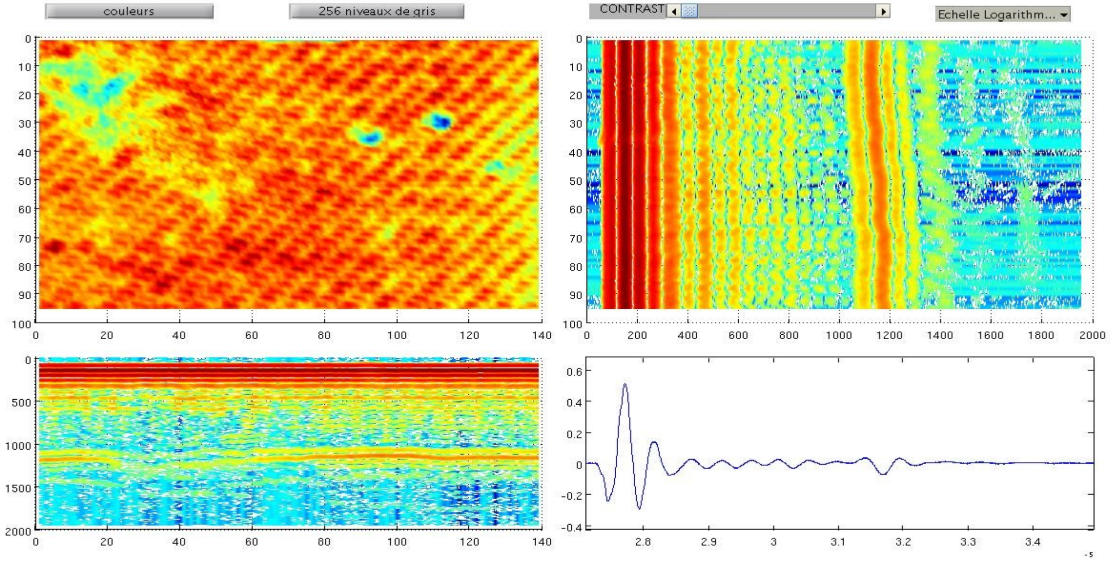
Non-Destructive Testing
Ultrasonic Testing



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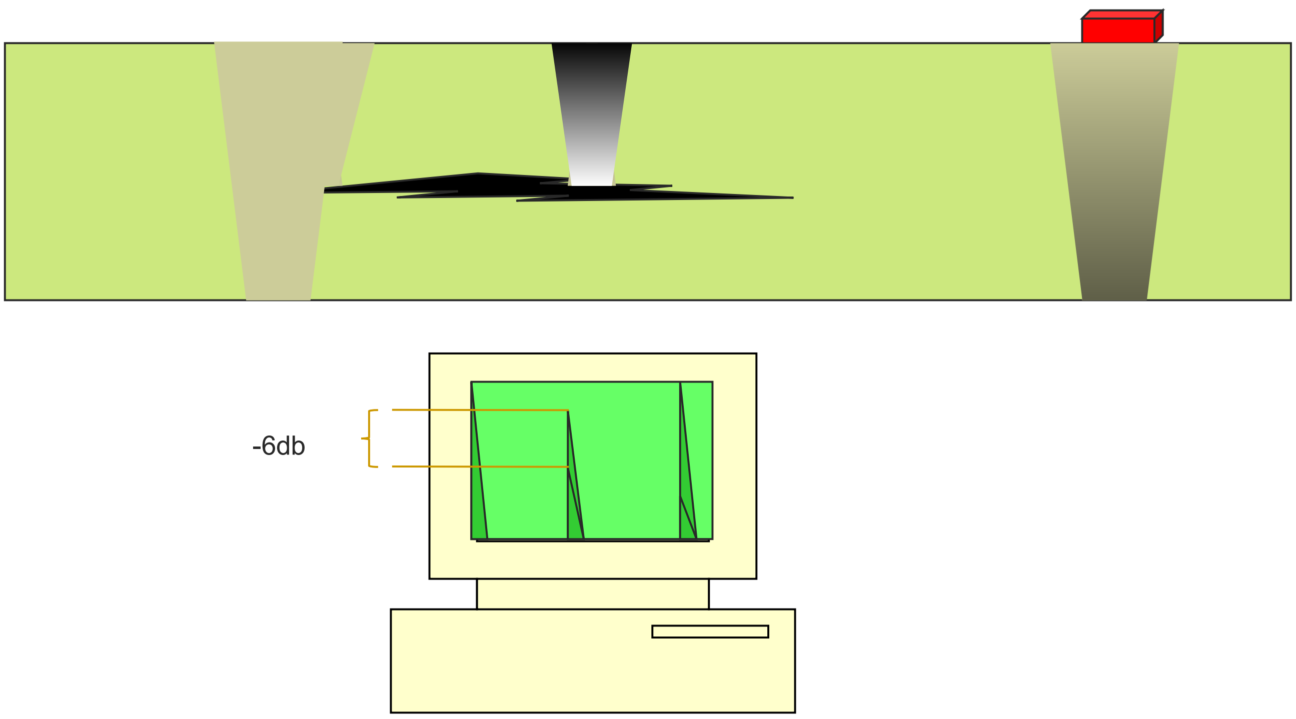
Flaws sizing methods

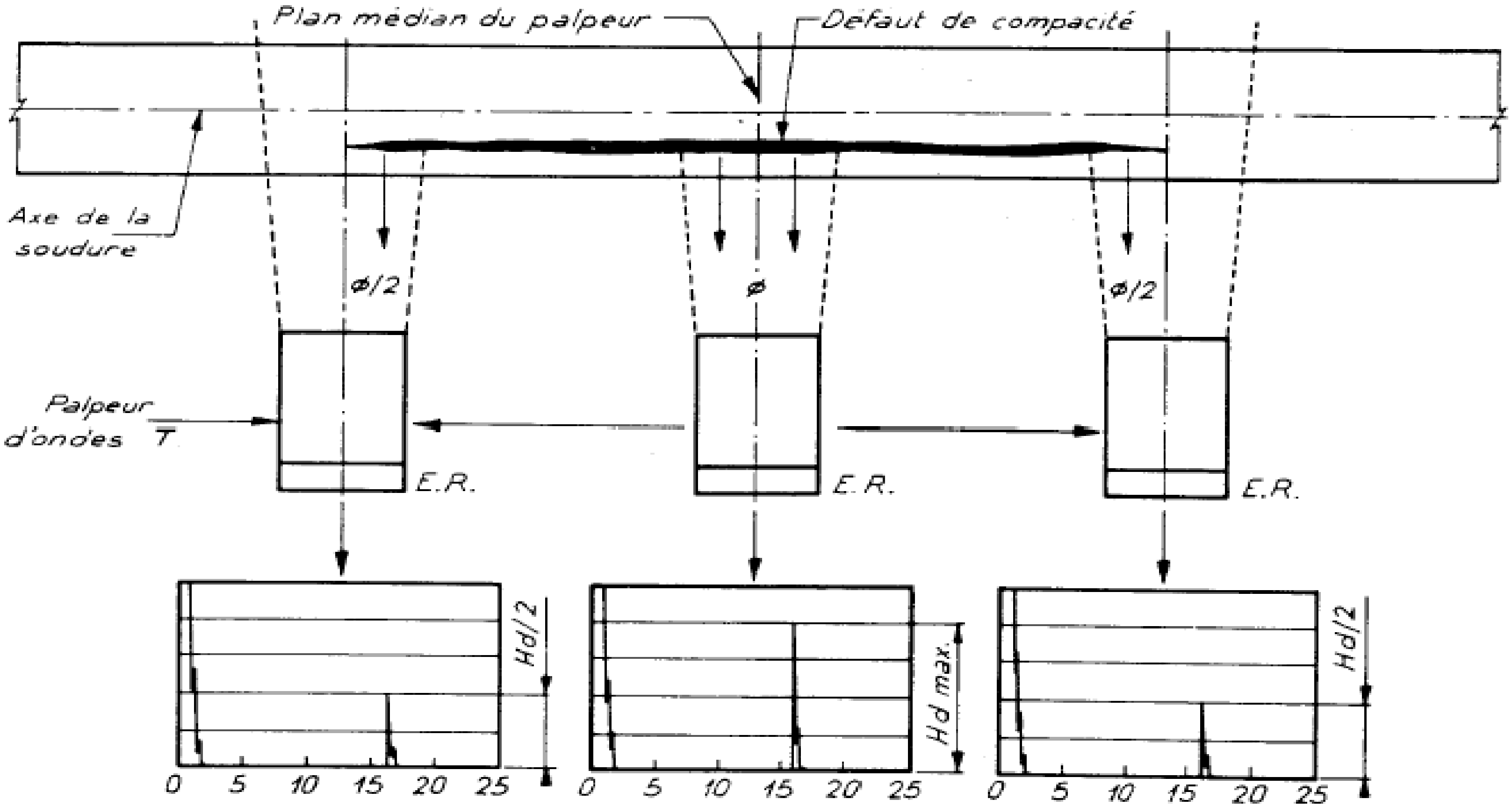
- 6dB drop method
- Distance Amplitude Correction (DAC)
- Distance Gain Size method (DGS (en) or AVG (german)).

