

Characterization and modeling challenges of multiple dynamics materials aka metamaterials

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In this talk :

- acoustic excitation
in air saturated porous materials / structures
- no active structures or "diode" effect
(the latter require a flow)
- no ~~black holes~~ (retardant structures)
- the time convention is $e^{+j\omega t}$

We can't be exhaustive on references.
If we forgot some awesome works,
submit them to @ljaouen or luc.jaouen@matelys.com

- These slides with some interactive documents at:
<http://apmr.matelys.com>

"Usual" rigid-frame porous materials

2 dynamic behaviors

based on Kirchhoff [-Langevin] theory

low frequencies high frequencies

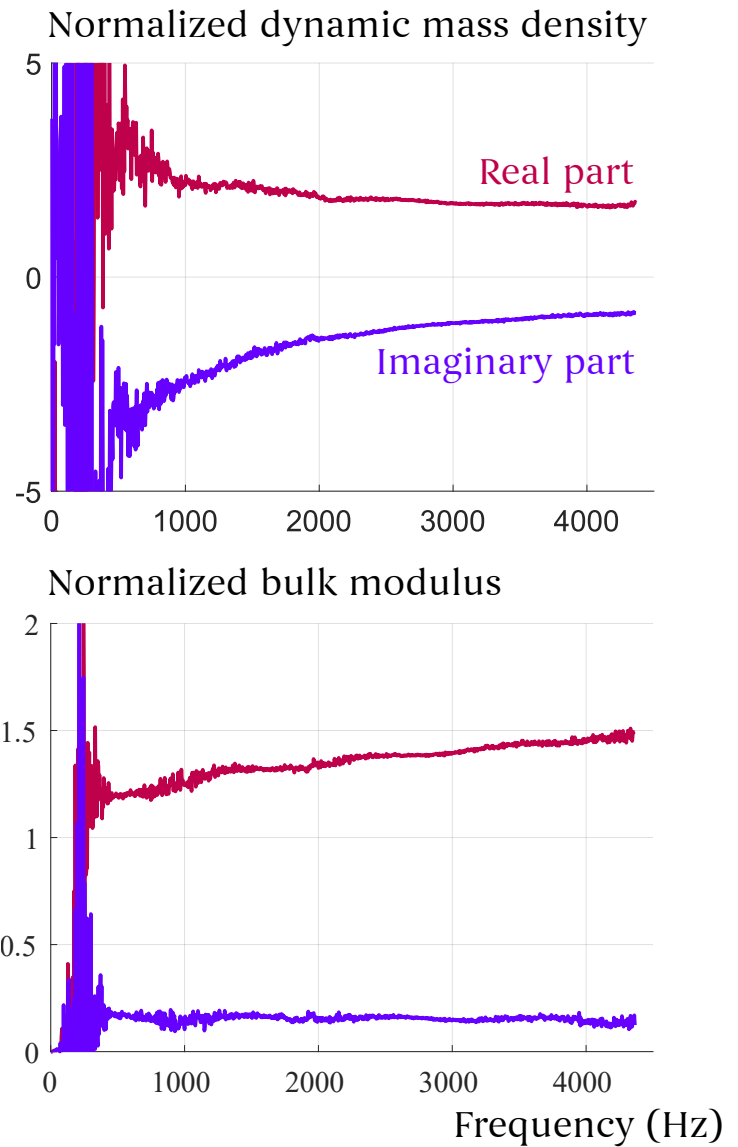
viscous flow → inertial flow

transitions
(with losses)

isothermal → adiabatic
behavior behavior

"Usual" rigid-frame porous materials

2 dynamic behaviors
based on Kirchhoff [-Langevin] theory



Materials with multiple scales of porosity

addition of pressure diffusion



[Olny, Boutin, 2003, 10.1121/1.1534607](#)

[Sgard, Olny, Atalla, Castel, 2005](#)

[Bécot, Jaouen, Gourdon, 2008, 10.3813/AAA.918088](#)

