COMSOL CONFERENCE
ROTTERDAM2013

Laser-Ultrasonics Wave Generation and Propagation FE Model in Metallic Materials

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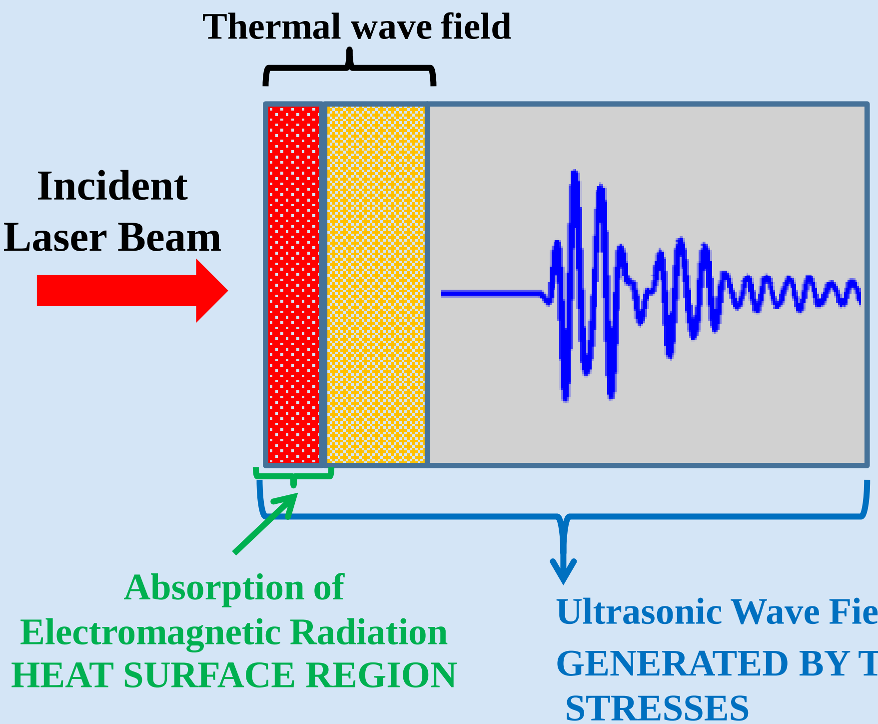
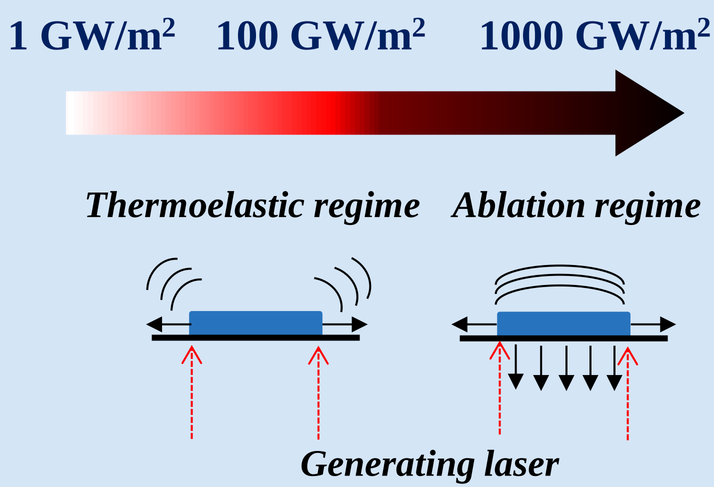
Introduction: Laser-Ultrasonics