Implementation of the 6dB drop method

- The transducers is moved in front of the test specimen and the A-scans are observed. When a flaw is detected, we seek for the center of the flaw. If the defect is wider than the beam the backwall echo disappears and the amplitude of the echo is calibrated to 80% of the screen.
- Then the edges are found when the defect echo amplitude is divided by 2 (-6dB).



Méthodes d'estimations de la taille des défauts Méthode à -6dB



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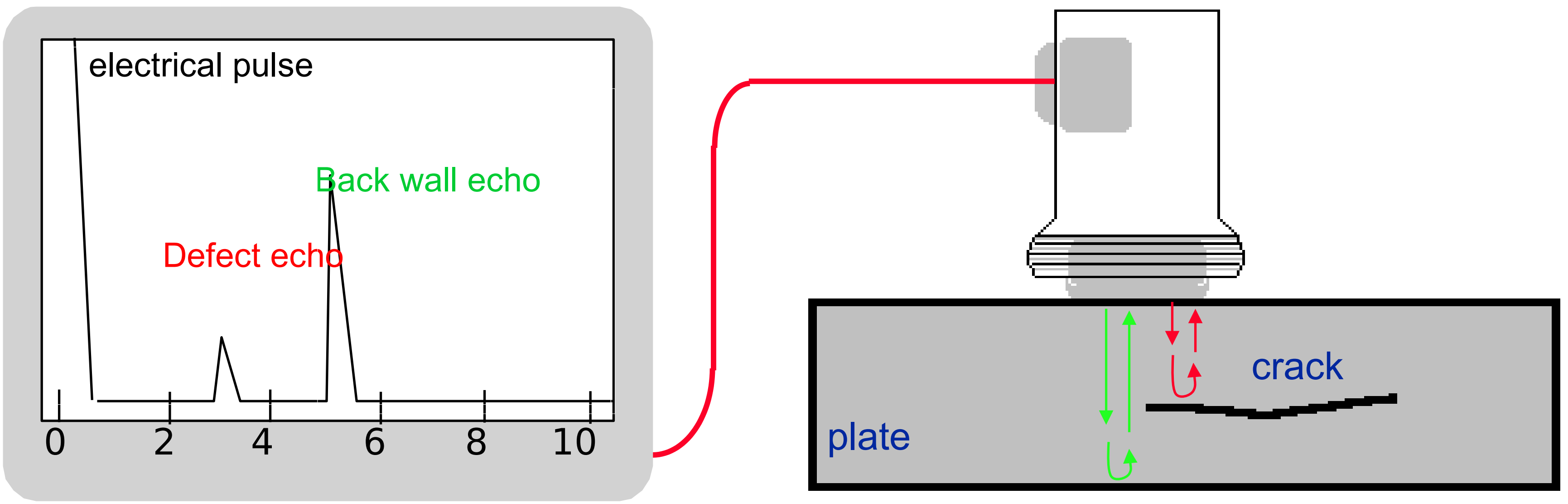
Implementation of the 6dB drop method

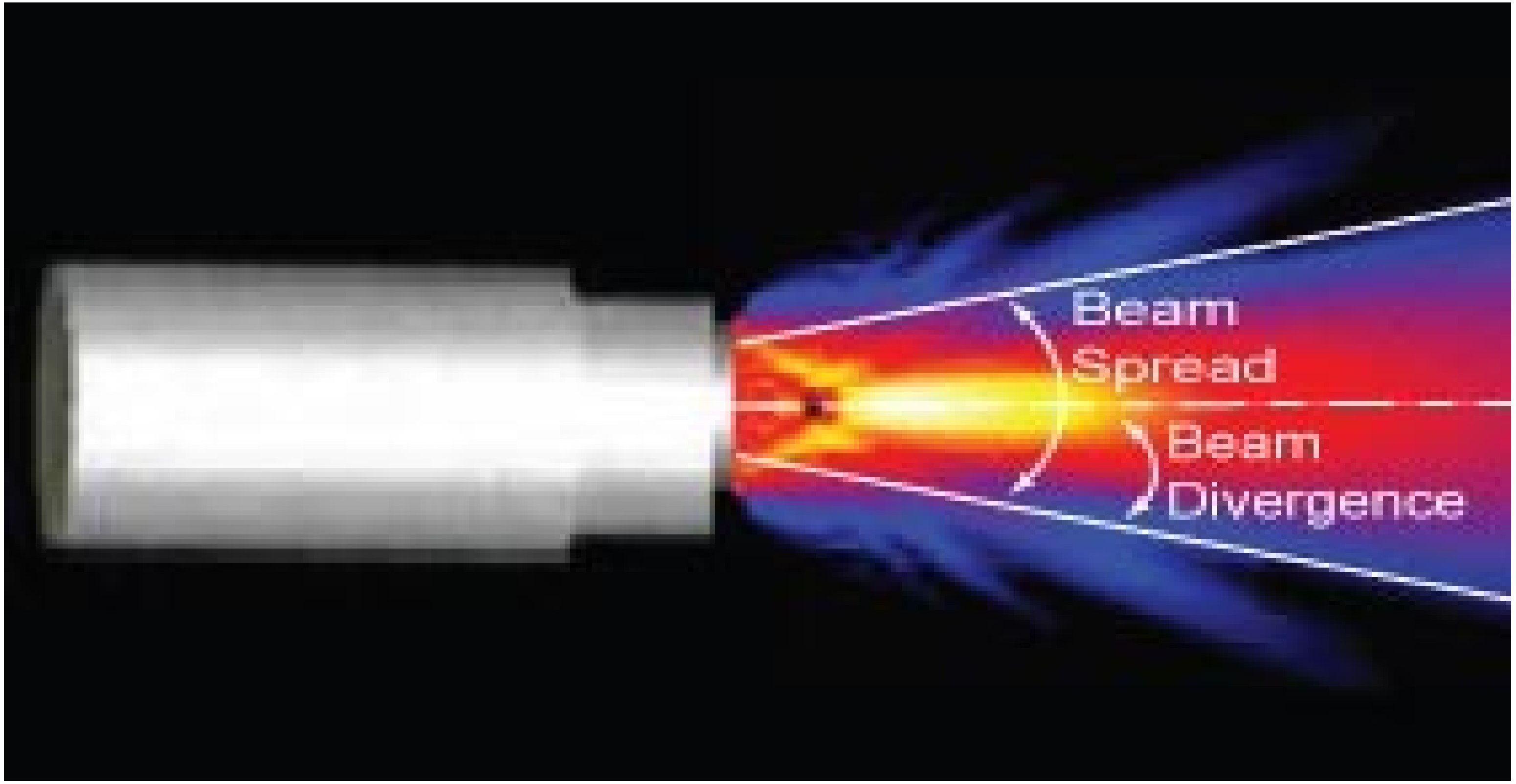
- In practice, we can use a compensation method, by adding 6 dB to the gain and the find the positions for again DE at 80% of the screen)
- This method can be performed in an automated way. C-Scan images + contour detection at -6dB or by steps of -6dB (-6dB, -12dB, -20db etc...) according to the used standards.



