COMSOL CONFERENCE EUROPE 2012

Università di Cagliari

Calibration of Ultrasonic Testing for faults detection in stone masonry

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Outline

- Introduction
  - Non-Destructive Testing
  - Ultrasonic Testing
- Experimental session
- Simulations with COMSOL Multiphisycs
- Comparison between experimental and simulated data
- Results and conclusions

Introduction

The Research Group in Electrical Engineering of Cagliari, with colleagues of the Department of Civil Engineering, has developed skills and knowledge in the field of signal processing in **Non-Destructive-Testing-Techniques NDTs** on homogeneous materials (metals) and non-homogeneous materials (building materials).

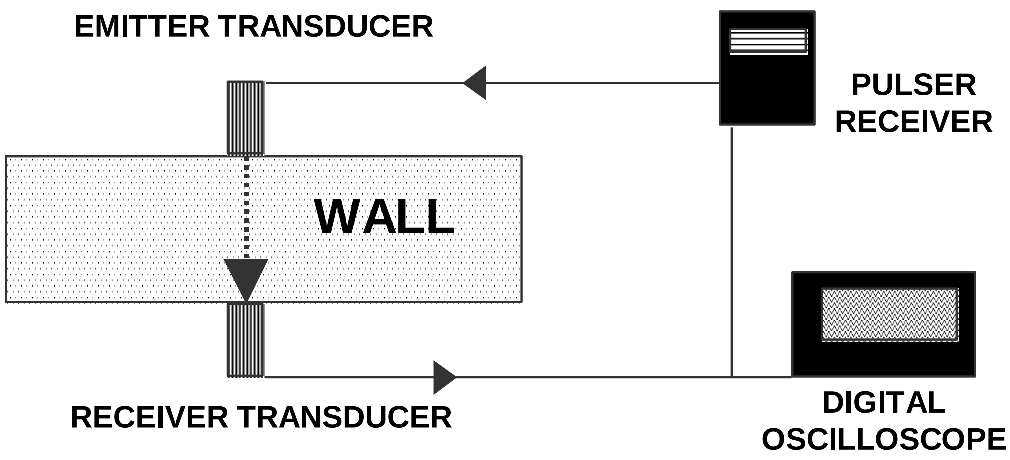
Introduction

- In the field of assessment methodologies, particular importance is given to **Non-Destructive-Testing-Techniques NDTs,** which aspire to achieve the highest number of information about materials and structures without altering their condition.

- The implementation of algorithms for signals post-processing consists in extracting information from test signals derived from the non-destructive tests.

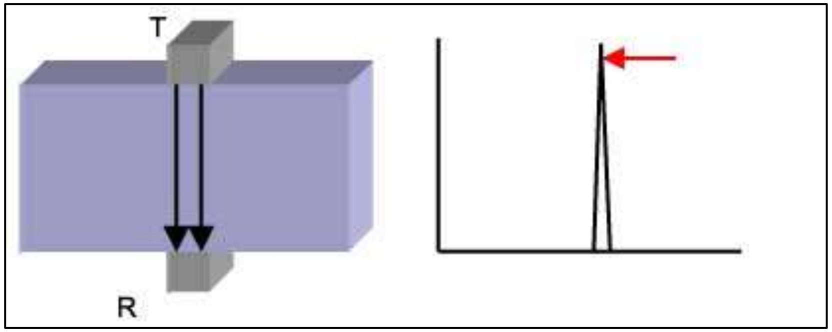
Non-Destructive Testing

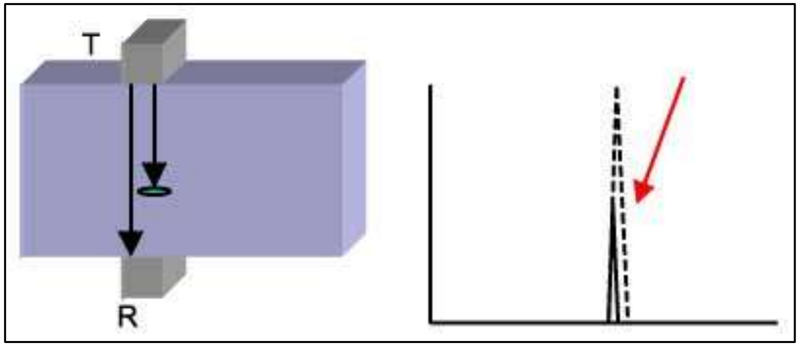
Among NDTs, Ultrasonic Testing exploits the transmission and reflection characteristics of mechanical waves with appropriate frequencies passing through the investigated item.



Ultrasonic Testing

Elastic waves propagate in different manner through solid materials and cavities, thus enabling fault detection.



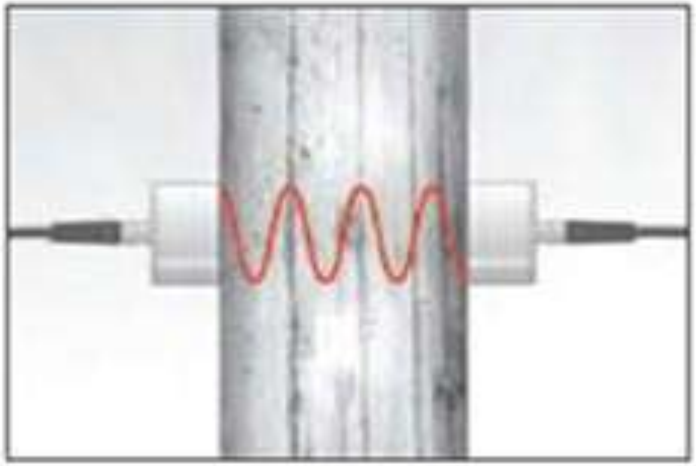


For example, the figure shows how in the presence of a fault, the transmitted wave gives rise to a signal of lower amplitude.

Ultrasonic Testing

The testing method is the **Direct Transmission Technique** (EN 14579 2004).

In this method, the ultrasonic wave is transmitted by a transducer (**T**ransmitter) through the test object and received by a second transducer (**R**eceiver) on the opposite side of the structure.



Ultrasonic Testing

Due to media dissipative effect, elastic waves are strongly attenuated

⇓

the emission cone of the signal source can be less divergent as possible.

