LASER ULTRASONICS IN A MULTILAYER STRUCTURE:

SEMI-ANALYTIC MODEL AND DIFFERENT EXAMPLES

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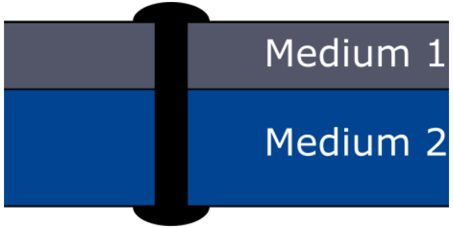
MOTIVATION

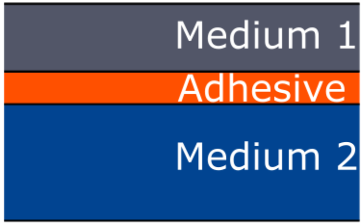
1. Motivation

Nondestructive evaluation (NDE) of adhesively bonded joints in aircraft structures

Environmental issues

- Reduction of greenhouse gases emissions
- Aircraft structures as light as possible
- Composite materials
- Bonded joints



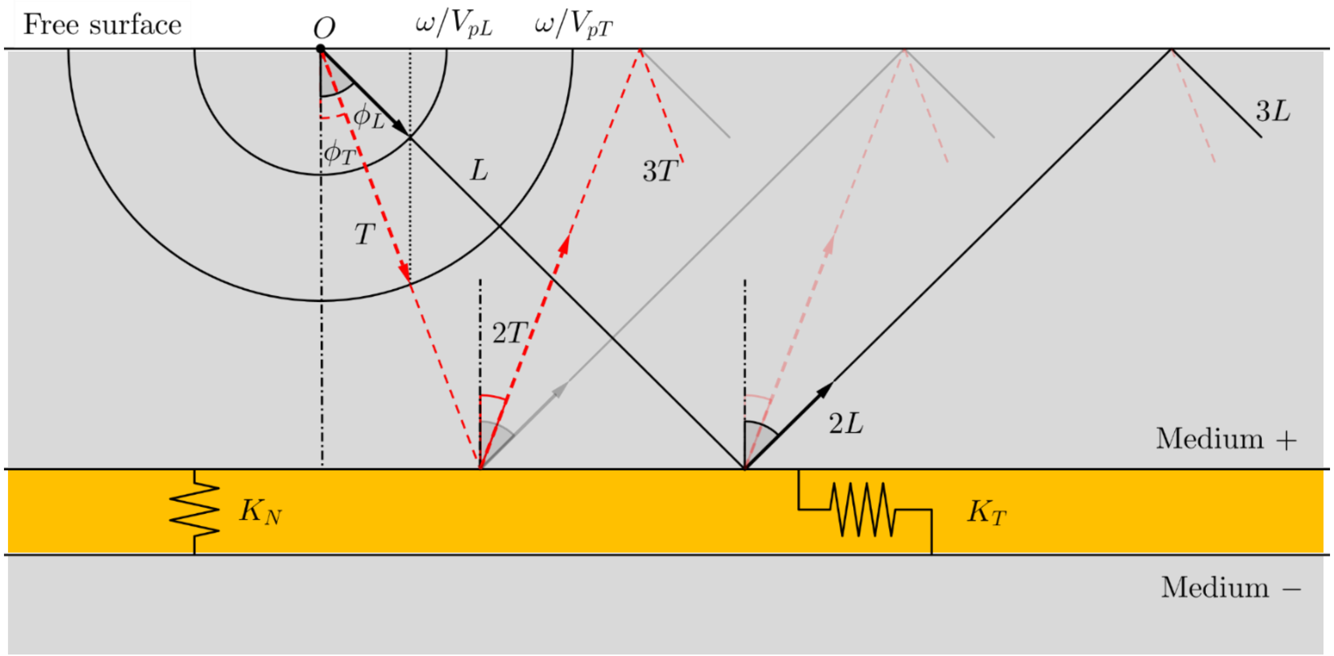


Safety

- Need of quantitative nondestructive methods to certify the mechanical strength of adhesively bonded joints

1. Characterization of adhesively bonded joints

Evaluation of elastic reflection coefficients
to evaluate the interfacial stiffnesses
for several incidence angles



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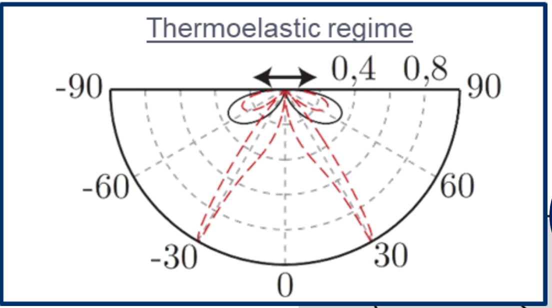
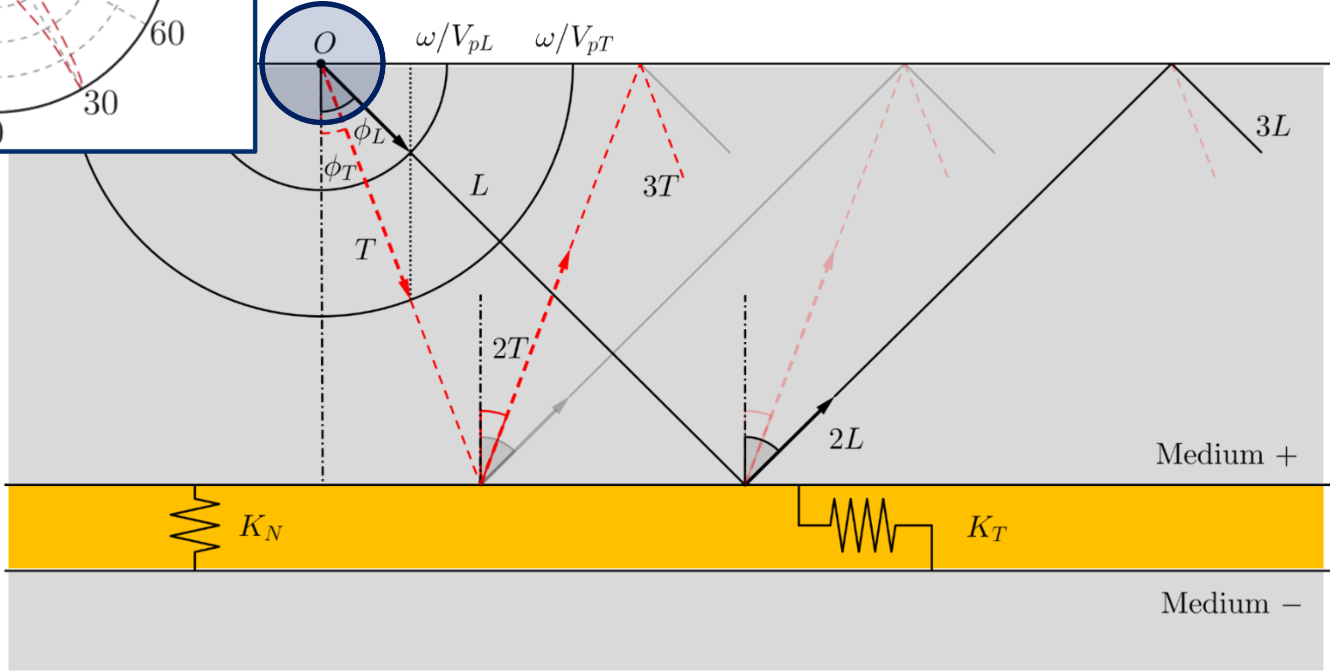


