Phase velocity method for guided wave measurements in composite plates.

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UIA-Madrid 23-25-/4/2014

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1.- Introduction

Objectives

- *Evaluation of composite plates using the phase velocity method applied to guided waves. (SV and SH).*
  - *Determination of elastic constant*
  - *Flaw evaluation (lamination)*

2.- Theoretical model

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Preliminary considerations

SV Waves (Lamb Waves)

- 2D dimension (plane x_1 ,x_2)
- Orthotropic material (plane x_1,x_2)

SH Waves

- Quasi-isotropic (plane x_1,x_3)

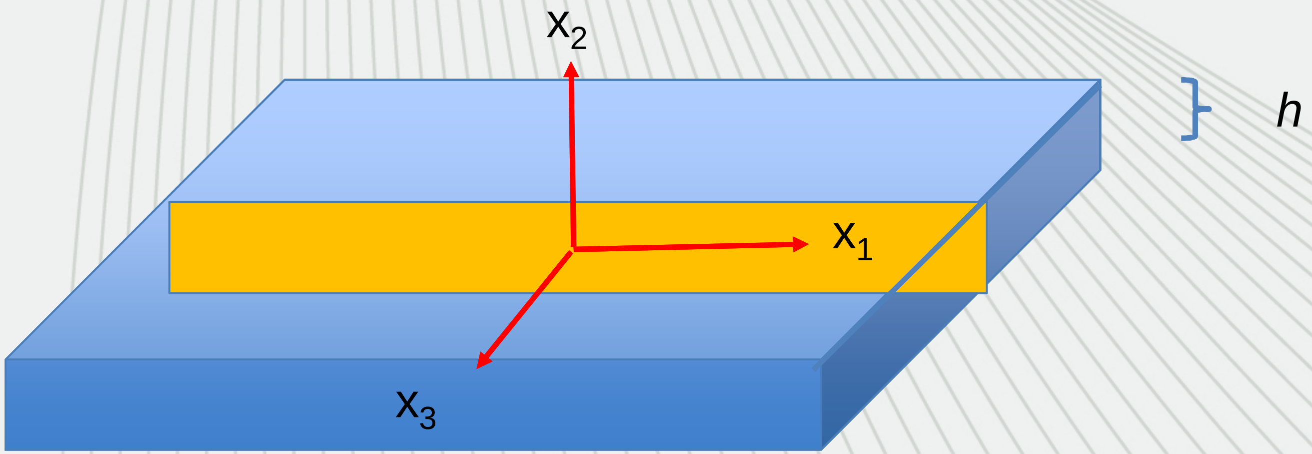
2.-Theoretical model

[Voigt notation]

Anisotropic material

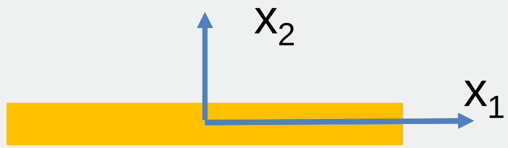
$$
\begin{pmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
 & C_{22} & C_{23} & 0 & 0 & 0 \\
 & & C_{33} & 0 & 0 & 0 \\
 & & & C_{44} & 0 & 0 \\
 & & & & C_{55} & 0 \\
 & & & & & C_{66}
\end{pmatrix}
$$

Stiffness Matrix



2.-Theoretical model

SV Considerations



Voigt notation

- C_{11}
- C_{22}
- C_{12}
- C_{66}

Engineering notation

E_1 and E_2 Young modulus

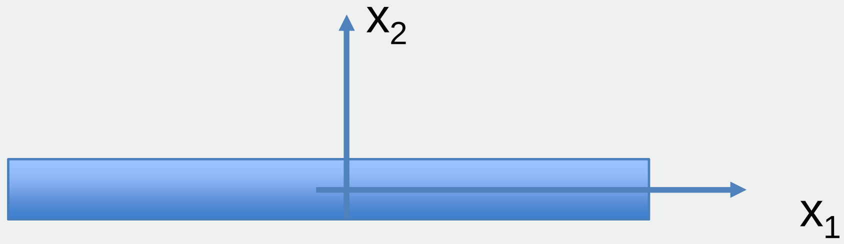
μ_{12} and μ_{21} Poisson ratio

G_{12} Shear Modulus

$$\epsilon = \frac{E_2}{E_1} = \frac{\mu_{21}}{\mu_{12}} \qquad \gamma = \frac{G_{12}}{E_1}$$

2.-Theoretical model

Relation Voigt vs engineering notation (2D)



$$C_{11} = \frac{E_1}{(1-\mu_{12}\mu_{21})} \qquad C_{12} = \frac{\mu_{12}E_1}{(1-\mu_{12}\mu_{21})} = \frac{\mu_{21}E_2}{(1-\mu_{12}\mu_{21})}$$

$$C_{22} = \frac{E_2}{(1-\mu_{12}\mu_{21})} \qquad C_{66} = G_{12}$$

$$\epsilon = \frac{E_2}{E_1} = \frac{\mu_{21}}{\mu_{12}} \qquad \gamma = \frac{G_{12}}{E_1}$$

David Richardson. The Fundamental Principles of Composite Material Stiffness Predictions. http://compositesgateway.org/presentation/Property-Prediction.pdf

2.-Theoretical model

Plane x_1 x_3

Quasi-isotropic

$$E_1 = E_3$$

$$\mu_{13} = \mu_{31}$$

$$C_{33} = C_{44} = G_{13} = \frac{E_1}{(1 + \mu_{13})}$$

2.-Theoretical model

Waves equations in x_1 x_2 plane

$$\rho \frac{\partial^2 u_1}{\partial t^2} = C_{11} \frac{\partial^2 u_1}{\partial x_1^2} + C_{12} \frac{\partial^2 u_2}{\partial x_1 \partial x_2} + C_{66} \frac{\partial^2 u_1}{\partial x_2^2} + C_{66} \frac{\partial^2 u_2}{\partial x_1 \partial x_2}$$

$$\rho \frac{\partial^2 u_2}{\partial t^2} = C_{12} \frac{\partial^2 u_1}{\partial x_1 \partial x_2} + C_{22} \frac{\partial^2 u_2}{\partial x_2^2} + C_{66} \frac{\partial^2 u_1}{\partial x_1 \partial x_2} + C_{66} \frac{\partial^2 u_2}{\partial x_1^2}$$

$\rho =$ density

u_1 and u_2 displacements

2.-Theoretical model

Dispersion relations of SV (Lamb Waves)

symmetric

$$\frac{th\frac{sh}{2}}{th\frac{qh}{2}} = \frac{B_0 C_0}{A_0 D_0}$$

$$\frac{qh}{2} = \pi\frac{h}{\lambda}\sqrt{-\frac{a}{2}+\sqrt{\left(\frac{a}{2}\right)^2 - b}}$$

antisymmetric

$$\frac{th\frac{qh}{2}}{th\frac{sh}{2}} = \frac{B_0 C_0}{A_0 D_0}$$

$$\frac{sh}{2} = \pi\frac{h}{\lambda}\sqrt{-\frac{a}{2}-\sqrt{\left(\frac{a}{2}\right)^2 - b}}$$

$$a = \frac{C_{12}^2}{C_{22}C_{66}} + \frac{2C_{12}}{C_{22}} - \frac{C_{11}}{C_{66}} + \rho c^2\left(\frac{1}{C_{66}} + \frac{1}{C_{22}}\right)$$

$$b = \frac{C_{11}}{C_{22}} - \rho c^2\frac{(C_{11}+C_{66})}{C_{22}C_{66}} + \rho^2 c^4\left(\frac{1}{C_{66}C_{22}}\right)$$

c= phase velocity

λ= ***wavelength***

Martincek G. Theory and Methods of Dynamic Nondestructive Testing of Plane Elements. VEDA , Bratislava 1975

2.-Theoretical model

Dispersion relations of SV (Lamb Waves).. cont..

$$A_0 = \frac{q}{k}\left[-\rho c^2 + C_{11} - \frac{C_{12}(C_{12}+C_{66})}{C_{22}}\right] - C_{66}\left(\frac{q}{k}\right)^3$$

$$B_0 = \frac{s}{k}\left[-\rho c^2 + C_{11} - \frac{C_{12}(C_{12}+C_{66})}{C_{22}}\right] - C_{66}\left(\frac{s}{k}\right)^3$$

$$C_0 = -\rho c^2 + C_{11} + C_{12}\left(\frac{q}{k}\right)^2$$

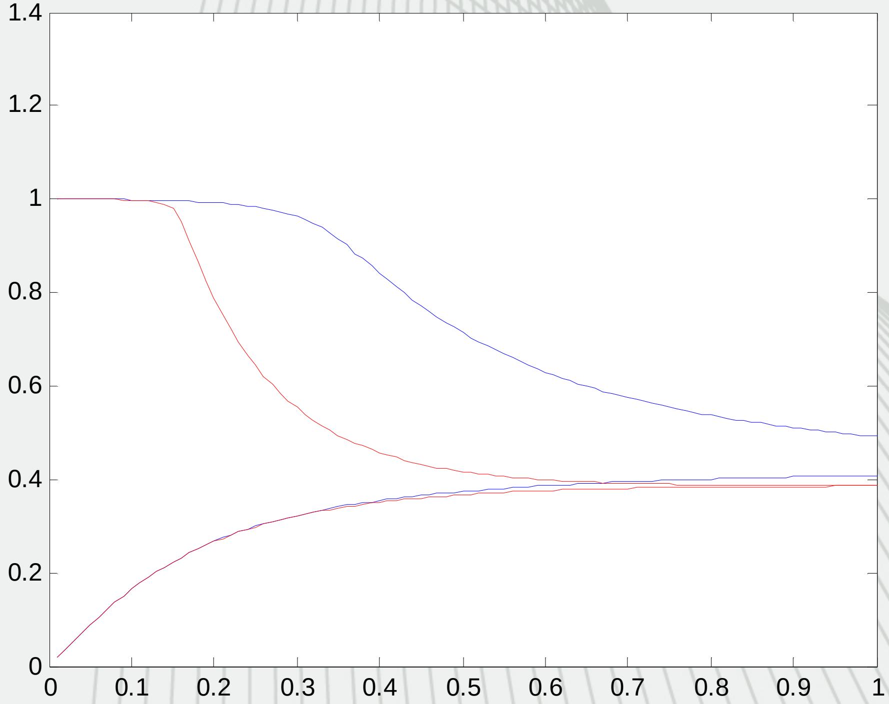
$$D_0 = -\rho c^2 + C_{11} + C_{21}\left(\frac{s}{k}\right)^2$$