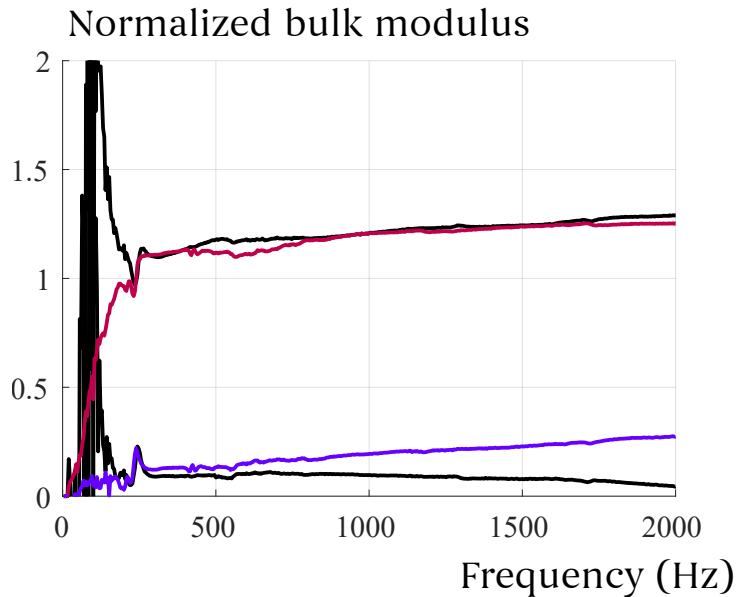
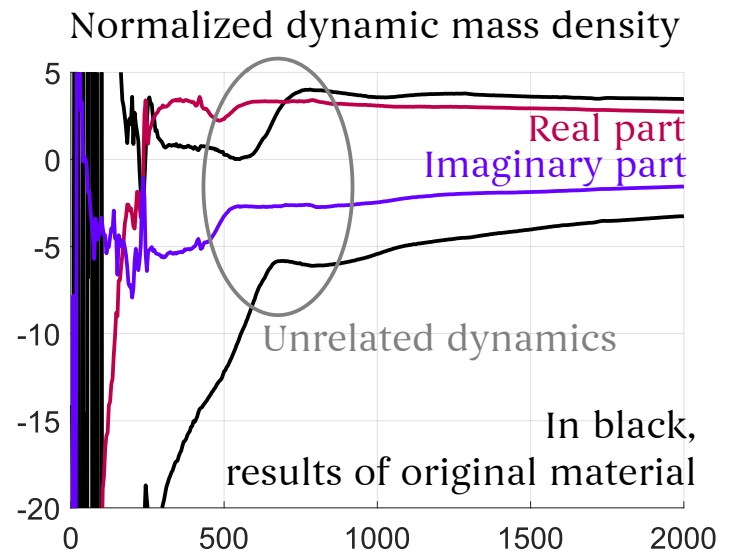
[Venegas, Umnova, 2011, 10.1121/1.3644915](#)

[Glé, Gourdon, Arnaud, 2011,
10.1016/j.apacoust.2010.11.003](#)

[Chevillotte, Jaouen, Bécot, 2015, 10.1121/1.4937773](#)

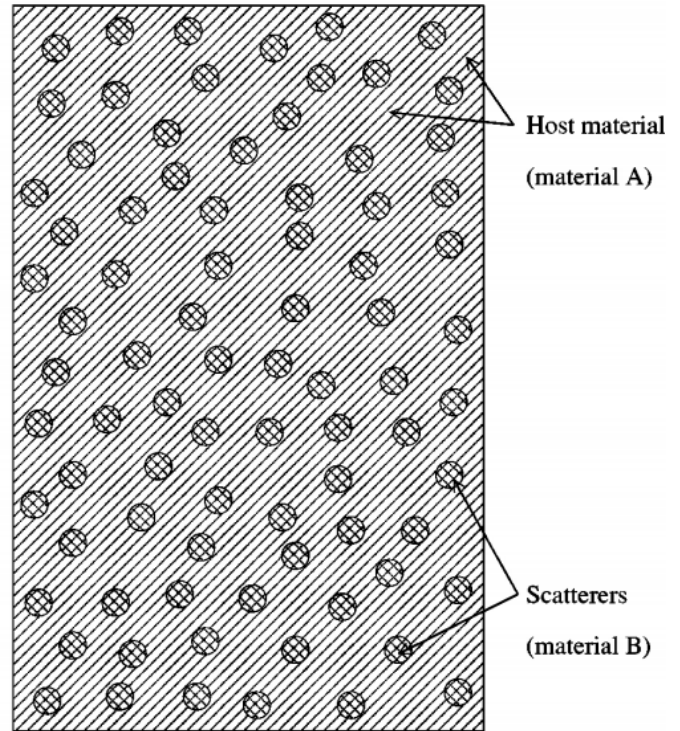
[Venegas, Boutin, 2018, 10.3813/AAA.919202](#)