Evaluation of elastic reflection coefficients to evaluate the interfacial stiffnesses for several incidence angles



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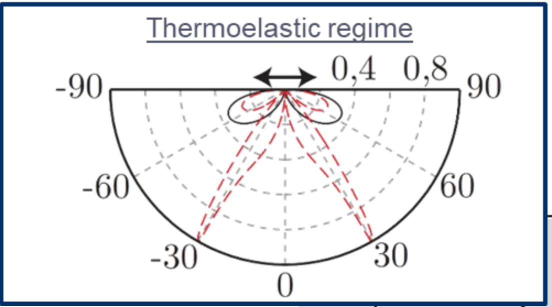

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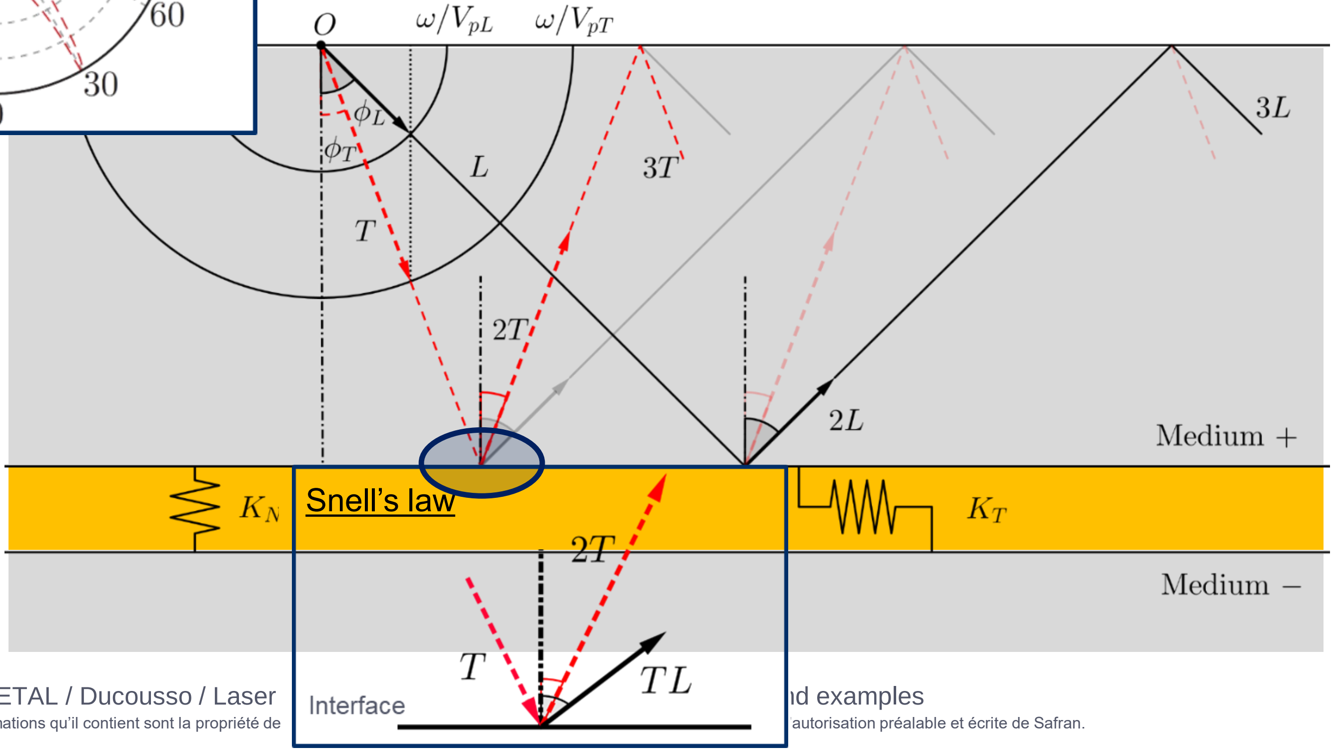

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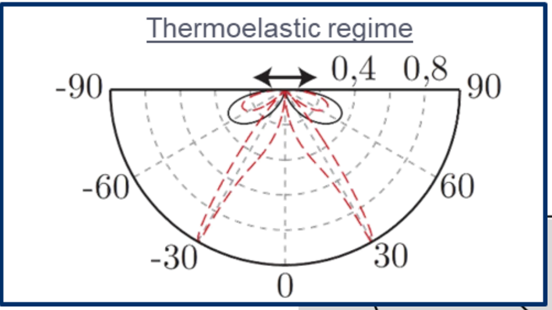

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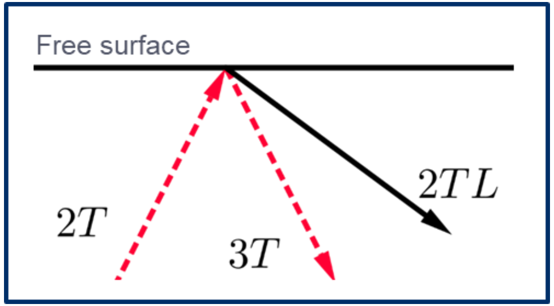

