GREMAN
matériaux microélectronique
acoustique nanotechnologies

Ultrasonic non destructive testing
Principles and applications

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Introduction

Ultrasonic waves

Ultrasonic waves excitation

Ultrasonic nondestructive techniques

Nondestructive evaluation

What is NDT ?

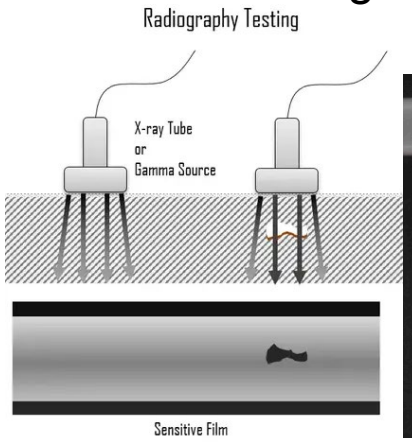
- NDT refers to an array of inspection techniques that allow inspectors to collect data about a material without damaging it.
- The goal of NDT is to ensure that critical infrastructure is properly maintained in order to avoid accidents.

Non-Destructive Testing (NDT) Services Technique Outlook

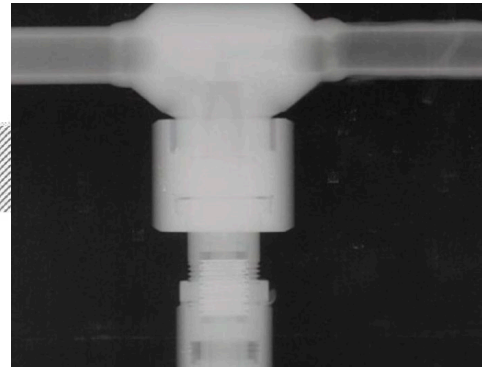
Ultrasonic testing

https://www.olympus-ims.com/en/

Radiographic testing

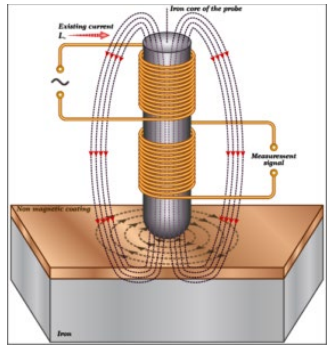


https://www.applus.com



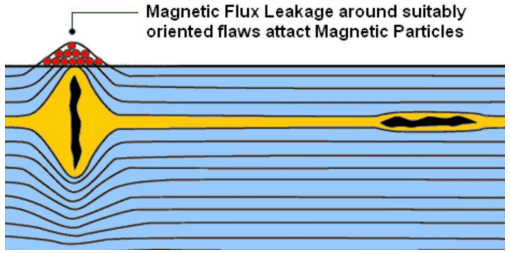
https://eclgh.com/radiographic-testing-advantages-and-disadvantages/

Eddy-current testing



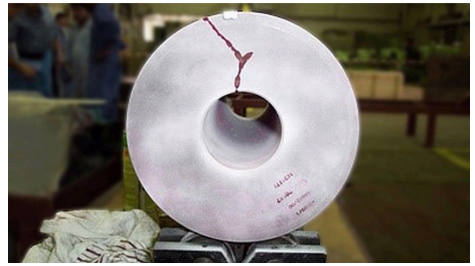
https://americanefficiency.com/eddy-current-testing/

Magnetic particle testing



https://www.onestopndt.com/ndt-articles/basic-principles-of-magnetic-particle-testing

Liquid testing



https://www.dekra.com/en/liquid-penetrant-testing/

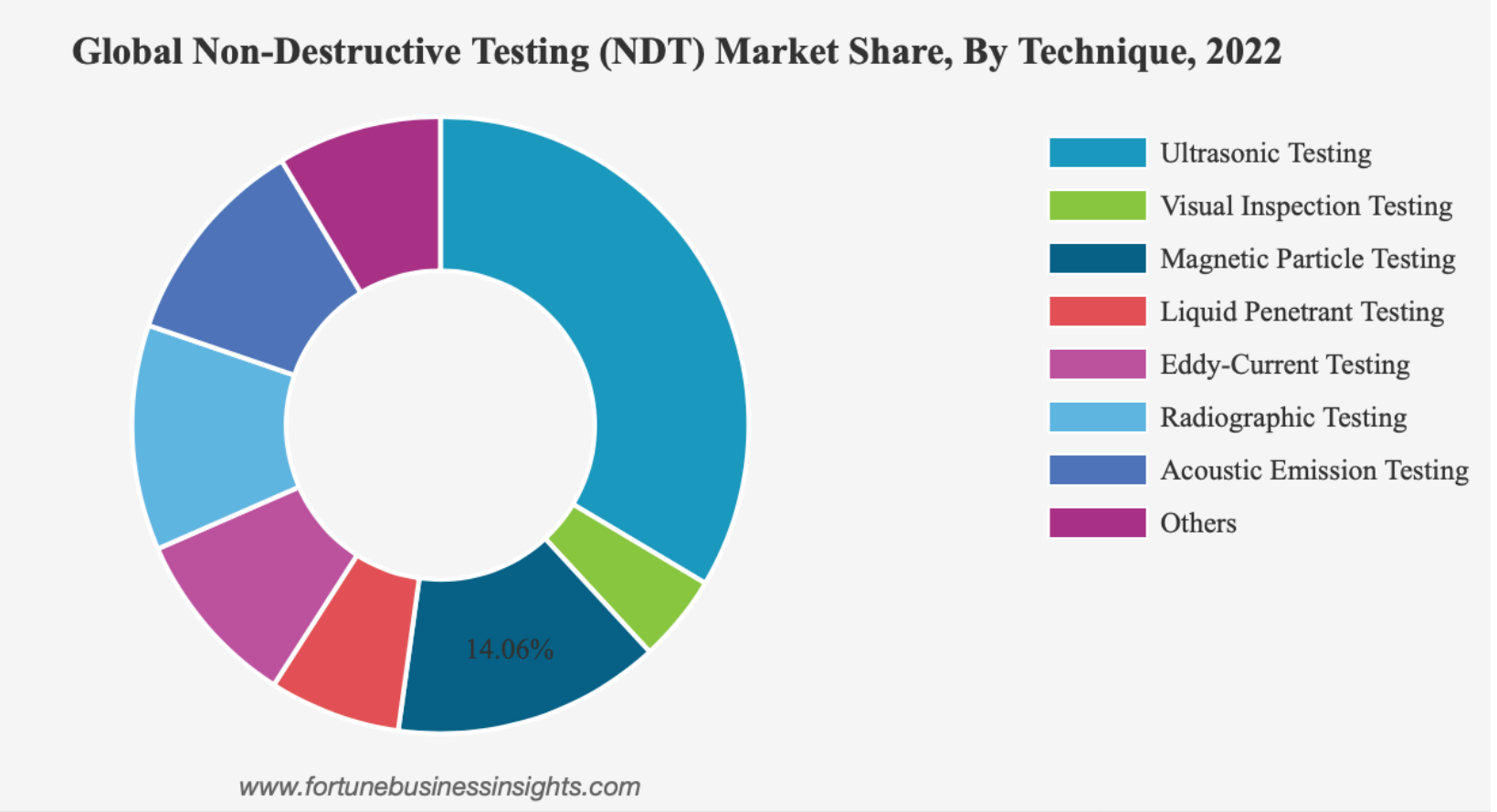
Market :

8.5 Billions in 2021

US technique 4.5 B

Main areas: North America Europe Asia

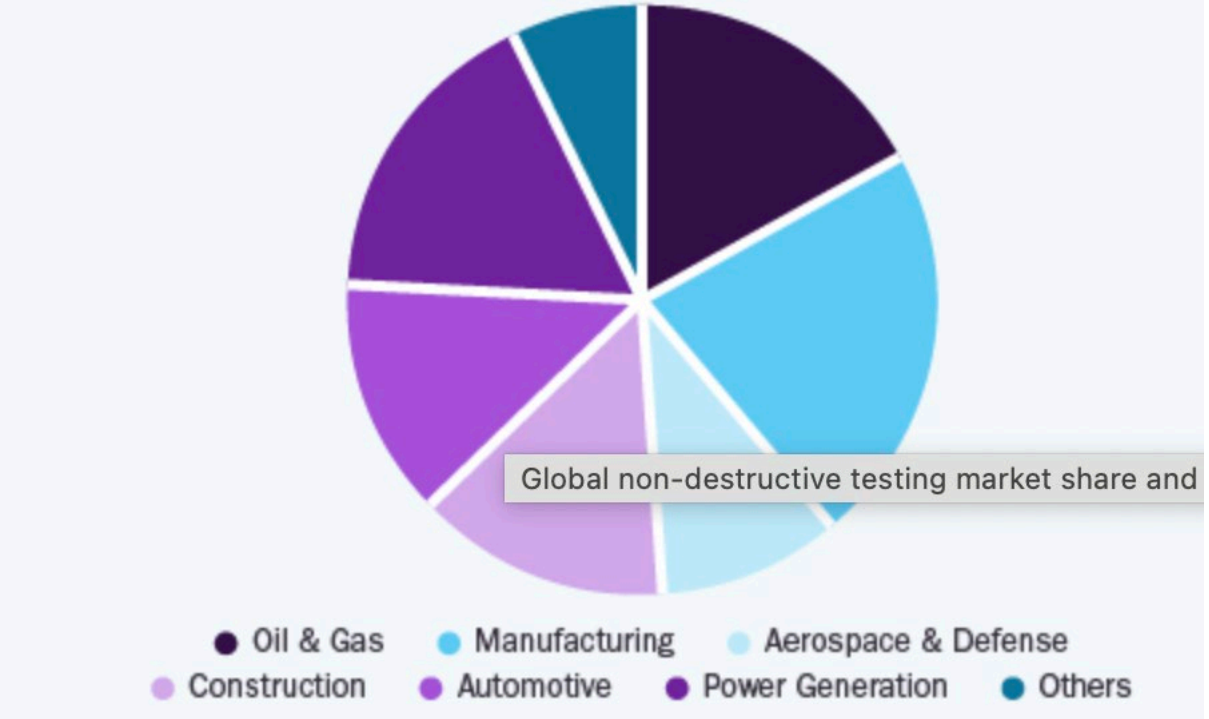
Expected growth rate: 13.5 %



Market

- Non-Destructive Testing (NDT) Services Application Outlook
- Flaw detection
- Leak detection
- Dimensional measurement
- Estimation of physical properties
- Chemical composition determination
- Stress and structure analysis

Non-Destructive Testing (NDT) Services Outlook



Introduction

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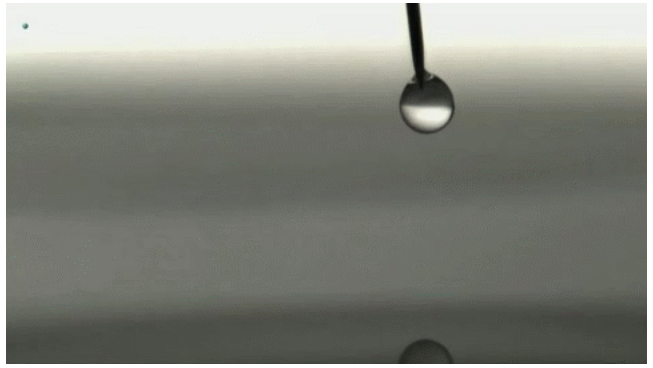
Ultrasonic waves excitation

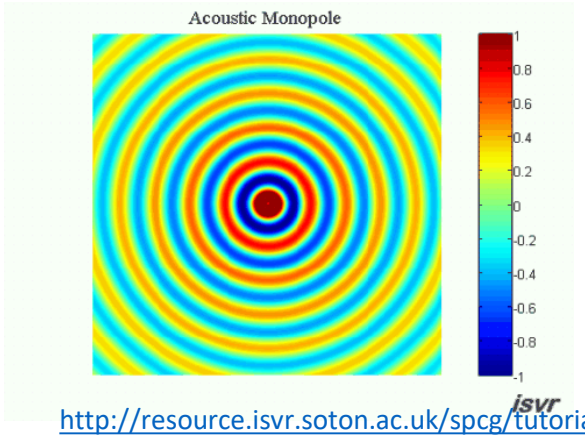
Ultrasonic nondestructive techniques

Nondestructive evaluation

Acoustic waves



https://forums.tumult.com/t/is-it-possible-to-create-a-water-drop-and-water-wave-animation/11138



http://resource.isvr.soton.ac.uk/spcg/tutorial/tutorial/StartCD.htm

Ex : Circle water, speaker , wave

Fundamenal characteristics

Celerity m/s

Frequency f=1/T Hz, pulsation ω= 2πf

Wavelength $\lambda = cT = \frac{c}{f}$

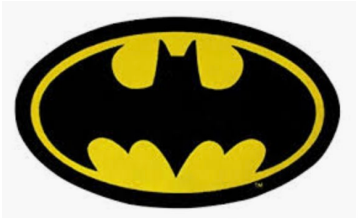
In acoustic.

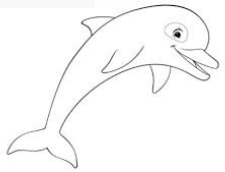
A medium is required

Pressure, strain, or force
Displacement, velocity

Acoustic landscape

© Can Stock Photo





Bat

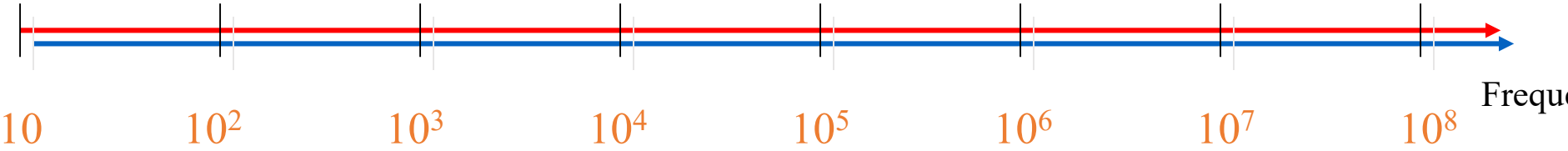
Crédit Photo : © Docteurs Levaillant et Benoit */**, avec leur autorisation

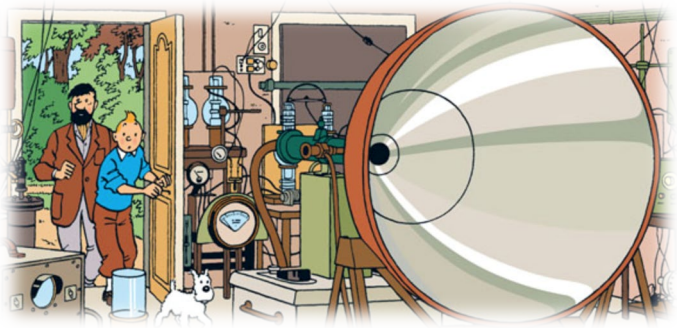
infrasounds

Human ear

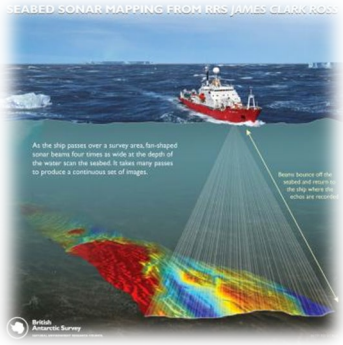
Sonars

Industrial and medical ultrasounds

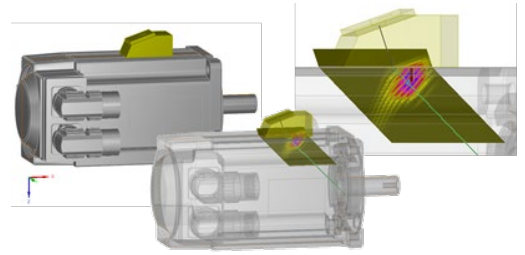




Tintin : L'affaire Tournesol



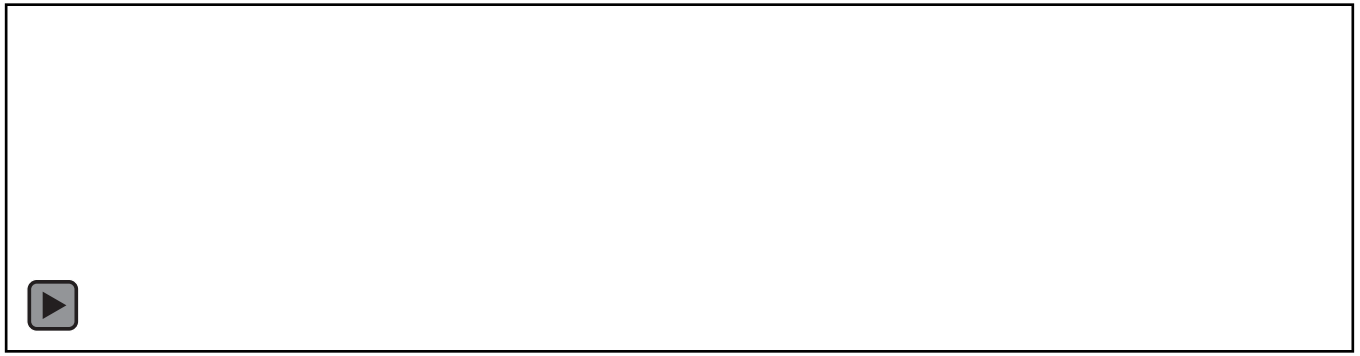
https://www.eurekalert.org/multimedia/pub/13882.php



http://www.extende.com/fr/controle-par-ultrasons-avec-civa

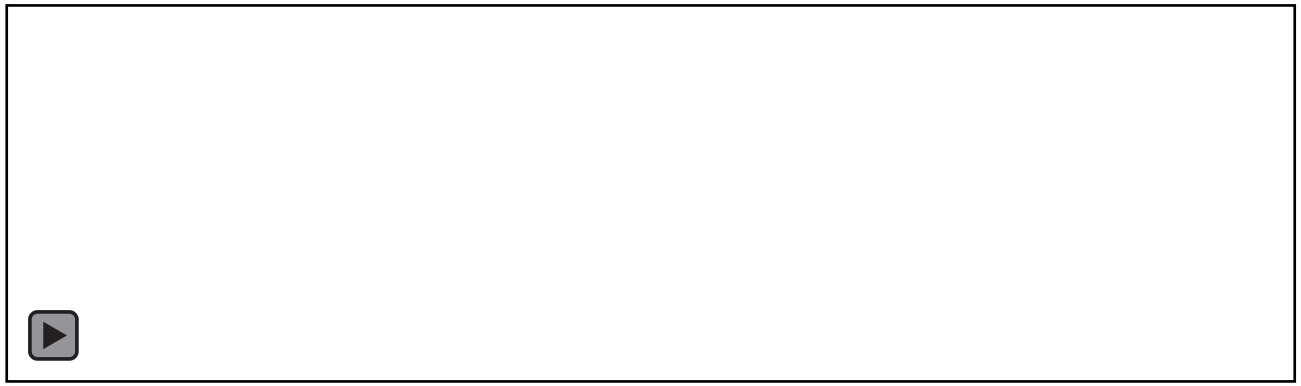
Ultrasonic waves: longitudinal waves

- Particle displacements and acoustic propagation are in the same direction
- Longitudinal waves exist in fluids and solids



