Characterization of complex and "microstructured" media using elastic guided waves

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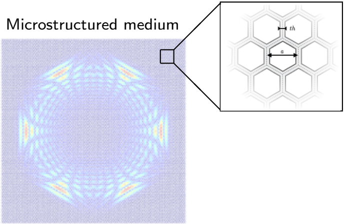
Biomechanics group

Workshop on elastodynamics of microstructured media,
École des Ponts – ParisTech – Champs sur Marne

Motivation

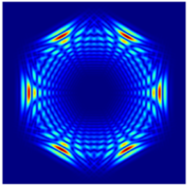
Continuum modeling of frequency dependent acoustic beam in hexagonal lattices

Microstructured medium



Strain gradient elasticity

Continuum model



Identification of the constitutive law of strain gradient elasticity models

$$\begin{pmatrix} \underline{p} \\ \underset{\sim}{q} \\ \underset{\sim}{\sigma} \\ \underset{\approx}{\underline{\tau}} \end{pmatrix} = \begin{pmatrix} \rho \underset{\sim}{I} & 0 & 0 & 0 \\ 0 & \underset{\approx}{J} & 0 & 0 \\ 0 & 0 & \underset{\approx}{C} & 0 \\ 0 & 0 & 0 & \underset{\underset{\sim}{\approx}}{A} \end{pmatrix} \begin{pmatrix} \underline{v} \\ \underset{\sim}{\nabla v} \\ \underset{\sim}{\epsilon} \\ \underset{\approx}{\underline{\eta}} \end{pmatrix}$$

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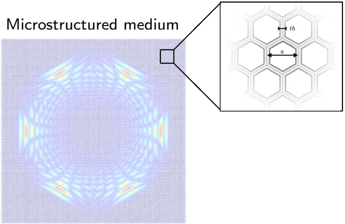

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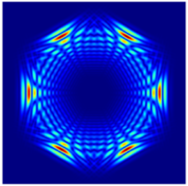

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- Identification of the model parameters $(a_S,\ a_P,\ a_D,\ J_P,\ J_S)$?
- Influence of the unit cell characteristics $(a,\ th)$?

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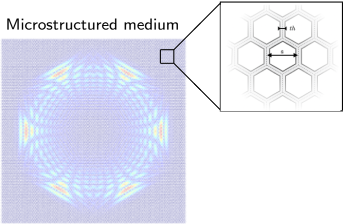

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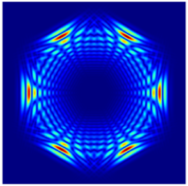

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Can we take advantage of guided waves measurements to retreive such parameters ?

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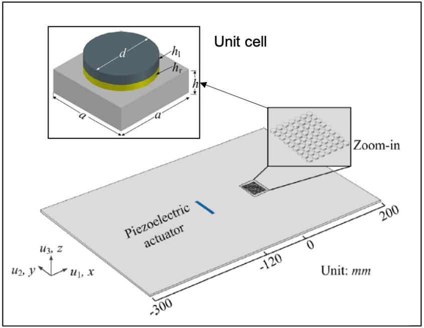
Background and objective

Elastic guided waves in media with surface structures

Guided waves focusing using metamaterials



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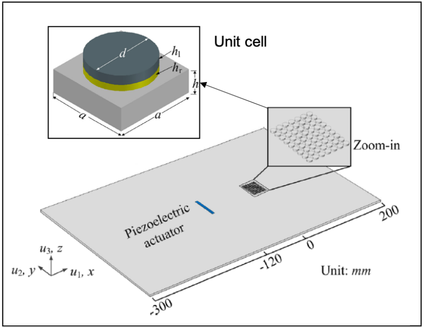
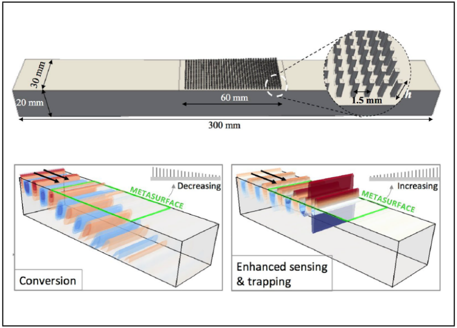


Rayleigh waves conversion using metasurfaces



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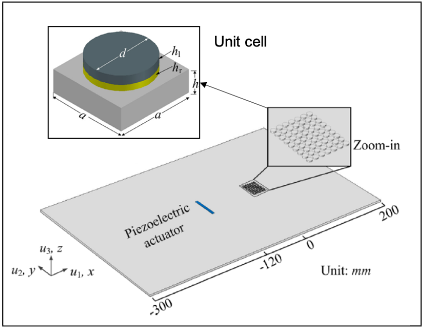

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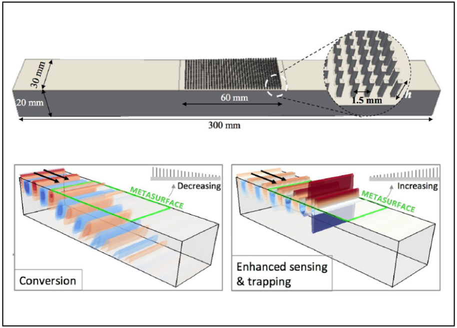

- Little work has been done using micro-architectured media **through-the-thickness**
- Can we use **recent experimental advances** as a starting point ?

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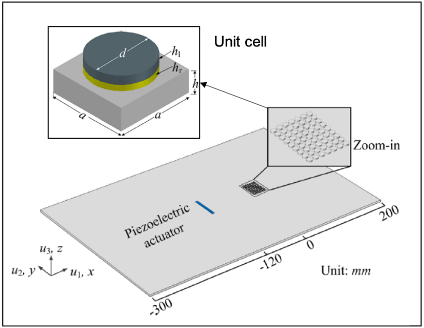

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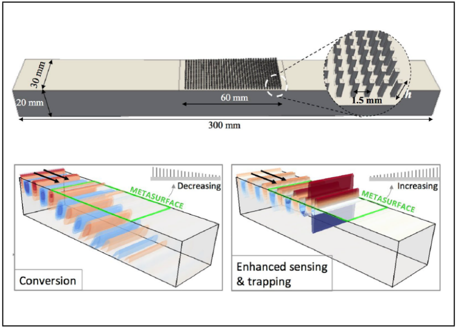

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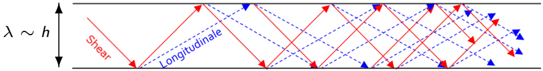