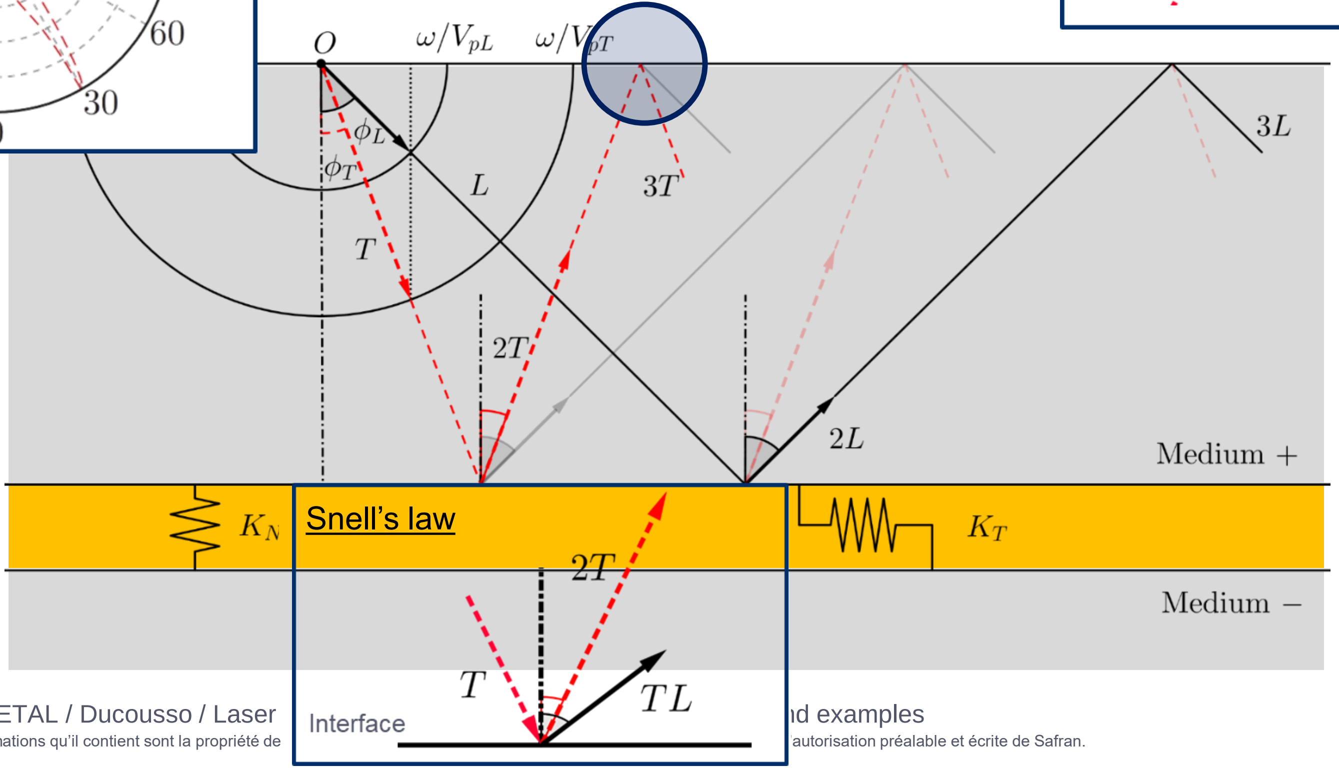

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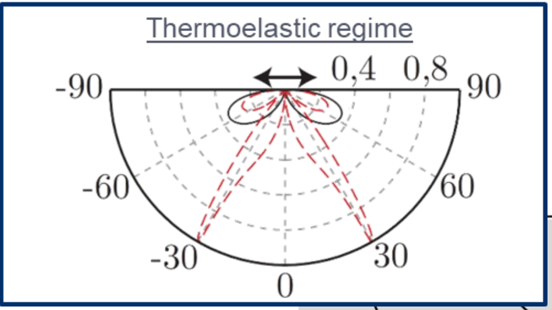
1. Characterization of adhesively bonded joints



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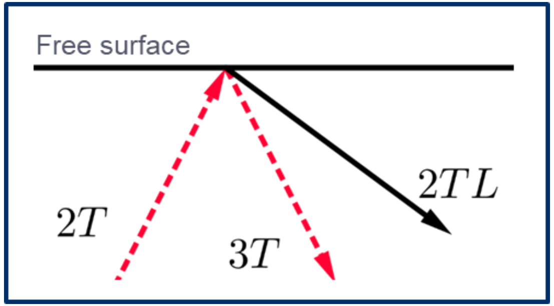

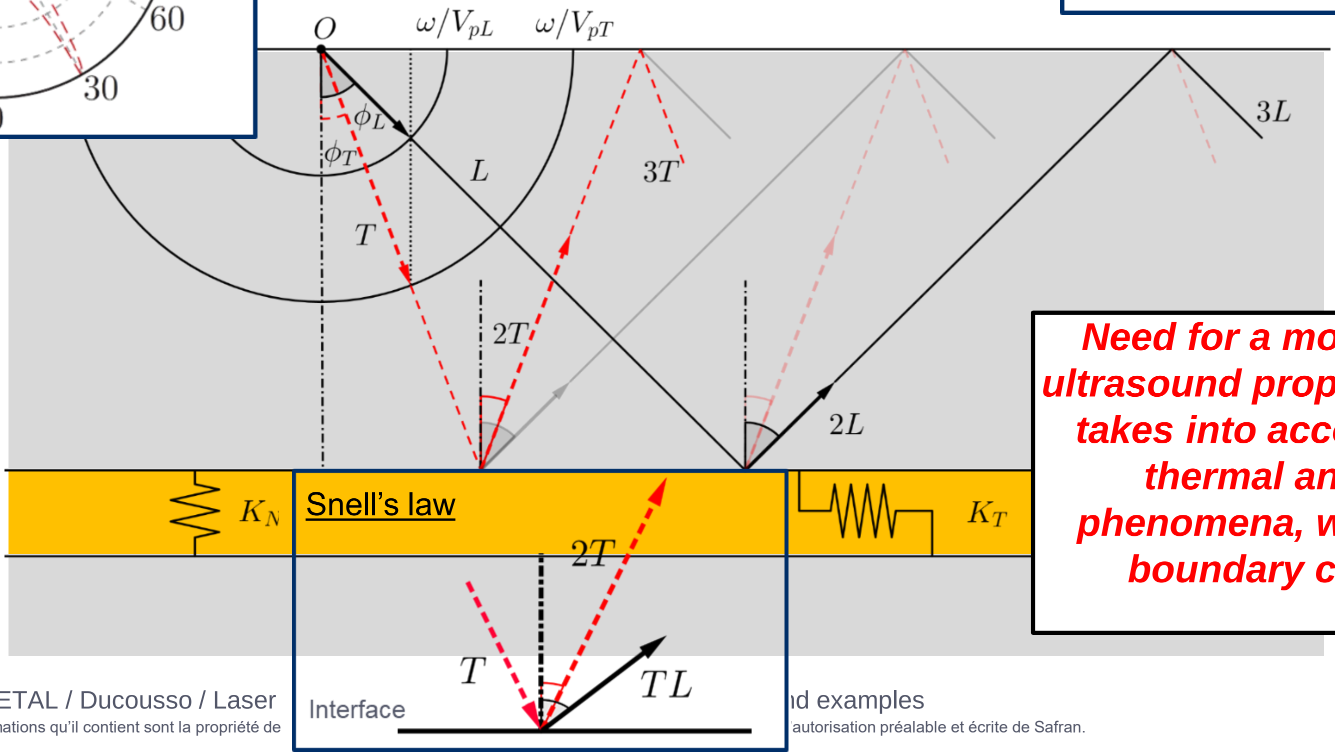

Need for a model of laser-ultrasound propagation which takes into account optical, thermal and elastic phenomena, with complex boundary conditions

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2

LASER ULTRASONICS IN A MULTILAYER STRUCTURE : MODEL

Low coupling

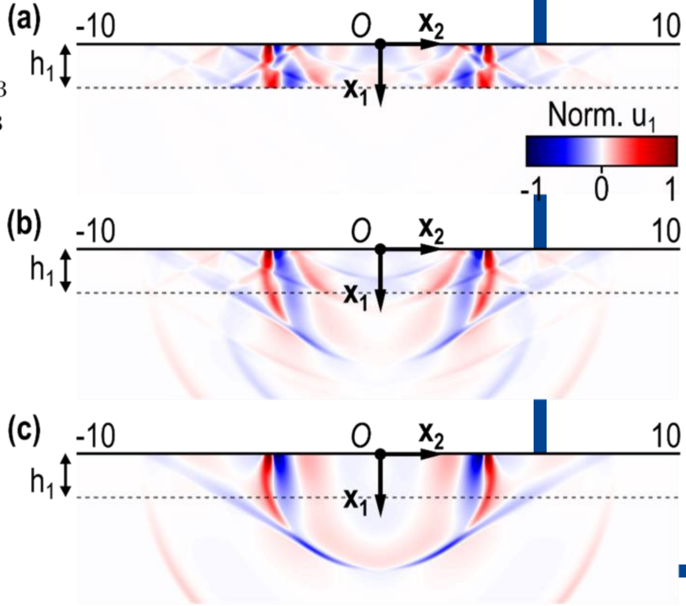
$K_N = 10^{-3}\ \mathrm{kN\,mm^{-3}}$
$K_T = 10^{-3}\ \mathrm{kN\,mm^{-3}}$