Oscilloscope, or UT device

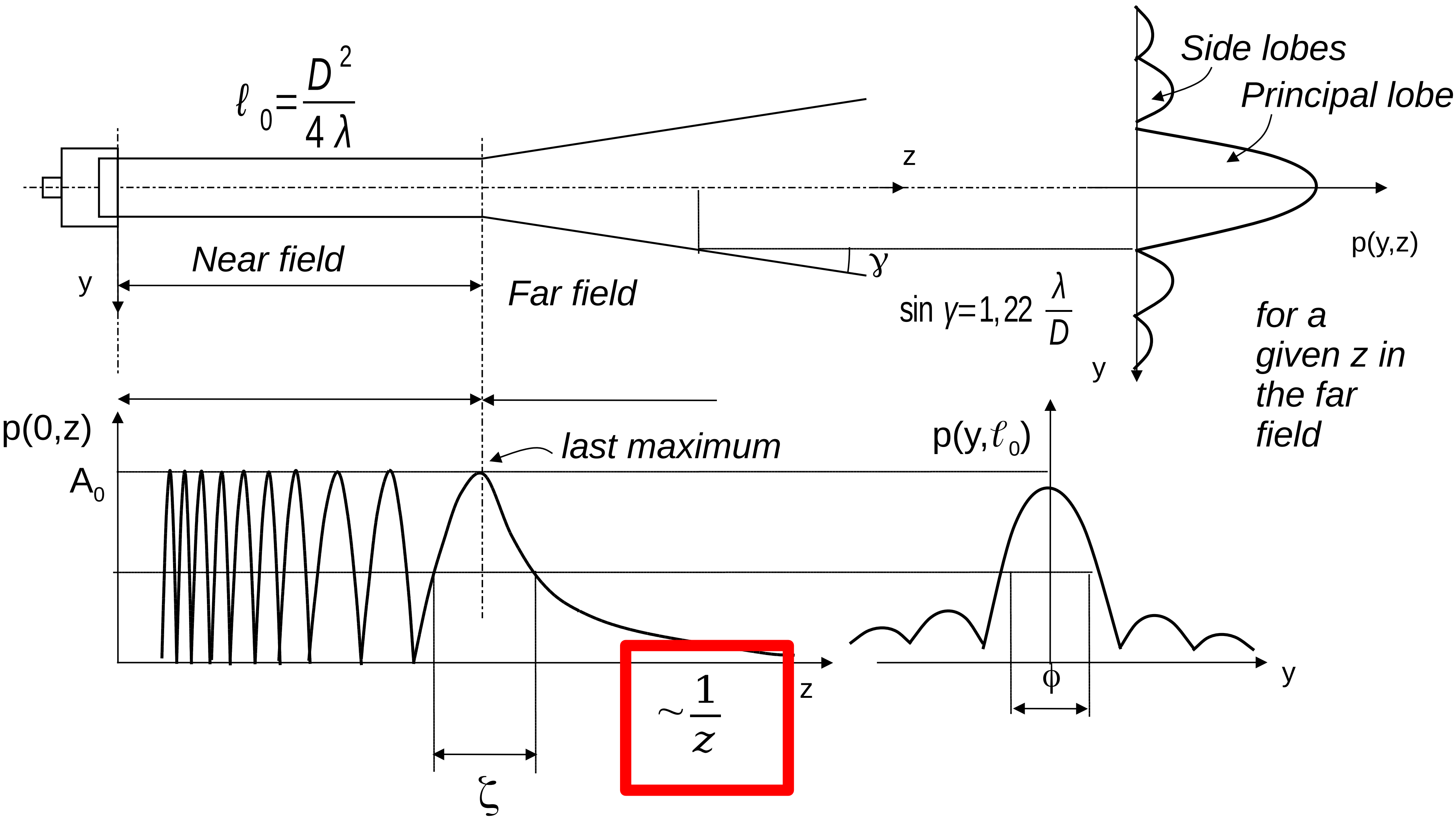
TWI - animation

How to account for actual beam structure ?



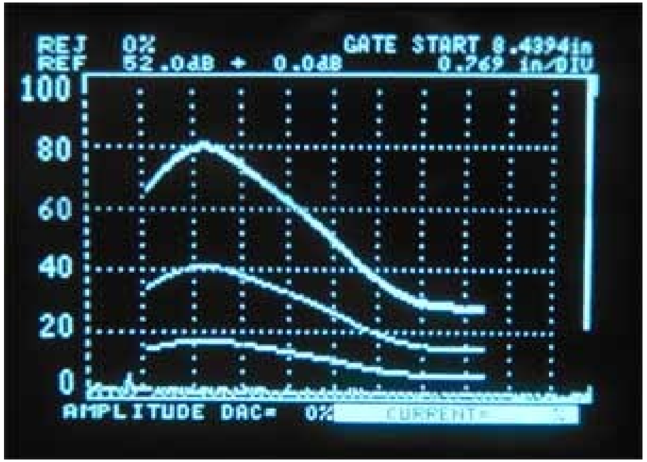
ndt-ed.org

Properties of the beams (from diffraction theory)

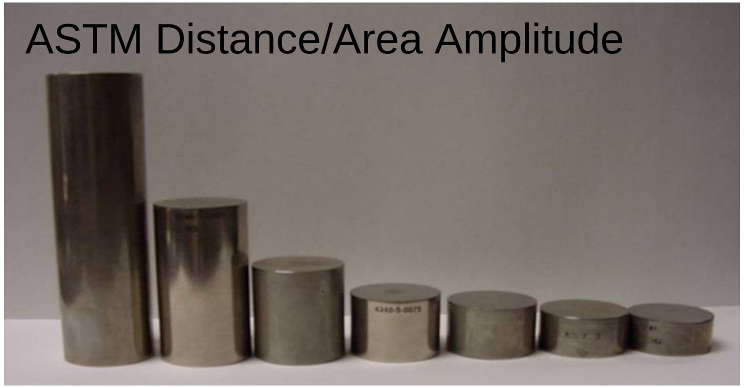


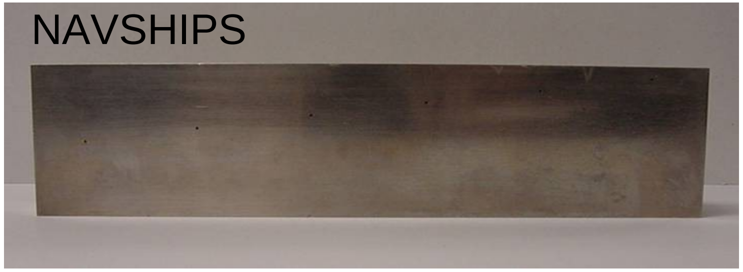
DAC Method (Distance Amplitude Compenation)