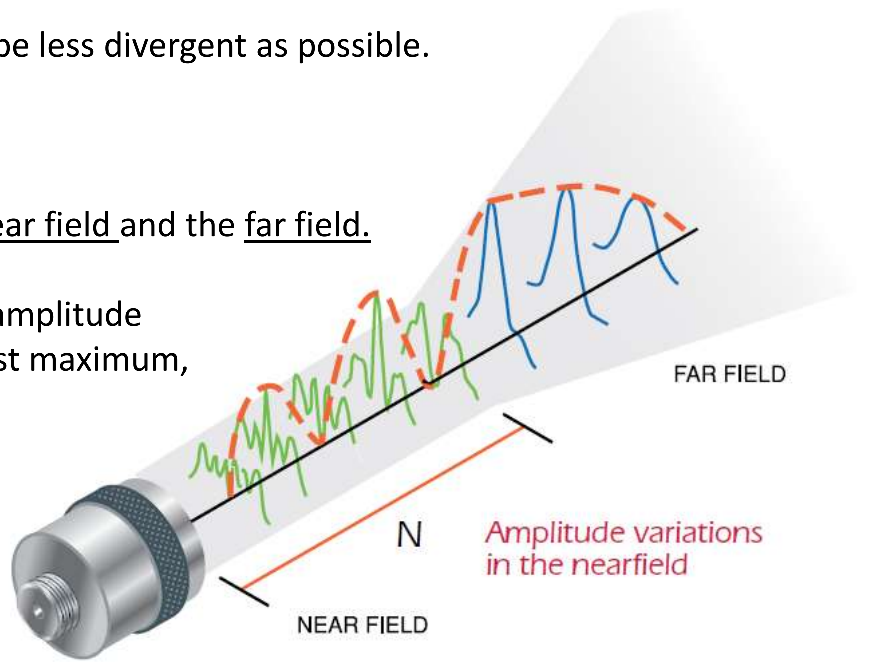
Acoustic field of the transducer

The sound field of a transducer is divided into two zones: the near field and the far field.

Near field: region directly in front of the transducer where the amplitude goes through a series of maxima and minima and ends at the last maximum, at distance N from the transducer.

Far field: area beyond N, where the sound field pressure gradually drops to zero.

Because of the variations within the near field it can be difficult to accurately evaluate flaws using amplitude based techniques.



D → diameter of the Transducer source

λ → wavelength of the wave

$$N = \frac{D^2}{4\lambda}$$ → Near field distance

Ultrasonic Testing

Due to media dissipative effect, elastic waves are strongly attenuated

⬇

the emission cone of the signal source can be less divergent as possible.

Beam Spread and Half Angle

All ultrasonic beams diverge

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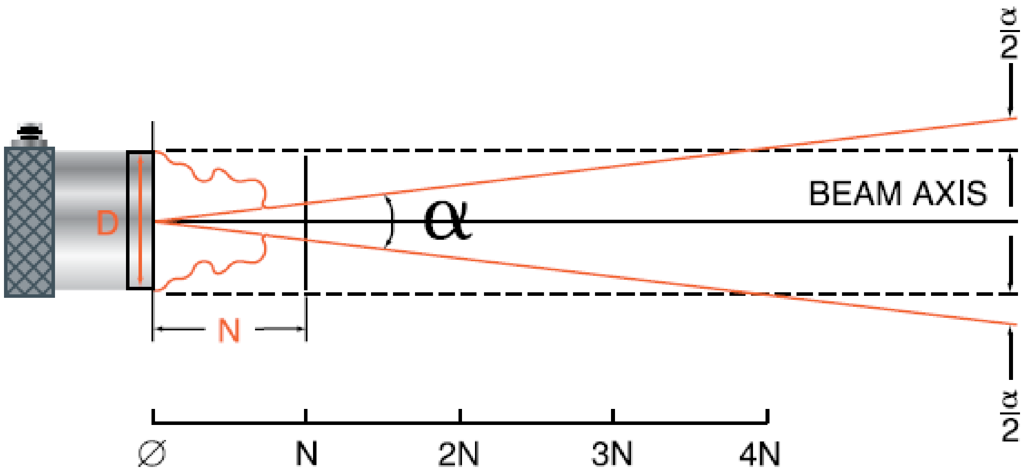
the beam spread is a function of wavelength

$$\sin\alpha = \frac{1.2\lambda}{D}$$



If **D >> λ** the wave is emitted with a not very divergent cone.

As **λ** is in inverse proportion to frequency **f**, it is understandable how high frequency signals enable waves to be highly directional.

Ultrasonic Testing

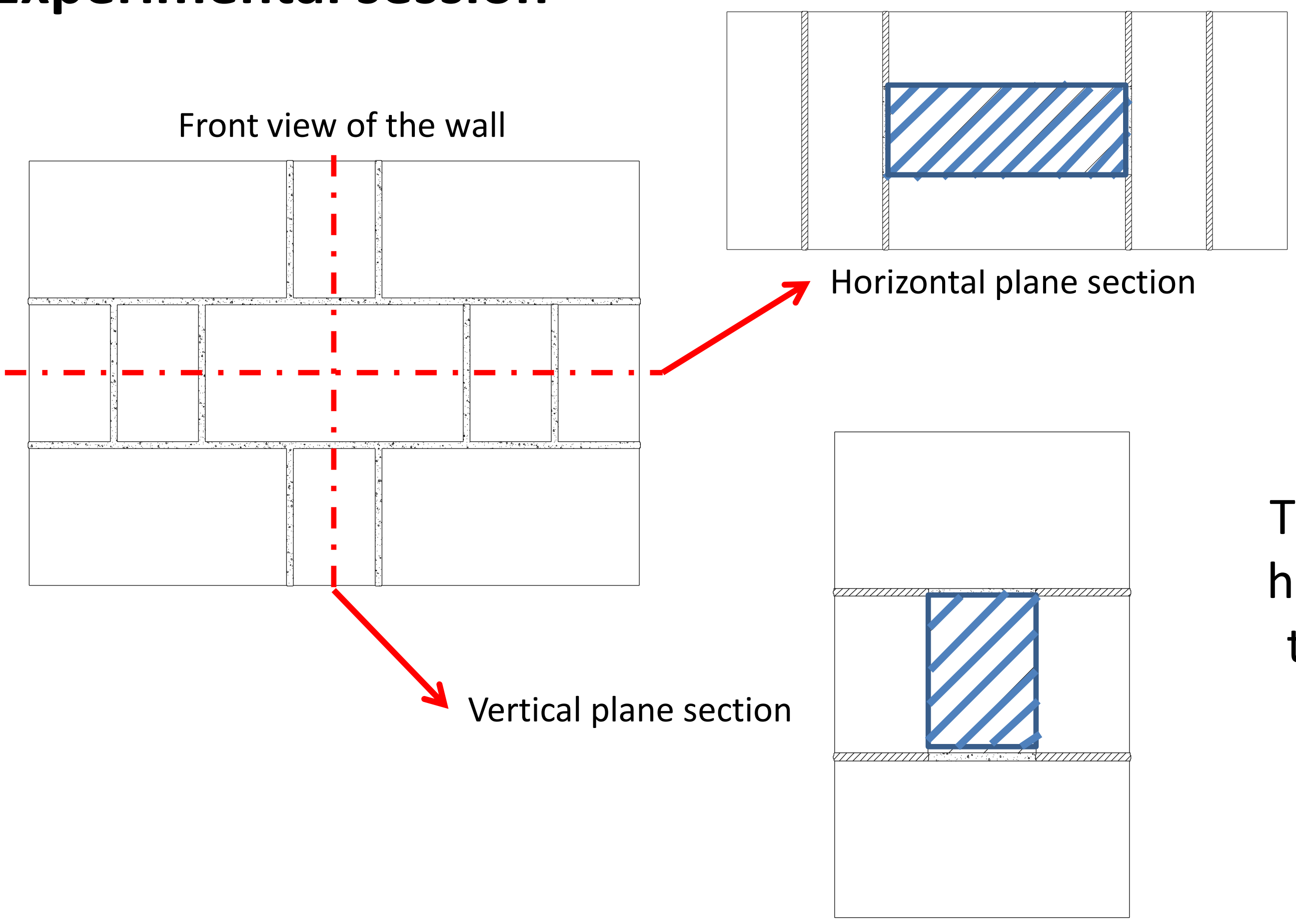
These studies need the highest number of signals as possible.