Int. coupling

$K_N = 10^{3}\ \mathrm{kN\,mm^{-3}}$
$K_T = 10^{1}\ \mathrm{kN\,mm^{-3}}$

High coupling

$K_N = 10^{5}\ \mathrm{kN\,mm^{-3}}$
$K_T = 10^{5}\ \mathrm{kN\,mm^{-3}}$



2. Semi-analytic model of laser-ultrasonics in a multilayer structure

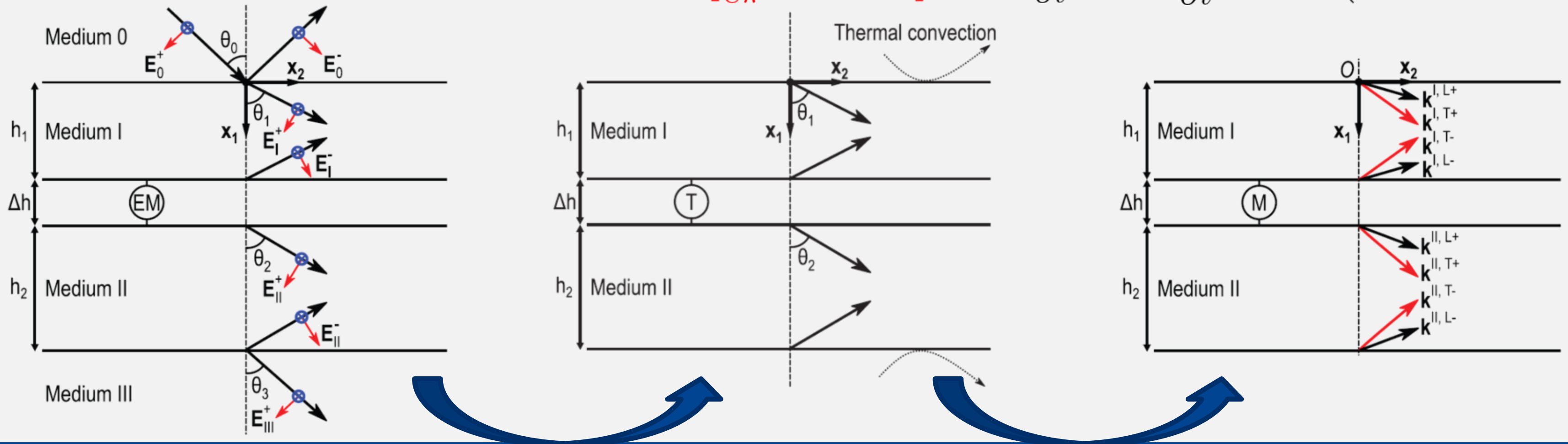
Presentation of the model

- 2D semi-analytic approach to successively solve electromagnetic, thermal, and elastodynamic problems (orthotropic materials) in multilayer using the transfer matrix method
- Complex thermal and mechanical coupling conditions are considered
- Developed code is provided for free : see Hode *et al.* J. Acoust. Soc. Am., **150**(3), 2021

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0$$

$$\underline{\lambda} \nabla^2 T - \nabla \cdot \left[\frac{c_0}{8\pi} \Re(\mathbf{E} \times \overline{\mathbf{H}}) \right] = \rho c_p \frac{\partial T}{\partial t}$$

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \left(\underline{\underline{C}} : \underline{\varepsilon} - \underline{\underline{C}} : \underline{\alpha} \Delta T \right)$$



2. Semi-analytic model of laser-ultrasonics in a multilayer structure

Output : (k,w) space

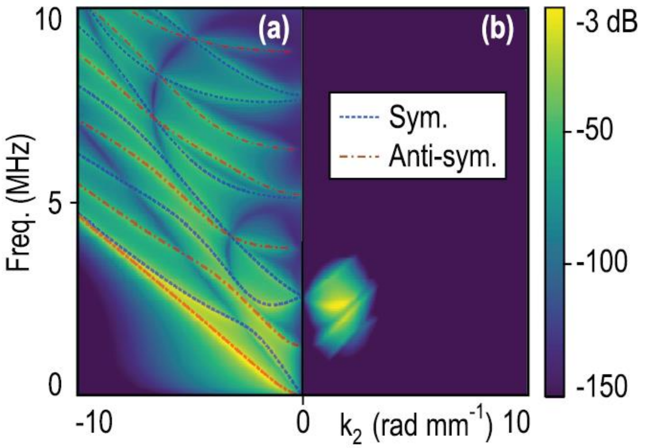


FIG. 4. (Color online) Zoom views of f–k diagrams (plotted in dB with the colormap), for a 1.23 mm–thick aluminum alloy plate at $x_1 = 1.23$ mm, for two different laser sources. (a) Gaussian laser pulse ($\tau_p = 8$ ns, $a_s = 0.2$ mm). (b) Modulated laser source in time (tone burst of 2.5 MHz central frequency) and space (phase mask of 1.5 rad mm^{-1} central wavenumber). A good agreement is obtained with the dispersion curves simulated with the commercial software CIVA 2020 in dashed (dash-dotted) lines for symmetric (antisymmetric) modes, which are superimposed on the f–k diagrams calculated with the developed model.

Output : (x,t) space

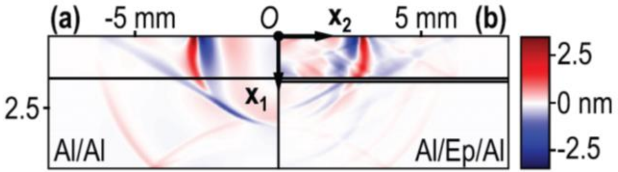


FIG. 5. (Color online) Normal displacements $u_1(x_1, x_2, t)$ simulated at $t = 1$ μs in (a) a bilayer Al (1.5 mm)/Al (3.1 mm) and (b) a trilayer Al (1.5 mm)/Epoxy (0.1 mm)/Al (3.0 mm). See the supplementary material (Ref. 23) for the animations.

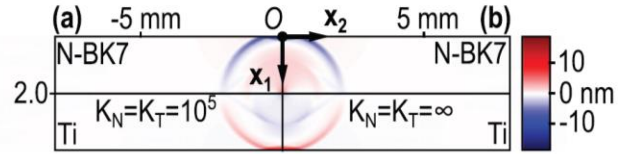


FIG. 6. (Color online) Normal displacements $u_1(x_1, x_2, t)$ simulated at $t = 0.35$ μs in a bilayer glass (2 mm)/Ti (2 mm) with interfacial stiffnesses equal to: (a) $K_N = K_T = 10^5$ kN mm^{-3} and (b) $K_N = K_T = \infty$ kN mm^{-3}. See the supplementary material (Ref. 23) for the animations.