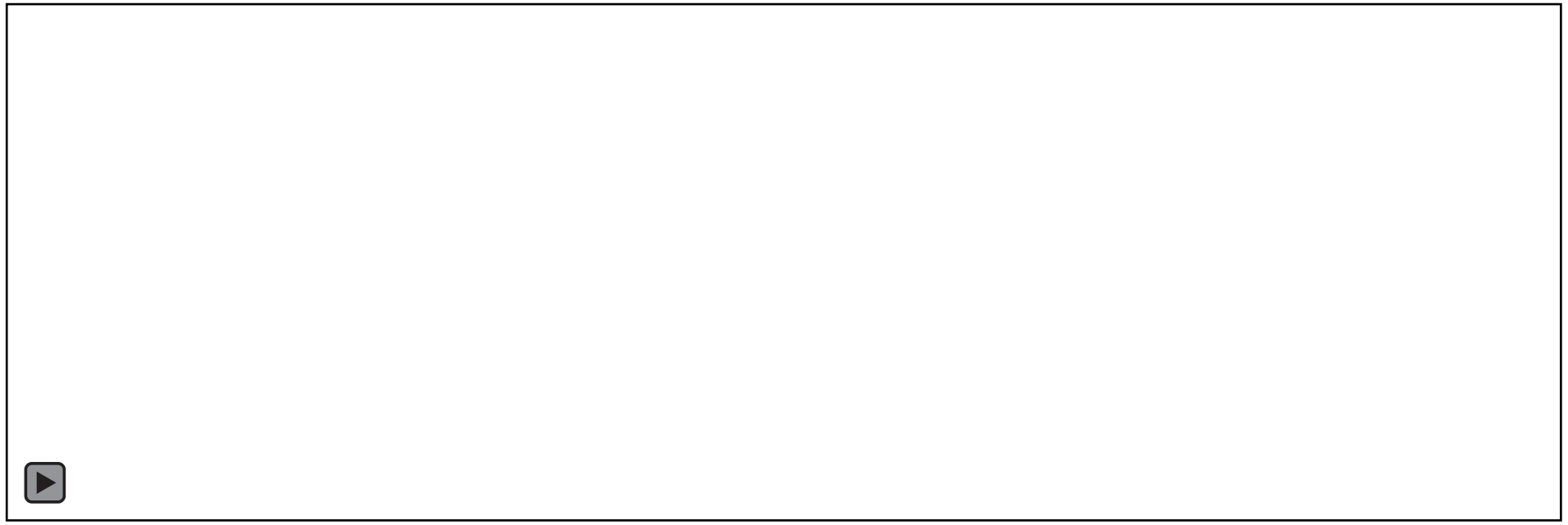
Ultrasonic waves: transversal waves

- Particles displacements perpendicular to the propagation direction
- Transversal waves exist only in solids



Ultrasonic waves: surface waves

- Compression and shear waves: elliptical polarization
- Particle displacements near the surface. (depth inferior to the wavelength)



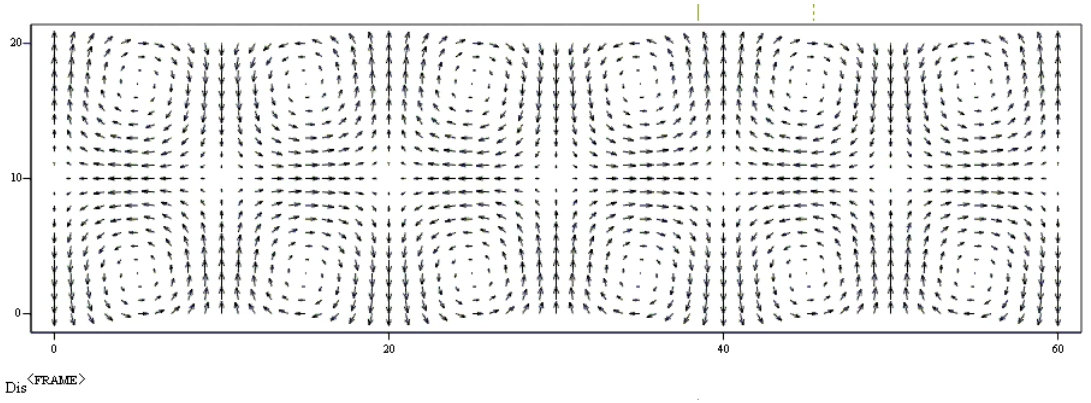
Ultrasonic waves: guided waves in solids

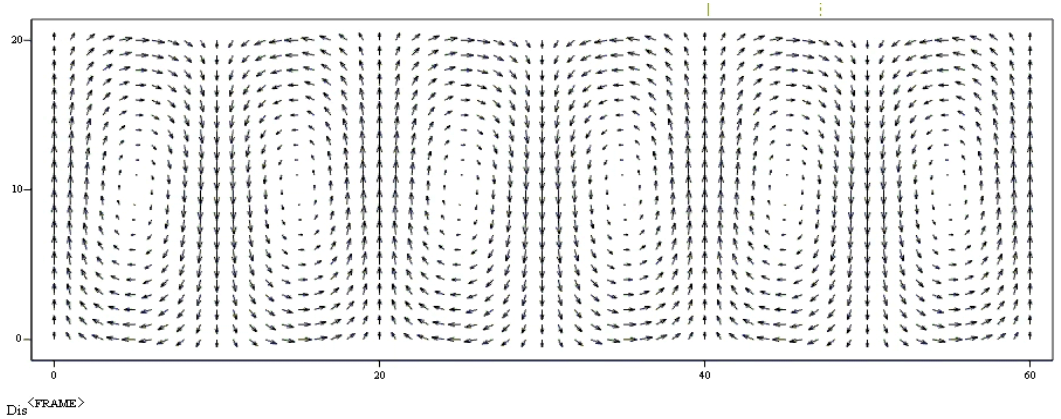
- Propagation in finite thickness material

- Two wave types
  - S mode: symmetrical:

    Transversal displacement of particles are symmetric
  - A mode Mode A: antisymmetric

    Transversal displacements of particles are antisymmetric





Summary

- Volumic waves
  - Longitudinal waves
  - Transversal waves

- Guided waves
  - Rayleigh waves
  - Lamb waves

 Choice of wave type for specific nondestructive testing

Ultrasonic celerity

In solids

$$c = \sqrt{\frac{1}{\rho_0 \chi}}$$ In fluids

$$c_L = \sqrt{\frac{M}{\rho_0}}$$

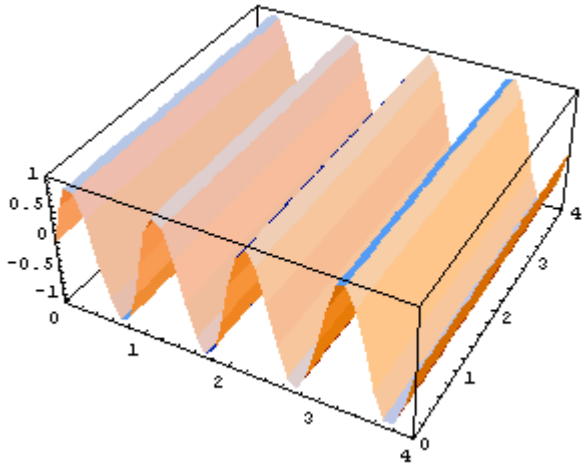
$$c_T = \sqrt{\frac{G}{\rho_0}}$$

$$M = K + \frac{4}{3}G$$

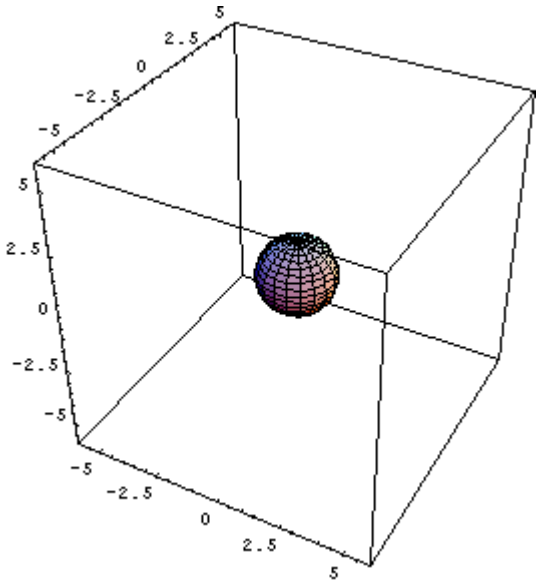
Material	Density [Kg/m3]	Longitudinal celerity [m/s]	Shear velocity [m/s]
Air (0 degree)	1,293	331	
Air (20 degree)	1,20	344	
Alcohol	790	1207	
Water (pure)	998	1480	
Aluminum	2790	6320	3130
Steel	7800	5900	3200

Waveform

Plane waves



Spherical waves



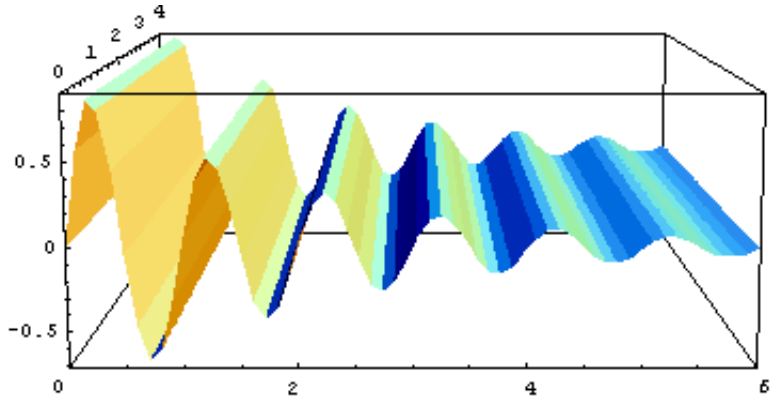
$$u_x = U_M \cos(\omega t - \frac{\omega}{c} x)$$

Attenuation: diffusion, viscosity

$$u_x = U_M e^{-\alpha x} \cos(\omega t - \frac{\omega}{c} x)$$

Attenuation factor

$$\alpha = 8.686 \times a\omega^2 \quad \text{dB/m}$$



Water α= 0.22 dB/m @ 1MHz

Characteristics of Ultrasonic waves

- In fluid:

$$c = \frac{1}{\sqrt{\rho\chi}}$$

ρ : density

χ : compressibility

- In solid:

$$c_L = \sqrt{\frac{C_{33}}{\rho}}$$

C_{33} : elastic constant

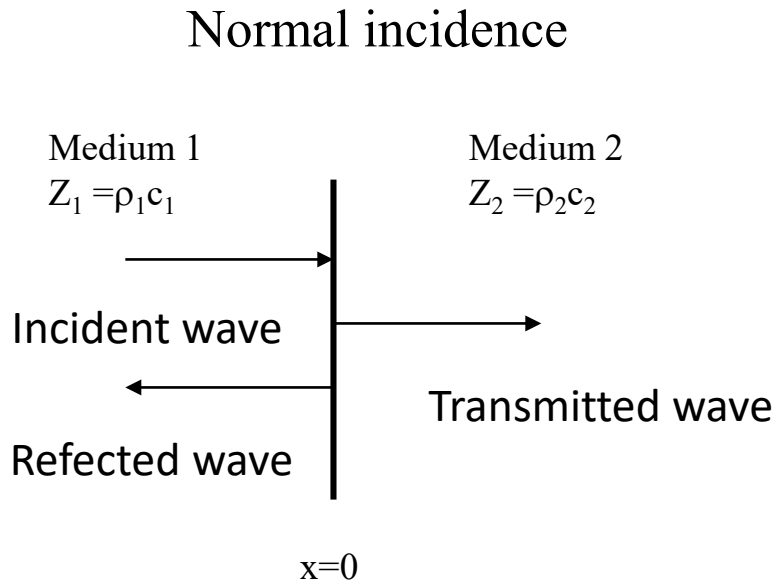
$$c_T = \sqrt{\frac{C_{44}}{\rho}}$$

C_{44} : shear modulus

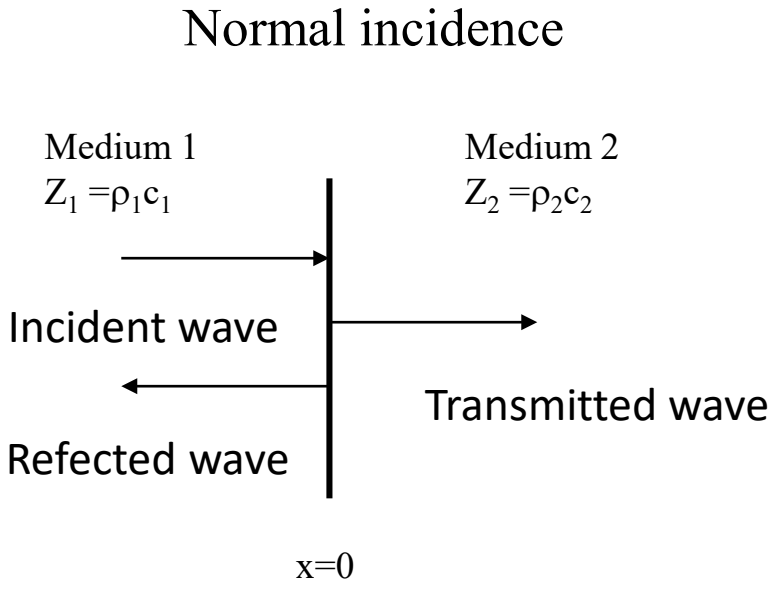
- Surface Rayleigh waves have celerity lower than C_T

Reflexion and tranmission

- In normal incidence
  - All acoustic field can be seen as a sum of plane waves
  - Z = ρ.c : acoustic impedance of propagation medium



Reflexion and transmission



- amplitude reflexion coefficient $r = \frac{Z_2 - Z_1}{Z_2 + Z_1}$

- Amplitude transmission coefficient $t = \frac{2Z_2}{Z_2 + Z_1}$

Reflexion and transmission

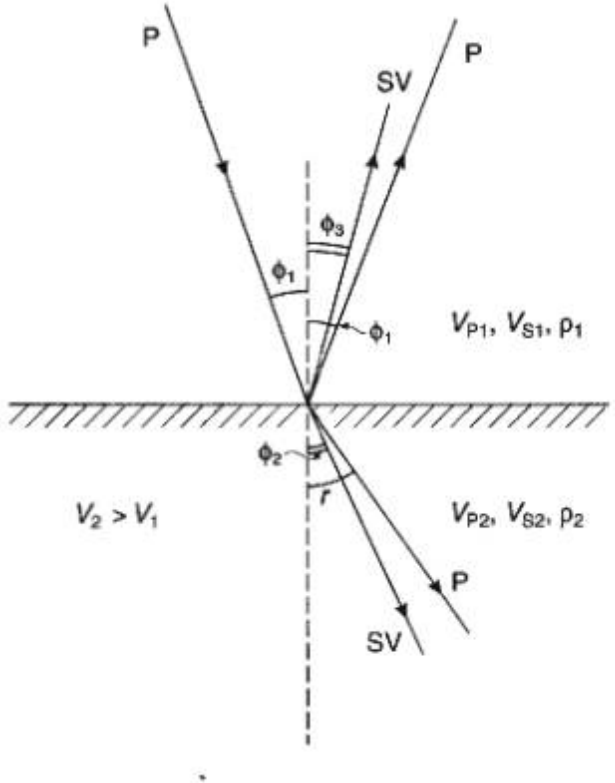
Energy conservation, the intensity $I_i = I_r + I_t$

- Intensity reflexion coefficient $$R_I = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

- Intensity transmission coefficient $$T_I = \frac{4Z_2.Z_1}{(Z_2 + Z_1)^2}$$

Reflexion and transmission

- With an incidence angle

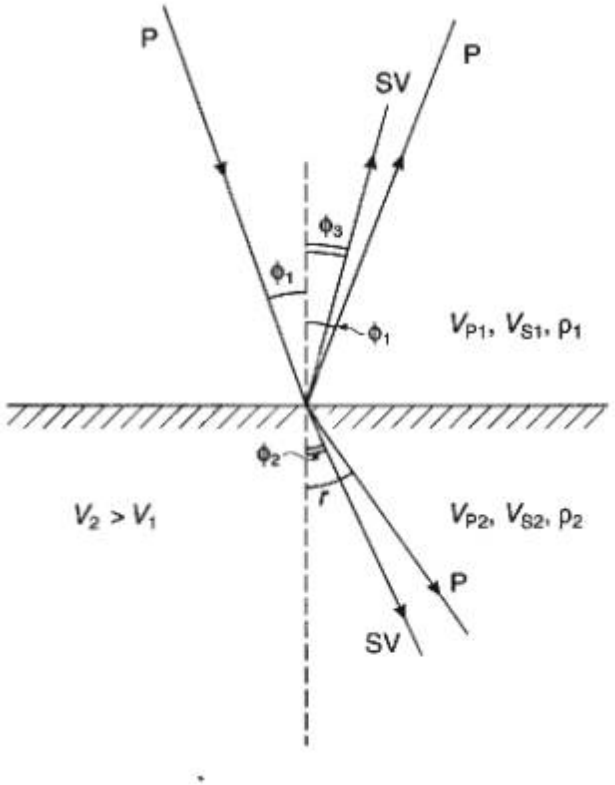


- Longitudinal and transversal waves are reflected and transmitted.
- Snell-Descartes laws.

$$\sin\frac{\phi_1}{V_1} = \sin\frac{\phi_2}{V_2}$$

Reflexion and transmission

- Incident wave: L wave with an incidence angle θ_{1L}
  - Reflected L wave $\phi_1 = \phi_1$
  - Reflected T waves $\phi_3 < \phi_1$
  - Transmitted L wave (angle r)
    - $r < \phi_1$ if $V_{P2} < V_{P1}$
    - $r > \phi_1$ if $V_{P2} > V_{P1}$
  - Transmitted T wave (angle ϕ_2)
    - ϕ_2 < r



