From the microstructure to condensed meta-material models

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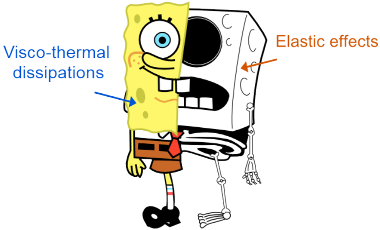
Sorrento SAPEM'23 常熟

Hypothesis

- Zwikker & Kosten (1949) introduce the hypothesis of a decoupling between the visco-inertial and (micro)thermal effects.
- Biot (1956) considers visco-inertio-thermal effects & elastical effects and their coupling.



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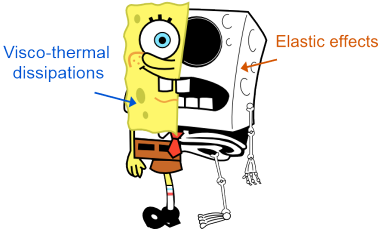
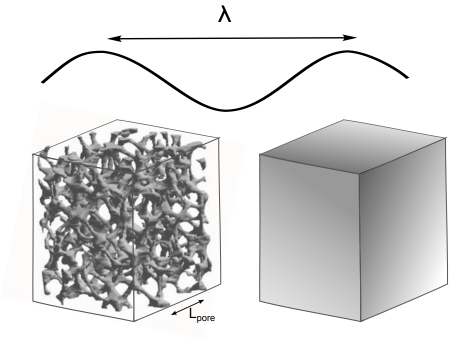


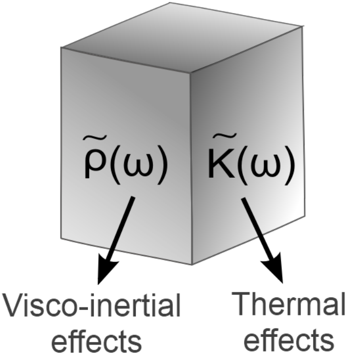
Equivalent fluid



- A porous material may be viewed as an **equivalent fluid** only if there is an order of magnitude between the observation wavelength λ and the cell characteristic size ℓ.

Equivalent fluid

- Visco-thermal dissipation are taken into account using the dynamic **mass density** $\tilde{\rho}(\omega)$ and the dynamic **bulk modulus** $\tilde{K}(\omega)$.

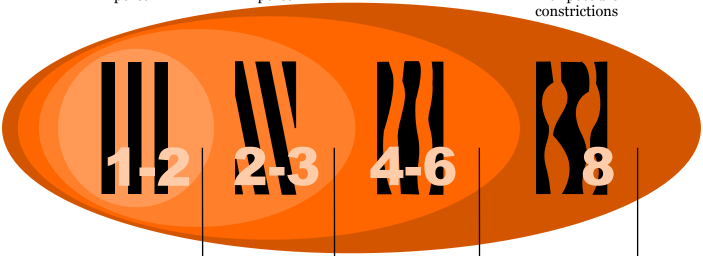


These quantities are complex and frequency dependent.

Models of visco-thermal dissipation

Straight cylindrical pores — Slanted cylindrical pores — Non uniform sections — Non-uniform sections with possible constrictions

Material morphology and number of parameters



Model and parameter examples

Zwikker-Kosten
ϕ $\sigma = \eta / k_0$

Miki
ϕ σ α_∞

Attenborough
ϕ σ α_∞ b

Wilson
ρ_0 τ_{vor} K_∞ τ_{ent}

Johnson-Champoux-Allard
ϕ σ α_∞ Λ Λ' k_0'

Johnson-Champoux-Allard-Pride-Lafarge
ϕ σ α_∞ Λ p Λ' k_0' p'

Macroscopic parameters

- ϕ: open porosity
- σ: static air flow resistivity
- Λ: viscous characteristic length
- Λ': thermal characteristic length
- α_∞: high frequency limit of tortuosity
- k'_0: static thermal permeability

- α_0: static viscous tortuosity
- α'_0: static thermal tortuosity
- k_0: static viscous permeability $(= \eta/\sigma)$

Analytical computation : perforated plate

- A **perforated plate** may be viewed as a **porous material.**

- **Macroscopic parameters:**

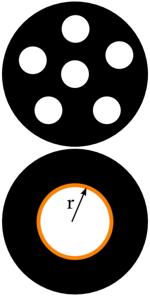
  ϕ: perforation rate

  $$\Lambda = \Lambda' = r$$

  $$\sigma = \frac{8\eta}{\phi r^2}$$

  $$\alpha_\infty = 1 + \frac{n\epsilon}{L}$$

Atalla N, Sgard F. "Modeling of perforated plates and screens using rigid frame porous models", J. Sound Vib. 303 (2007).

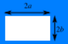


L: Thickness of the plate

ϵ: Length correction

n: Factor depending on the nature of upstream and downstream materials

Analytic computation: constant cross-section

SOUND PROPAGATION THROUGH SOME MATERIALS WITH CYLINDRICAL PORES OF CONSTANT CROSS-SECTIONS	Dynamic mass density $\tilde{\rho}_{eq}$	Dynamic bulk modulus $\tilde{K}_{eq}$
Circular (radius r) 	$\frac{\rho_0}{\phi} \times 1/\left[1 - \frac{2}{\beta\sqrt{-j}} \frac{J_1(\beta\sqrt{-j})}{J_0(\beta\sqrt{-j})}\right]$ with $\beta = \overline{r}\sqrt{\frac{\omega\rho_0}{\eta}}$ and $\overline{r}$ the hydraulic radius equals to	$\frac{P_0}{\phi} \times \gamma/\left[1 + (\gamma - 1)\frac{2}{\beta\sqrt{-j\,\mathrm{Pr}}} \frac{J_1(\beta\sqrt{-j\,\mathrm{Pr}})}{J_0(\beta\sqrt{-j\,\mathrm{Pr}})}\right]$ Formulas from C. Zwikker & C. W. Kosten 1949 after work by J. W. Strutt (lord Rayleigh).
Slit (width $2a$) 	$\frac{\rho_0}{\phi} \times 1/\left[1 - \frac{\tanh(\beta\sqrt{j})}{\beta\sqrt{j}}\right]$ with $\beta = \overline{r}\sqrt{\frac{\omega\rho_0}{\eta}}$ and $\overline{r}$ the hydraulic radius equals to	$\frac{P_0}{\phi} \times \gamma/\left[1 + (\gamma - 1)\frac{\tanh(\beta\sqrt{j\mathrm{Pr}})}{\beta\sqrt{j\mathrm{Pr}}}\right]$ Formulas attributed to M. Biot.
Equilateral triangle (length d) 	$\frac{\rho_0}{\phi} \times \epsilon^2/\left[\epsilon^2 - 3\epsilon\coth(\epsilon) + 3\right]$ with $\epsilon = \frac{\sqrt{3}}{4}\sqrt{\frac{j\omega\rho_0}{\eta}}d$	$\frac{P_0}{\phi} \times \gamma/\left(\gamma - \frac{\gamma - 1}{\mathrm{Pr}\,\epsilon^2}\left[\mathrm{Pr}\,\epsilon^2 - 3\sqrt{\mathrm{Pr}}\,\epsilon\coth(\sqrt{\mathrm{Pr}}\,\epsilon) + 3\right]\right)$ M. R. Stinson & Y. Champoux, J. Acoust. Soc. Am. 91, 685-695, 1992.
Rectangle ($2a \times 2b$) 	$\frac{\rho_0}{\phi} \times \frac{\eta a^2 b^2}{4j\omega\rho_0}/\left[\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{1}{\alpha_m^2\beta_n^2(\alpha_m^2 + \beta_n^2 + j\omega\rho_0/\eta)}\right]$ with $\alpha_m = (m + 1/2)\pi/a$ and $\beta_n = (n + 1/2)\pi/b$	$\frac{P_0}{\phi} \times \gamma/\left(\gamma - (\gamma - 1)\frac{4j\omega\rho_0\mathrm{Pr}}{\eta a^2 b^2}\left[\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{1}{\alpha_m^2\beta_n^2(\alpha_m^2 + \beta_n^2 + j\omega\rho_0\mathrm{Pr}/\eta)}\right]\right)$ M. R. Stinson, J. Acoust. Soc. Am. 89, 550-558, 1991. H. Roh, W. P. Arnott, J. M. Sabatier & R. Raspet, J. Acoust. Soc. Am. 89, 2617-2624, 1991.

ρ_0	Density of air at rest	$\mathrm{kg.m^{-3}}$
η	Dynamic viscosity of air	$\mathrm{N.s.m^{-2}}$
γ	Ratio of specific heat	
P_0	Static/Atmospheric pressure	Pa
Pr	Prandtl's number	
ω	Pulsation (angular frequency)	$\mathrm{s^{-1}}$
ϕ	Open porosity of the material	

$j = \sqrt{-1}$

J_n Bessel function of the first kind

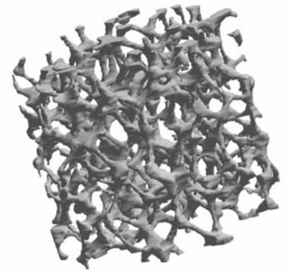
With a $\exp(+j\omega t)$ time convention, characteristic impedance and wavenumber are deduced from:
$Z_c = \sqrt{\tilde{\rho}_{eq}\tilde{K}_{eq}}$ and $k_c = \omega\sqrt{\tilde{\rho}_{eq}/\tilde{K}_{eq}}$

Micro-macro approaches

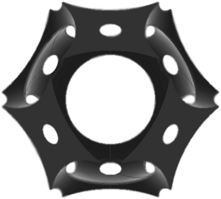
Objectives of micro-macro approaches :

- to link the microstructure to macroscopic parameters,
- to understand the material response according to various physics,
- to communicate between the different actors of the manufacturing.