3

PLANE WAVE SYNTHESIS AND INVERSE PROBLEM FOR NONDESTRUCTIVE EVALUATION OF ADHESIVE BONDINGS

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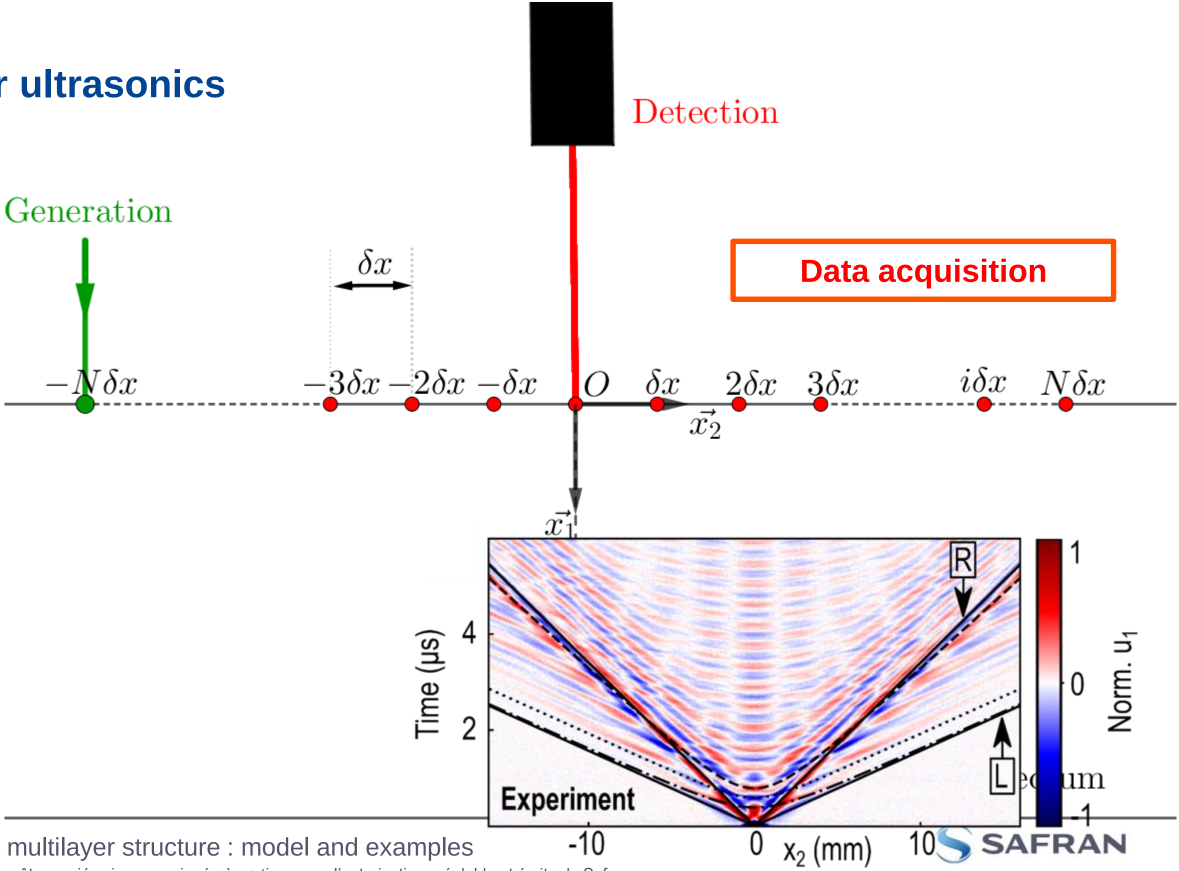
3. Presentation of the plane wave synthesis

Plane wave synthesis in laser ultrasonics

- **Data acquisition:**
  - Generation : $2N + 1$ positions;
  - Detection: fixed detection point.
- Post-processing:
  - Delay δt between sources:

$$s(t) = \sum_{i=-N}^{N} s_i(t + i\delta t).$$

$$\frac{1}{V_S} = \frac{\delta t}{\delta x} = \frac{\sin \phi_p}{V_p}.$$



F. Reverdy, PhD Thesis, 2000.
F. Reverdy and B. Audoin. J. Appl. Phys. **90**, 4829, 2001

3. Presentation of the plane wave synthesis

Post-processing

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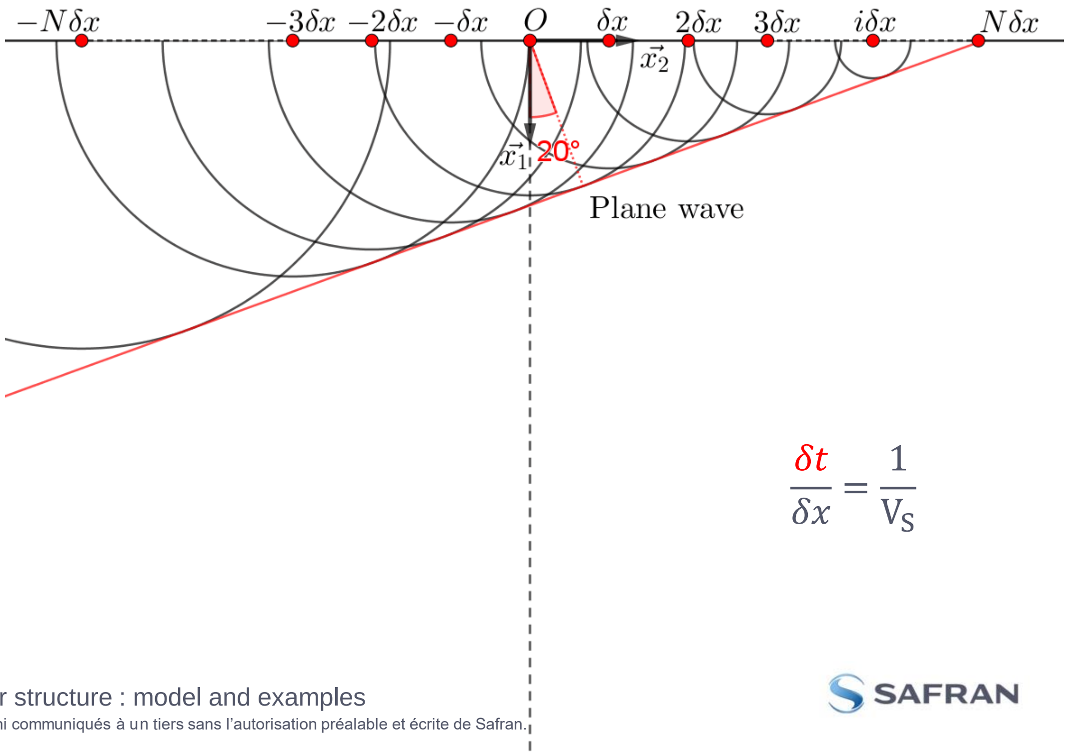
$$\phi_p = 20°$$