Reflexion and transmission

- Critical angles V2>V1 evanescent waves
  - 1st critical angle (r = 90°)

$$\phi_{CL} = \arcsin\frac{V_{P1}}{V_{P2}}$$

  - 2nd critical angle (ϕ_2 = 90°)

$$\phi_{CT} = \arcsin\frac{V_{P1}}{V_{S2}}$$

  - Rayleigh wave generation angle

$$\phi_{CR} = \arcsin\frac{V_{P1}}{V_{R2}}$$

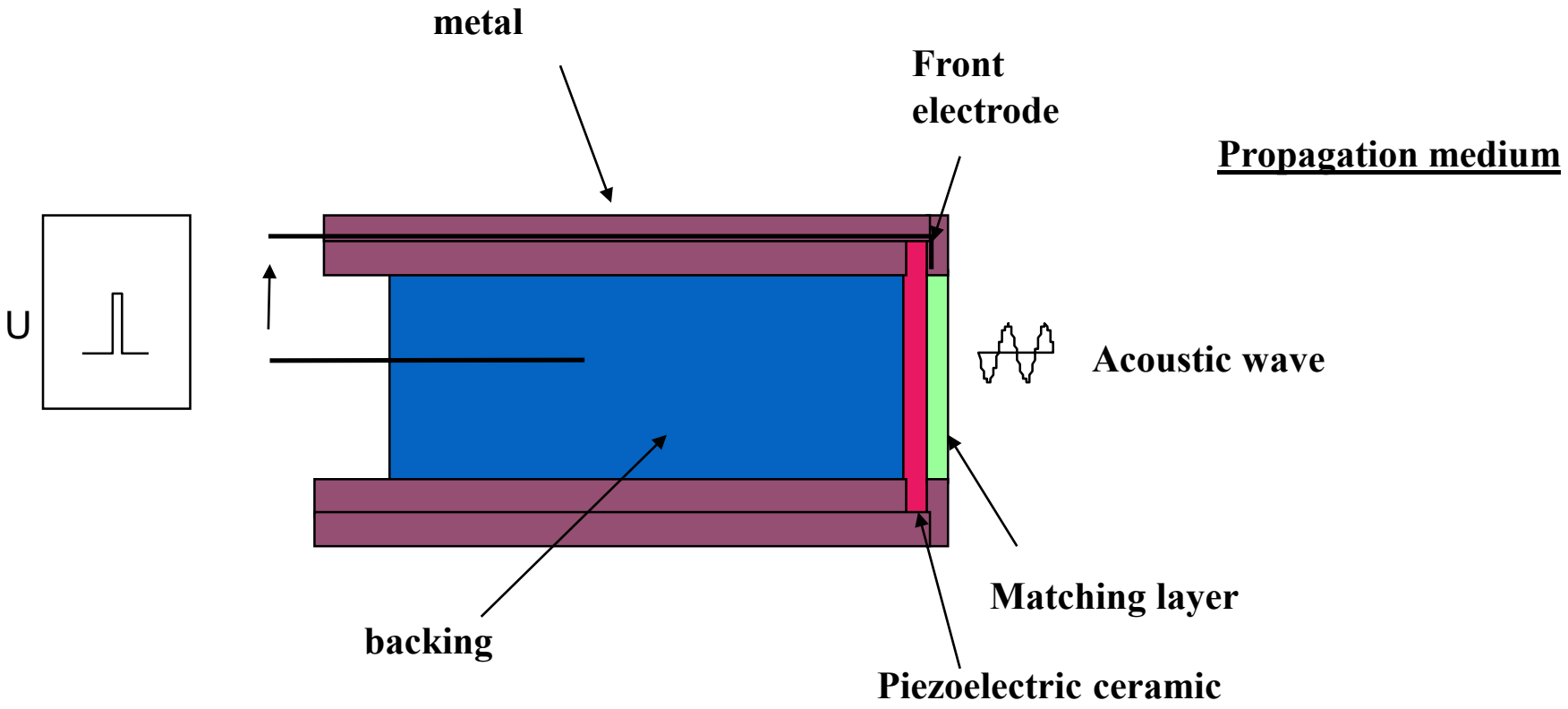
Ultrasonic waves

Ultrasonic waves excitation

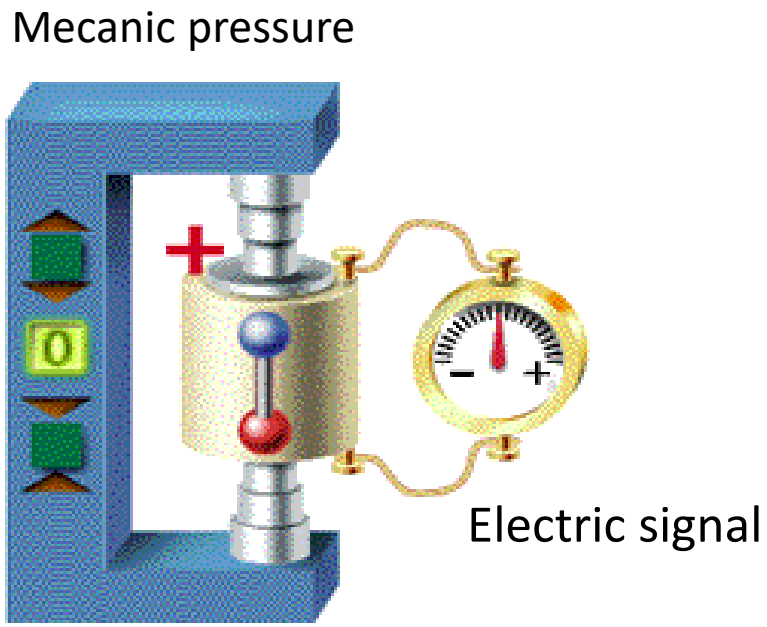
Ultrasonic nondestructive technique

Non destructive evaluation

Ultrasonic transducer

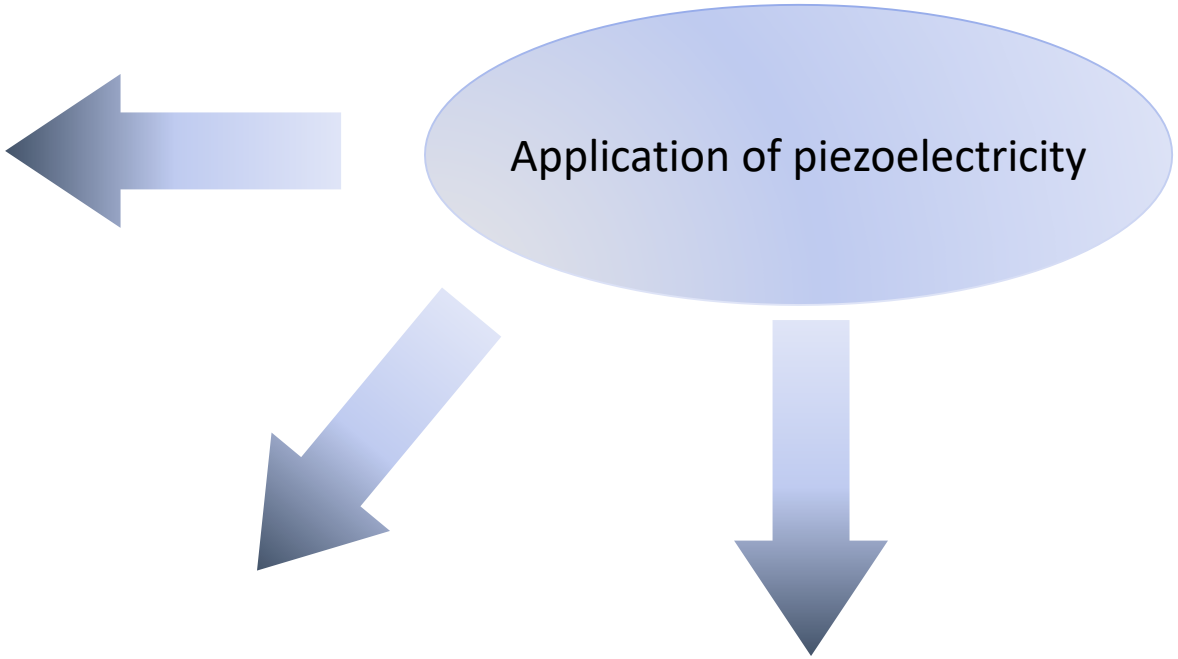


The piezoelectricity is the property of several materials that are able to generate an electric charge when mechanically deformed. Conversely, when an external electric field is applied to piezoelectric materials they mechanically deform.



Converse effect: actuartors...

- Loud speakers
- Sonar
- actuators
- motors



Both effects

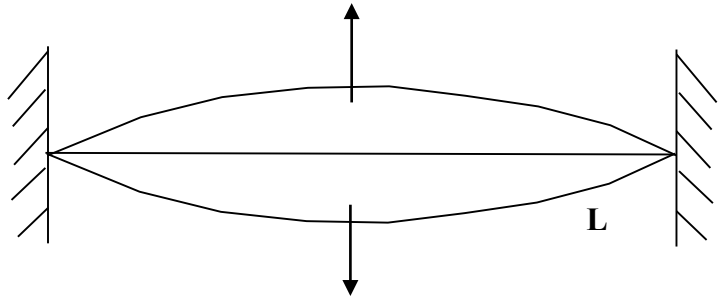
- Clocking, filters in electronics
- Sensors (chemical physical
- Ultrasounds medicine & industry

Direct effect : sensors

- Microphones
- Accelerometers
- Hydrophones
- Energy harvesting
- Passive sensors…

Vibration of a piezoelectric ceramic

Vibrating string :



First mode : $L = \frac{\lambda}{2}$

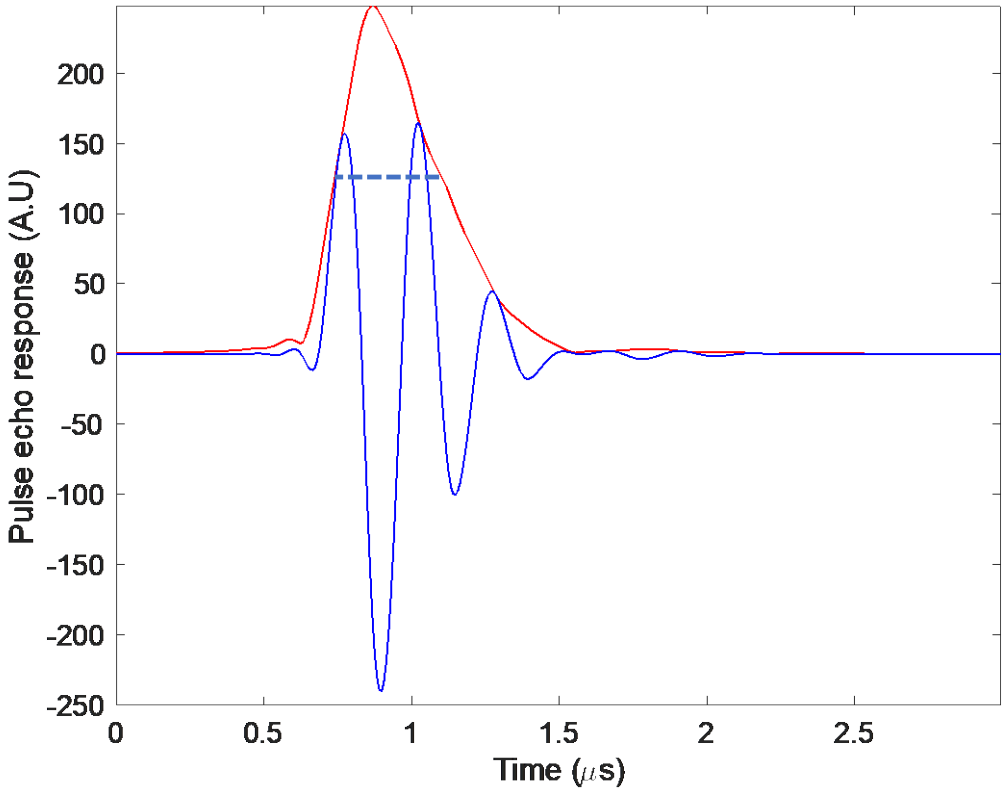
The center frequency $f_0 = \frac{c}{\lambda} = \frac{c}{2L}$

Ceramic : c =4000 m/s

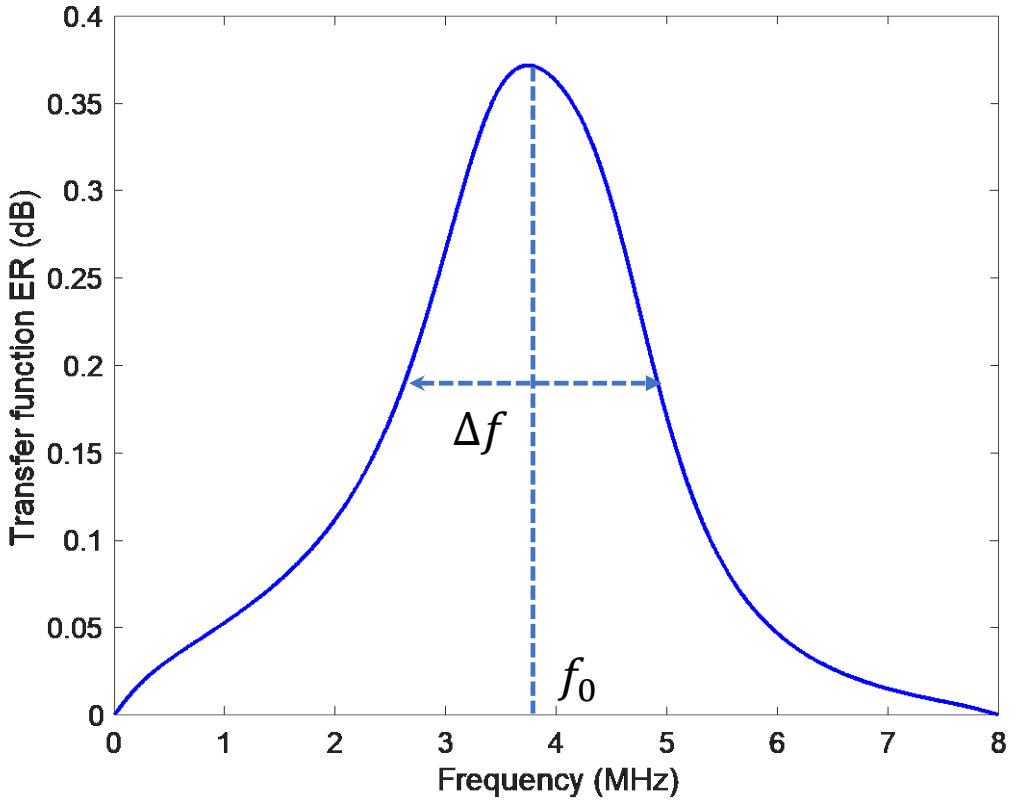
$$e = 1\ mm$$

$$f_0 = \frac{4000}{0.002} = 2\ MHz$$

Transducer characteristics : axial resolution Band-width

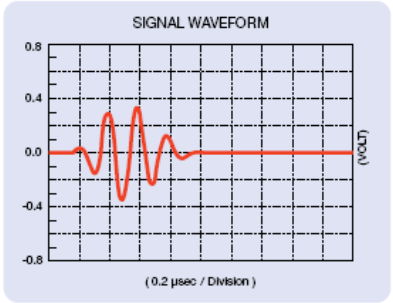


$$R_{-6db} = \Delta t \times c \; in \; mm$$



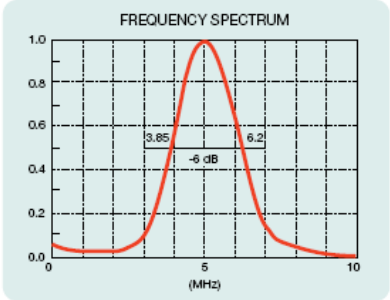
$$BP = \frac{f_0}{\Delta f} \; in \; \%$$

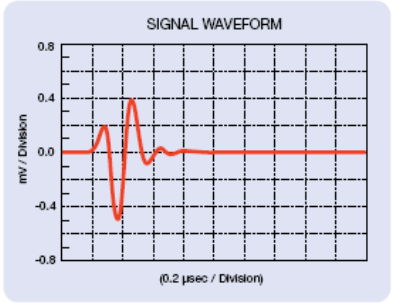
Transducer bandwidth



Accuscan "S"

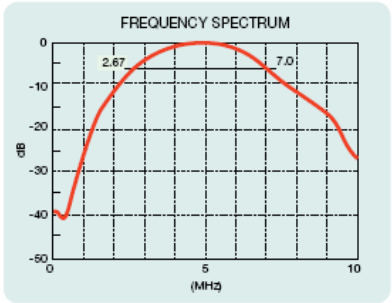
The Accuscan S series is intended to provide excellent sensitivity in those situations where axial resolution is not of primary importance. Typically this series will have a longer wave form duration and a relatively narrow frequency bandwidth.

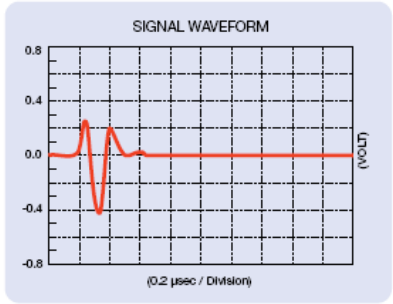




Centrascan™

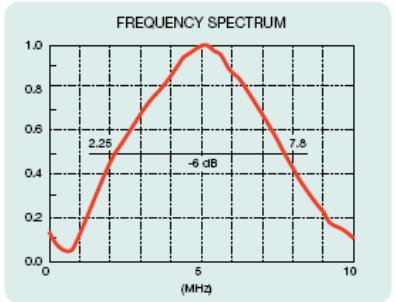
The piezocomposite element Centrascan Series transducers provide excellent sensitivity with a high signal-to-noise ratio in difficult-to-penetrate materials. They have exceptional acoustic matching to plastics and other low impedance materials.





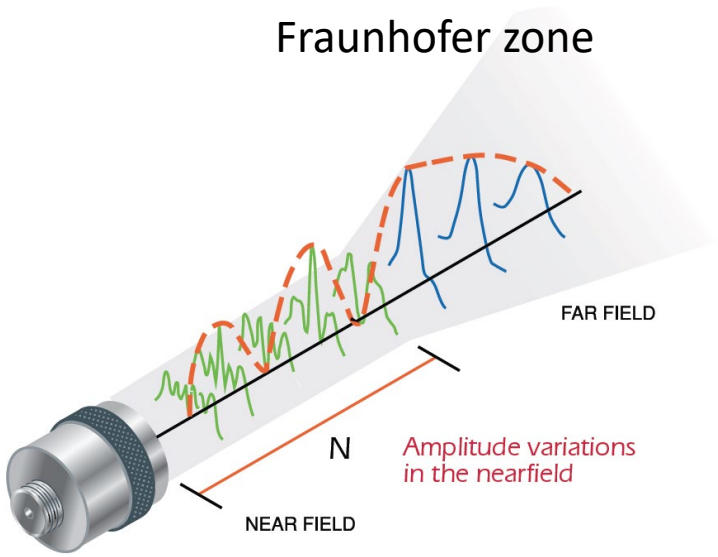
Videoscan

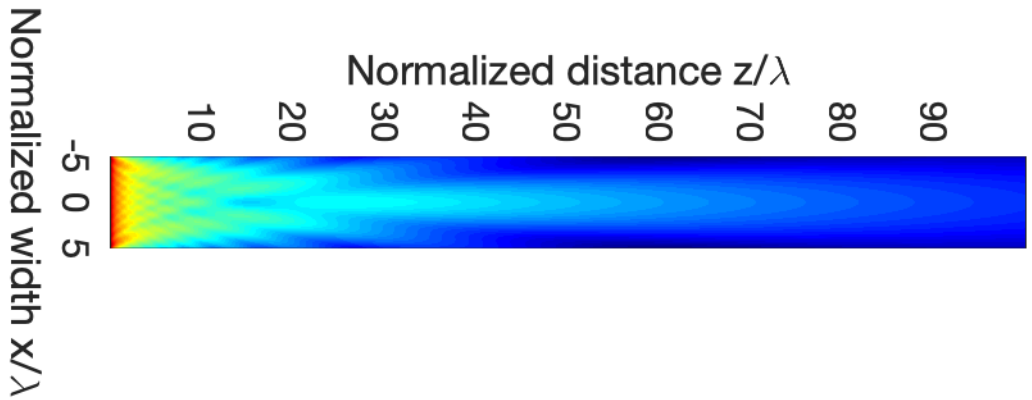
Videoscan transducers are untuned transducers that provide heavily damped broadband performance. They are the best choice in applications where good axial or distance resolution is necessary or in tests that require improved signal-to-noise in attenuating or scattering materials.