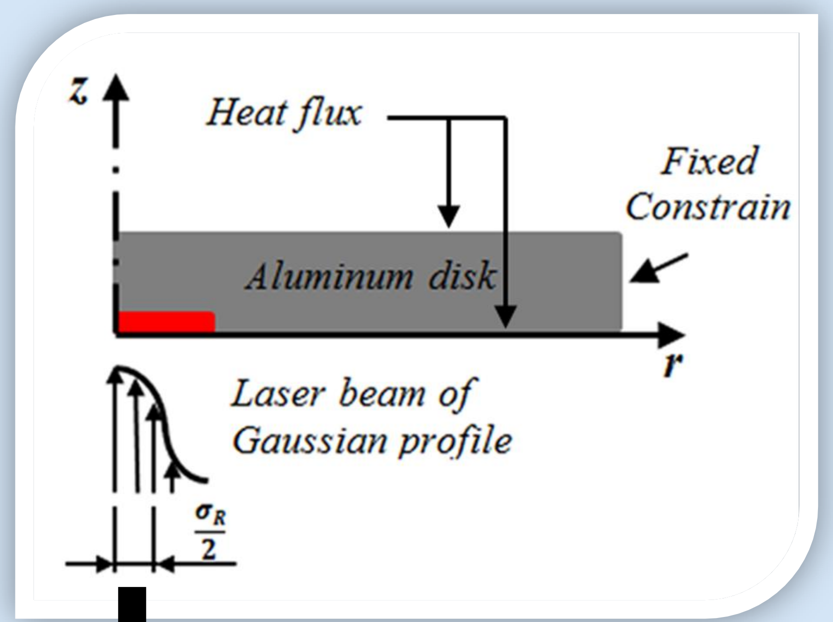


LASER-ULTRASONICS:

- noncontact, leading to increased speed of inspection;
- non-destructive if the optical power is kept sufficiently small;
- suitable for in situ measurements in an industrial setting;
- couplant independent;
- applicable on curved complex surfaces;
- broadband systems.

Use of COMSOL Multiphysics

- A 2D axisymmetric model has been performed simulating the half cross section of an aluminium disk of radius 10 mm and 3 mm thick.



Laser diameter (σ_R)	**0.6 mm**
Laser energy	**140 mJ**
Laser pulse duration	**12 ns**

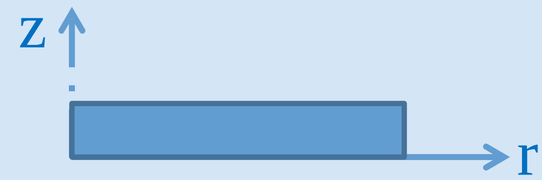
Two different physics have to be considered in Laser-Ultrasonics:

- Thermo-elasticity for the ultrasonic wave generation due to the thermo-stress induced by the laser impulse.
- Acoustics for the ultrasonic wave propagation within the material.

Comsol - Physics used:
- **THERMAL STRESS**
- **TRANSIENT ACUSTICS-SOLID INTERACTION**

Use of COMSOL Multiphysics

❑ Thermal diffusion equation



$$\rho C_v \frac{\partial T}{\partial t} + \rho C_v \boldsymbol{u}_1 \nabla T = \nabla(k \nabla T) + Q \Rightarrow Q(r,z,t) = Q_o f(r) g(t) \delta(z)$$

T	Temperature raise
k	Thermal conduction coefficient
ρ	Density
Cv	Constant volume specific heat
$\mathbf{Q(r,z,t)}$	Power density of the heat source

- ***Q_o*** is the total absorbed heat;
- ***f(r)*** is the radial distribution of the laser irradiance;
- ***g(t)*** gives its temporal distribution;
- ***δ(z)*** considers the effect of absorption.

BOUNDARY CONDITIONS

❑ Heat flux on the top and bottom surface simulates convective cooling.

❑ Other boundaries are assumed to be thermally insulated.

❑ Heat source:

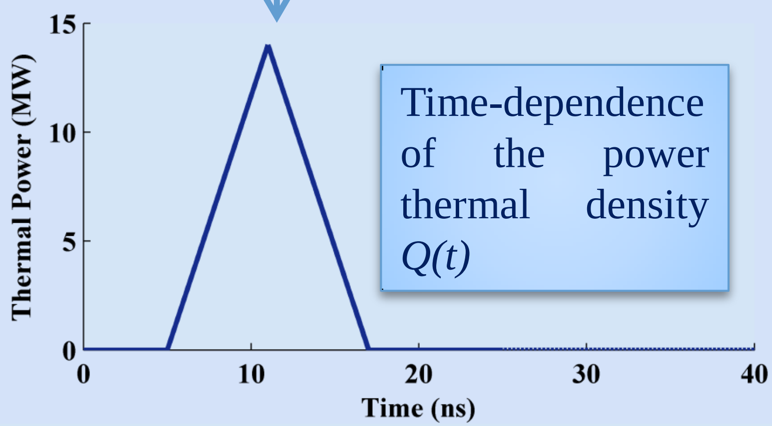
$$Q_{in}(r,z,t) = Q(t)(1 - R_c)\left(\frac{A_c}{\pi \sigma_r^2}\right) e^{-\left(\frac{r^2}{2\sigma_r^2}\right)} e^{-A_c z}$$

Use of COMSOL Multiphysics

- **Skin depth** $\delta = (\pi\sigma\mu_r\mu_0\nu)^{-1/2}$
- **Reflection coefficient** $R_c = 1 - 4/(\mu_0\sigma c\delta) \cong 0.9$
- **Absorption coefficient** $A_c = 1/\delta \cong 2x108\ 1/m$

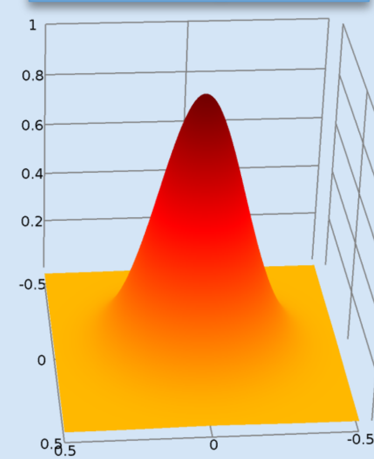
σ	Conductivity	$4x10^7\ (\Omega m)^{-1}$
μ_r	Relative permeability	~1
μ_0	Permeability of free space	$4\pi x10^7\ Hm^{-1}$
ν	Frequency of the radiation	$2.8x10^{14}$ Hz

$$Q_{in}(r,z,t) = Q(t)(1 - R_c)\left(\frac{A_c}{\pi\sigma_r^2}\right) e^{-\left(\frac{r^2}{2\sigma_r^2}\right)} e^{-A_c z}$$

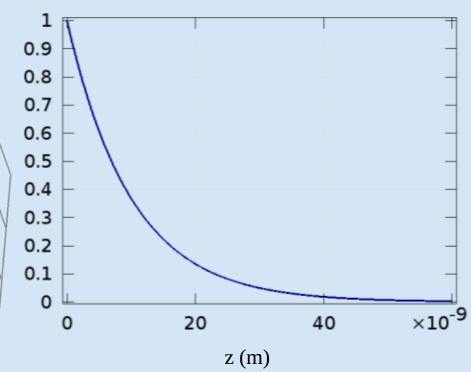


Time-dependence of the power thermal density $Q(t)$

Gaussian profile



Effect of absorption



Use of COMSOL Multiphysics

The acoustic model allows to connect the elastic wave propagation with the thermal deformation evaluated in the thermal stress module

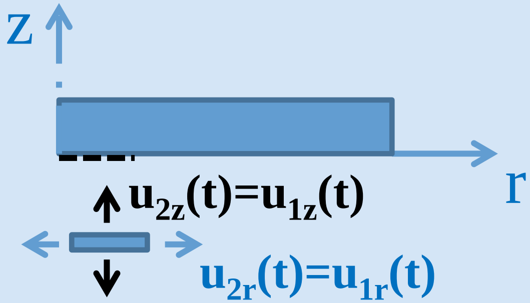
NEWTON'S SECOND LAW:

$$\rho \frac{\partial^2 \boldsymbol{u_2}}{\partial t^2} - \nabla \boldsymbol{s} = \boldsymbol{F_v}$$

- $\boldsymbol{u_2}$: displacement vector.
- $\boldsymbol{s}$: stress tensor.
- $\boldsymbol{F_v}$: volume force vector.

