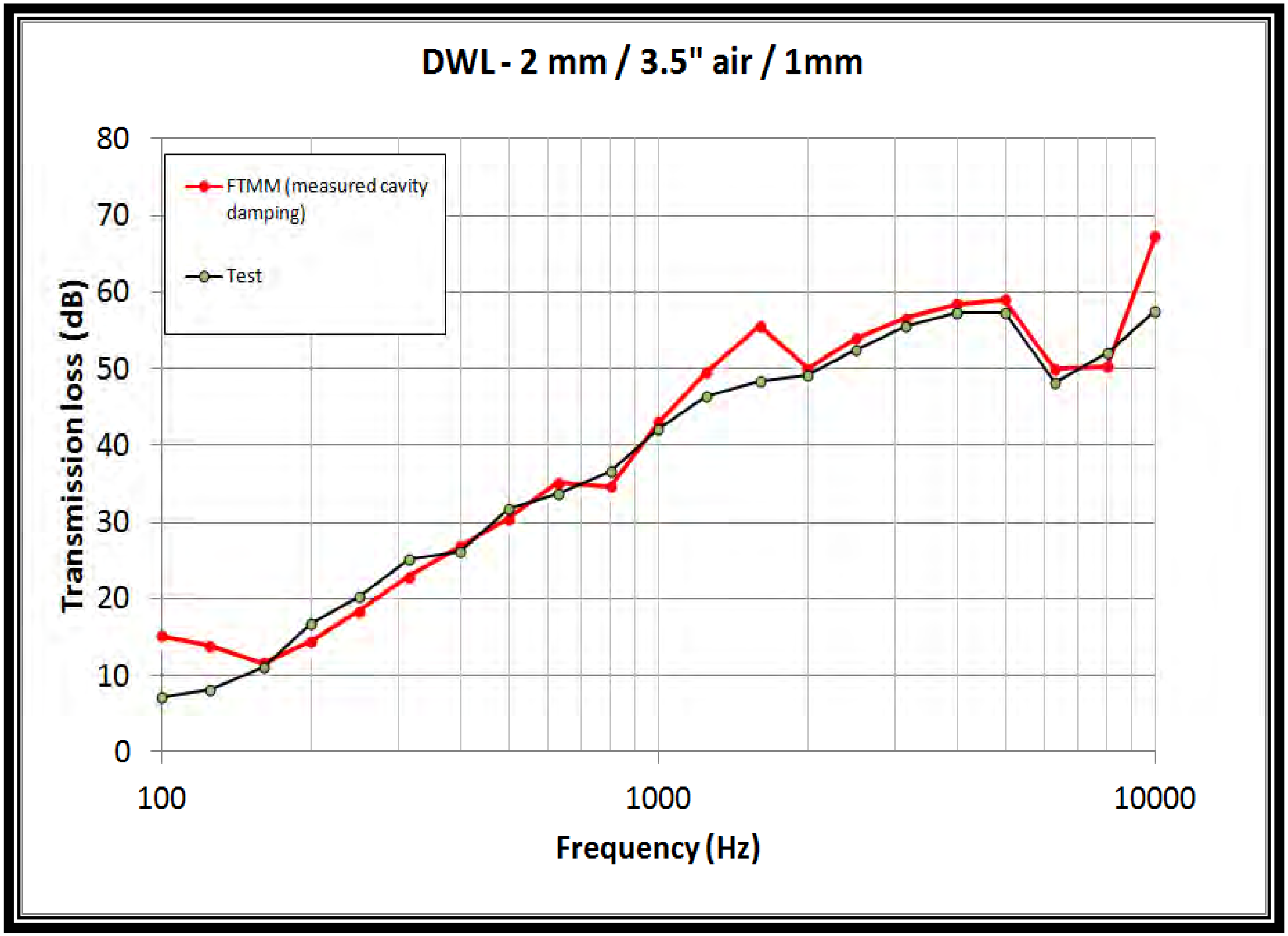
Impedance tube

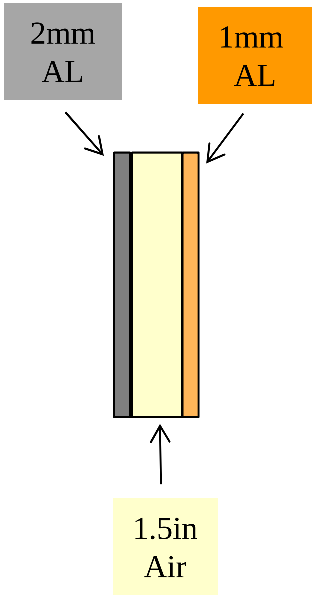


Ref. Wojtowicki and Panneton (SAE, 2005)

Experimental validation for a DWL system

Transmission Loss estimation of a DWL system

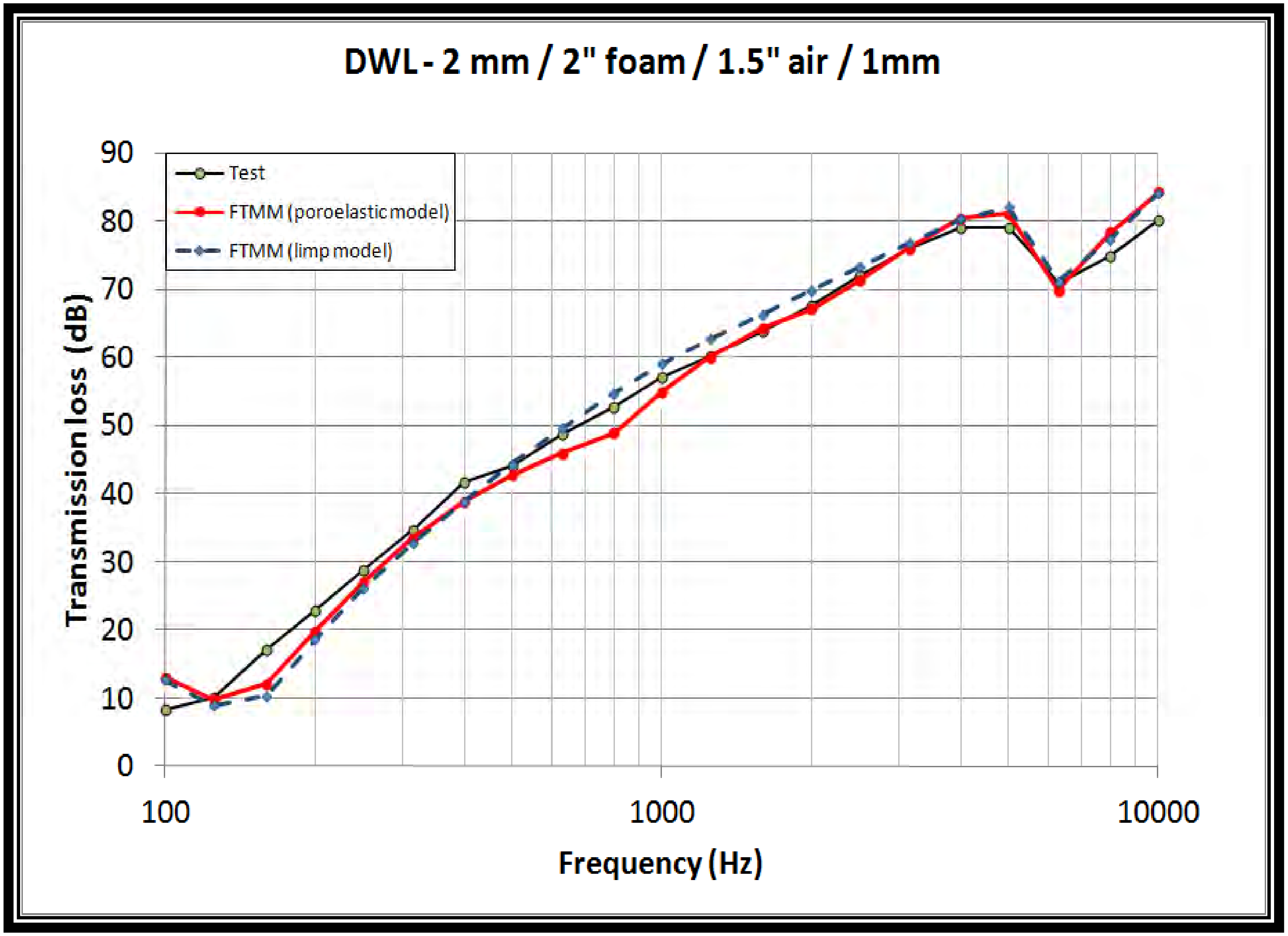


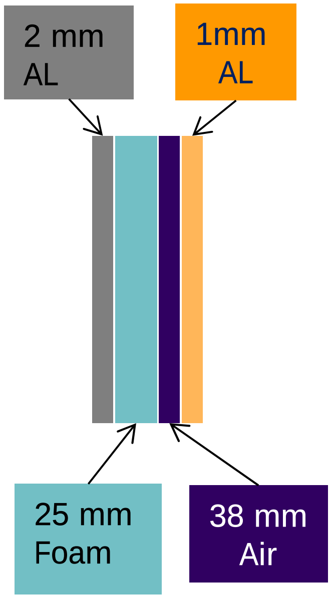


Excellent agreement (the challenge is rather the test to reduce flanking paths)

Experimental validation for a DWL system

Transmission Loss estimation of a DWL system





2 mm AL

1mm AL

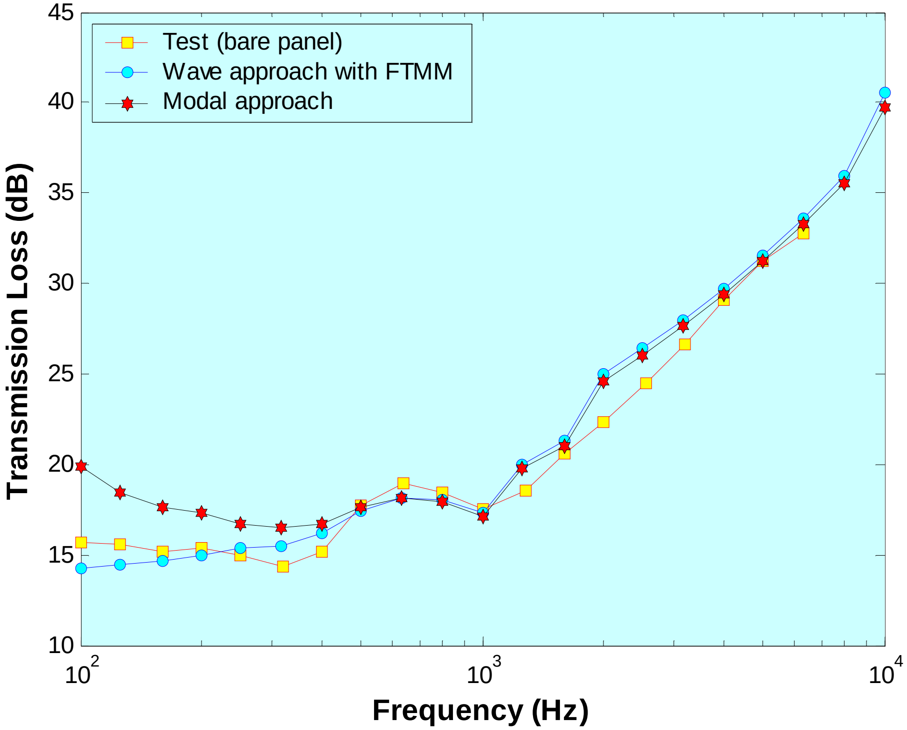
25 mm Foam

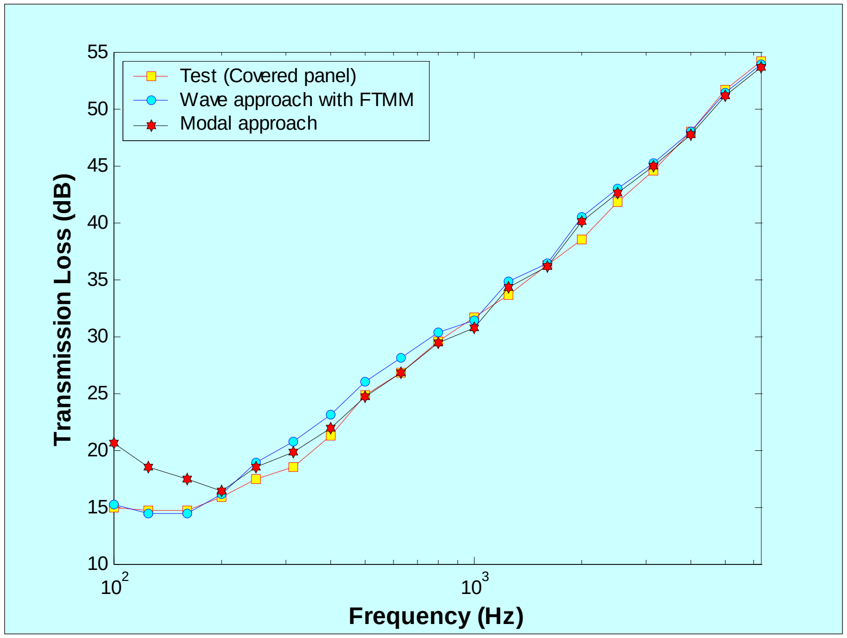
38 mm Air

Excellent agreement (the challenge is rather the test →reduce flanking paths)

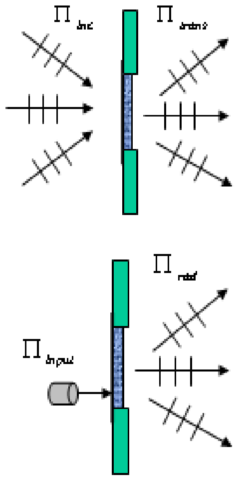
Example 1 – Effect of curvature

Transmission Loss of a Curved sandwich-composite Panel (R=2m; GE/RH110)





Example 2: Airborne vs. structure borne excitation



- Structure-borne Insertion Loss (SBIL)

$$SBIL = 10\log\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{trimmed} - 10\log\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{bare}$$

- Airborne Insertion Loss (ABIL)

$$ABIL = 10\log\left(\frac{\Pi_{inc}}{\Pi_{trans}}\right)_{trimmed} - 10\log\left(\frac{\Pi_{inc}}{\Pi_{trans}}\right)_{bare} = TL_{trimmed} - TL_{bare}$$

$$SBIL = 10\log 10\left|\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{Trim}\right| - 0\log 10\left|\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{Bare}\right|$$

Interest:
- Rank sound-packages
- Use in SEA models

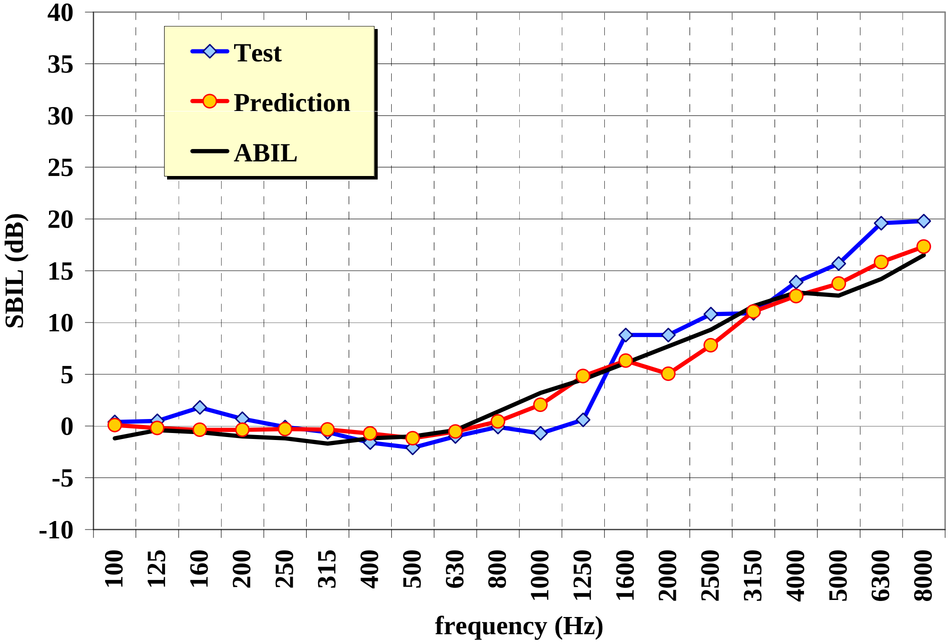
Methodology:
- Airborne ➔ calssical
- For structure-borne excitation* ➔ there are several methods (Power balance based, modal based, wave based)

*Rhazi D & Atalla (JSV, 2009)

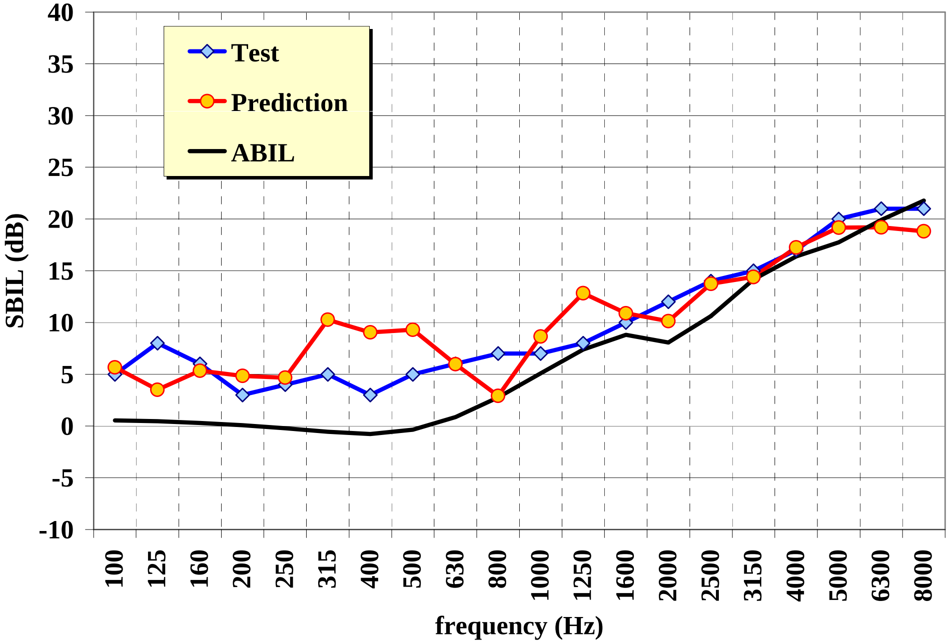
Example 2: Airborne vs. structure borne excitation

$$\mathrm{SBIL} = 10\log\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{\mathrm{trimmed}} - 10\log\left(\frac{\Pi_{input}}{\Pi_{rad}}\right)_{\mathrm{bare}}$$

Highly damped (MPM)



Undamped(steel)



- **SBIL ≠ ABIL for the undamped panel due to added damping from the carpet**
- **Good correlation with simulations using modified TMM**

Conclusion

- Presented the validity of simple TMM based models to predict the vibroacoustics response of structures with added **acoustic materials**.

- The models are **Quick & accurate enough** to be used for design and what if questions…

- Comparison with Tests & FE simulations show that they are even acceptable for large **curved panel** (aerospace applications; low ring frequency) and various types of excitations

Perspectives:

- More studies with various panel constructions, radius of curvatures & excitations (DAF & TBL)
- Efficient combination with FE models ➔ hybrid models
- Accounting for input parameters variance, anisotropy and dependence on mounting conditions ➔ importance of ***accurate characterization of material properties (Part II)***

Part 2

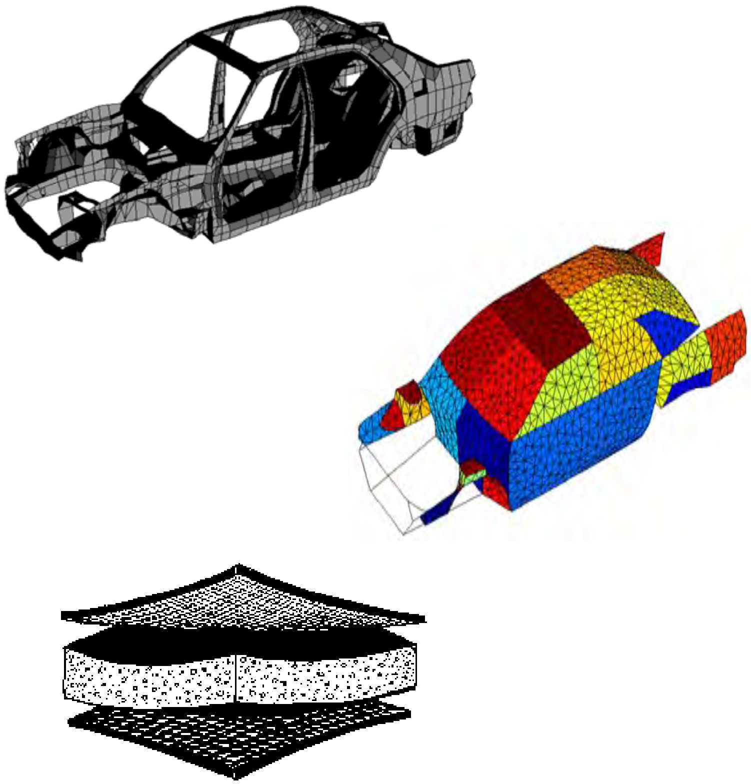
Characterizing Noise Control Materials

Pr Raymond Panneton
GAUS, Université de Sherbrooke
Mecanum Inc.
www.gaus.ca ● www.mecanum.com

raymond.panneton@usherbrooke.ca noureddine.atalla@usherbrooke.ca

Motivation

- Sound quality now starts at the design stage
- Models are used to simulate the acoustics
- Models are used to develop and optimize noise control materials



Material properties are the input parameters to models

ϕ σ α_∞

Λ Λ' ρ

E ν η

Objectives

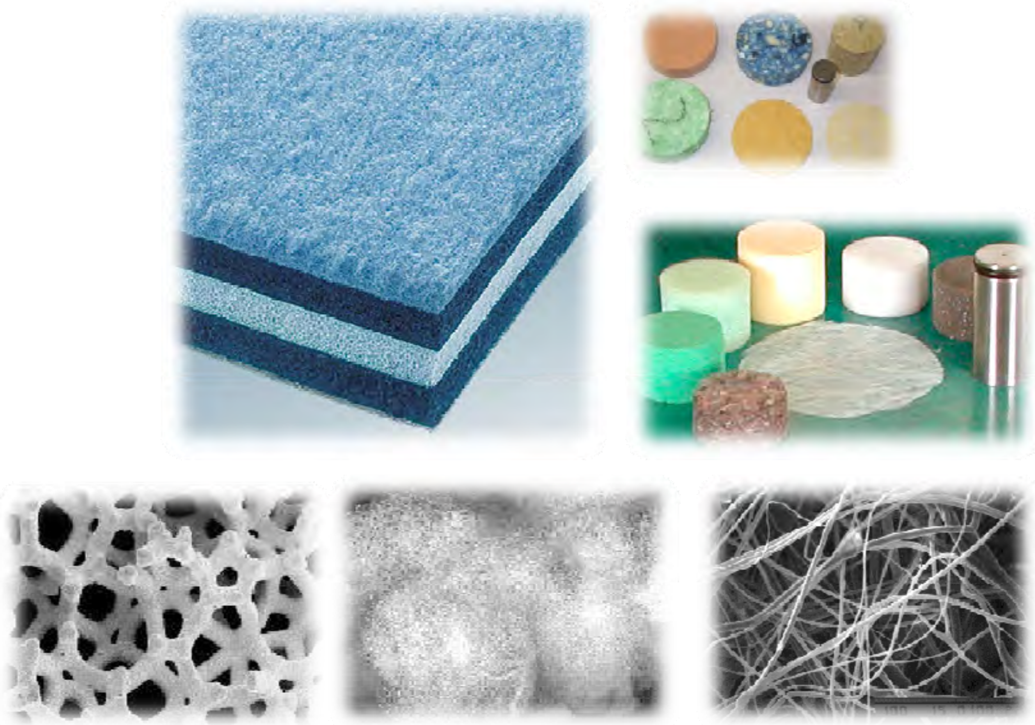
- Develop efficient methods and equipments for the characterization of the material properties of a wide range of porous materials used in sound packages
- Develop rigorous procedures and, where possible, standardized to prevent misuse of characterization methods
- Build database for noise control materials to populate prediction software

Challenges

- ☐ The experimenter often lacks knowledge about porous materials and their properties
- ☐ The experimenter is not aware of the difficulties inherent in certain measurement methods and standards
- ☐ Standards do not say everything
- ☐ Material samples are not perfect
- ☐ Preparation of test samples is not always easy and straightforward

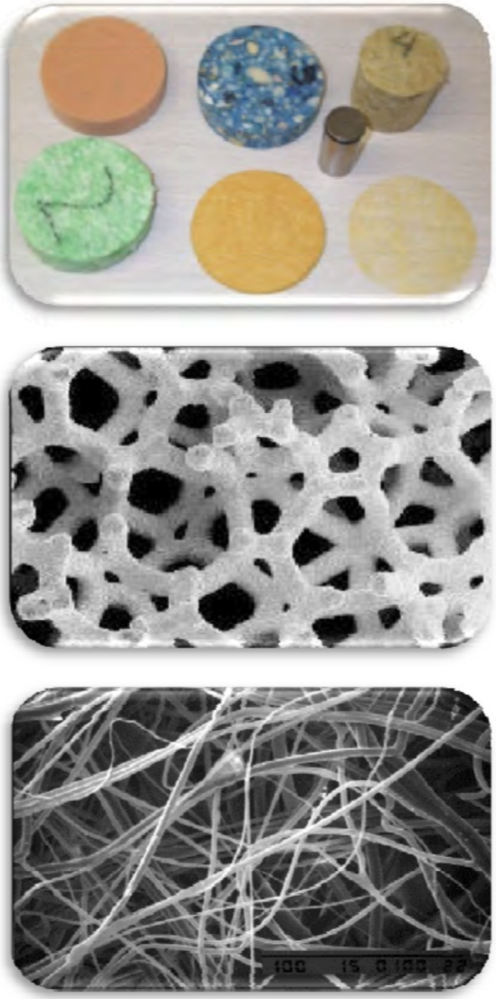
What about sound packages ?