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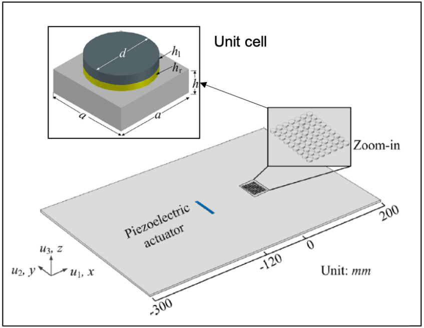

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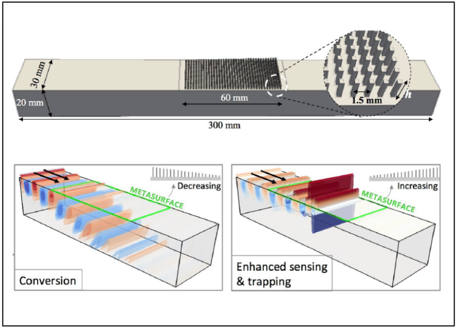

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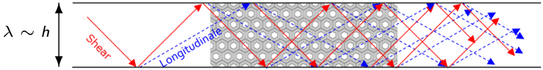

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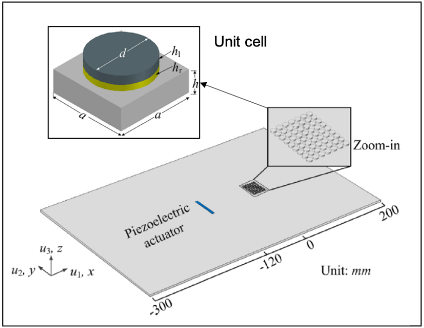

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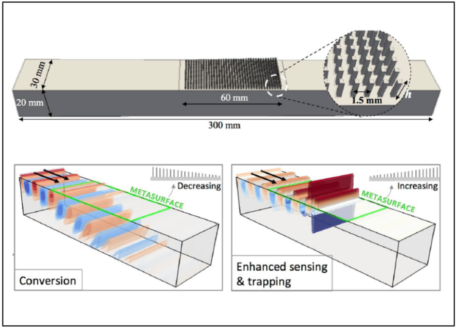

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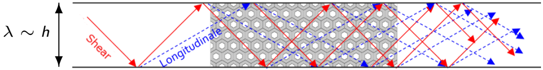

- Guided wave measurements
- Waveguide models
- Inverse problem

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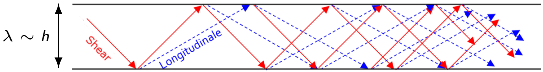
Theoretical reminder on guided waves

Elastic guided waves in a homogeneous and isotropic solid

- Modes conversion at the interfaces ($\lambda \sim h$)



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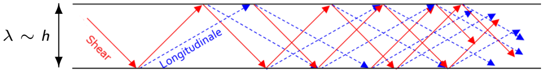

- Rayleigh-Lamb equation

$$\frac{\omega^4}{{V_T}^4} = 4k^2q^2\left[1 - \frac{p\tan(ph+\alpha)}{q\tan(qh+\alpha)}\right], \text{ avec } p^2 = \frac{\omega^2}{{V_L}^2} - k^2,\ q^2 = \frac{\omega^2}{{V_T}^2} - k^2,\ \alpha = \{0, \pi/2\}$$

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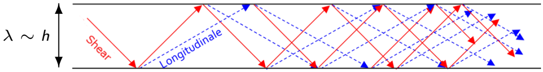

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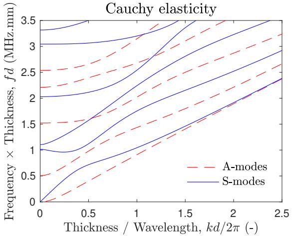
- Solutions: dispersion curves $f(k)$



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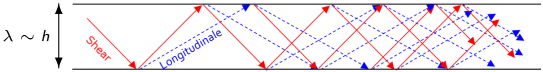

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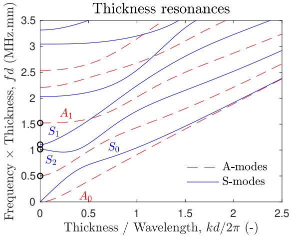

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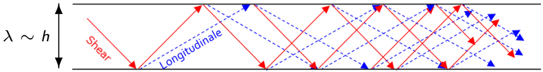

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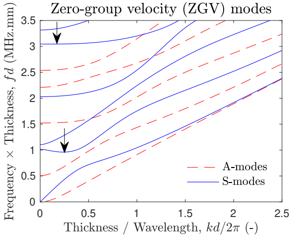

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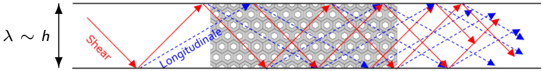

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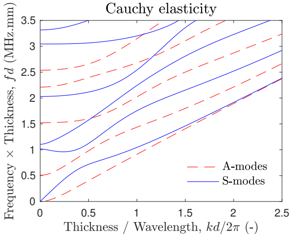
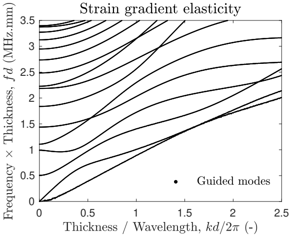
- Solutions: dispersion curves $f(k)$ $\quad + \{a_{11}, a_{12}, a_{22}, a_{23}, a_{44}, J_P, J_S\}$





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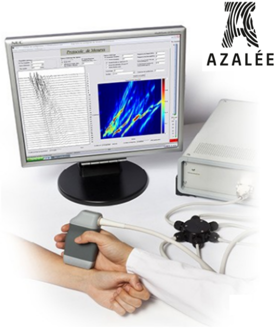
Overview of recent experimental advances

Guided waves characterization of complex media with "microstructures"

1. Cortical bone assessment



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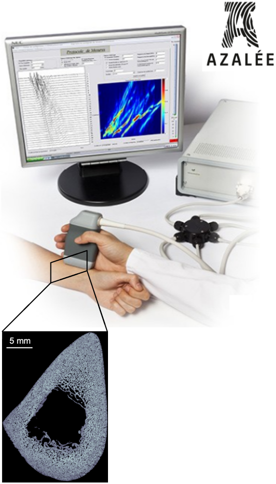

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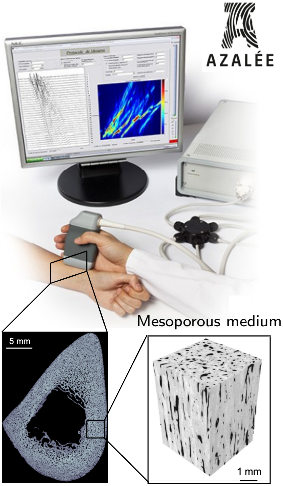