$$\frac{\delta t}{\delta x} = \frac{1}{V_S}$$

F. Reverdy, PhD Thesis, 2000.
F. Reverdy and B. Audoin. J. Appl. Phys. **90**, 4829, 2001

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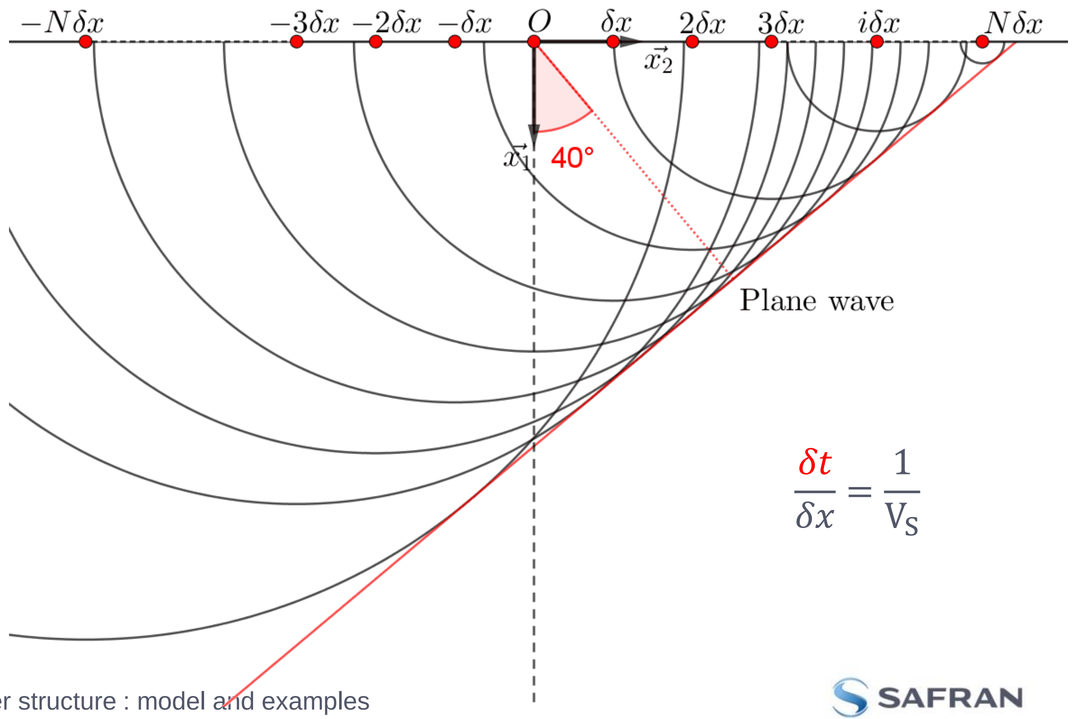
$\phi_p = 40°$



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3. Presentation of the plane wave synthesis

Post-processing

Plane wave synthesis in laser ultrasonics

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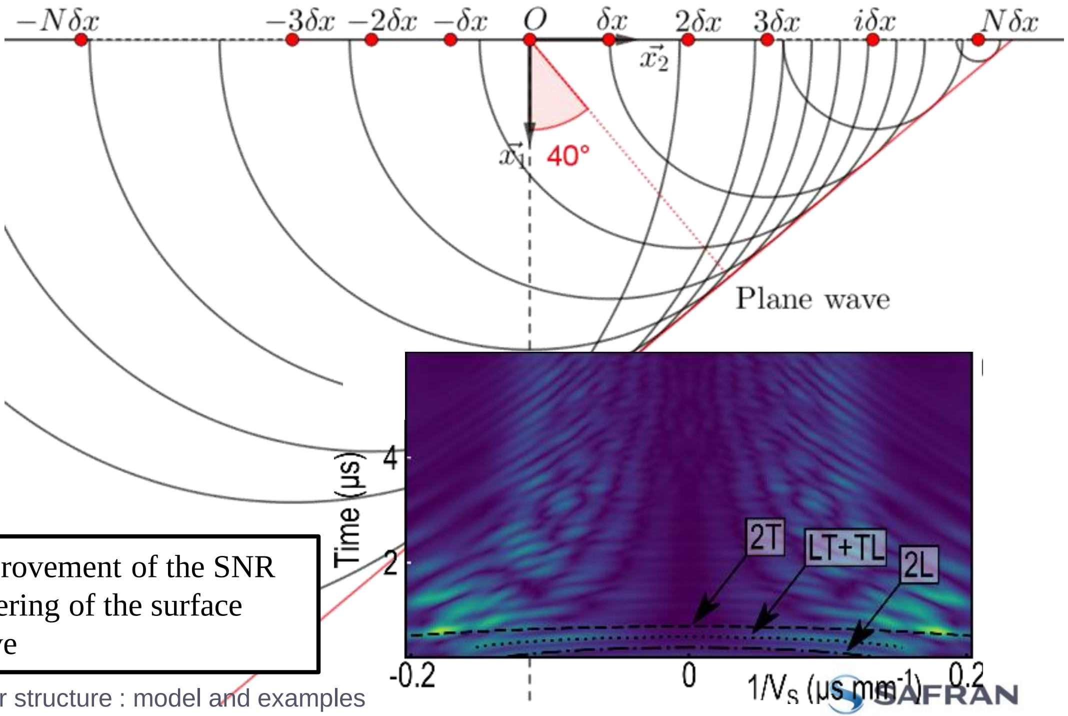


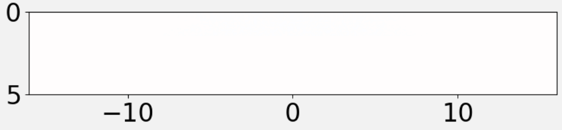
- Improvement of the SNR
- Filtering of the surface wave