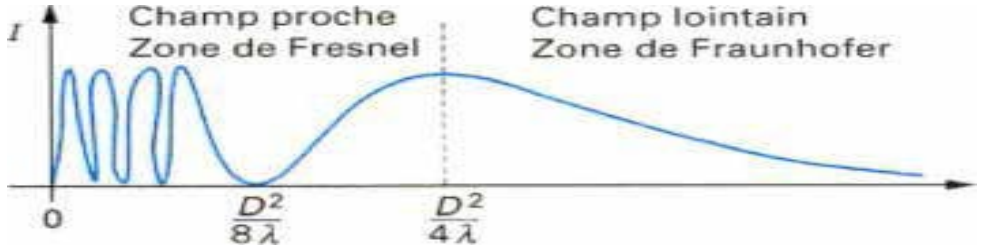
Transducer radiation field

Fraunhofer zone

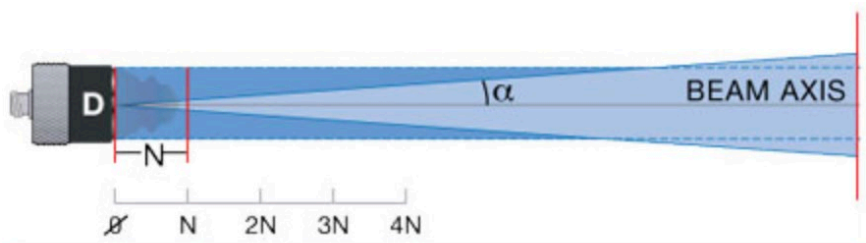




Fresnel zone



Transducer radiation field Beam spreading

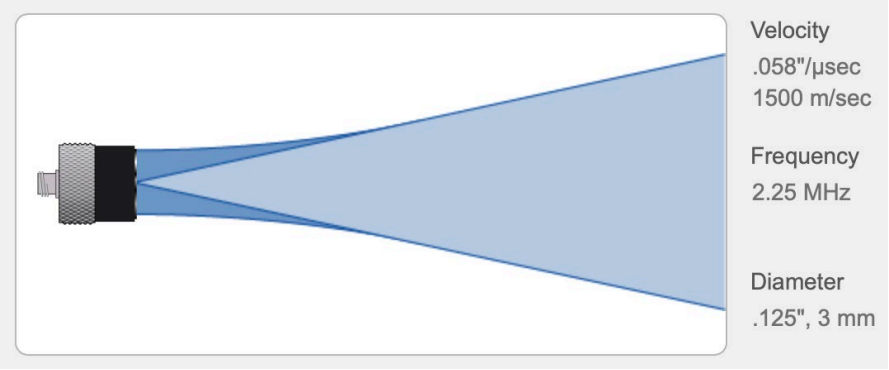


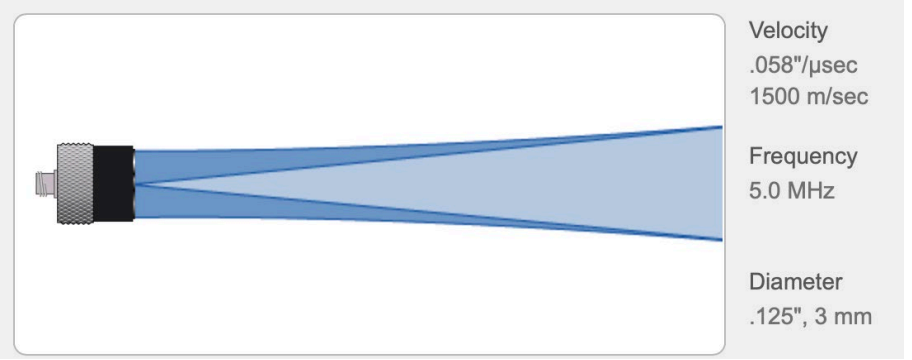
– 6 dB half-beam spread angle (α) of an unfocused transducer

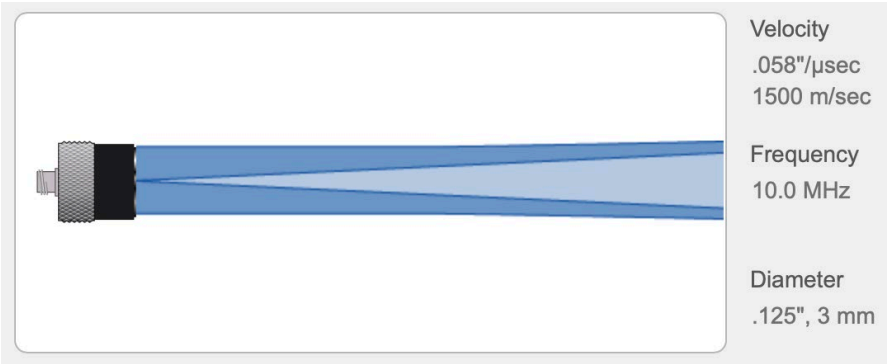
$$\alpha = \text{Sin}^{-1}(.514c/fD)$$

Where

D = element diameter or aperture
f = frequency
c = sound velocity in test material

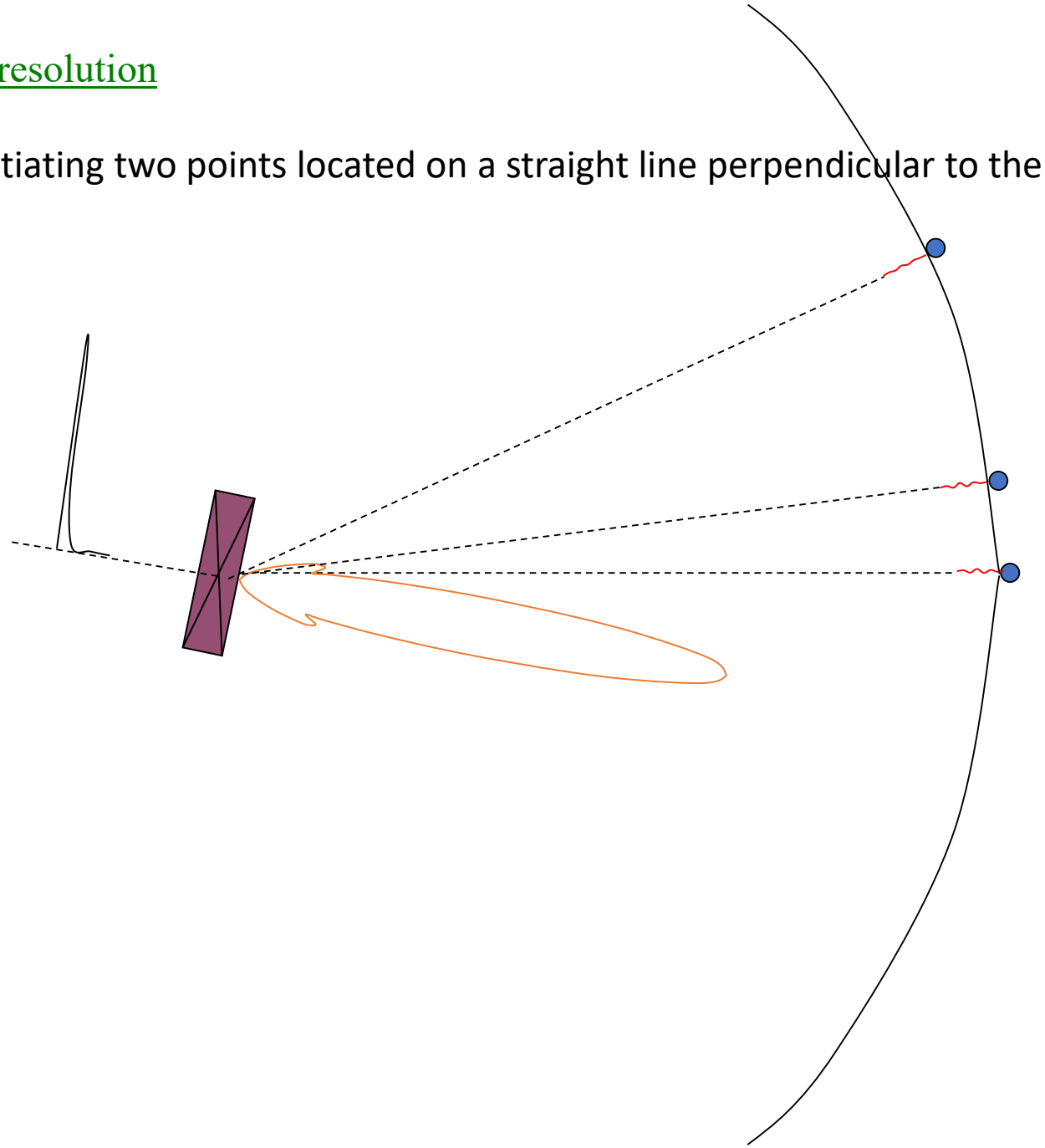


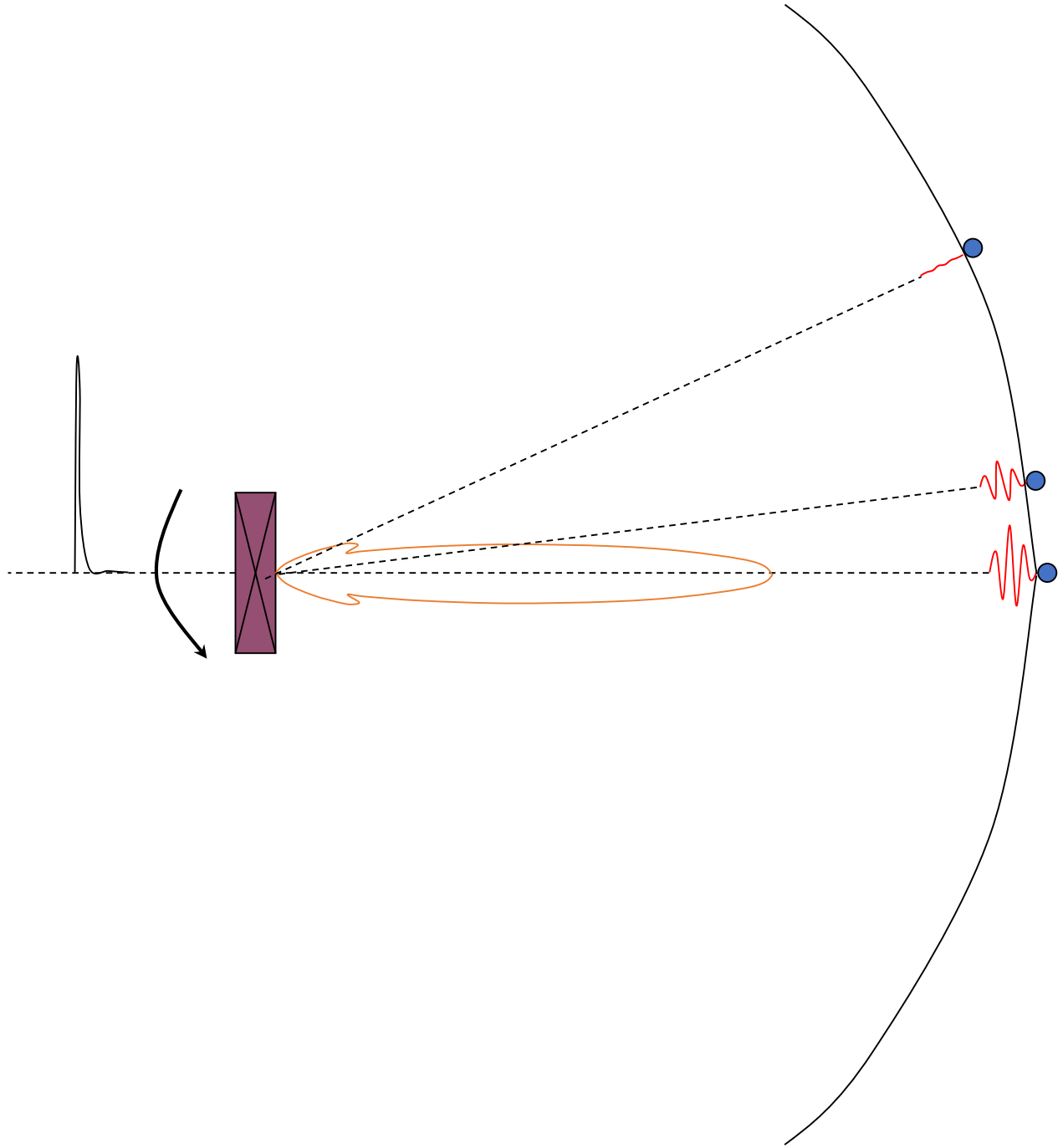




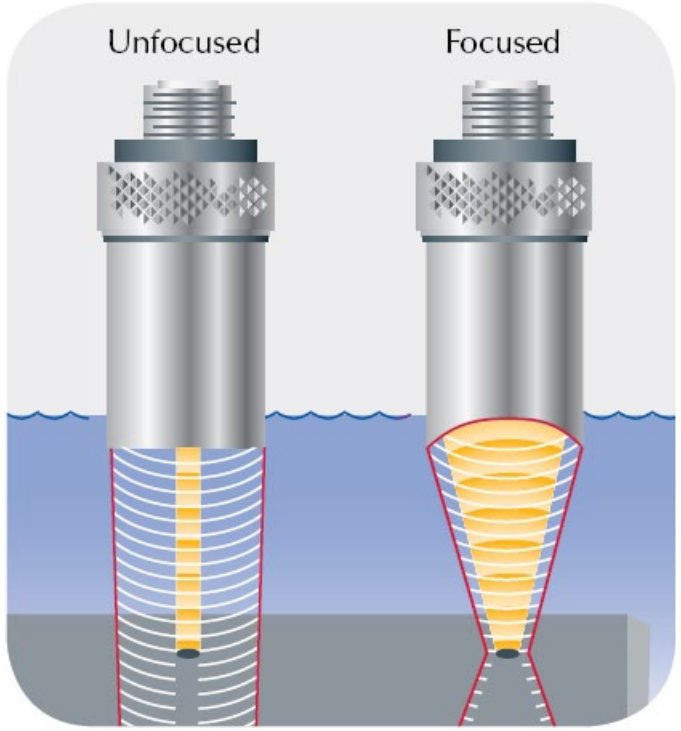
Lateral resolution

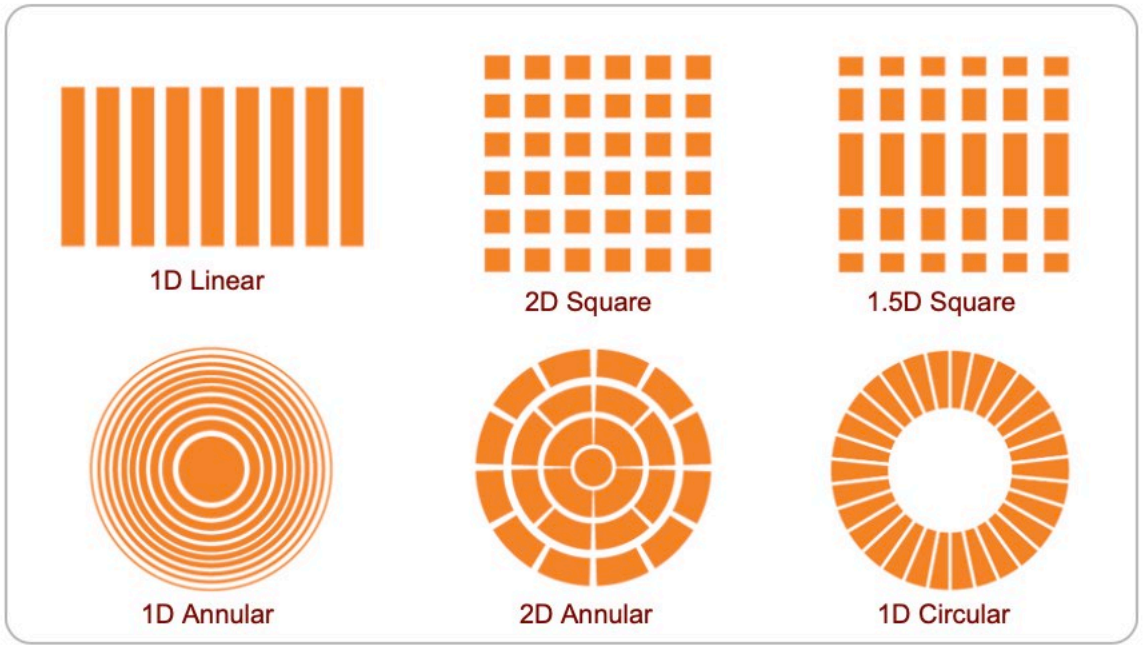
differentiating two points located on a straight line perpendicular to the axis of propagation.

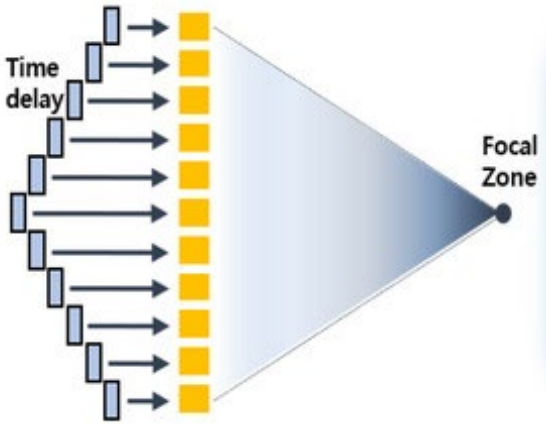


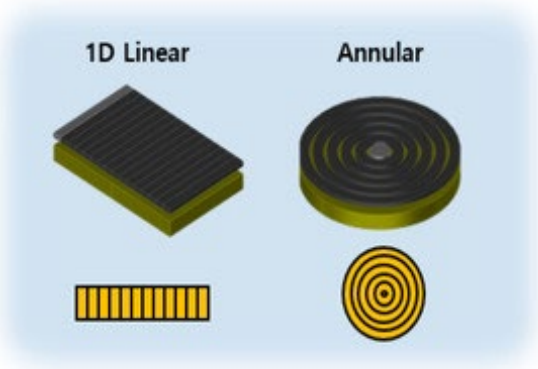


Focused and Array transducers









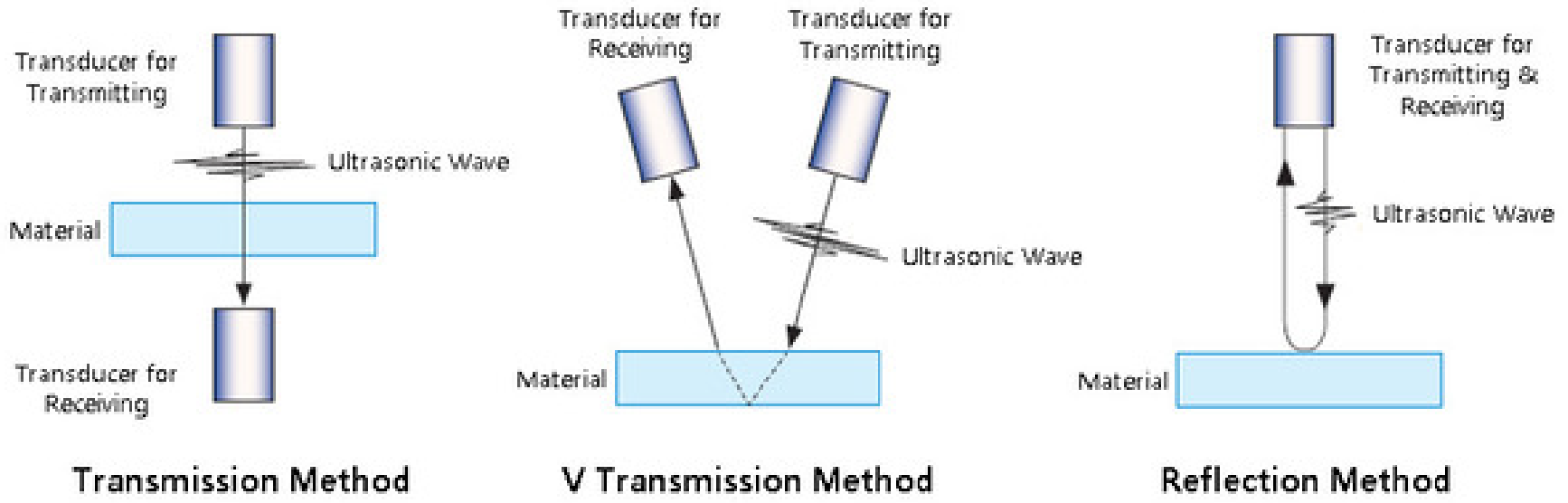
Ultrasonic waves

Ultrasonic waves excitation

Ultrasonic non-destructive techniques

Non-destructive evaluation

NDT acoustic technics



- wave type
  - Transversal waves longitudinal waves
  - Lamb wave, Rayleigh waves

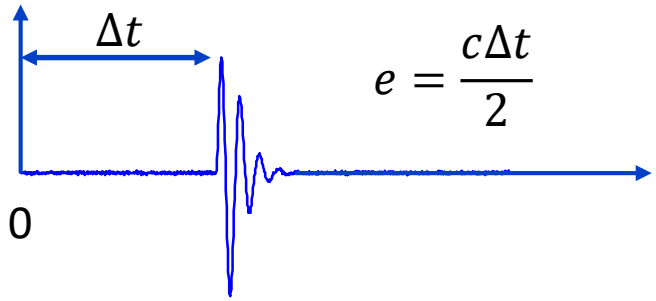
Thickness measurement

Longitudinal waves

Coupling (oil, aqueous gel…)

Transvesal wave

Coupling (honey…)



• **Measurement from one side:** Ultrasonic gauges require access to only one side of pipes, tanks, tubing, containers, hollow castings, large metal or plastic sheets,

• **Completely nondestructive:** No cutting or sectioning

• **Highly reliable:** accurate, repeatable, and reliable.