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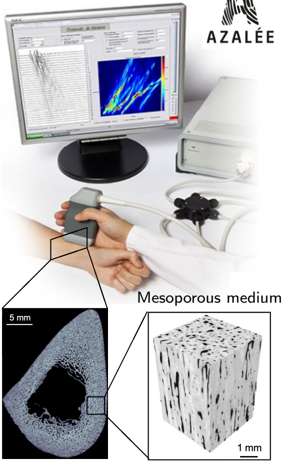
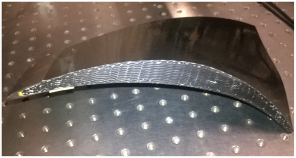


2. Adhesion of bonded layers



Safran Tech

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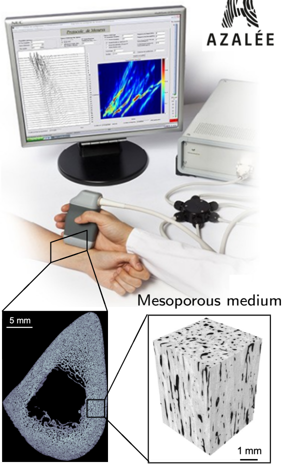

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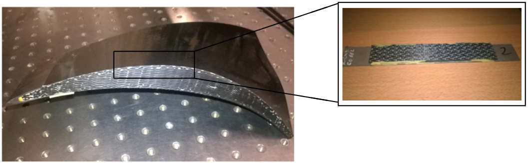

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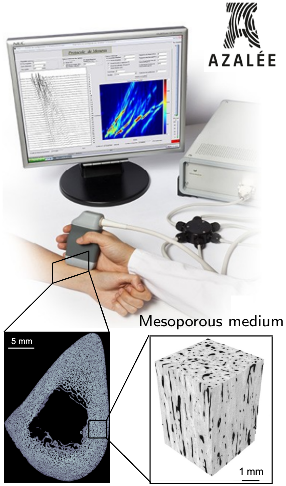

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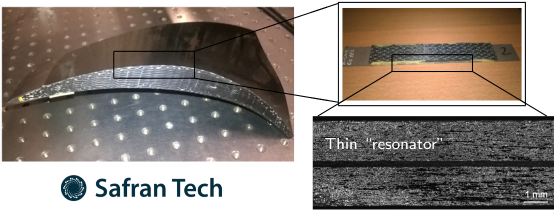

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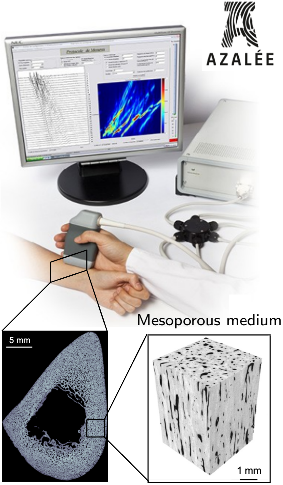

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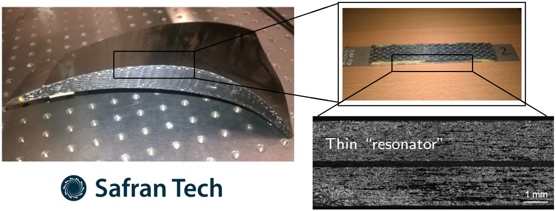

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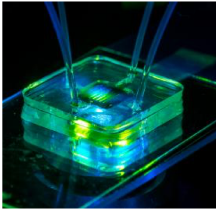

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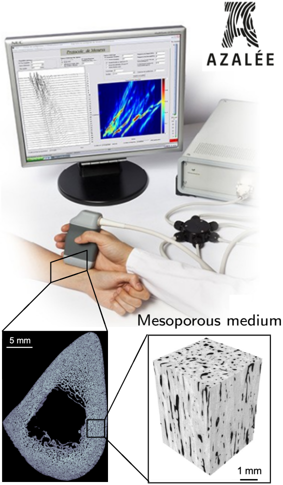

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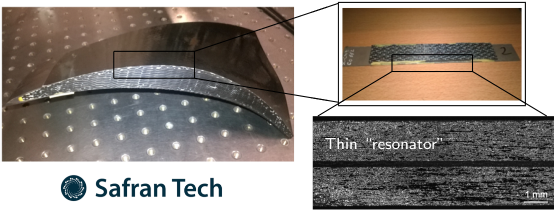

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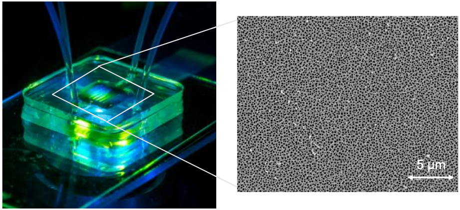

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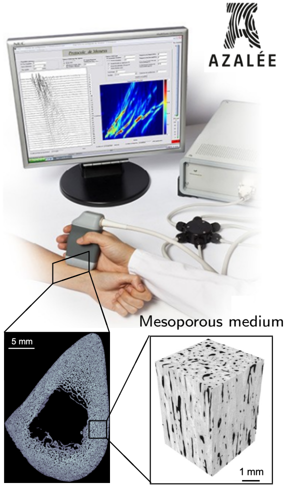

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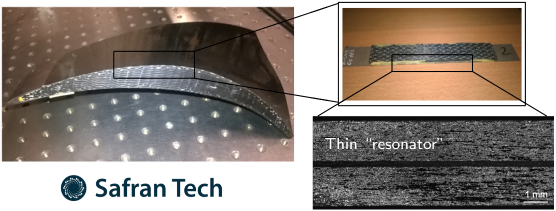
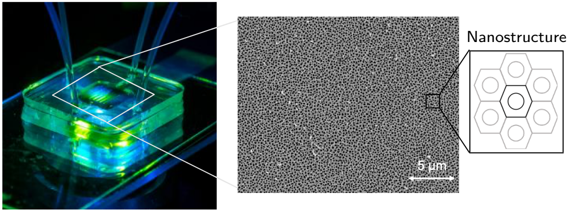


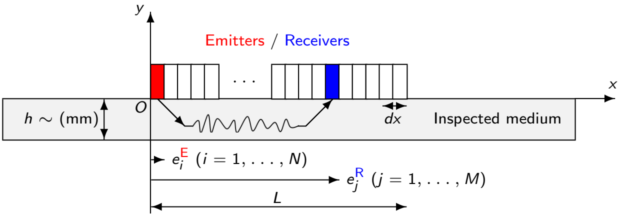
3. Nanoporous silicon membranes

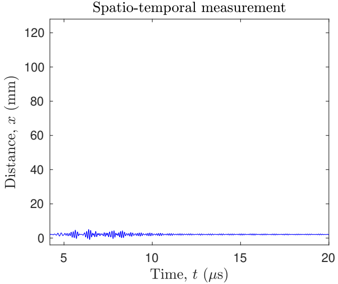


[1] Biomedical Imaging Laboratory, Paris; [2] Institut Langevin, Paris; [3] Institute of Materials Physics and Technology (TUHH).