- **Very empirical approach**
- **Takes into account the actual shape and characteristics of the beam :**
  Beam illustration
- **Utilize standard flat bottom holes or side drilled holes to establish known reflector size with changes in sound path from the entry surface**
- **Plots several DAC curves A = f(d) with the hole diameter as a parameter**
- **When a flaw is detected at a given depth its amplitude is compared to the DAC curves defined previously**
- **Can be used in angle beam inspection.**

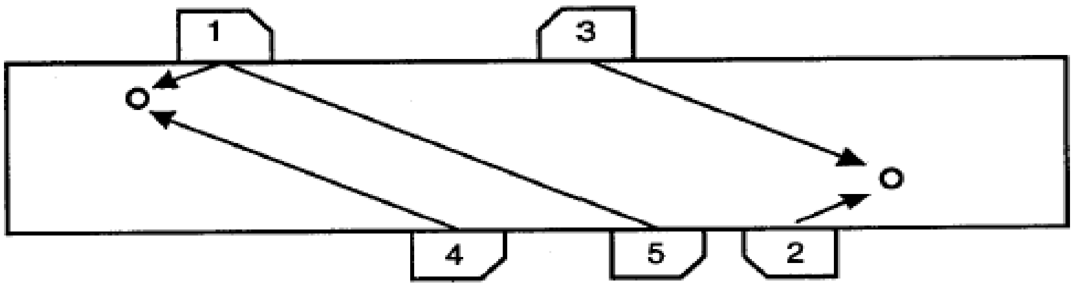


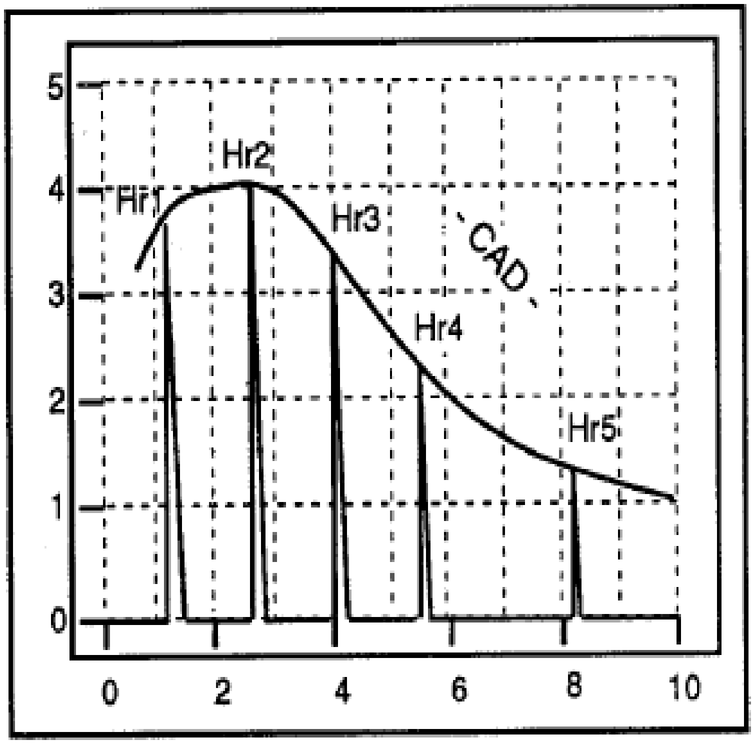
see applet

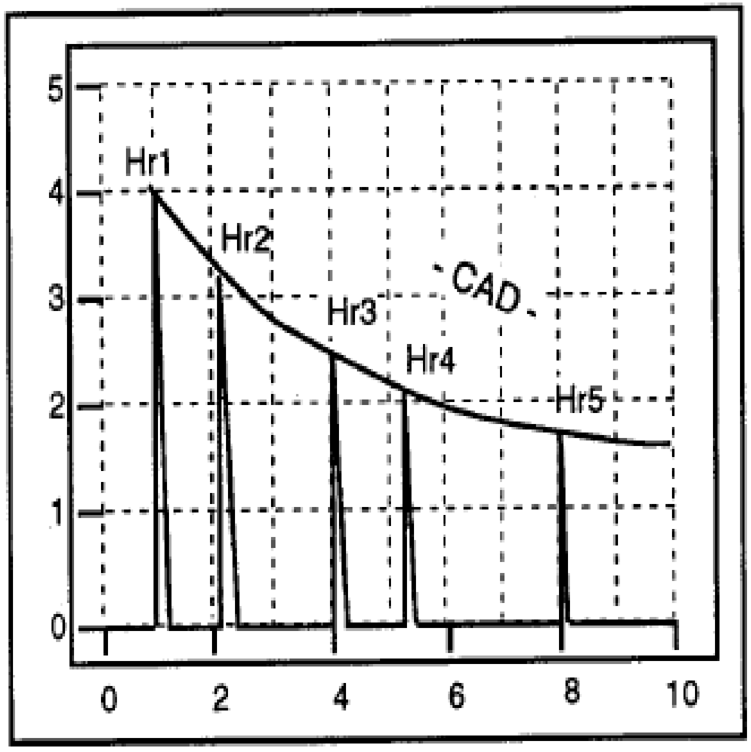

ASTM Distance/Area Amplitude


NAVSHIPS

Example of a DAC acquisition

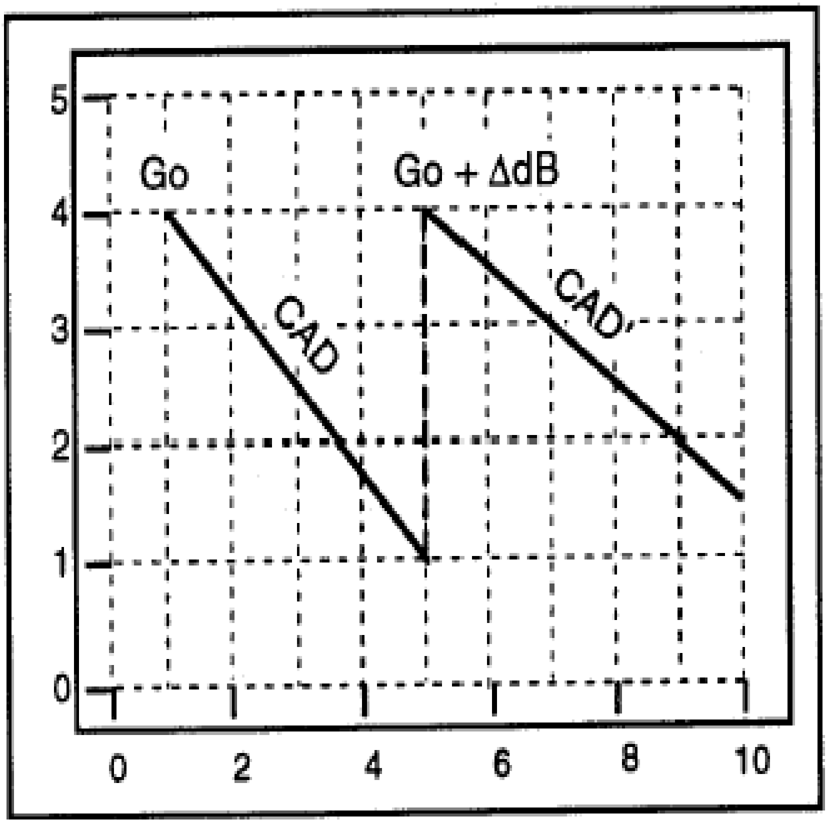




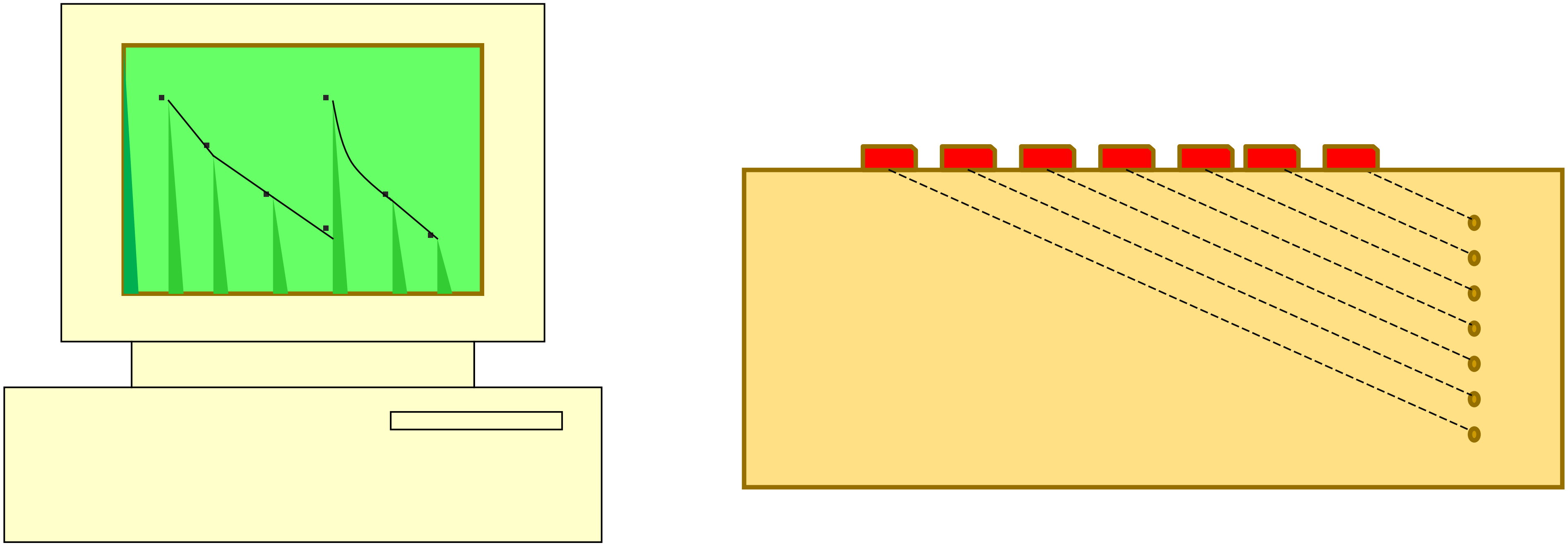


DAC Method

- It is recommended to keep the DAC between 20% and 80% of the screen
- For long distances the curve can be divided in two parts.