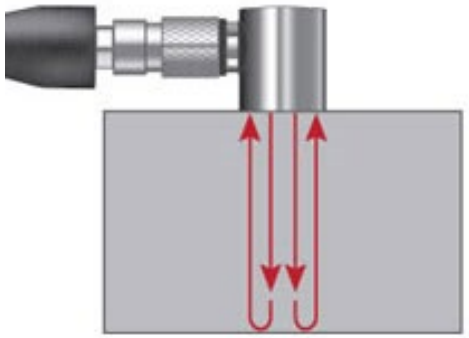
• **Versatile:** All common engineering materials can be measured
• **Wide measurement range:** 0.08 mm (0.003 in.) minimum to 635 mm (25 in.) Resolution can be as fine as 0.001 mm or 0.0001 in.
• **Easy to use:** ultrasonic gauging require only a small amount of operator interaction.

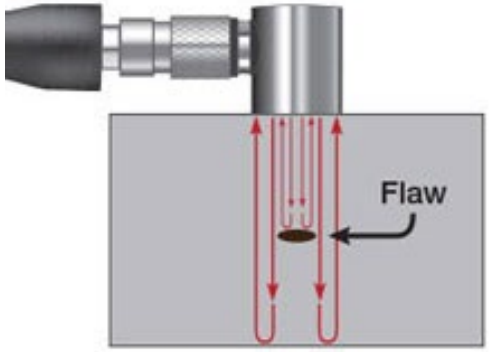
• **Instant response:** takes only one or two seconds per point

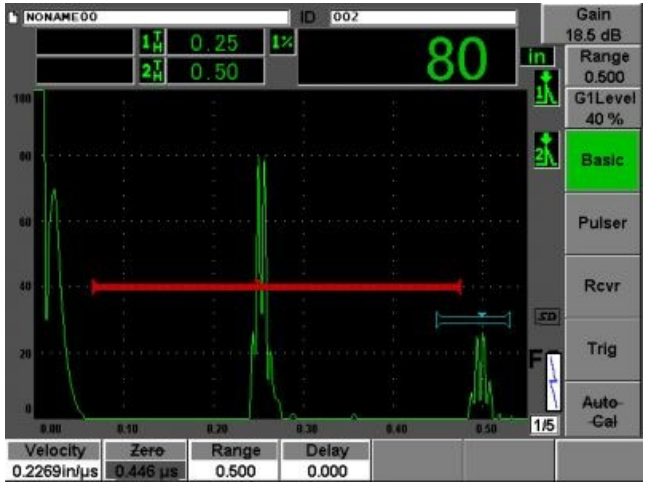
• **Compatible with data logging and statistical analysis programs**

Flaw detection

Ascan





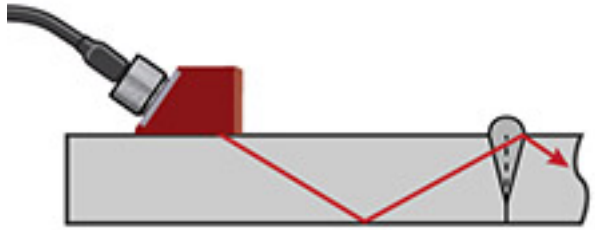


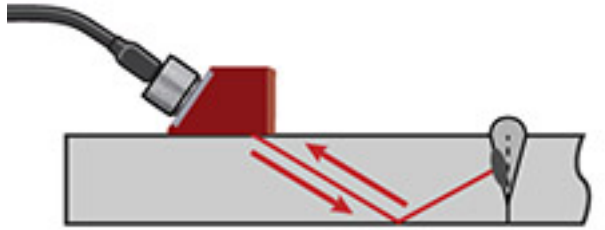
Time of flight measurement
Amplitude measurement

Ultrasonic flaw detection can potentially be applied to any standard engineering material to find hidden cracks, voids, porosity, inclusion, and similar discontinuities.

- Weld inspection
- Primary metals
- Infrastructure
- Petrochemical
- In-service testing
- Manufacturing
- Composites

Flaw detection Weld inspection





Imaging techniques Echo….graphy

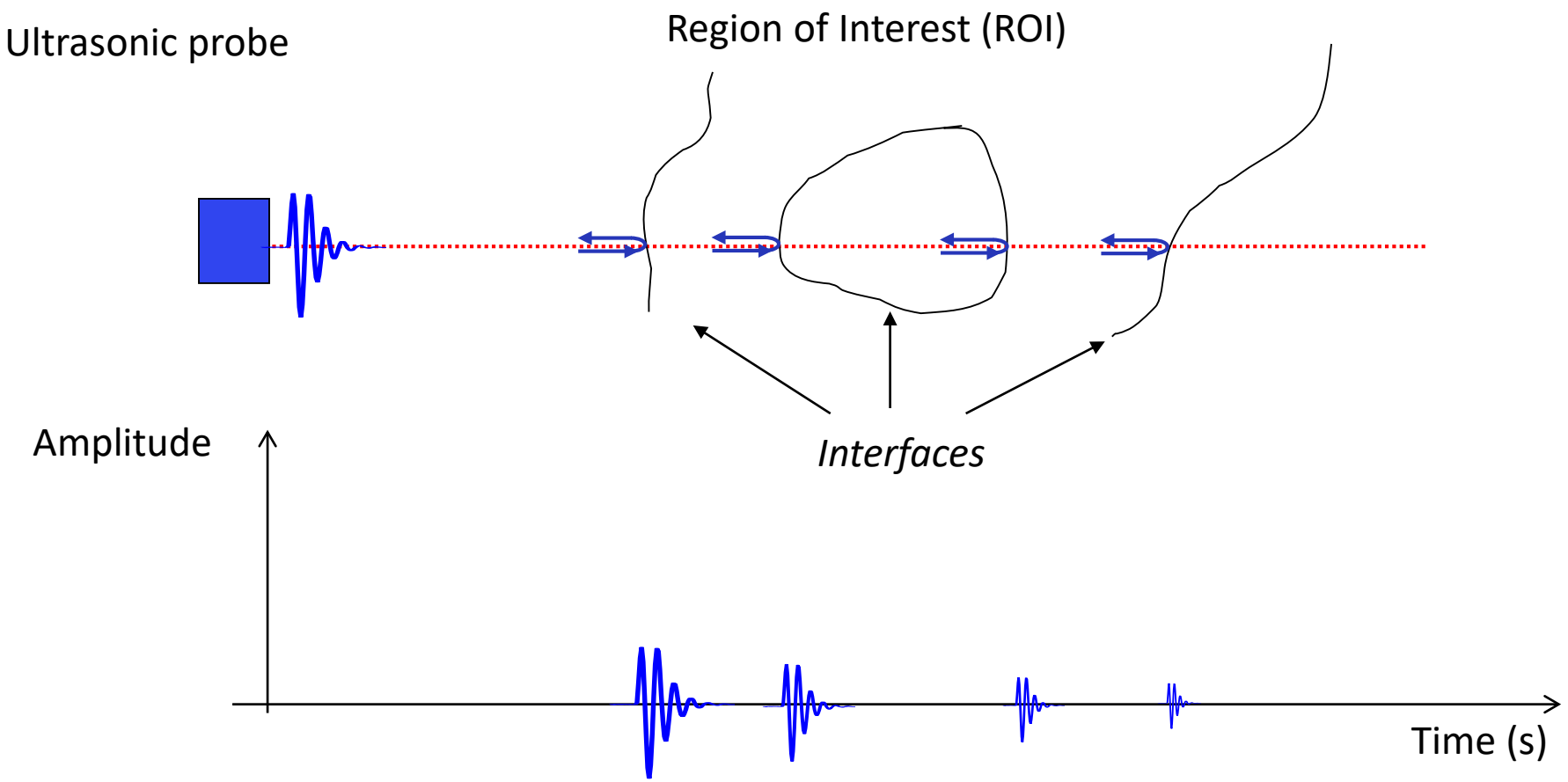
The nymph Echo was condemned by Hera
to repeat the last words she heard.

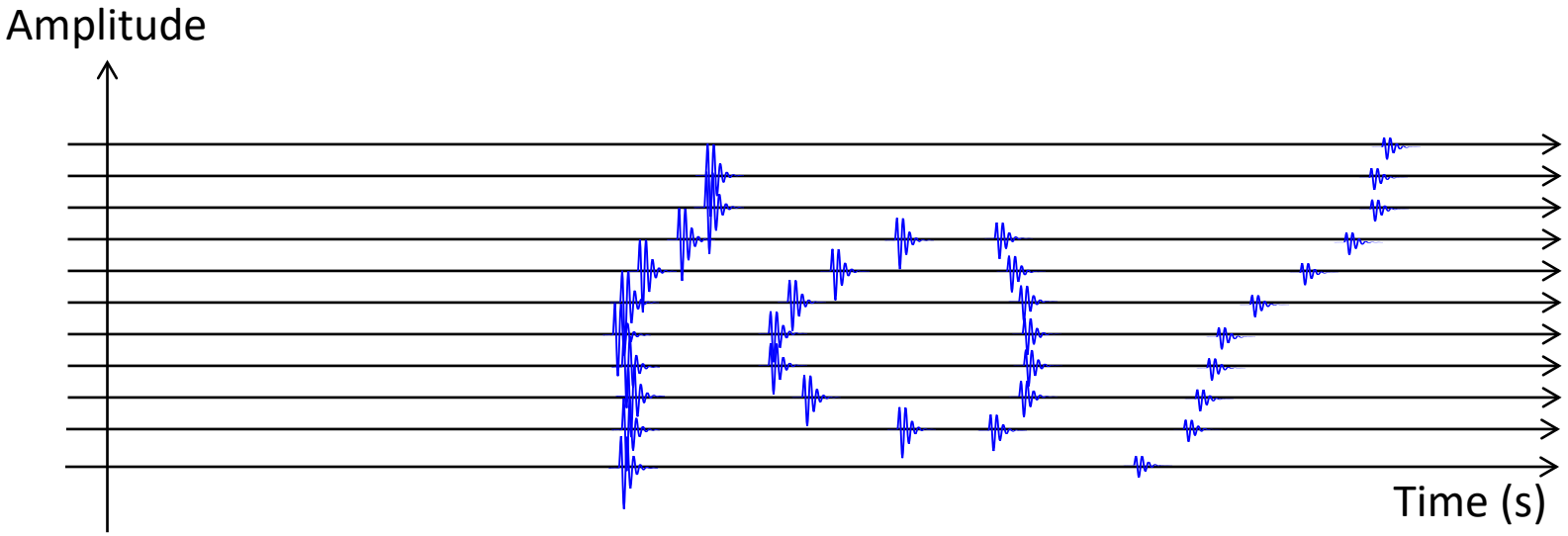
La nymphe Echo, Paul Lemoyne, 1822, Musée du Louvre

Then, in love with Narcissus, she withers away...

Only her voice remains.

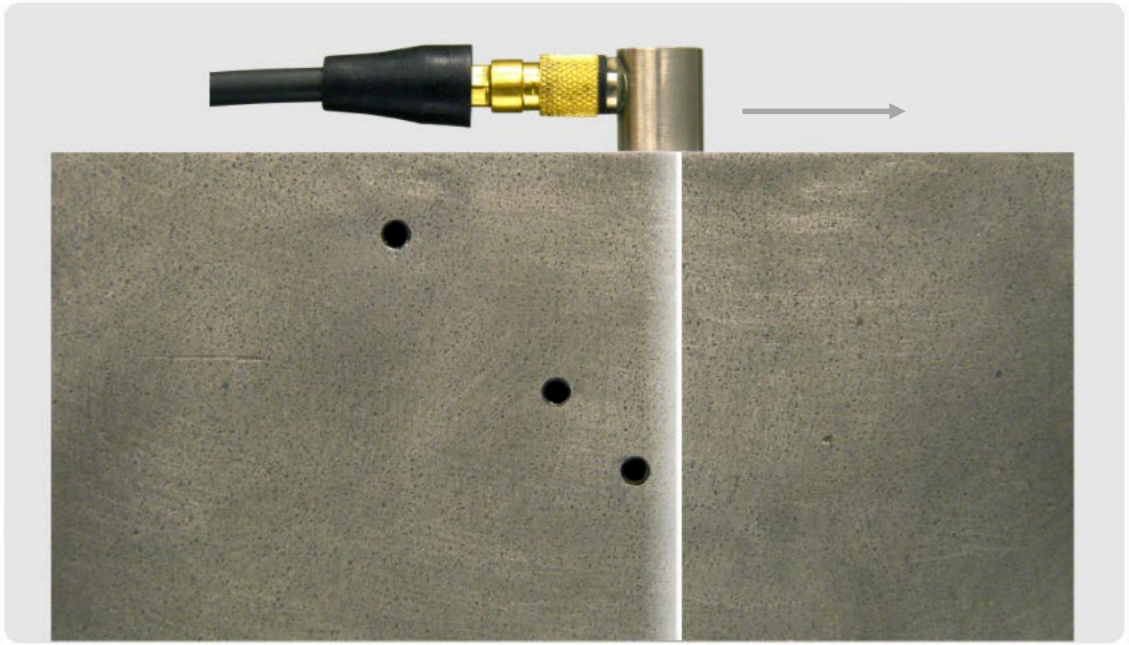
Ultrasound image formation

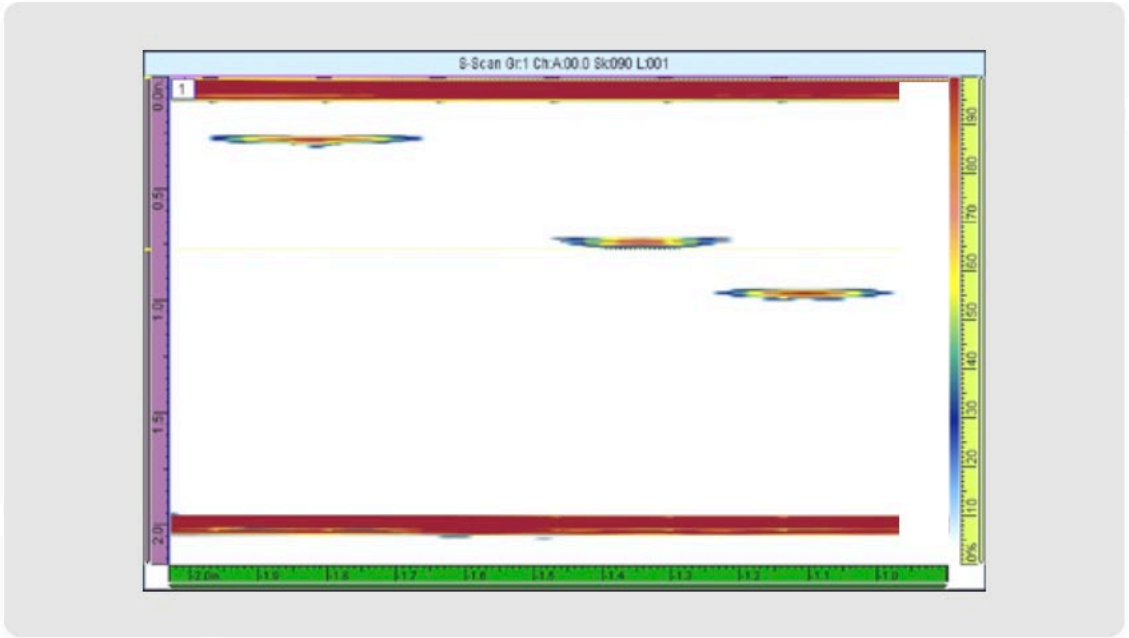



Amplitude
Time (s)

Imaging techniques :