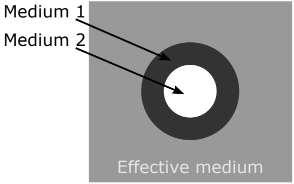
Approaches



a) Real microstructure

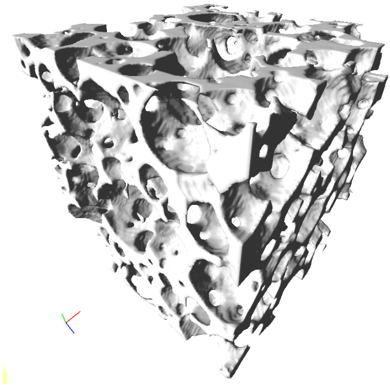


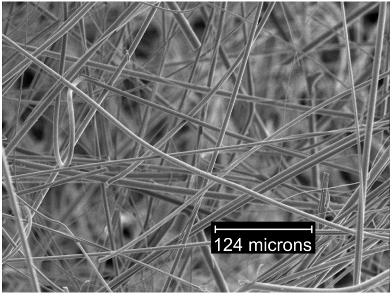
b) Idealized cell



c) Self consistent model

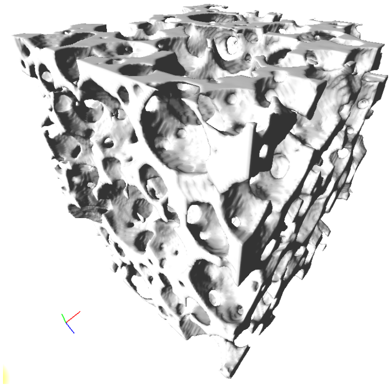
Real microstructure

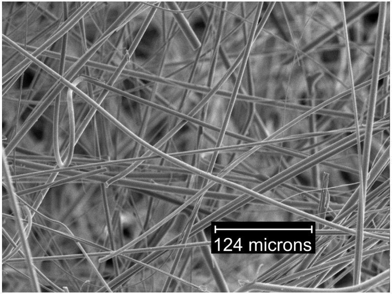




+ Real microstructure
- Expensive in memory and time
- Not adapted for optimisation

Real microstructure





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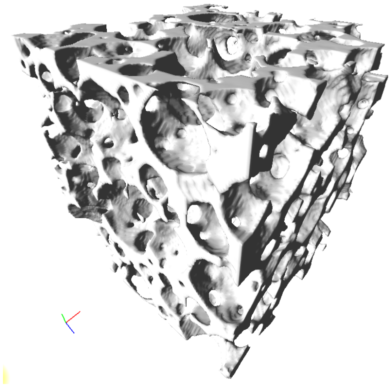

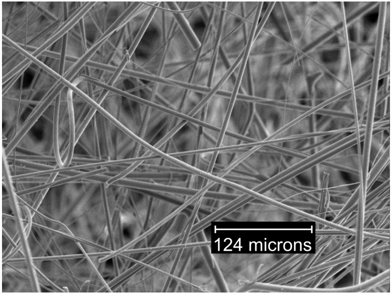

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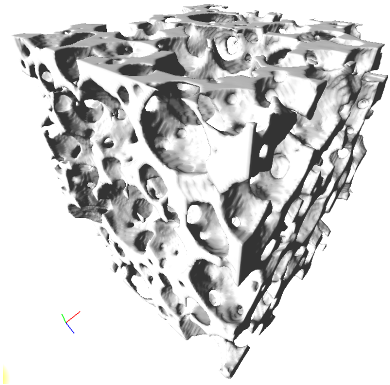

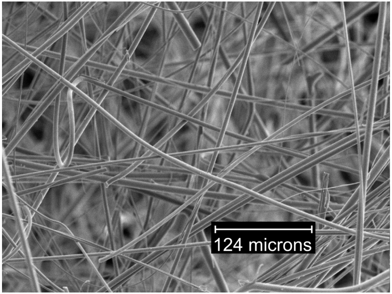

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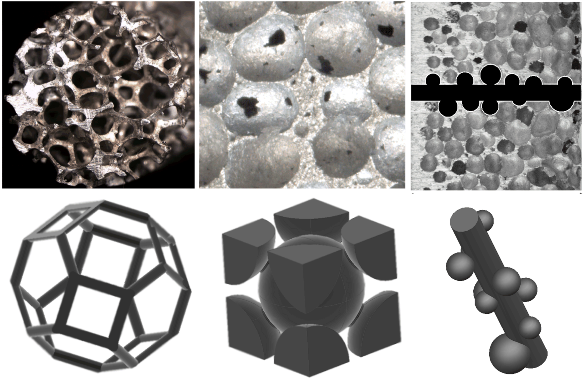
Idealized cell



(a) (b) (c)

+ Adapted for optimisation
- Difficulty in the selection and sizing of the cell

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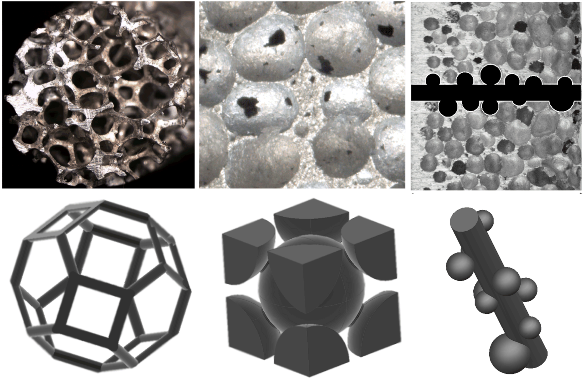

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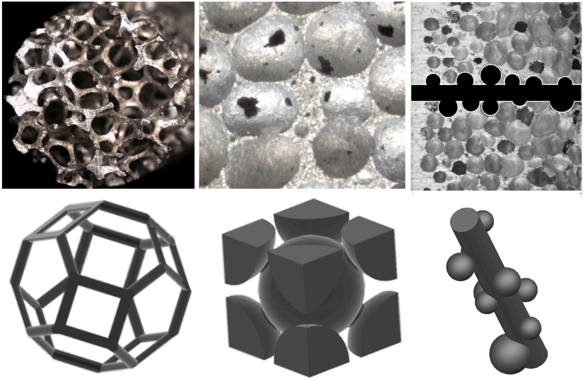
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Direct method: microscopic scale

- **Resolution** of two equations at the **microscopic scale** in dynamic regime

- Viscous effects (Navier-Stokes equation):

$$j\omega\rho_0\vec{u} = -\vec{\nabla}\tilde{p} + \eta\nabla^2\vec{u}$$

- Thermal effects (Heat conduction equation):

$$j\omega\rho_0 c_p\tilde{\tau} = j\omega\tilde{p} + \kappa\nabla^2\tilde{\tau}$$

$\vec{u}$: velocity field
$\tilde{p}$: pressure field
$\tilde{\tau}$: temperature field
ρ_0, c_p, η, κ: properties of the fluid (air)

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$$\tilde{\rho}_{eq}(\omega) = \frac{\eta}{j\omega \tilde{k}(\omega)}$$

- Thermal effects:

$$\phi \langle \tilde{\tau} \rangle = j\omega \frac{\tilde{k}'}{\kappa} \langle \tilde{p} \rangle$$

$$\tilde{\beta}(\omega) = \gamma - (\gamma - 1) \frac{j\omega}{\nu'} \frac{\tilde{k}'(\omega)}{\phi} \quad \text{and} \quad \tilde{K}_{eq}(\omega) = \frac{\gamma Po}{\phi \tilde{\beta}(\omega)}$$

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Hybrid method

The **hybrid method** contains two stages :

- Computation of the macroscopic parameters $(\phi, \sigma, \Lambda, \Lambda', \alpha_\infty, ...)$ from asymptotic behaviour (LF & HF) of the visco-inertial and thermal effects.
- Computation of the **dynamic mass density** $\tilde{\rho}(\omega)$ and of the **dynamic bulk modulus** $\tilde{K}(\omega)$ from semi-phenomenological models (JCA, JCAL, JCAPL, ...).

The two **main advantages** of this method are :

- the prediction on broad frequency range from only **three computations**,
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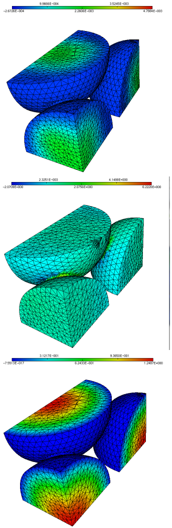
Hybrid method : summary



- **Geometric mesh** :
  - porosity ϕ
  - thermal characteristic length Λ'
- **LF viscous computation** (Stokes):
  - static air flow resistivity σ
  - static viscous tortuosity α_0 (Optional)
- **HF inertial computation** (Perfect fluid)($\approx$ electrical conduction):
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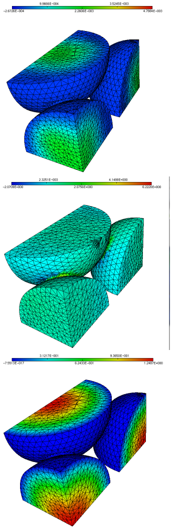

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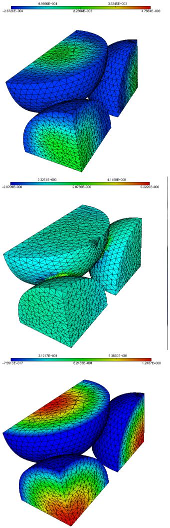

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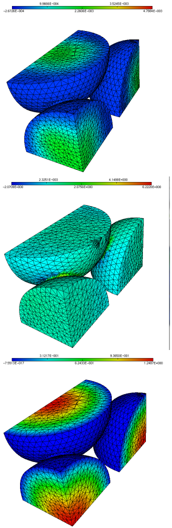

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Adding elastic effects

- Using Biot's theory, it is possible to couple elastic effects to any visco-thermal model

  F.-X. Bécot, L. Jaouen, "Alternative Biot's form for porous media" (2013)

- Mixing laws: $E = E_1(1 - \phi_{meso}) + E_2\phi_{meso}$

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- Micro-macro approaches for elastic properties

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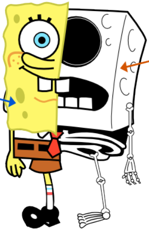