- Sound packages are made up from a combination of materials, notably:
  - Porous materials
    - Foams
    - Fibers
    - Felts
    - Carpets
    - Porous films
    - Fabrics
  - Damping materials
  - Plate and solid layers



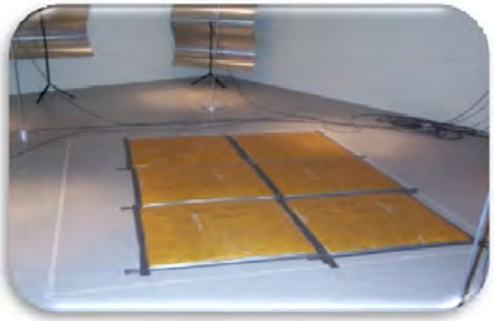
What is a porous material ?

- Porous materials
  - Two phases :solid and fluid
  - Elastic coupling
  - Visco-inertial coupling
- What do they do ?
  - Transform acoustic energy into heat
- How do they dissipate energy ?
  - viscous effect
  - thermal effect
  - structural damping



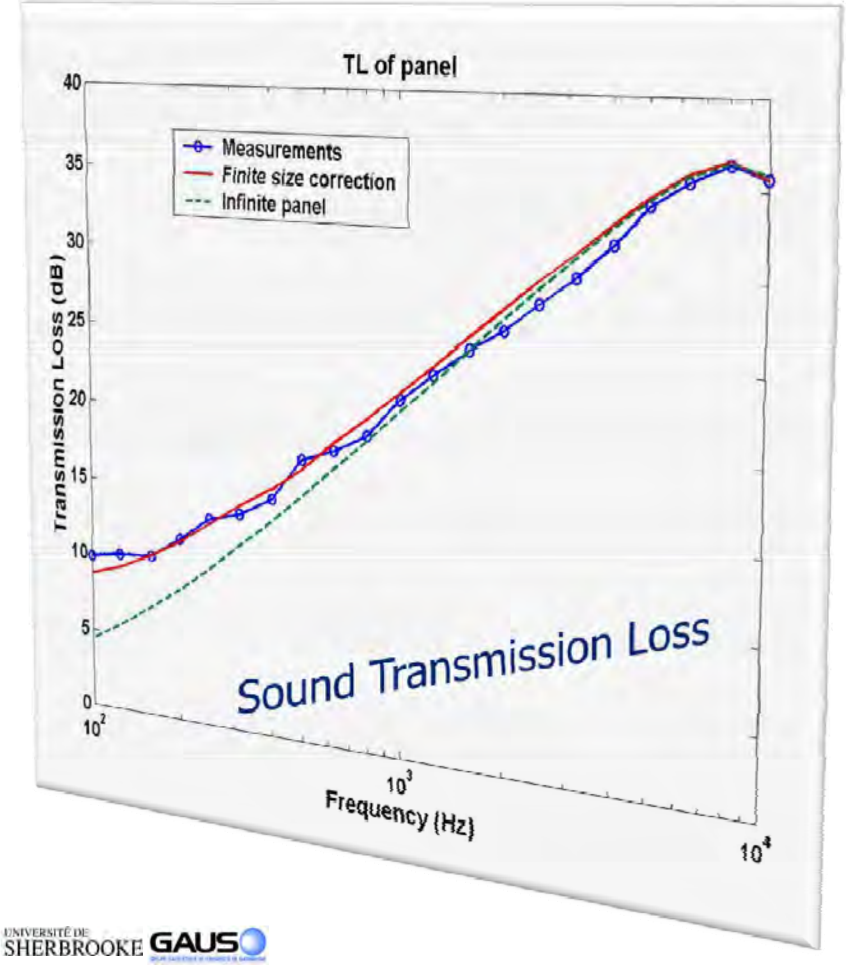
What about their performance?

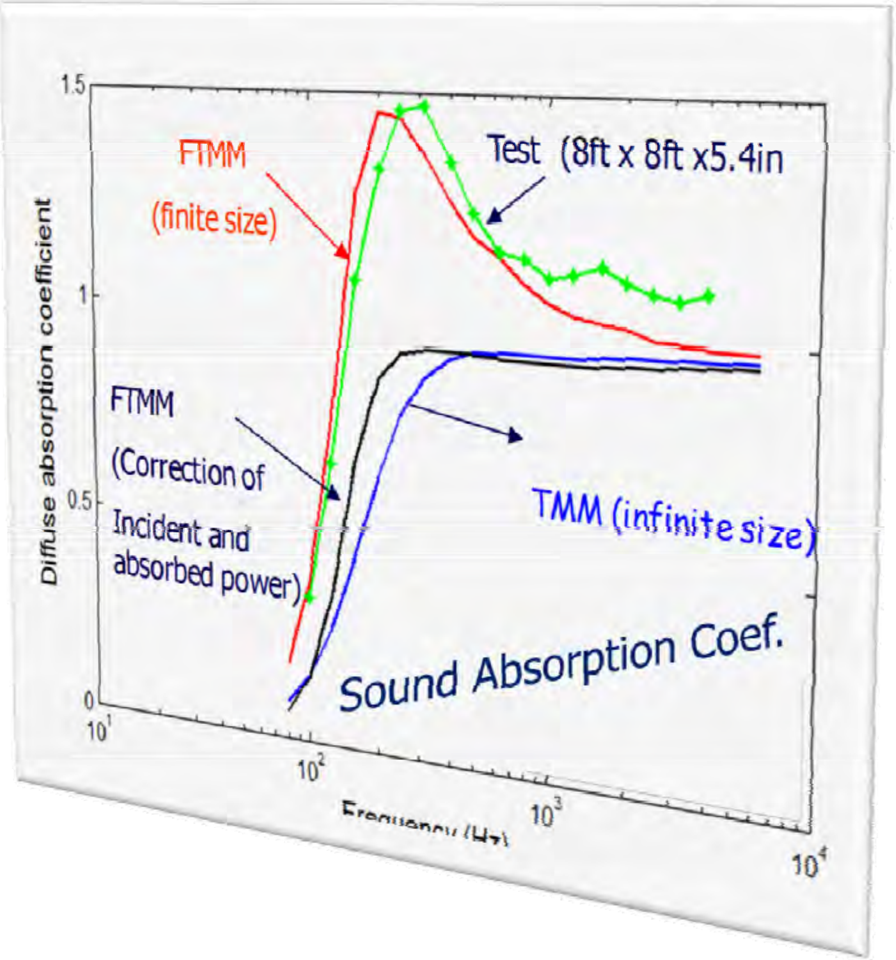
❑ Typical diffuse field indicators
  - Sound absorption coefficient by the reverberant room method [ASTM C423-09a, ISO 354:2003]
  - Sound transmission loss – 2 reverberant room method [ASTM E90-09],
  - Sound transmission loss – Intensity method [ASTM E2249-02, ISO 15186]
  - Alpha cabin (not for weakly absorbing materials) [ISO 354]



What about their performance?

- ❑ Typical diffuse field results





What about their performance?

☐ Typical normal incidence indicators

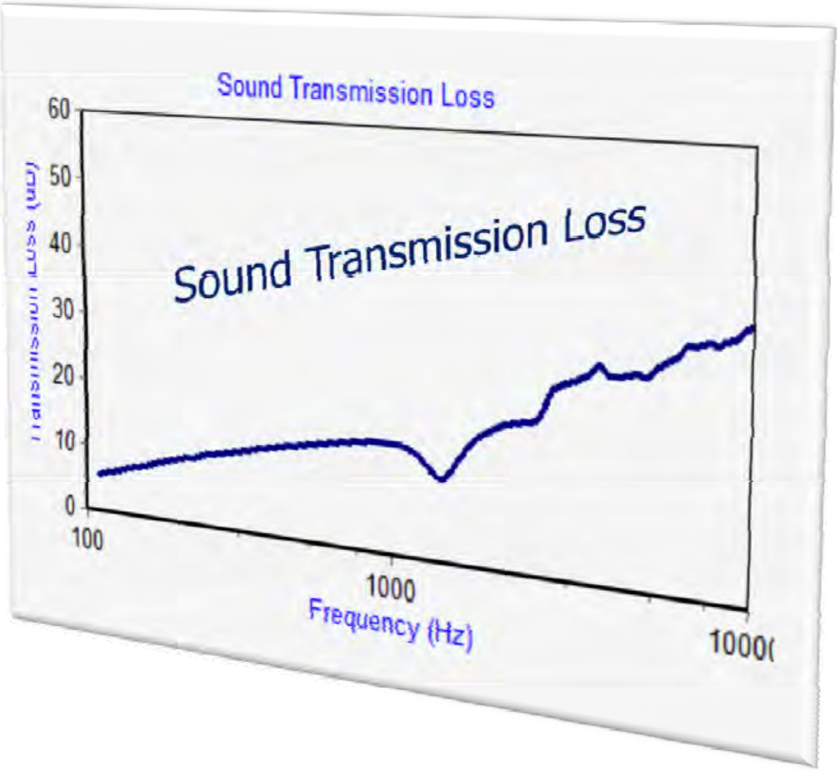
- Sound absorption coefficient
- Reflection coefficient
- Surface impedance
- Sound transmission loss

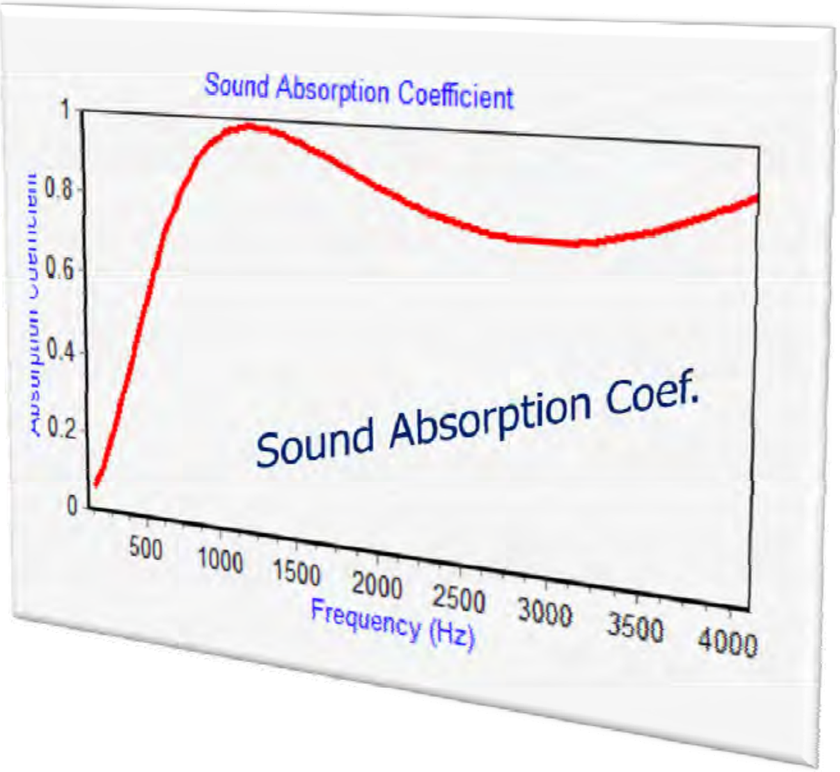
by

- Impedance tube method [ASTM E 1050-12, ISO 10534-2]
- Transmission tube method [ASTM E2611-09]

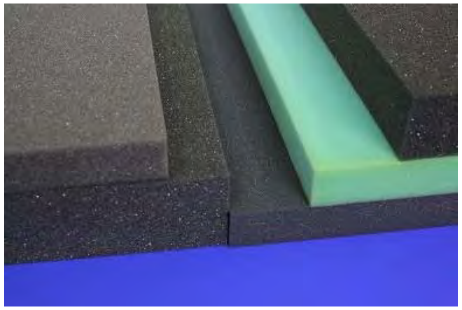
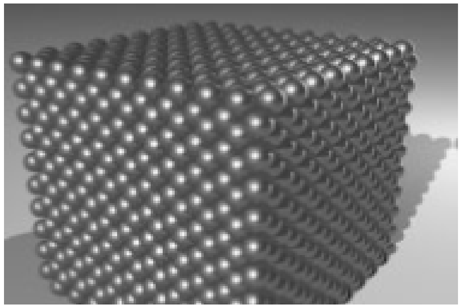
What about their performance?

- ❑ Typical normal incidence results

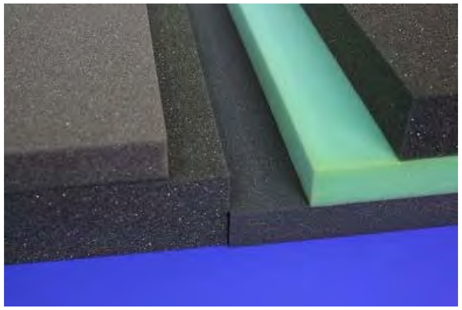
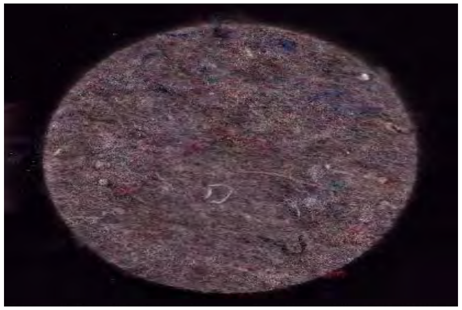




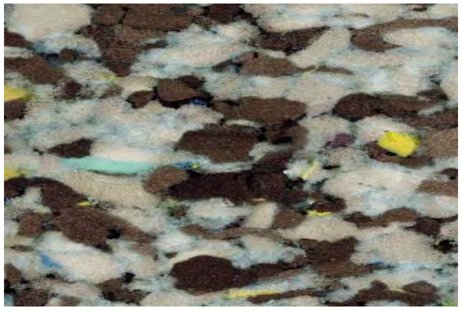
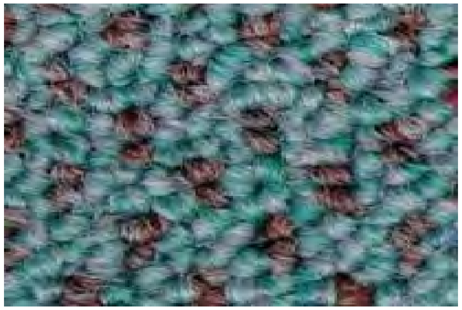
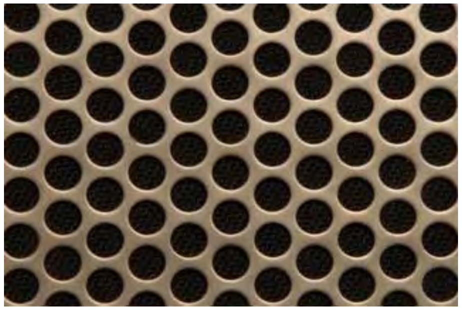
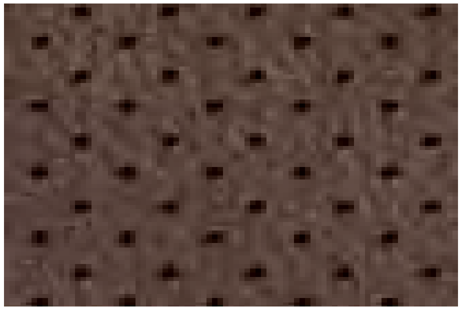
What about their frame ?

Elastic frame 	**Rigid frame** 
Limp frame 	**Granular** 

Types of porous materials

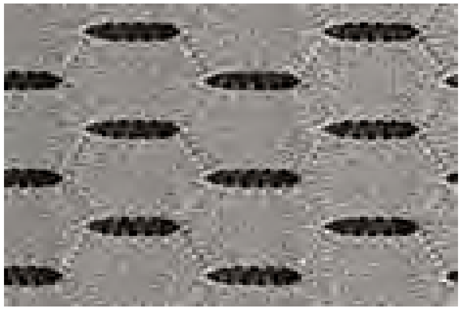
Polymeric foam 	**Metallic foam** 
Natural/Mineral wools 	**Felt** 

Types of porous materials

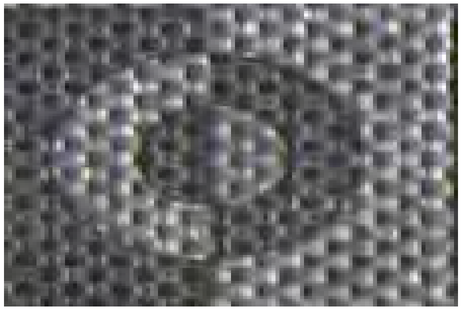
Recycled 	**Carpets** 
Perforated Panels 	**Perforated Leather** 

Types of porous materials

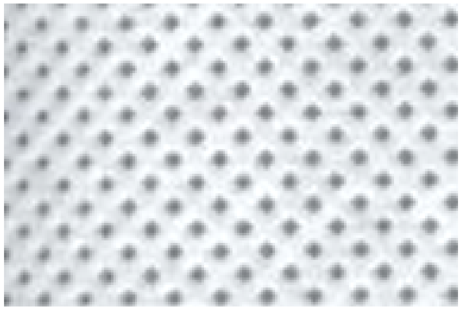
Cloth



Woven fabrics



Non-woven fabrics



Multilayer / Laminates

Modeled by Biot's poroelastic theory

BIOT (u,p) formulation worked out by ATALLA and PANNETON governs the propagation of the coupled elastic waves (compression and shear) and acoustic wave (compression).

$$\tilde{\mu} u_{i,jj} + \left(\tilde{\lambda} + \tilde{\mu}\right) u_{j,ij} + \omega^2 \tilde{\rho}_s u_i = -\tilde{\gamma}\; p_{,i}$$

Elasto-dynamic equation

$$\frac{1}{\omega^2 \tilde{\rho}_e} p_{,ii} + \frac{1}{\tilde{K}_e} p = \tilde{\gamma}\, u_{i,i}$$

Helmholtz equation

[J. Acoust. Soc. Am. 104(3),p. 1444-1452]

Biot's macroscopic parameters

u : solid phase macroscopic displacement vectors
p : fluid phase macroscopic pressure
~: denotes a complex and frequency dependent quantity (Dynamic properties)
λ,μ : Effective solid phase Lamé coefficients
K_e : Effective fluid phase bulk modulus
ρ_s : Effective solid phase density
ρ_e : Effective fluid phase density
γ : Fluid-solid coupling coefficient

Ref.: Allard & Atalla: Propagation of Sound in Porous Media. 2nd Edition, Wiley, 2009

Equivalent fluid model

Rigid frame (Limit of Biot's model when frame is motionless)

Helmholtz equation with equivalent density and bulk modulus

$$\Delta p + \omega^2 \frac{\rho_{eq}}{K_{eq}} p = 0$$

Limp frame (Limit of Biot's model when frame is limp)

Helmholtz equation with equivalent density and bulk modulus

$$\rho_{eq} \rightarrow \frac{\rho_{eq} M - \rho_0^2}{M + \rho_{eq} - 2\rho_0}$$

$$M = \rho_1 + \phi\rho_0$$

Total apparent mass of the bulk volume

Ref.: http://dx.doi.org/10.1121/1.2800895
Panneton: Comments on the limp frame equivalent fluid model for porous media, J. Acoust. Soc. Am. 122 (2007)

Equivalent fluid model

Equivalent dynamic density

- *Takes into account viscous and inertial effects*
- *Some recent models:*
    - ***Johnson et al. (1987)*** **- ϕ, σ, α_{∞}, Λ**
    - *Pride et al. (1993)* - ϕ, σ, α_{∞}, Λ, α_0

$$\rho_{eq}$$

$$\tilde{\rho}_{EQ} = \tilde{\rho}_e / \phi$$

Equivalent dynamic bulk modulus

- *Takes into account thermal effects*
- *Some recent models:*
    - ***Champoux and Allard (1991)*** **- ϕ, Λ'**
    - ***Lafarge I (1993,1997)*** **- ϕ, Λ', k_0'**
    - *Lafarge II (1993)* - ϕ, Λ', k_0', α_0'

$$K_{eq}$$

$$\tilde{K}_{EQ} = \tilde{K}_e / \phi$$

JCA model *JL model*

Macroscopic parameters

ϕ - Open porosity

α_{∞} - Tortuosity

σ - Static airflow resistivity

Λ - Viscous characteristic length

α_0 - Static viscous tortuosity

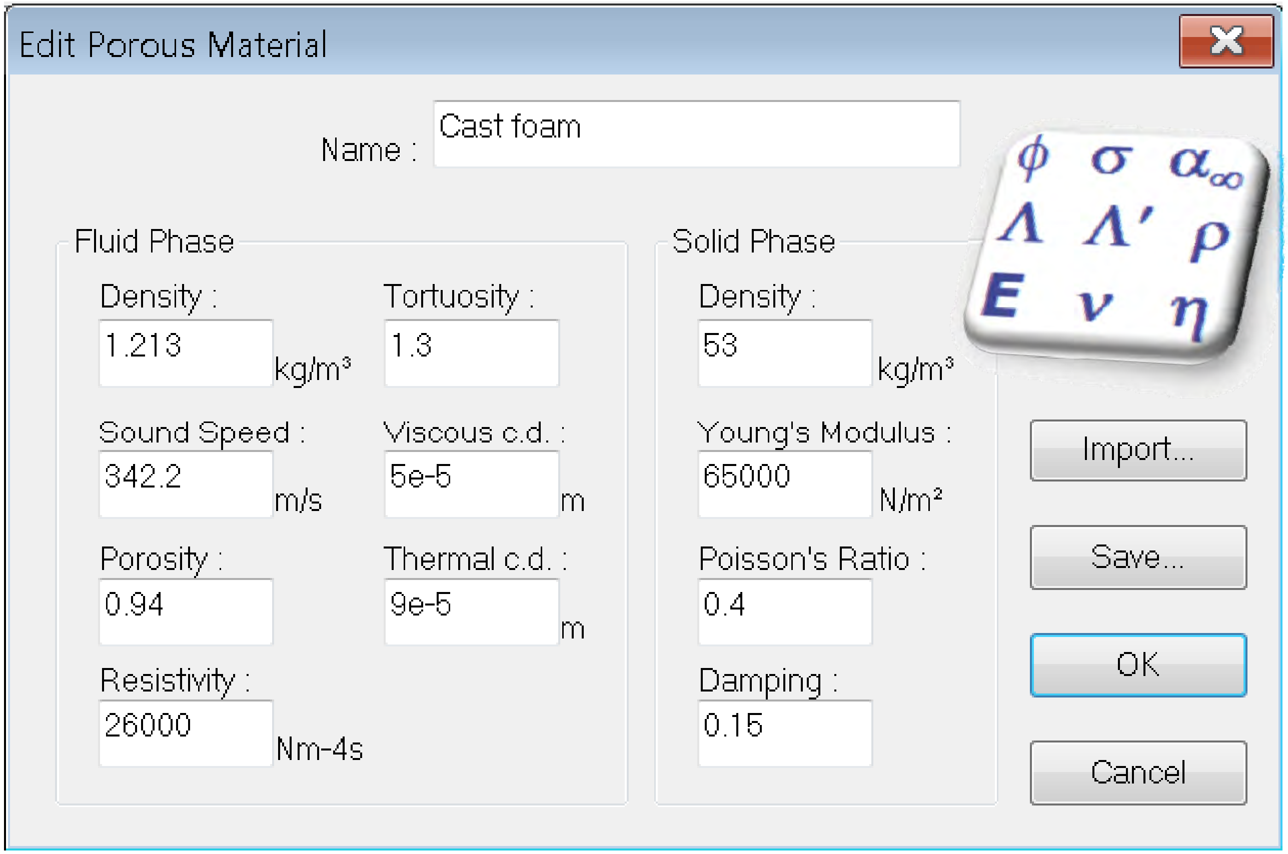
k_0' - Static thermal permeability

Λ' - Thermal characteristic length

α_0' - Static thermal tortuosity

Parameters populating Biot model

Example for Mecanum's NOVA software based on the Biot-Allard model: ***9 parameters***



Edit Porous Material

Name : Cast foam

Fluid Phase

Density : 1.213 kg/m³

Tortuosity : 1.3

Sound Speed : 342.2 m/s

Viscous c.d. : 5e-5 m

Porosity : 0.94

Thermal c.d. : 9e-5 m

Resistivity : 26000 Nm-4s

Solid Phase

Density : 53 kg/m³

Young's Modulus : 65000 N/m²

Poisson's Ratio : 0.4

Damping : 0.15

Source: GUI from **Nova** software

<u>Compatibles with:</u>

- ESI / Nova
- ESI / VA One
- FFT/Actran
- CSTB / AcouSYS
- COMSOL / Acoustics
- LMS Virtual Lab

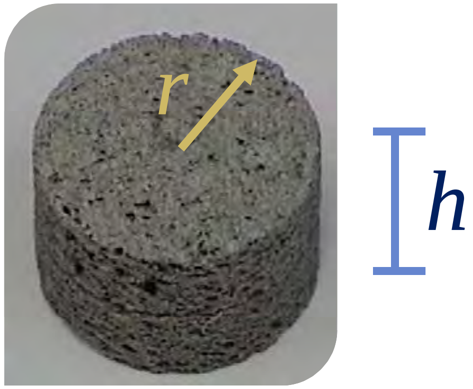
Definition of the 9 porous material properties ...

Bulk density [ρ_1]

Following the Biot theory, the bulk density is the ratio between the *in-vacuum* mass of the porous aggregate and its *bulk volume*.

$$\rho_1 = \frac{M}{V_t}$$

$$\rho_1 = \frac{M}{\pi r^2 h}$$



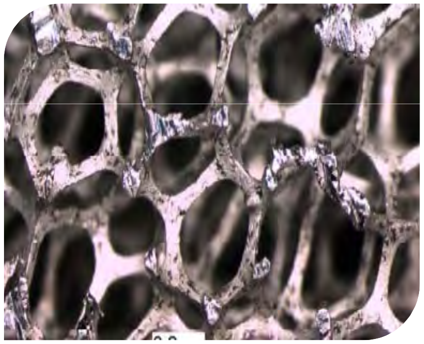
Open Porosity [ϕ]

Open porosity is defined as the fraction of the *interconnected* pore fluid volume to the total bulk volume of the porous aggregate.

$$\phi = \frac{V_f}{V_t}$$

$$\phi = 1 - \frac{V_s}{V_t} = 1 - \frac{\rho_1}{\rho_s}$$

Typical values
For perforates : < 50%
For light fibrous: ~ 99%
For foams: > 90%



V_s : *Solid phase volume*
ρ_s : *Density of solid phase material*

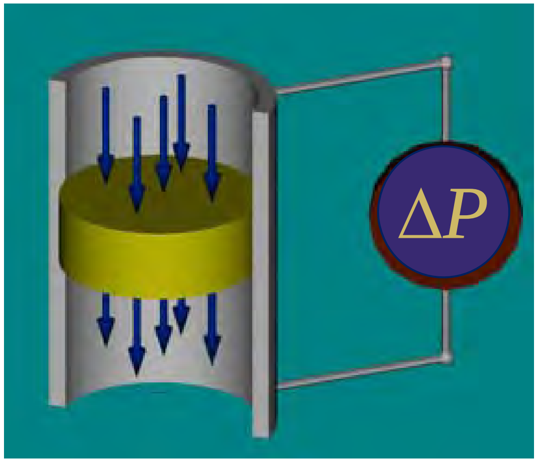
Static airflow resistivity [σ]

Static airflow resistivity governs the *low-frequency viscous effects* in open-cell porous media, where the viscous skin depth is of the order of magnitude of the characteristic size of the cells.