❑ BOUNDARY CONDITION

Prescribed displacement (in *r* and *z* directions) has been set in order to impose the thermal displacement, output of the thermal stress module, as input of the acoustic one.



❑ MESH

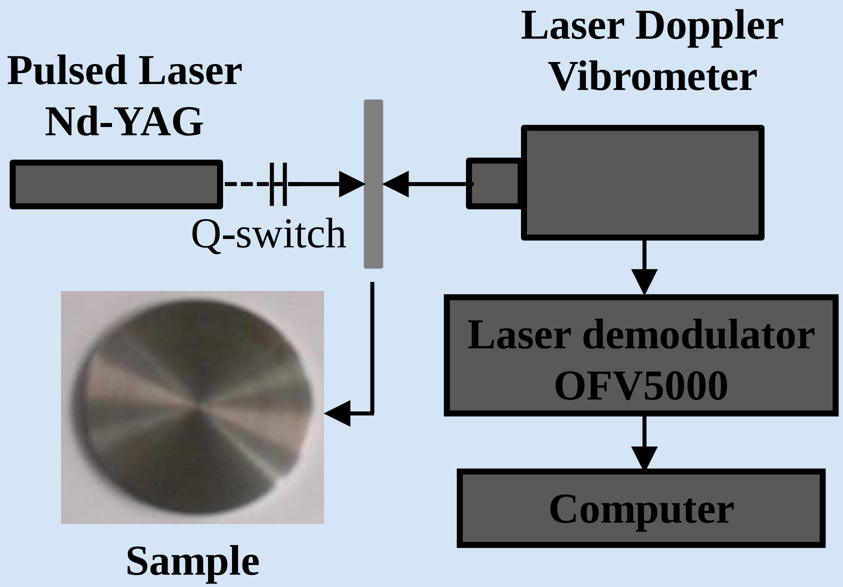
A structured quadrilateral mesh with maximum dimension size of 1 µm was used. Distribution node configuration has been used in order to increase the number of element in the heat source region.

❑ SOLVER

The solver used is the time dependent-solver, with the generalized alpha method for computing the time step. Simulation time : 5 µs

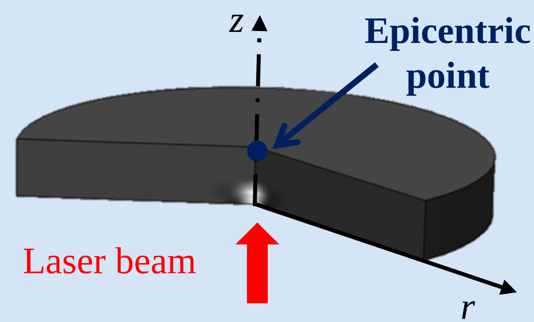
Experimental set-up for model validation

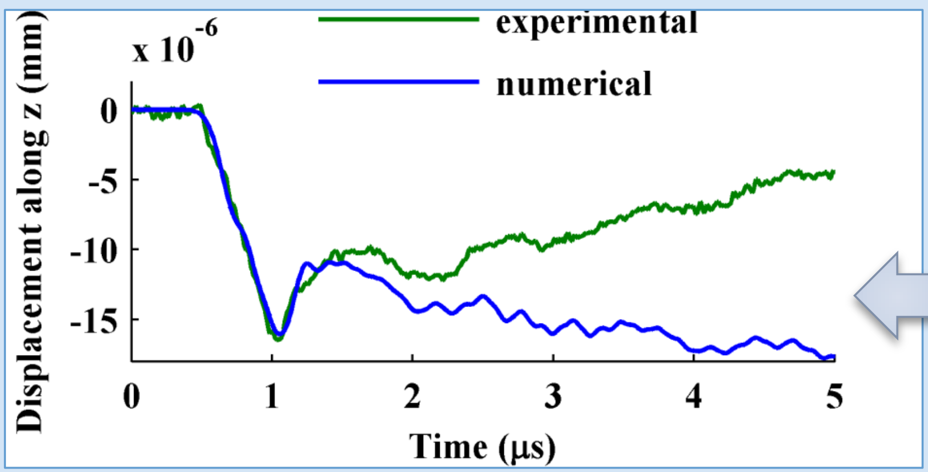
❑ EXPERIMENTAL SET-UP



Nd-YAG laser		
λ (μm)	E (mJ)	**τ** (ns)
1.06	140	12
Laser Doppler Vibrometer		
Frequency bandwidth (MHz)	Displacement resolution (pm)	
20	1	