Materials with
multiple scales of porosity
addition of pressure diffusion



Materials with solid inclusions (scatterers)

addition of multiple scattering
(i.e. a diffusion effect)



Sanchez-Perez, Caballero, Martinez-Sala, Rubio, Sanchez-Dehesa, Meseguer, Llinares, Galvez, 1998
[10.1103/PhysRevLett.80.5325](https://doi.org/10.1103/PhysRevLett.80.5325)

Tournat, Pagneux, Lafarge, Jaouen, 2004,
[10.1103/PhysRevE.70.026609](https://doi.org/10.1103/PhysRevE.70.026609)

Omnova, Attenborough, Linton, 2006, [10.1121/1.2133715](https://doi.org/10.1121/1.2133715)

Boutin, 2007 [10.1121/1.2756755](https://doi.org/10.1121/1.2756755)

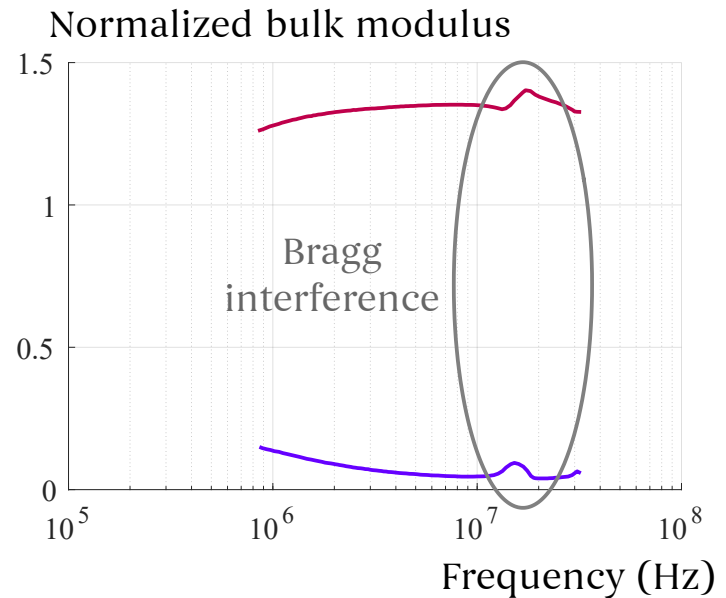
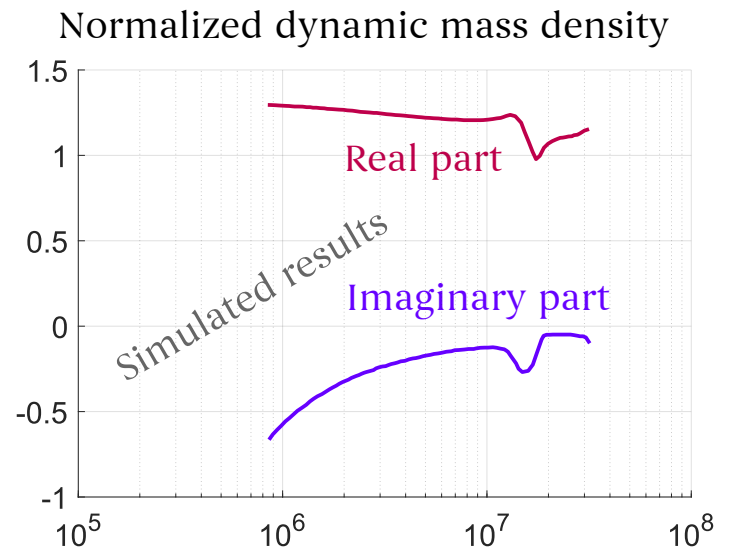
Romero-Garcia, Lagarrigue, Groby, Richoux, Tournat, 2013.
[10.1088/0022-3727/46/30/305108](https://doi.org/10.1088/0022-3727/46/30/305108)