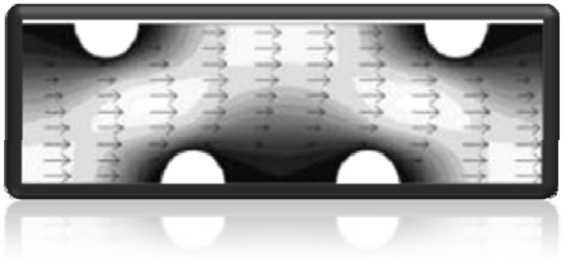
It is defined as the limit, when flow tends to zero, of the quotient of the air pressure difference across a specimen divided by its thickness and the velocity of airflow through it.

$$\sigma = \frac{\Delta P}{v}\frac{1}{h}$$

[Ns/m^4 or MKS Rayls/m]

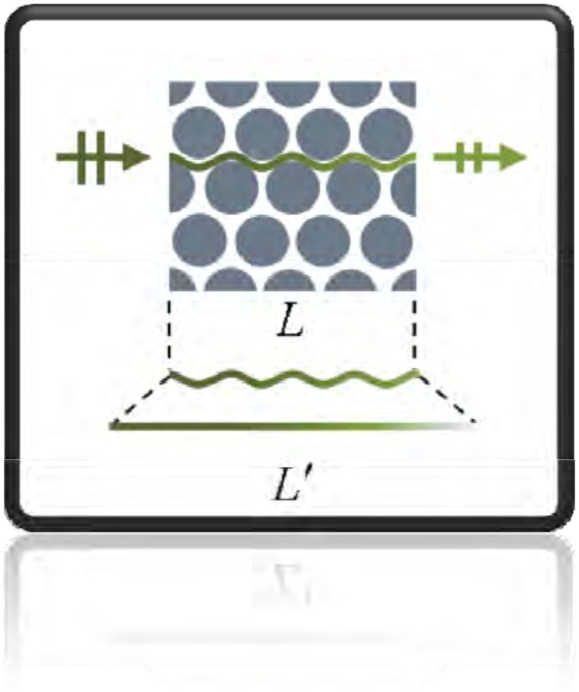


Tortuosity [α_∞]



Tortuosity accounts for the apparent *increase in the fluid density* when the fluid saturates a porous structure.

It can be seen as the *effective length* of the path follows by acoustical wave through the material.



$$\alpha_\infty = \left(\frac{L'}{L}\right)^2$$

$$\alpha_\infty \geq 1$$

Typical values

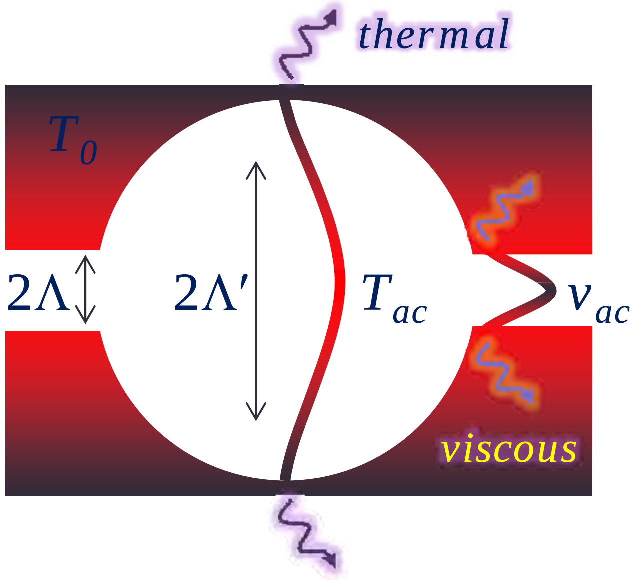
- *Low density fibrous:* $\alpha_\infty = 1.00$
- *Mid/High density fibrous:* $1.00 \leq \alpha_\infty \leq 1.45$
- *Reticulated foams:* $1.00 \leq \alpha_\infty \leq 2.0$
- Partially reticulated foams : $2.0 \leq \alpha_\infty \leq 3.0$

Thermal characteristic length $[\Lambda']$

The thermal characteristic length describes the thermal dissipation effects at medium and *high frequencies*.

It is of the order of magnitude of the average *radius of the larger cells* where thermal losses dominate viscous losses.

$$\Lambda' = 2\,\frac{\int_{V_f} dV}{\int_{\Gamma} dS}$$



V_f : *Pore volume*
Γ: *Wet surface boundary*

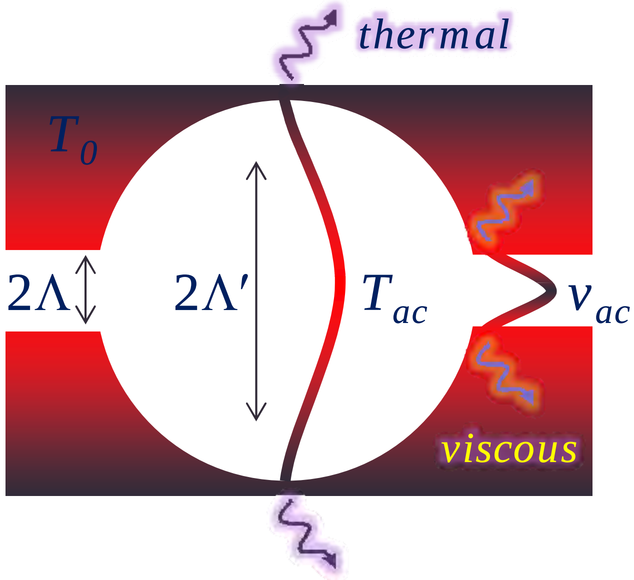
Typical values
From 10 µm to 500 µm

Viscous characteristic length [Λ]

The viscous characteristic length describes the viscous dissipation effects at medium and *high frequencies*.

It is of the order of magnitude of the average *radius of the smaller cells* and necks where viscous losses dominate thermal losses.

$$\Lambda = 2\,\frac{\int_{V_f} v^2\,dV}{\int_{\Gamma} v^2\,dS} \leq \Lambda'$$



V_f : *Pore volume*

Γ: *Wet surface boundary*

Typical values

From 10 µm to 500 µm

Elastic properties [E,ν,η]

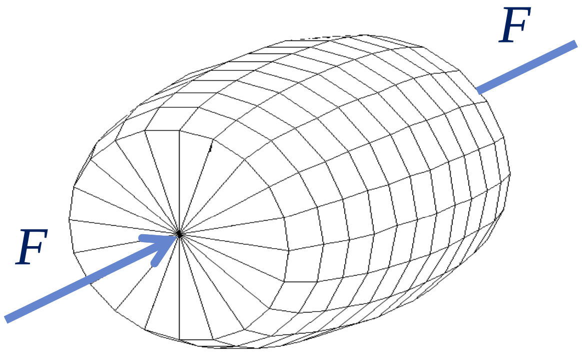
Young's modulus [Pa], Poisson's ratio and damping loss factor follow the same definitions as for elastic materials.

Porous materials are generally not isotropic.

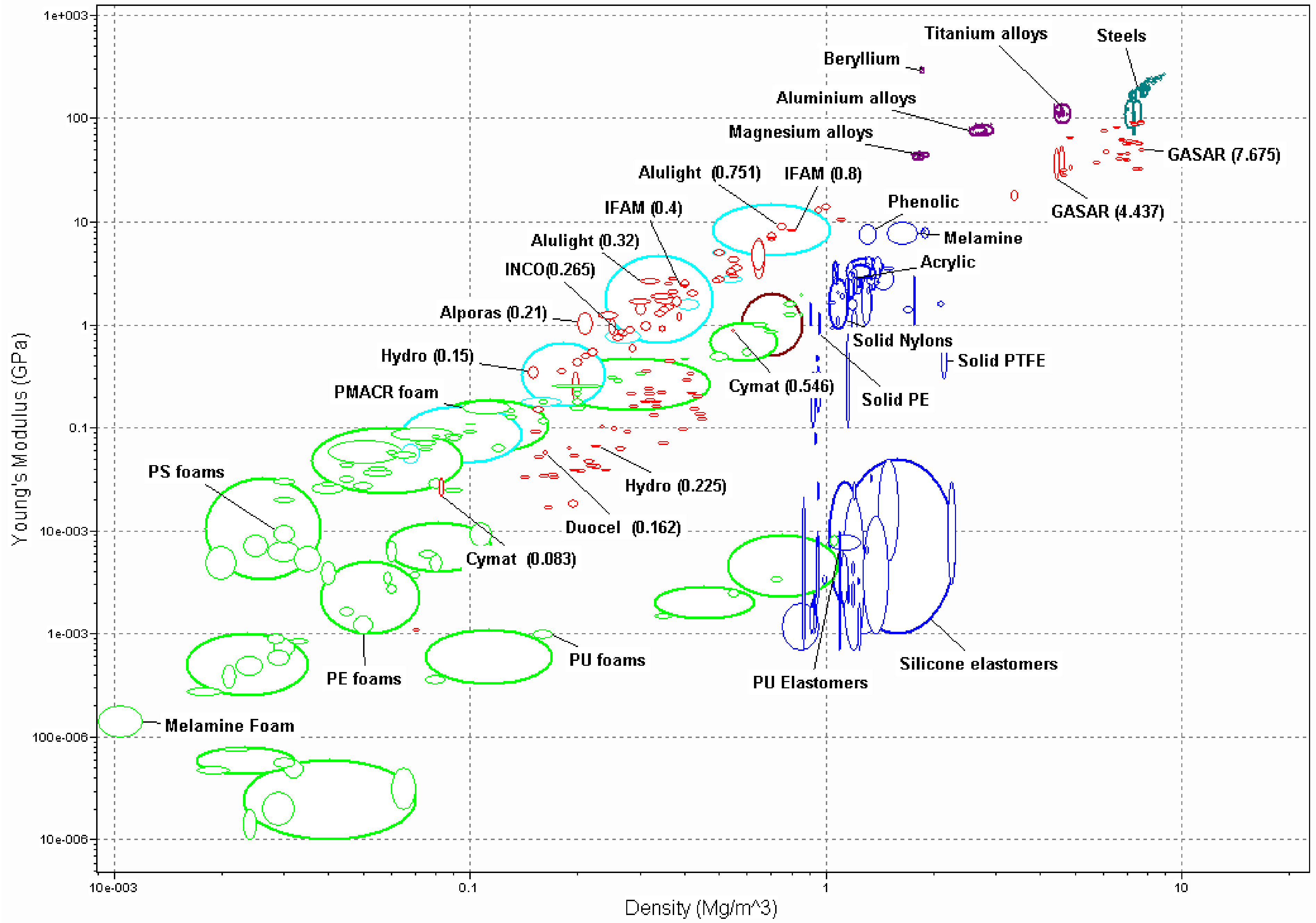
Most of the time, only the normal properties (under tension or compression) are used.

Typical values

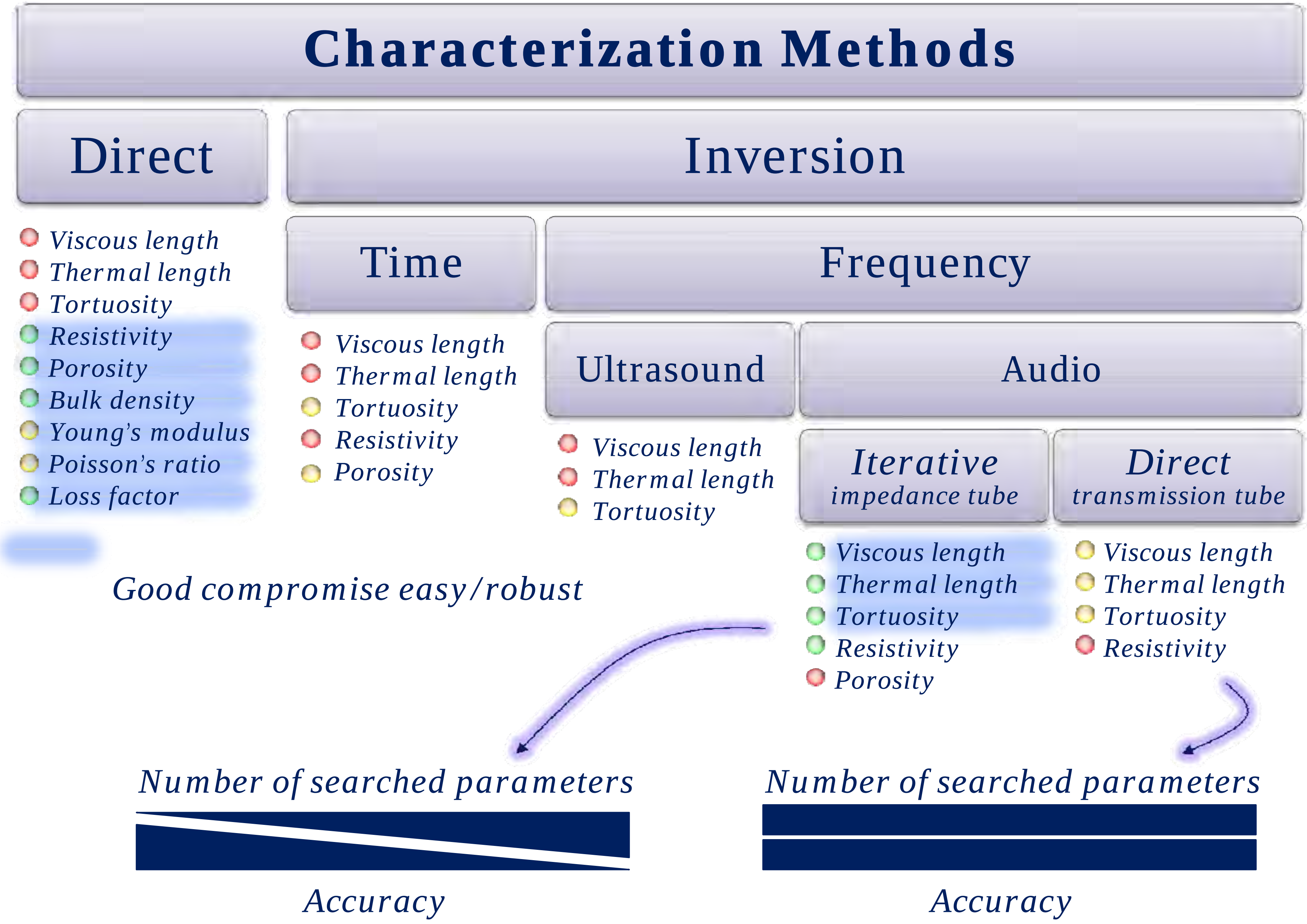
- *Low density fibrous:* $E \leq 10$ kPa; $\nu=0$
- *Mid/High density fibrous:* 10 kPa $\leq E \leq$ 150 kPa
- *Elastic foams :* 50 kPa $\leq E \leq$ 500 kPa
- *Rigid foams :* 500 kPa $\leq E \leq$ 2 Mpa
- *Metal foams :* $E \leq$ 30 MPa



Source: http://www.grantadesign.com/images/metalfoams.gif



Characterization of porous material properties …



Characterization Methods

Direct

- 🔴 *Viscous length*
- 🔴 *Thermal length*
- 🔴 *Tortuosity*
- 🟢 *Resistivity*
- 🟢 *Porosity*
- 🟢 *Bulk density*
- 🟡 *Young's modulus*
- 🟡 *Poisson's ratio*
- 🟢 *Loss factor*

Inversion

Time

- 🔴 *Viscous length*
- 🔴 *Thermal length*
- 🟡 *Tortuosity*
- 🔴 *Resistivity*
- 🟡 *Porosity*

Frequency

Ultrasound

- 🔴 *Viscous length*
- 🔴 *Thermal length*
- 🟡 *Tortuosity*

Audio

Iterative *impedance tube*

- 🟢 *Viscous length*
- 🟢 *Thermal length*
- 🟢 *Tortuosity*
- 🟢 *Resistivity*
- 🔴 *Porosity*

Direct *transmission tube*

- 🟡 *Viscous length*
- 🟡 *Thermal length*
- 🟡 *Tortuosity*
- 🔴 *Resistivity*

🟦 *Good compromise easy/robust*

Number of searched parameters

Accuracy

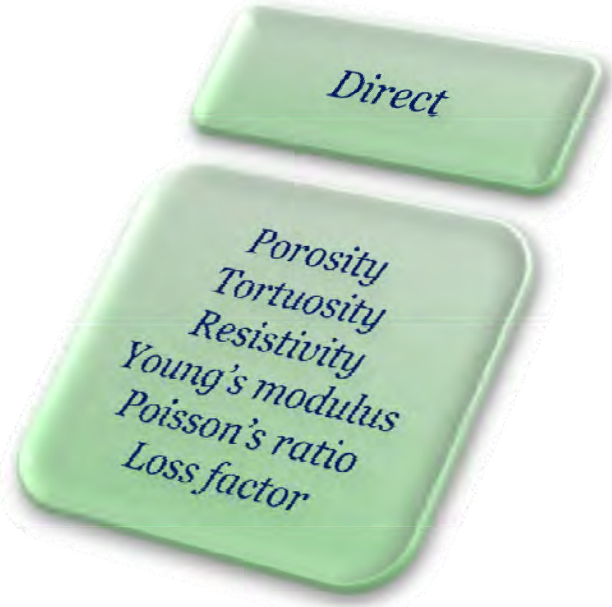
Number of searched parameters

Accuracy

UNIVERSITÉ DE SHERBROOKE GAUS

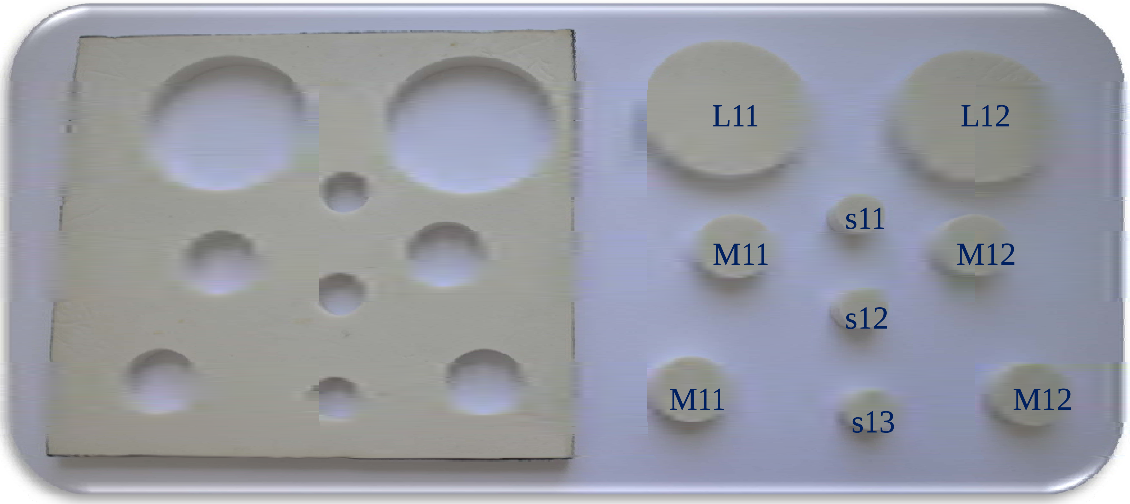
Direct characterization ...

1) Preparation of test specimens
2) Open porosity and bulk density
3) Static airflow resistivity
4) Elastic properties



Preparation of test specimens

1) 2 x (30 x 30 cm²) material samples
2) Cut on each sample, ideally using pressurized water jet:
   - Large sample of 100-mm diameter
   - Medium sample of 29-mm diameter
   - Small sample of 29-mm diameter



Cast foam A

Preparation of test specimens

3) Make a visual inspection, and note defects

Surface defect – impervious film
(usual for cast foams)

Large air cavity

Non homogeneous thickness
(usual for limp fibrous)

Preparation of test specimens

4) Correct deficiencies noted on specimens or discard them

5) Measure the thickness of the test specimens

Preparation of test specimens

6) If material is fluffy (very limp), use special holders to fix the thickness of the material (representative of final application)

Direct characterization ...

1) Preparation of test specimens
2) Open porosity and bulk density
3) Static airflow resistivity
4) Elastic properties

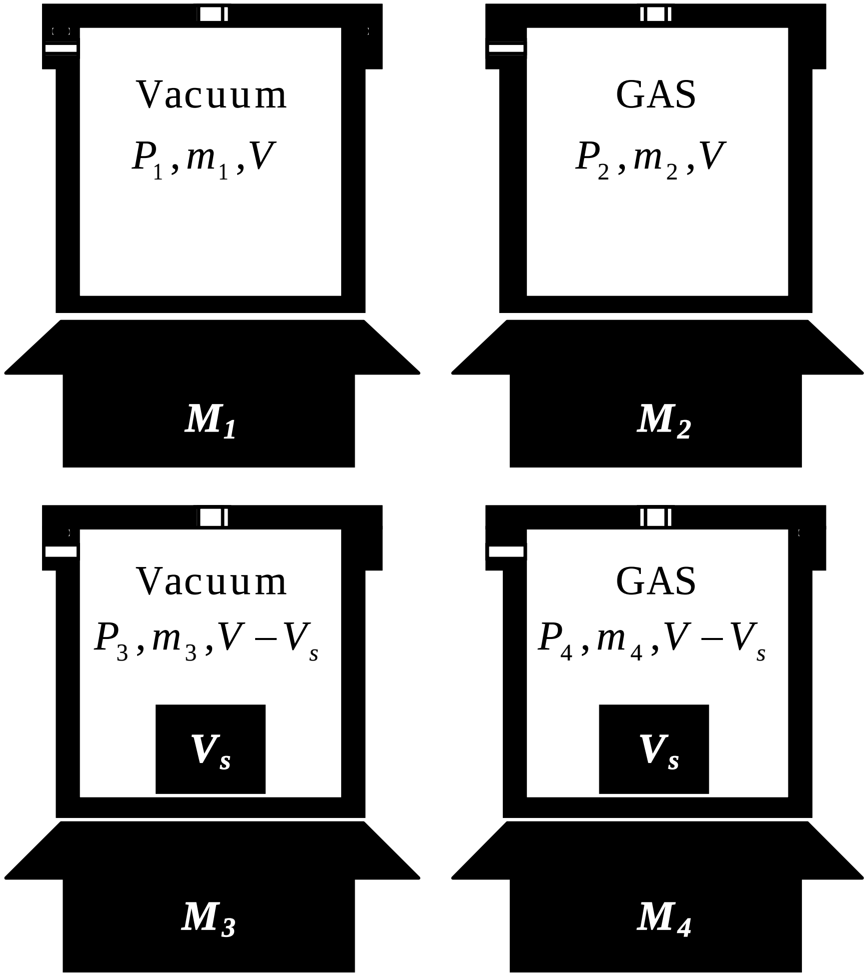
Open porosity and bulk density

❑ Method:

- Pressure/Mass method
- Perfect gas law
- Assume isothermal process
- Heavier gas reduces uncertainty: Air, Argon, Krypton, Xenon
- Uncertainty mainly control by bulk volume of porous aggregate
- Bulk volume larger than 350 cm for absolute error less than 1%

$$\phi = 1 - \frac{RT}{V_t}\left(\frac{m_2 - m_1}{P_2 - P_1} - \frac{m_4 - m_3}{P_4 - P_3}\right)$$

$$\rho_1 = \frac{m_3 - m_1}{V_t}$$



Ref.: http://dx.doi.org/10.1063/1.2749486
Salissou and Panneton: Pressure/mass method to measure open porosity of porous solids, J. Appl. Phys. 101 (2007)