Laboratory tests must be accurate and repeated several times to obtain reliable signals.

↓

In this phase of the work becomes important to simulate effectively the real models with a suitable FEM code.

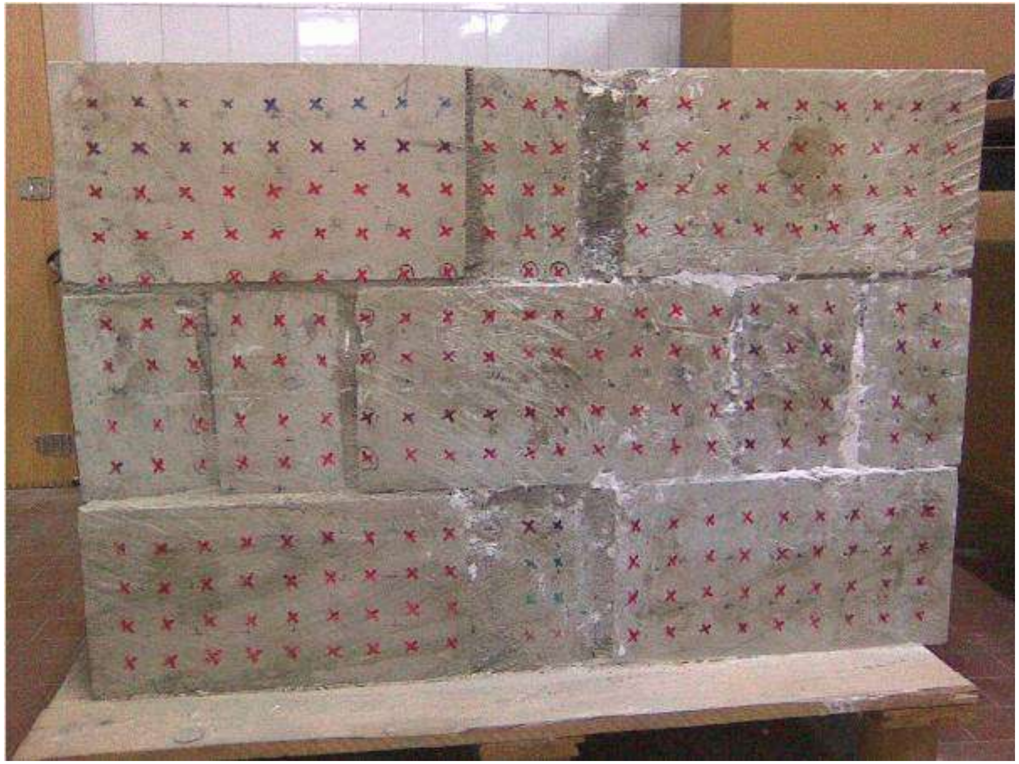
Experimental session



The Ultrasonic Technique has been carried out on a trachyte stone masonry with a cavity inside.

Experimental session

The wall is 90 cm wide, 62 cm high and 38 cm thick, and it is made of **trachyte** blocks sized 20 × 38 × 12 cm^3 joined with **mortar**.

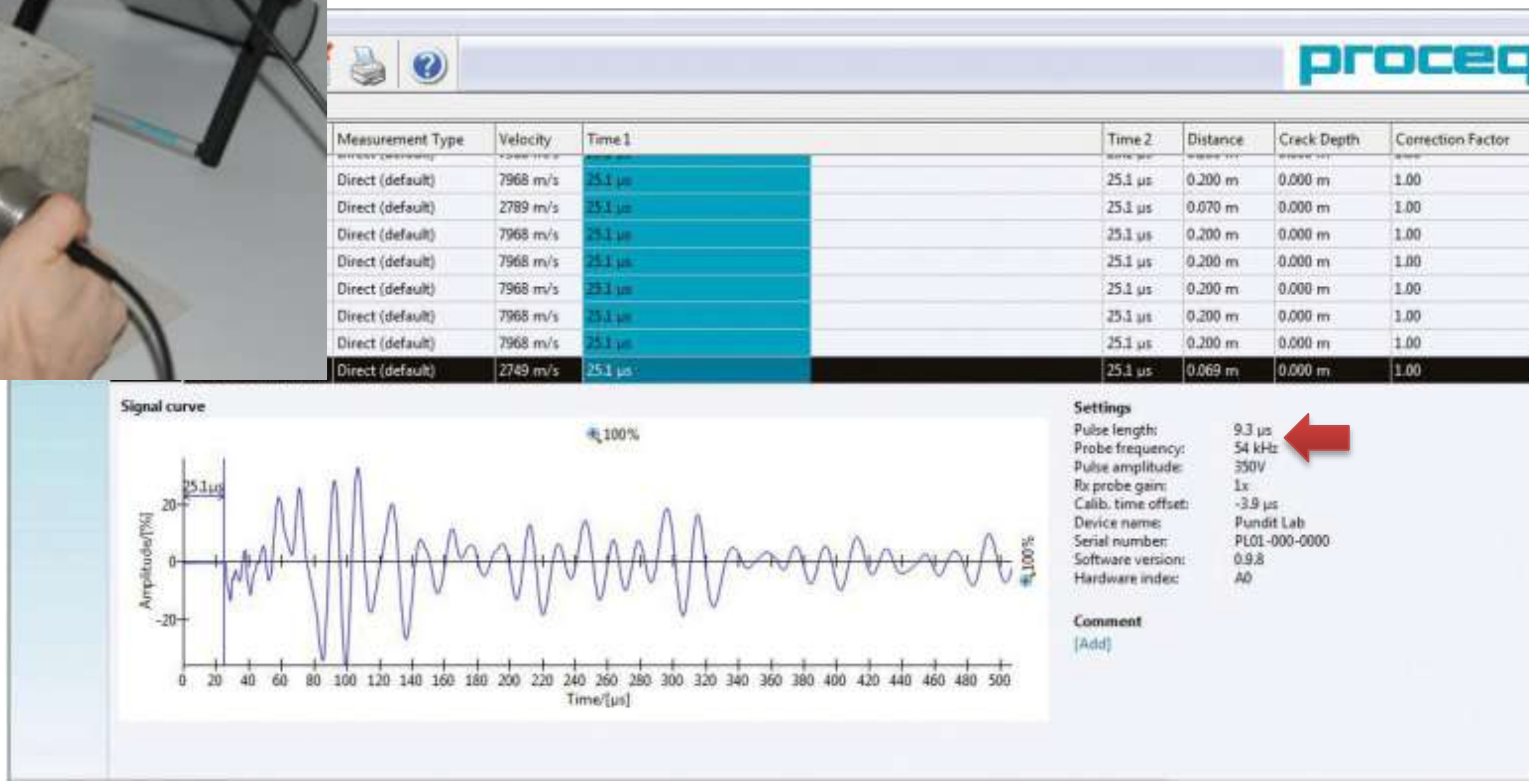


To map the faults

308 points for the emitter transducer and 308 points for the receiver transducer have been arranged in a grid of 14 x 22 nodes in the opposite surfaces of the wall.