Measurements of multimode dispersion curves

I. Multi-elements probe driven by a programmable multi-channel electronics





[1] Minonzio et al, *J Acoust Soc Am*, 2010; [2] Alleyne and Cawley, *J Acoust Soc Am*, 1991.

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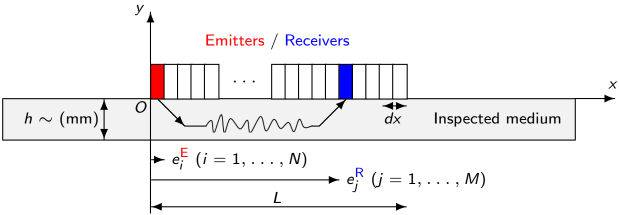

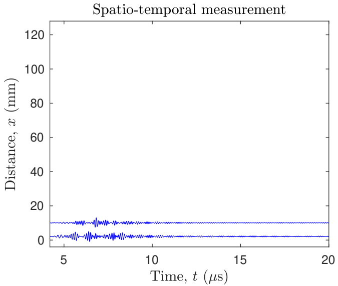

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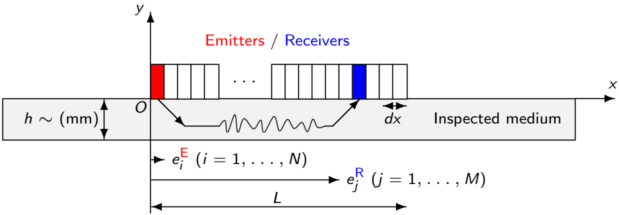

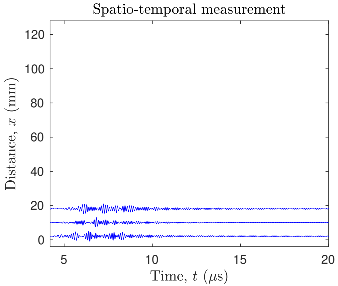

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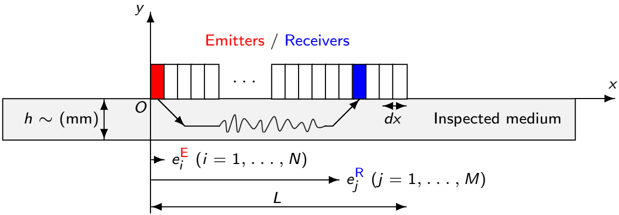

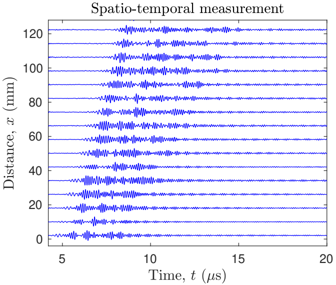

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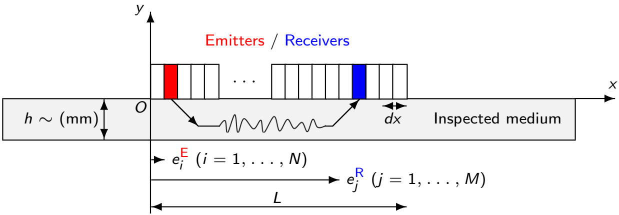

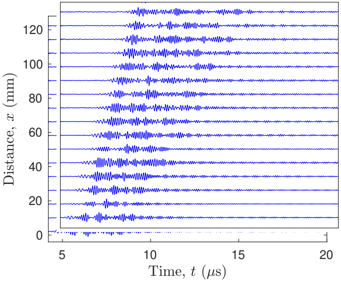

[1] Minonzio et al, *J Acoust Soc Am*, 2010; [2] Alleyne and Cawley, *J Acoust Soc Am*, 1991.

Measurements of multimode dispersion curves

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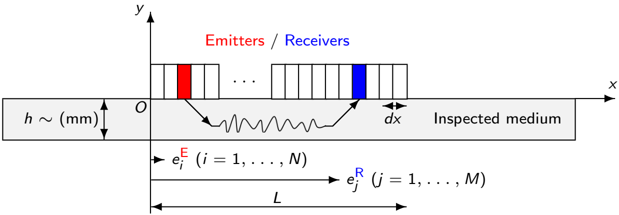
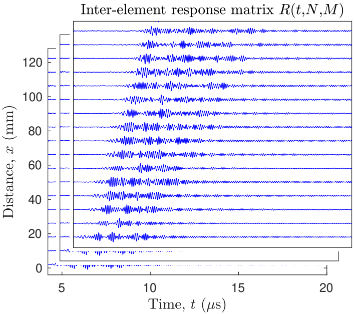
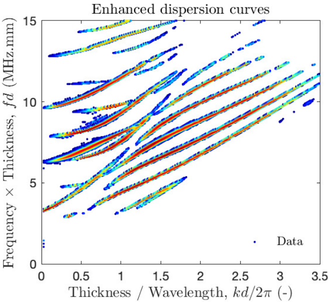




2D–FFT + SVD



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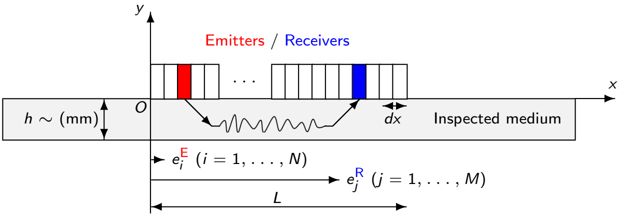
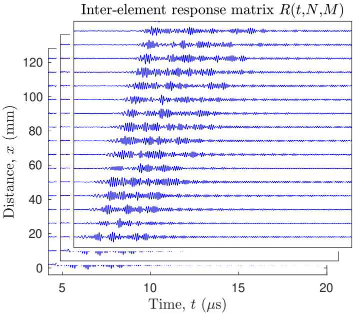
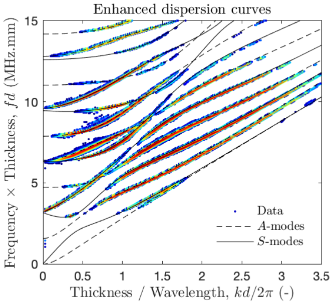




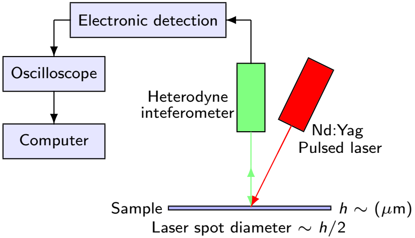
2D–FFT + SVD →

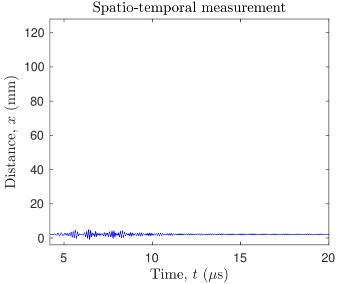


[1] Minonzio et al, *J Acoust Soc Am*, 2010; [2] Alleyne and Cawley, *J Acoust Soc Am*, 1991.