Direct measurement of

Open porosity and bulk density

- ☐ Setup

Porosity Meter by Mecanum

www.mecanum.com

Cast foam A

Specimens L11,L12,L21,L22

Specimen thickness: 19.68 mm

Diameter: 100 mm

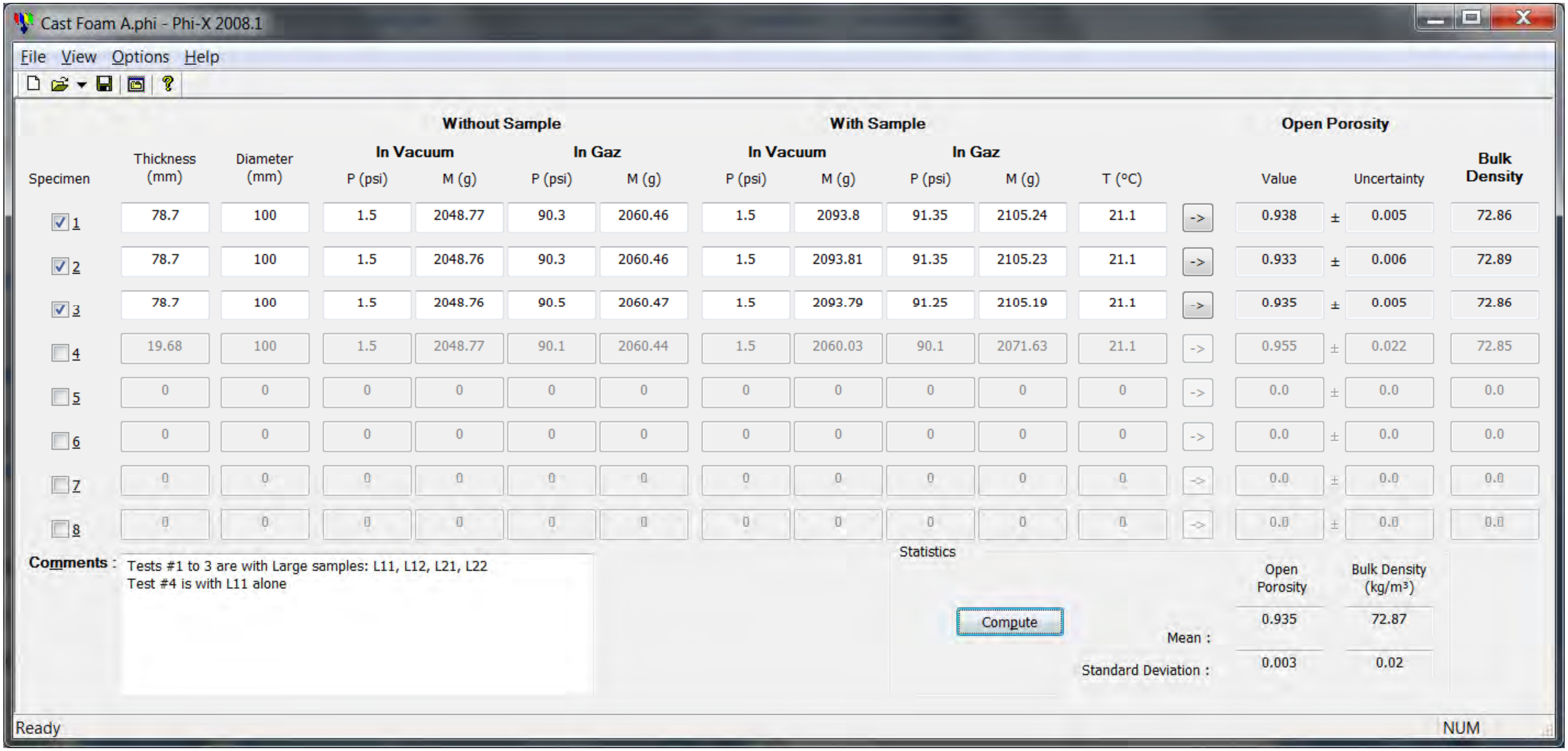
Bulk volume for 1 specimen: 154 cm³

Bulk volume for 4 specimens: 618 cm³

Direct measurement of

Open porosity and bulk density

❑ Results



			Without Sample				With Sample						Open Porosity			
			In Vacuum		In Gaz		In Vacuum		In Gaz							Bulk Density
Specimen	Thickness (mm)	Diameter (mm)	P (psi)	M (g)	P (psi)	M (g)	P (psi)	M (g)	P (psi)	M (g)	T (°C)		Value		Uncertainty	
☑ 1	78.7	100	1.5	2048.77	90.3	2060.46	1.5	2093.8	91.35	2105.24	21.1	->	0.938	±	0.005	72.86
☑ 2	78.7	100	1.5	2048.76	90.3	2060.46	1.5	2093.81	91.35	2105.23	21.1	->	0.933	±	0.006	72.89
☑ 3	78.7	100	1.5	2048.76	90.5	2060.47	1.5	2093.79	91.25	2105.19	21.1	->	0.935	±	0.005	72.86
☐ 4	19.68	100	1.5	2048.77	90.1	2060.44	1.5	2060.03	90.1	2071.63	21.1	->	0.955	±	0.022	72.85
☐ 5	0	0	0	0	0	0	0	0	0	0	0	->	0.0	±	0.0	0.0
☐ 6	0	0	0	0	0	0	0	0	0	0	0	->	0.0	±	0.0	0.0
☐ 7	0	0	0	0	0	0	0	0	0	0	0	->	0.0	±	0.0	0.0
☐ 8	0	0	0	0	0	0	0	0	0	0	0	->	0.0	±	0.0	0.0

Comments : Tests #1 to 3 are with Large samples: L11, L12, L21, L22
Test #4 is with L11 alone

Statistics

	Open Porosity	Bulk Density (kg/m³)
Mean :	0.935	72.87
Standard Deviation :	0.003	0.02

Source: GUI from **Phi-X** software (www.mecanum.com)

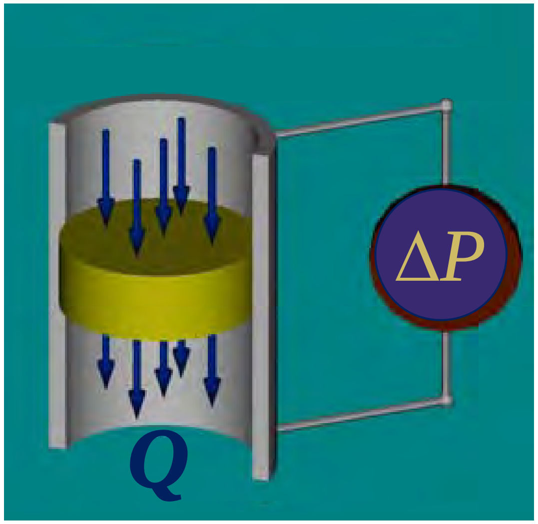
Direct characterization ...

1) Preparation of test specimens
2) Open porosity and bulk density
3) Static airflow resistivity
4) Elastic properties

Direct measurement of

Static airflow resistivity

- ❑ Method:
  - Direct method based on ASTM C522 or ISO 9053
  - Ideally on 100-mm diameter specimen
  - Minimum of 3 specimens
  - If pressure drop too small, stack specimens up to maxium of 5
  - Measurement at 0.5 mm/s (~ sound pressure of 80 dB-ref20µPa) or stepwise down to lower limit of system and extrapolated to 0.5 mm/s.
  - 0.5 mm/s correspond to a flow of 240 CCM for 100-mm diameter



$$\sigma = \frac{\Delta P}{Q}\frac{A}{h} \qquad [\mathrm{Ns/m^4 \ or \ MKS \ Rayls/m}]$$

Direct measurement of

Static airflow resistivity

- ☐ Setup

Resistivity Meter by Mecanum
www.mecanum.com

Cast foam A
Specimens L11,L12,L21,L22
Specimen thickness: 19.68 mm
Diameter: 100 mm

Direct measurement of

Static airflow resistivity

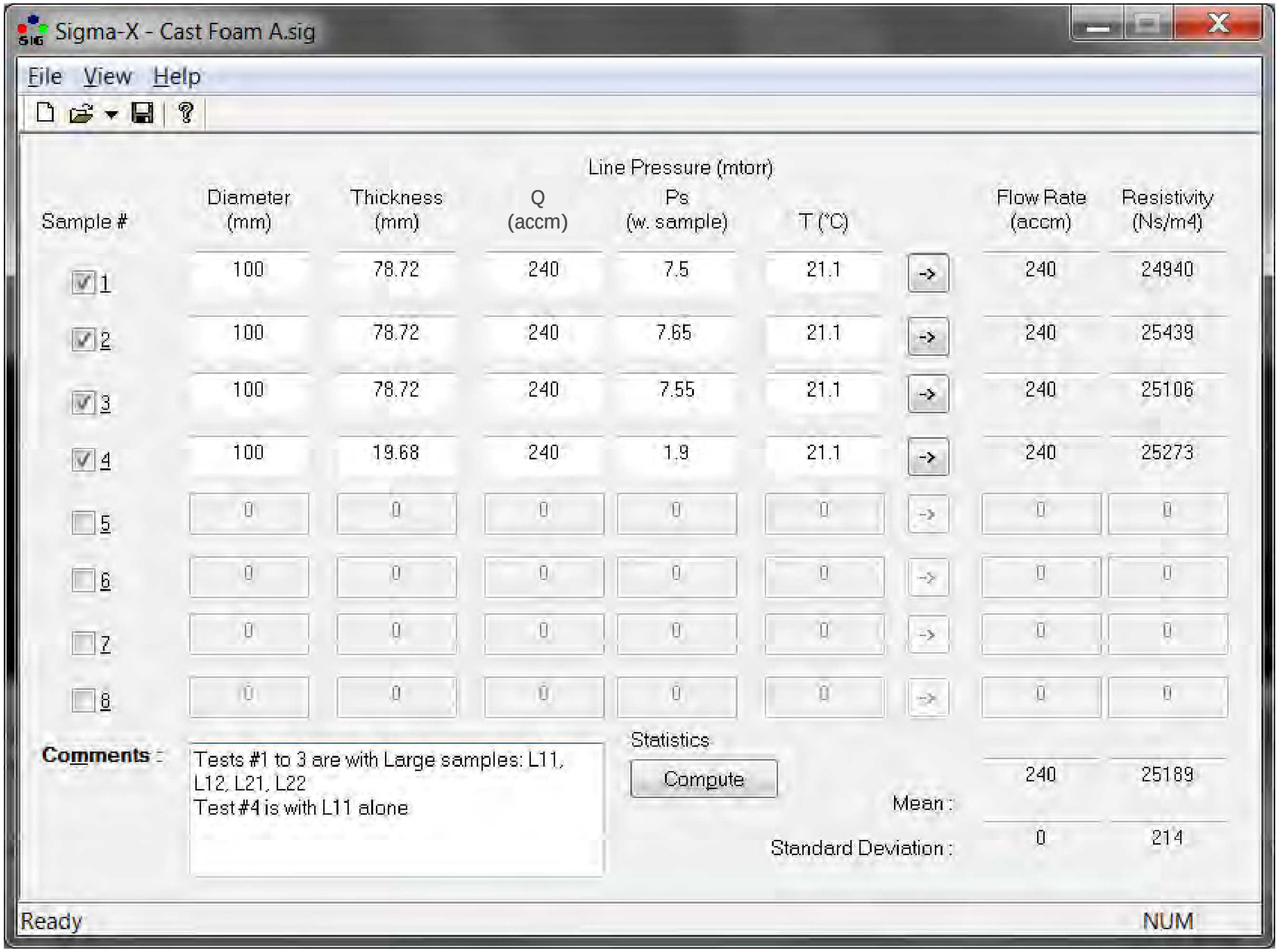
- Special cares to prevent leaks

Wall of mounting rings should be thin; however diameter correction may be applied in the calculations

Direct measurement of

Static airflow resistivity

- ☐ Results



			Line Pressure (mtorr)					
Sample #	Diameter (mm)	Thickness (mm)	Q (accm)	Ps (w. sample)	T (°C)		Flow Rate (accm)	Resistivity (Ns/m4)
☑ 1	100	78.72	240	7.5	21.1	->	240	24940
☑ 2	100	78.72	240	7.65	21.1	->	240	25439
☑ 3	100	78.72	240	7.55	21.1	->	240	25106
☑ 4	100	19.68	240	1.9	21.1	->	240	25273
☐ 5	0	0	0	0	0	->	0	0
☐ 6	0	0	0	0	0	->	0	0
☐ 7	0	0	0	0	0	->	0	0
☐ 8	0	0	0	0	0	->	0	0

Comments :
Tests #1 to 3 are with Large samples: L11, L12, L21, L22
Test #4 is with L11 alone

Statistics

Statistics	Flow Rate (accm)	Resistivity (Ns/m4)
Mean :	240	25189
Standard Deviation :	0	214

Source: GUI from **Sigma-X** software (www.mecanum.com)

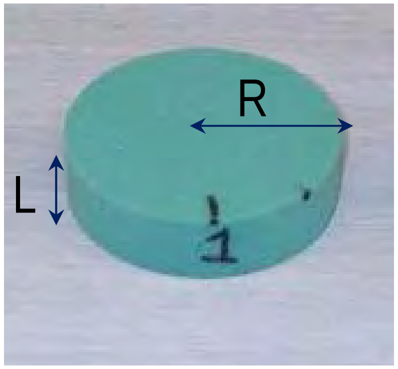
Direct characterization ...

1) Preparation of test specimens
2) Open porosity and bulk density
3) Static airflow resistivity
4) Elastic properties

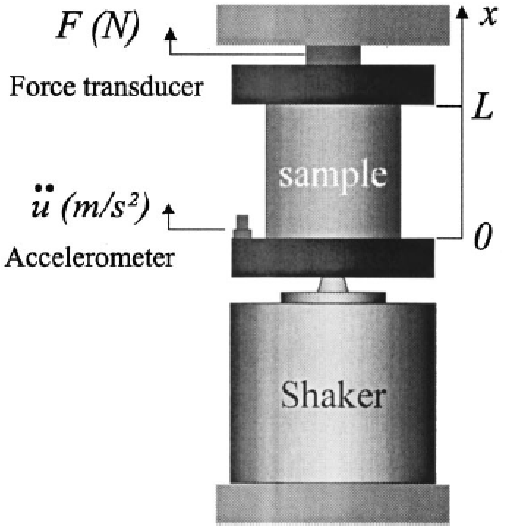
Elastic properties

❑ Method:

- Based on compression tests using disk shaped samples
- Properties:
    - Gives true elastic properties (E,ν,η)
    - Account for boundary conditions
- Excitation frequencies below 1st resonance of the system (5Hz - 60Hz)
- A minimum of two *(2) samples of different shape factors* are required



$$s = \frac{R}{2L}$$



Ref.: http://dx.doi.org/10.1121/1.1419091
Langlois, Panneton, Atalla: Mechanical characterization of poroelastic materials, J. Acoust. Soc. Am. 110 (2001)

Direct measurement of

Elastic properties

❑ Method:

- The compression test yields the mechanical impedance *Z* of the sample
- From Z, loss factor and apparent Young’s modulus are found

$$Z(\omega) = K(\omega) + jX(\omega) = \frac{F(\omega)}{u(\omega)}$$

$$\eta(\omega) = \frac{\mathrm{Im}(Z)}{\mathrm{Re}(Z)}$$ ✓

$$K = \mathrm{Re}\left(\frac{F}{u}\right) = \frac{E'A}{L} \to E' = \frac{KL}{A}$$ ✗

$$\uparrow$$

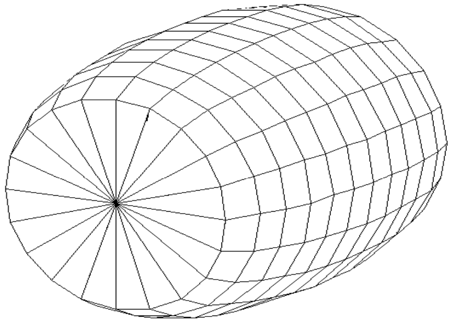
Apparent Young’s modulus

A large correction is needed for large shape factors or large Poisson's ratio.

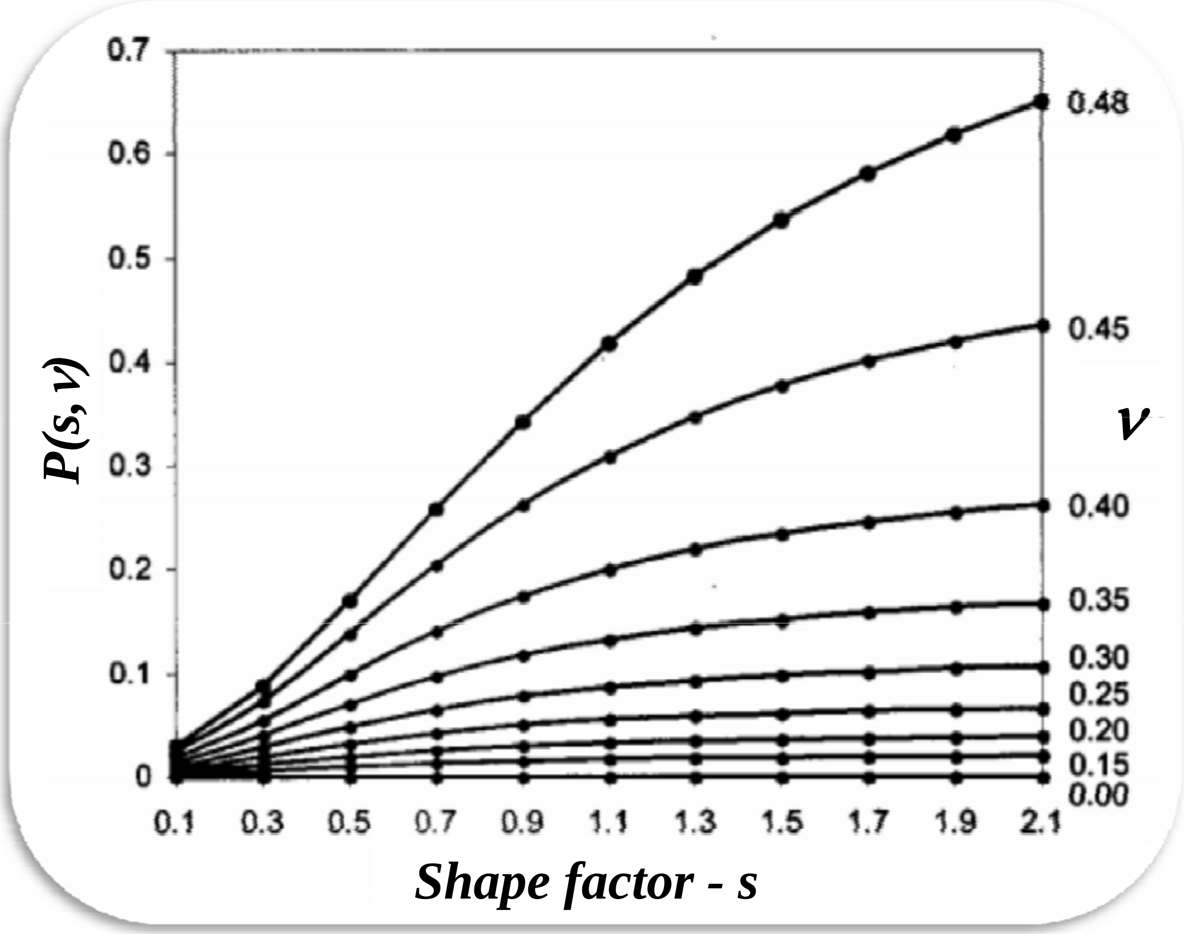
Measured (Apparent)

$$\boxed{E = \frac{E'}{P(s,\nu)}}$$

True



Bulge out effect



The correction factor ***P*** depends on:

-Shape factor "s=R/2L"

-Boundary conditions

-Poisson's ratio "ν"

An Axisymmetrical high-order solid FEM model of the experimental set-up is used to solve and tabulate the correction factors for various (s,ν).

Measuring mechanical impedance on two samples with different shape factors yields…

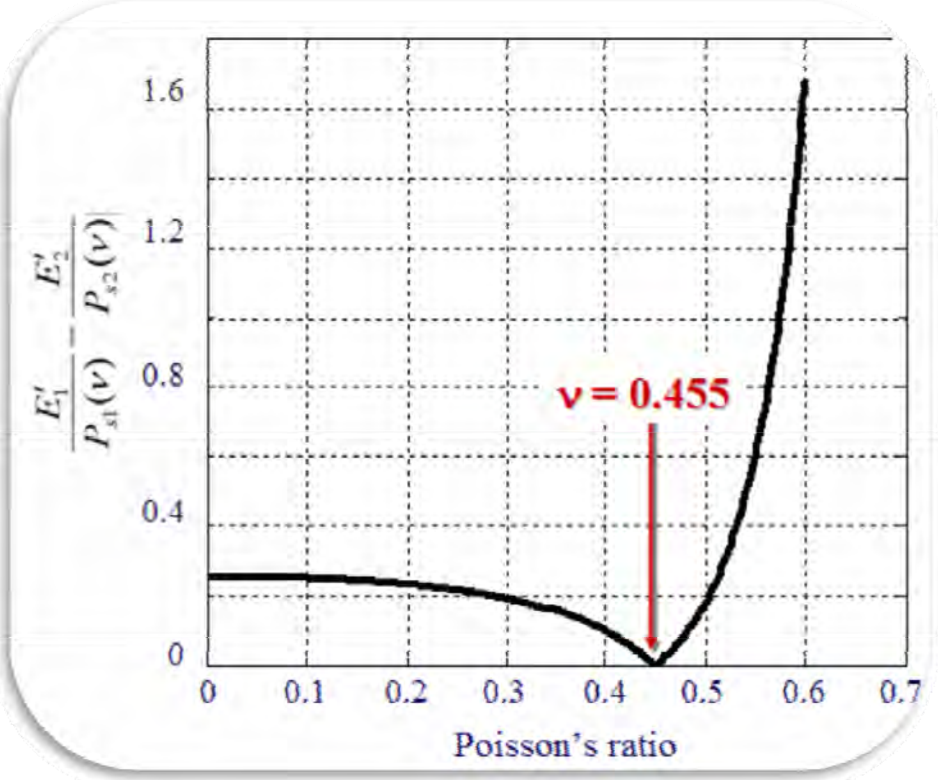
$$\frac{E_1'}{P(s_1,\nu)} - \frac{E_2'}{P(s_2,\nu)} = 0$$

→ **1 equation**
1 unknown (ν) → **ν** ✓

From the Tabulated Correction Values, and polynomial curvefits, the correction factors *P_{s1}* and *P_{s2}* are found.

$$E = \frac{E_1'}{P(s_1,\nu)} \text{ or } \frac{E_2'}{P(s_2,\nu)}$$

✓



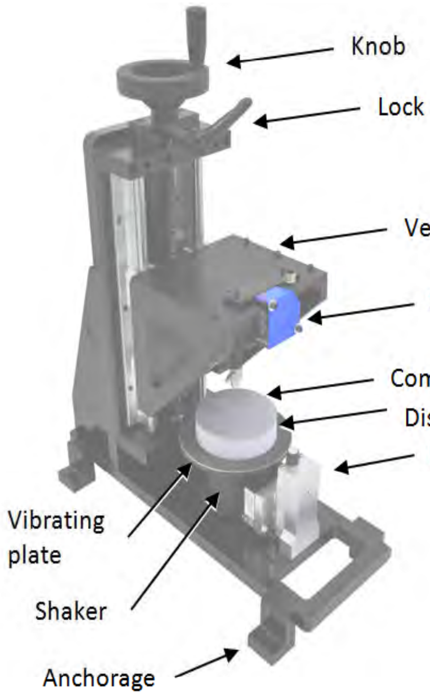
Direct measurement of

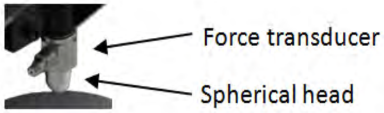
Elastic properties

- ☐ Setup and results

Cast foam A

Specimens M11,M12,M13,L11,L12
Specimen thickness: 19.68 mm
Diameters: 44.44 and 100 mm
Shape factors : 0.56 and 1.27



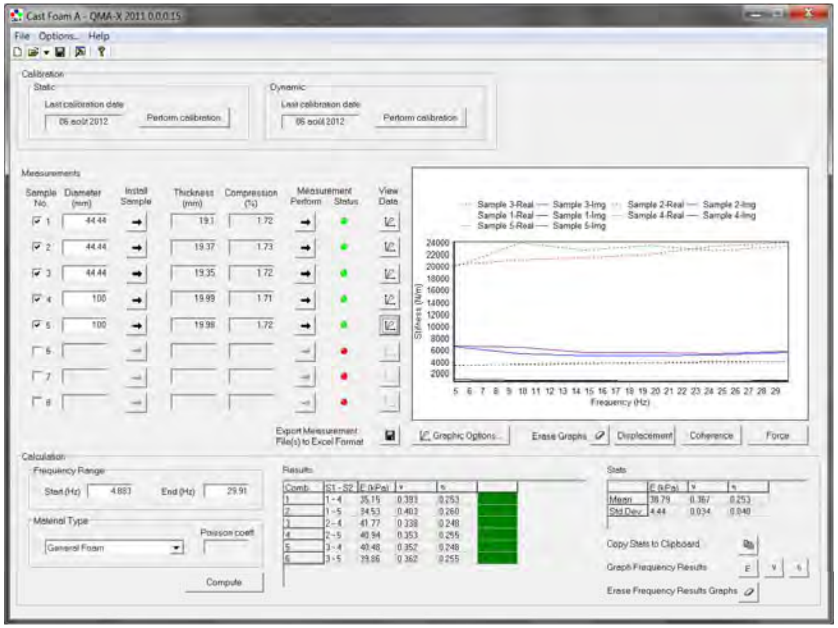


Calibration gauges (10, 25, and 50 mm thick)
(for static calibration)

DAQ

Calibration springs
(for dynamic calibration)

Quasi-static Mechanical Analyzer (QMA)
www.mecanum.com



Last calibration date: 06 août 2012

Last calibration date: 06 août 2012

Sample No.	Diameter (mm)	Thickness (mm)	Compression (%)	Measurement Status
☑ 1	44.44	19.1	1.72	●
☑ 2	44.44	19.37	1.73	●
☑ 3	44.44	19.35	1.72	●
☑ 4	100	19.99	1.71	●
☑ 5	100	19.98	1.72	●
☐ 6				●
☐ 7				●
☐ 8				●

Calculation

Frequency Range: Start (Hz) 4.883 End (Hz) 29.91

Material Type: General Foam

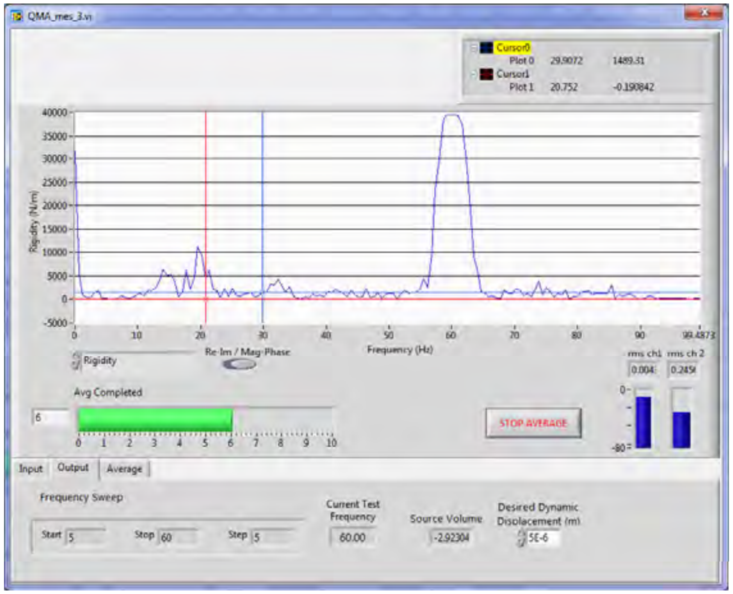
Poisson coeff:

Results

Comb.	S1 - S2	E (kPa)	ν	η	
1	1 - 4	35.15	0.393	0.253	🟩
2	1 - 5	34.53	0.403	0.260	🟩
3	2 - 4	41.77	0.338	0.248	🟩
4	2 - 5	40.94	0.353	0.255	🟩
5	3 - 4	40.48	0.352	0.248	🟩
6	3 - 5	39.86	0.362	0.255	🟩

Stats

	E (kPa)	ν	η
Mean	38.79	0.367	0.253
Std Dev	4.44	0.034	0.040



Cursor0	Plot 0	29.9072	1489.31
Cursor1	Plot 1	20.752	-0.190842

rms ch1: 0.004 rms ch 2: 0.2454

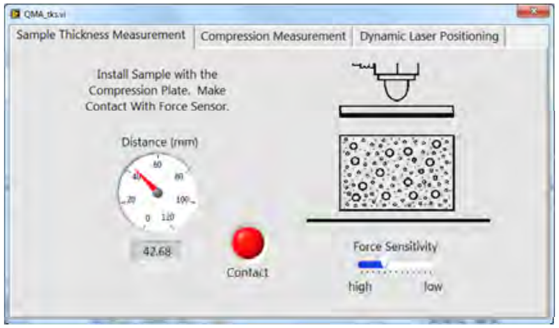
Avg Completed: 6

Start 5 Stop 60 Step 5

Current Test Frequency: 60.00

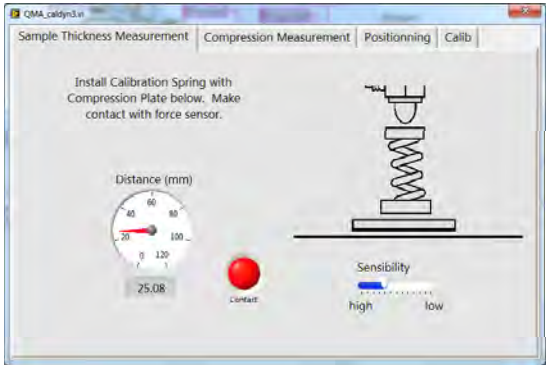
Source Volume: -2.92304

Desired Dynamic Displacement (m): 5E-6



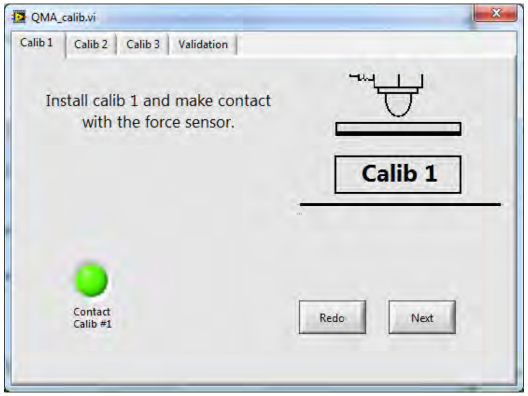
Install Sample with the Compression Plate. Make Contact With Force Sensor.