$$k = {}^{2\pi}/_{\lambda}$$

2.-Theoretical model

Dispersion curves Case 1

C/C_1 ← $C_1 = \sqrt{E_1/\rho}$



h/λ

Blue { ε=0,5; γ= 0,2

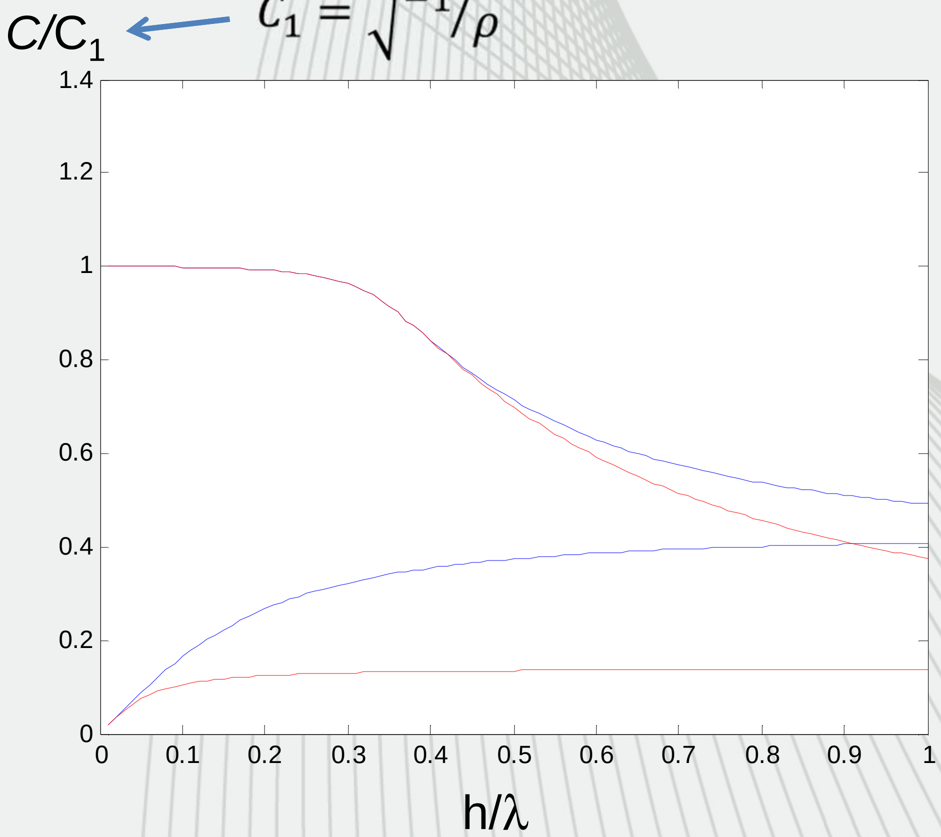
Red { ε=0,1; γ= 0,2

$$\epsilon = \frac{E_2}{E_1} = \frac{\mu_{21}}{\mu_{12}} \qquad \gamma = \frac{G_{12}}{E_1}$$

2.-Theoretical model

Dispersion curves Case 2

$$C_1 = \sqrt{E_1/\rho}$$



Blue: $\varepsilon = 0{,}5$, $\gamma = 0{,}2$

Red: $\varepsilon = 0{,}5$, $\gamma = 0{,}02$

$$\epsilon = \frac{E_2}{E_1} = \frac{\mu_{21}}{\mu_{12}} \qquad \gamma = \frac{G_{12}}{E_1}$$

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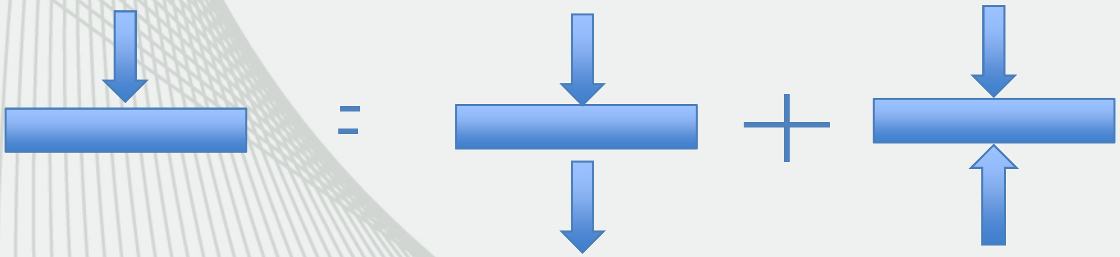
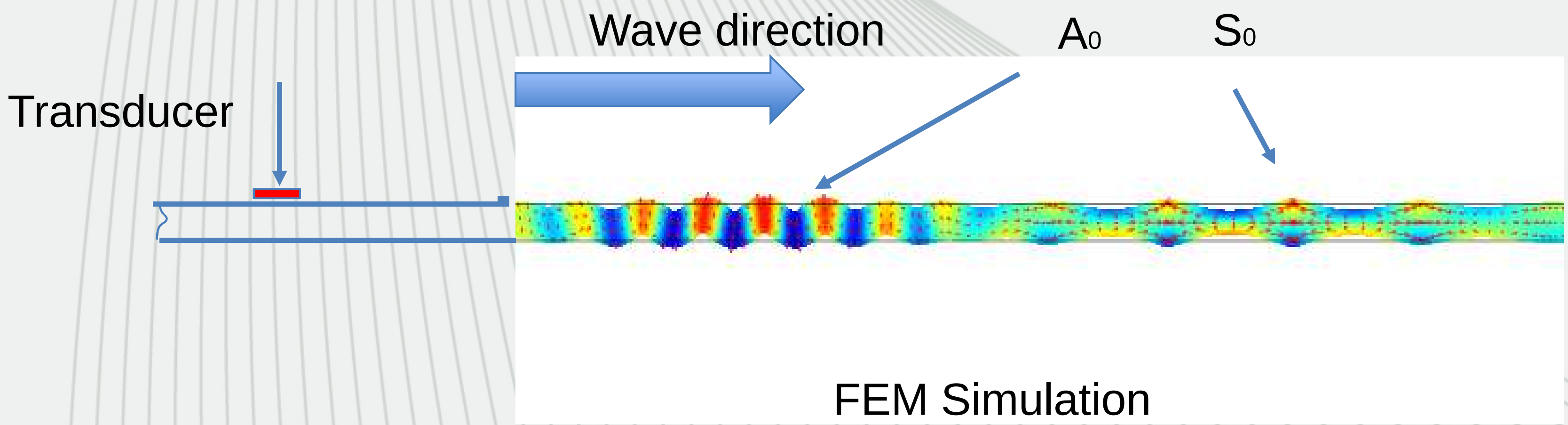
2.-Theoretical model

Influence of Transducer ("one side")





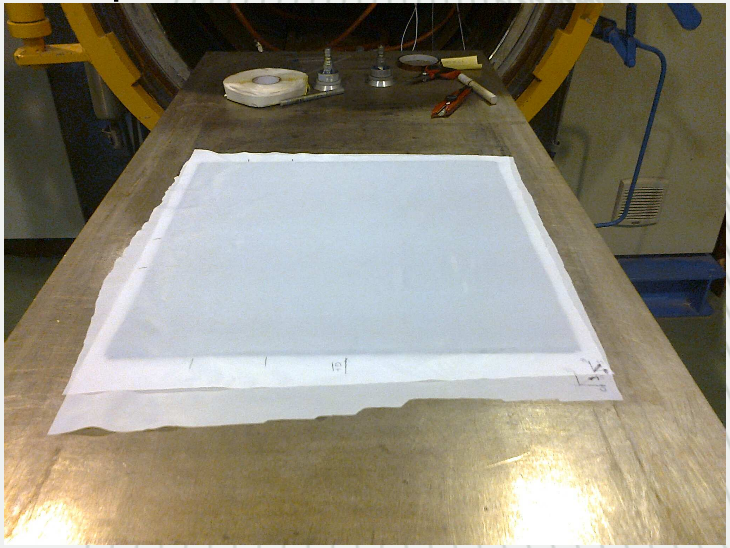
- Nieuwenhius et al. Generation and detection of guided waves using PZT wafer transducer. http://users.ece.cmu.edu/~dwg/research/Waves25rev.pdf
- V. Giurgiutiu, "Lamb Wave Generation with Piezoelectric Wafer Active Sensors for Structural Health Monitoring," Smart Structures and Materials 2003: Smart Structures and Integrated Systems, 111