❑ NUMERICAL MODEL



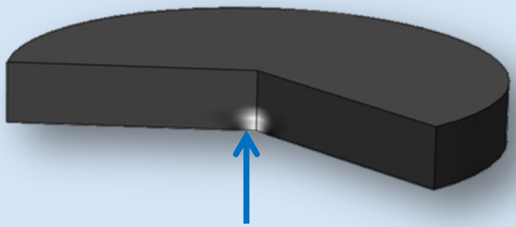


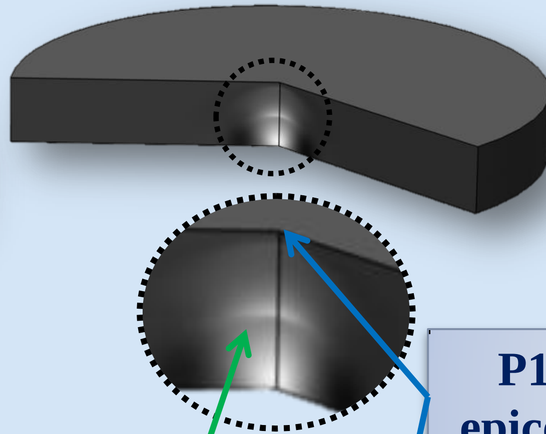
Quantitative comparison between displacement amplitude calculated numerically and measured experimentally

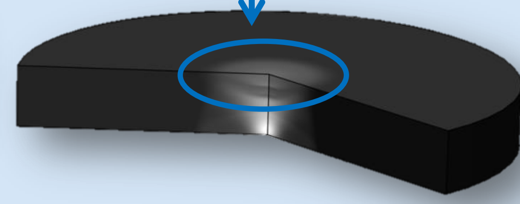
3D- Elastic waves propagation

❑ **TEST SAMPLE REALIZED IN THE MODEL**

Surface wave (t=1 μs)





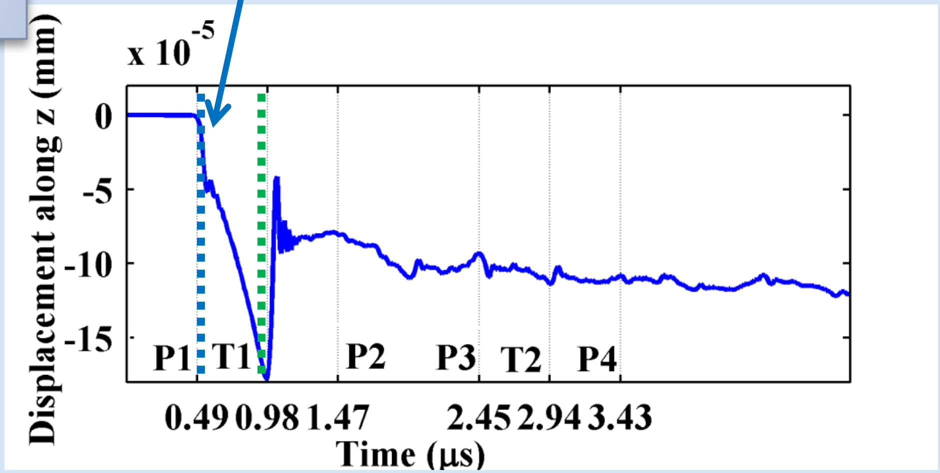


Longitudinal (P1) wave (t=0.2 μs)

P1 wave arrival at the epicentric face (t=0.49 μs)