Distance (mm): 42.68

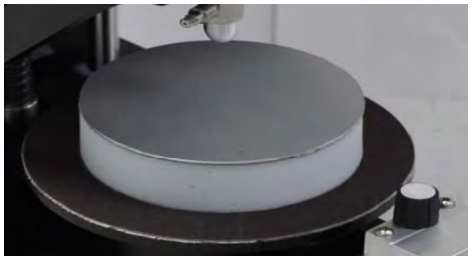


Install Calibration Spring with Compression Plate below. Make contact with force sensor.

Distance (mm): 25.08

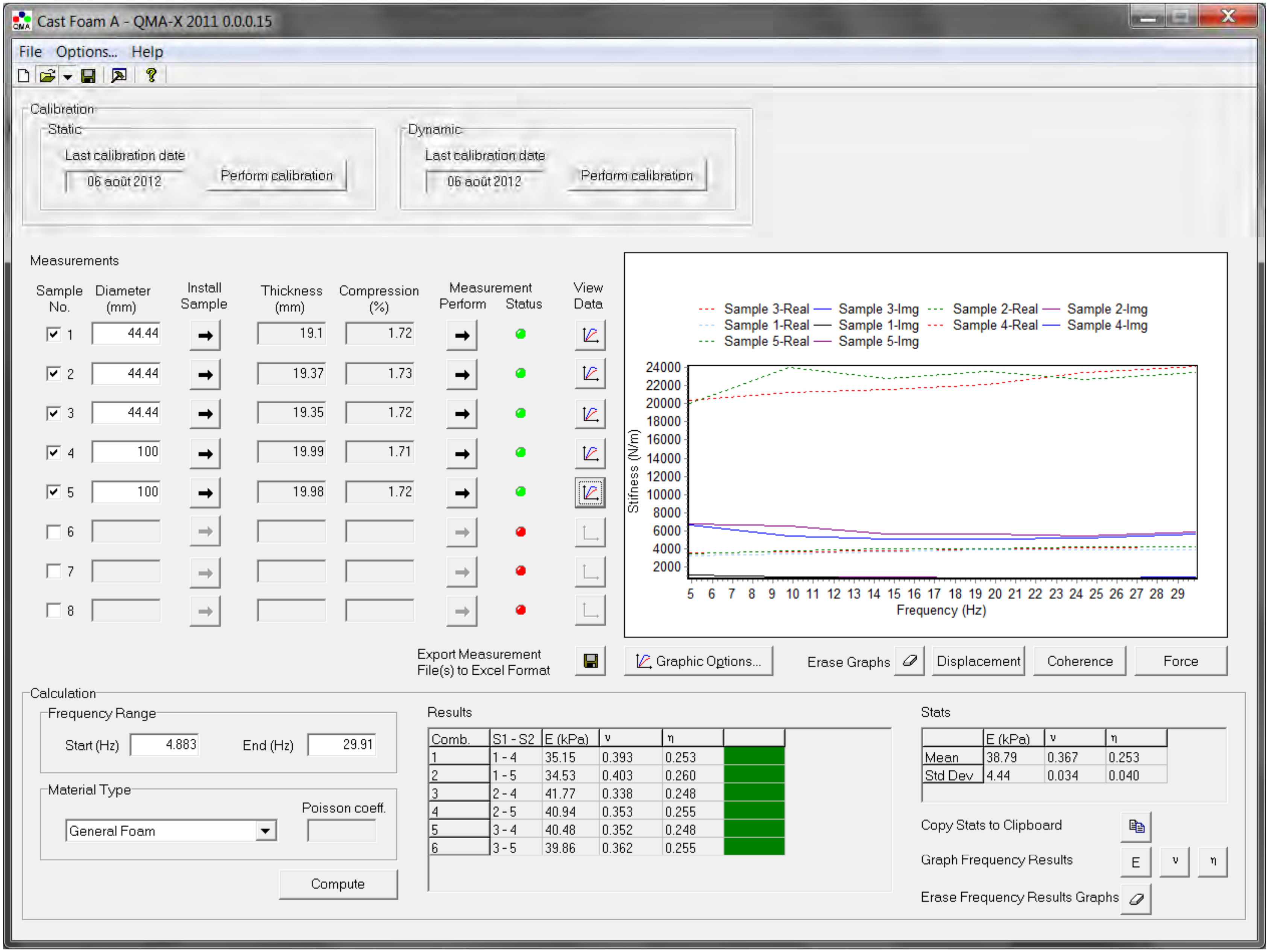


Install calib 1 and make contact with the force sensor.



Source: GUI from **QMA-X** software (www.mecanum.com)

Results of elastic characterization



Calibration

Static — Last calibration date: 06 août 2012

Dynamic — Last calibration date: 06 août 2012

Measurements

Sample No.	Diameter (mm)	Thickness (mm)	Compression (%)	Measurement Status
☑ 1	44.44	19.1	1.72	🟢
☑ 2	44.44	19.37	1.73	🟢
☑ 3	44.44	19.35	1.72	🟢
☑ 4	100	19.99	1.71	🟢
☑ 5	100	19.98	1.72	🟢
☐ 6				🔴
☐ 7				🔴
☐ 8				🔴

Calculation

Frequency Range: Start (Hz) 4.883 End (Hz) 29.91

Material Type: General Foam

Poisson coeff.

Results

Comb.	S1 - S2	E (kPa)	ν	η	
1	1 - 4	35.15	0.393	0.253	🟩
2	1 - 5	34.53	0.403	0.260	🟩
3	2 - 4	41.77	0.338	0.248	🟩
4	2 - 5	40.94	0.353	0.255	🟩
5	3 - 4	40.48	0.352	0.248	🟩
6	3 - 5	39.86	0.362	0.255	🟩

Stats

	E (kPa)	ν	η
Mean	38.79	0.367	0.253
Std Dev	4.44	0.034	0.040

Source: GUI from **QMA-X** software (www.mecanum.com)

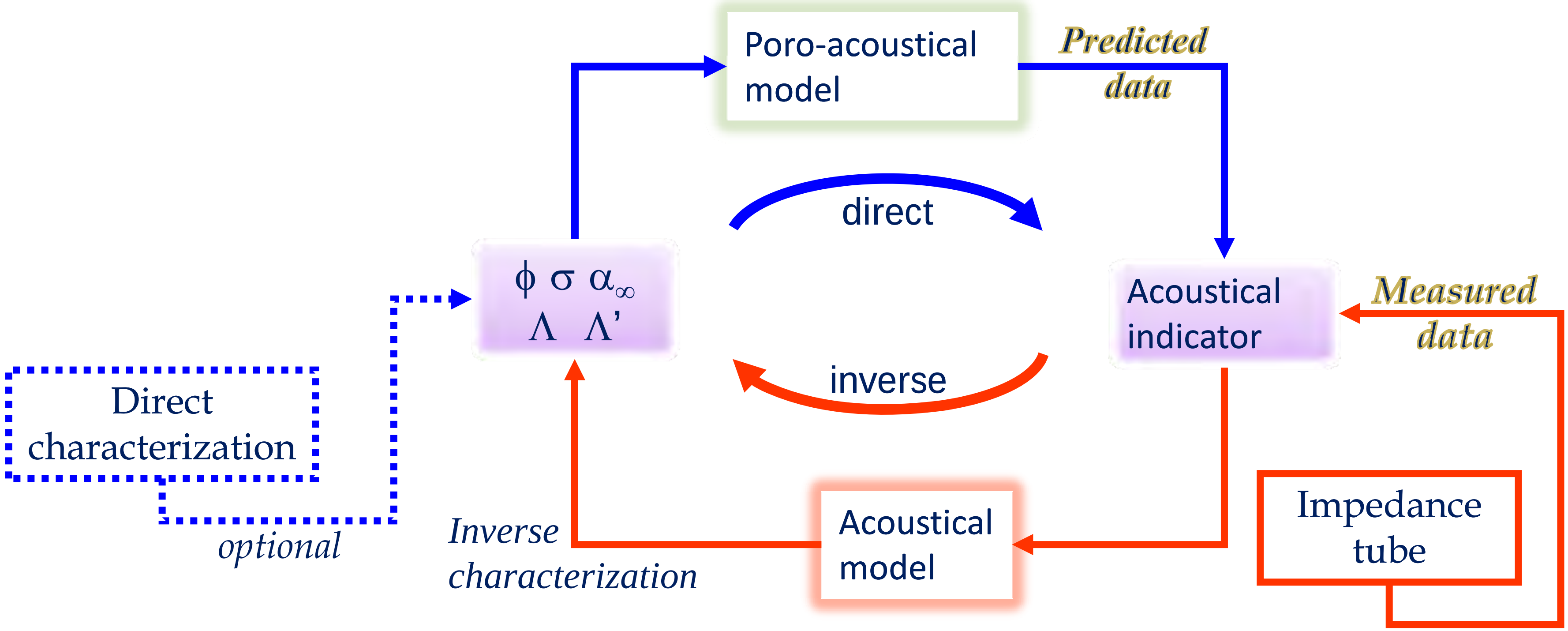
Iterative inversion method

1) Introduction
2) Preparation of test specimens
3) Transmission tube measurements
4) Inversion identification of material properties

Introduction

- ☐ Optimization process

  Iteratively adjust model parameters so that the model predicts impedance tube measurements



Poro-acoustical model

Predicted data

direct

ϕ σ α_∞
Λ Λ'

Acoustical indicator

Measured data

inverse

Direct characterization

optional

Inverse characterization

Acoustical model

Impedance tube

Ref.: http://www.mecanum.com/files/InversePaper.pdf

Y. Atalla, R. Panneton: Inverse Acoustical Chararacterization..., Canadian Acoustics 33 (2001)

Introduction

❑ Optimization process

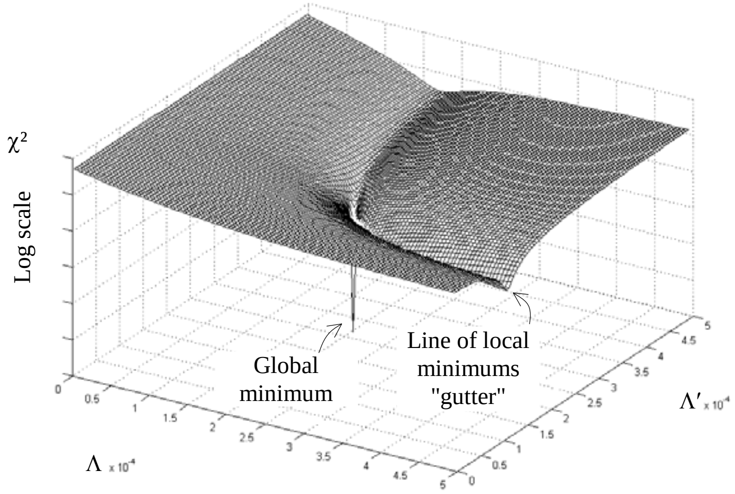
Minimization of a cost function

$$\chi^2(a) = \sum_{i=1}^{N}\left[\frac{\left(\Phi_i - \Phi\left(\omega_i ; a\right)\right)^2}{\sigma_i^2}\right]$$

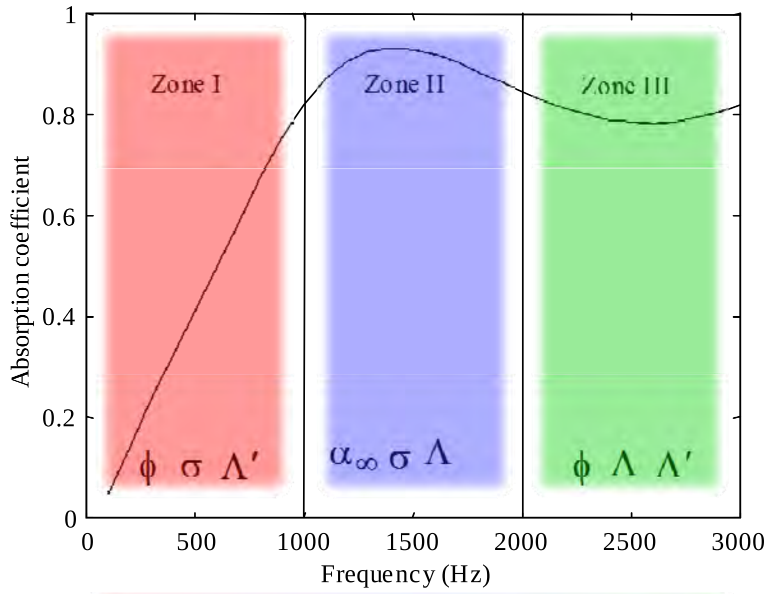
Φ_i : *Measured data*

$\Phi(\omega_i,\mathbf{a})$: *Predicted data*

$\mathbf{a} = \{\alpha_\infty\ \Lambda\ \ \Lambda'\}$



Visualization of the global minimum for a 2-parameter inversion : $\mathbf{a} = \{\Lambda\ \ \Lambda'\}$



Give iterative inverse characterization a chance

Iterative inversion method

1) Introduction
2) Preparation of test specimens
3) Transmission tube measurements
4) Inversion identification of material properties

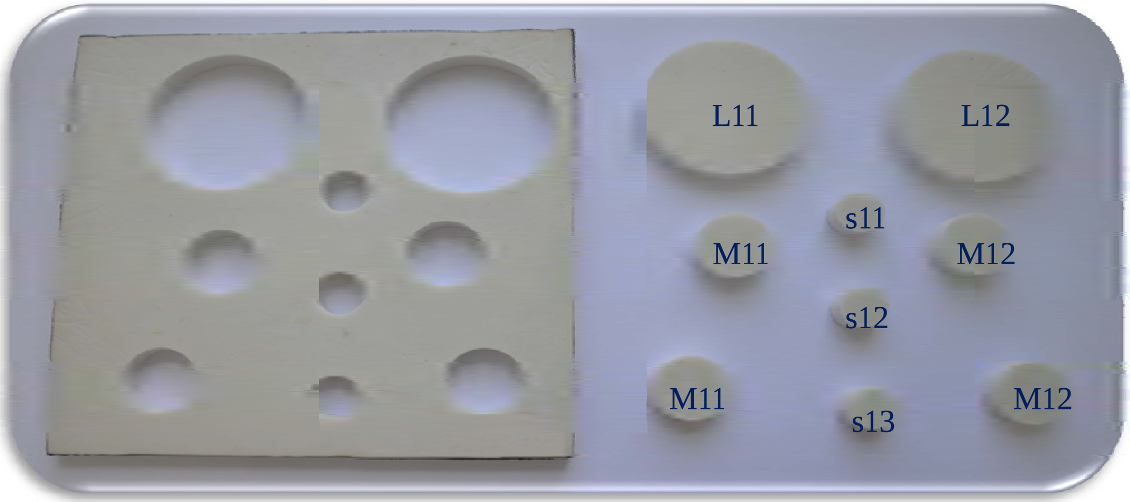
Preparation of test specimens

1) Similar to those prepared for direct characterization

2) Preferred diameter : MEDIUM

   Good compromise between frequency range and sensitivity to boundary conditions in tube

   - *Large sample of 100-mm diameter: (50 – 1800 Hz)*
   - *Medium sample of 29-mm diameter: (100 – 4100 Hz)*
   - *Small sample of 29-mm diameter: (500 – 6000 Hz)*



Cast foam A

Preparation of test specimens

3) For high resistivity materials, use ring and grease to prevent leaks
4) If material is fluffy (very limp), use special holders to fix the thickness of the material (representative of final application and as done for resistivity and porosity measurements)

Iterative inversion method

1) Introduction
2) Preparation of test specimens
3) Transmission tube measurements
4) Inversion identification of material properties

Transmission tube measurements

☐ Properties:

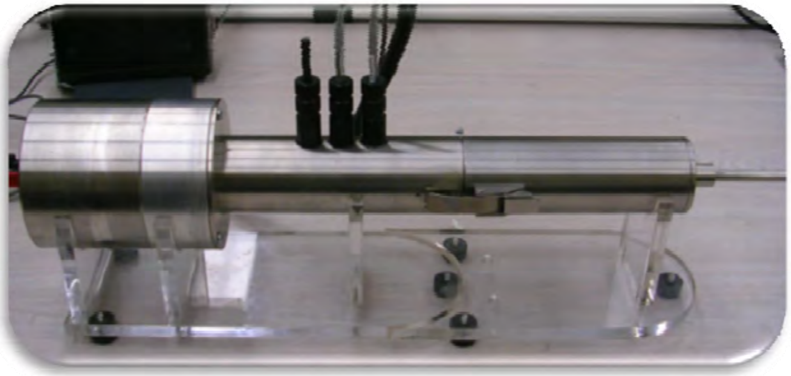
- Absorption coefficient
- Transmission loss
- Transfer matrix
- Reflection coefficient
- Surface impedance
- Characteristic impedance
- Wave number

☐ Standards:

- Method with 2 mics
  ASTM E1050
  → Surface properties
- Method with 3 mics and 1 cavity
  ASTM E2611
  → Surface & transmission properties

☐ Acquisition software

- Should correct for temperature, barometric pressure, and tube attenuation

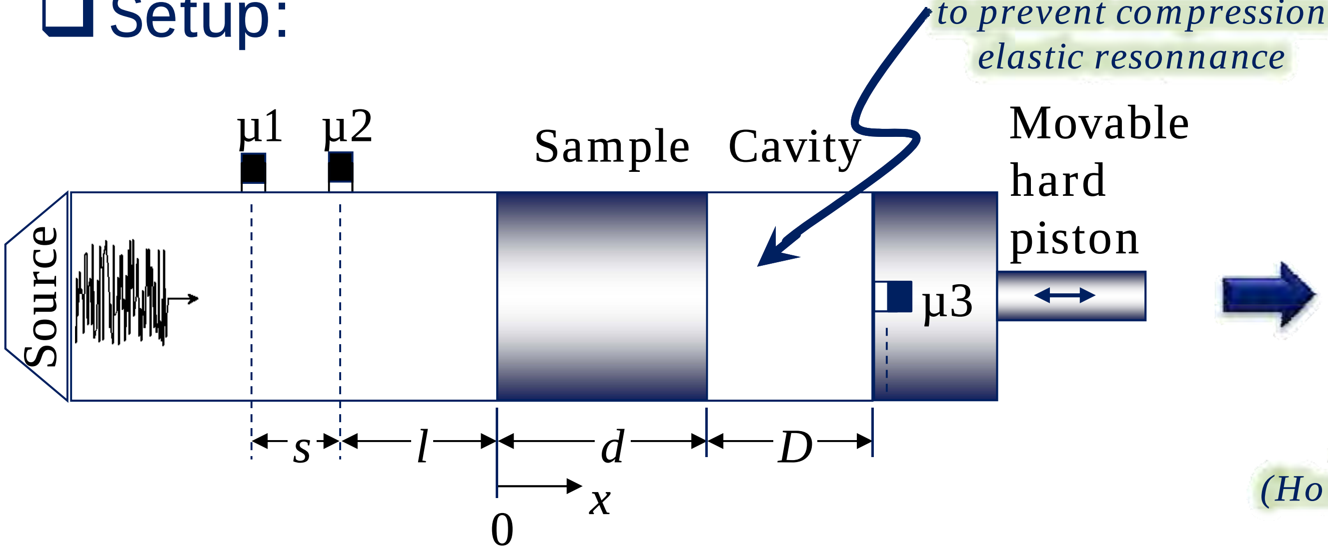


3-mic transmission tube
www.mecanum.com

Ref.: http://dx.doi.org/10.1121/1.3681016
Salissou, Panneton, Doutres: (...) Transmission loss with three microphones, JASA 131 (2012)

Transmission tube measurements

- ❑ Setup:



Add air cavity to prevent compression elastic resonnance

ASTM E2611

$$\mathbf{T} = \begin{pmatrix} A & B \\ C & A \end{pmatrix}$$

Material is symmetric (Homogeneous along thickness)

$$TL = 20\log\left|A + \frac{B}{\rho c} + \rho c C + D\right| - 6\text{ dB}$$

$$R = \frac{A - \rho c C}{A + \rho c C}$$

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

for iterative inversion

$$\tilde{k} = \frac{1}{d}\cos^{-1} A$$

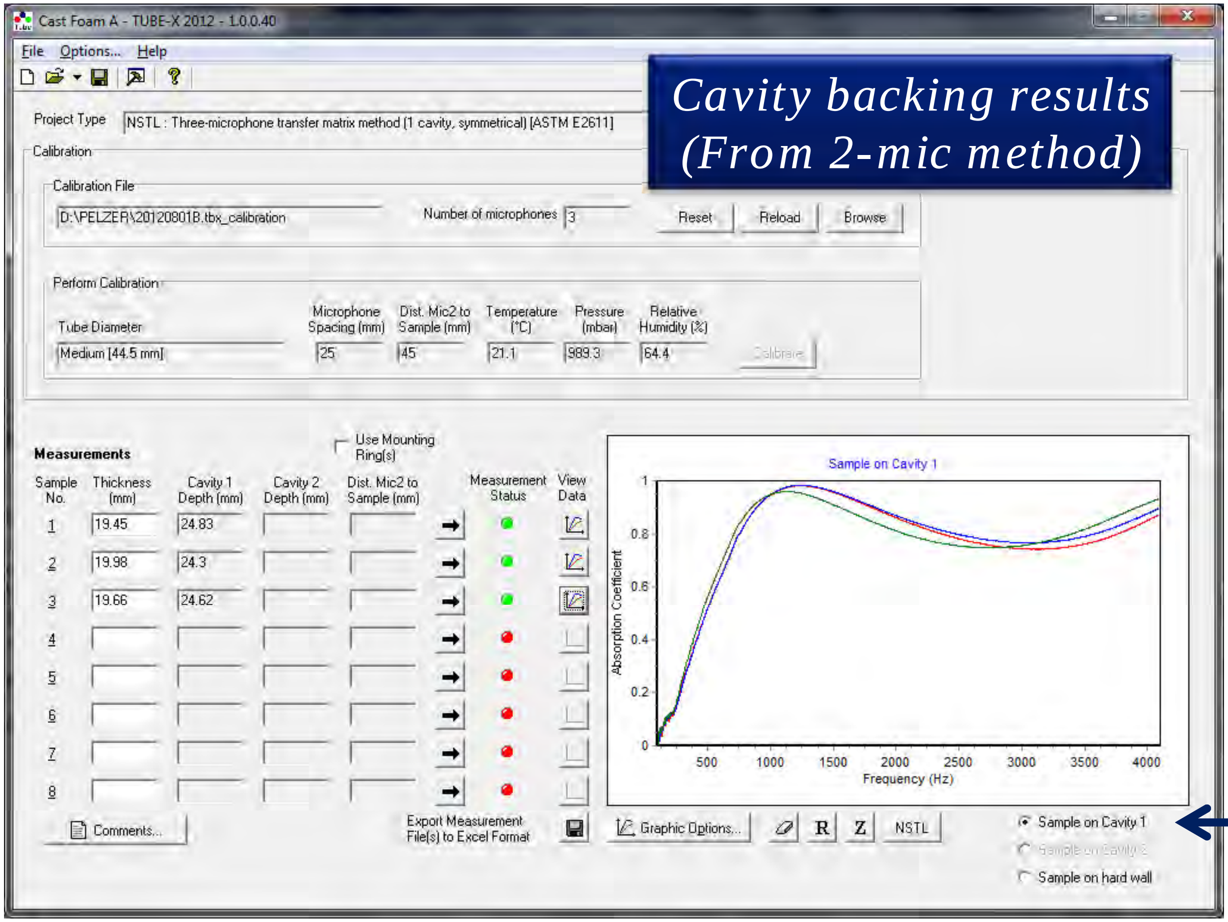
$$\tilde{z}_c = \sqrt{B/C}$$

$$\tilde{\rho}_{EQ} = \tilde{z}_c \tilde{k} / \omega$$

$$\tilde{K}_{EQ} = \omega \tilde{z}_c / \tilde{k}$$

Transmission tube measurements

- Results:



Cast Foam A - TUBE-X 2012 - 1.0.0.40

Project Type: NSTL : Three-microphone transfer matrix method (1 cavity, symmetrical) [ASTM E2611]