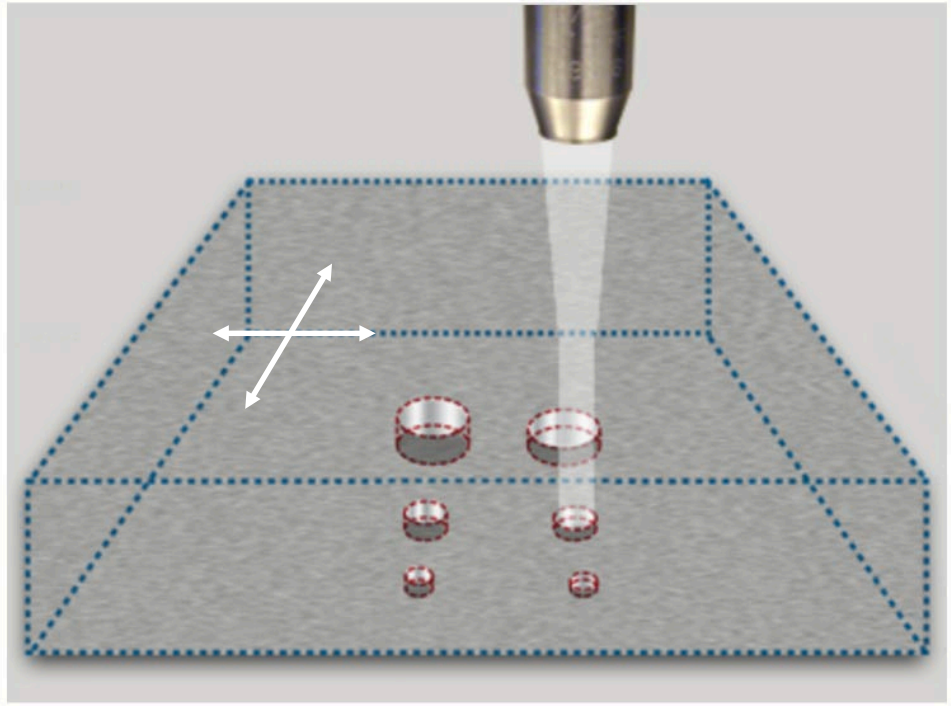
- Bscan

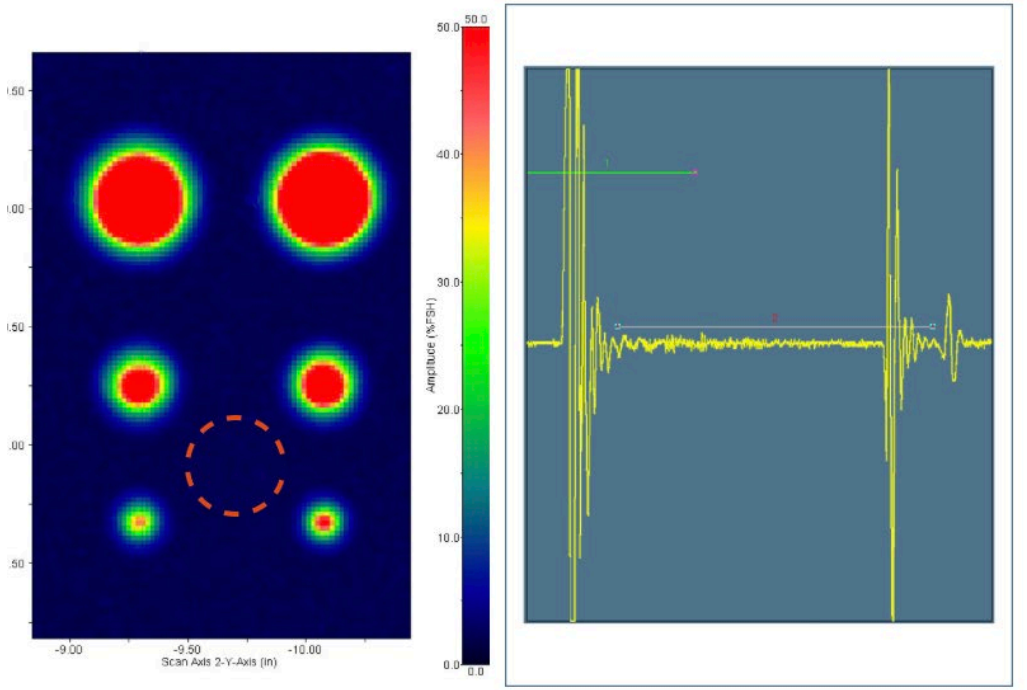




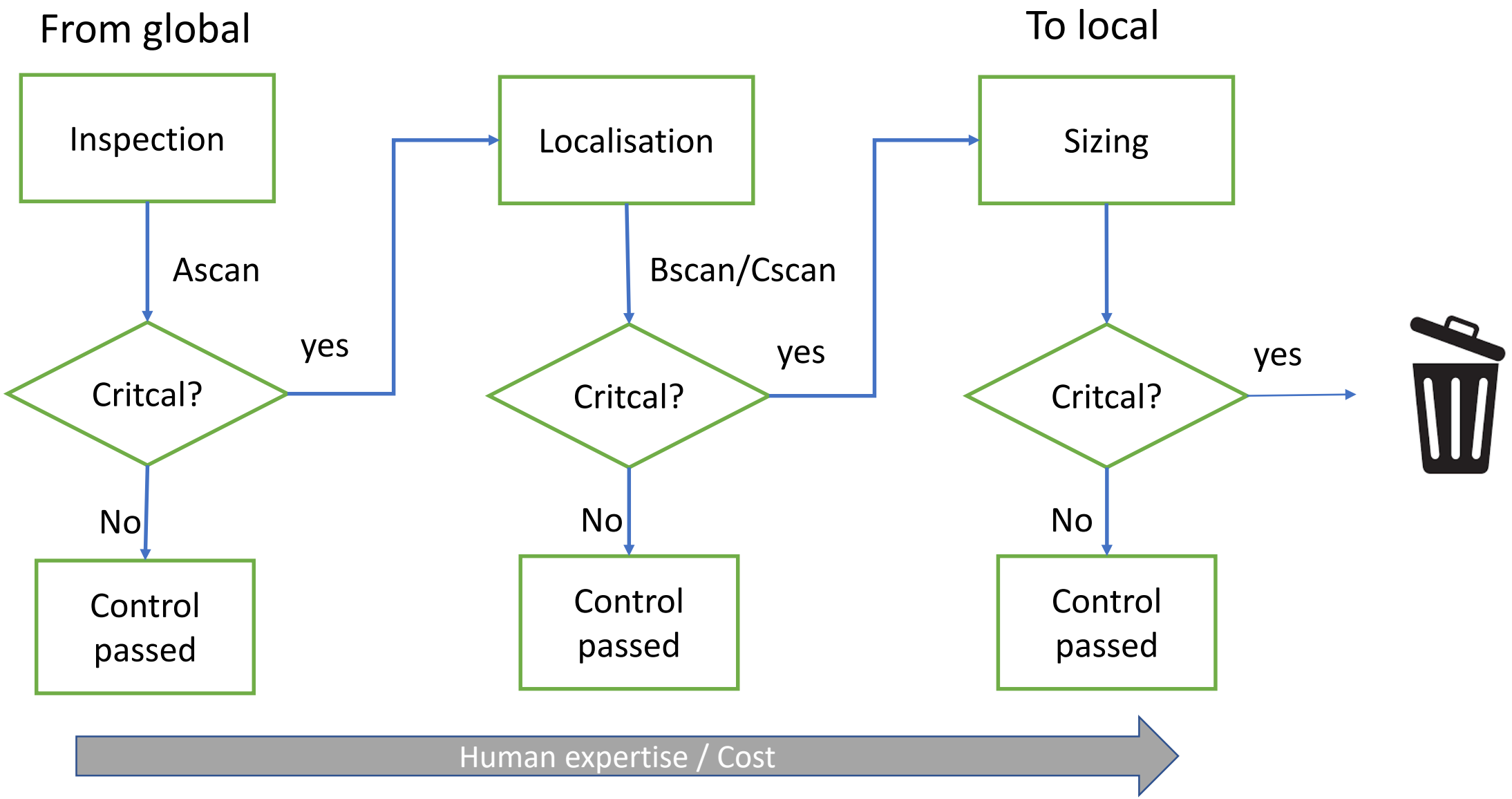
Imaging techniques :

- Cscan conventional
- Cscan Array





NDT strategy



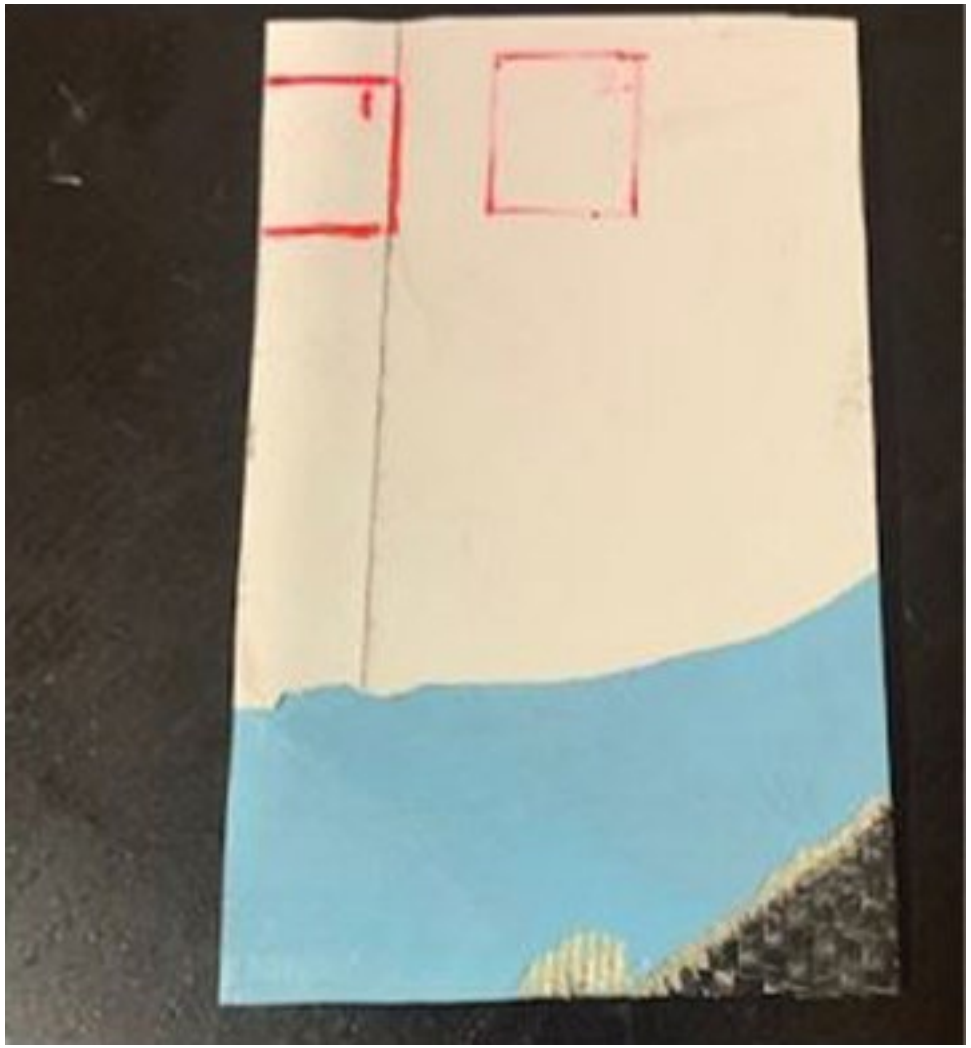
Braze Joint Testing Olympus case study

Good

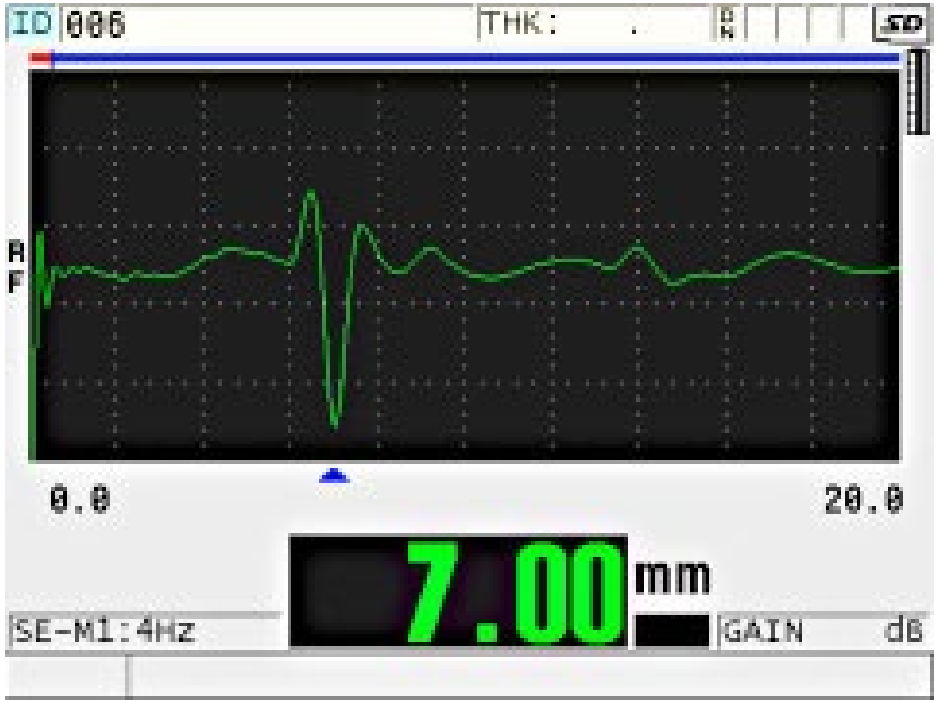
Bad

Measuring Coating Thickness on Composite Aircraft: From Total Thickness to Individual Layers

Case study olympus

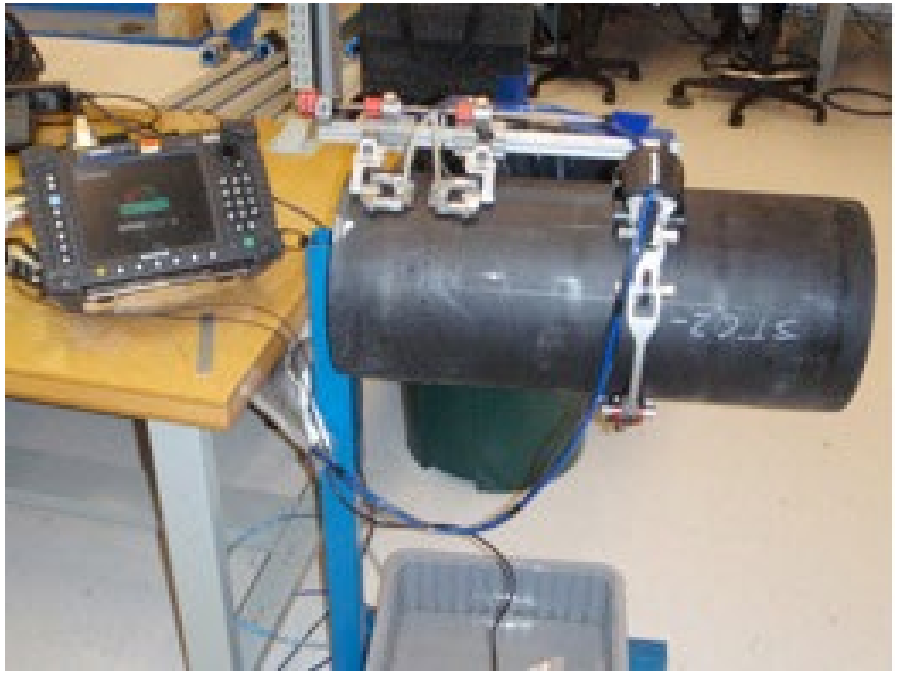


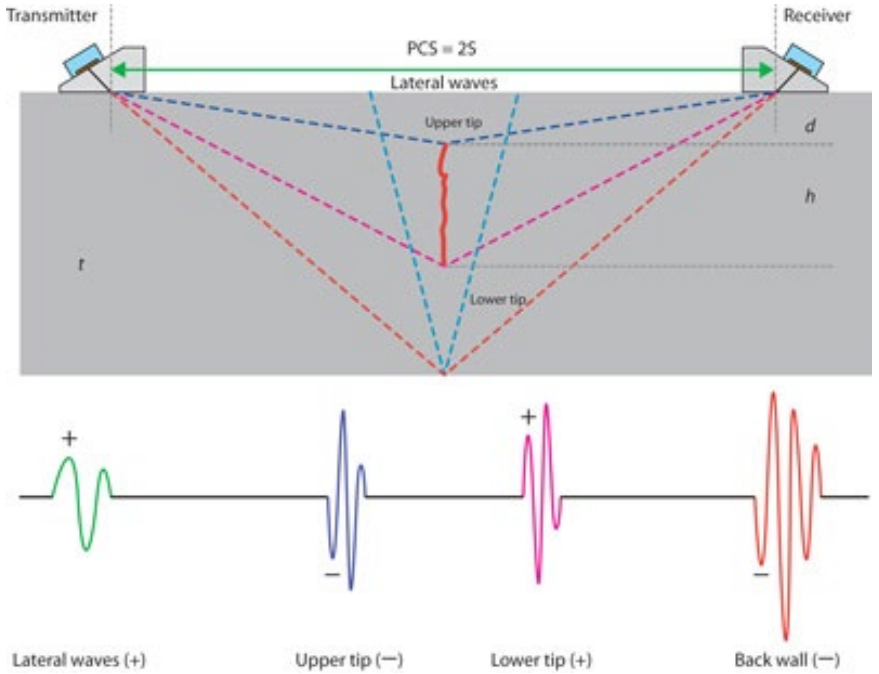
Thickness Testing of Reinforced Rubber Conveyor Belts
Olympus case study



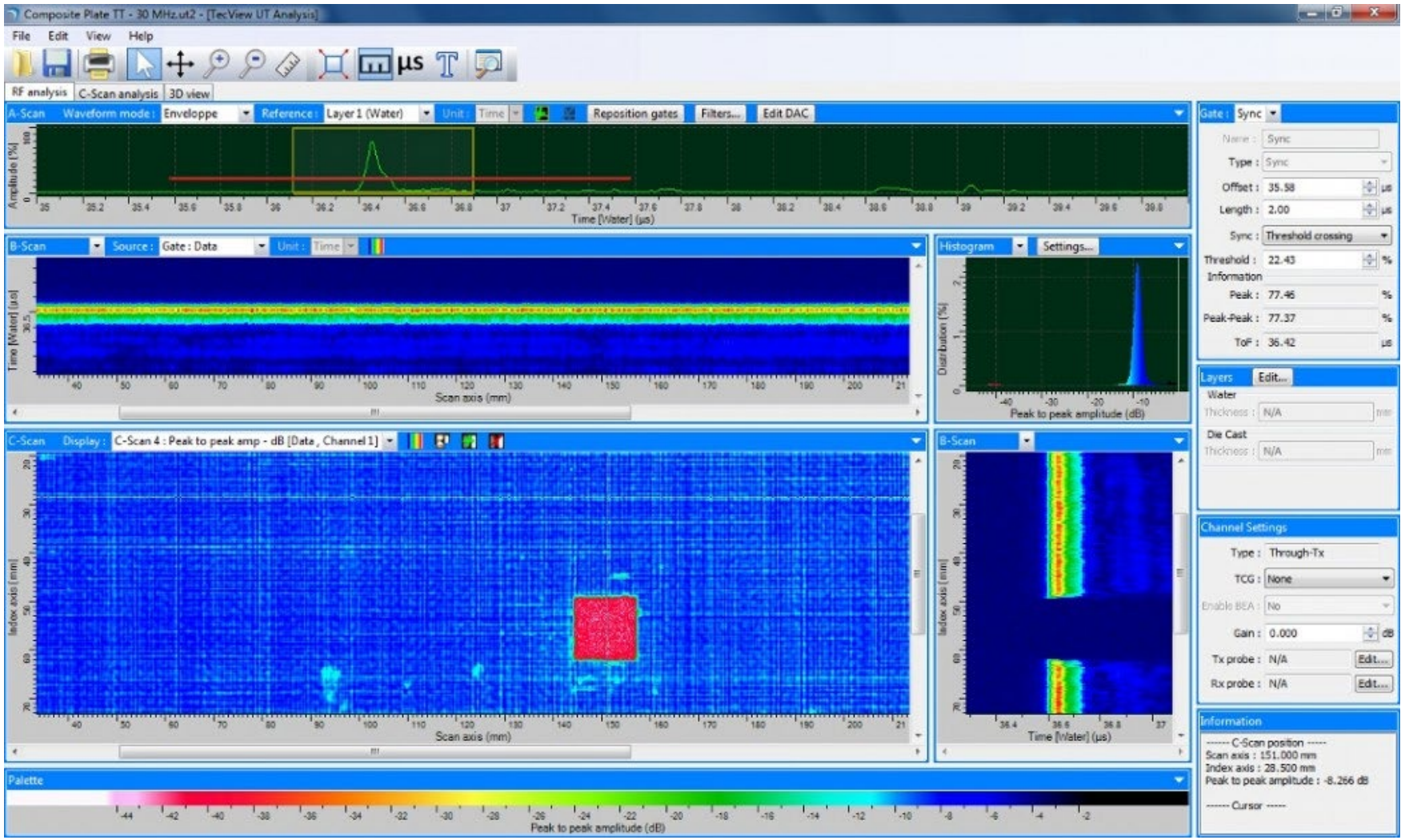
Ultrasonic time-of-flight-diffraction (TOFD) examination of butt-fusion joints of high-density polyethylene (HDPE)