3.- Materials and Methods

3.-Materials and Methods

CFRP Laminates

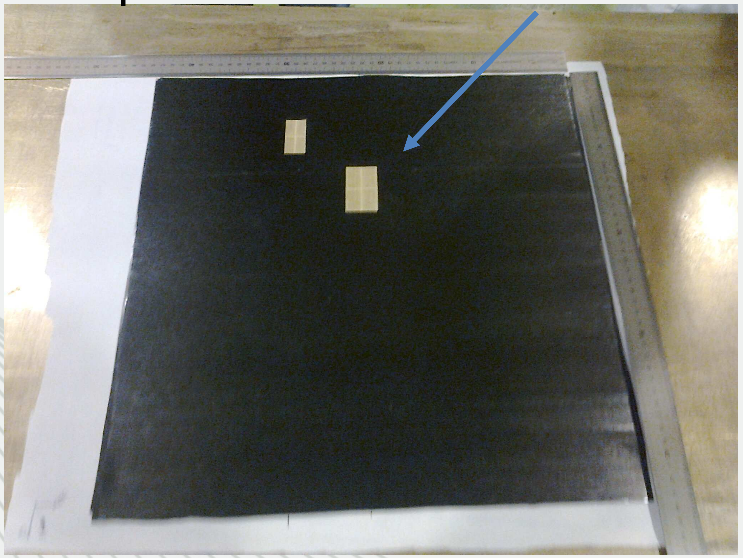
Sample 1



660x460x2,9 mm

Sample 2

Cardboard

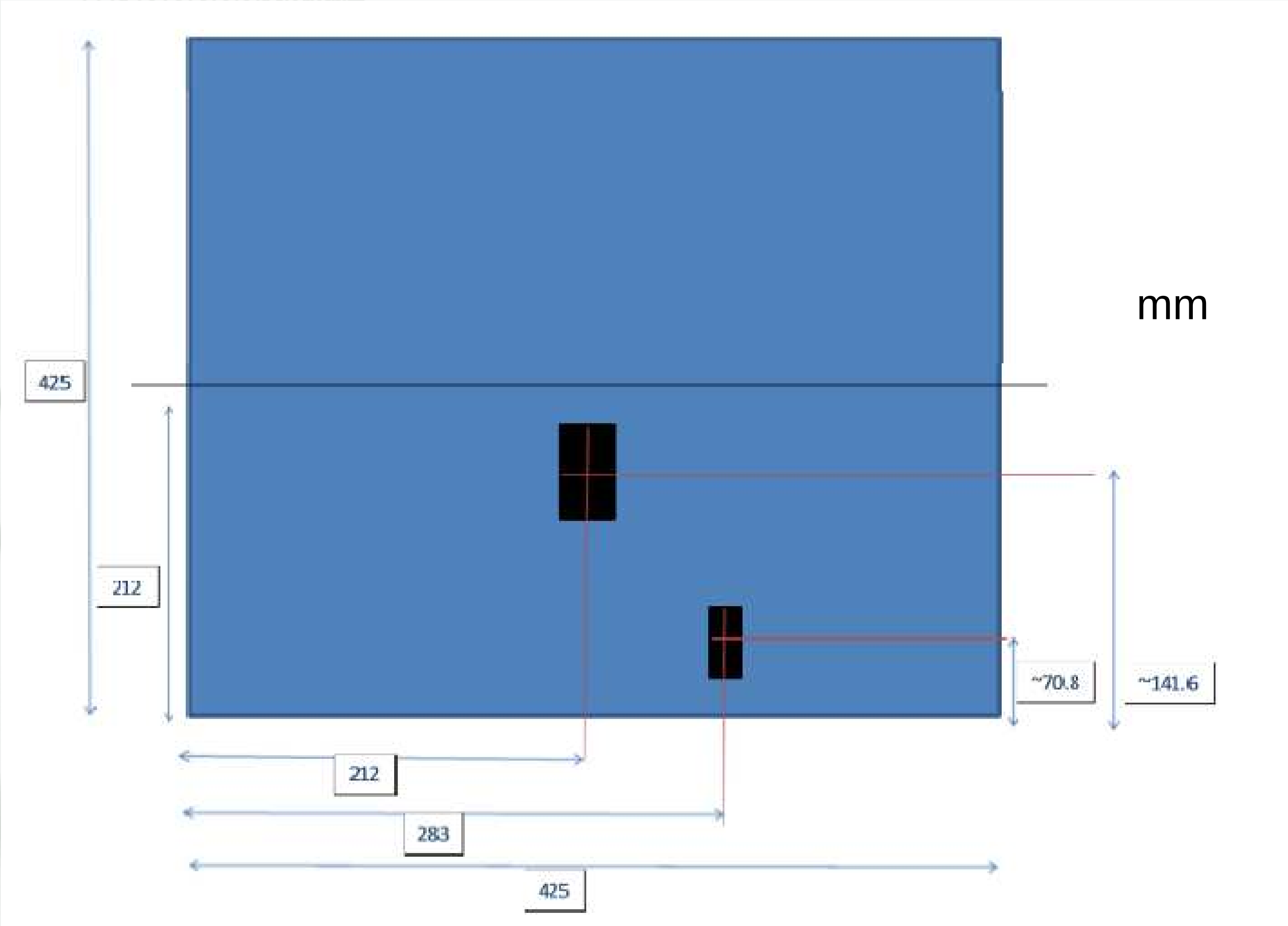


CFRP: -45/+45/90/0/0/90/+45/-45 / “ Symmetrical” → Quasi-symmetrical

ρ=1,25 g/cm^3

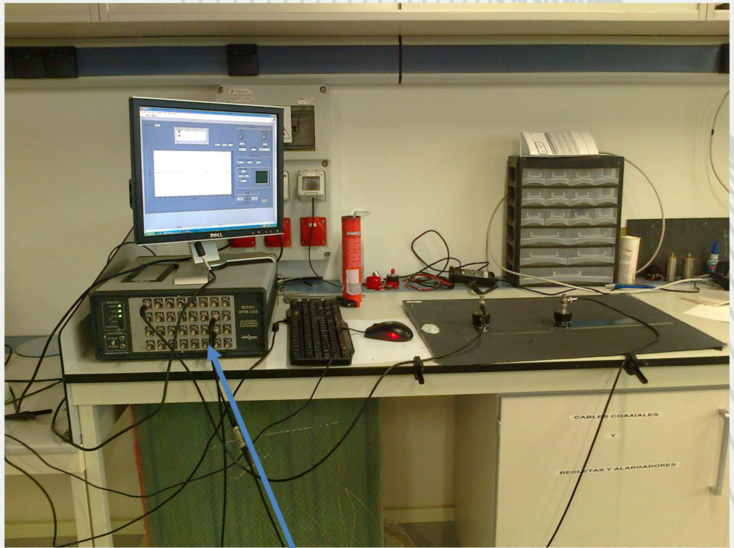
3.-Materials and Methods

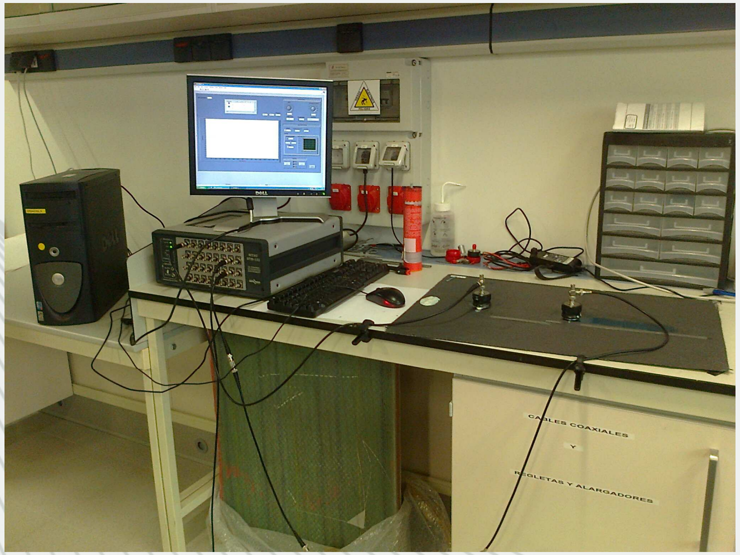
Flaw embedded (“lamination”)



3.-Materials and Methods

Equipment



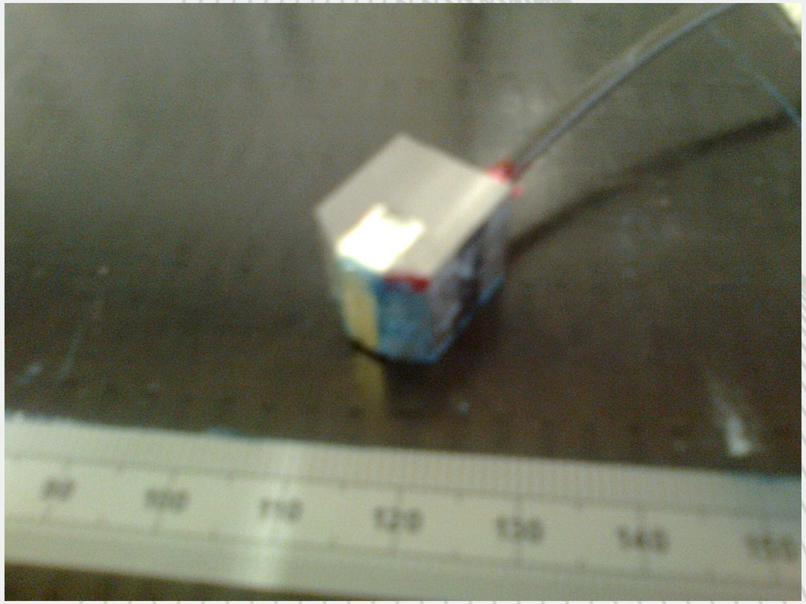


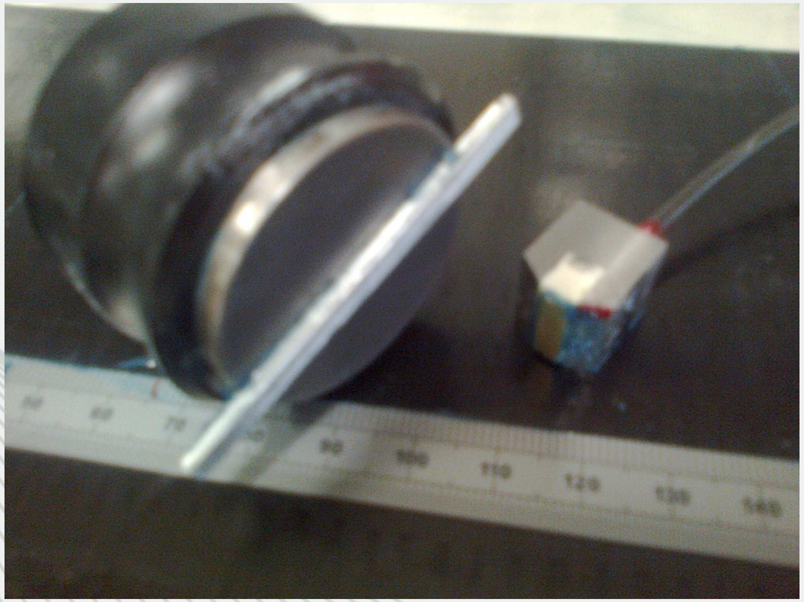
Ultrasonic System Sitau , Dasel SL
Labview GUI