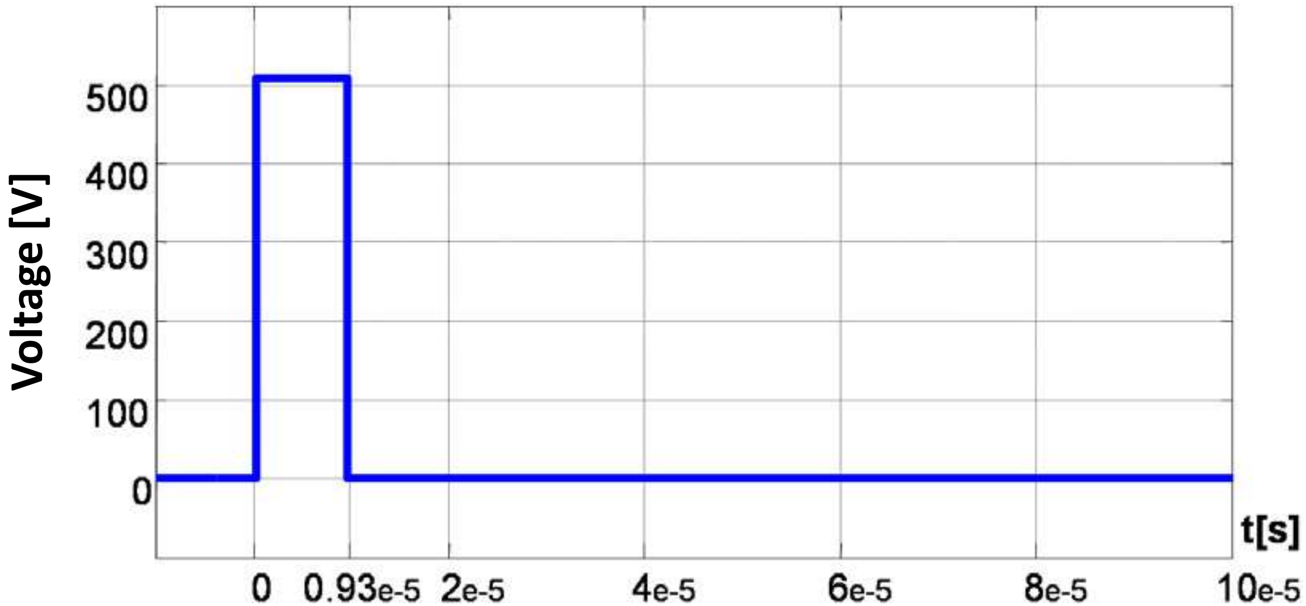
Experimental set-up

Ultrasonic measurements have been carried out using the ultrasonic test equipment **Pundit Lab+**, developed by Proceq, with standard **54 KHz** transducers .



Experimental session

The energizing signal is a ***square wave*** with high input voltage of **500 V**, which develops in a time interval of **9.3µs.**



The high intensity of this signal allowed signals on the other side of the wall to be detected even if strongly attenuated.

Experimental session

A signal has been acquired in each point of the grid of receivers. From each node of the grid, several features in both **time** and **frequency** domain can been extracted.

Time domain

- Propagation velocity
- Maximum peak-peak amplitude
- Maximum absolute amplitude
- Minimum absolute amplitude
- Mean value of normalized amplitude
- Variance of normalized amplitude
- Time–reversibility
- Third order auto-covariance
- Mean value of normalized signal envelope
- Variance of normalized signal envelope
- Local rise time from 25% level to peak of normalized signal envelope
- Local rise time from 50% level to peak of normalized signal envelope
- Signal power
- Travel time

Frequency Domain

- Spectrum principal frequency
- Spectrum normalized maximum amplitude
- Input signal attenuation
- Spectrum central frequency
- Spectrum Bandwidth
- Spectrum normalized mean value
- Spectrum normalized variance

Some of the features that are normally considered to extract information about faults from the signal

Experimental session

Received signals have different patterns depending on the nature of the materials crossed.

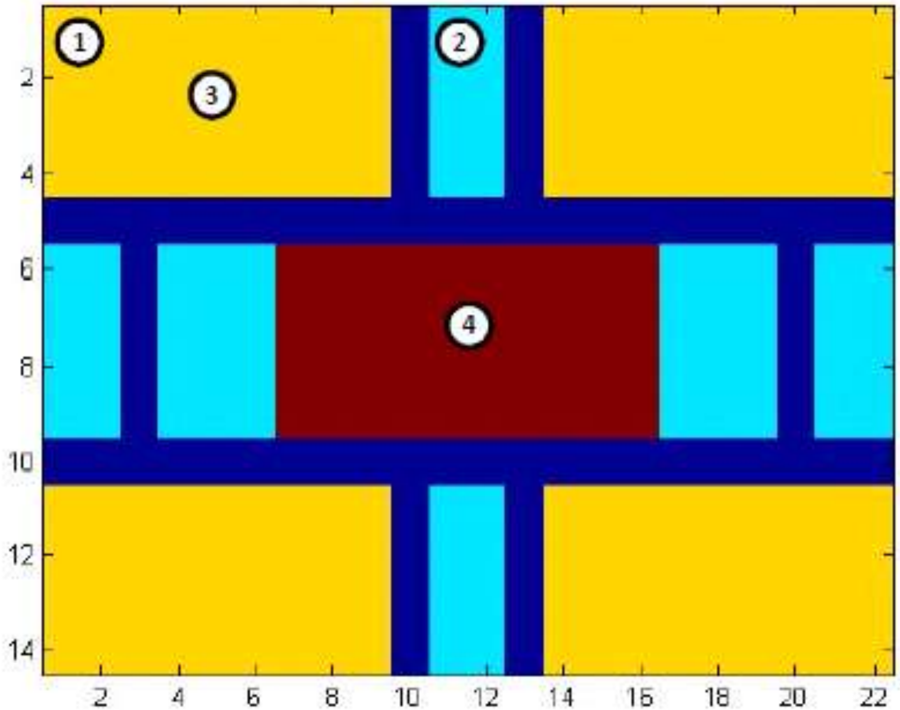
It is possible to distinguish different types of signal paths, corresponding to different materials regions in the wall :

trachyte path (pale blue) → 2

trachyte-mortar path (yellow) → 1 and 3

trachyte-mortar-air path (brown) → 4

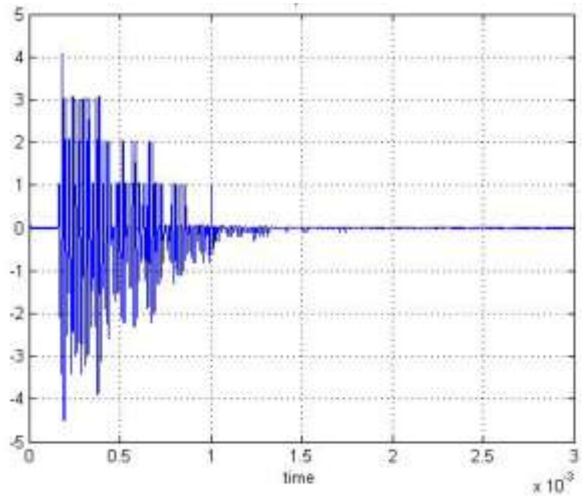
Map associated to the different materials which make up the wall.