Weisser, Groby, Dazel, Gautier, Deckers, Futatsugi, Monteiro, 2016, [10.1121/1.4940669](https://doi.org/10.1121/1.4940669)

Nemati, Lee, Lafarge, Duclos, Fang, 2017,
[10.1103/PhysRevB.95.224304](https://doi.org/10.1103/PhysRevB.95.224304)

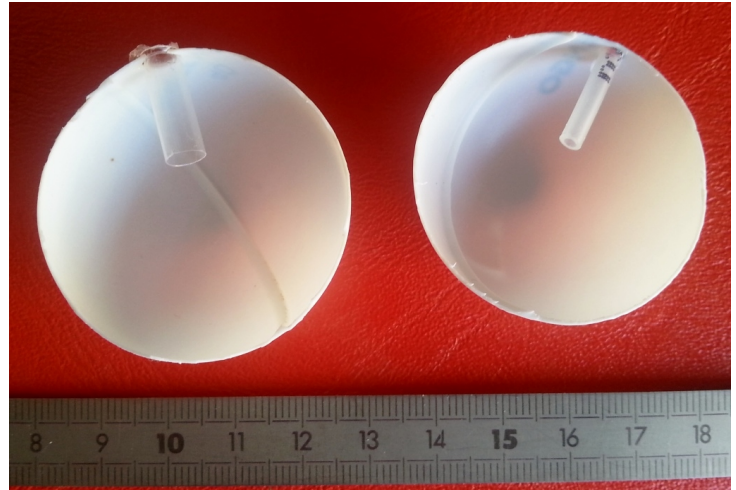
Materials with solid inclusions (scatterers)

addition of multiple scattering
(i.e. a diffusion effect)