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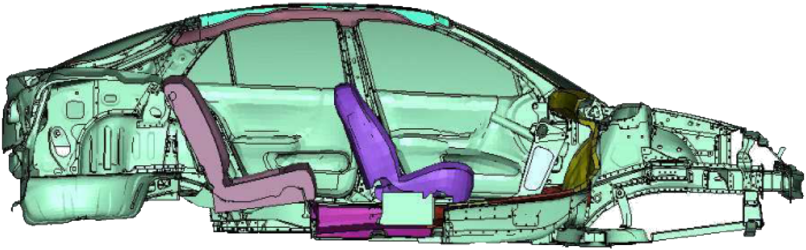
Condensed models

- Example of a car with acoustical sound package



Source: A. Duval - Sapem 2005

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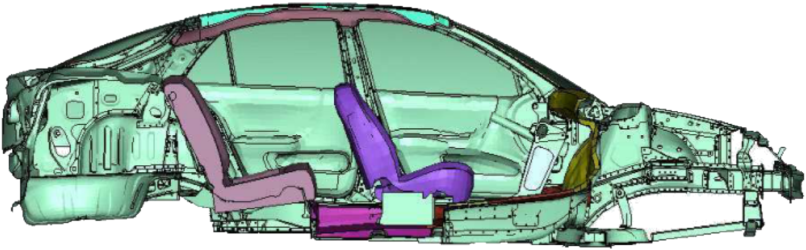

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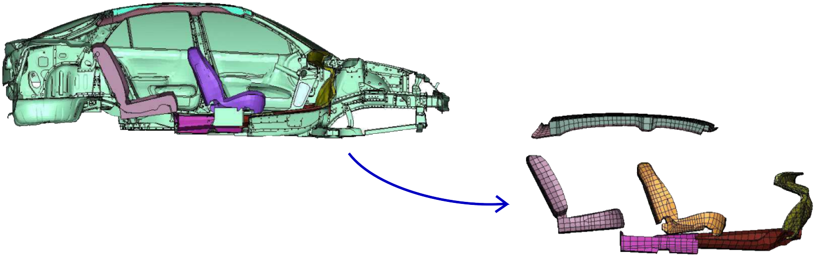
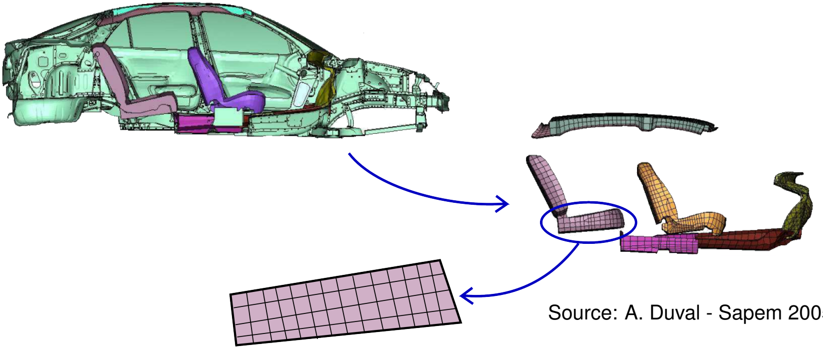
- How to add physics to the models to reduce their size?

- Focus on the porous parts



Source: A. Duval - Sapem 2005

- Focus on one porous part



Source: A. Duval - Sapem 2005

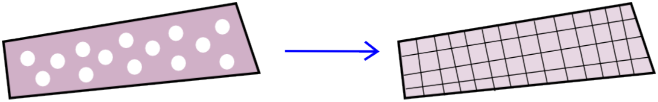
- Is it possible to model rigid or elastic meta-materials as a condensed model?

Non-conventional phenomena involved in meta-materials

- **Multi-scale material with diffusion processes**
  - Double porosity media (air inclusions)
  - Solid inclusions
  - Porous inclusions
  - Sorption
- **Acoustical resonators**
- **Soft membranes**
- **Periodicity**
- **Impedance matching**

Double porosity media

- Porous media with **air inclusions**



- Weight reduction
- Can take advantage from additional diffusion effects

$$\tilde{\rho}_{eq} = \frac{1}{\frac{(1-\phi_{meso})}{\tilde{\rho}_{eq\_micro}} + \frac{1}{\tilde{\rho}_{eq\_meso}}}$$

$$\tilde{K}_{eq} = \frac{1}{\frac{(1-\phi_{meso})\,F_d}{\tilde{K}_{eq\_micro}} + \frac{1}{\tilde{K}_{eq\_meso}}}$$

F_d: Dynamic diffusion function.

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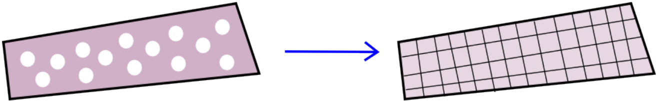

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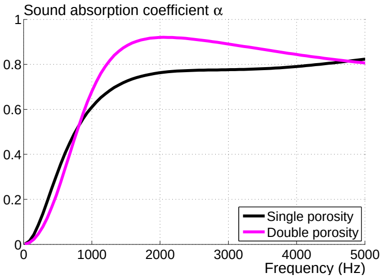

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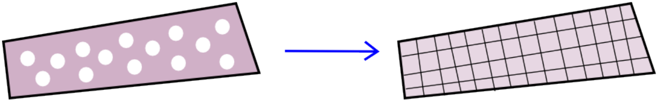

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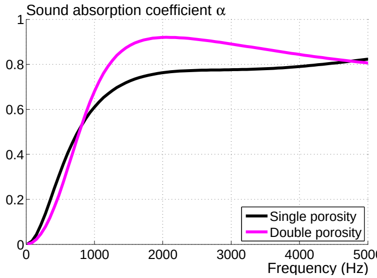

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Solid inclusions

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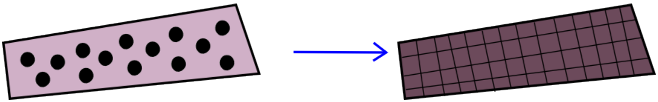

- Tortuous effect
- Eventually add multiple scattering effect

V. Tournat, V. Pagneux, D. Lafarge, L. Jaouen, "Multiple scattering of acoustic waves and porous absorbing media", *Phys. Rev. E* 70, 026609, (2004)

F. Chevillotte, L. Jaouen, F.-X. Bécot, "On the modeling of visco-thermal dissipations in heterogeneous porous media",*J. Acoust. Soc. Am.* **138**(6), 3922-3929 (2015)

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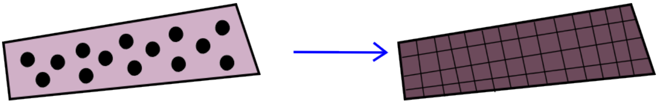

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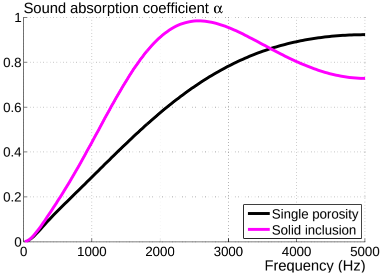

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Porous inclusions

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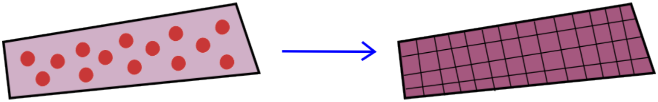

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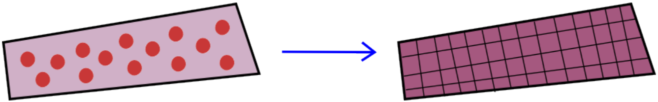

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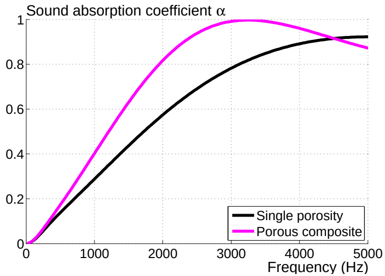

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Sorption

- Double porosity with nanoscale (third scale of porosity)
- The diffusion process can be enhanced by using sorption process (adsorption/desorption)
- Activated carbon for instance
- Reducing the bulk modulus (virtually increasing the volume of a cavity)

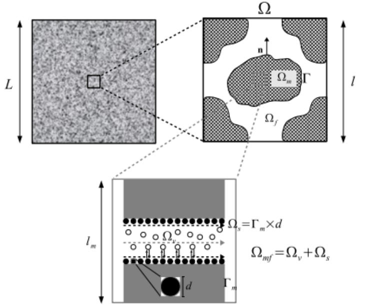
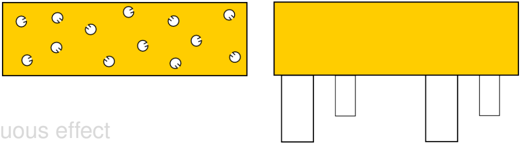


Fig. 1. Diagram of the scales of a hierarchical sorptive porous material.

R. Venegas, O. Umnova, "Influence of sorption on sound propagation in granular activated carbon",*J. Acoust. Soc. Am.* **68**, 162-181 (2017)
R. Venegas, C. Boutin, "Acoustics of sorptive porous materials.",*Wavemotion* **828**, 135-174 (2017)

Acoustical resonators

- Porous media with **(inner) resonators**



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$$\tilde{K}_{eq} = \frac{1}{\frac{(1-\phi_{meso})}{\tilde{K}_{eq\_micro}} + \frac{\phi_{meso}}{\tilde{K}_{eq\_res}}}$$

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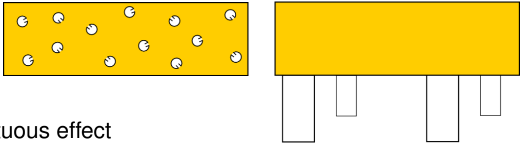

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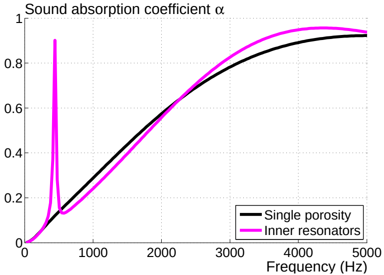

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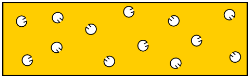