Measurements of multimode dispersion curves

II. Non-contact laser ultrasound measurements





[1] Clorennec et al, *Appl Phys Lett*, 2006; [2] Ces et al., *J Acoust Soc Am*, 2012.

Measurements of multimode dispersion curves

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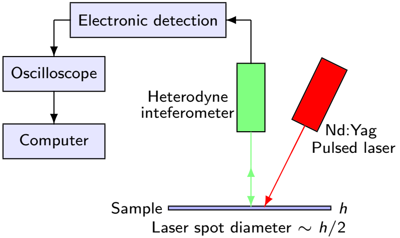

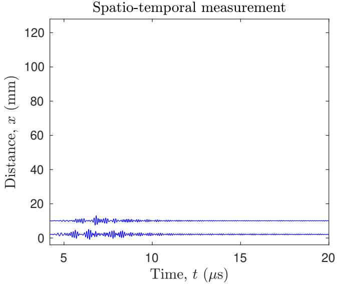

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Measurements of multimode dispersion curves

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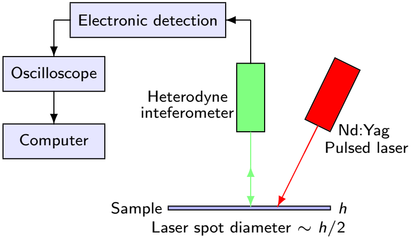

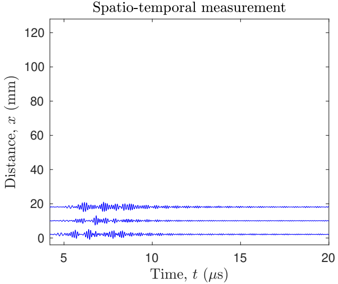

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Measurements of multimode dispersion curves

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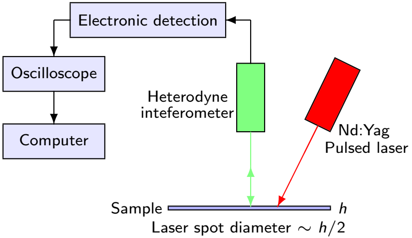

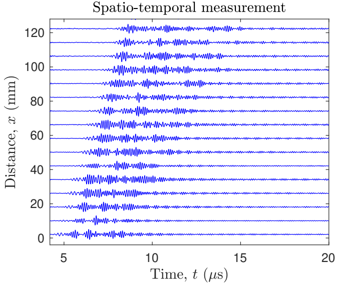

2D–FFT

[1] Clorennec et al, *Appl Phys Lett*, 2006; [2] Ces et al., *J Acoust Soc Am*, 2012.

Measurements of multimode dispersion curves

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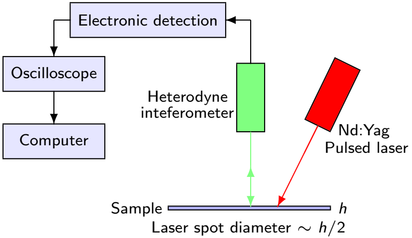

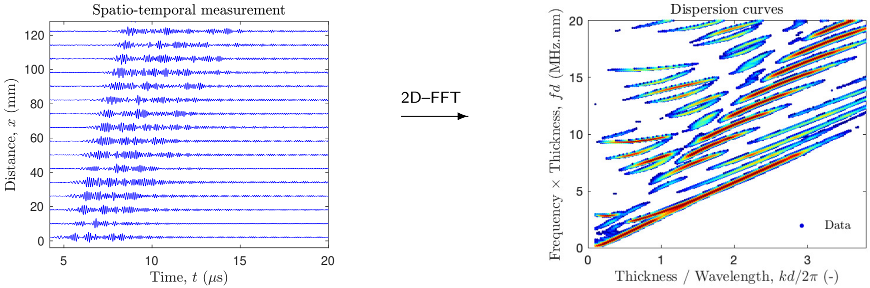

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Measurements of multimode dispersion curves

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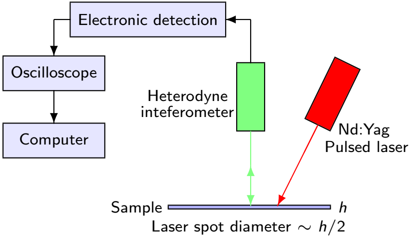
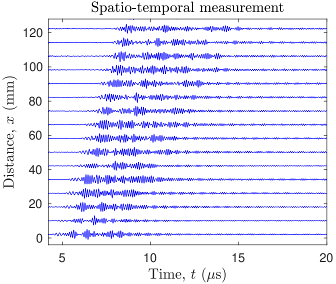
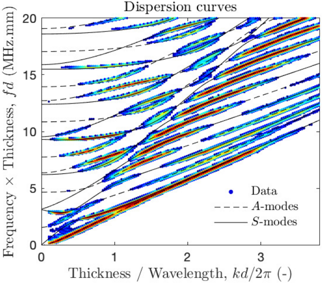




2D–FFT



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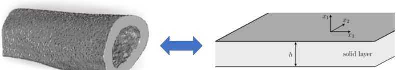
Waveguide models: solving the forward problem

1. Cortical bone assessment

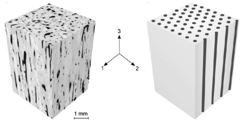
Hypothesis 1: 2-D transverse isotropic free plate



$\{h, C_{ij}\}$

Hypothesis 2: homogenized elasticity

C_{ij}



p

[1] Parnell et al, *Biomech Model Mechanobiol*, 2012; [2] Mezil et al, *J Acoust Soc Am*, 2015; [3] Gor et al, *Appl Phys Lett*, 2015.