Case study Olympus



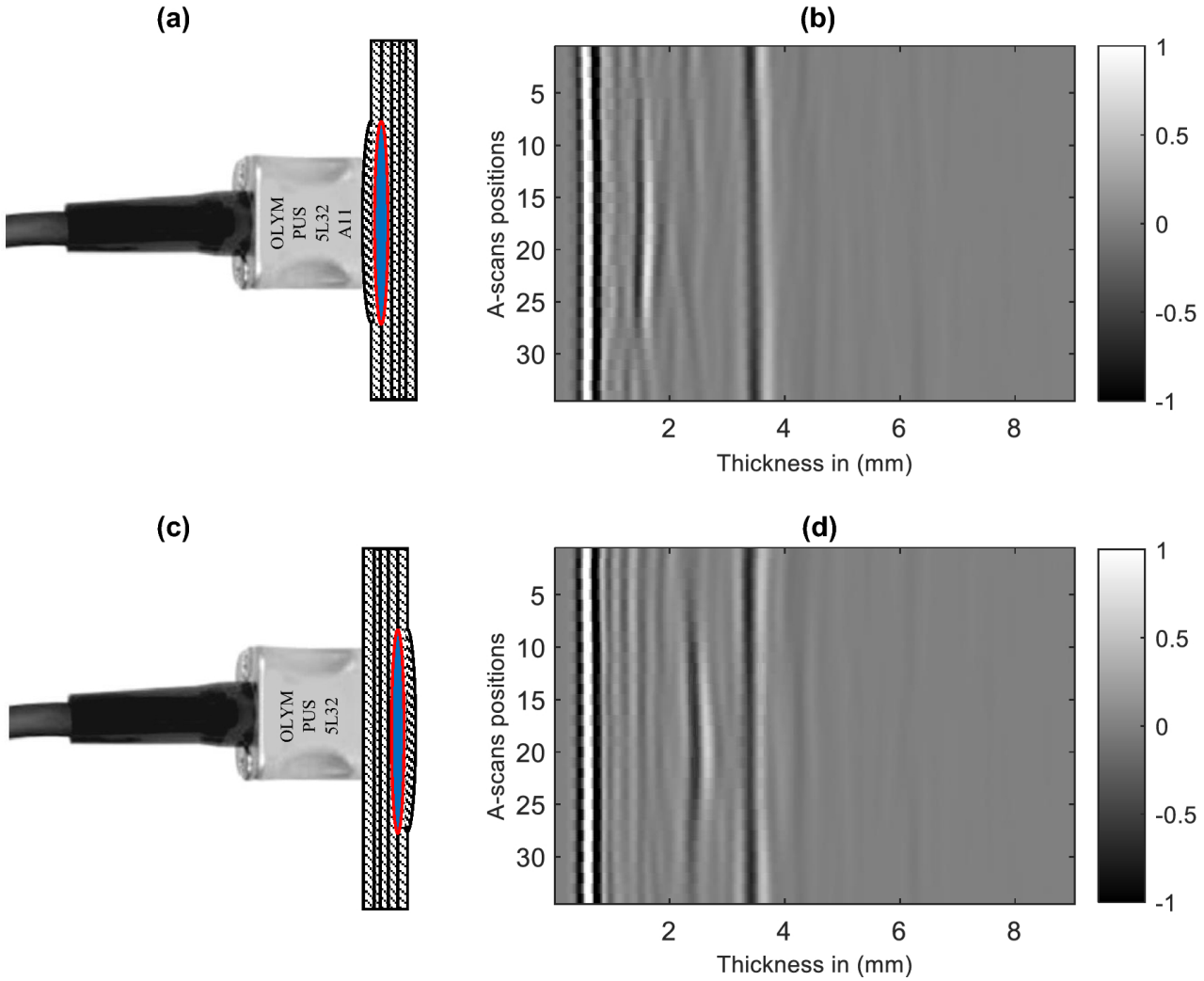


Composite delamination



Tecscan

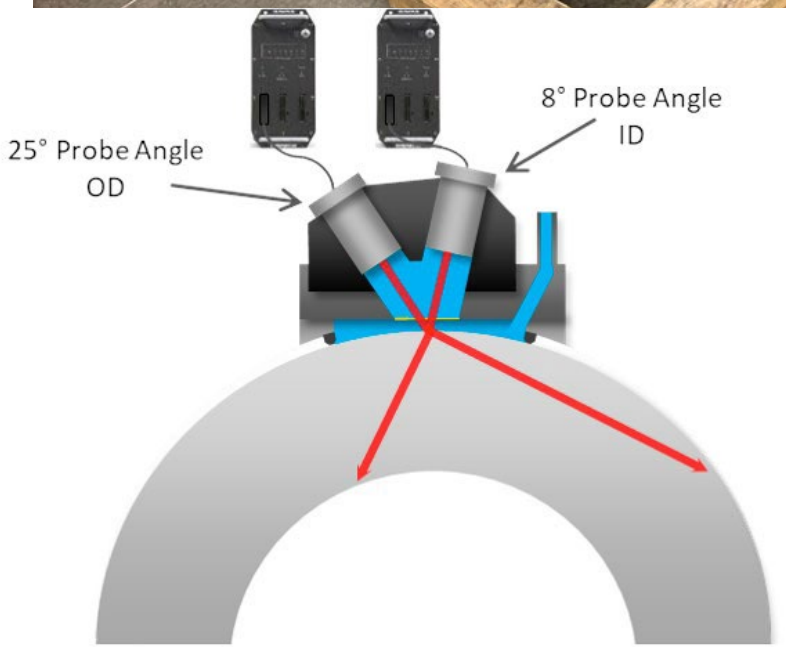
Composite delamination

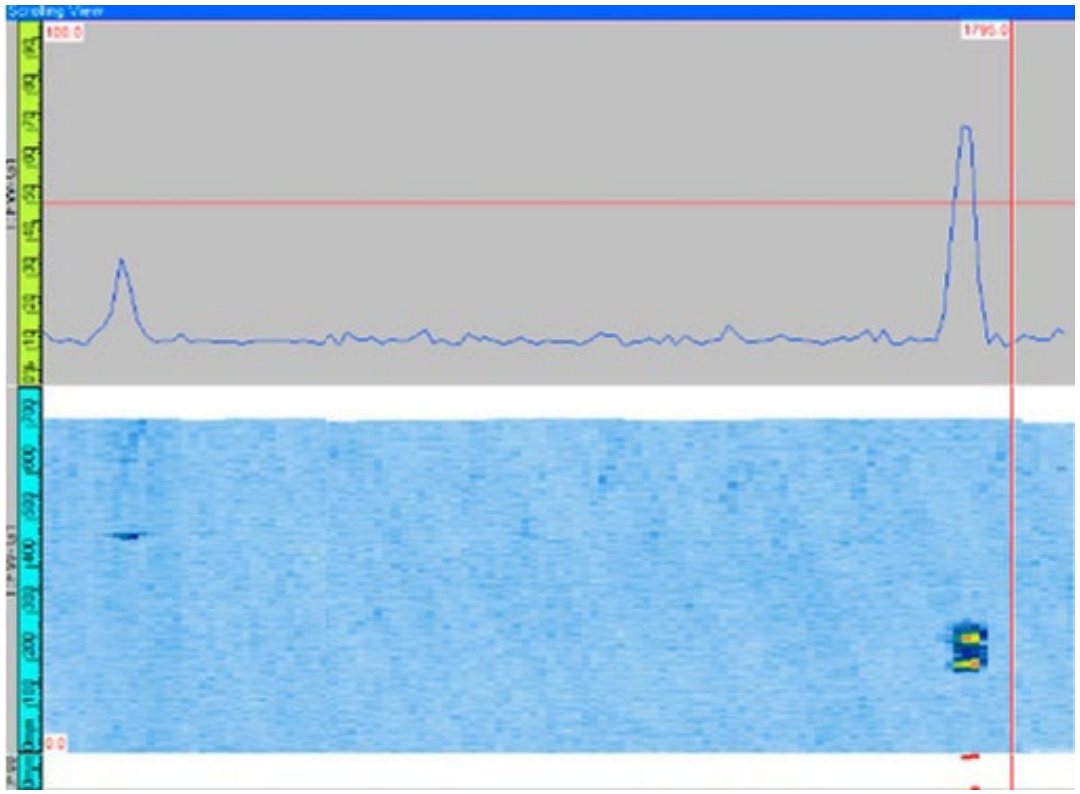


Benyahia, A., et al. *J Nondestruct Eval* **41**, 36 (2022). https://doi.org/10.1007/s10921-022-00868-z

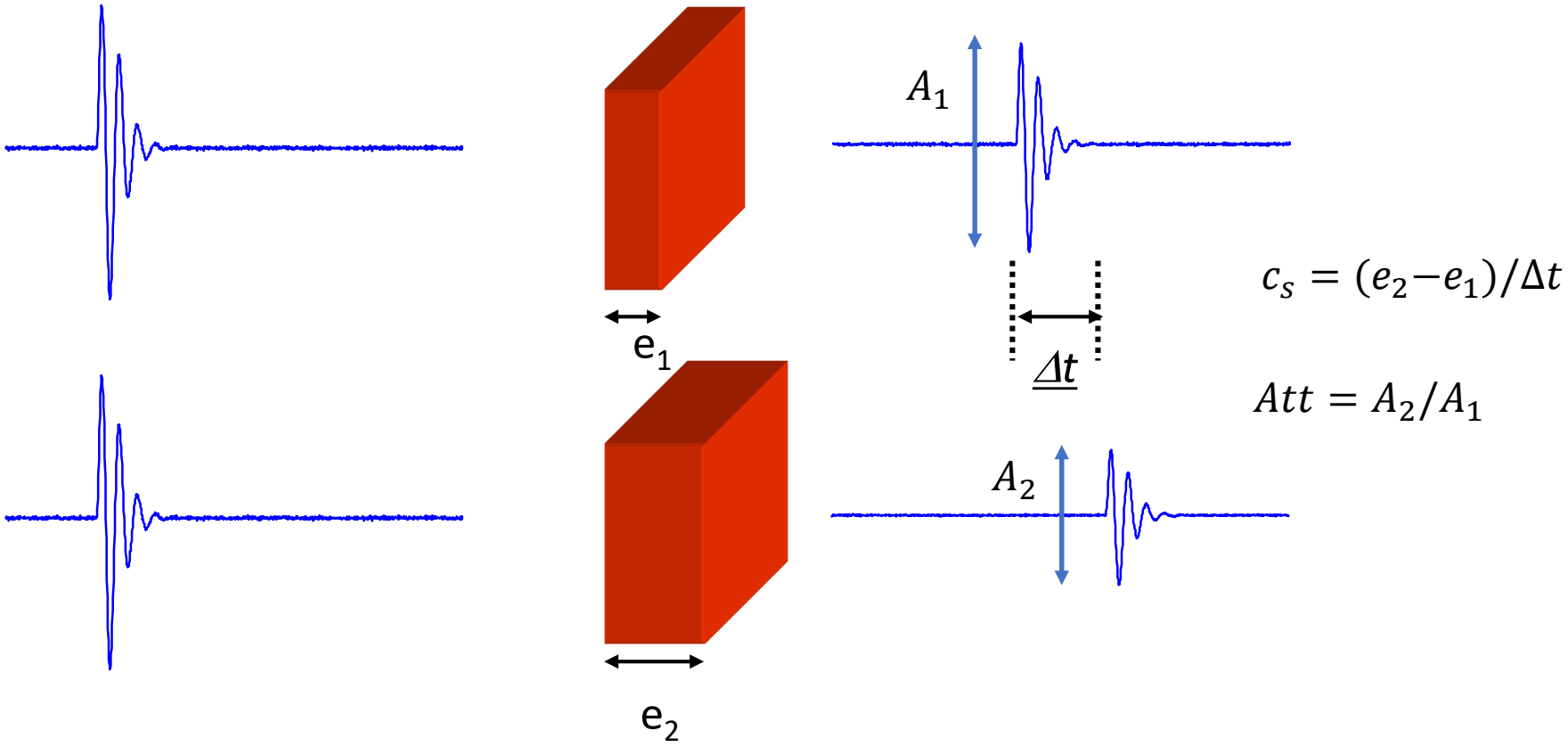
Phased Array to Inspect Pipes with Wall Thickness above 50.8 mm (2 Inches)

Case study Evident





Material characterization/quantitative ultrasound



$$c_s = (e_2 - e_1)/\Delta t$$

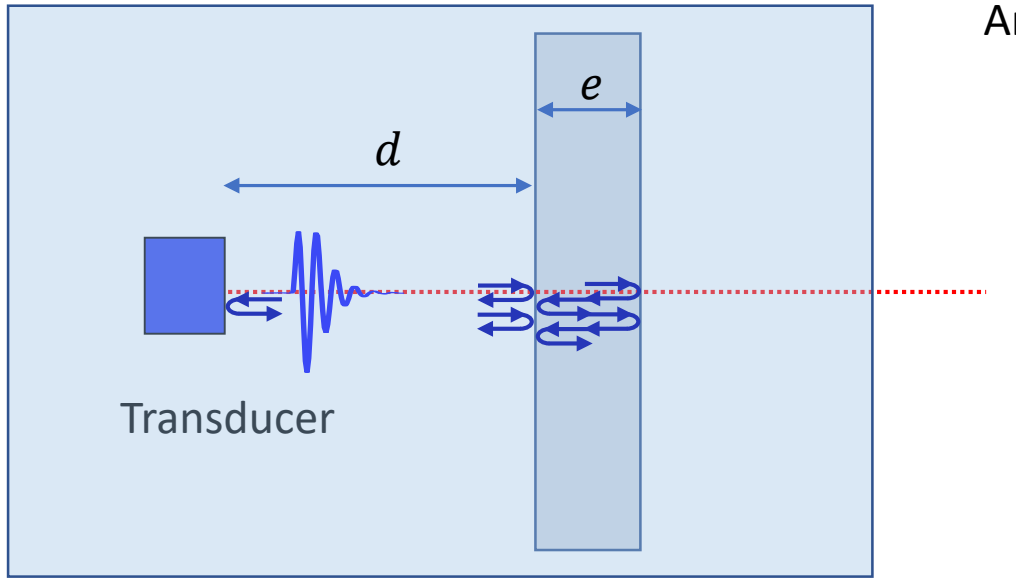
$$Att = A_2/A_1$$

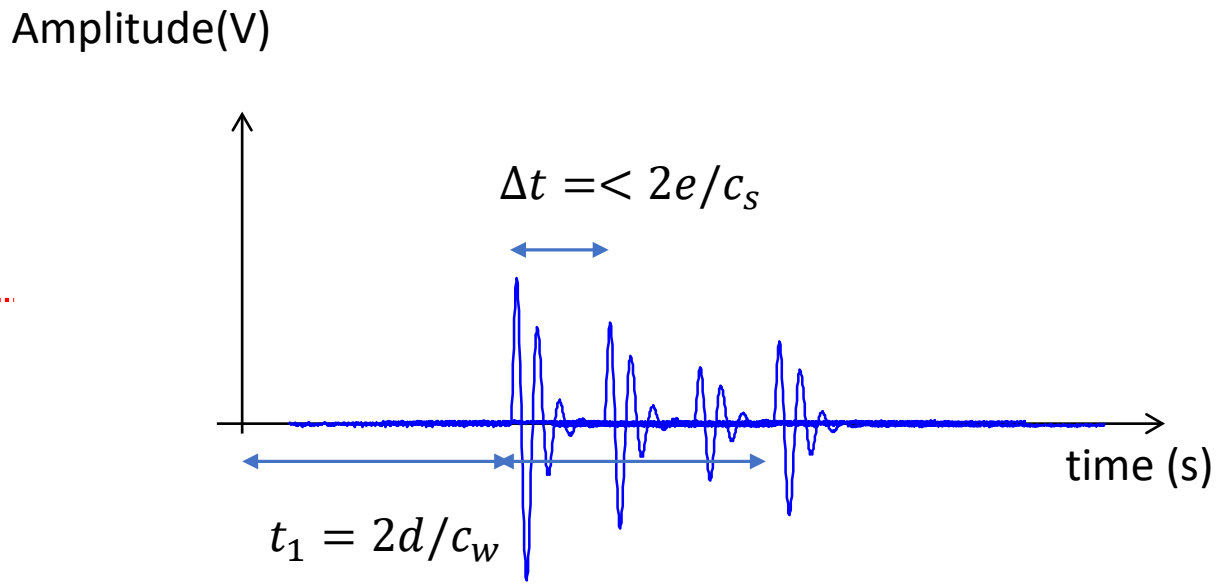
pro : simple
Adapted to solid not liquids

cons : coupling medium, same material with 2 thicknesses

Material characterization/quantitative ultrasound

Reflection techniques

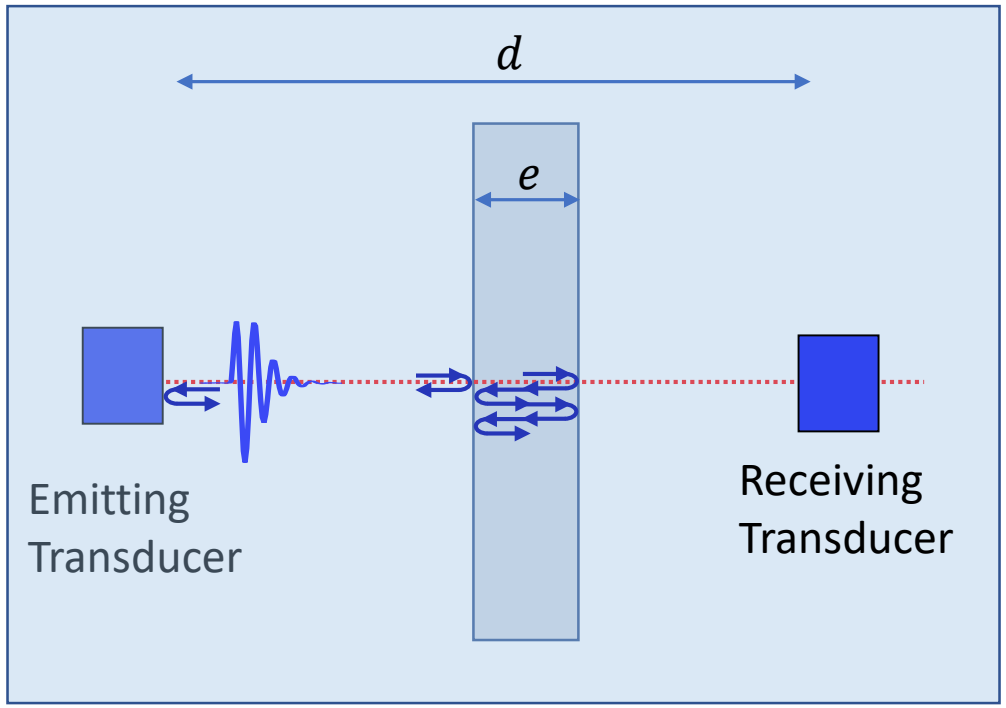




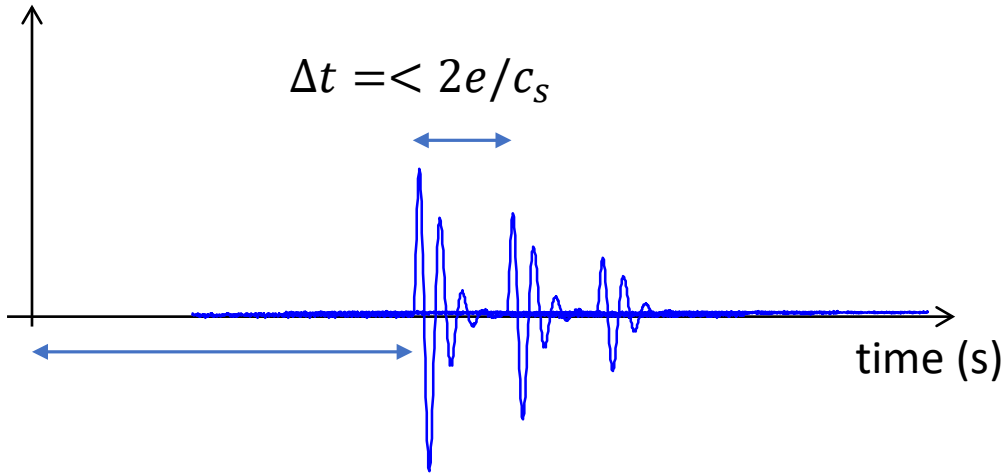
If reflexion/transmission coefficient are known: attenuation measurements are possible