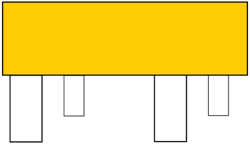

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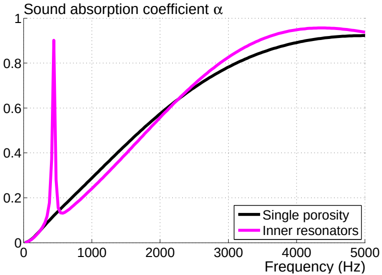

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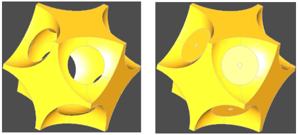
Soft membranes

- Rigid membranes are known to increase the airflow resistivity as well as the tortuosity



- The use of **soft membranes** allows a **permeo-elastic** coupling

C. Gaulon, J. Pierre, C. Derec, L. Jaouen, F.-X. Bécot, F. Chevillotte, F. Elias, W. Drenckhan, and V. Leroy, "Acoustic absorption of solid foams with thin membranes.",*Appl. Phys. Lett.* **112**(261904), (2018)
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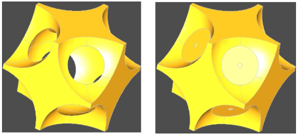

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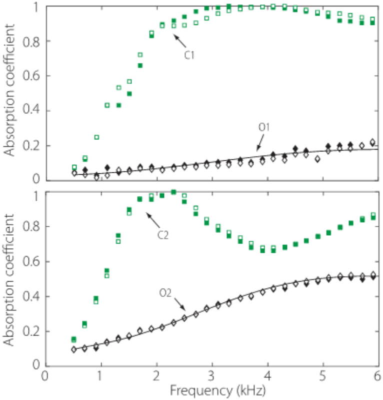

FIG. 3. Measured absorption versus frequency for open cell foams (O1 and O2, black symbols) and closed-cell foams (C1 and C2, green symbols). Samples were 2 cm thick. Reproducibility was tested by measuring 2 samples of each type (solid and open symbols). Solid black lines show JCAL model for the open-cell foams.

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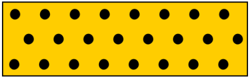
Periodicity

- Porous media with **periodic** solid inclusions



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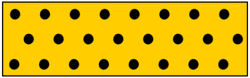

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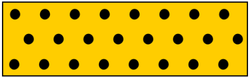

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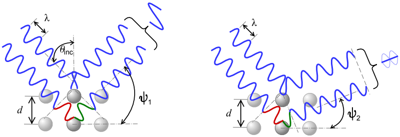

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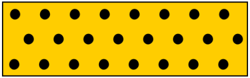

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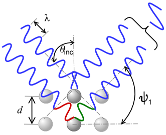

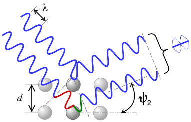

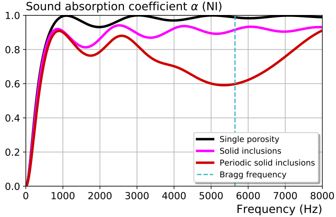

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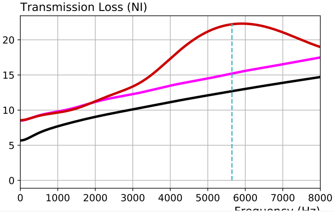

Impedance matching

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- Generally achieved by **modyfing the topology**

- Functionnally **graded materials** are also good candidates

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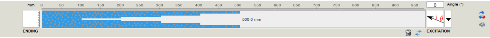

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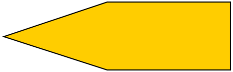

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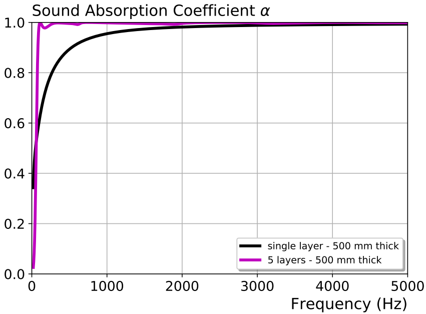

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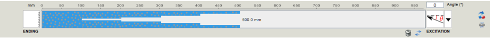

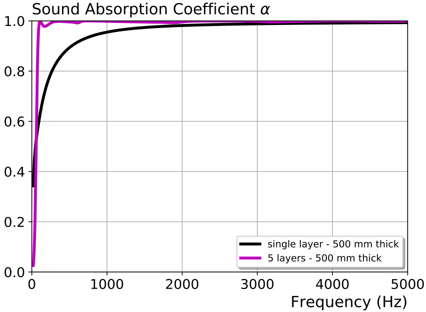

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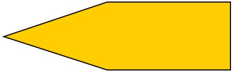

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Non-conventional phenomena involved in meta-materials

Summary of analytical condensed models:

- **Multi-scale material with diffusion processes**
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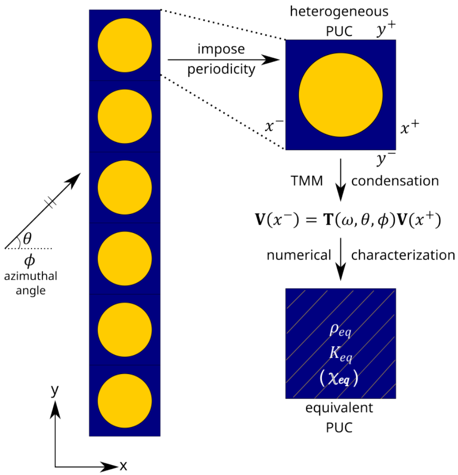

A. Parrinello, A., G. Ghiringhelli "Transfer matrix rep resentation for periodic planar media," Journal of Sound and Vibration 371, 196–20, 2016
A. Parrinello, A., G. Ghiringhelli, N. Atalla "Generalized transfer matrix method for periodic planar media," Journal of Sound and Vibration 464, 11499, 2020
A. Sreekumar, F. Chevillotte, E. Gourdon "Numerical characterization of heterogeneous meta-materials." Forum Acusticum 2023, Turin, Italy. Submitted to J. Acous. Soc. Am.

Numerical condensation

- Condensed fluid matrix (inc. angle dependent, propagation along x)

$$\mathbf{T} = \begin{bmatrix} \cos(k_x l) & j\frac{\rho_{\text{eq}}\omega}{k_x}\sin(k_x l) \\ j\frac{k_x}{\rho_{\text{eq}}\omega}\sin(k_x l) & \cos(k_x l) \end{bmatrix} \text{ with } k_x = \sqrt{k_{\text{eq}}^2 - k_t^2}$$

and $k_t = k_0 \sin(\theta)$

- Using the Stroh formalism:

$$\mathbf{T} = \exp(\mathbf{A}l) \quad \text{with } \mathbf{A} = j\omega \begin{bmatrix} \chi & \rho_{\text{eq}} \\ \frac{1}{K_{\text{eq}}} - \frac{k_t^2}{\rho_{\text{eq}}\omega^2} & -\chi \end{bmatrix}$$

χ enables to account for asymmetry

J.-P. Groby, M. Malléjac, A. Merkel, V. Romero-Garcia, V. Tournat, D. Torrent, and J. Li, "Analytical modeling of one-dimensional resonant asymmetric and reciprocal acoustic structures as Willis materials," New Journal of Physics 23(5), 466 053020, 2021

F. Marchetti, F. Chevillotte, "On the use of an additional parameter for thecharacterization and the condensation ofheterogeneous or non-symmetric multilayered materials", SAPEM, Changshu and Sorrento, China and Italy, 2023

Numerical condensation

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$$\mathbf{T} = \begin{bmatrix} \cos(k_x l) & j\frac{\rho_{\text{eq}}\omega}{k_x}\sin(k_x l) \\ j\frac{k_x}{\rho_{\text{eq}}\omega}\sin(k_x l) & \cos(k_x l) \end{bmatrix} \text{ with } k_x = \sqrt{k_{\text{eq}}^2 - k_t^2}$$

$$\text{and } k_t = k_0 \sin(\theta)$$

- Using the Stroh formalism:

$$\mathbf{T} = \exp(\mathbf{A}l) \quad \text{with } \mathbf{A} = j\omega \begin{bmatrix} \chi & \rho_{\text{eq}} \\ \frac{1}{K_{\text{eq}}} - \frac{k_t^2}{\rho_{\text{eq}}\omega^2} & -\chi \end{bmatrix}$$

χ enables to account for asymmetry

J.-P. Groby, M. Malléjac, A. Merkel, V. Romero-Garcia, V. Tournat, D. Torrent, and J. Li, "Analytical modeling of one-dimensional resonant asymmetric and reciprocal acoustic structures as Willis materials," New Journal of Physics 23(5), 466 053020, 2021
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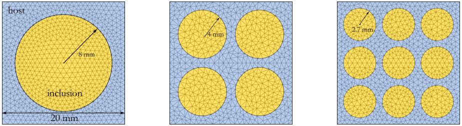
Numerical condensation

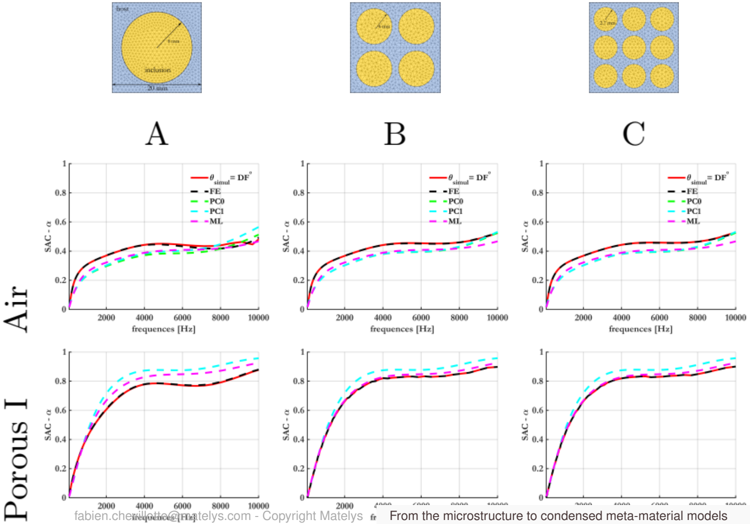
- Configurations and material parameters