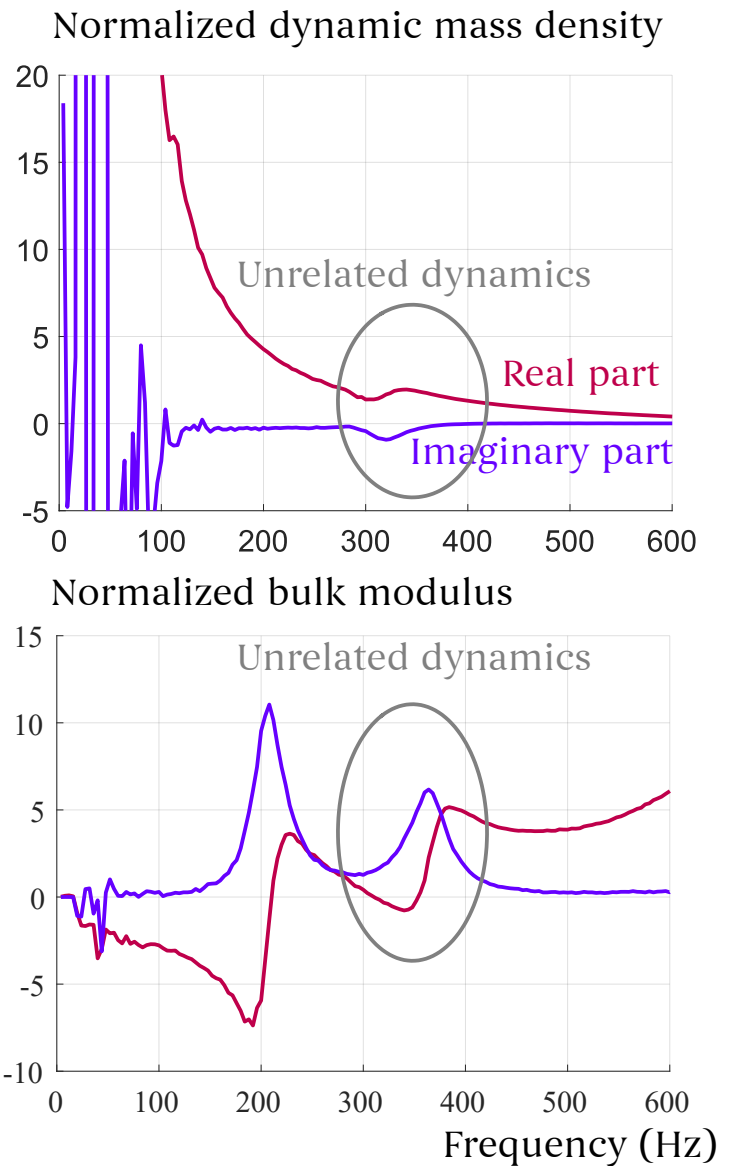
Materials with Helmholtz resonators

addition of resonances



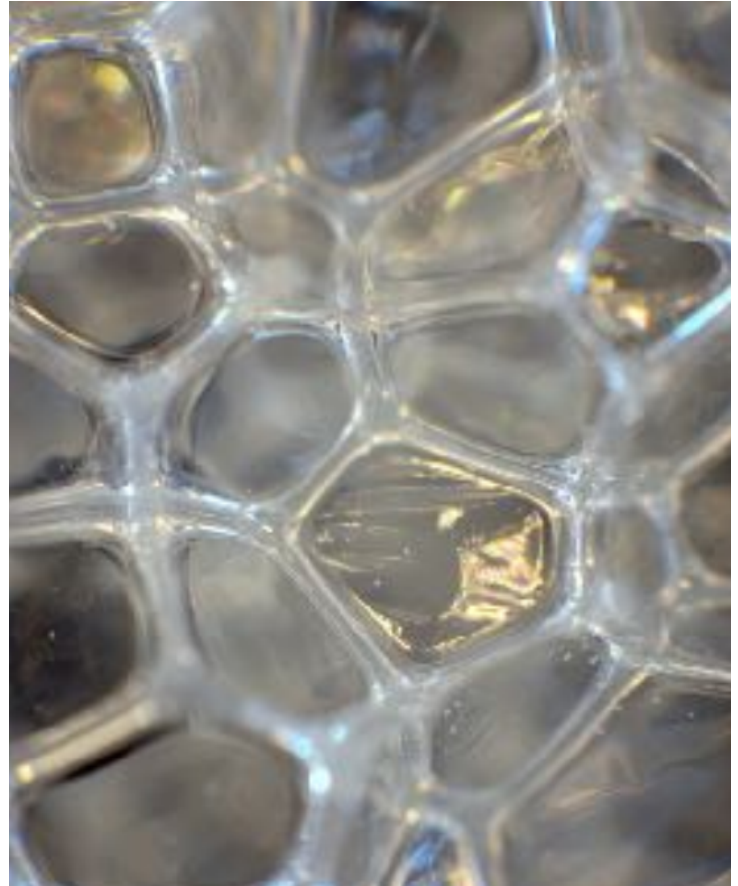
Fang, Xi, Xu, Ambati, Srituravanich, Sun, Zhang, 2006, [10.1038/nmat1644](https://doi.org/10.1038/nmat1644)
Boutin, 2013, [10.1121/1.4824965](https://doi.org/10.1121/1.4824965)
Laguarigue, Groby, Tournat, Dazel, Umnova, 2013, [10.1121/1.4824843](https://doi.org/10.1121/1.4824843)
Lafarge, Nemati, 2013, [10.1016/j.wavemoti.2013.04.007](https://doi.org/10.1016/j.wavemoti.2013.04.007)
Boutin, Bécot, 2015, [10.1016/j.wavemoti.2014.11.013](https://doi.org/10.1016/j.wavemoti.2014.11.013)
Jimenez, Romero-Garcia, Pagneux, Groby, 2017, [10.1038/s41598-017-13706-4](https://doi.org/10.1038/s41598-017-13706-4)