Calibration

Calibration File: D:\PELZER\20120801B.tbx_calibration

Number of microphones: 3

Perform Calibration

Tube Diameter	Microphone Spacing (mm)	Dist. Mic2 to Sample (mm)	Temperature (°C)	Pressure (mbar)	Relative Humidity (%)
Medium [44.5 mm]	25	45	21.1	989.3	64.4

Measurements

☐ Use Mounting Ring(s)

Sample No.	Thickness (mm)	Cavity 1 Depth (mm)	Cavity 2 Depth (mm)	Dist. Mic2 to Sample (mm)	Measurement Status
1	19.45	24.83			🟢
2	19.98	24.3			🟢
3	19.66	24.62			🟢
4					🔴
5					🔴
6					🔴
7					🔴
8					🔴

● Sample on Cavity 1
○ Sample on Cavity 2
○ Sample on hard wall

Cavity backing results (From 2-mic method)

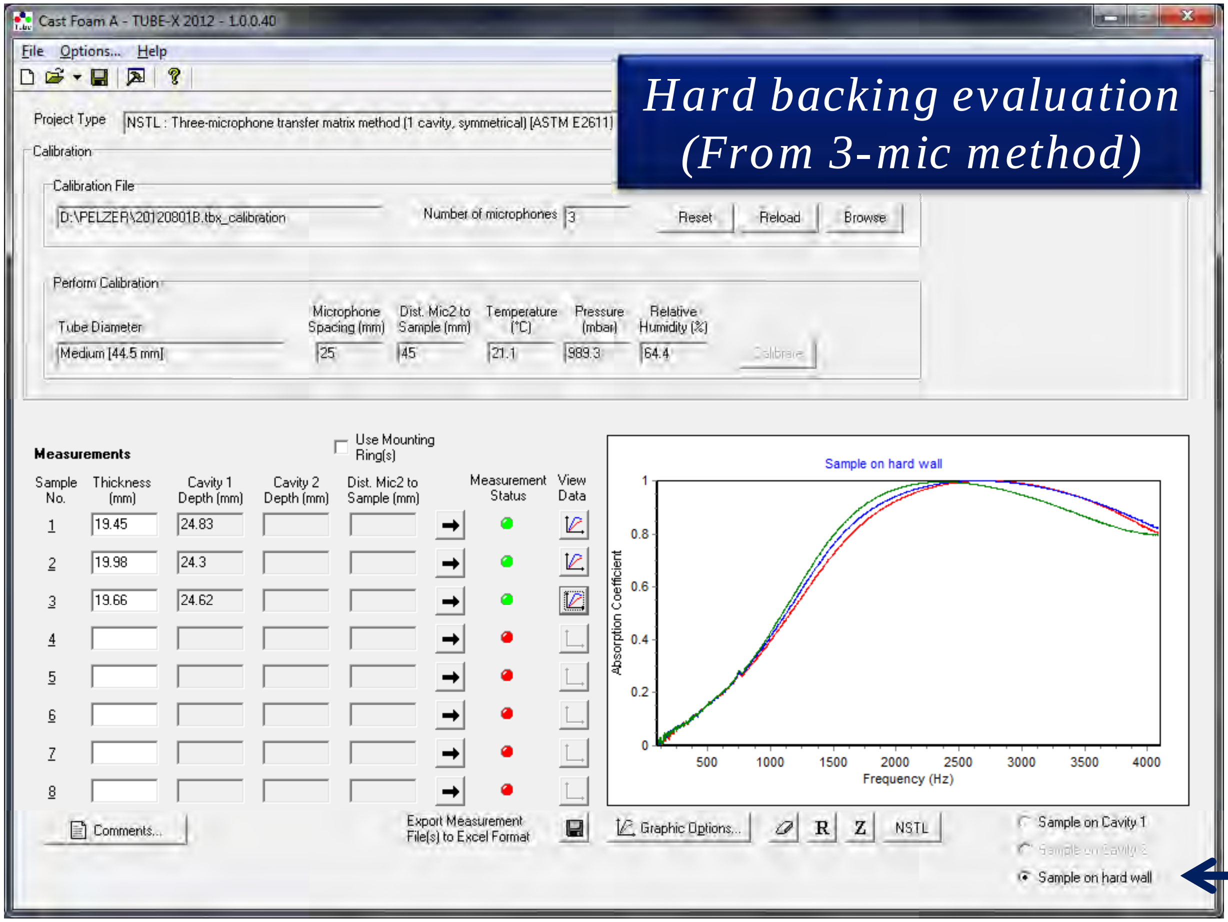
Cast foam A

Specimens M11,M12,M13
Thickness: 19.68 mm
Diameters: 44.44 mm

Source: GUI from **TUBE-X** software (www.mecanum.com)

Transmission tube measurements

- ☐ Results:



Project Type: NSTL : Three-microphone transfer matrix method (1 cavity, symmetrical) [ASTM E2611]

Calibration

Calibration File: D:\PELZER\20120801B.tbx_calibration

Number of microphones: 3

Perform Calibration

Tube Diameter	Microphone Spacing (mm)	Dist. Mic2 to Sample (mm)	Temperature (°C)	Pressure (mbar)	Relative Humidity (%)
Medium [44.5 mm]	25	45	21.1	989.3	64.4

Measurements

☐ Use Mounting Ring(s)

Sample No.	Thickness (mm)	Cavity 1 Depth (mm)	Cavity 2 Depth (mm)	Dist. Mic2 to Sample (mm)	Measurement Status
1	19.45	24.83			🟢
2	19.98	24.3			🟢
3	19.66	24.62			🟢
4					🔴
5					🔴
6					🔴
7					🔴
8					🔴

○ Sample on Cavity 1
○ Sample on Cavity 2
● Sample on hard wall ←

Hard backing evaluation
(From 3-mic method)

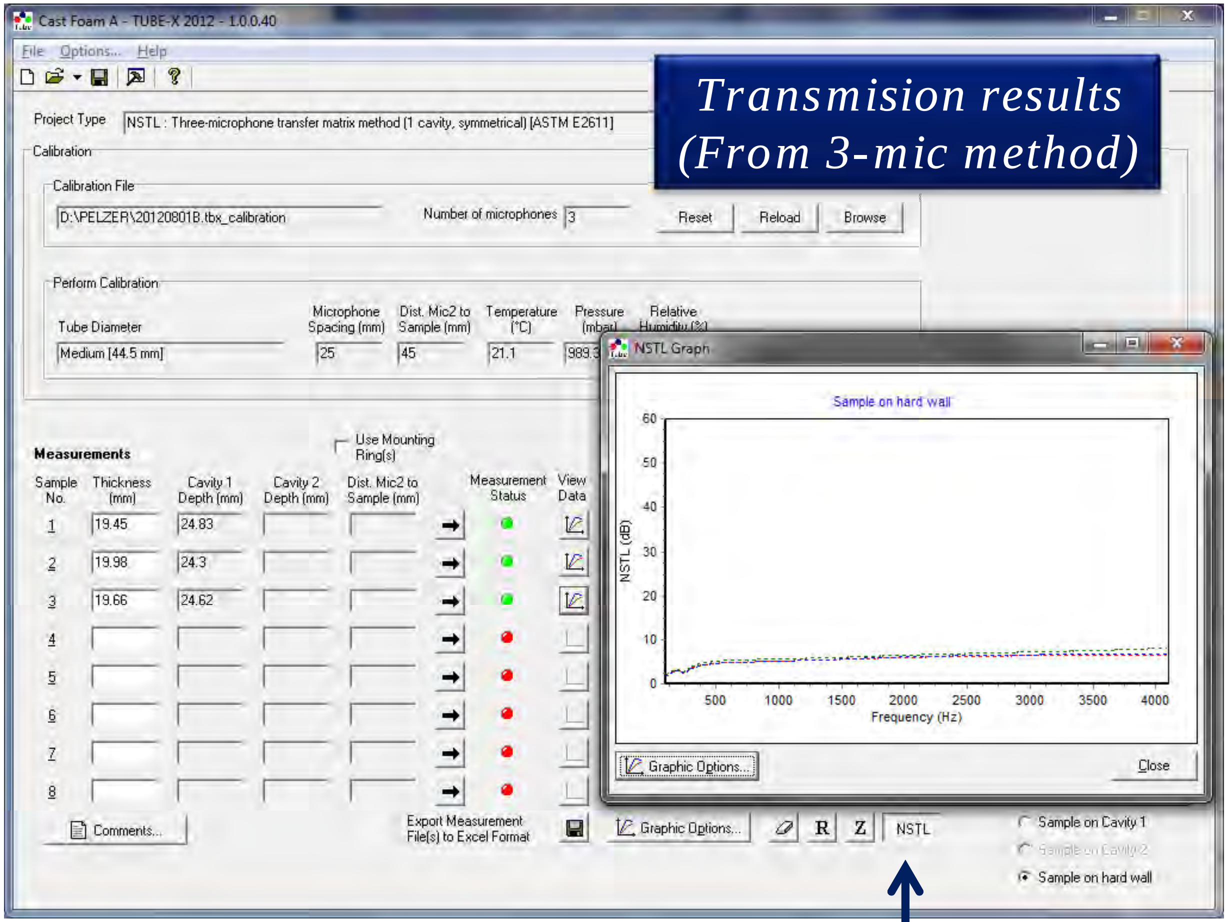
Cast foam A

Specimens M11,M12,M13
Thickness: 19.68 mm
Diameters: 44.44 mm

Source: GUI from **TUBE-X** software (www.mecanum.com)

Transmission tube measurements

- ☐ Results:



Project Type: NSTL : Three-microphone transfer matrix method (1 cavity, symmetrical) [ASTM E2611]

Calibration

Calibration File: D:\PELZER\20120801B.tbx_calibration

Number of microphones: 3

Perform Calibration

Tube Diameter	Microphone Spacing (mm)	Dist. Mic2 to Sample (mm)	Temperature (°C)	Pressure (mbar)	Relative Humidity (%)
Medium [44.5 mm]	25	45	21.1	989.3	

Measurements

☐ Use Mounting Ring(s)

Sample No.	Thickness (mm)	Cavity 1 Depth (mm)	Cavity 2 Depth (mm)	Dist. Mic2 to Sample (mm)		Measurement Status	View Data
1	19.45	24.83			➡	🟢	
2	19.98	24.3			➡	🟢	
3	19.66	24.62			➡	🟢	
4					➡	🔴	
5					➡	🔴	
6					➡	🔴	
7					➡	🔴	
8					➡	🔴	

○ Sample on Cavity 1
○ Sample on Cavity 2
● Sample on hard wall

Transmision results (From 3-mic method)

Source: GUI from **TUBE-X** software (www.mecanum.com)

Cast foam A

Specimens M11,M12,M13
Thickness: 19.68 mm
Diameters: 44.44 mm

Iterative inversion method

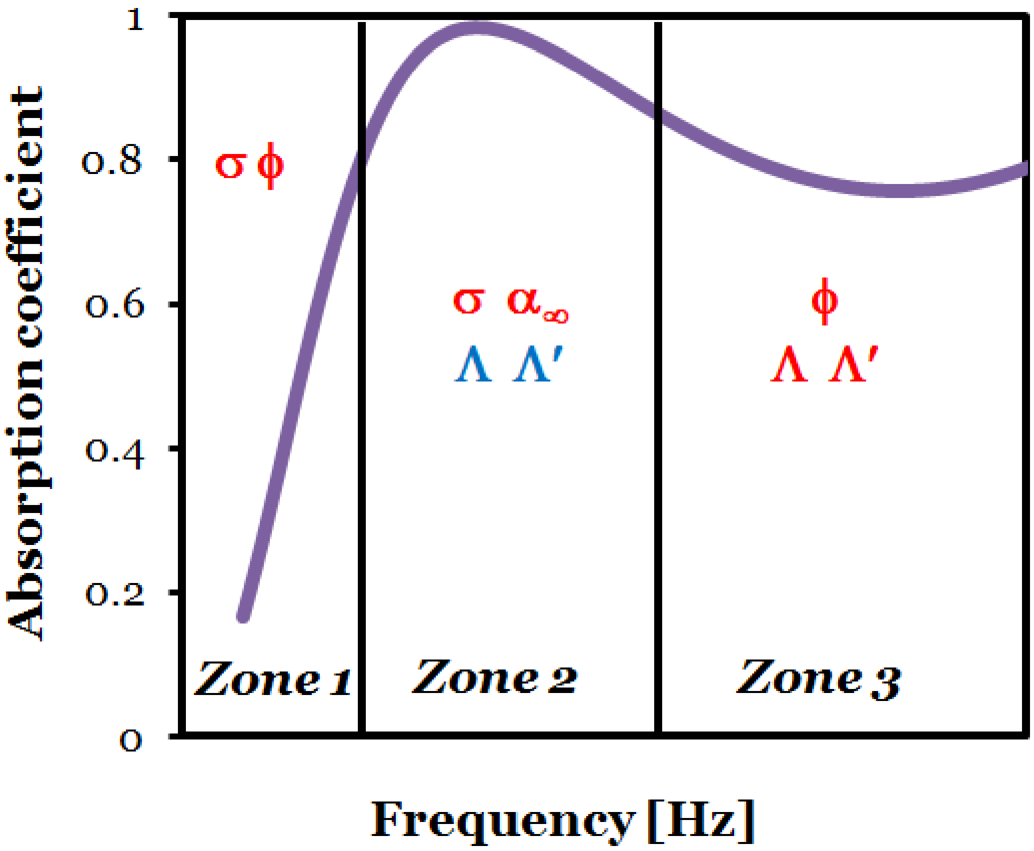
1) Introduction
2) Preparation of test specimens
3) Transmission tube measurements
4) Inversion identification of material properties

Assumption to verify

For inverse (iterative or direct) characterizations, impedance tube measurements must verify following tests :

1. Sample is saturated by air at rest.
2. Linear acoustics
3. The resistivity and open porosity of the sample are known.
4. Acoustical response mostly follows that of an equivalent fluid.
5. All the physics is captured by the absorption curves.
6. Sample is homogeneous (~symmetric).
7. Boundary conditions do not influence tube measurements.

Test 5 *Is all the physics captured in the absorption curves?*



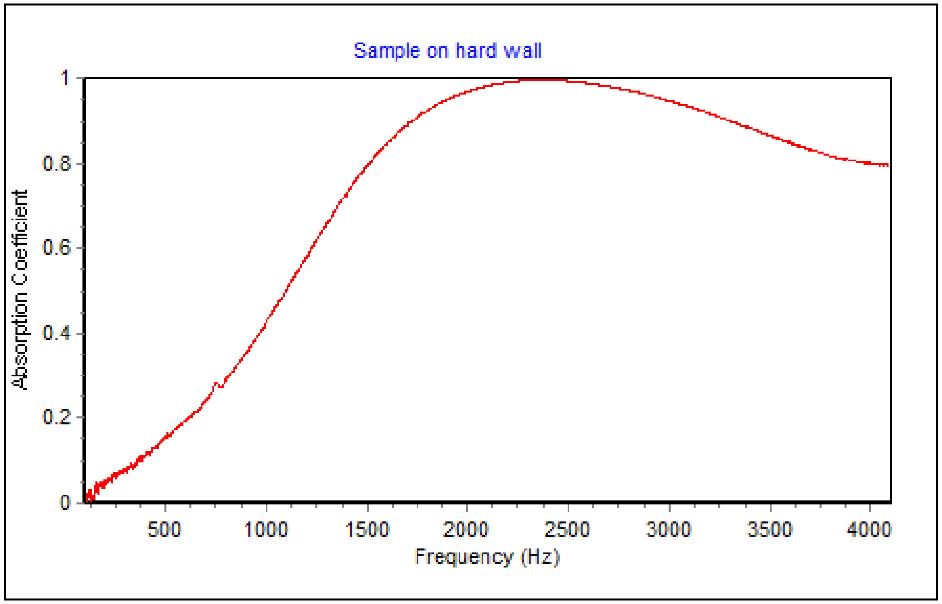
Large number of open-cell porous media follow this typical behavior

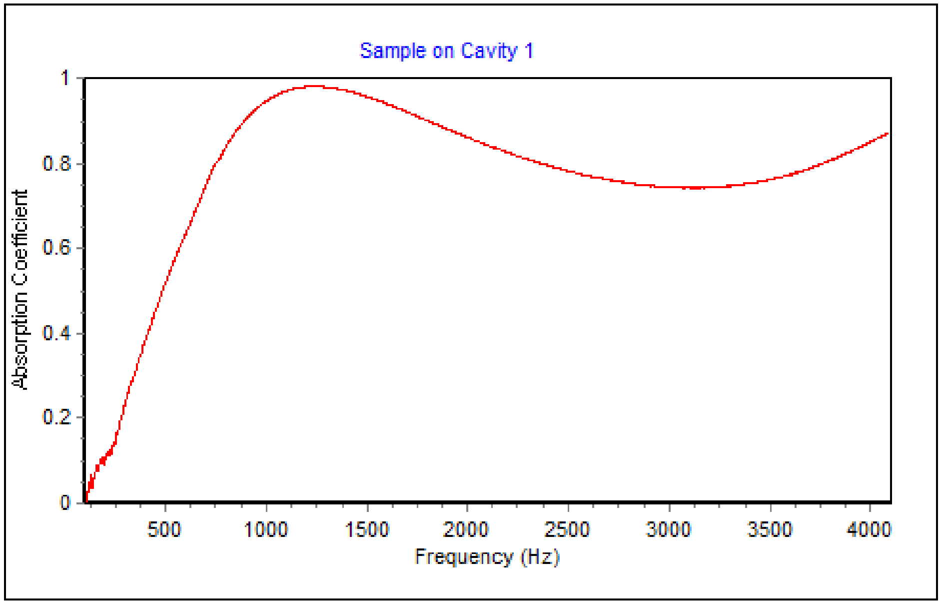
Exception: high resistivity materials, where viscous length dominate viscous forces over resistivity

Zones I + II are necessary
Zone III is highly recommended
for accurate estimations of the parameters

Test 5 *Is all the physics captured in the absorption curves?*

☐ Results for : *Cast foam A* ✔ **ok**



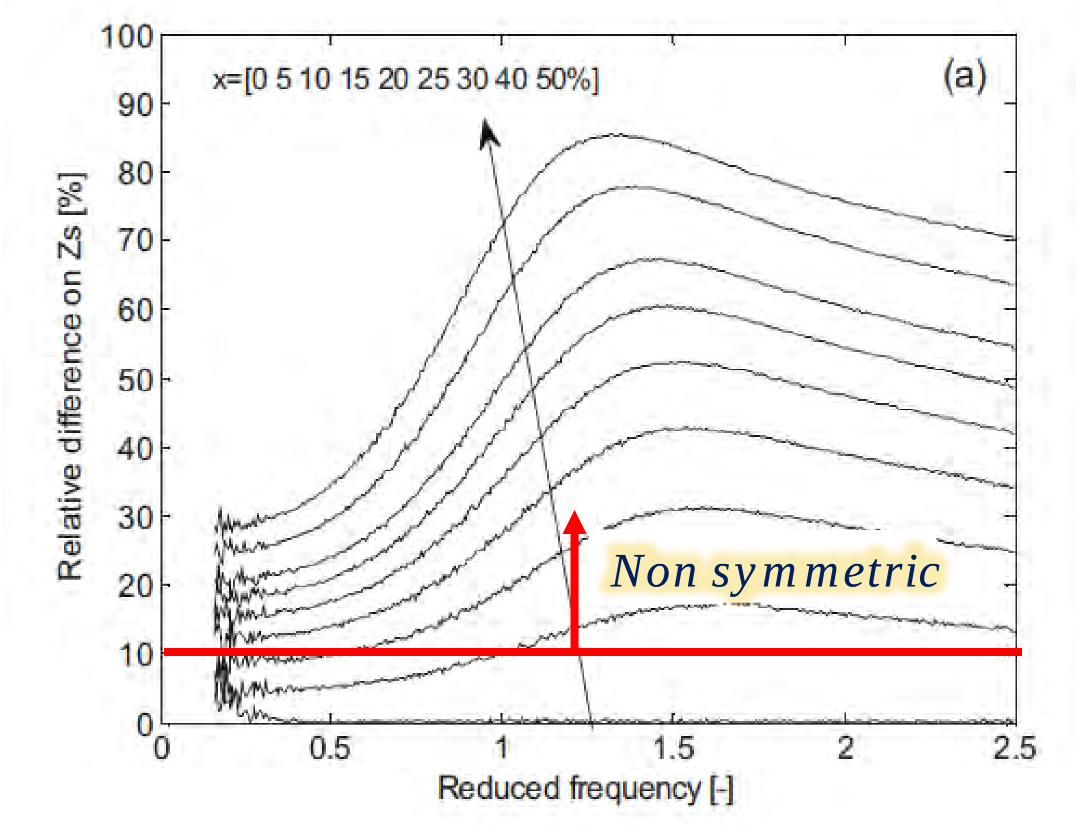


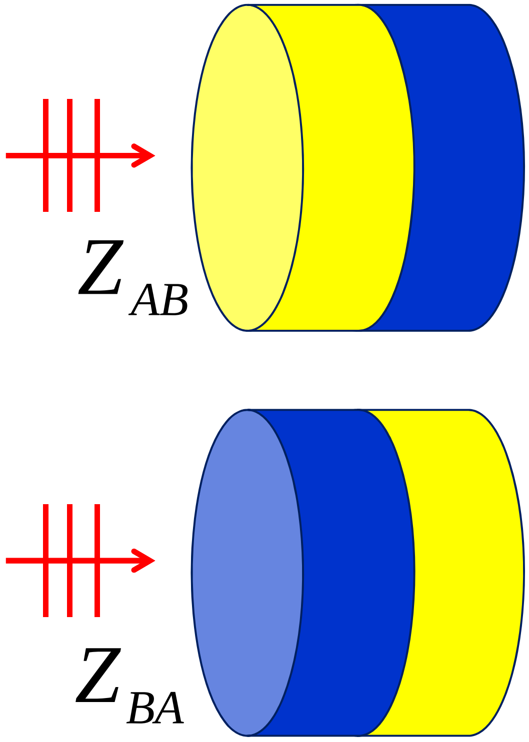
Increase thickness or add a cavity

Test 6

Is the material homogeneous along thickness (through-thickness symmetry) ?

$$x = RD(\omega) = \frac{\left|Z_{AB}(\omega) - Z_{BA}(\omega)\right|}{\max\left(\left|Z_{AB}(\omega)\right|, \left|Z_{BA}(\omega)\right|\right)}$$





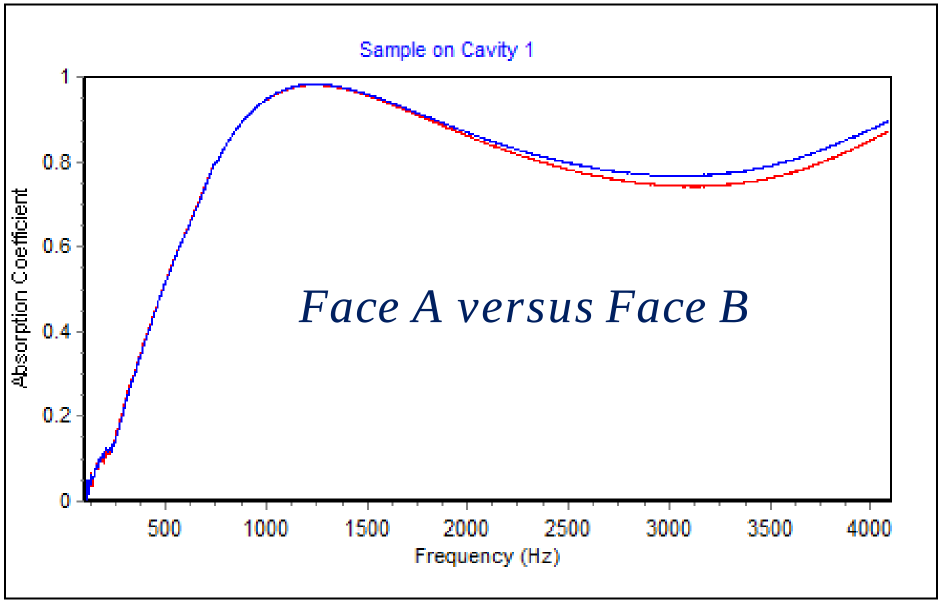
Ref.: http://dx.doi.org/10.1121/1.2947625
Salissou, Panneton: Quantifying through-thickness asymmetry of sound absorbing materials, JASA 124 (2008)

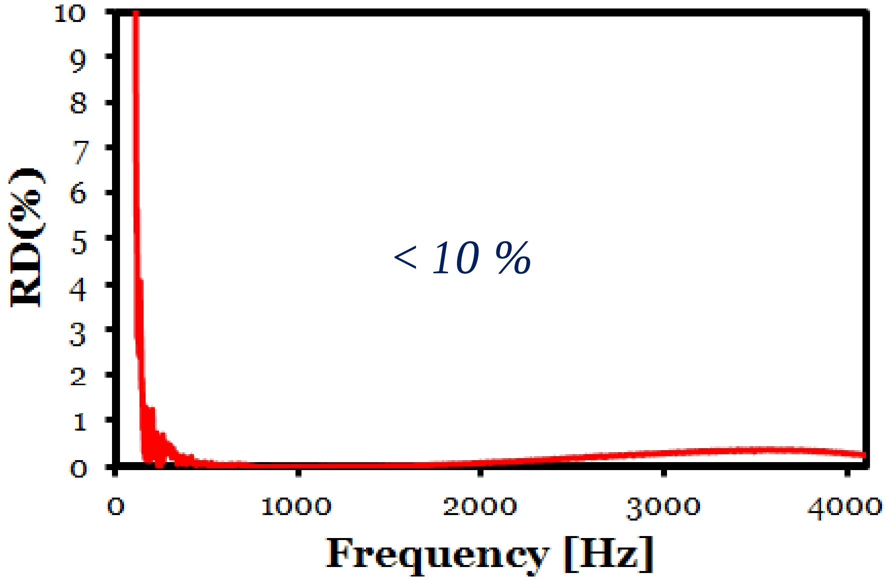
Test 6

Is the material homogeneous along thickness (through-thickness symmetry) ?