	Host	Inclusion				
		Air	**Porous I**	**Porous II**	**Porous III**	**Rigid**
σ $[N \cdot m \cdot s^{-4}]$	8900	-	2×10^4	2×10^5	2×10^7	-
ϕ	0.95	-	0.95	0.95	0.95	-
α_∞	1.42	-	1	1	1	-
Λ $[m]$	100×10^{-6}	-	8.802×10^{-5}	2.783×10^{-5}	2.783×10^{-6}	
Λ' $[m]$	360×10^{-6}	-	8.802×10^{-5}	2.783×10^{-5}	2.783×10^{-6}	

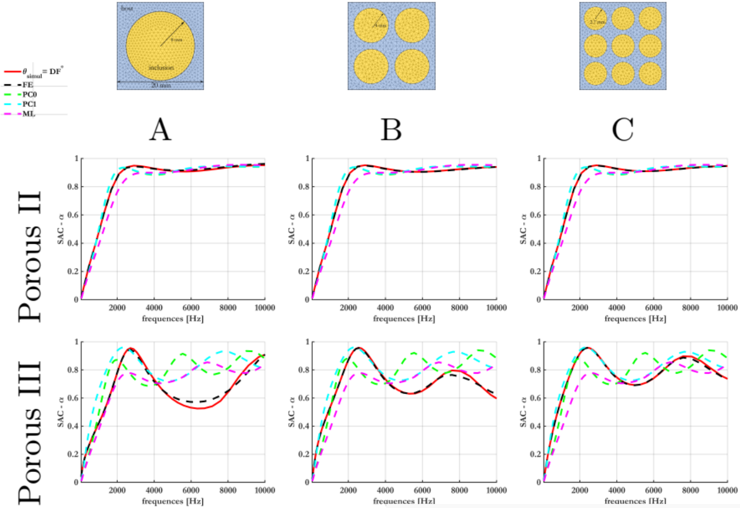
Numerical condensation

- Sound absorption coefficients under DF (1/3)



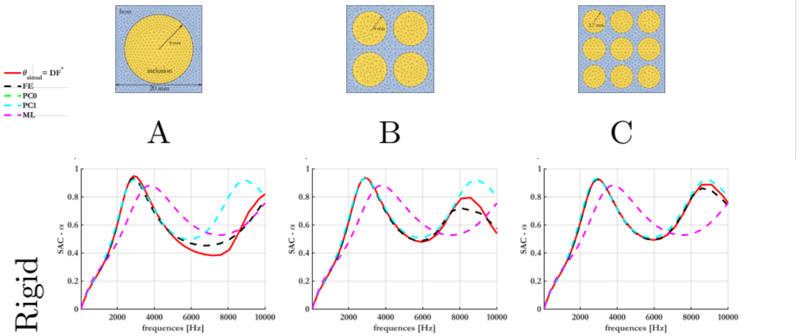
Numerical condensation

- Sound absorption coefficients under DF (2/3)



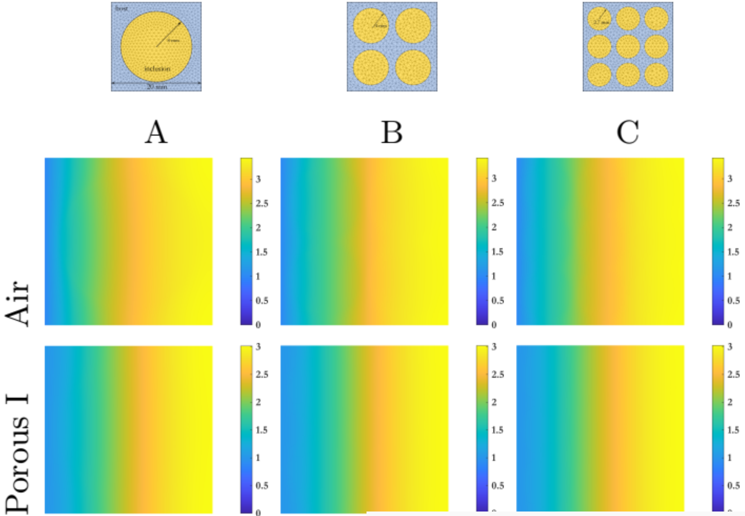
Numerical condensation

- Sound absorption coefficients under DF (3/3)



Numerical condensation

- Pressure fields @ 3064 Hz (1/3)



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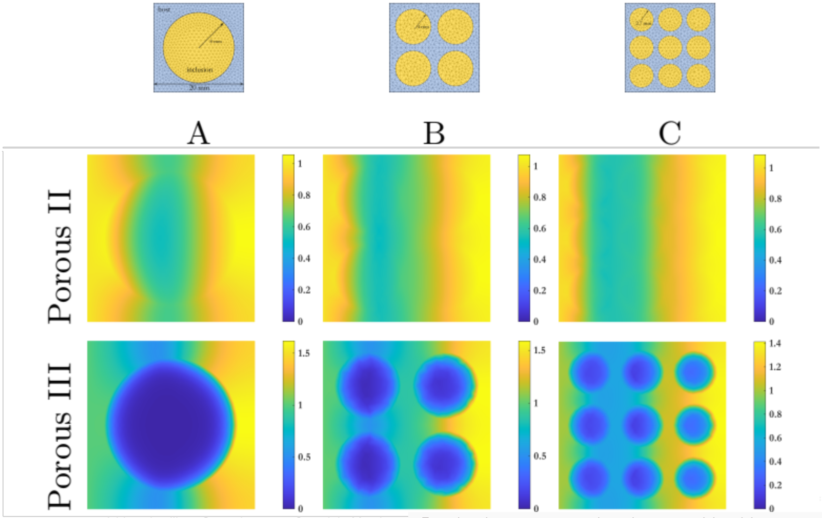

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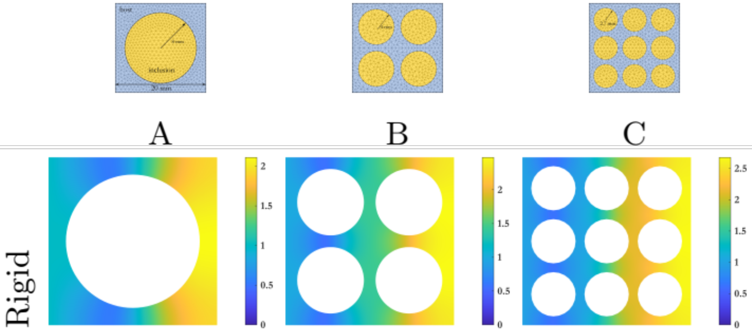

Conclusion

- The equivalent fluid formalism enables to embed complex phenomena into condensed models (flow distorsion, pressure diffusion, inner resonance, ...).
- Simple micro- or meso-structures can be described from analytical formulas
- Micro-macro methods can be used when dealing with more complex shapes
- Numerous homogeneisation models are available for non-conventional phenomena involved in meta-materials.
- Otherwise, numerical characterization procedure can be employed.

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- This formalism is compatible with the Biot's theory. It is thus simple to add elastic effects, especially for transmission purposes.
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Thank You for your Attention!

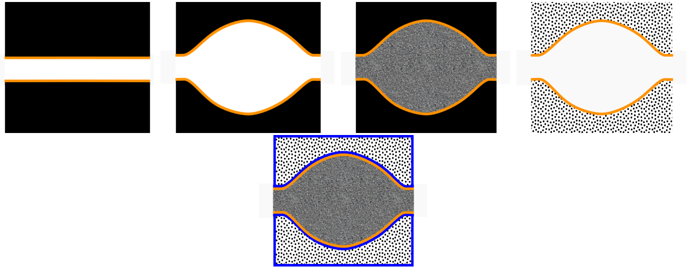
MATELYS
Research Lab

fabien.chevillotte@matelys.com

Composite model

- A composite model has recently been presented.

  F. Chevillotte, L. Jaouen, F.-X. Bécot, "On the modeling of visco-thermal dissipations in heterogeneous porous media",*J. Acoust. Soc. Am.* **138**(6), 3922-3929 (2015)
- Consideration of the **shape** of the mesoscopic parts.
- Consideration of the flow distortion.
- Consideration of the pressure diffusion effect.



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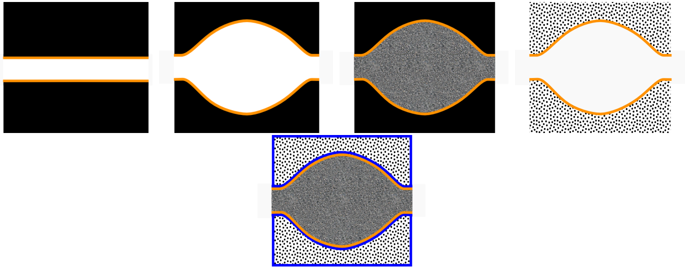
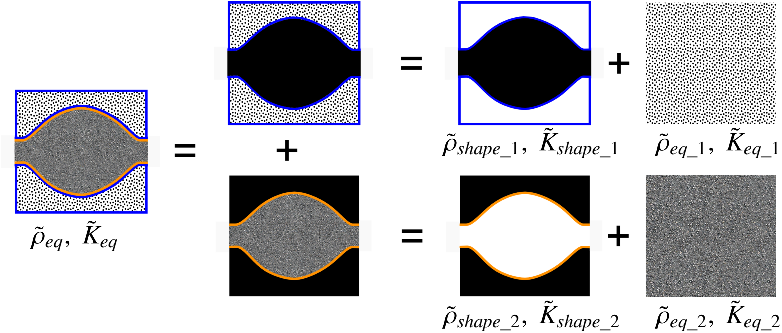