Materials with
Helmholtz resonators
addition of resonances



Materials with soft membranes

addition of resonances
and maybe something else



Quash™ by Dow Chemical

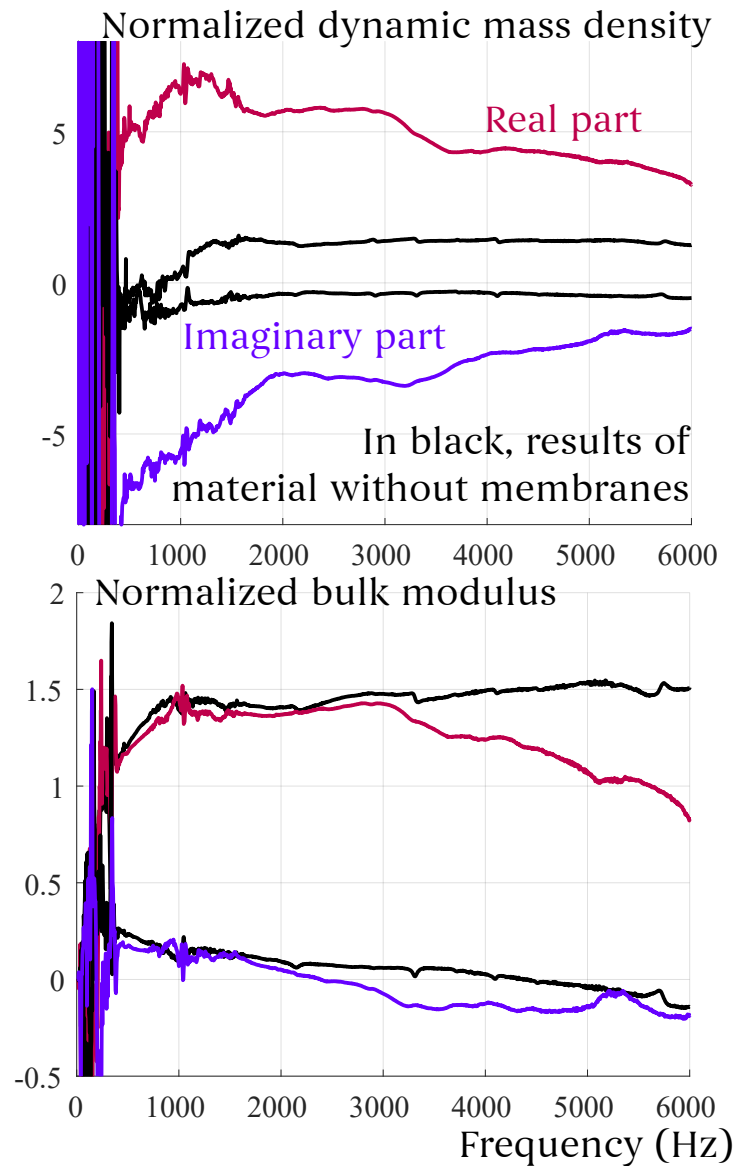
Bolton, 2013 (publication of Ray W. Herrick Lab)

Venegas, Boutin, 2017, [10.1017/jfm.2017.505](https://doi.org/10.1017/jfm.2017.505)

Gaulon, Pierre, Derec, Jaouen, Bécot, Chevillotte,
Elias, Drenckhan, Leroy, 2018, [10.1063/1.5025407](https://doi.org/10.1063/1.5025407)

Materials with soft membranes

addition of resonances and maybe something else



Physical phenomena in multiple dynamic materials

- resonances

localized, "weakly" damped

- acoustics : (Helmholtz, $\lambda/4$)
- mechanics : not discussed here
except non-local skeleton motion
- ...

- diffusion

broader, "highly" damped

- scattering
- pressure diffusion
- ...