Experimental signals crossing the 4 paths (Time domain)

To different paths correspond different signals with unlike <u>amplitudes</u> and <u>harmonic content</u>.

Due to edge effects, signals travelling close to the boundary of a material region are different from those crossing the inner part of the same region.



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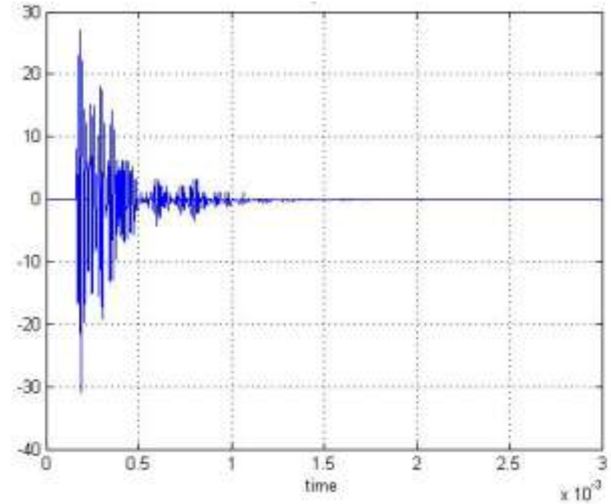

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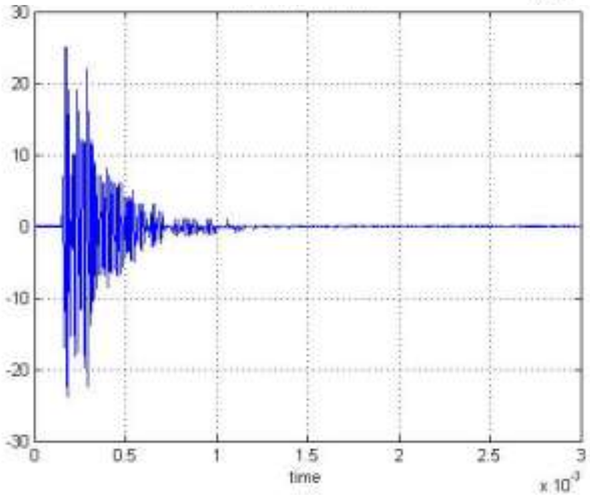

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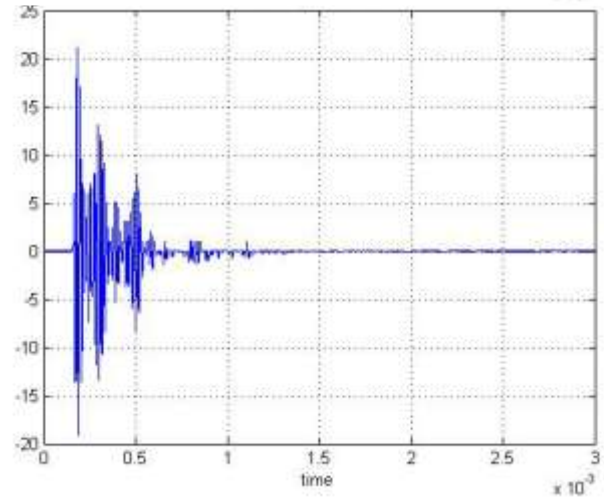

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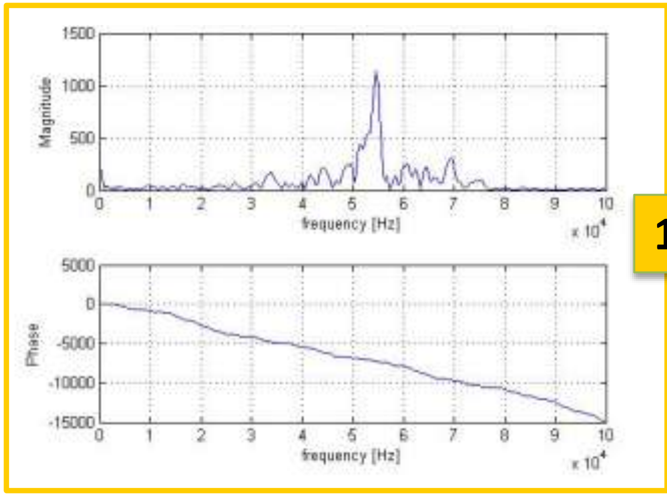
Spectra (Frequency domain)

The harmonic content of the signals takes place around the resonant frequency of the transducer (54 KHz) and differs for each path.



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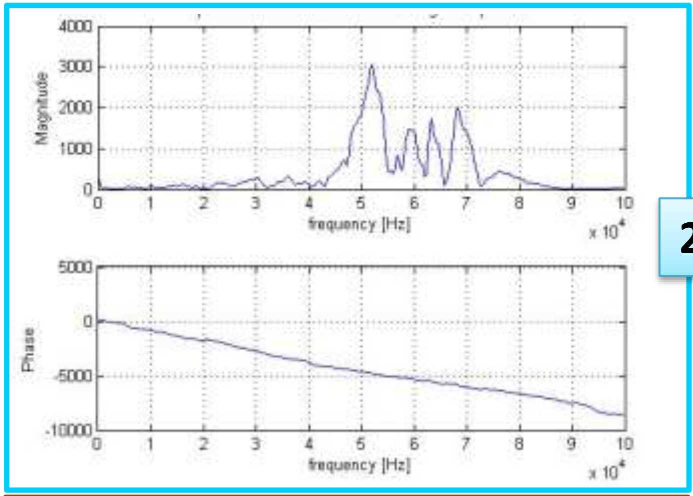

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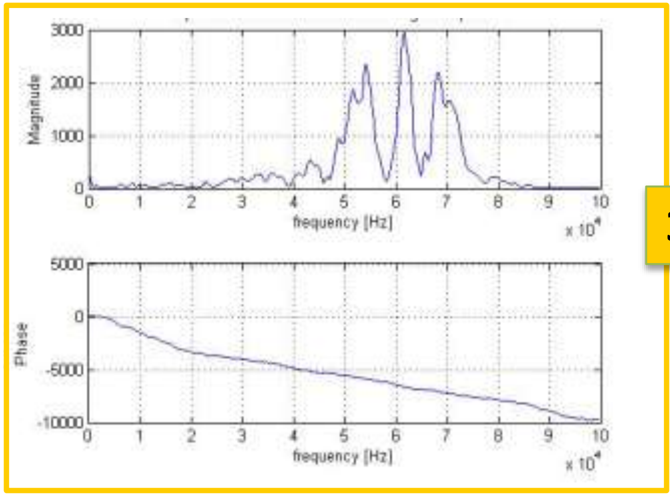