Perforated plate | Usual model | Porous inclusion | Double porosity | Composite

Composite porous media



Shape consideration

Visco-inertial effects

$$\tilde{\rho}_{shape}(\omega) = \tilde{\rho}_{eq}(\omega)\alpha_\infty \left[1 - j\frac{\omega_v}{\omega}\tilde{G}(\omega)\right]$$

$$\tilde{G}(\omega) = \sqrt{1 + \frac{1}{2} jM \frac{\omega}{\omega_v}}$$

$$M = \frac{8k_0\alpha_\infty}{\phi\Lambda^2}; \quad \omega_v = \frac{\nu\phi}{k_0\alpha_\infty}$$

$$\nu = \frac{\eta}{\tilde{\rho}_{eq}(\omega)}$$

Thermal effects

$$\tilde{K}_{shape}(\omega) = \frac{\tilde{K}_{eq}(\omega)}{\gamma - (\gamma - 1)\left[1 - j\frac{\omega_t}{\omega}\tilde{G}'(\omega)\right]^{-1}}$$

$$\tilde{G}'(\omega) = \sqrt{1 + \frac{1}{2} jM' \frac{\omega}{\omega_t}}$$

$$M' = \frac{8k_0'}{\phi\Lambda'^2}; \quad \omega_t = \frac{\nu'\phi}{k_0'}$$

$$\nu' = \frac{\kappa}{\tilde{\rho}_{eq}(\omega) C_p}$$

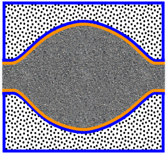
Porous composite

$$\tilde{\rho}_{eq} = \frac{1}{\dfrac{1}{\tilde{\rho}_{eq\_shape\_1}} + \dfrac{1}{\tilde{\rho}_{eq\_shape\_2}}}$$

$$\tilde{K}_{eq} = \frac{1}{\dfrac{\tilde{F}^1_{dw}}{\tilde{K}_{eq\_shape\_1}} + \dfrac{\tilde{F}^2_{dw}}{\tilde{K}_{eq\_shape\_2}}}$$

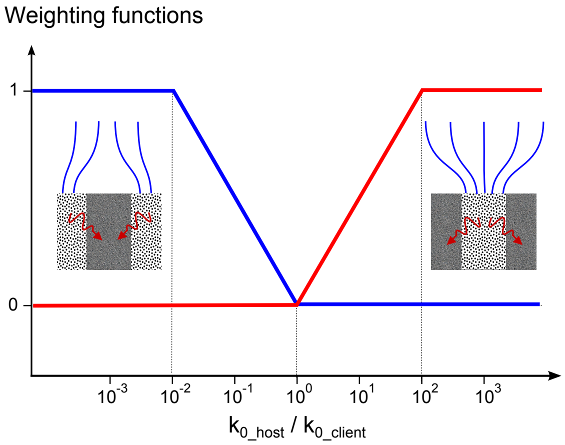
$$\phi_{meso} = \phi_{shape\_1}$$

$$1 - \phi_{meso} = \phi_{shape\_2}$$

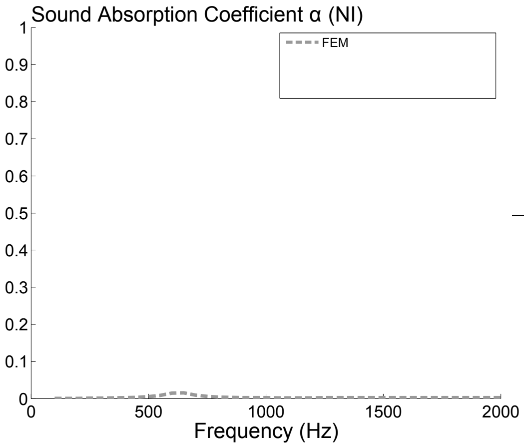


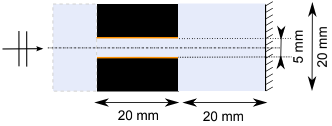
$\tilde{F}^1_{dw}$ et $\tilde{F}^2_{dw}$: Diffusion functions $2 \rightarrow 1$ et $1 \rightarrow 2$.

Consideration of diffusion and flow distorsion



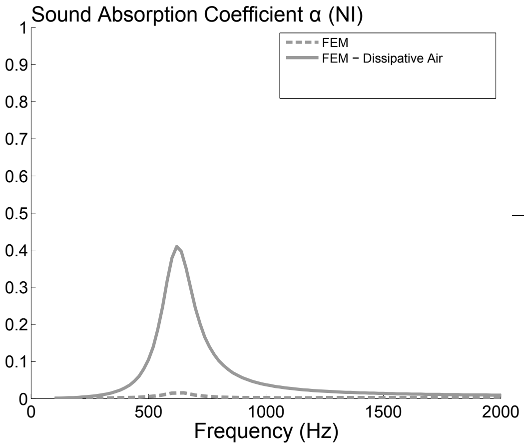
Perforated plate

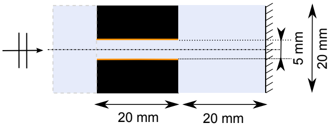




- Validation with flow distorsion.

Perforated plate





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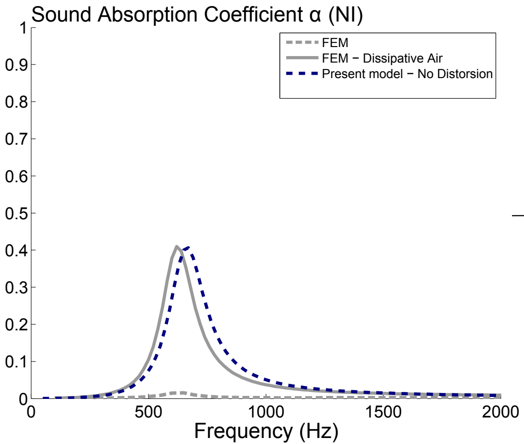

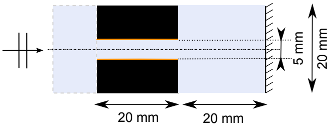

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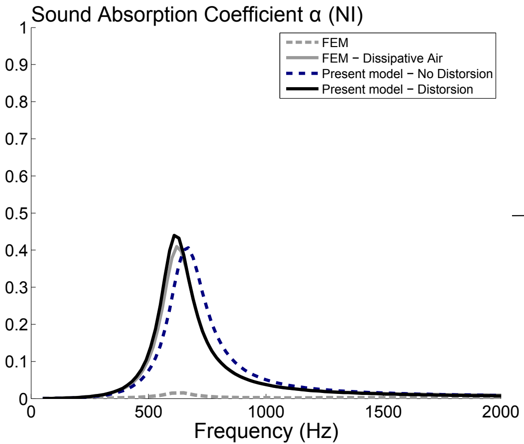

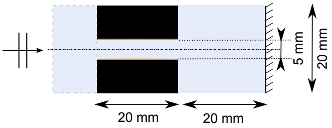

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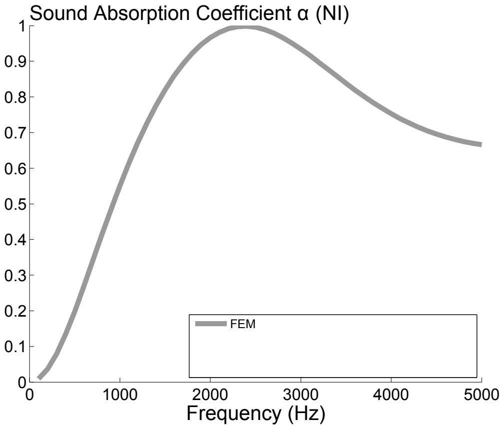
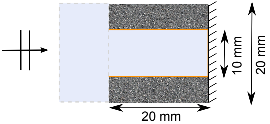
Double porosity media

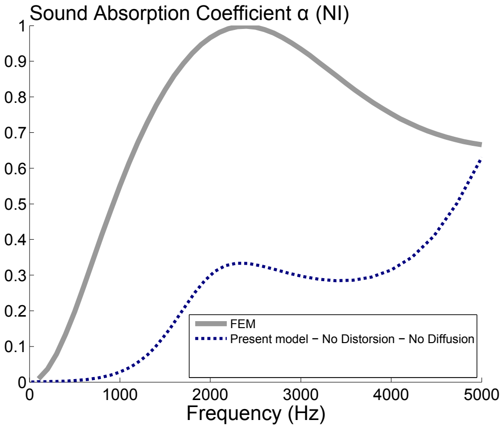


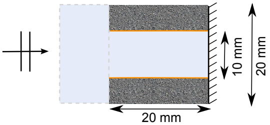


Host: $\sigma = 1\ 000\ 000$ N.s.m^{-4}
Client: Air

- Validation with diffusion.

Double porosity media





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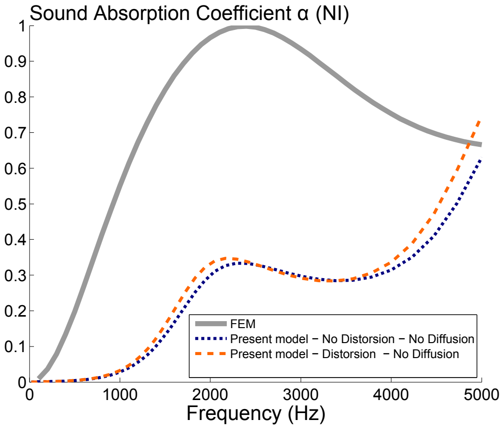

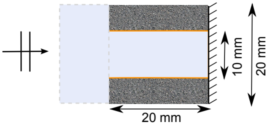

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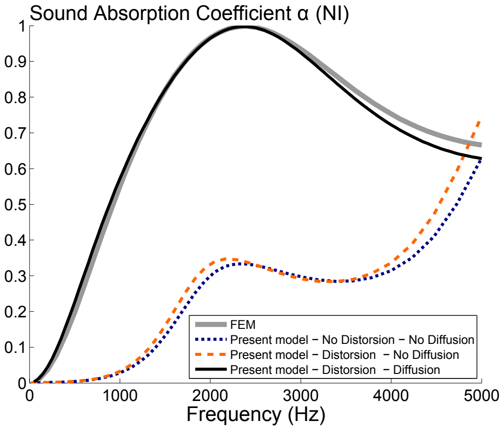

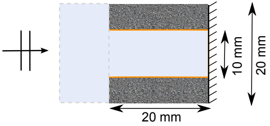

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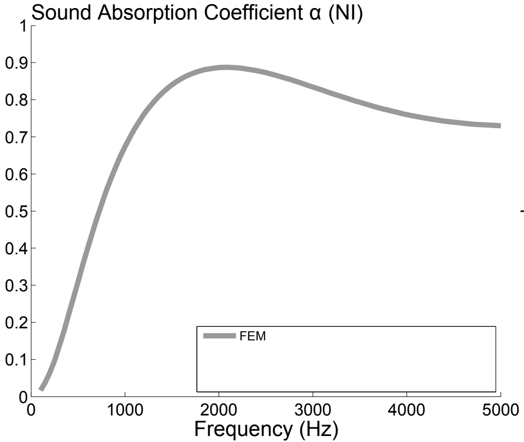
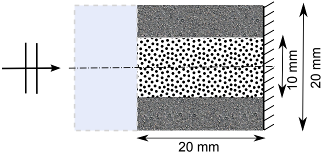
Porous composite - simple shape





Host: σ = 1 000 000 N.s.m^{-4}
Client: σ = 11 500 N.s.m^{-4}

- Validation with diffusion between porous media.