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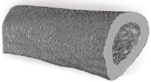
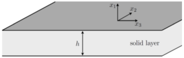
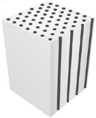




$\{h, C_{ij}\}$

Hypothesis 2: homogenized elasticity

C_{ij}



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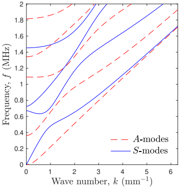

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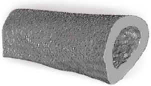
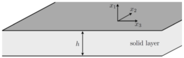
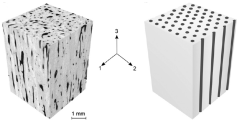
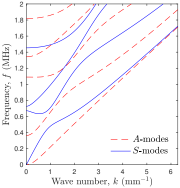




$\{h, C_{ij}\}$

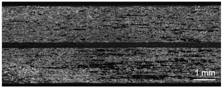
Hypothesis 2: homogenized elasticity

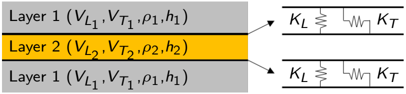




2. Adhesion of bonded layers

Hypothesis: rheological model for symmetric structures





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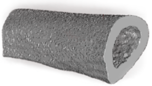
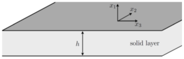
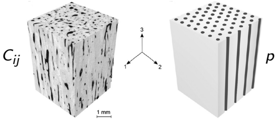
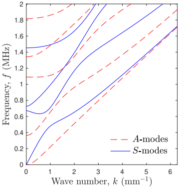




$\{h, C_{ij}\}$

Hypothesis 2: homogenized elasticity





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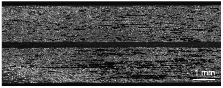

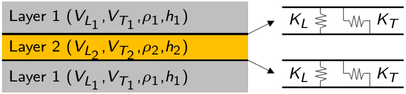

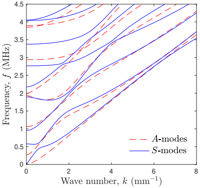

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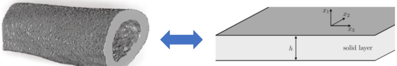
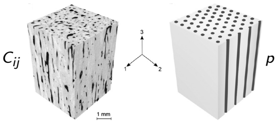
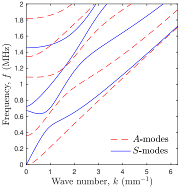


$\{h, C_{ij}\}$

Hypothesis 2: homogenized elasticity





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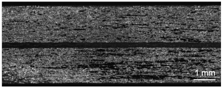
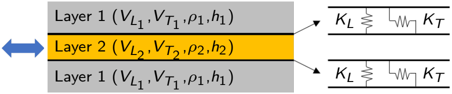
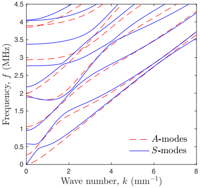
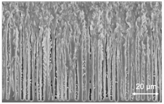


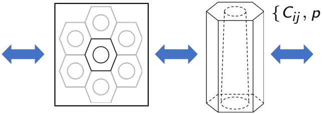




3. Nanoporous silicon membranes

Hypothesis: conical-shaped mesopores distributed periodically





$\{C_{ij}, p, \alpha, h\}$

Numerical simulations using Floquet-Bloch analysis

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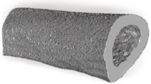
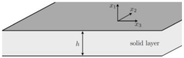
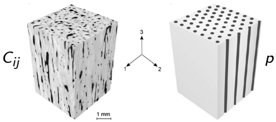
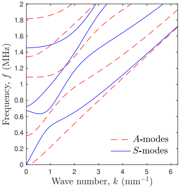




$\{h,\ C_{ij}\}$

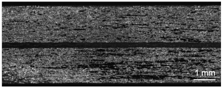
Hypothesis 2: homogenized elasticity

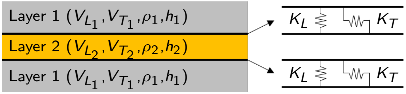


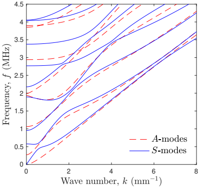


2. Adhesion of bonded layers

Hypothesis: rheological model for symmetric structures

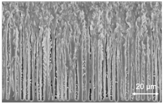


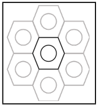


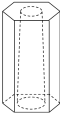


3. Nanoporous silicon membranes

Hypothesis: conical-shaped mesopores distributed periodically

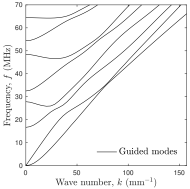






$\{C_{ij},\ p,\ \alpha,\ h\}$

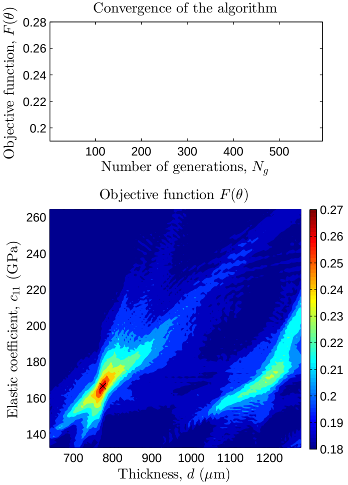
Numerical simulations using Floquet-Bloch analysis

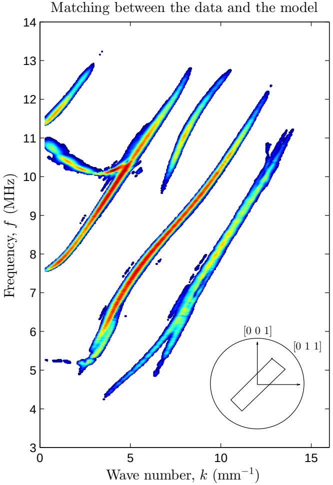


[1] Parnell et al, *Biomech Model Mechanobiol*, 2012; [2] Mezil et al, *J Acoust Soc Am*, 2015; [3] Gor et al, *Appl Phys Lett*, 2015.

Multi-parametric inverse problem

Maximization of $F(\theta)$ using genetic algorithms: Example for a silicon wafer

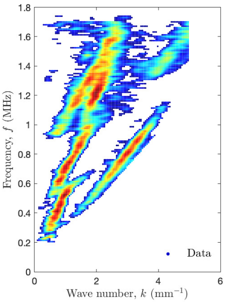




[1] Goldberg, *Genetic algorithms in search, optimization and machine learning*, 1989; [2] Bochud et al, *J Acoust Soc Am*, 2018.