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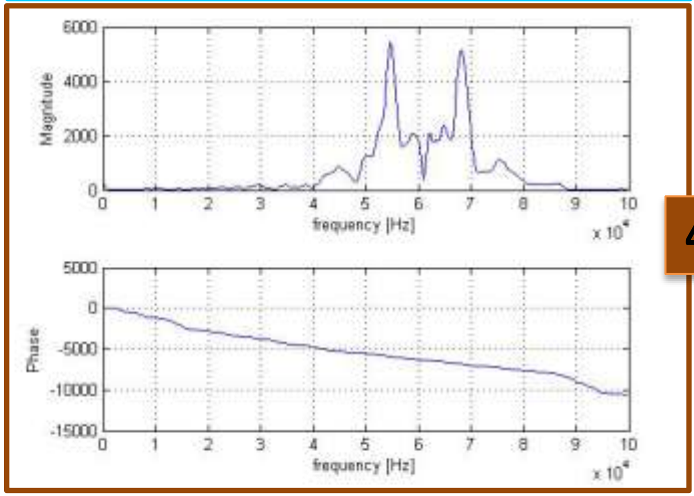

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Simulations with COMSOL Multiphisycs

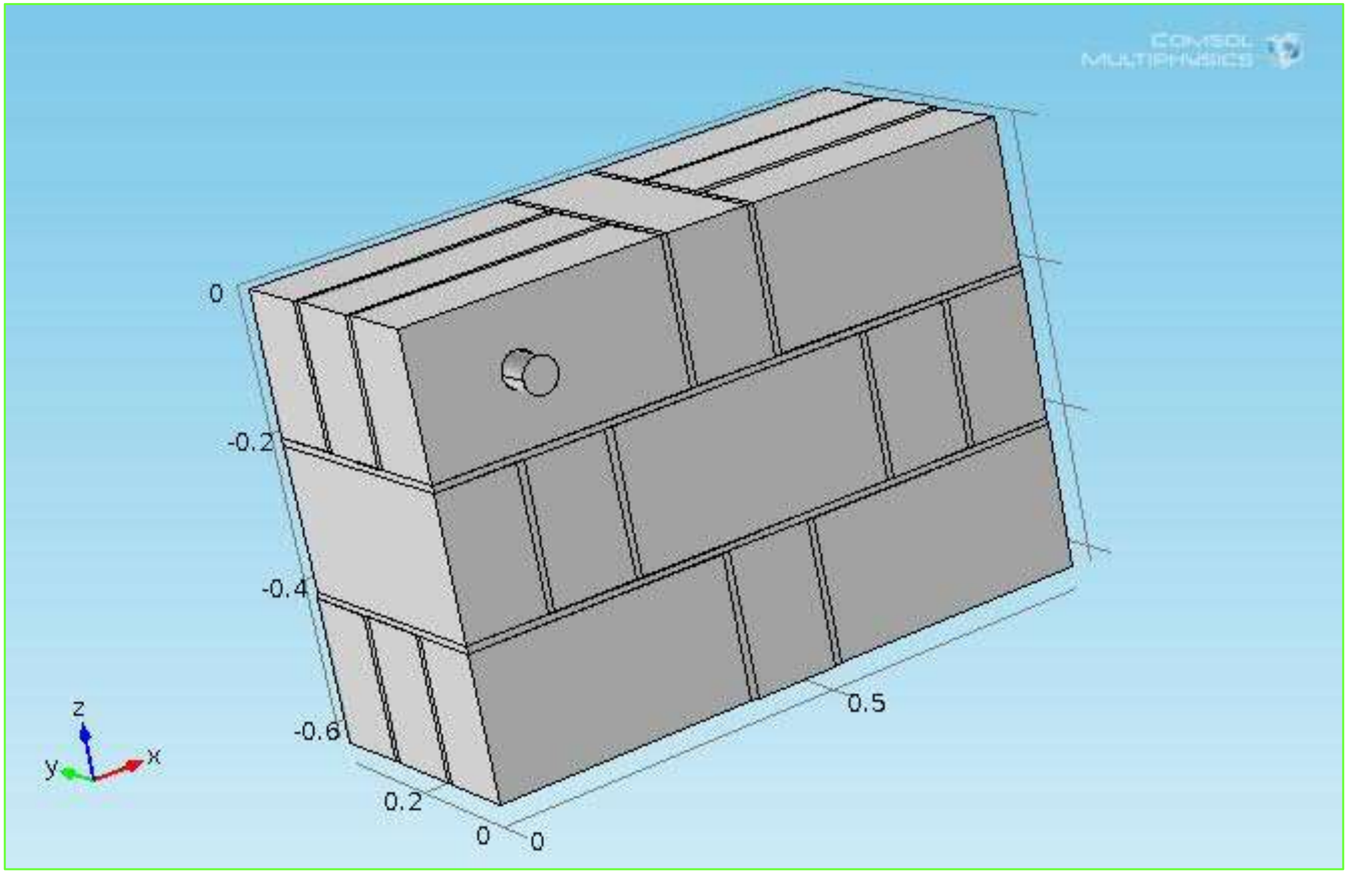
The numerical analyses have performed using a **Pressure Acoustics model** and the **Piezoelectric Devices Interface** belonging to the **COMSOL Acoustics Module.**

In order to decrease the size of the resolution matrices, with significant reduction of processing time and computational errors :

- the **frequency domain** rather than the time domain has been chosen to solve the model. The sound field is described and solved by the pressure *p*, so we can simulate only one transducer (the emitter)

- **two sub-models coupled** using the **Extrusion Model Couplings** option of COMSOL have been considered:
  one for the emission transducer (2D axisymmetric) and another for the wall (3D).

Simulations with COMSOL Multiphisycs

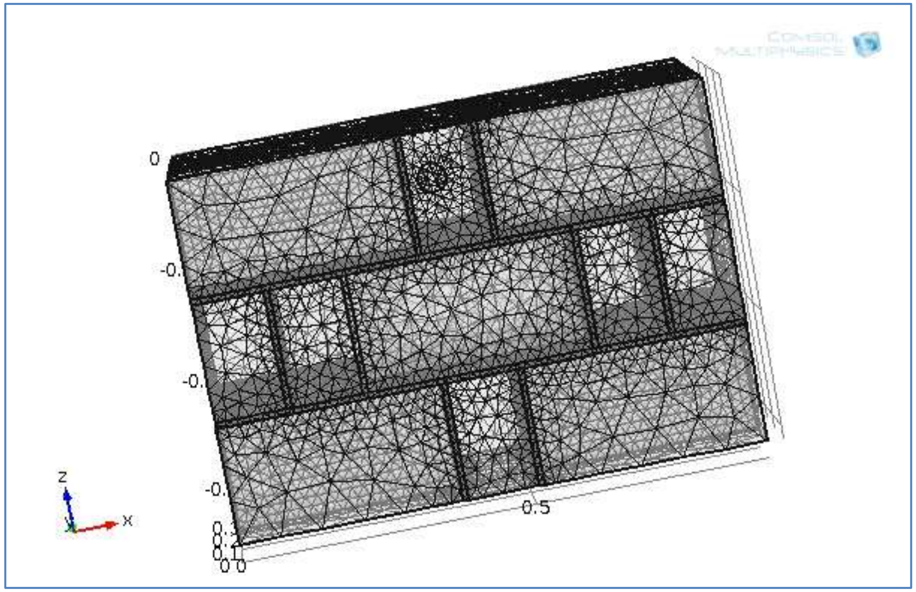


The **wall** and the **emitter transducer** have been simulated with **two submodels**