- Increase of the gain by Δ dB, in the second part (to reach 80% again)



Example of a DAC acquisition



DGS Curves description

- **Calculation of the field radiated by the transducer**
  - **Calculation of the reflection on a very large reflector normal to the beam axis.**
  - **Calculation of the reflection on small reflectors normal to the beam axis.**
- **Calculation of the reflected received amplitude in the far field.**
- **Experimental completion of the curves in the near field.**
- **Plotting of universal curves**

In the far field

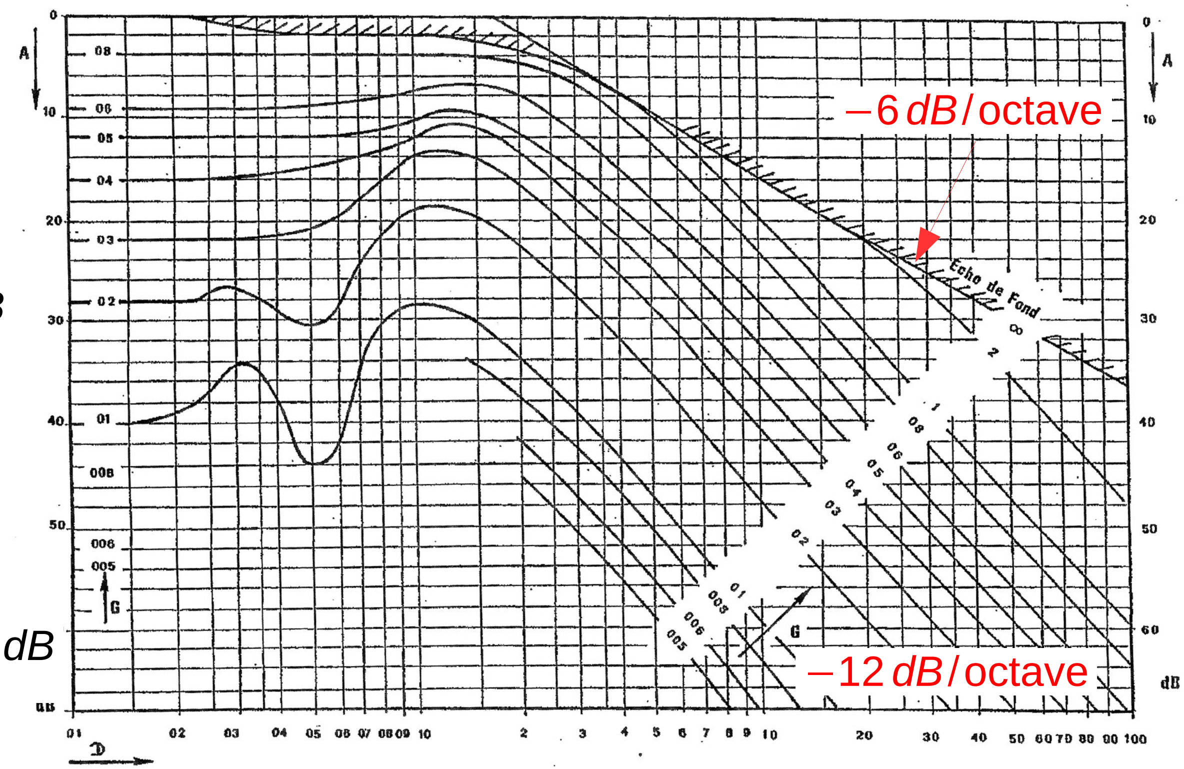
For a large reflector $p(r) \propto \frac{1}{r}$

$$\Delta A_{dB} = 20 \log_{10}\left(\frac{p(2r)}{p(r)}\right) = 20 \log_{10}\left(\frac{1}{2}\right) = -6\,dB$$

For a small reflector acting as a point source

$$p(r) \propto \frac{1}{r^2}$$

$$\Delta A_{dB} = 20 \log_{10}\left(\frac{p(2r)}{p(r)}\right) = 20 \log_{10}\left(\frac{r}{2r}\right)^2 = -12\,dB$$