Periodicity adds Bragg interferences

but is not necessary to take advantage of other phenomena

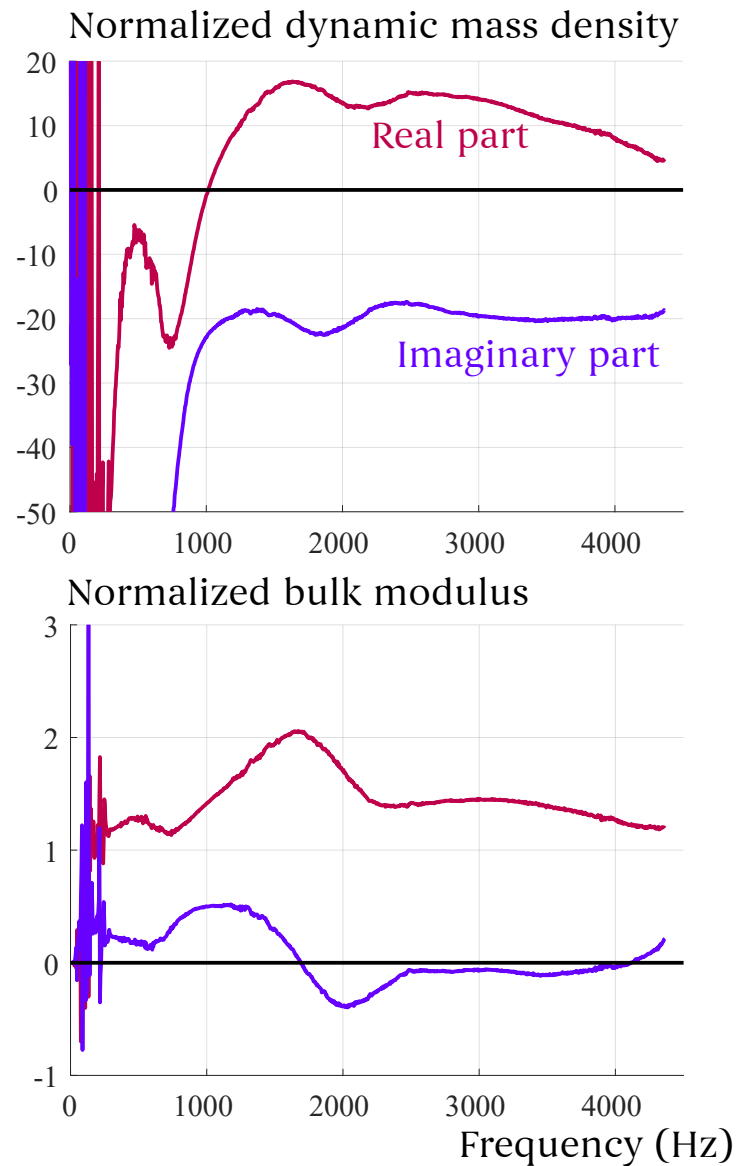
Modelling

Some issues

- Analytical solutions yet limited to simple geometries. Other cases require "heavy" computations.
- Dissipation is a key factor and should be accounted for accurately.
[See evolution of models with time](#)
- Vibration of skeleton is partially or not accounted for (while essential for applications to transmission)

"Usual" porous materials with elastic skeletons

3 dynamic behaviors !
the frame resonances add 1 dynamic



Modelling

Some developments

- Lafarge's non local theory
i.e. an extension of Zwikker & Kosten to space dispersion
 $\rho(\omega, k)$ and $K(\omega, k)$
[Lafarge, Nemati, 2013, 10.1016/j.wavemoti.2013.04.007](#)
- There's ongoing works on skeleton motion / coupling
[Groby, Dazel, Depollier, Ogam, Kelders, 2012, 10.1121/1.4725763](#)
[Dazel, Bécot, Jaouen, 2012, 10.3813/AAA.918538](#)
[Boutin, Royer, 2015, 10.1093/gji/ggv378](#)
[Boutin, Venegas, 2016, 10.1016/j.mechmat.2016.08.005](#)

Measurement challenges

Too big or too small samples

- Large for resonators or diffusers
- Small for micro & nano-scale materials
[Cai, Yang, 2018, 10.1121/1.5080557](#)
- A solution :
dedicated tubes or horn-style extensions



[Schultz, Cattafesta III, Sheplak, 2006, 10.1121/1.2360423](#)
[Coulon, Chevillotte, Bécot, Jaouen, 2012 in Proc. of Acoustics 2012 \(Nantes, France\)](#)
[Prisutova, Horoshenkov, Groby, Brouard, 2014, 10.1121/1.4900598](#)