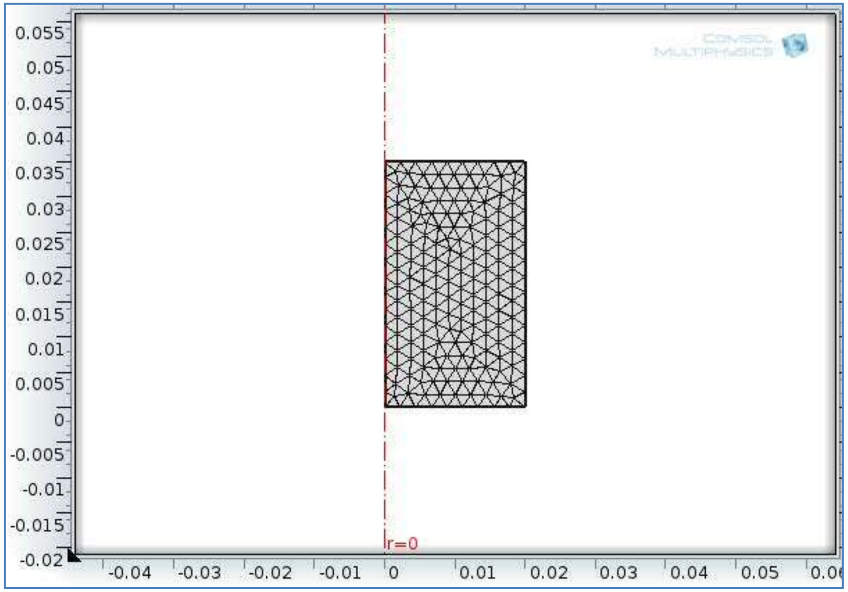
Simulations with COMSOL Multiphisycs

Two sub-models coupled

Wall model (3D)



Emission transducer model (2D axisymmetric)



Simulations with COMSOL Multiphisycs

The sound field is described and solved by the pressure ***p***.

The acoustic pressure in the time domain ***p(t)*** is obtained as a function of the spectral components as:

$$p(t) = \sum_{i=1}^{N} \left[p_{amp}(f_i) \cdot \cos\left(2\pi f \cdot t + p_{phase}(f_i)\right) \right]$$

$$f_i = \left[f_{\min} \div f_{\max} \right]$$

N → number of components of the spectra in the frequency range

Simulations with COMSOL Multiphisycs

Analytic model of Pressure Acoustics, Frequency Domain interface

The acoustic pressure *p(t)* in a medium is governed by the following equation that is an **inhomogeneous Helmholtz equation**:

$$\nabla \cdot \frac{1}{\rho_c}(\nabla p_t) - k_{eq}^2 \frac{p_t}{\rho_c} = Q$$

$$p_t = p + p_b$$

$$k_{eq} = \left(\frac{\omega}{c}\right)^2; \; k = \frac{\omega}{c} - j\alpha; \; \rho_c = \frac{\rho c^2}{c_c^2}$$

- $\boldsymbol{\rho}$ is the density of the material [kg/m^3],
- ***c*** is the speed of sound [m/s];
- ***Q*** [1/s^2] is a monopole acoustic source

Simulations with COMSOL Multiphisycs

Analytic model of Piezoelectric Devices interface

The mathematical formulation of this model is described by the equations:

$$-\rho\omega^2 u - \nabla\sigma = F_v e^{j\phi}$$

$$\nabla \cdot D = \rho_V$$

where

- $\boldsymbol{F_v}$ is deformation gradient,
- $\boldsymbol{\rho_V}$ is the volume charge density,
- ***u*** is the displacement,
- **D** is the electric displacement and
- **σ** is the stress-charge.

Simulations with COMSOL Multiphisycs

At the interface between the transducer and the wall, the **boundary condition** for the acoustics interface is that the pressure is equal to the normal acceleration of the solid domain:

$$\vec{n} \cdot \left(\frac{1}{\rho_0} (\nabla p) \right) = \vec{a}_n$$

where a_n is the normal acceleration.
This drives the pressure in the wall domain.

Simulations with COMSOL Multiphisycs

The implementation of the Comsol Model has required a series of simulations to develop all the parameters, until than the results were consistent with the experimental ones.

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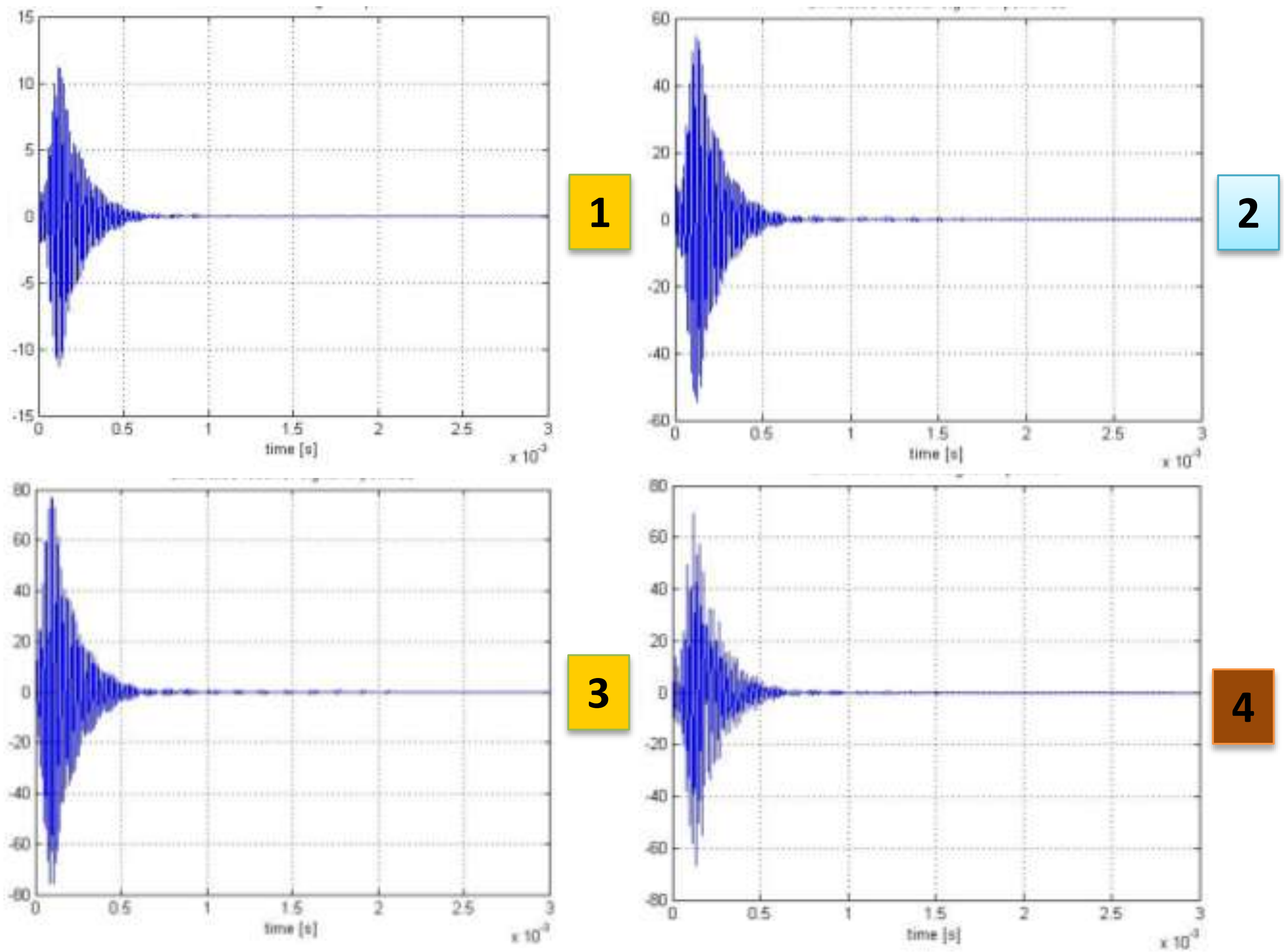
Simulated signals crossing the 4 paths (Time domain)