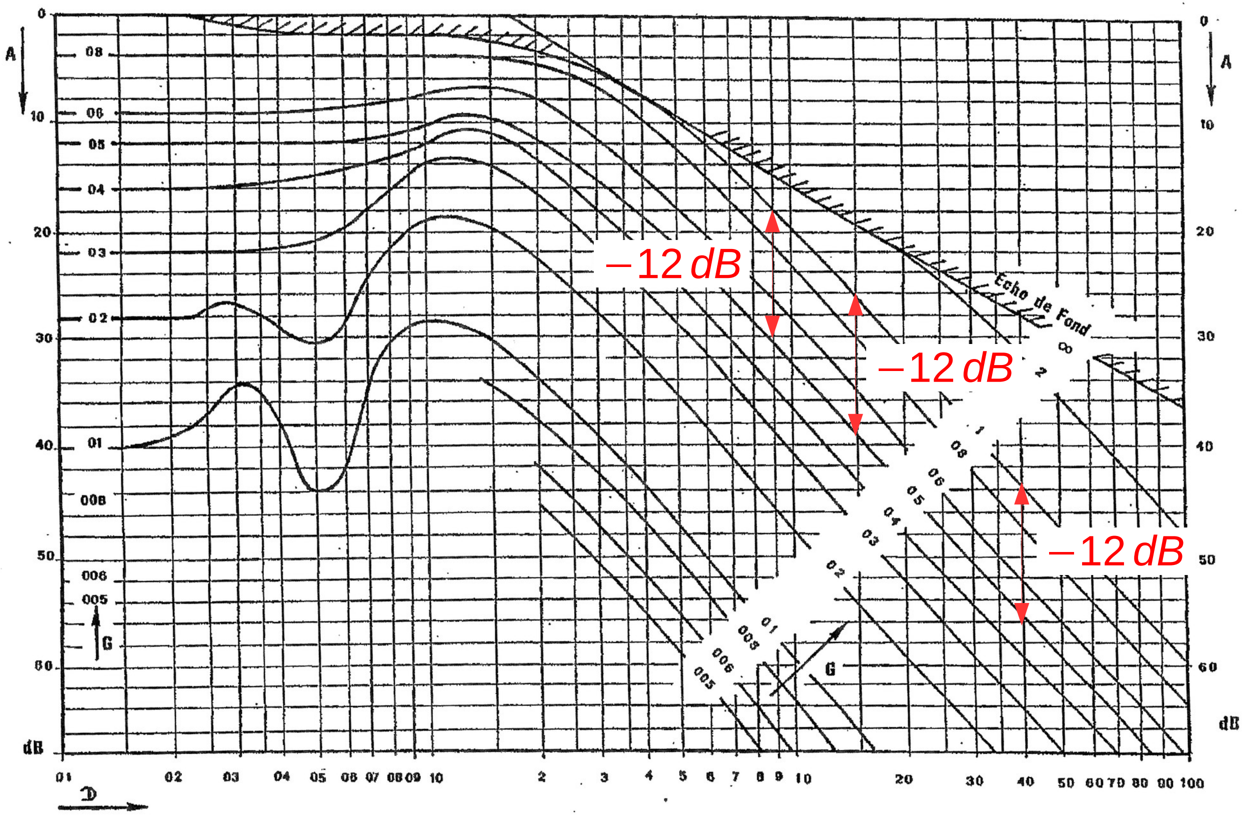


DGS Curves description

In the far field

Interaction with small flaws : Ermolov formula : $p(r) = \dfrac{P_0 S_{transducer} S_{flaw}}{\lambda^2 r^2}$

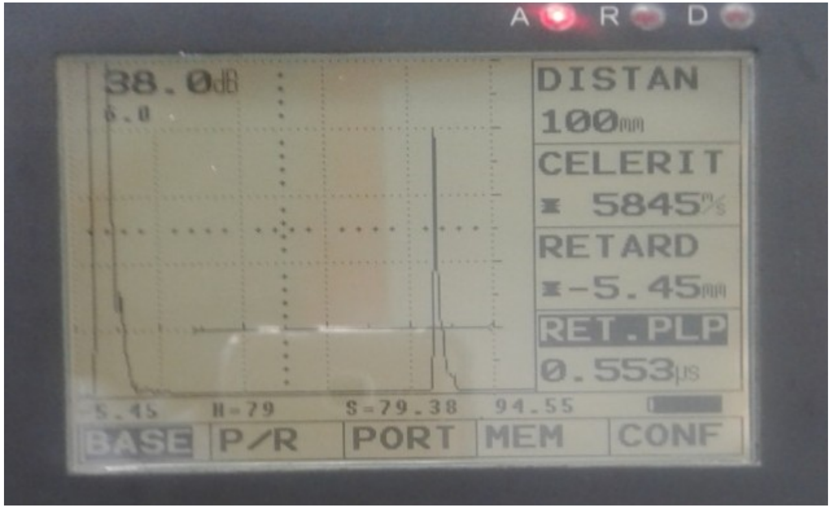
So at a given distance $\Delta A_{dB} = 20\log_{10}\left(\dfrac{S_{flaw}}{S_{tra}}\right) = 20\log_{10}\left(\dfrac{\Phi_{flaw}}{\Phi_{tra}}\right)^2 \Rightarrow$ for $\dfrac{\Phi_{flaw}}{\Phi_{tra}} = 0.5 \Rightarrow -12\,dB$



How to use these curves ?

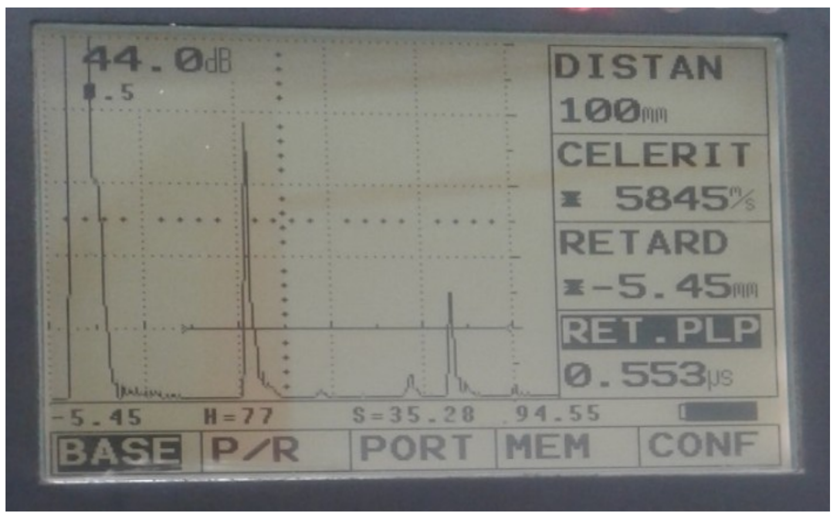
How to use these curves ?