Results: identification of the model parameters

1. Ex vivo human radius



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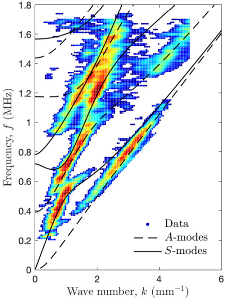

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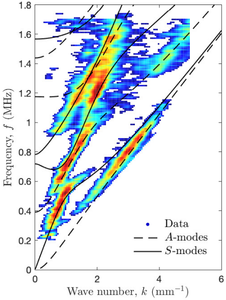
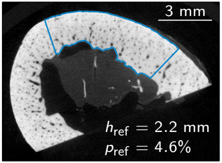


Validation using μ-CT



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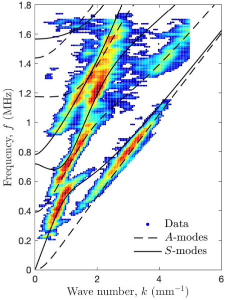

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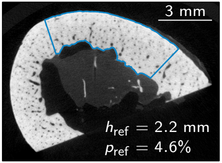
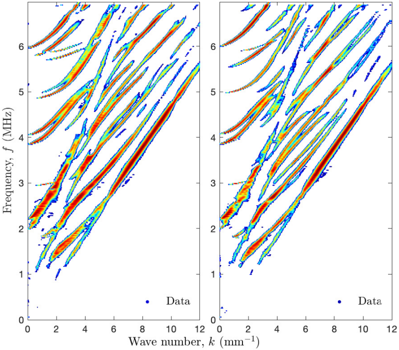


2. Adhesion of bonded layers

Good mechanical strength Bad mechanical strength



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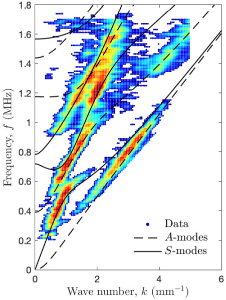

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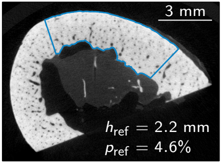

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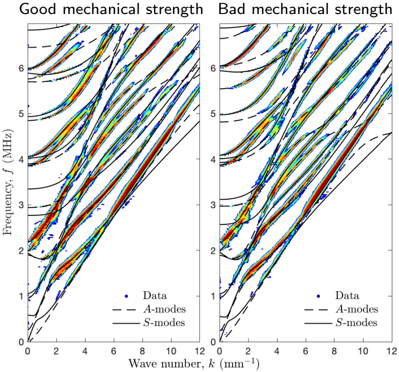

Estimates: $\theta = [V_{L_2}\ V_{T_2}\ h_2\ K_L\ K_T]$

$\hat{\theta}_G = [2.5\ 1.1\ 180\ 10^5\ 10^4]$
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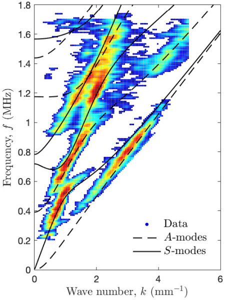

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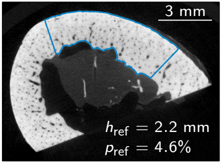

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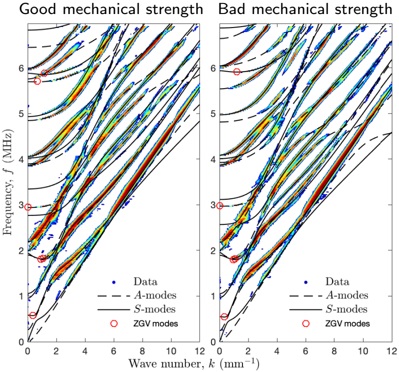

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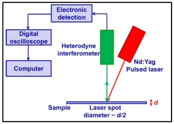
Validation using ZGV modes measured by laser ultrasonics



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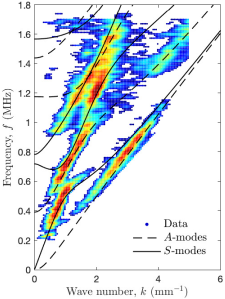

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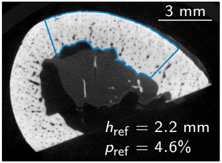

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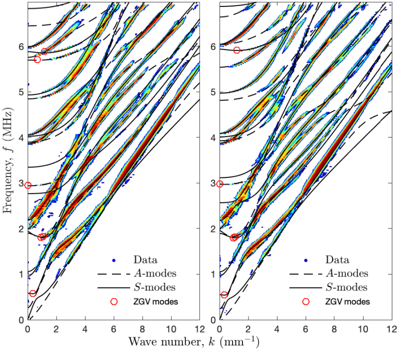

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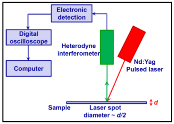
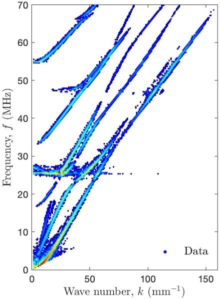


3. Nanoporous silicon

npSi sample with 50% porosity



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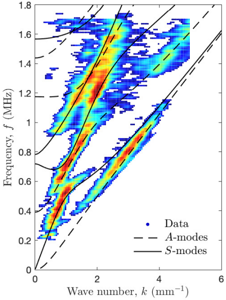

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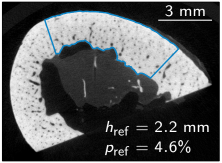

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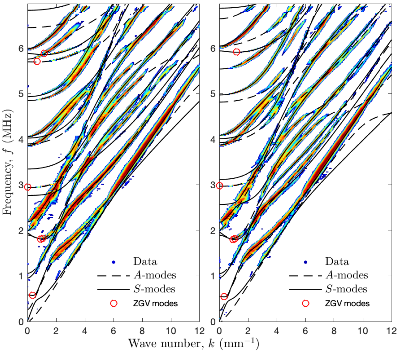

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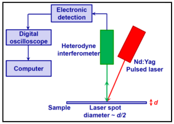

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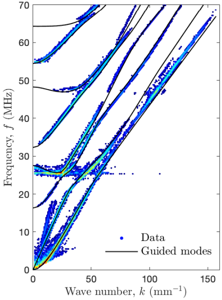

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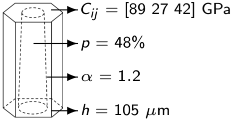

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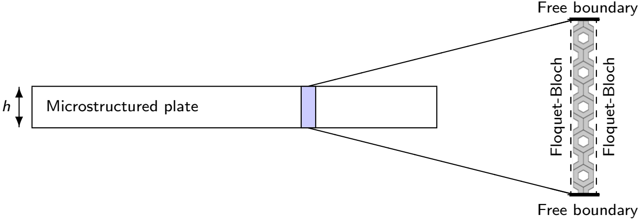
Perspectives