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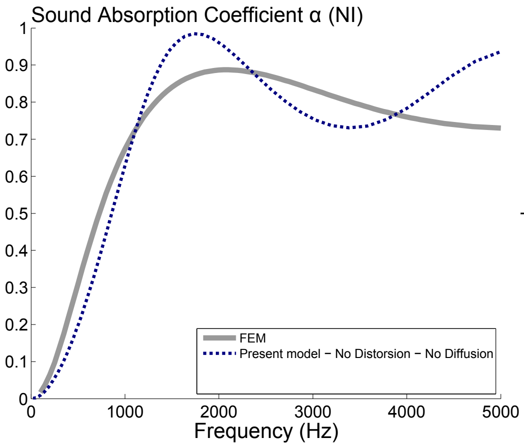

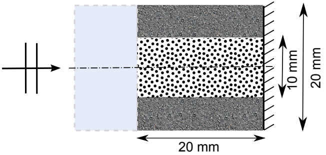

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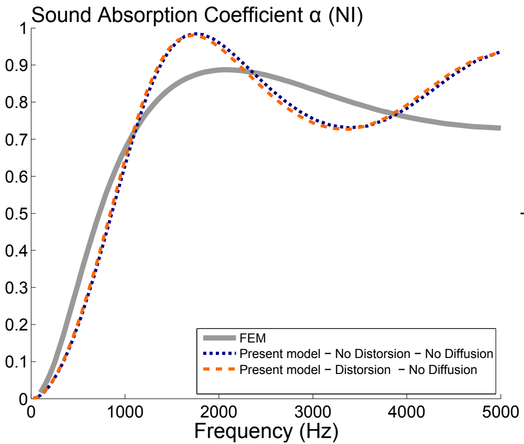

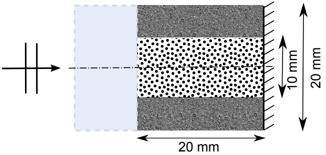

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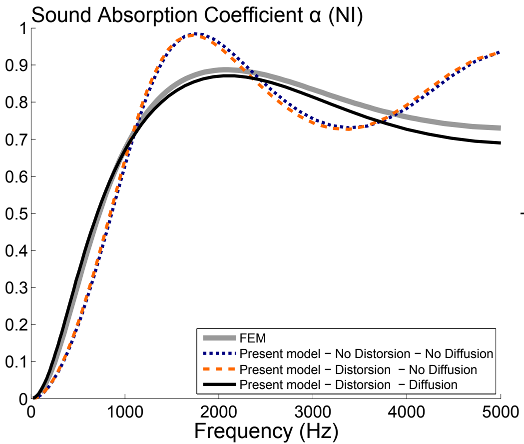

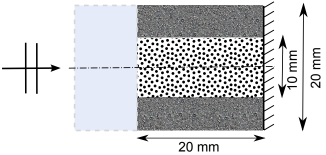

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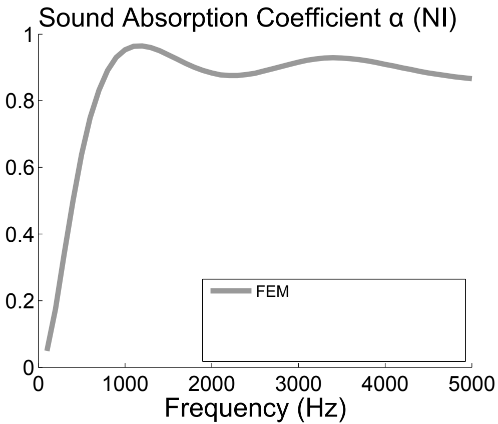
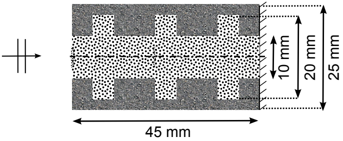
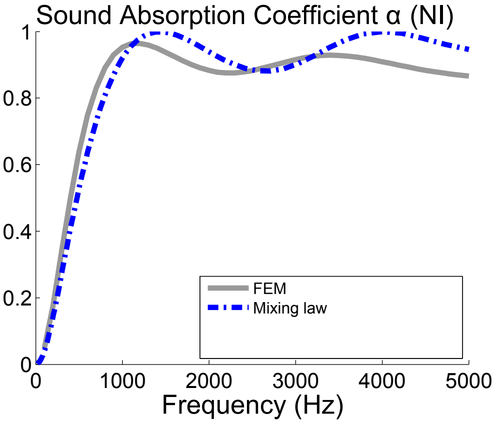


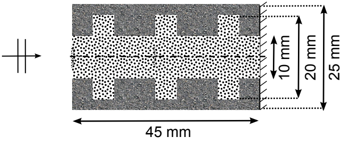


Host: σ = 1 000 000 N.s.m^{-4}
Client: σ = 11 500 N.s.m^{-4}

- Validation with shape and diffusion.

Porous composite - complex shape





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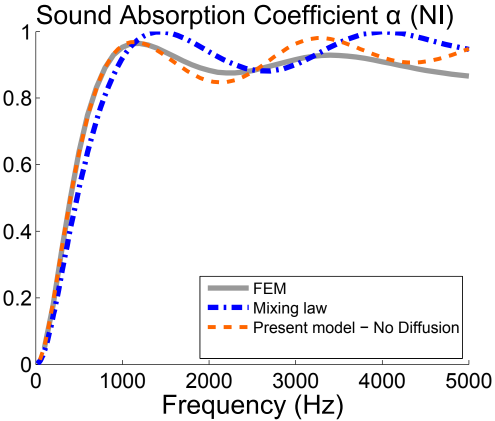

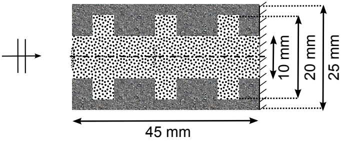

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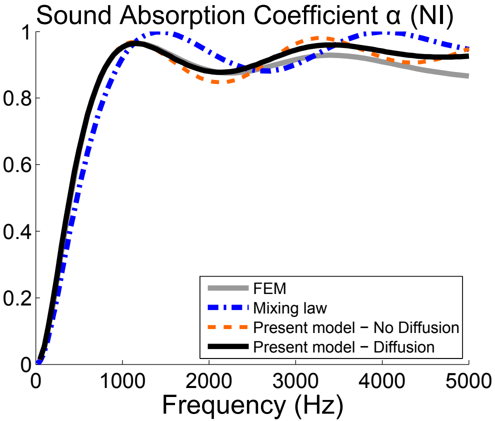
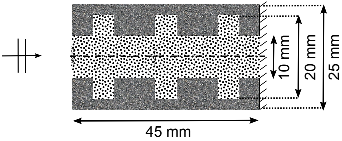
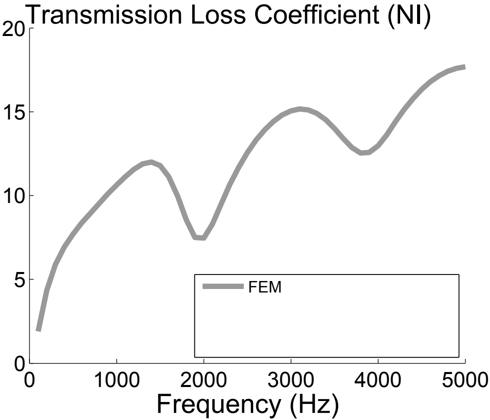


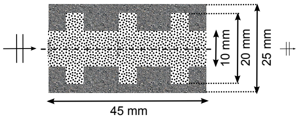


Host: σ = 1 000 000 N.s.m^{-4}
Client: σ = 11 500 N.s.m^{-4}

- Validation with shape and diffusion.

Porous composite - Transmission



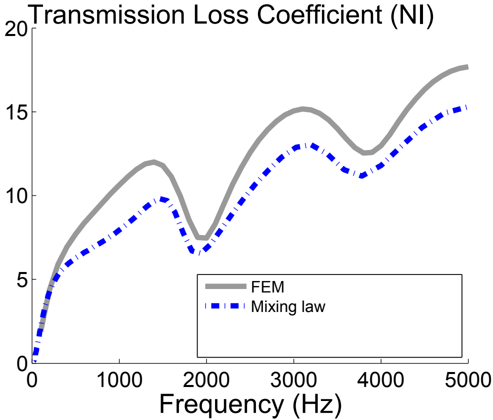


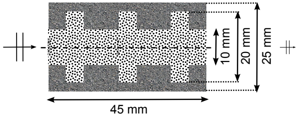
Host: $\sigma = 150\,000$ N.s.m^{-4}
$E = 500\,000$ Pa
Client: $\sigma = 10\,000$ N.s.m^{-4}
$E = 200\,000$ Pa

- Consideration for elastic effects:

J. C. Halpin , J. L. Kardos , "The Halpin-Tsai equations: A review", Polymer Engineering and Science, 16 (5), 344 - 352 1976).