Burst excitation
Pulse Transmission mode

3.-Materials and Methods

Transducers



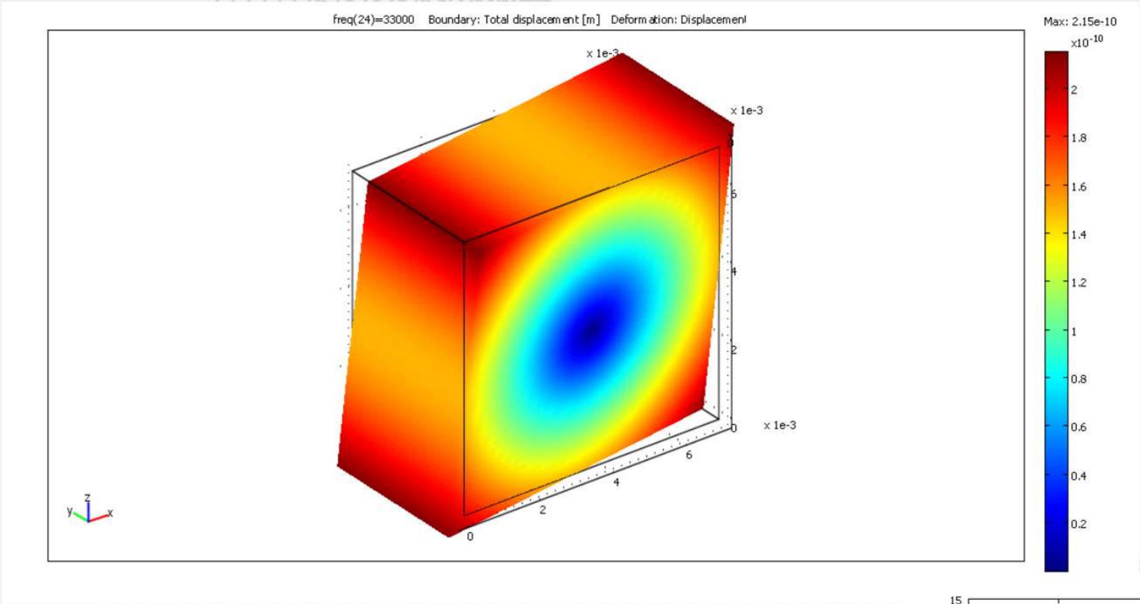


SH Transducer
(made in Tecnalia)

SV – L Transducer
Panametrics
Rx= 0.5 MHz (V191)
Tx= 1 MHz (V194)

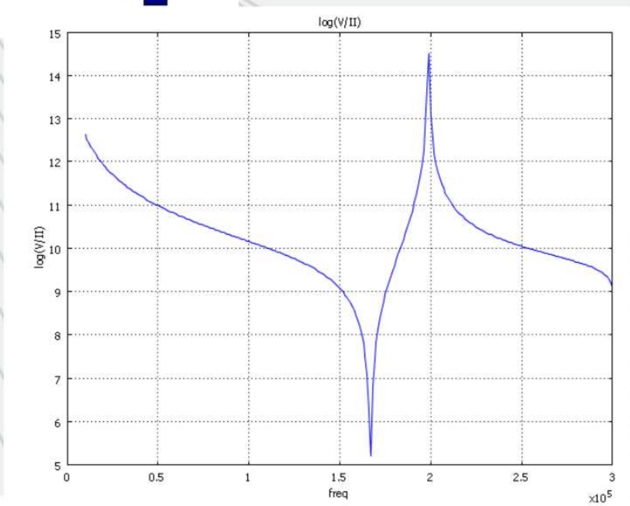
3.-Materials and Methods

SH transducer. Piezoelectric material



FEM Simulation

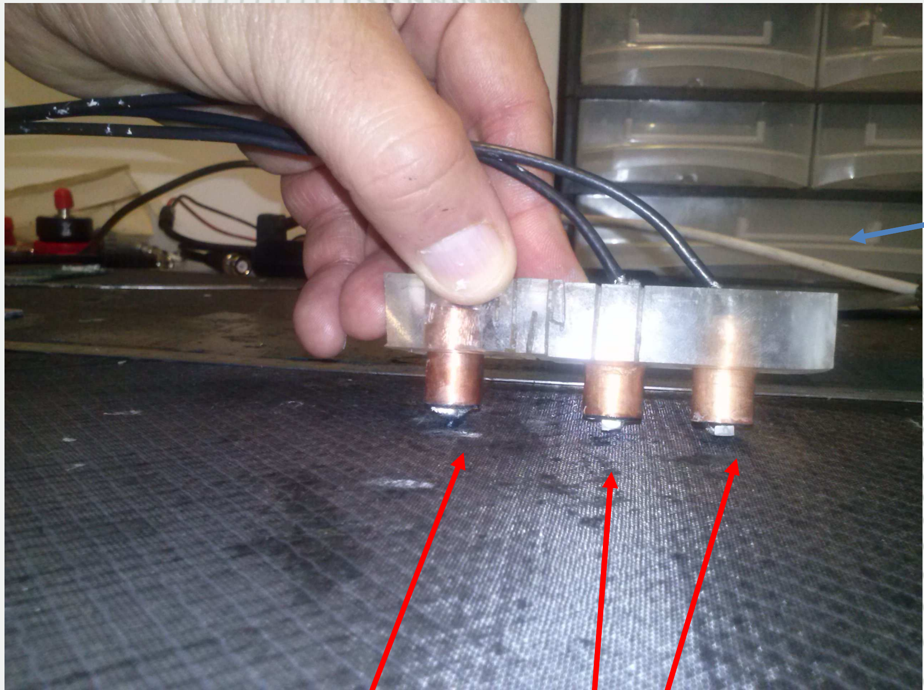
Impedance module

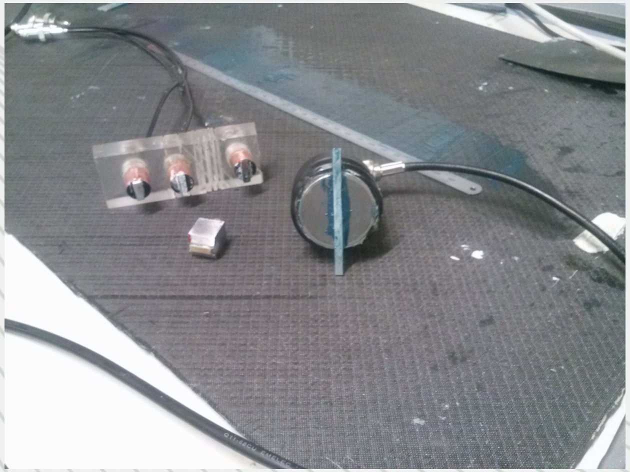


3.-Materials and Methods

Transducers

Transducers for flaw detection (longitudinal)