Material characterization/quantitative ultrasound

Transmission technique



Amplitude(V)



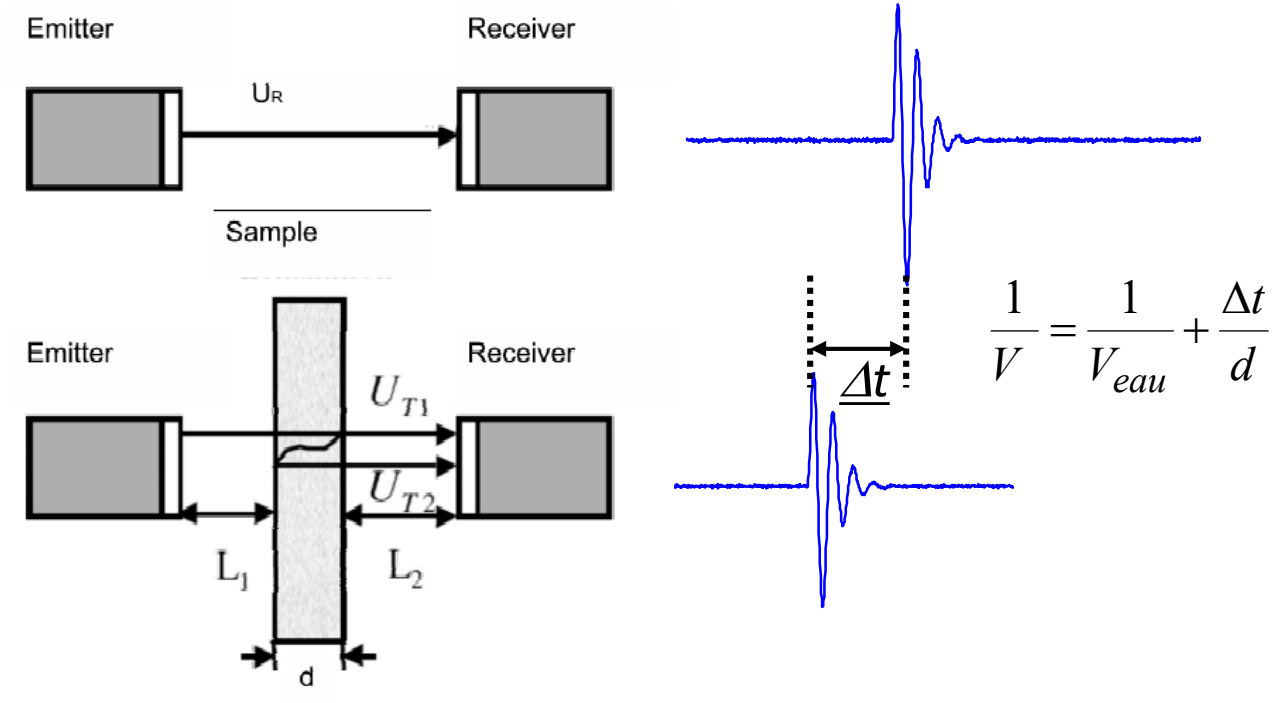
$$t_1 = \frac{d-e}{c_w} + \frac{e}{c_s}$$

If reflexion/transmission coefficient are known: attenuation measurements are possible

Material characterization/quantitative ultrasound

Transmission technique

Référence medium : water



Pro : adapted to liquids and solids
simple

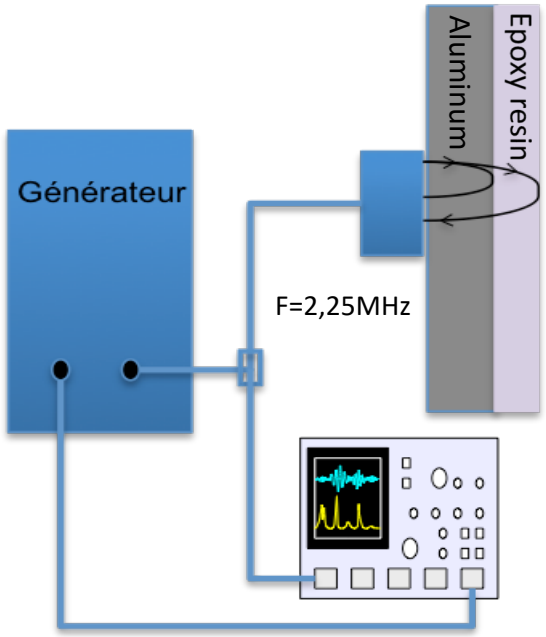
Cons: reference medium is needed

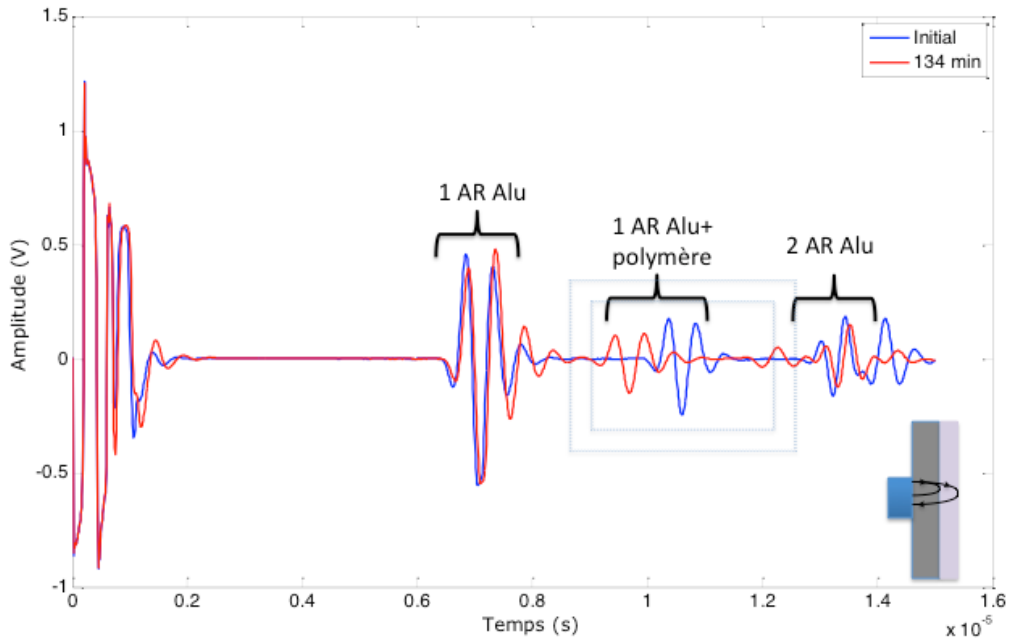
Characterization during the polymerization reaction

Context: Viscosity measurement during a rotomolding process
Materials: thermosetting polymers (epoxy resin, polyurethane)

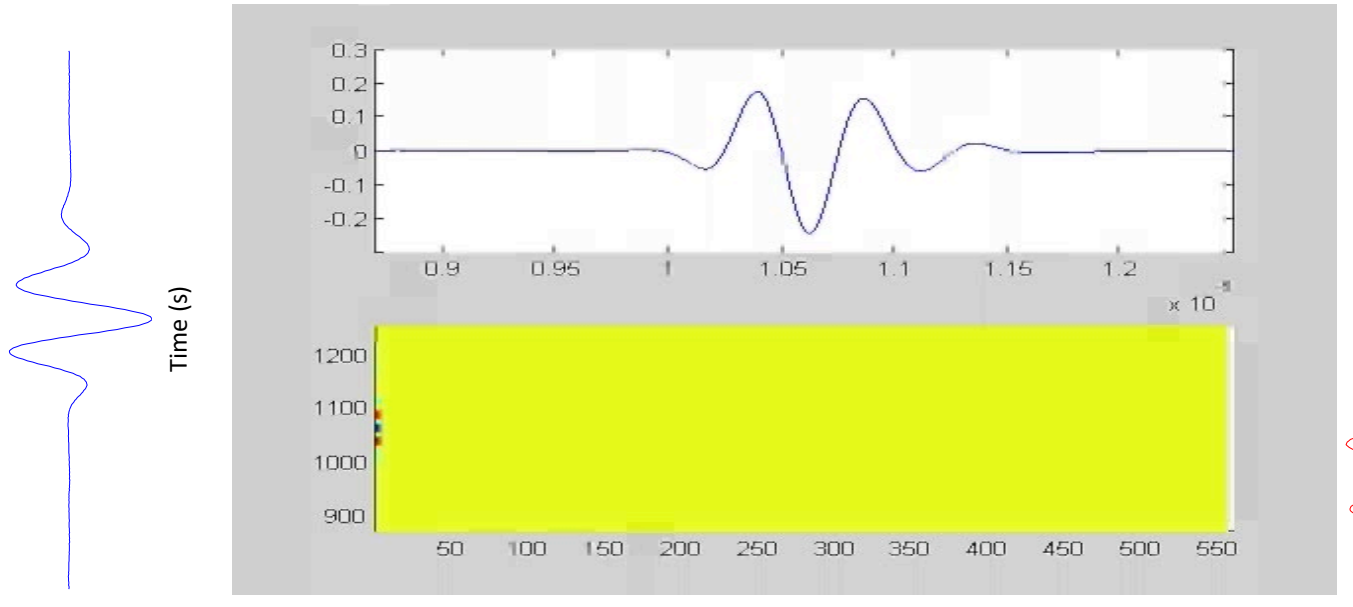
Material properties evolution, local thickness variation

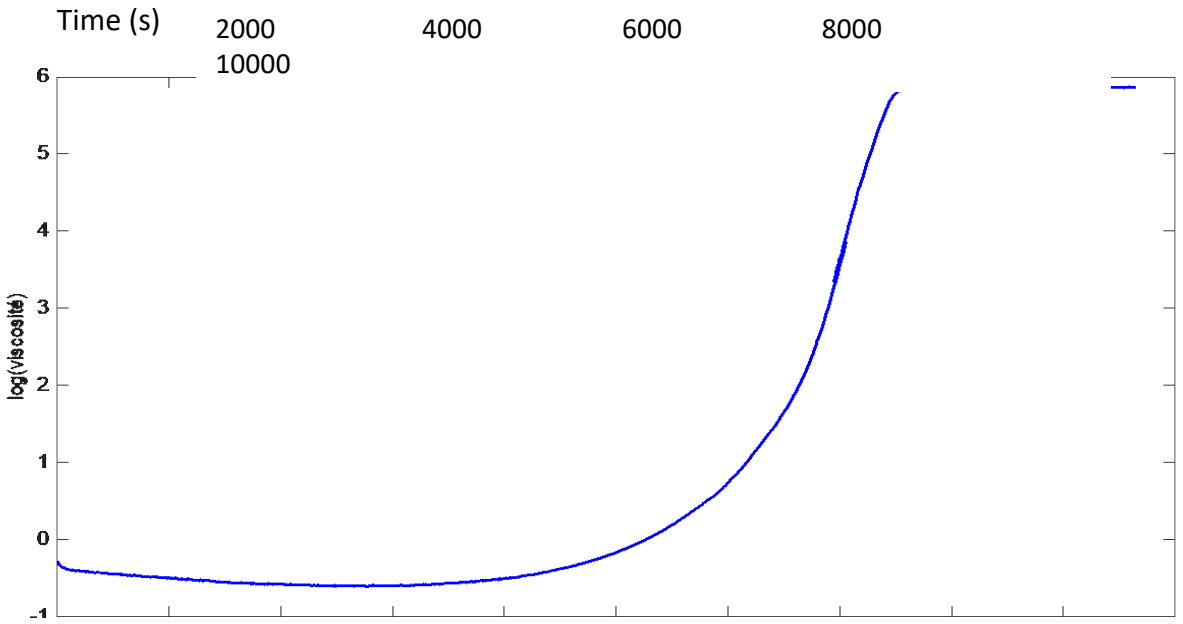
→ Implementation of the ultrasonic technique on a plane mold





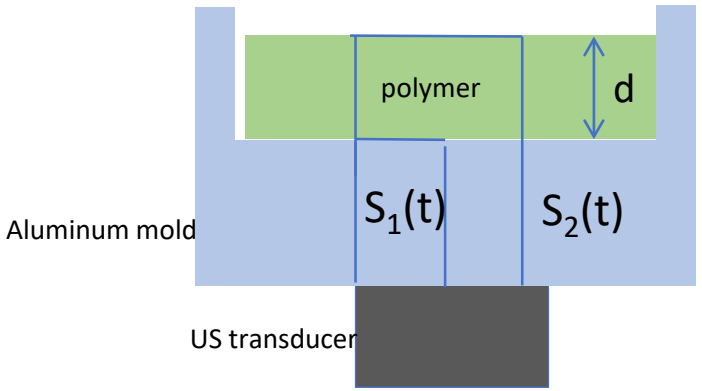
Characterization during the polymerization reaction





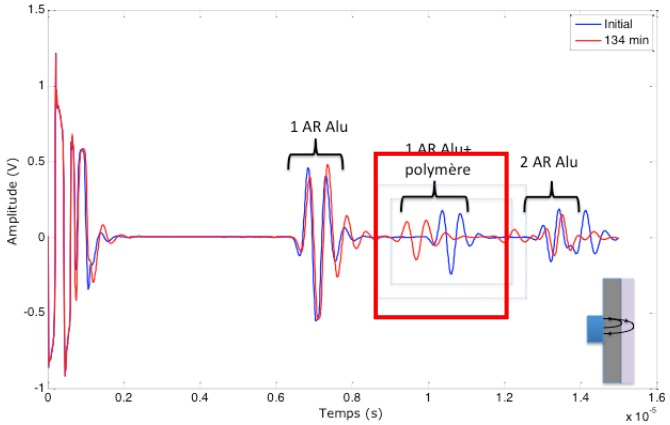
Characterization during the polymerization reaction

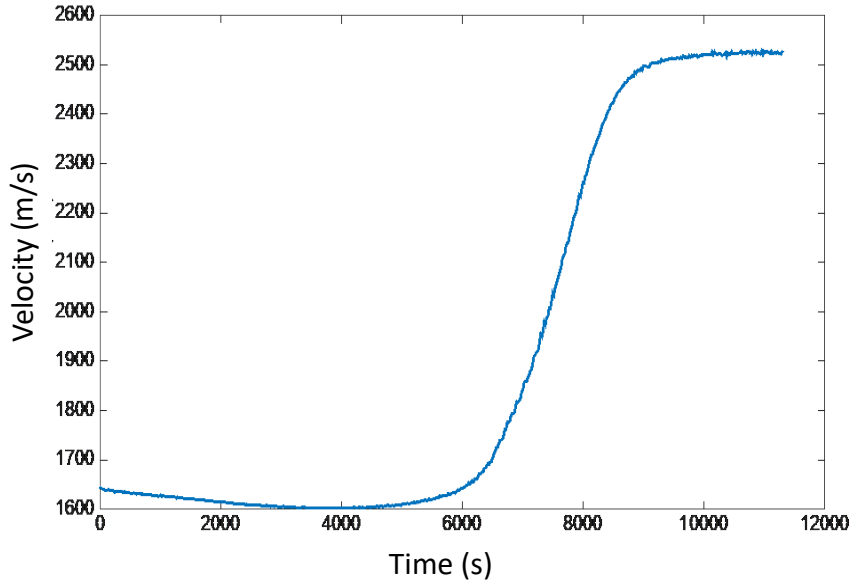
Polymer thickness: d= 2.9 mm
Ultrasonic velocity deduced from time of flight measurements
Attenuation determination based on two reflection signals measurement

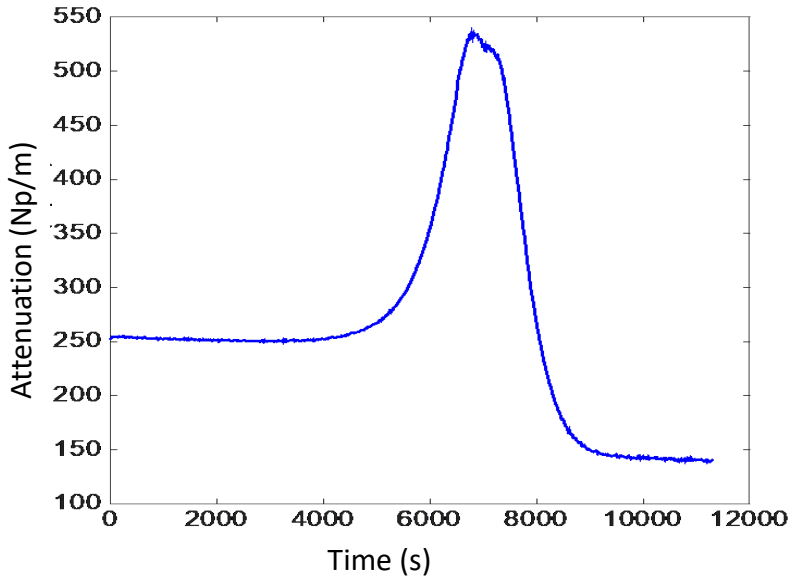


$$v_{poly} = \frac{2d}{S_2(t) - S_1(t)}$$

$$\alpha_{poly} = \frac{1}{d} \ln\left(\frac{R.S_2}{T^2 S_1}\right)$$







Conclusion

- NDT is essential to maintaining the safety and security of numerous systems
  - That concerns Industry, Power plants, automotive and aeronautics…
  - Among the different techniques, ultrasounds occupy a prior place as non-invasive, non-ionizing, low-cost

- Transducers have to fit various shapes according to the numerous geometries.
  - Transducer selection is very wide: contact, immersion or air coupling transducer single element or arrays
  - In addition, considerations of the wave characteristics, the frequency used, and the bandwidth have to be considered

- Very often signals or images are complex and need to be analyzed by experts.
  - These experts are certified by independent structures which make the analysis reliable. However, operator dependence exists. In several cases, control can reach 1/3 of the equipment.

- In terms of techniques 2D and 3D images are very promising, as well as quantitative ultrasounds

- IA as a support to operators is also rising an encountered a growing interest: aid to the diagnosis

Thank You !