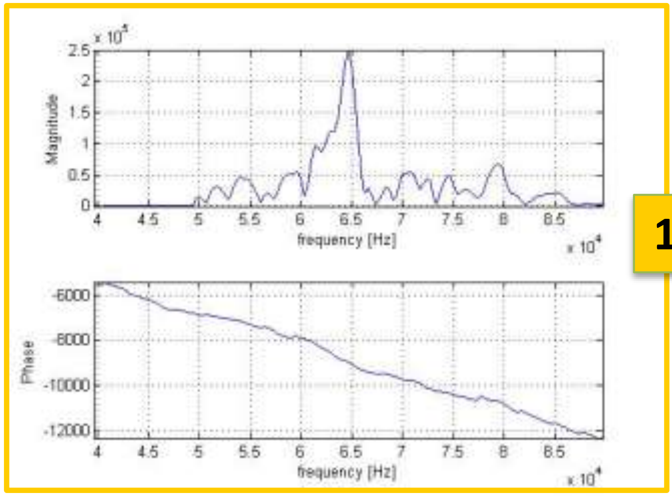
Simulated signals show a performance in good agreement with experimental signals

Amplitudes in the time domain are scaled to the average gain of the emission transducer



Simulated Spectra (Frequency domain)

Spectral bandwidth are shifted to higher values , as expected



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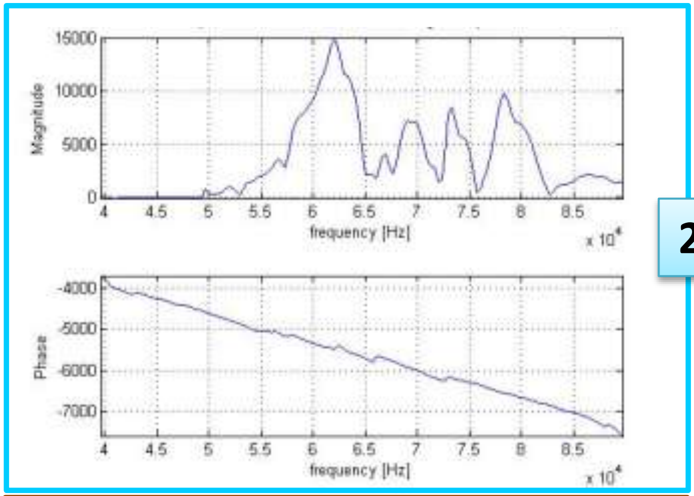

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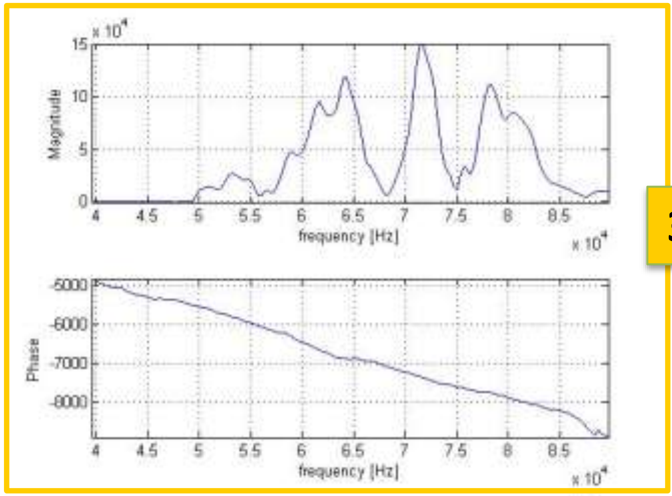

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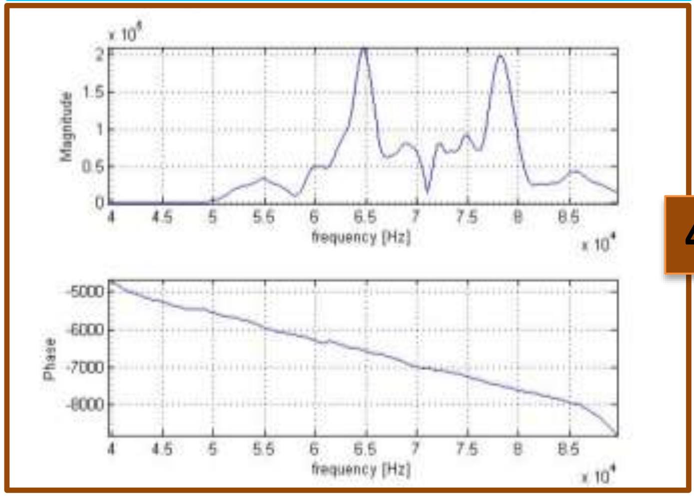

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Results

Similarly to what is found for the measured signals:

also the simulated signals present different performances for the different types of paths both in time and frequency domain, and this allows to post-process them to map the macro defects.

Conclusions

- The purpose of this work was to create a model of a prototype of a trachyte wall, built and tested in the laboratory, in order to simulate the ultrasonic signal propagation and thus be able to perform parametric studies freed from the experimental sessions.
- Model calibration has been achieved by comparison of a significant sample of simulated signal to the correspondent signals obtained from the experimental sessions
- Results show that the implemented COMSOL model is suitable to effectively simulate the ultrasonic signals transmission through the stone wall
- The simulated signals can be used to obtain, through post-processing analysis, maps for detecting the presence of macro defects with cluster algorithms or non supervised Neural Networks as Self organizing Maps (SOM)

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Thanks for your kind attention

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Thanks for your kind attention