Tx

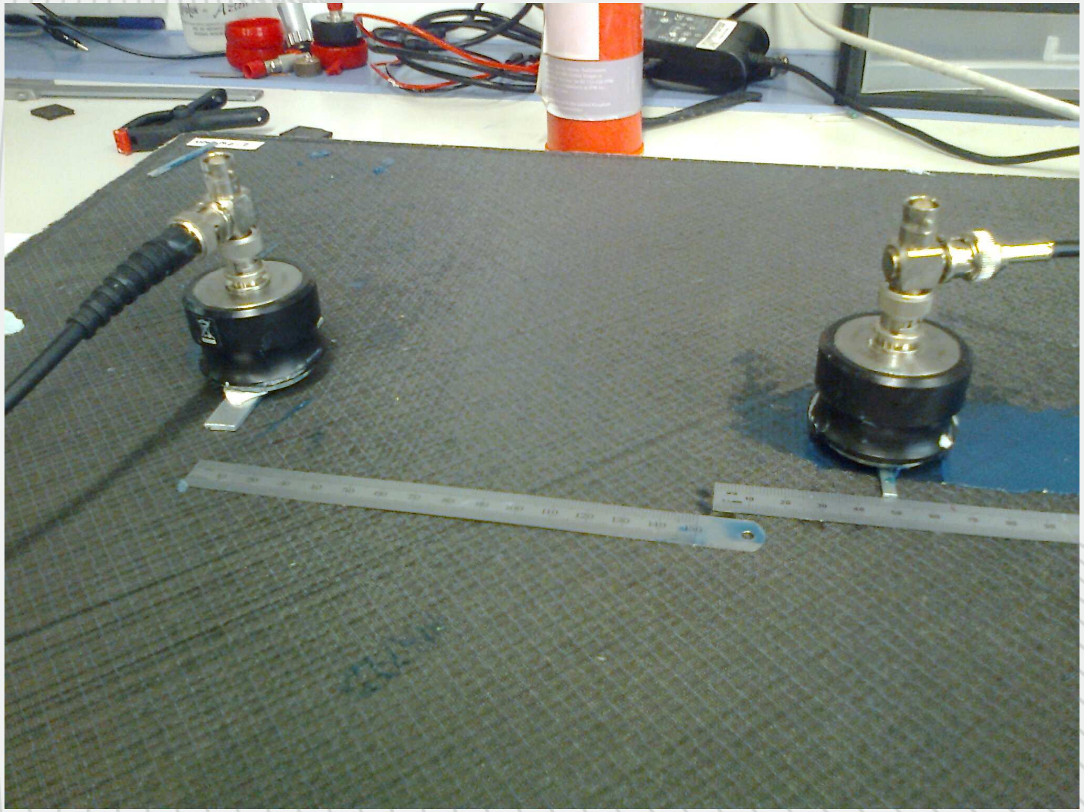
Rx

3.-Materials and Methods

Basic Configuration

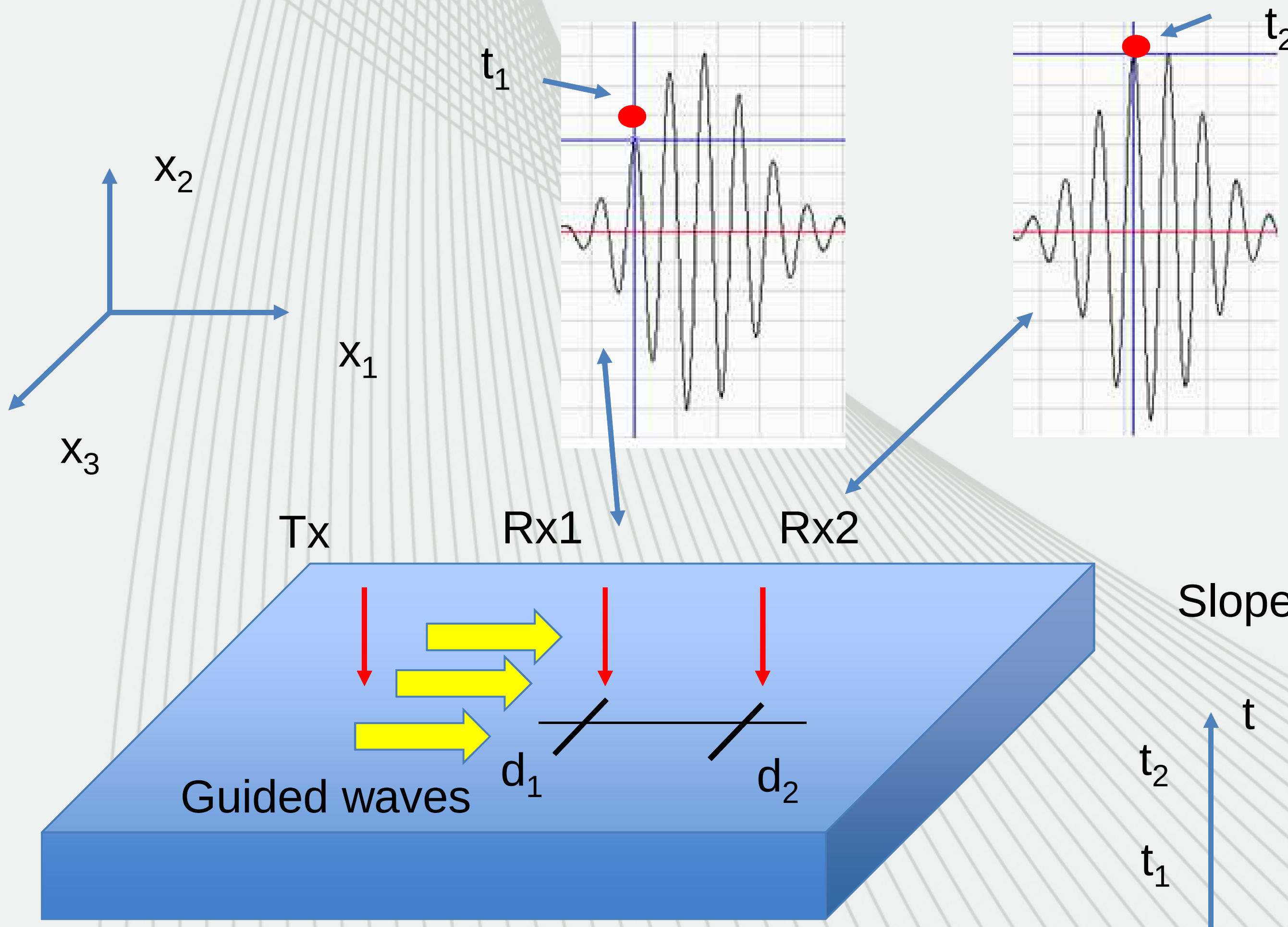
3.-Materials and Methods

Basic Configuration



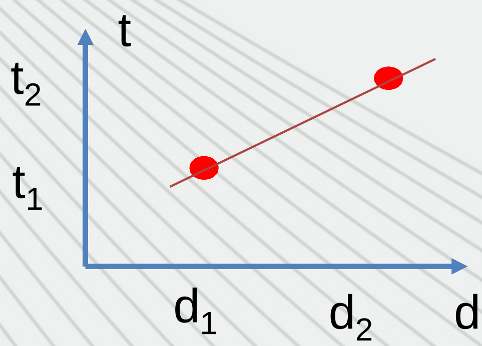
3.-Materials and Methods

Phase velocity method



In pulses!!!

Slope=1/phase velocity (*C*)



Moreno E, et al. **Thickness measurement in composite materials using Lamb waves. Ultrasonic.** Ultrasonics 01/1998;

4.- Results

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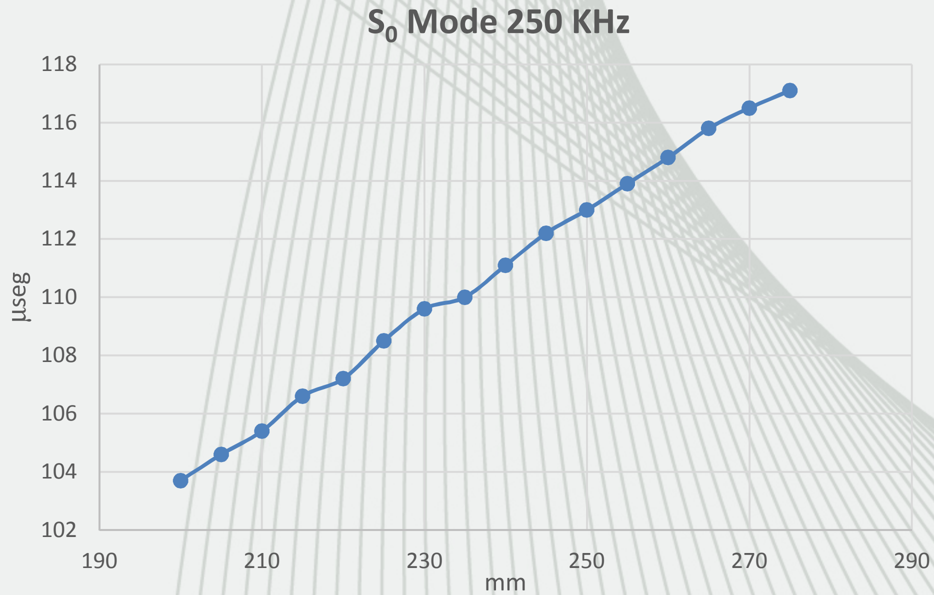
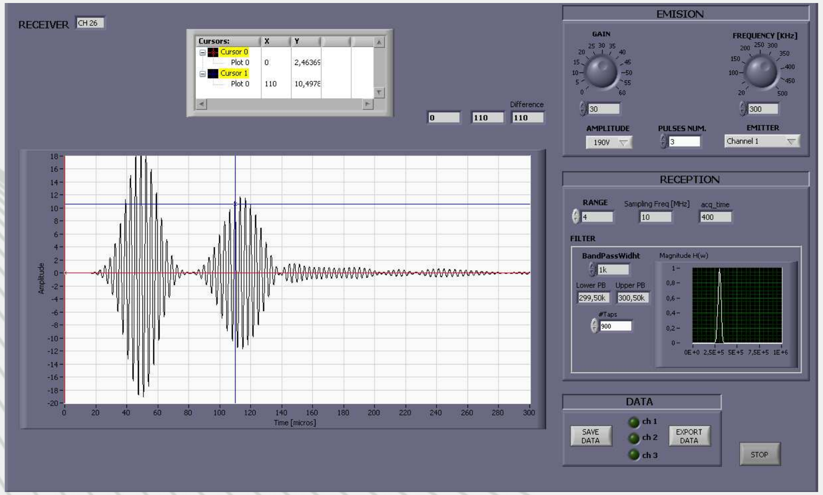
4.-Results



S0 Mode



Sample No. 1

C_S=5455 +/- 61 m/s

C_1

(h/λ)=0.13 !!!!

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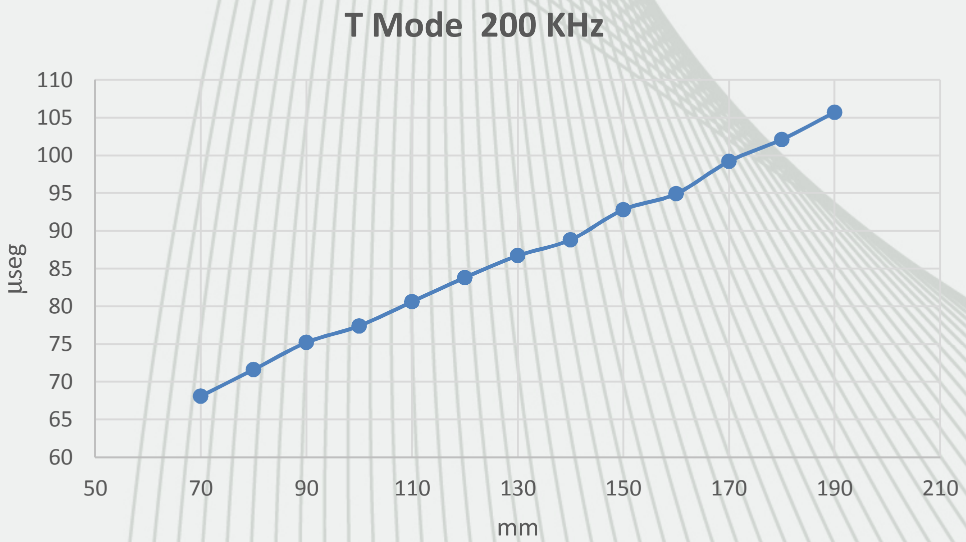
4.-Results