F. Reverdy and B. Audoin. J. Appl. Phys. **90**, 4829, 2001.

4. Nondestructive evaluation of adhesive bondings

Generation of a database of different bonding stiffenesses

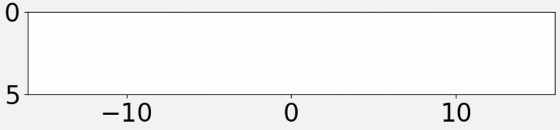
Without adhesion



$K_N = 10^{-3} kN/mm^3$

$K_T = 10^{-3} kN/mm^3$

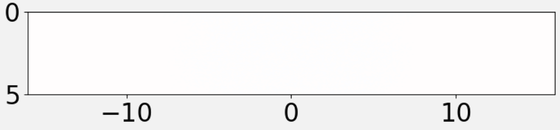
Bad adhesion



$K_N = 10^{3} kN/mm^3$

$K_T = 10^{1} kN/mm^3$

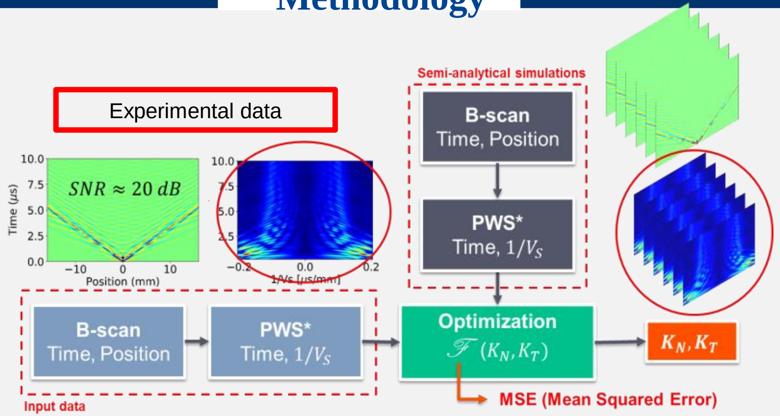
Perfect adhesion



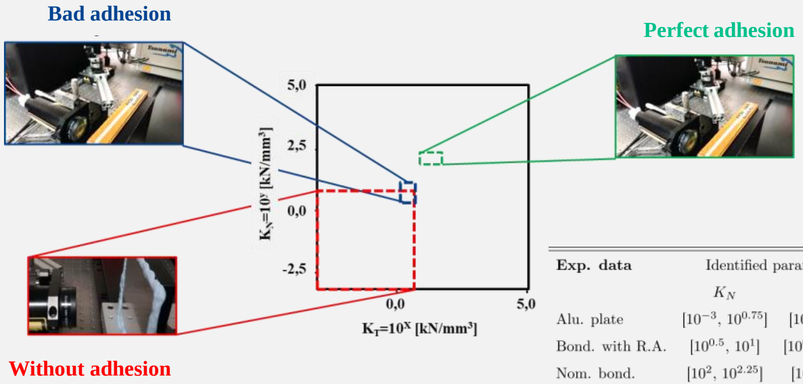
$K_N = 10^{5} kN/mm^3$

$K_T = 10^{5} kN/mm^3$

Methodology



Experimental results



Exp. data	Identified parameters	
	K_N	K_T
Alu. plate	$[10^{-3}, 10^{0.75}]$	$[10^{-3}, 10^{0.5}]$
Bond. with R.A.	$[10^{0.5}, 10^{1}]$	$[10^{0.25}, 10^{0.5}]$
Nom. bond.	$[10^{2}, 10^{2.25}]$	$[10^{1}, 10^{1.5}]$

Hode et al. J. Acoust. Soc. Am., 150(3), 2021

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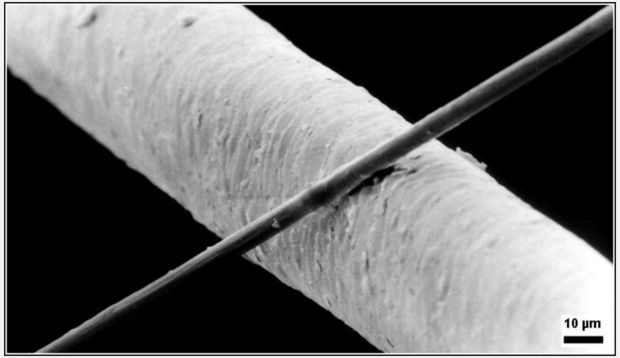
OTHER APPLICATIONS

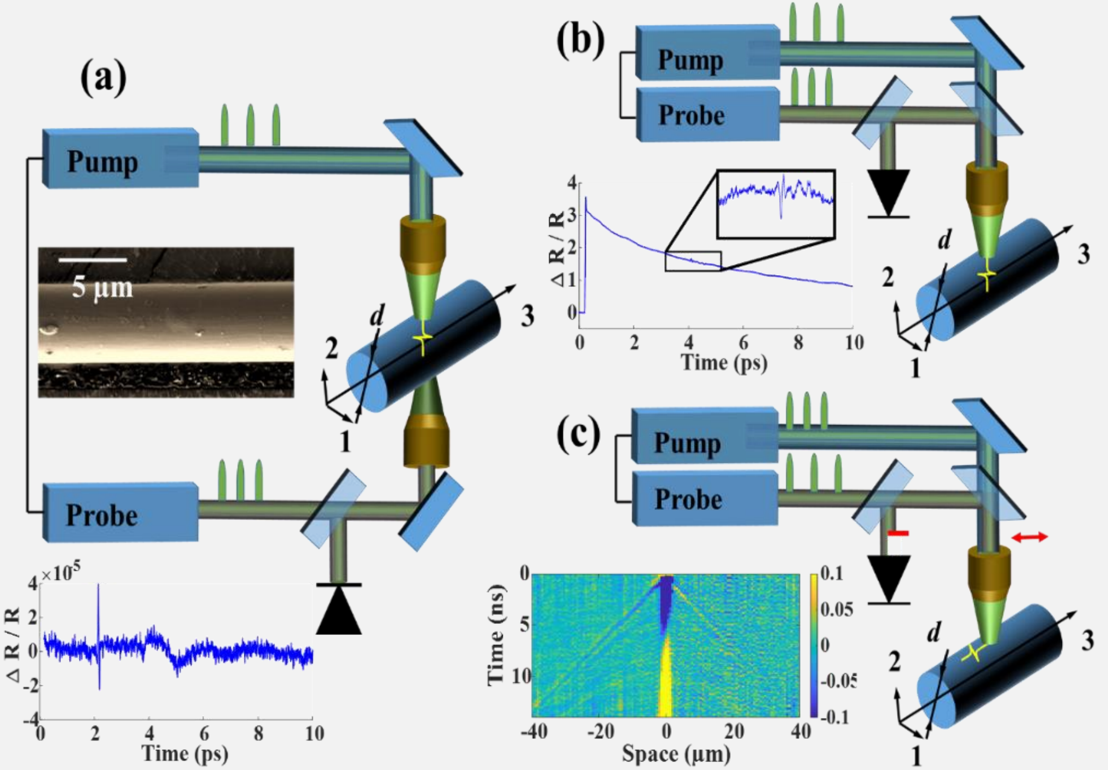
Picosecond ultrasonics in a single carbon fiber

Experiments

- NETA heterodyne system
- λ_{pump} = 532 nm ; λ_{probe} = 512 nm; τ = 200 fs
- focus = 1 µm FWHM



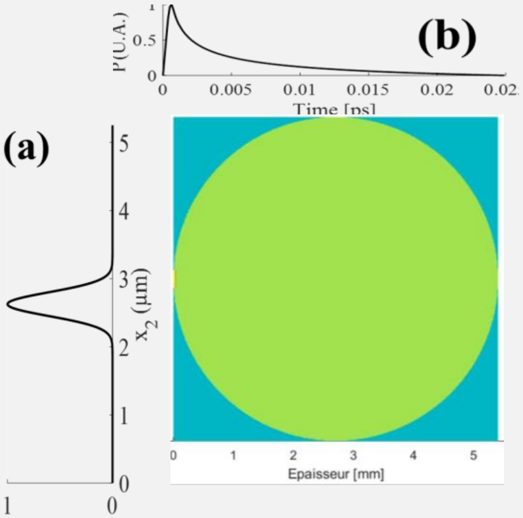
Carbon fiber compared with human hair

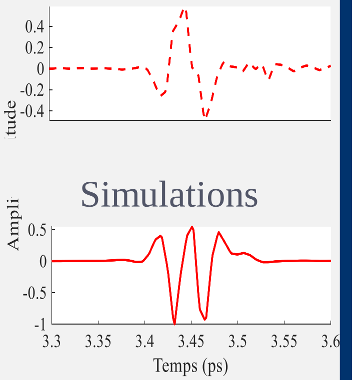


Modeling

Bulk waves - FDTD

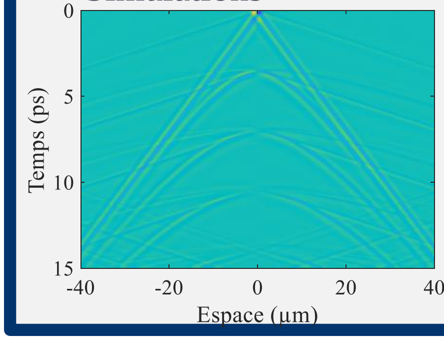
- 2D Finite differences modeling in the time domain (4th order) according to a Virieux scheme of the elastodynamic equations
- Open source : Cuenca *et al.*, J. Appl. Phys., **128**(244903), 2020
- Calculation : > 11 h one a classical laptop