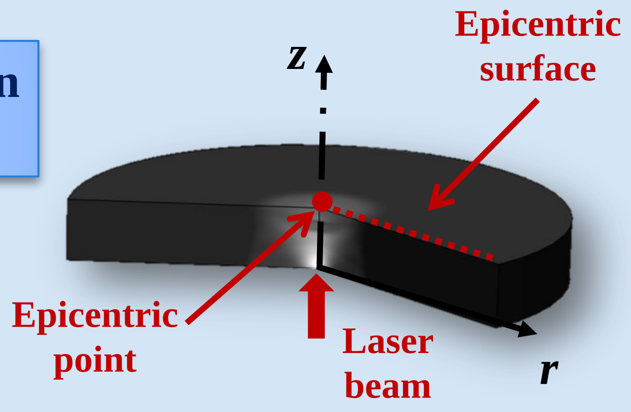
Transverse wave (T1)

Wave	Arrival time	Speed
Longitudinal (P1)	0.49 μs	6153 m/s
Transverse (T1)	0.98 μs	3061 m/s

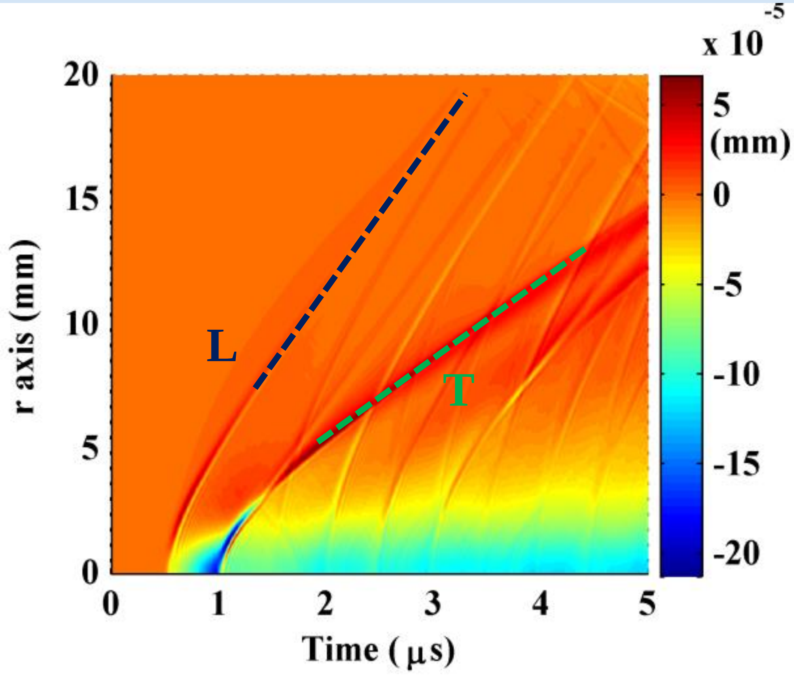


Numerical and Experimental B-Scan

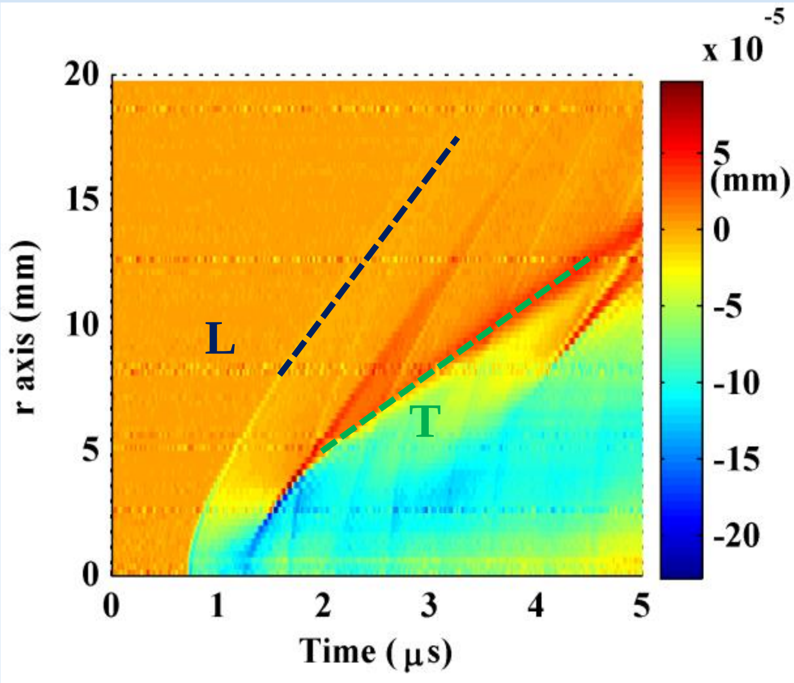
The Waterfalls represent the displacement in the *z*-direction on the epicentric surface