Fundamental Poisson ratio



$$\mu_{13} = \frac{1}{2}\left(\frac{C_1}{C_T}\right)^2 - 1$$

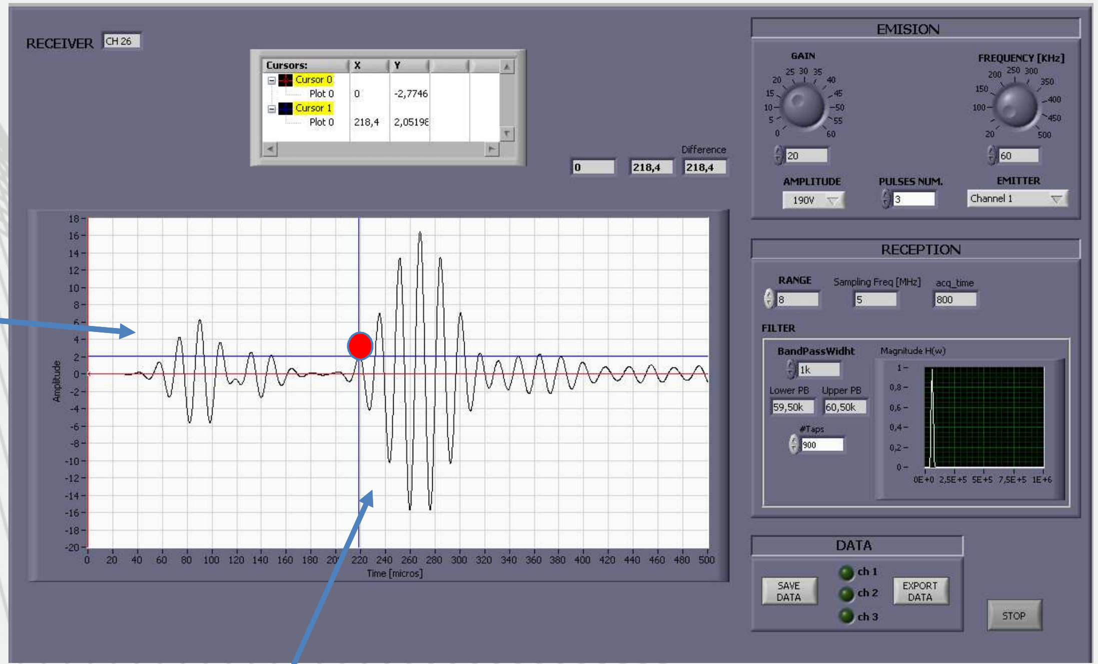
$$\mu_{13} = 0{,}39$$

Sample No. 1

C_T=3267 +/- 41 m/s

4.-Results

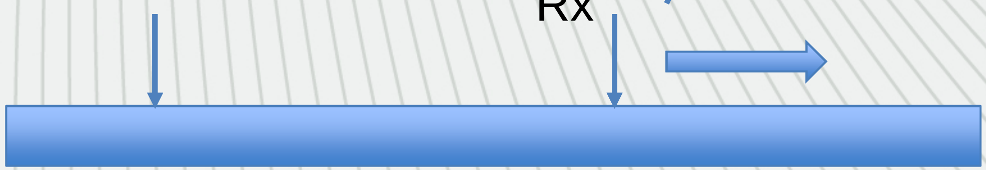
A_0 Mode. Evolution with distance



Initial Pulse

Tx

Rx



60 KHz

Sample No. 1

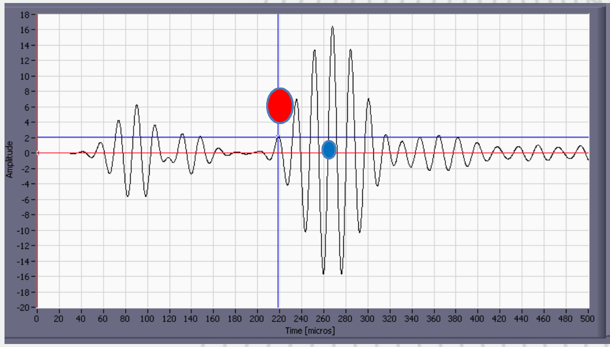
4.-Results

Evolution with distance

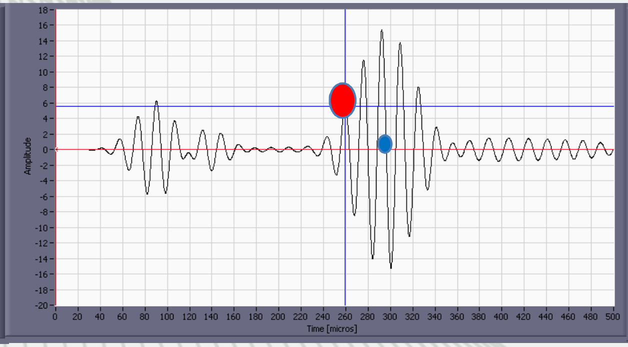
● for phase velocity

● for group velocity

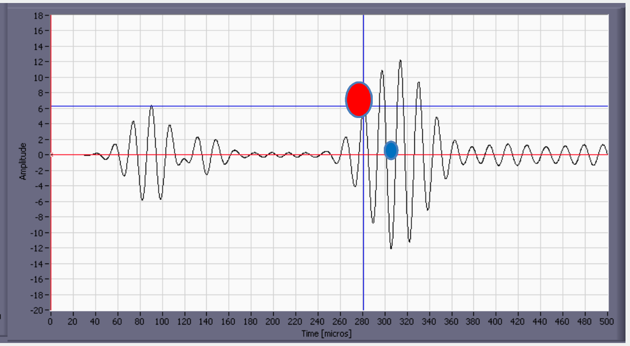
100 mm



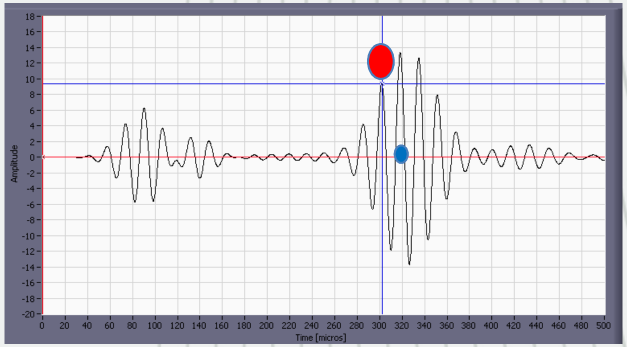
110 mm



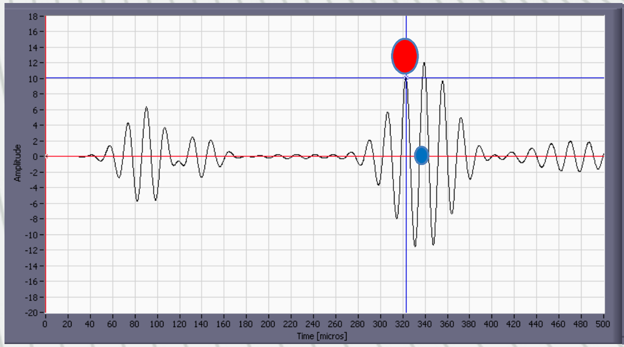
120 mm



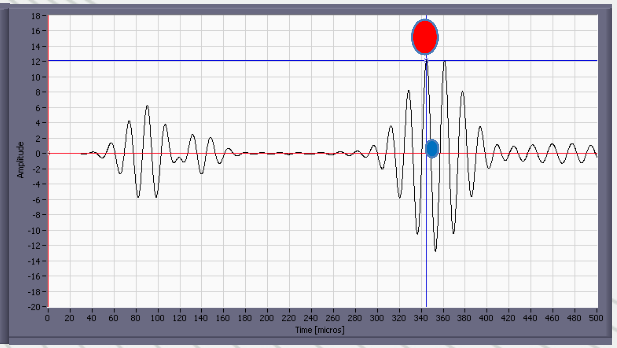
140 mm



160 mm



180 mm



A_0 mode 60 KHz

Sample No. 1

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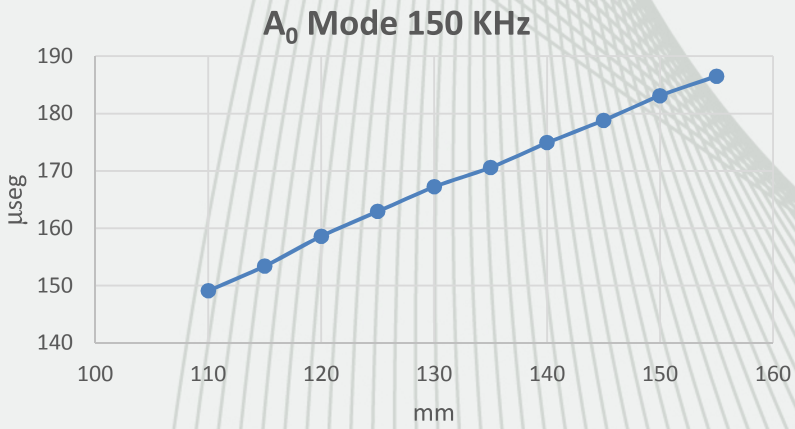
4.-Results