Preliminary results on microstructured plates



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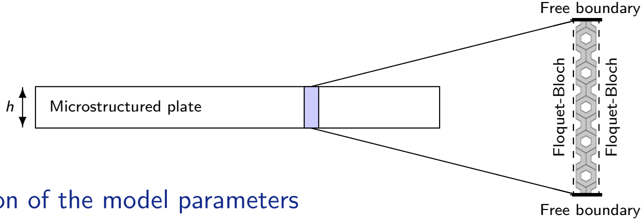

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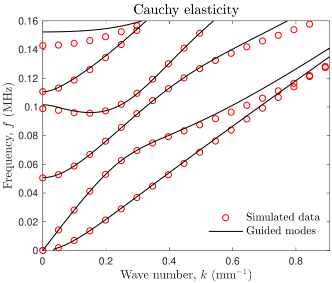

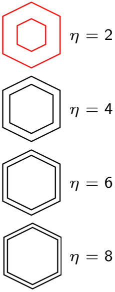

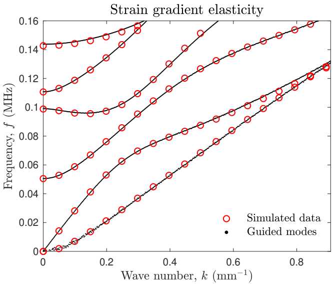

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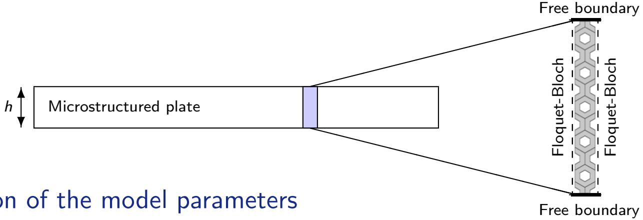

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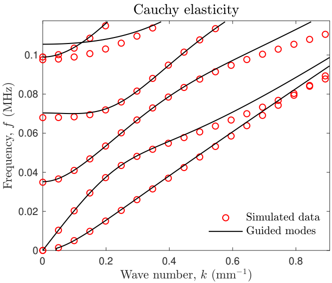

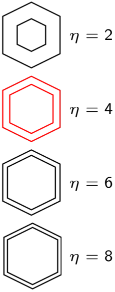

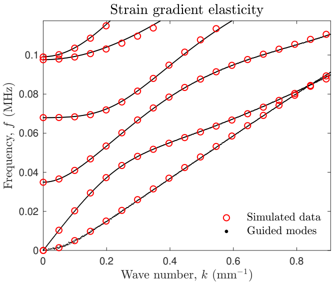

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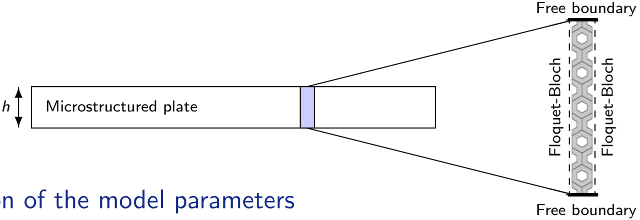

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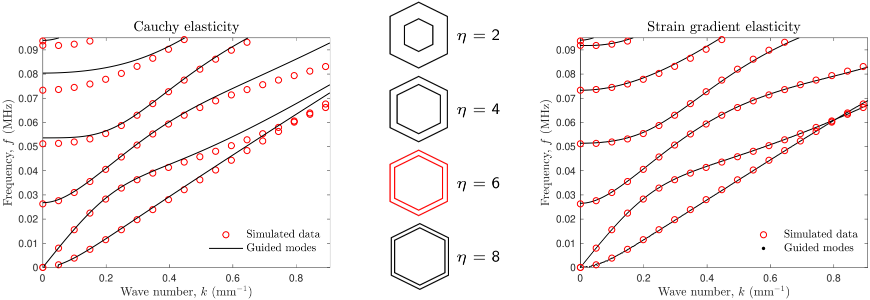

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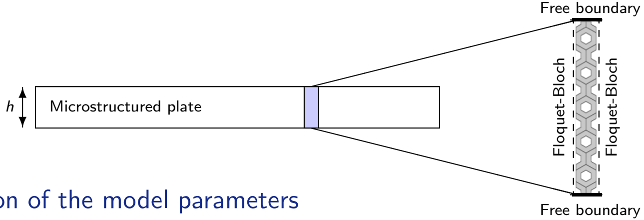

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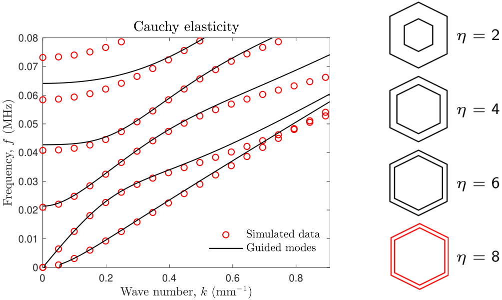

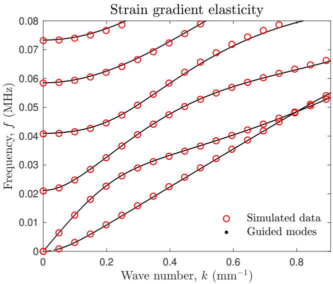

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Conclusion

- Two **experimental approaches** for measuring guided waves in complex media:
  - A multi-element approach using a programmable multi-channel electronics
    - \+ Real-time measurement ($f \in 0 - 15$ MHz)) mm-thick samples
    - \+ Enhanced dispersion curves $\Rightarrow$ SVD-based processing
    - − Contact measurement $\nRightarrow$ non-metallic or complex geometries
  - A non-contact laser ultrasonics approach:
    - \+ Extremely broadband measurement ($f \in 0 - 100$ MHz) μm-thick samples
    - \+ Dispersion curves and ZGV Lamb modes
    - − Complex setup
- Associated **models** and **inverse problem** procedures to infer model parameters
  - Examples: cortical bone, bonded layers, nanoporous membranes
- Preliminary results on **microstructured** plates using strain gradient elasticity
  - Extend the study to 3D (*e.g.*, gyroids) to mimic biological substitutes
  - Design microstructured samples using additive manufacturing
  - Measurements using ultrasound or vibro-acoustics

Thank you for your attention

Laboratoire d'Imagerie Biomédicale

Institut Langevin
ONDES ET IMAGES

TUHH
Technische Universität Hamburg-Harburg