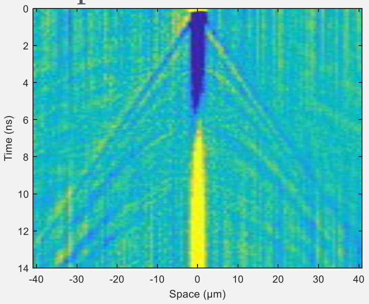




Surface wave – analytic model

- Optical penetration, thermal diffusivity and visco-elastic propagation are taken into account in a plane configuration
- Open source : Hode *et al.*, J. Acoust. Soc. Am., **150**(3), 2021
- Calculation : ~ 30 s one a classical laptop

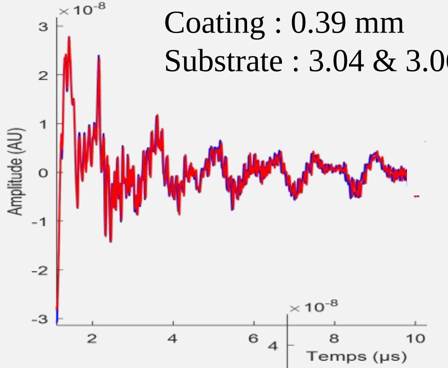




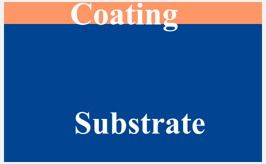
5. Thickness evaluation on bilayer using local resonances and supervised machine learning

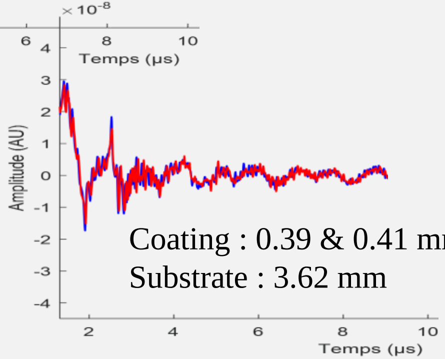
Simulation of the elastic propagation

More than 2000 simulations of elastic propagation in a bilayer with thicknesses variations (substrat and coating) ➔ few hours of calculation

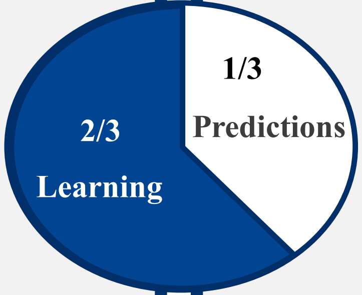


Coating : 0.39 mm
Substrate : 3.04 & 3.06 mm





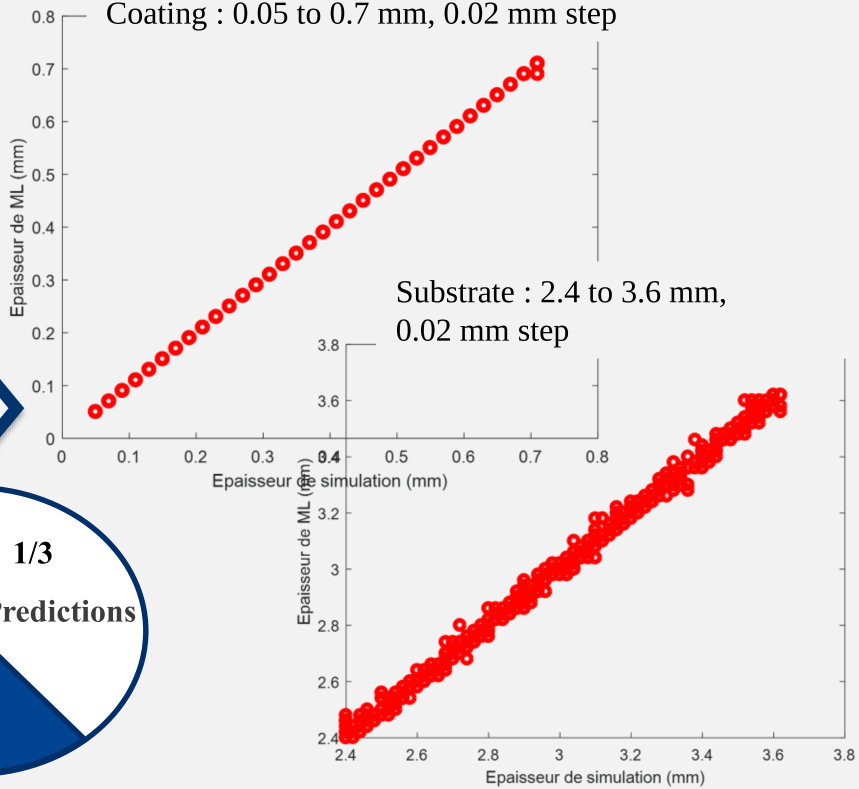
Coating : 0.39 & 0.41 mm
Substrate : 3.62 mm



Supervised ML analysis

Coating : 0.05 to 0.7 mm, 0.02 mm step

Substrate : 2.4 to 3.6 mm, 0.02 mm step



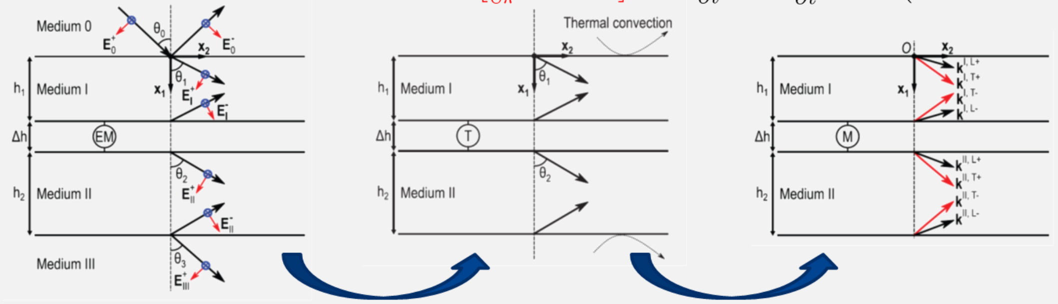
Supervised Learning Workflow and Algorithms - MATLAB & Simulink - MathWorks France

Conclusion

Conclusions

- A multilayer model have been proposed to successively solve electromagnetic, thermal, and elastodynamic coupled problems in laser ultrasonics. The optical penetration and angle of the laser line source are considered, as well as thermal conduction and convection. Complex thermal and mechanical coupling conditions are considered between the upper and lower media of the multilayer.

$$\nabla^2 \mathbf{E} + k^2\mathbf{E} = 0 \qquad \lambda\nabla^2 T - \nabla\cdot\left[\frac{c_0}{8\pi}\Re(\mathbf{E}\times\overline{\mathbf{H}})\right] = \rho c_p \frac{\partial T}{\partial t} \qquad \rho\frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla\cdot\left(\underline{\underline{C}}:\varepsilon - \underline{\underline{C}}:\underline{\alpha}\Delta T\right)$$



- We illustrated the model on NDE of bonded assemblies, on picosecond ultrasonics or supervised machine learning applications