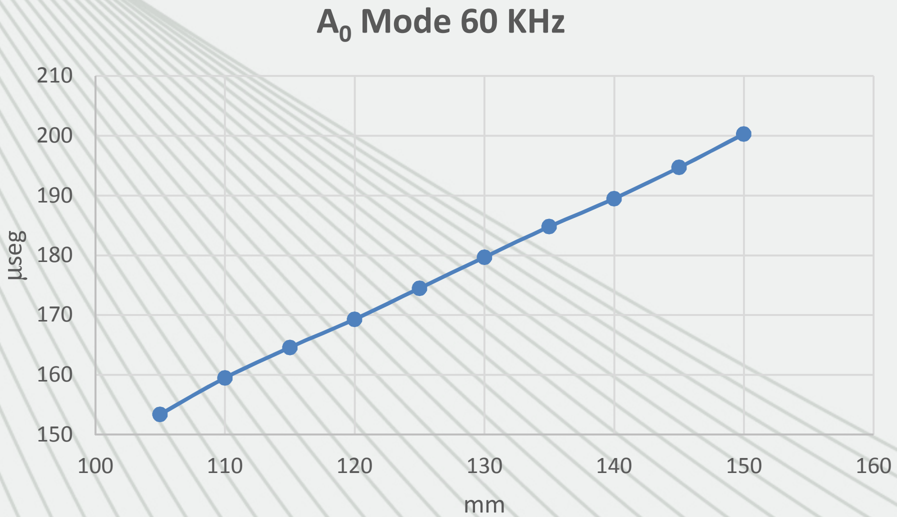
A0 mode. Some examples



Sample No. 1

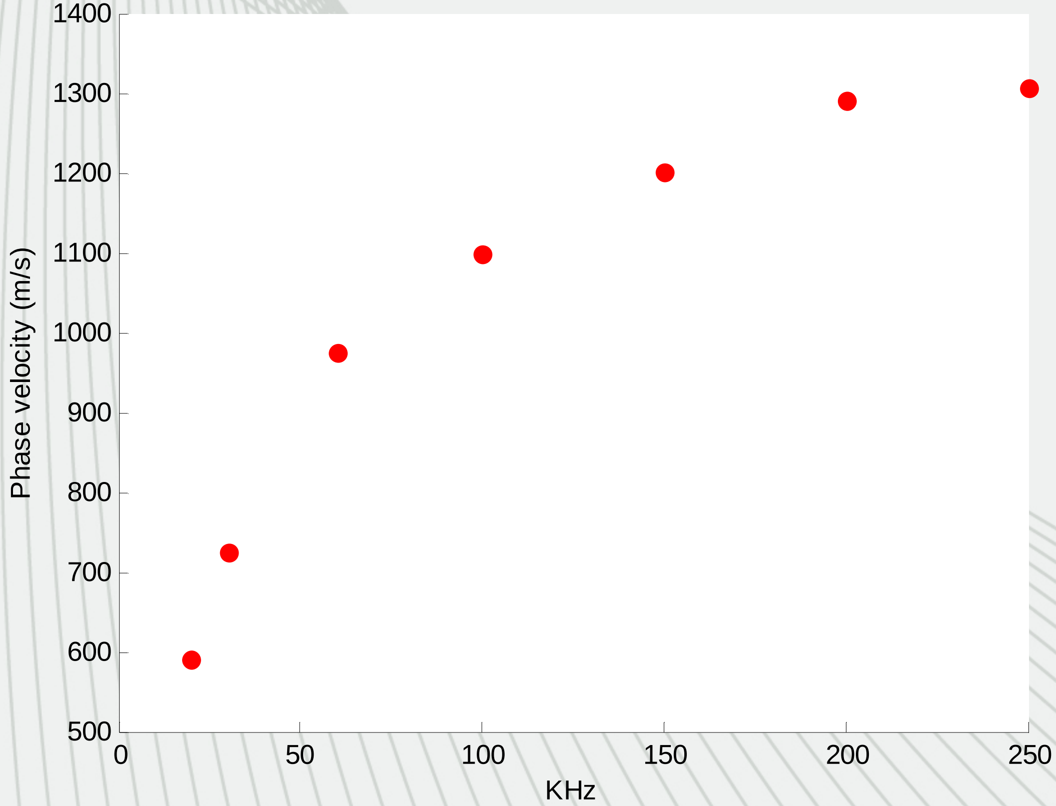
C=1202+/-18 m/s

976+/- 7 m/s



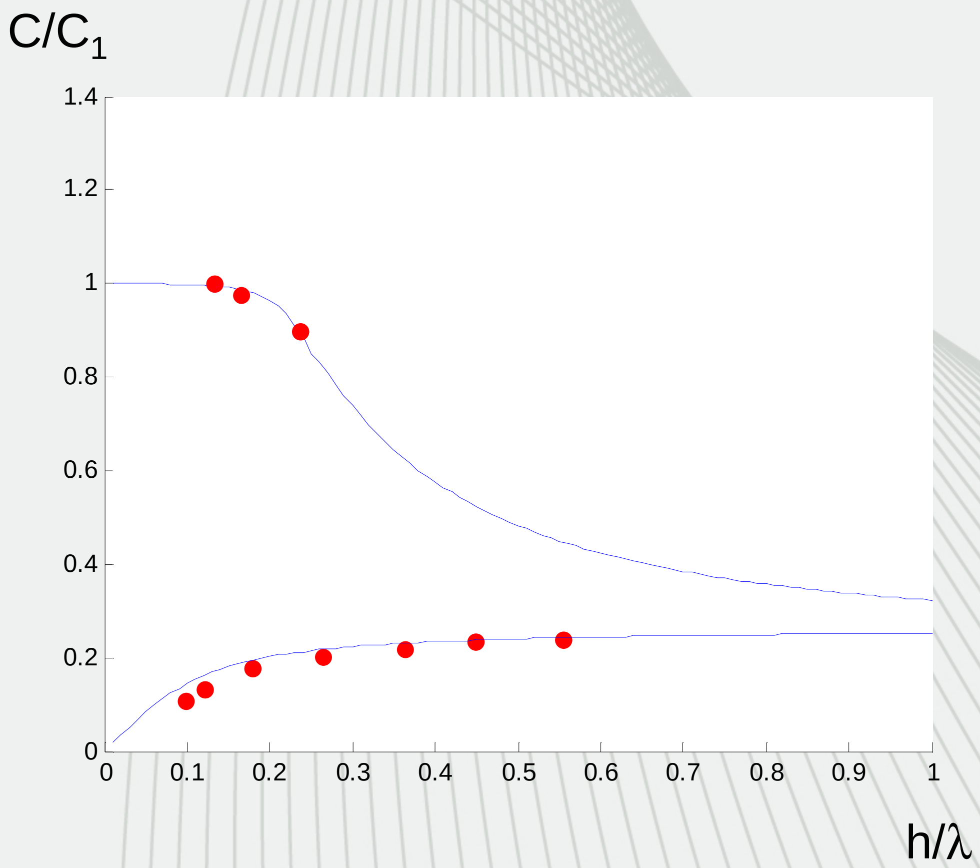
4.-Results

A_0 Mode. Experimental dispersion curve
Sample No 1



4.-Results

Experimental vs theoretical



ε=0.2

γ=0.07

μ_{12} =0.4

4.-Results

Elastic Constants obtained

Engineering constants

E_1 (GPa)	E_2 (GPa)	G_{13} (Gpa)	G_{12} (Gpa)	u_{13}
37,2	7,4	13,3	2,6	0,39

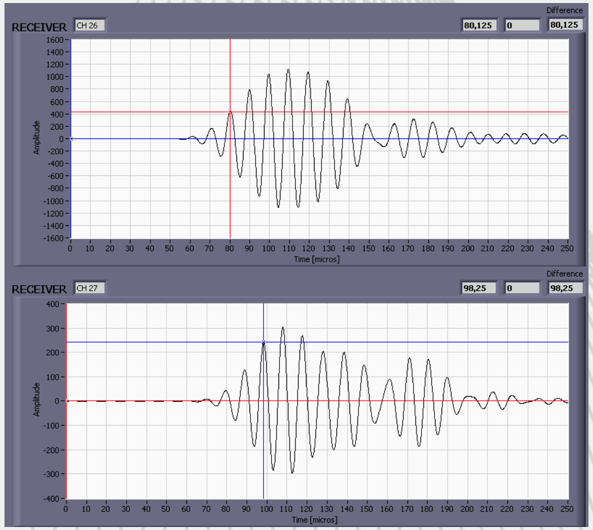
Voigt

C_{11} (GPa)	C_{22} (GPa)	C_{12} (GPa)	C_{66} (GPa)
38,4	7,7	3	2,6

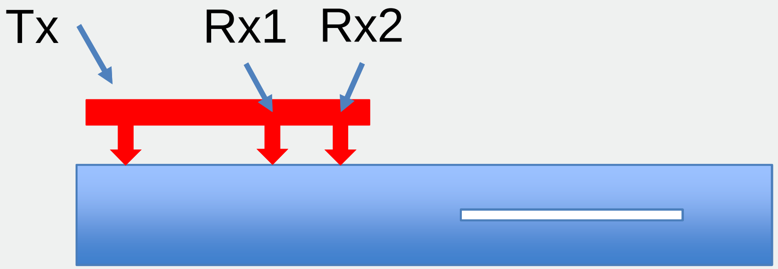
4.-Results

Flaw evaluation

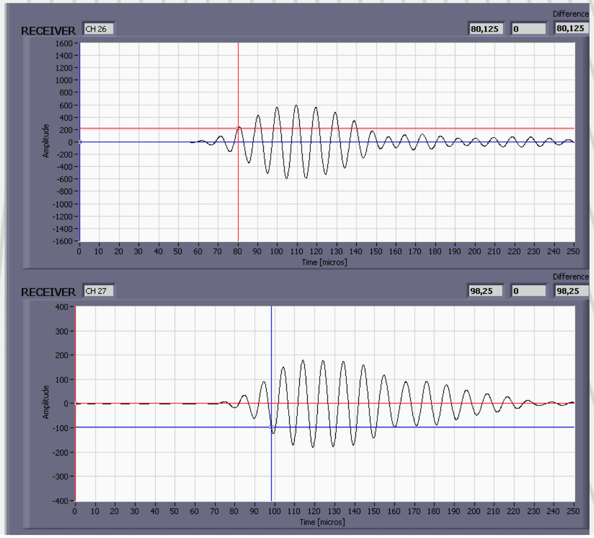
Rx1



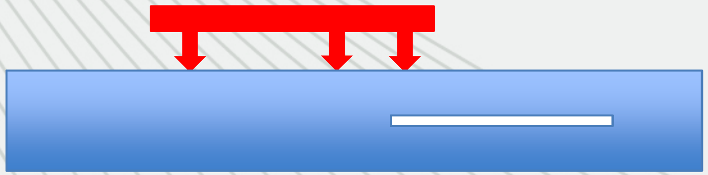
Rx2



Rx1



Rx2



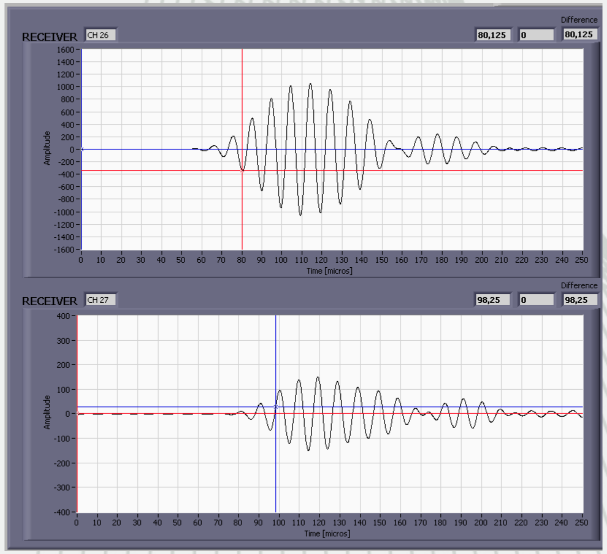
Sample No. 2

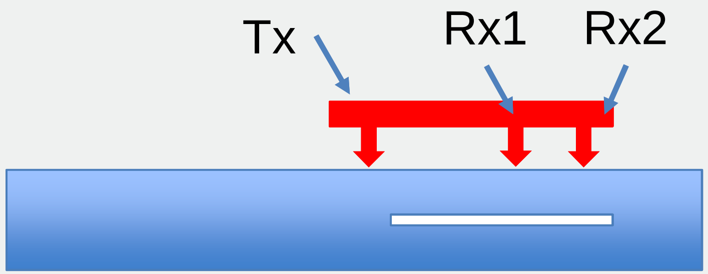
4.-Results

Flaw evaluation

Rx1

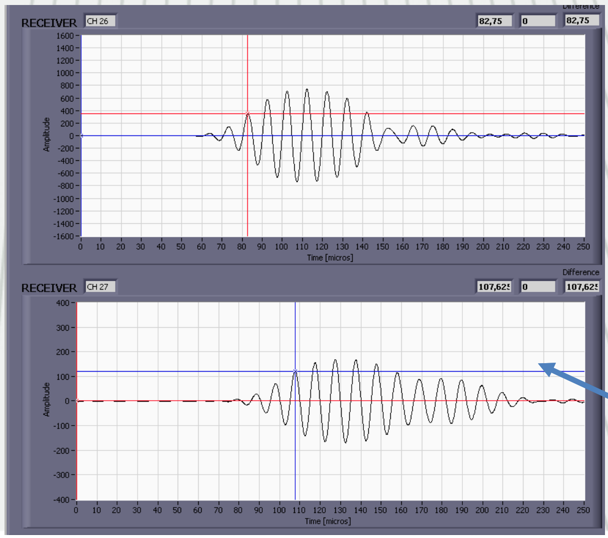
Rx2

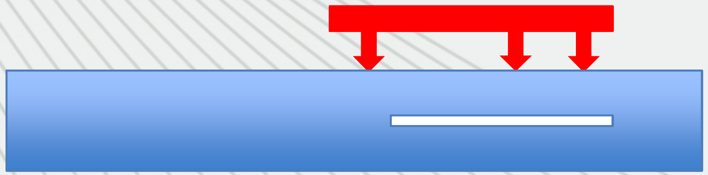




Rx1

Rx2





New cursor position

Sample No. 2

4.-Results

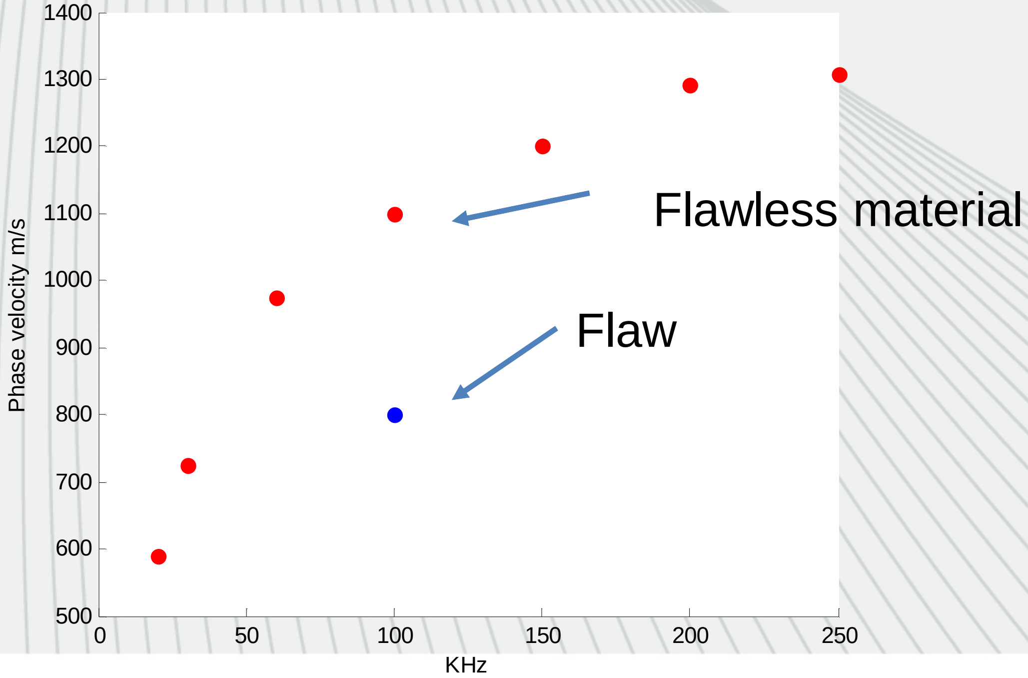
Numerical evaluation

If c=1.1 mm/µseg at 100 KHz

Then A=Time difference in flawless position=18,125 µseg