L:	**Longitudinal wave**
T:	**Transverse wave**

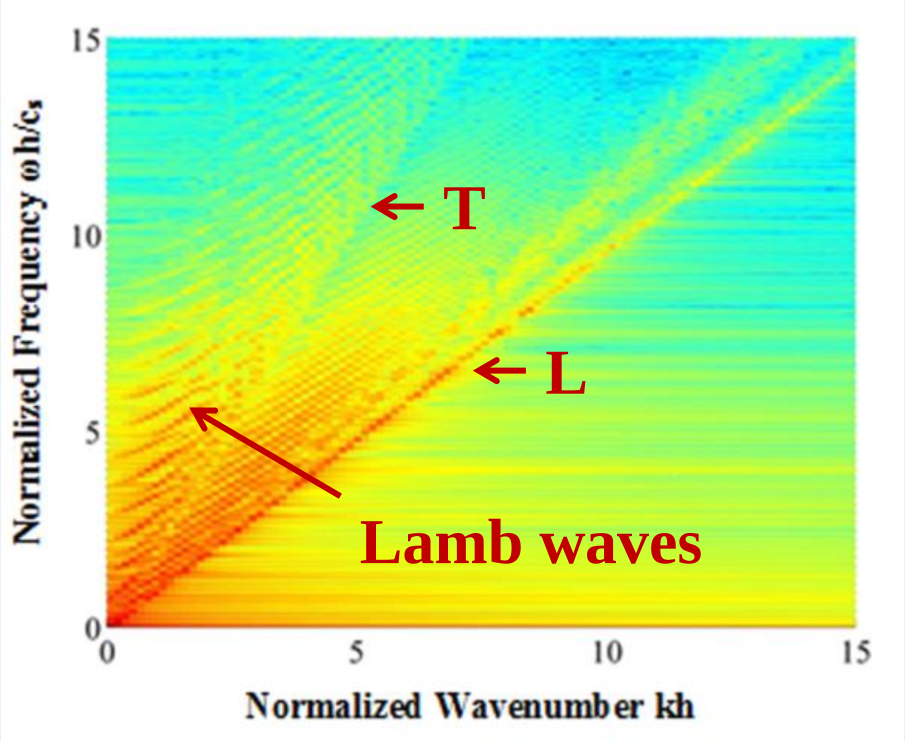


NUMERICAL



EXPERIMENTAL

Dispersion curves in the normalized wavenumber-frequency domain



- The normalization has been performed taking into account the test object thickness (h) and the shear bulk wave speed (c_S).
- The dispersion curves have been obtained with a simulation time of 100 μs.
- The spatial/frequency resolution of the analysis is not sufficient to separate the different Lamb waves components, but their distribution is clearly visible.

CONCLUSIONS

- The model has been validated with experimental data, showing a good correspondence both in terms of propagation mechanisms (P, T bulk waves) and ultrasonic wave amplitude.
- In a future work the model will be exploited to perform a sensitivity analysis to the laser characteristic parameters (i.e. laser energy, diameter and pulse duration).
- Once validated the model, these parameters can be set in advance in relation to the measurement conditions, testing object material and damage typologies (i.e. surface or in-depth defect, convex defect due to fatigue or concave defect due to fretting, defect dimension).

The research is funded by Ministry of Instruction, Research and Education in a PRIN project.

THANK YOU FOR YOUR ATTENTION!