- ☐ Results for : *Cast foam A*

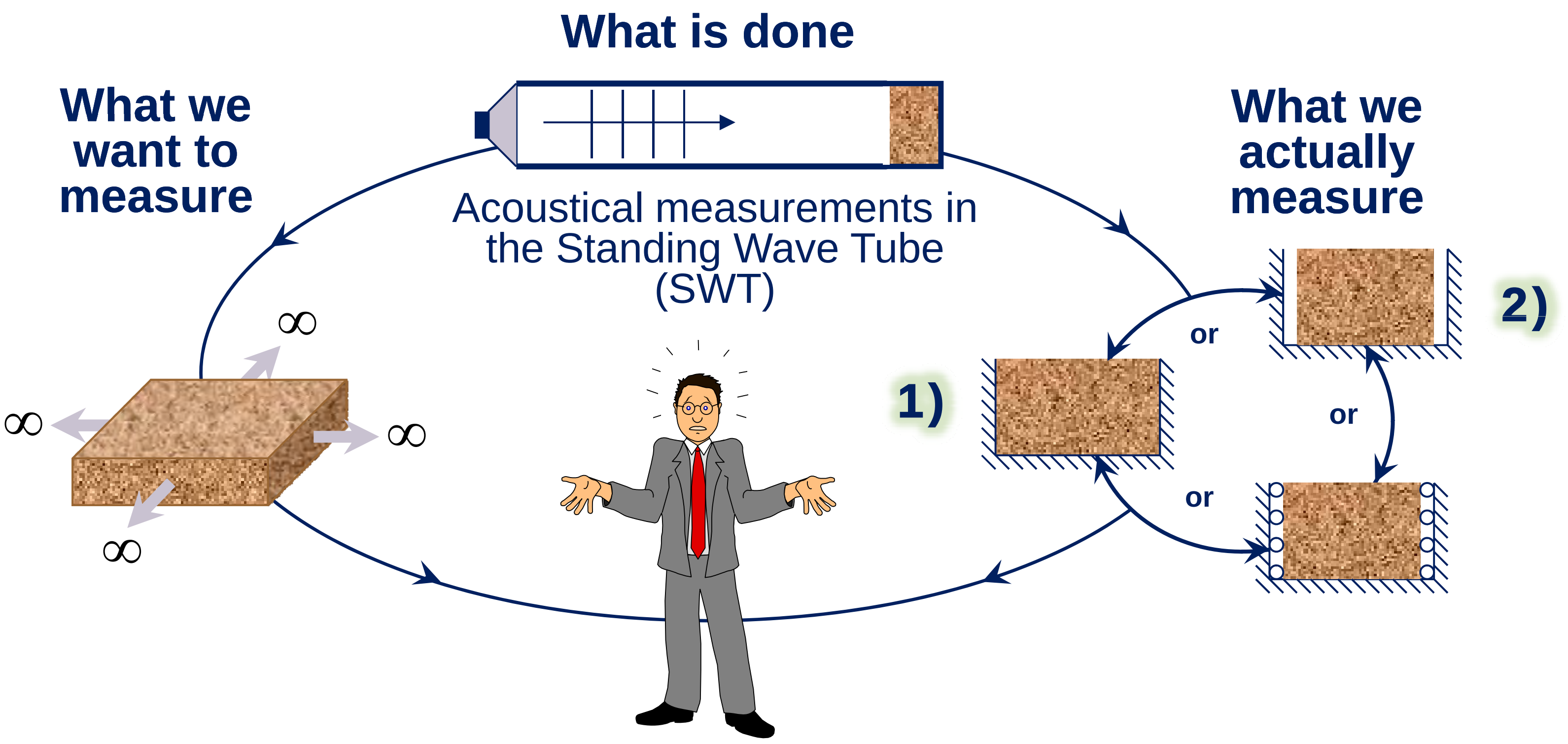
✓ **ok**





Test 7

Are measurements not sensitive to boundary conditions in tube ?



What is done

What we want to measure

Acoustical measurements in the Standing Wave Tube (SWT)

What we actually measure

1) *Check for sensitivity to edge constraints*

2) *Check for sensitivity to edge acoustical leaks*

Ref.: http://dx.doi.org/10.1121/1.2947625
Pilon, Panneton, Sgard: Behavioral criterion quantifying …, JASA 124 (2008)

Test 7

Are measurements not sensitive to boundary conditions in tube ?

Edge constraints : from Frame Acoustical Excitability

✓ ok

$$FAE = 4\frac{\sigma E d^2}{\rho_1^2 D^2} \ \text{[W/kg]}$$

$$\boxed{FAE_{\text{CAST FOAM A}} = 0.12 \ \text{MW/kg}}$$

$$FAE < 1 \ \ \text{MW/kg} \rightarrow \alpha_m = \alpha_{th}$$

$$1 < \text{FAE} < 2 \ \ \text{MW/kg} \rightarrow \alpha_m \approx \alpha_{th}$$

$$\text{FAE} > 2 \ \ \text{MW/kg} \rightarrow \alpha_m \neq \alpha_{th}$$

Ref.: http://dx.doi.org/10.1121/1.1598193

Pilon, Panneton, Sgard: Behavioral criterion quantifying edge constrained effects ..., JASA 114 (2003)

Test 7

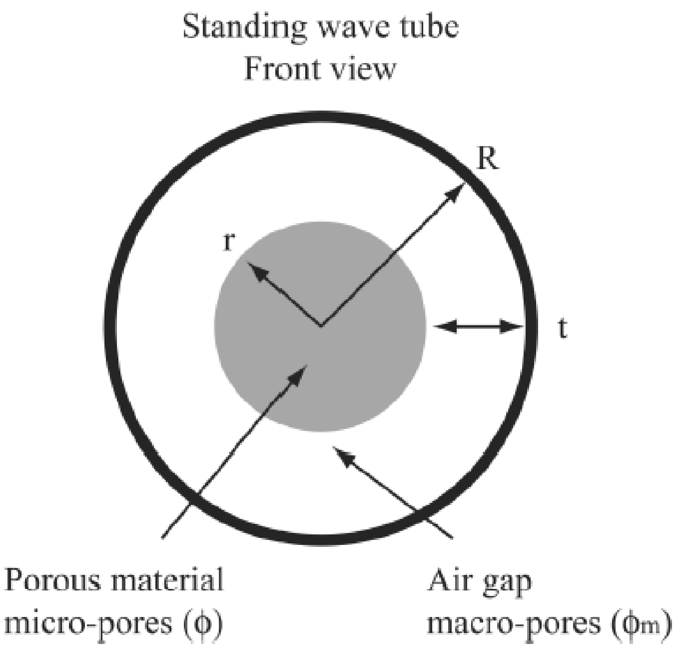
Are measurements not sensitive to boundary conditions in tube ?

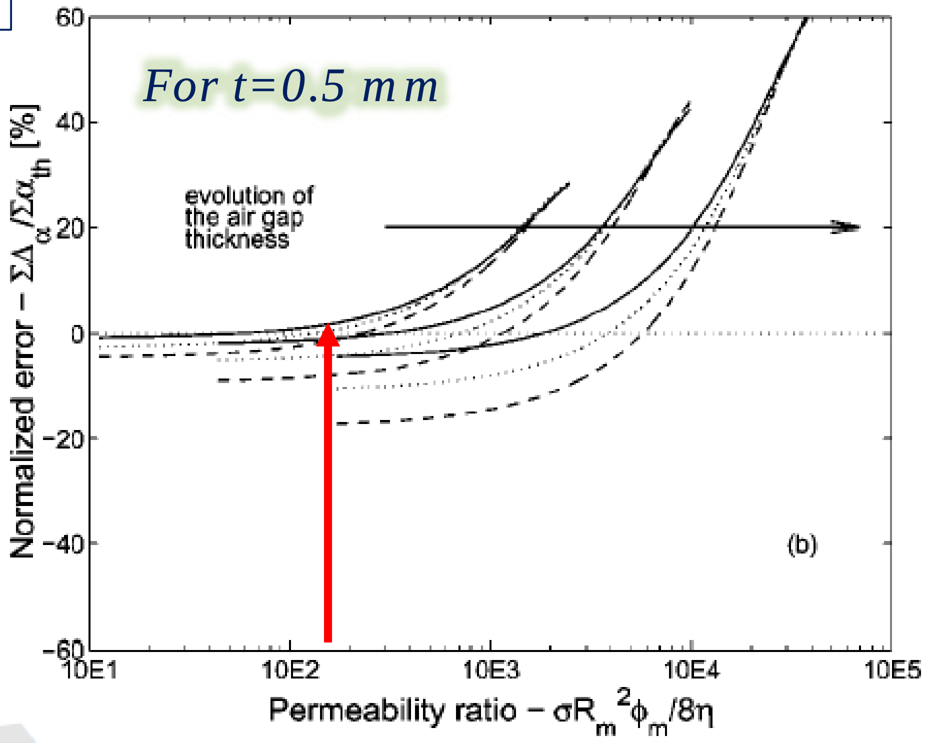
Acoustical leaks: from Permeability Ratio

✓ ok

$$PR = 6842\sigma R_m^2 \phi_m = 6842\frac{\sigma}{R^2}\left(2Rt - t^2\right)^2$$

$$\boxed{PR_{\text{CAST FOAM A}} = 184}$$




For t=0.5 mm

Ref.: http://dx.doi.org/10.1121/1.1756611
Pilon, Panneton, Sgard: Behavioral criterion quantifying the effects of circumferential air gaps..., JASA 116 (2004)

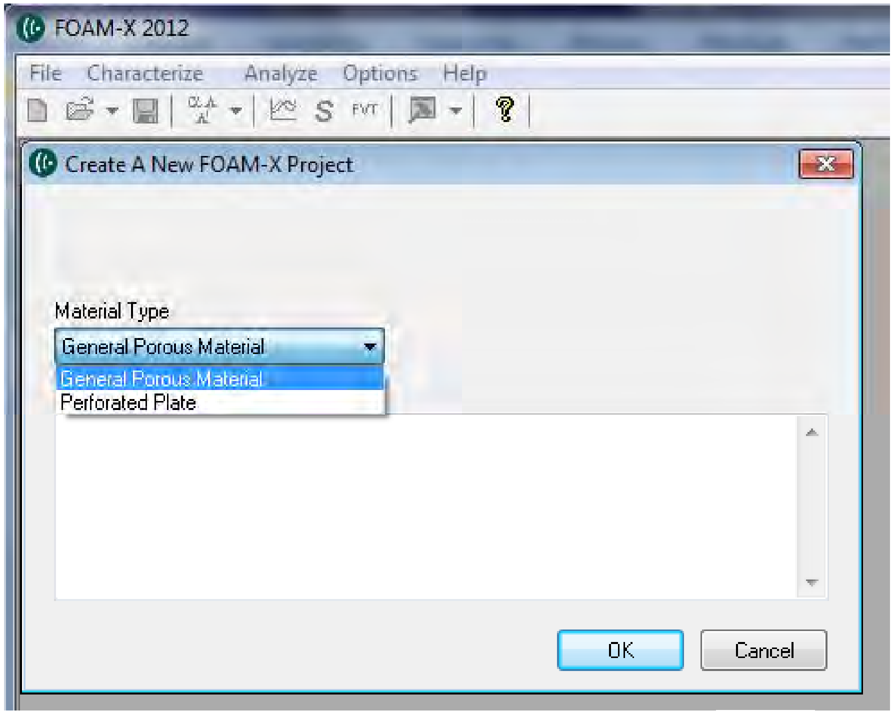
Iterative Inversion

- ☐ Iterative inversion algorithm coded into FOAM-X by Université de Sherbrooke, Mecanum Inc, and ESI-Group

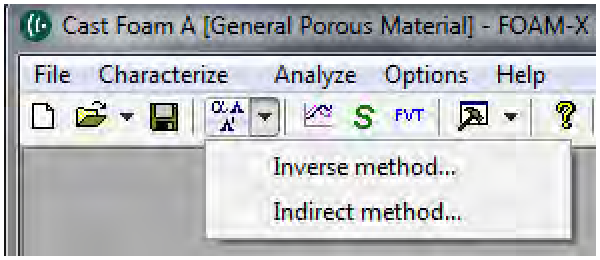
[http://www.esi-group.com/products/vibro-acoustics/VA%20One%20Modules/foam-x-1/foam-x]

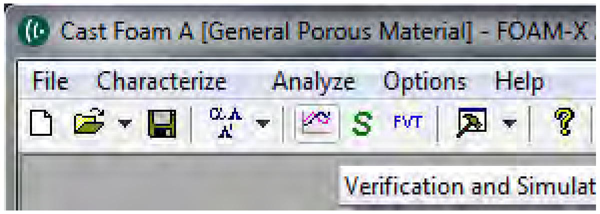
FOAM-X
version 2012 (2.0.1.2 f)
copyright © 2001-2012 Université de Sherbrooke,
Mecanum Inc. and ESI Group

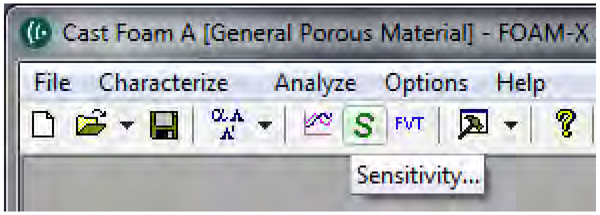
http://www.esi-group.com

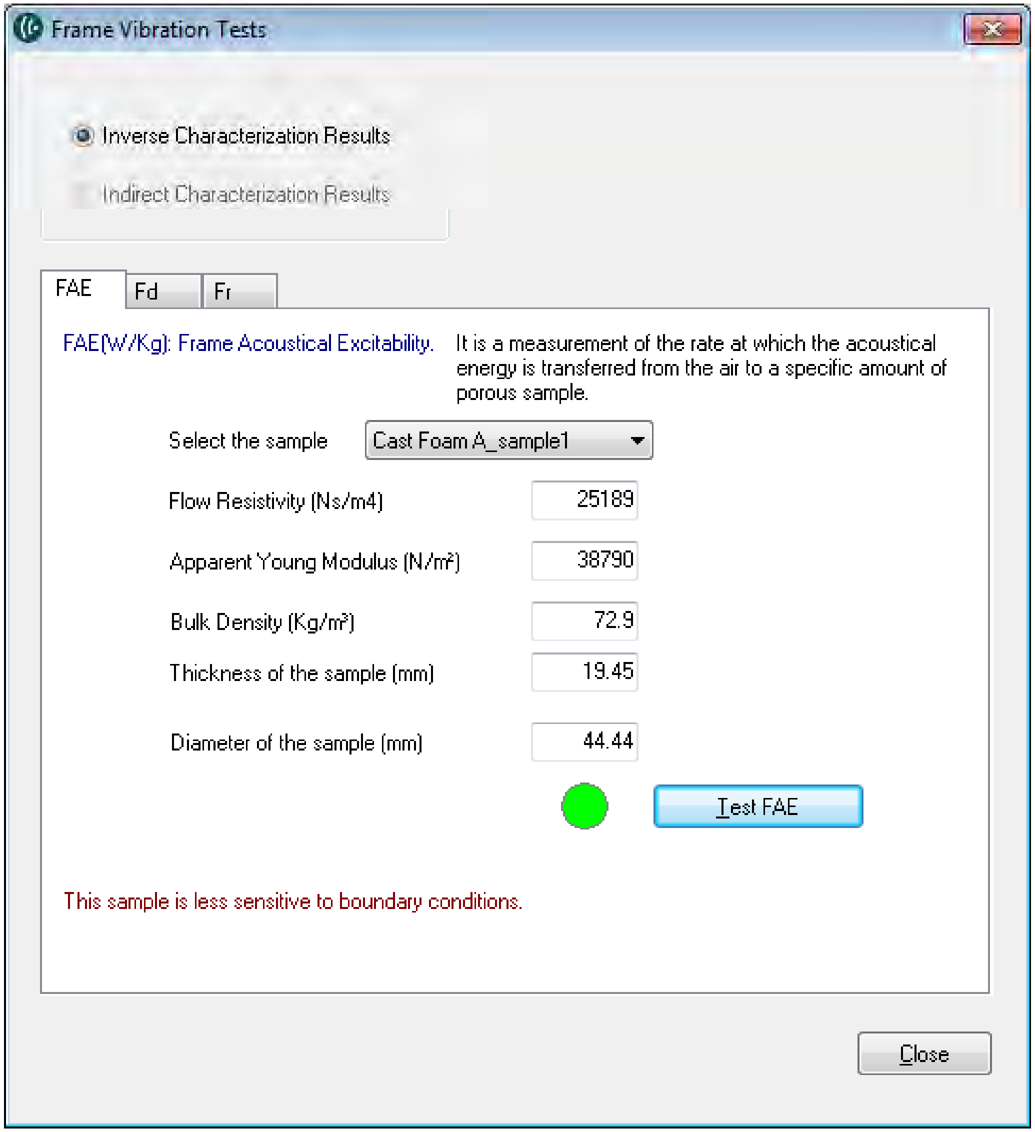


Material Type: General Porous Material









● Inverse Characterization Results

FAE(W/Kg): Frame Acoustical Excitability. It is a measurement of the rate at which the acoustical energy is transferred from the air to a specific amount of porous sample.

Select the sample: Cast Foam A_sample1

Flow Resistivity (Ns/m4): 25189

Apparent Young Modulus (N/m²): 38790

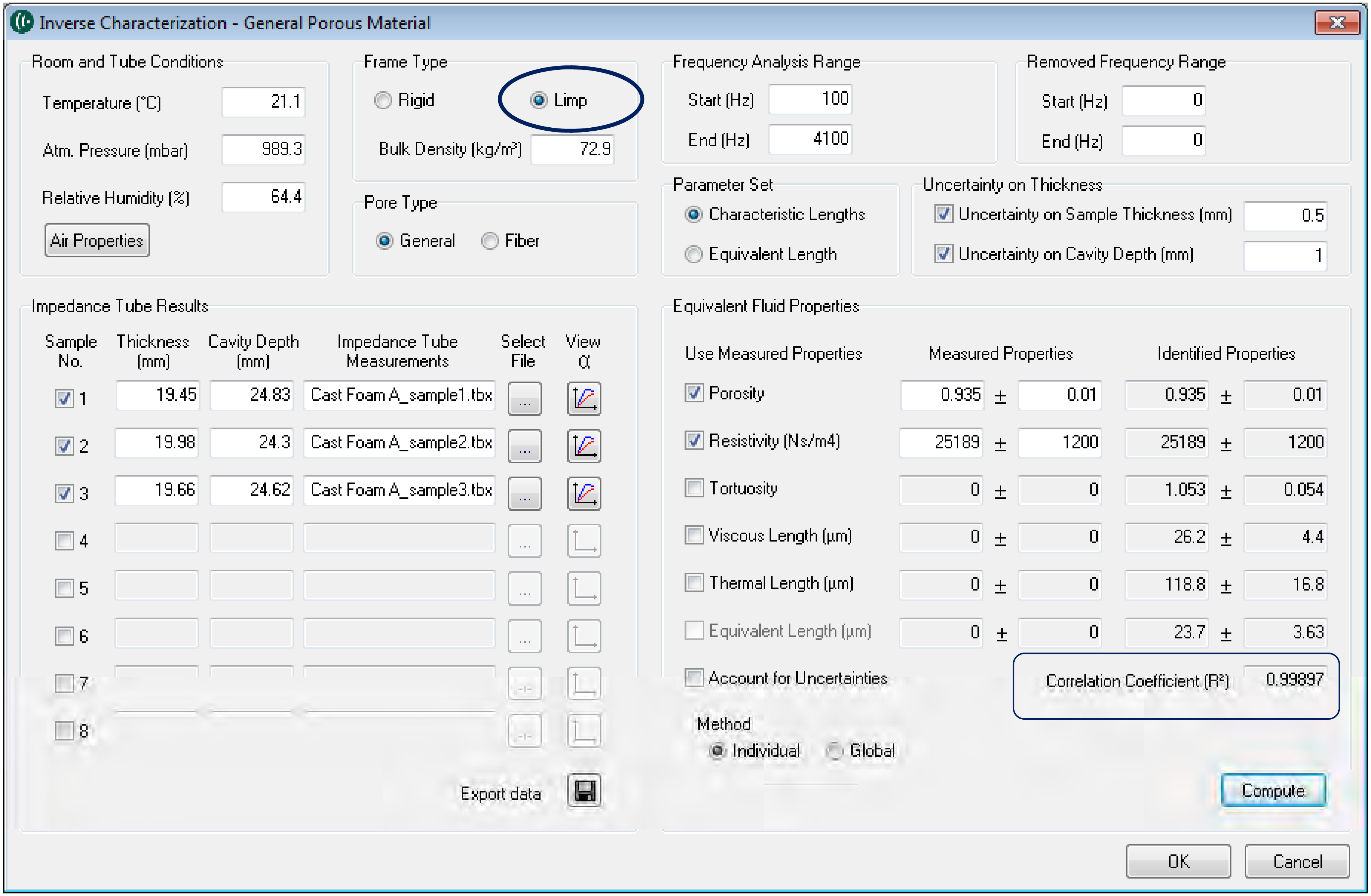
Bulk Density (Kg/m³): 72.9

Thickness of the sample (mm): 19.45

Diameter of the sample (mm): 44.44

This sample is less sensitive to boundary conditions.

Inversion Characterization Results



Inverse Characterization - General Porous Material

Room and Tube Conditions

Temperature (°C) 21.1
Atm. Pressure (mbar) 989.3
Relative Humidity (%) 64.4

Frame Type

○ Rigid ● Limp

Bulk Density (kg/m³) 72.9

Pore Type

● General ○ Fiber

Frequency Analysis Range

Start (Hz) 100
End (Hz) 4100

Removed Frequency Range

Start (Hz) 0
End (Hz) 0

Parameter Set

● Characteristic Lengths
○ Equivalent Length

Uncertainty on Thickness

☑ Uncertainty on Sample Thickness (mm) 0.5
☑ Uncertainty on Cavity Depth (mm) 1

Impedance Tube Results

Sample No.	Thickness (mm)	Cavity Depth (mm)	Impedance Tube Measurements	Select File	View α
☑ 1	19.45	24.83	Cast Foam A_sample1.tbx	...	
☑ 2	19.98	24.3	Cast Foam A_sample2.tbx	...	
☑ 3	19.66	24.62	Cast Foam A_sample3.tbx	...	
☐ 4				...	
☐ 5				...	
☐ 6				...	
☐ 7				...	
☐ 8				...	

Export data

Equivalent Fluid Properties

Use Measured Properties	Measured Properties			Identified Properties		
☑ Porosity	0.935	±	0.01	0.935	±	0.01
☑ Resistivity (Ns/m4)	25189	±	1200	25189	±	1200
☐ Tortuosity	0	±	0	1.053	±	0.054
☐ Viscous Length (µm)	0	±	0	26.2	±	4.4
☐ Thermal Length (µm)	0	±	0	118.8	±	16.8
☐ Equivalent Length (µm)	0	±	0	23.7	±	3.63

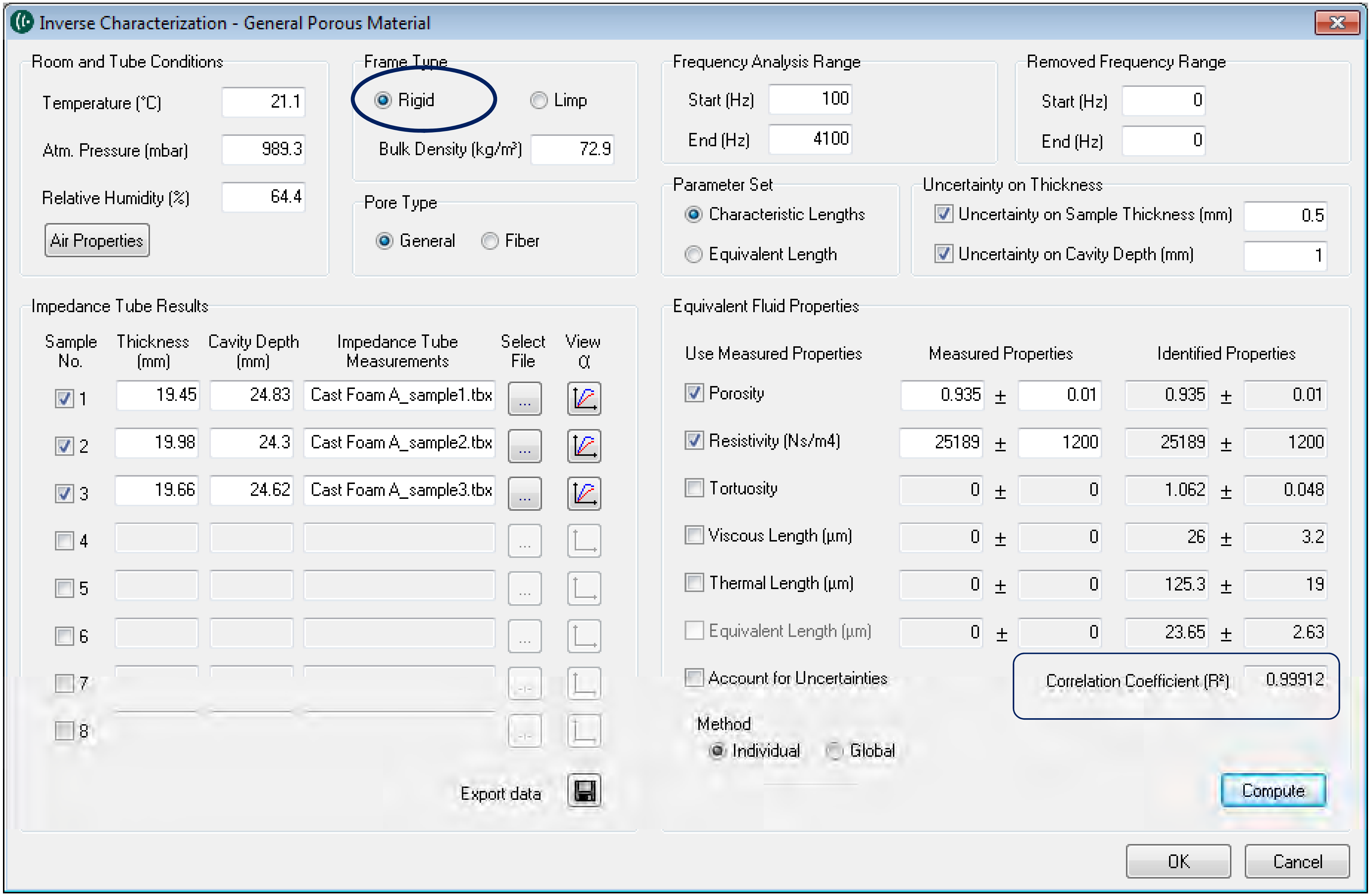
☐ Account for Uncertainties

Correlation Coefficient (R²) 0.99897

Method

● Individual ○ Global

Inversion Characterization Results



Inverse Characterization - General Porous Material

Room and Tube Conditions

Temperature (°C) 21.1

Atm. Pressure (mbar) 989.3

Relative Humidity (%) 64.4

Frame Type

● Rigid ○ Limp

Bulk Density (kg/m³) 72.9

Pore Type

● General ○ Fiber

Frequency Analysis Range

Start (Hz) 100

End (Hz) 4100

Removed Frequency Range

Start (Hz) 0

End (Hz) 0

Parameter Set

● Characteristic Lengths

○ Equivalent Length

Uncertainty on Thickness

☑ Uncertainty on Sample Thickness (mm) 0.5

☑ Uncertainty on Cavity Depth (mm) 1

Impedance Tube Results

Sample No.	Thickness (mm)	Cavity Depth (mm)	Impedance Tube Measurements	Select File	View α
☑ 1	19.45	24.83	Cast Foam A_sample1.tbx	...	
☑ 2	19.98	24.3	Cast Foam A_sample2.tbx	...	
☑ 3	19.66	24.62	Cast Foam A_sample3.tbx	...	
☐ 4				...	
☐ 5				...	
☐ 6				...	
☐ 7				...	
☐ 8				...	