Characterization challenges

- We're only at the beginning

Jaouen, Olny, 2005, in Proc. of 1st SAPEM (Lyon, France)

Bécot, Jaouen, Gourdon, 2008, 10.3813/AAA.918088

Venegas, Umnova, 2011, 10.1121/1.3644915

- Printed materials have an internal scale of porosity

as well as most natural fibers

& some minerals used in acoustic structures.

see e.g. Gaelle Benoit's, Philippe Glé's, Rodolfo Venegas's PhD theses

Any question ?

Yes or no, see you at :

SAPeM 2020

December 15-16-17

Purdue university

Lafayette (IN, USA)

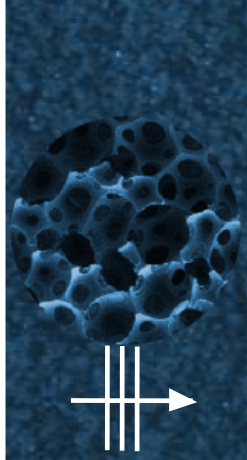
<http://sapem2020.matelys.com>

A general description of sound propagation in porous

Sets of properties describing propagation in a medium:

Characteristic impedance & wavenumber OR mass density & bulk modulus

$$(\quad Z_c \quad k \quad \rho_{eq} \quad K_{eq} \quad)$$



$$p(x) = p(0)e^{-jkx}e^{j\omega t}$$

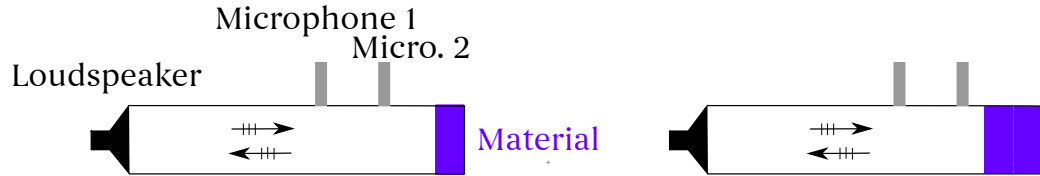
$$v(x) = p(x)/Z_c$$

$$\left\{ \begin{array}{l} k = \omega \sqrt{\frac{\rho_{eq}}{K_{eq}}} \quad [\text{m}^{-1}] \\ Z_c = \sqrt{\rho_{eq} K_{eq}} \quad [\text{N.s.m}^{-3}] \end{array} \right. \quad \left\{ \begin{array}{l} \rho_{eq} = \frac{Z_c k}{\omega} \quad [\text{kg.m}^{-3}] \\ K_{eq} = \frac{Z_c \omega}{k} \quad [\text{N.m}^{-2}] \end{array} \right.$$

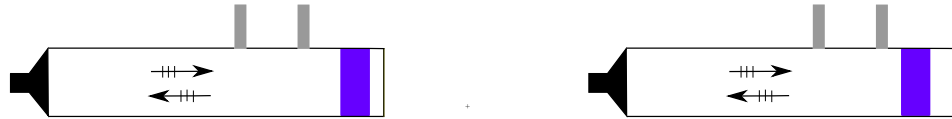
Measurements of ρ_{eq} and K_{eq}

3 techniques with a classical impedance tube (without transmission kit)

2 thicknesses : Smith Parrott 1983



2 cavities : Utsuno Tanaka Fujikawa Seybert 1989



3 microphones : T. Iwase & Y. Izumi, 1996
T. Iwase, Y. Izumi & R. Kawabata, 1998



Smith Parrott 1983 [10.1121/1.390119](https://doi.org/10.1121/1.390119)

Utsuno Tanaka Fujikawa Seybert 1989 [10.1121/1.398241](https://doi.org/10.1121/1.398241)

T. Iwase Y. Izumi, *J. Acoust. Soc. Jpn J* 52(6) pp. 411-419, 1996 (in Japanese)

T. Iwase Y. Izumi R. Kawabata, in proc. Internoise, 1998 (Christchurch, New Zealand)