D=10mm ; F= 4MHz ; V=5.845 mm/s => l_0 = 17.1mm



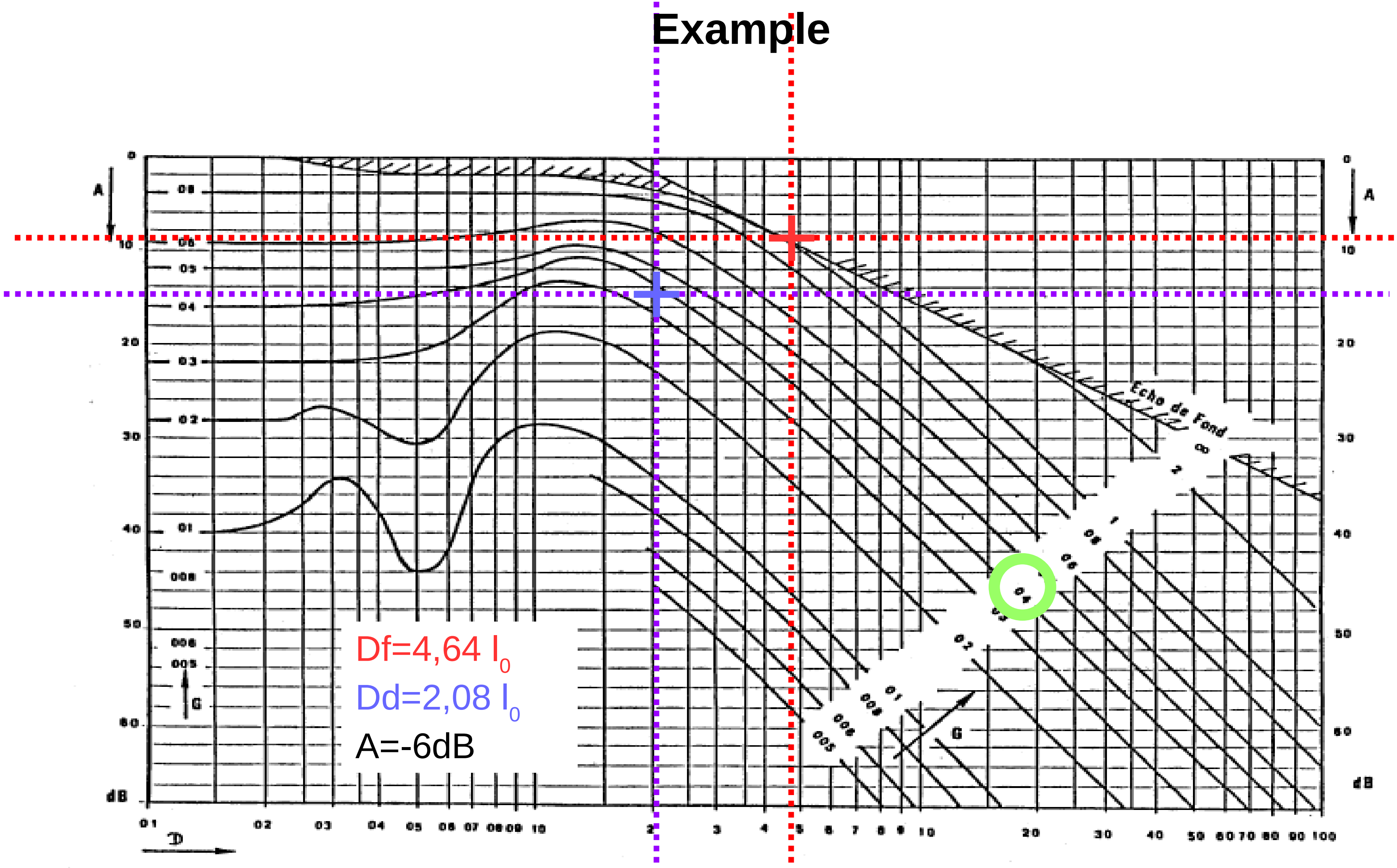
Z_b=79,89 mm = 4,64 l_0

Zd=35,64 mm = 2,08 l0



ΔA=38-44=-6dB

Example



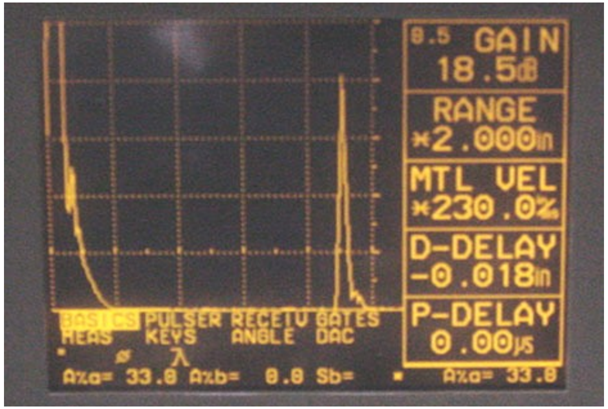
Df=4,64 l_0

Dd=2,08 l_0

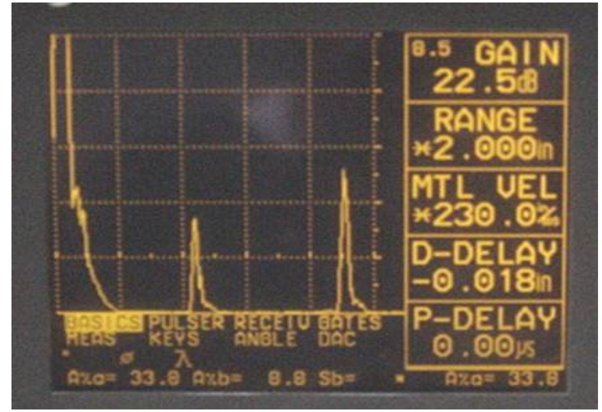
A=-6dB

Diamètre $TFP_{éq}$: 0,4 *10 = 5 mm

Example 2



v=230 ''/ms=5842 m/s



Depth of the back wall echo :
zf=4,5*2/5 =1.8 ''

Depth of the defect :
zd=2*2/5 =0.8''

amplitude drop :
20*log(1,8/4)-4=-10,93 dB

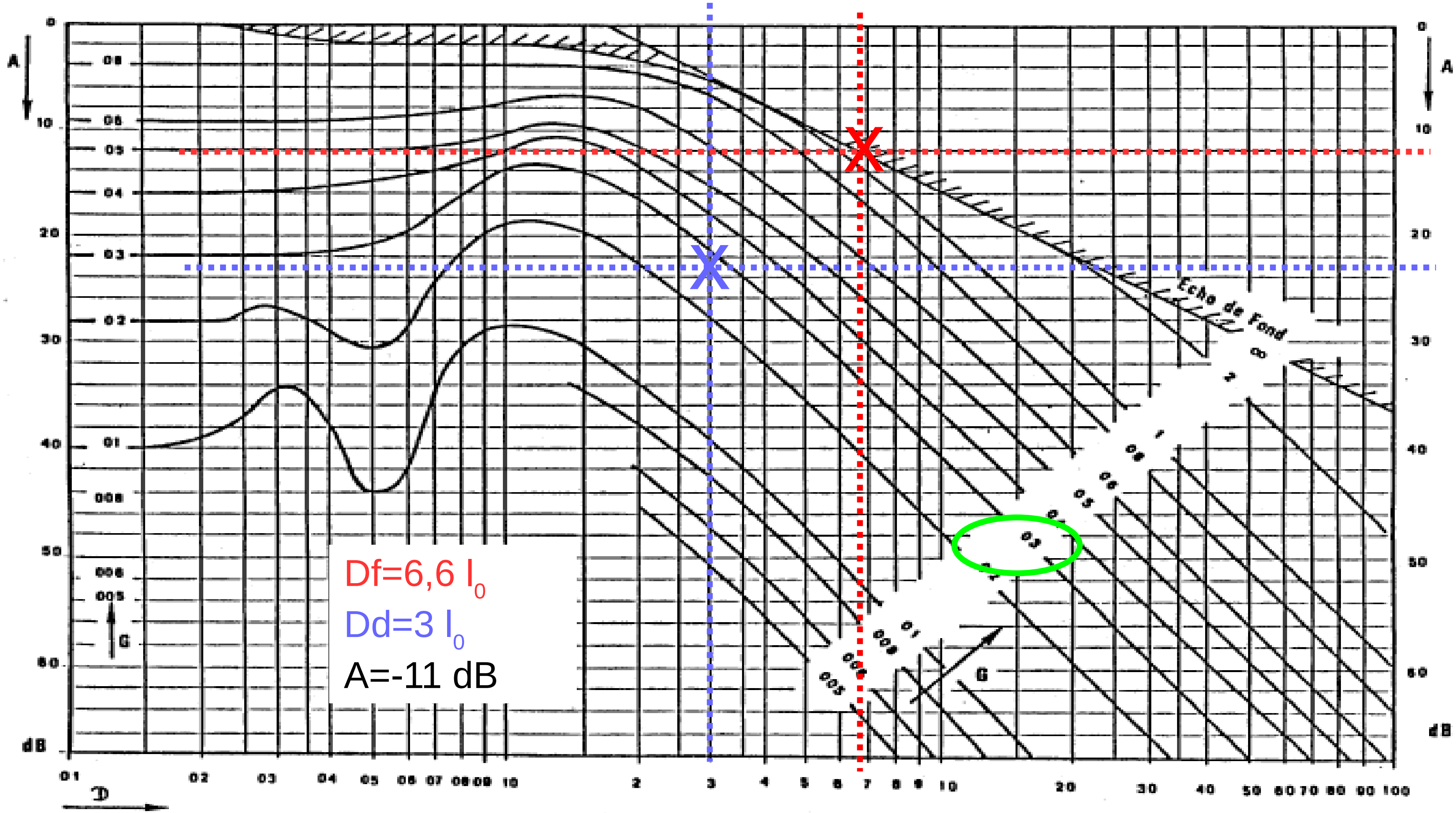
Transducer : Diameter = 0.5'' ; F = 1 MHz