Equivalent Fluid Properties

Use Measured Properties	Measured Properties			Identified Properties		
☑ Porosity	0.935	±	0.01	0.935	±	0.01
☑ Resistivity (Ns/m4)	25189	±	1200	25189	±	1200
☐ Tortuosity	0	±	0	1.062	±	0.048
☐ Viscous Length (µm)	0	±	0	26	±	3.2
☐ Thermal Length (µm)	0	±	0	125.3	±	19
☐ Equivalent Length (µm)	0	±	0	23.65	±	2.63

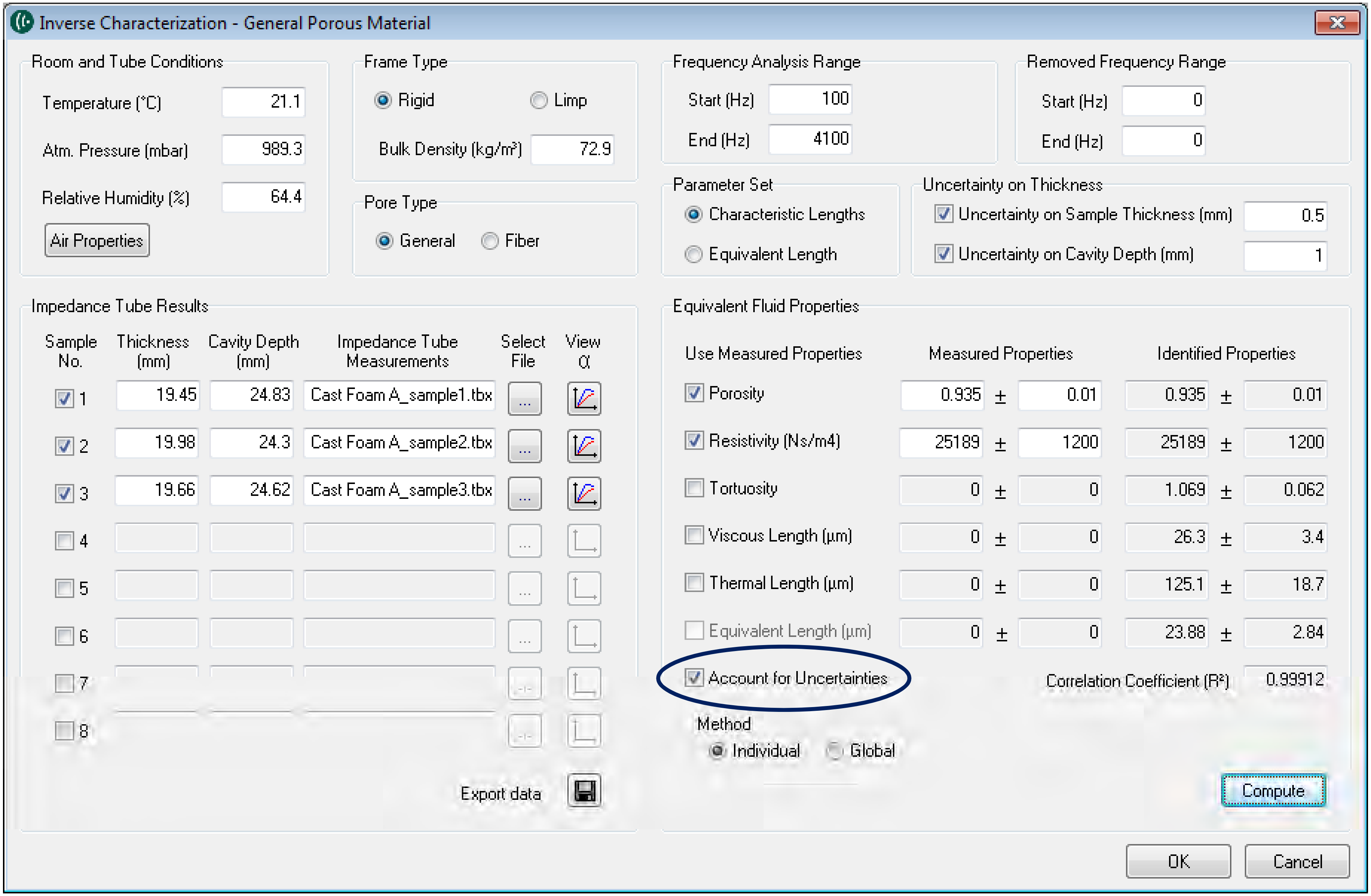
☐ Account for Uncertainties

Method

● Individual ○ Global

Correlation Coefficient (R²) 0.99912

Inversion Characterization Results



Inverse Characterization - General Porous Material

Room and Tube Conditions

Temperature (°C): 21.1

Atm. Pressure (mbar): 989.3

Relative Humidity (%): 64.4

Frame Type

● Rigid ○ Limp

Bulk Density (kg/m³): 72.9

Pore Type

● General ○ Fiber

Frequency Analysis Range

Start (Hz): 100

End (Hz): 4100

Removed Frequency Range

Start (Hz): 0

End (Hz): 0

Parameter Set

● Characteristic Lengths

○ Equivalent Length

Uncertainty on Thickness

☑ Uncertainty on Sample Thickness (mm): 0.5

☑ Uncertainty on Cavity Depth (mm): 1

Impedance Tube Results

Sample No.	Thickness (mm)	Cavity Depth (mm)	Impedance Tube Measurements	Select File	View α
☑ 1	19.45	24.83	Cast Foam A_sample1.tbx	...	
☑ 2	19.98	24.3	Cast Foam A_sample2.tbx	...	
☑ 3	19.66	24.62	Cast Foam A_sample3.tbx	...	
☐ 4				...	
☐ 5				...	
☐ 6				...	
☐ 7				...	
☐ 8				...	

Export data

Equivalent Fluid Properties

Use Measured Properties	Measured Properties			Identified Properties		
☑ Porosity	0.935	±	0.01	0.935	±	0.01
☑ Resistivity (Ns/m4)	25189	±	1200	25189	±	1200
☐ Tortuosity	0	±	0	1.069	±	0.062
☐ Viscous Length (µm)	0	±	0	26.3	±	3.4
☐ Thermal Length (µm)	0	±	0	125.1	±	18.7
☐ Equivalent Length (µm)	0	±	0	23.88	±	2.84

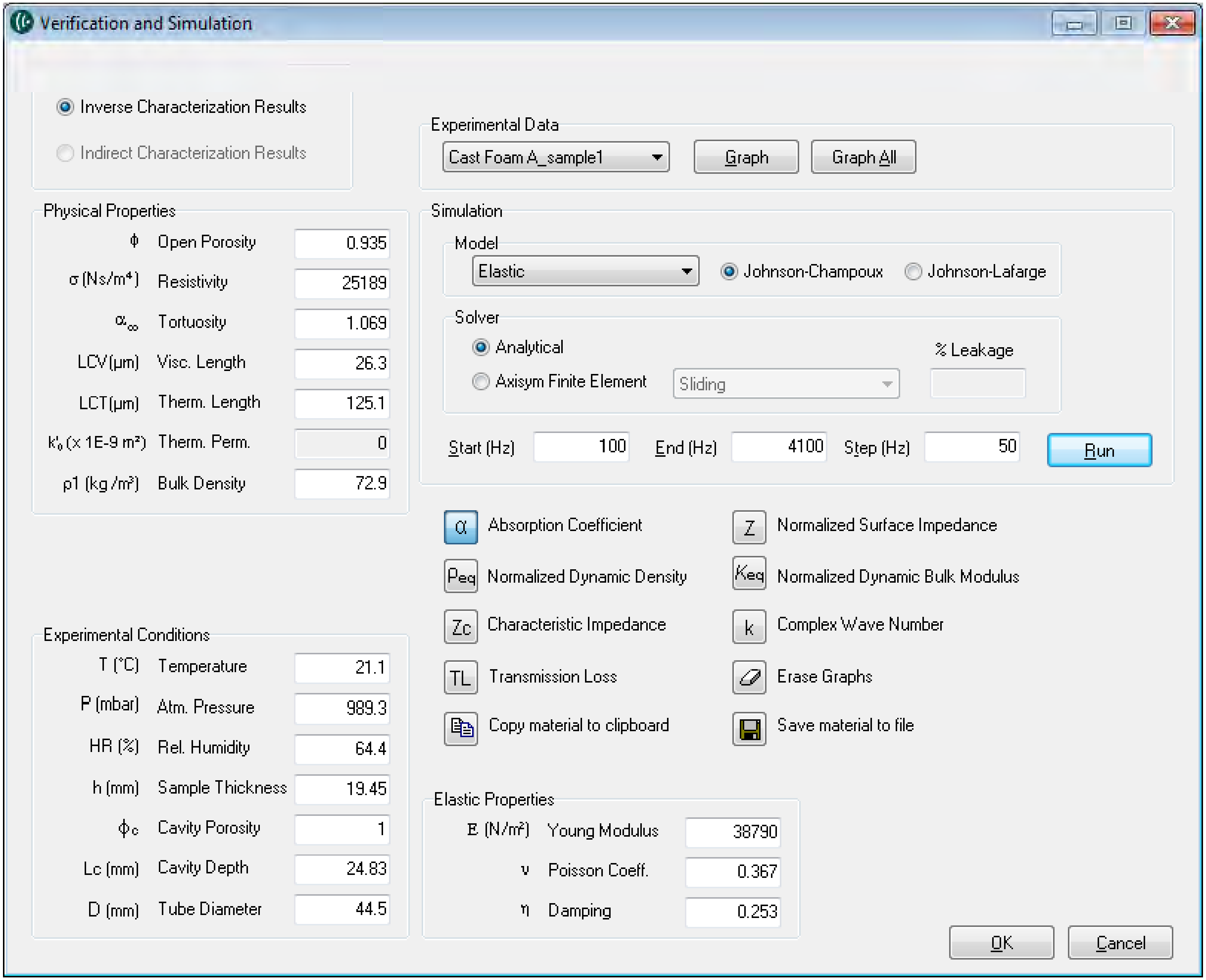
☑ Account for Uncertainties

Correlation Coefficient (R²): 0.99912

Method

● Individual ○ Global

Verification


Verification and Simulation

● Inverse Characterization Results

○ Indirect Characterization Results

Experimental Data: Cast Foam A_sample1

Physical Properties

ϕ	Open Porosity	0.935
σ (Ns/m⁴)	Resistivity	25189
α_∞	Tortuosity	1.069
LCV (µm)	Visc. Length	26.3
LCT (µm)	Therm. Length	125.1
k'_0 (x 1E-9 m²)	Therm. Perm.	0
ρ1 (kg/m³)	Bulk Density	72.9

Simulation

Model: Elastic ● Johnson-Champoux ○ Johnson-Lafarge

Solver: ● Analytical ○ Axisym Finite Element Sliding % Leakage

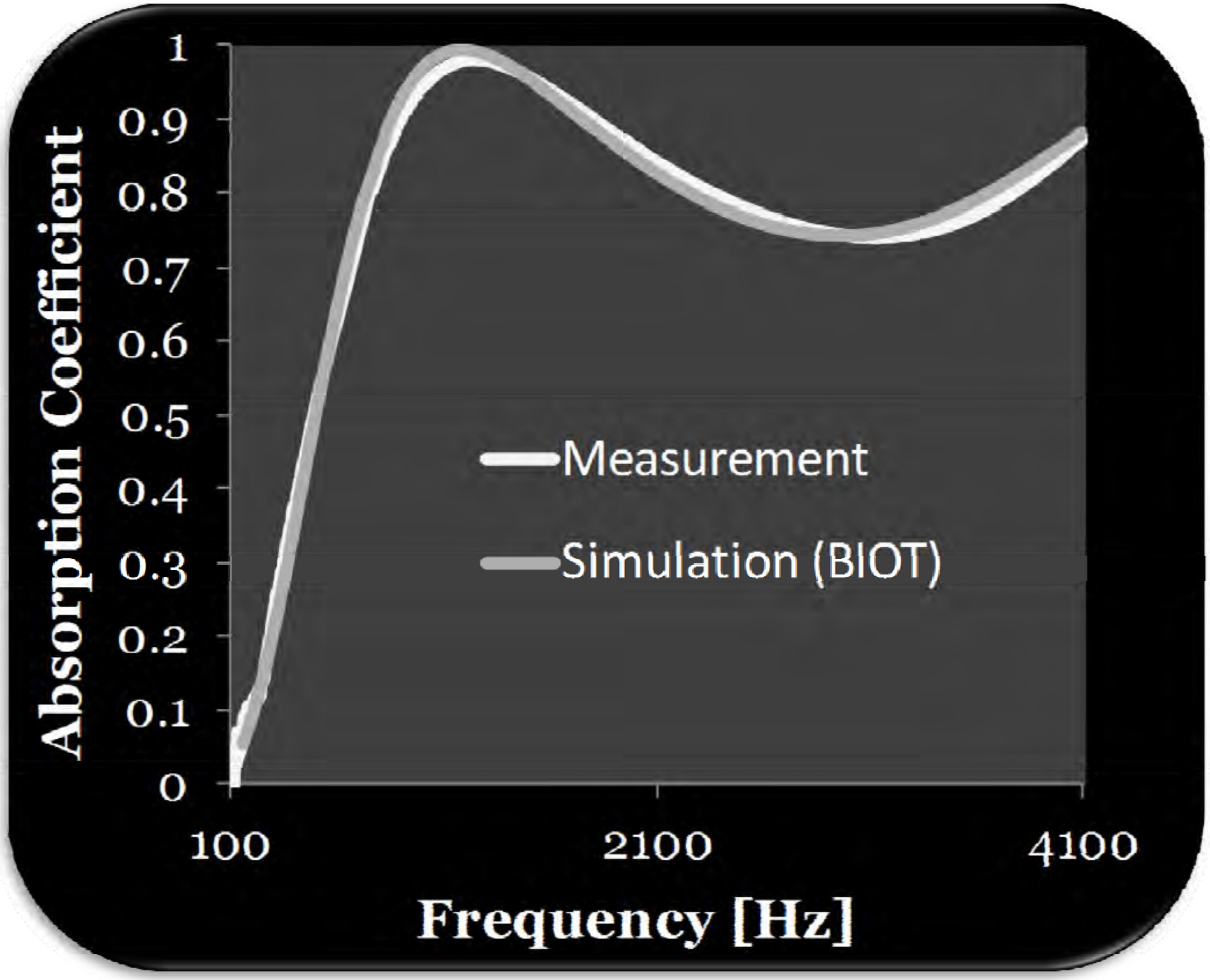
Start (Hz) 100 End (Hz) 4100 Step (Hz) 50

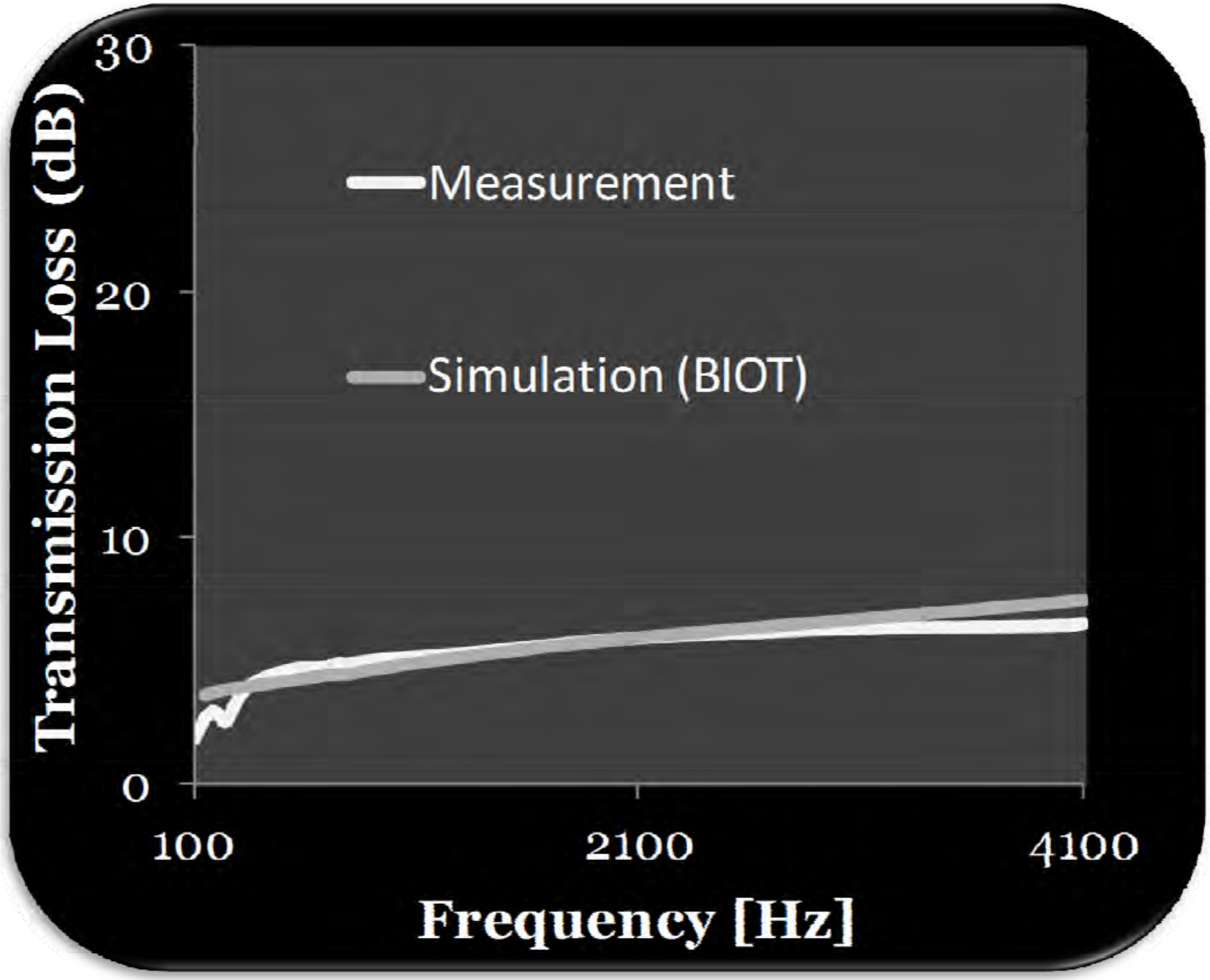
Experimental Conditions

T (°C)	Temperature	21.1
P (mbar)	Atm. Pressure	989.3
HR (%)	Rel. Humidity	64.4
h (mm)	Sample Thickness	19.45
ϕc	Cavity Porosity	1
Lc (mm)	Cavity Depth	24.83
D (mm)	Tube Diameter	44.5

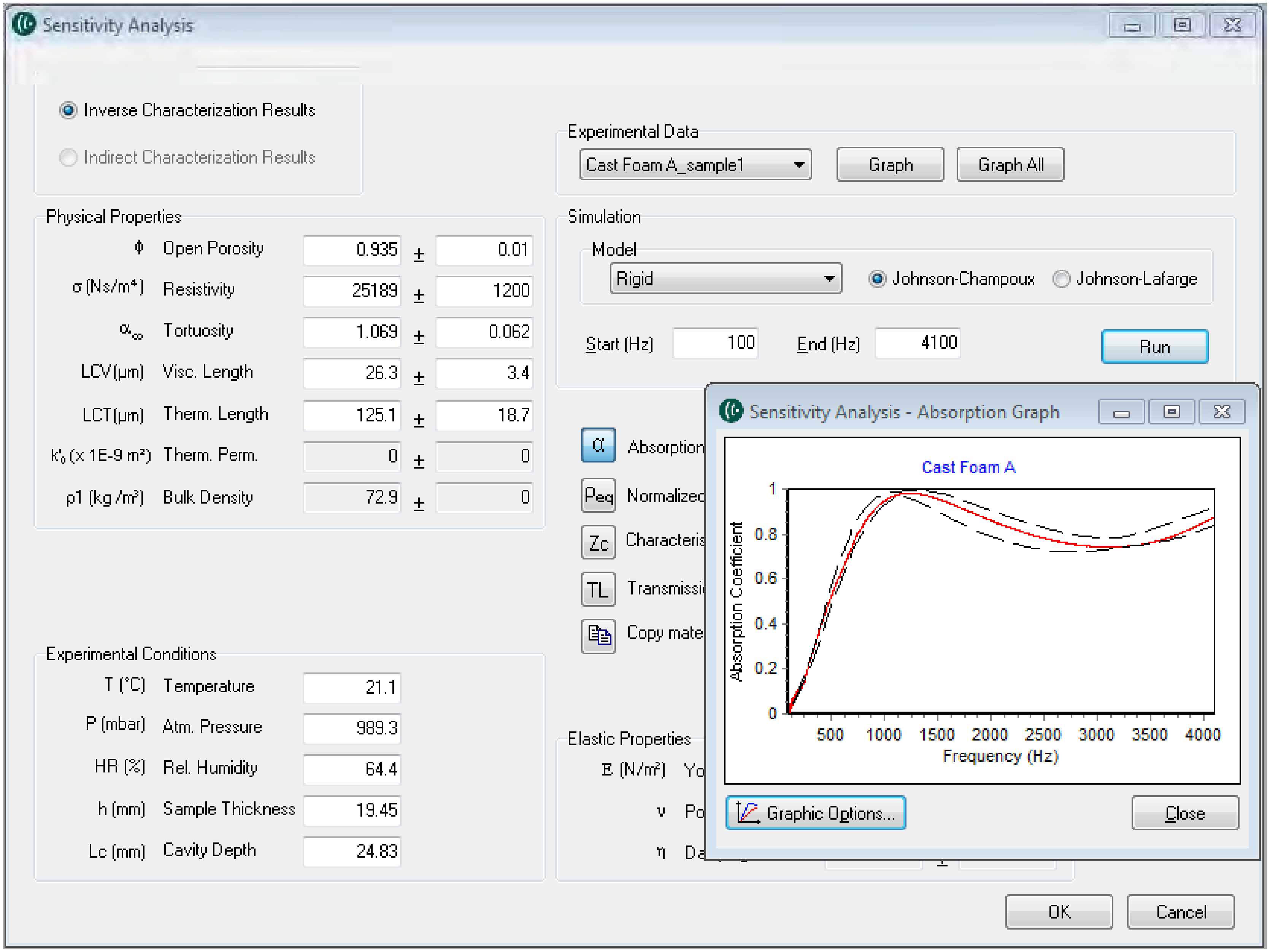
Elastic Properties

E (N/m²)	Young Modulus	38790
ν	Poisson Coeff.	0.367
η	Damping	0.253


Absorption Coefficient
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
100
2100
4100
Frequency [Hz]
Measurement
Simulation (BIOT)


Transmission Loss (dB)
30
20
10
0
Measurement
Simulation (BIOT)
100
2100
4100
Frequency [Hz]

Sensitivity Analysis



Sensitivity Analysis

● Inverse Characterization Results
○ Indirect Characterization Results

Experimental Data: Cast Foam A_sample1

Physical Properties

ϕ	Open Porosity	0.935	±	0.01
σ (Ns/m⁴)	Resistivity	25189	±	1200
α_∞	Tortuosity	1.069	±	0.062
LCV (µm)	Visc. Length	26.3	±	3.4
LCT (µm)	Therm. Length	125.1	±	18.7
k'_0 (x 1E-9 m²)	Therm. Perm.	0	±	0
$\rho 1$ (kg/m³)	Bulk Density	72.9	±	0

Simulation

Model: Rigid ● Johnson-Champoux ○ Johnson-Lafarge

Start (Hz) 100 End (Hz) 4100

Experimental Conditions

T (°C)	Temperature	21.1
P (mbar)	Atm. Pressure	989.3
HR (%)	Rel. Humidity	64.4
h (mm)	Sample Thickness	19.45
Lc (mm)	Cavity Depth	24.83

Sensitivity Analysis - Absorption Graph

Conclusion

- Performance of sound package relies on the used sound absorbing materials
- Sound absorbing materials are typically defined by **9** material properties ($\sigma,\alpha_\infty,\rho_1,\Lambda,\Lambda',E,\nu,\eta$)
- Many methods exist for the characterization of these material properties: Direct and Inverse, Frequency and Time domains
- The only robust method for the characterization of tortuosity and characteristic lengths is iterative inversion

Conclusion

- Proposed characterization procedure based on:
  - Direct measurement of :
    - open porosity and bulk density
    - Static airflow resistivity
    - Young’s modulus, Poisson’s ratio, loss factor
  - Inverse identification of:
    - Impedance/Transmission tube measurements
    - Tortuosity
    - Viscous characteristic length
    - Thermal characteristic length
  - Criteria on tube measurements

Conclusion

- Fine characterization depends on many factors:
    - Quality of specimens (geometry, homogeneity, ...)
    - Control of edge effects
    - Expertise of experimenter

- Lack of standards for full poroelastic characterization:
    - Resistivity (Ok, standards exist)
    - Open porosity and bulk density (no standard)
    - Tortuosity, VCL, TCL (no standard)
    - Elastic properties of porous materials (no standard)

Conclusion

- Impedance/transmission tube measurements used for characterization of porous materials:
  - Measurement method : Ok (standards exist)
  - Standards lack quantitative criteria for:
    - Homogeneity of material
    - Sensitivity to edge constraints
    - Sensitivity to acoustical leaks

Essential future work

Establish standard efficient and robust procedure for the characterization of poroelastic materials used in noise control sound packages