Porous composite - Transmission





Host: $\sigma = 150\,000$ N.s.m^{-4}
$E = 500\,000$ Pa
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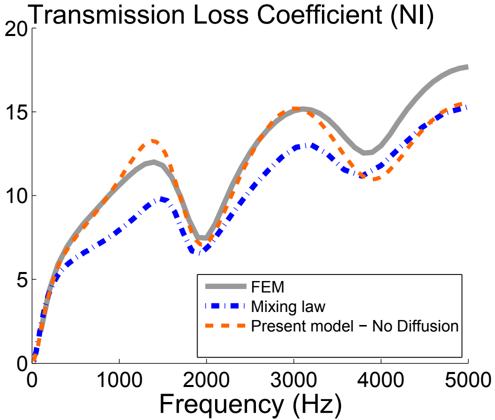

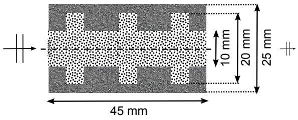

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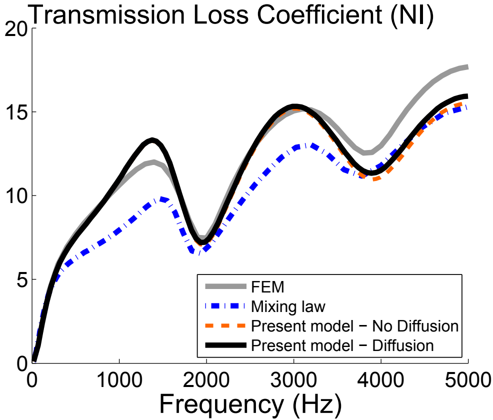

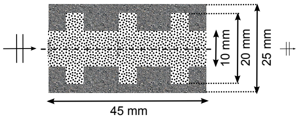

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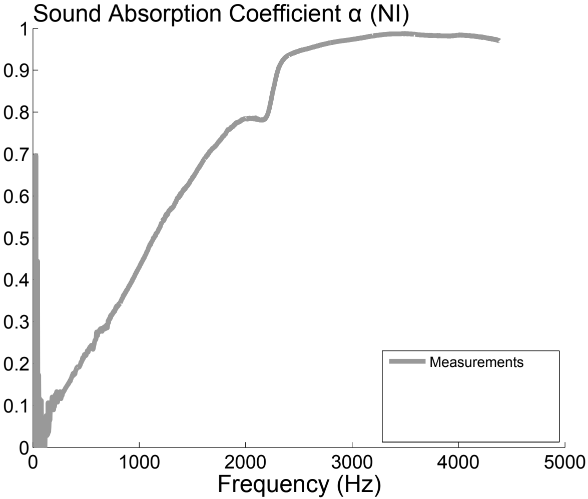
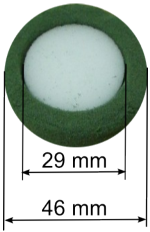
Experimental validation





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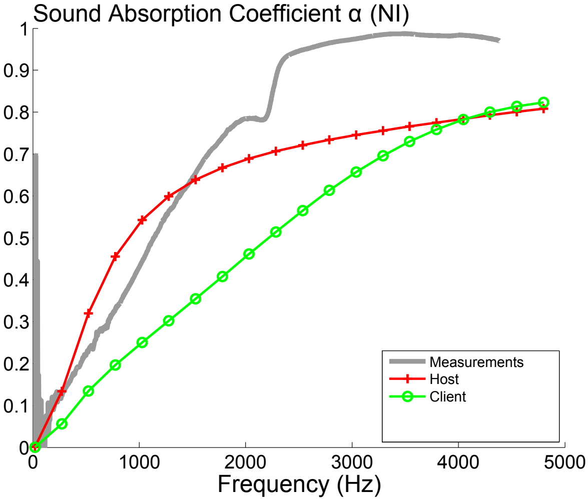

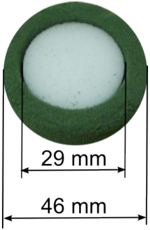

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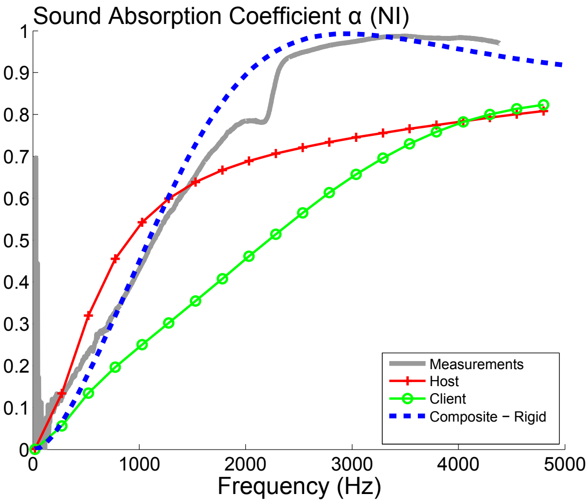

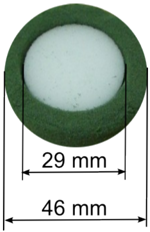

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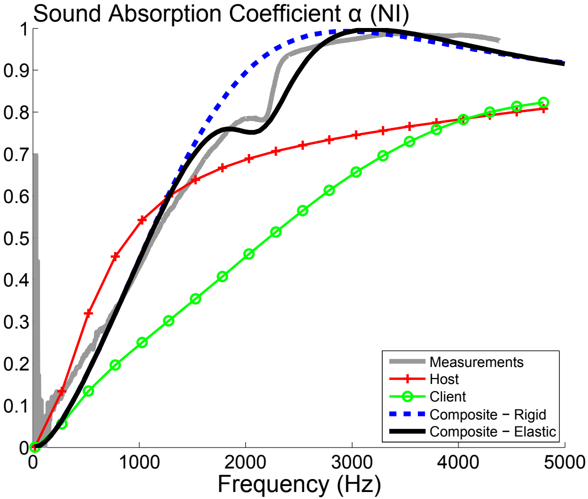

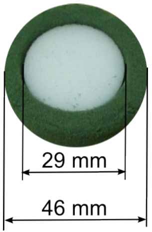

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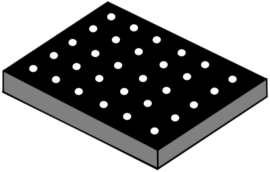
Examples with shape consideration

- Modified perforated plates.



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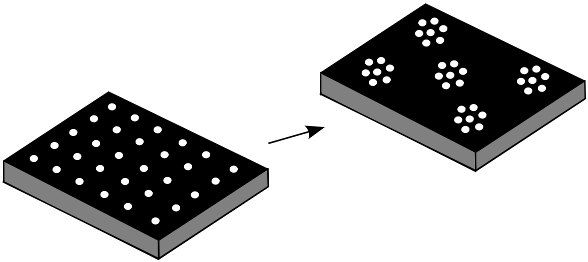

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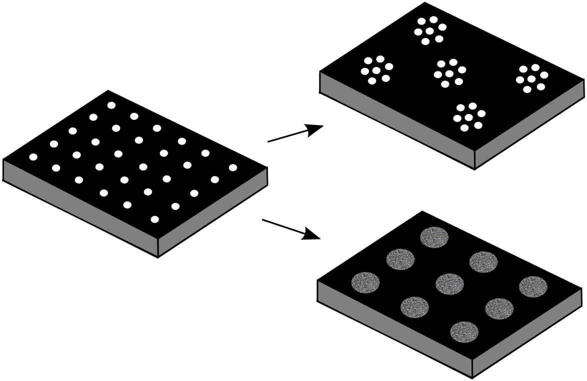

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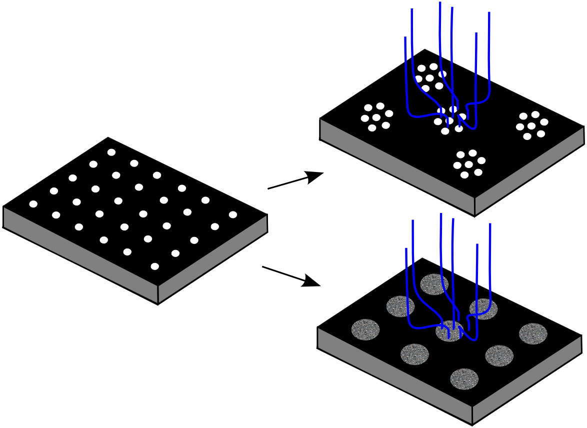

Examples with shape consideration

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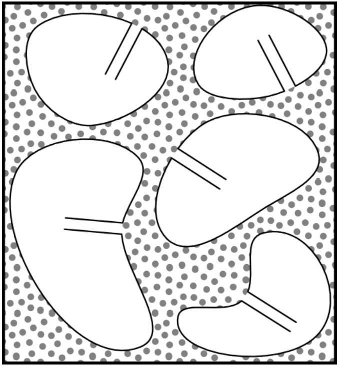

C. Boutin, "Acoustics of rigid porous media with inner resonators", J. Acoust. Soc. Am. 134 , 4717 (2013).

Alternative concepts

- **Mechanical resonators** can also be added to the structure
- **Spring-mass resonators**

F. Tateo, J. Michielsen, I. Lopez Arteaga, and H. Nijmeijer. “Resonant lattices for low-frequency vibro-acoustic control.” In Novem, Dubrovnik, Croatia, 2015.

- **Bending mode resonators**

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- **Non-linear mechanical resonators**

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E. Gourdon, N. A. Alexander, C. A. Taylor, C. H. Lamarque, and S. Pernot. “Nonlinear energy pumping under transient forcing with strongly nonlinear coupling: Theoretical and experimental results.” J. Sound Vib., 300(3-5): 522–551, 2007.

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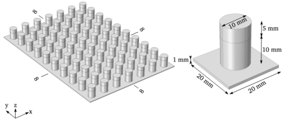

Figure 2. Considered elastic waveguide: 2D periodic lattice (left); unit cell (right).

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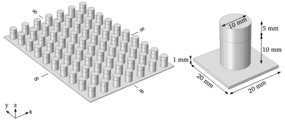

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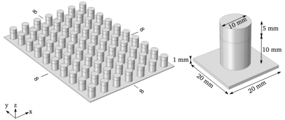

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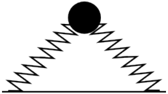

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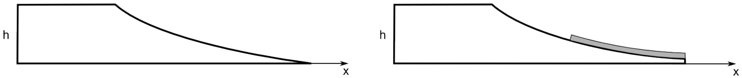
- **Impedance matching concept applied to structural vibrations (« Acoustic Black Hole »)**



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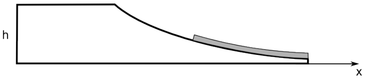

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