B=Time difference in flaw position=24.875 µseg

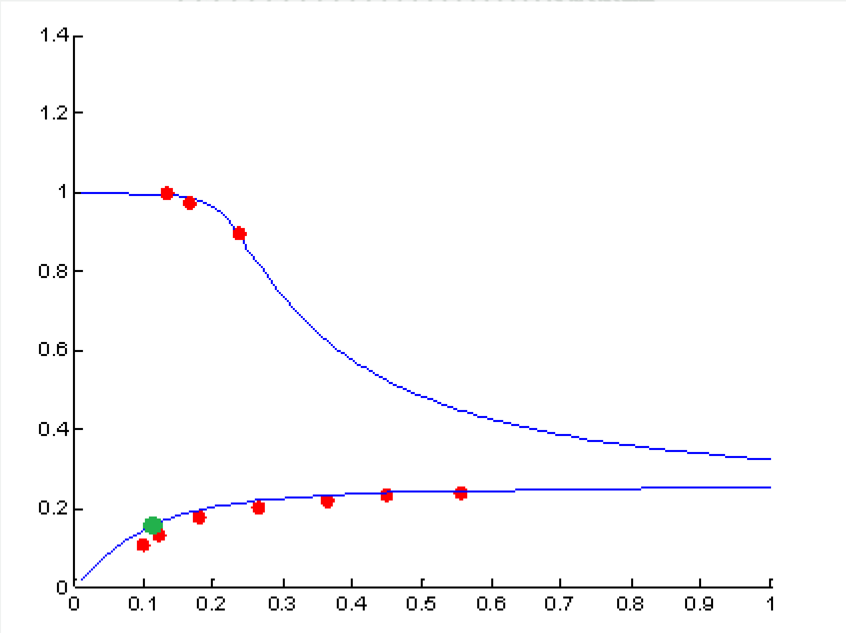
Velocity over the flaw= (A/B)*1,1= 0,801 mm/µseg= 801 m/s



4.-Results

Numerical evaluation vs. theoretical model

C/C_1



h/λ

h=1mm in the flaw region

Conclusions

- The phase velocity method was used for determination of elastic constants and the evaluation of plates.
- It was possible to use this method with SH and SV guided waves.
- A flaw evaluation (lamination) could be possible with this method.
- But the elastic model should be changed. (viscoelastic model)

Some extra details

- The "elastic" constants should be evaluated as viscoelastic "constants"

$$C_{ij} = C_{ijR} + iC_{ijI}$$

↓

$$C_{ij}(\omega) = C_{ijR}(\omega) + iC_{ijI}(\omega)$$

↓

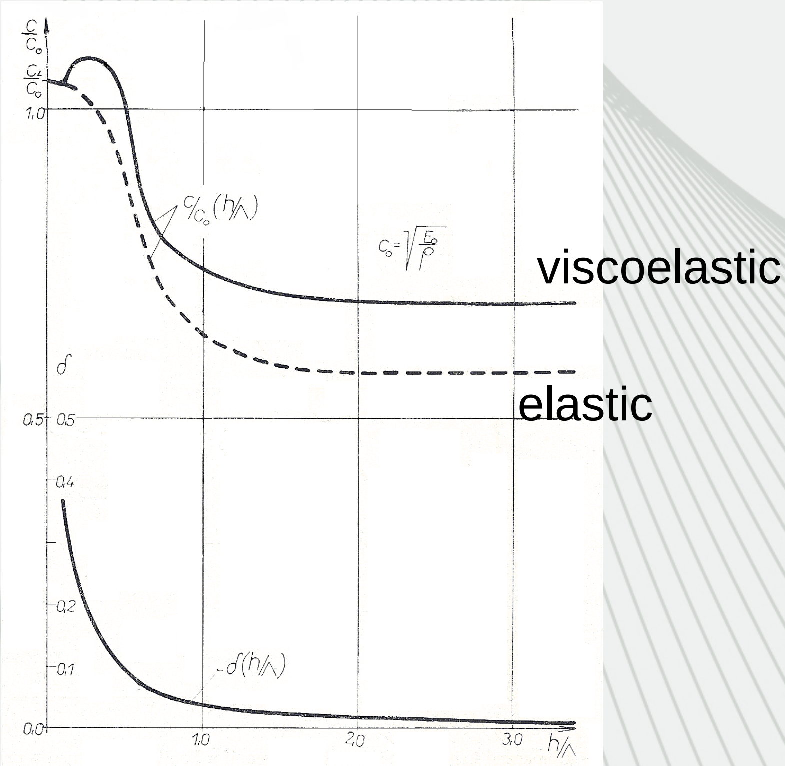
$$C_{ijI}(\omega) \Leftrightarrow C_{ijR}(\omega)$$

Dispersion
- Geometrical dispersion
- Viscoelastic dispersion

Some extra details

Viscoelastic dispersion model

From.:Martincek G. Theory and Methods of Dynamic Nondestructive Testing of Plane Elements. VEDA , Bratislava 1975



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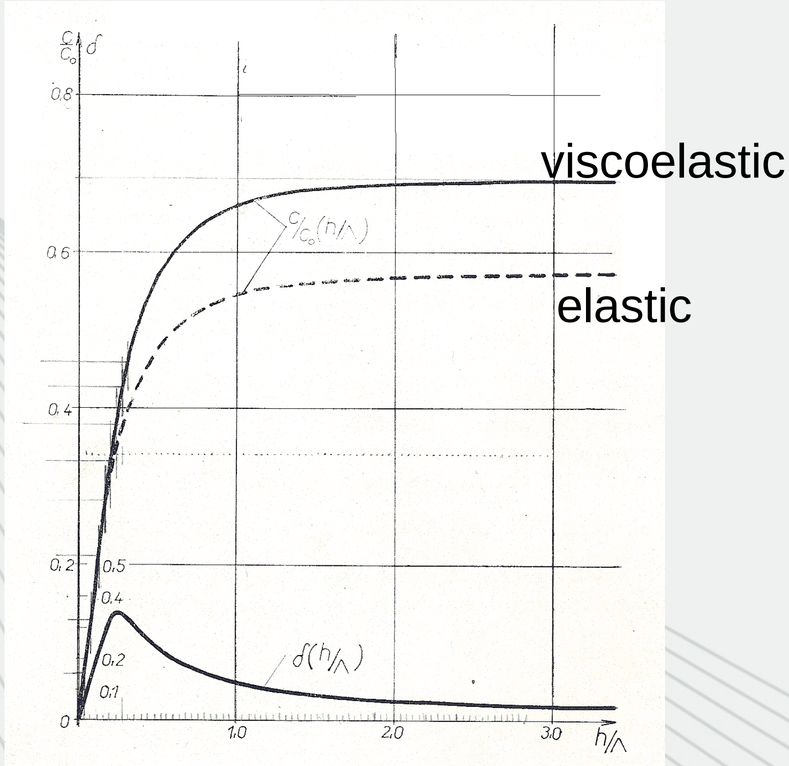

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