$l_0=(0,5)^2/(4*230.10^3)*10^6=0.27''$

thickness :
Df=1.8/0.26=6,66

Defect depth
Dd=0.8/0.27=2.96

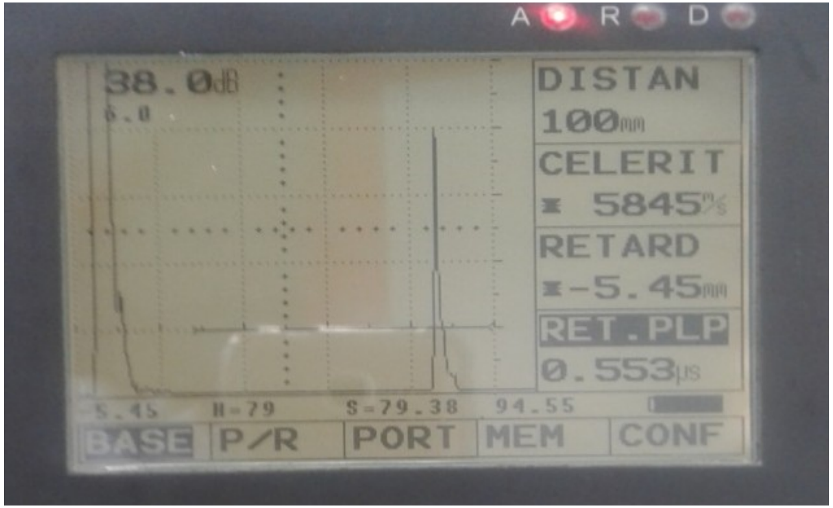
Example 2



Φ_d = 0.3 Φ_t =0.15”=3.8 mm

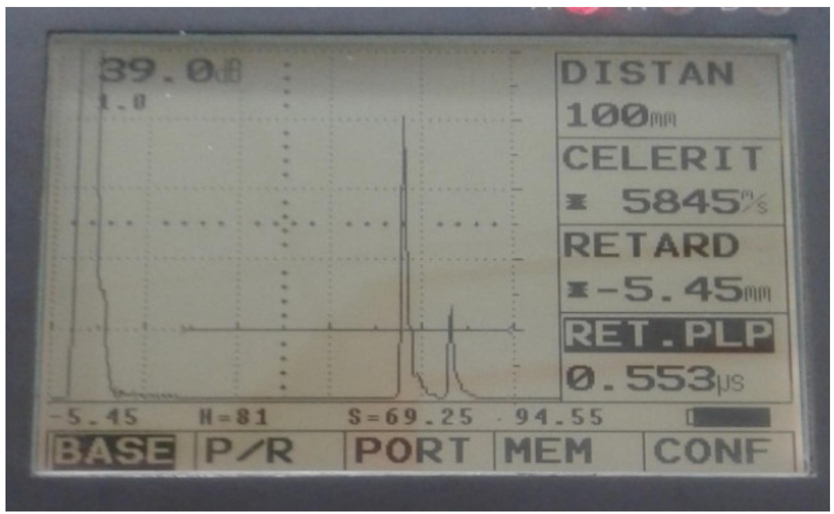
Example 3

D=10mm ; F= 4MHz ; V=5.845 mm/s => l_0 = 17.1mm



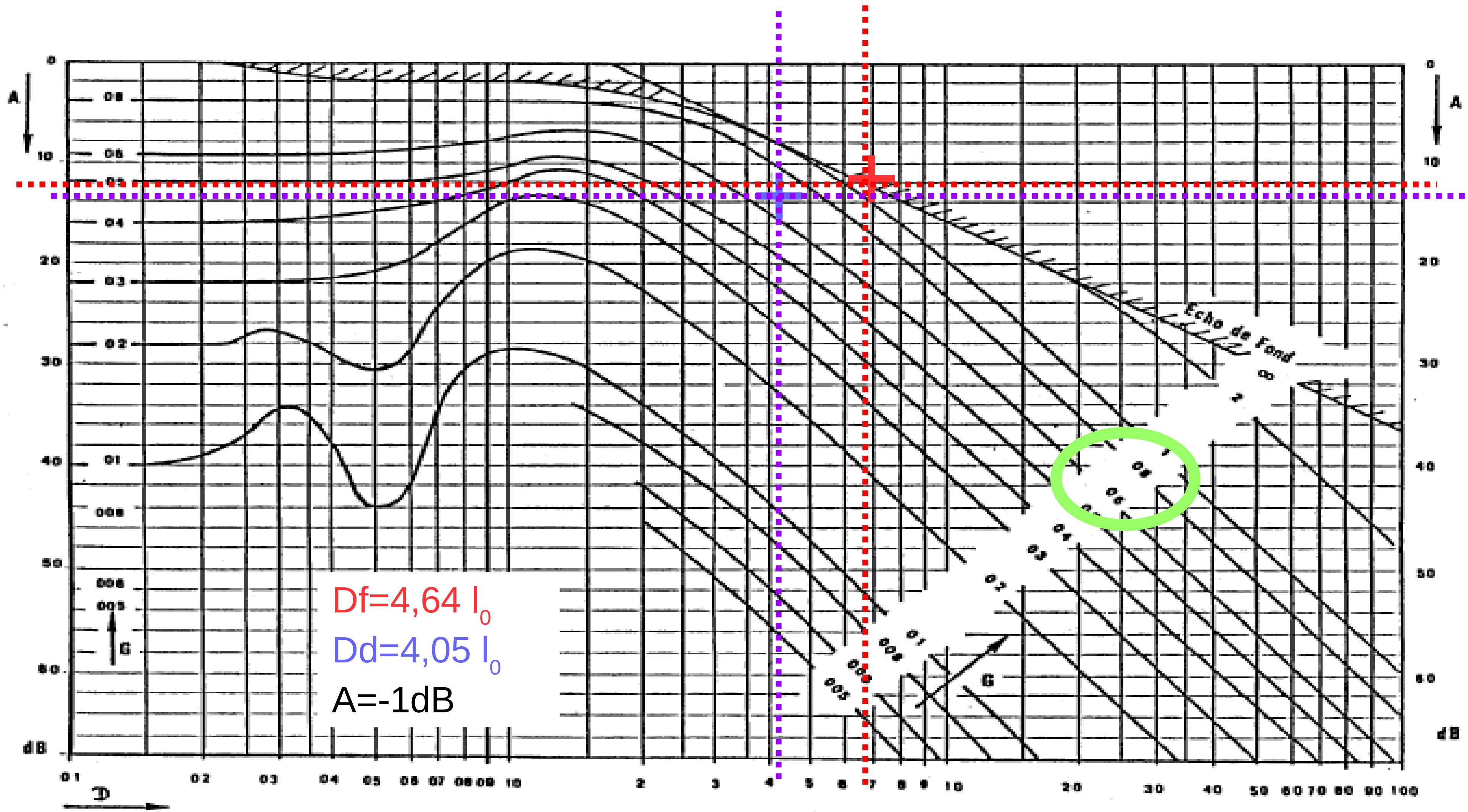
Z_b=79,89 mm = 4,64 l_0

Zd=69,25 mm = 4,05 l0



ΔA=38-39=-1dB

Example 3



Φ_d = 0.7 Φ_t = 7 mm

Limitations of the method

- **Valid for a given shape of transducer**
- **L_0 is defined in harmonic regime. In the case of the pulsed regime L_0=90% L_0 (harmonique))**
- **Low absorbion materials (or correction needed)**

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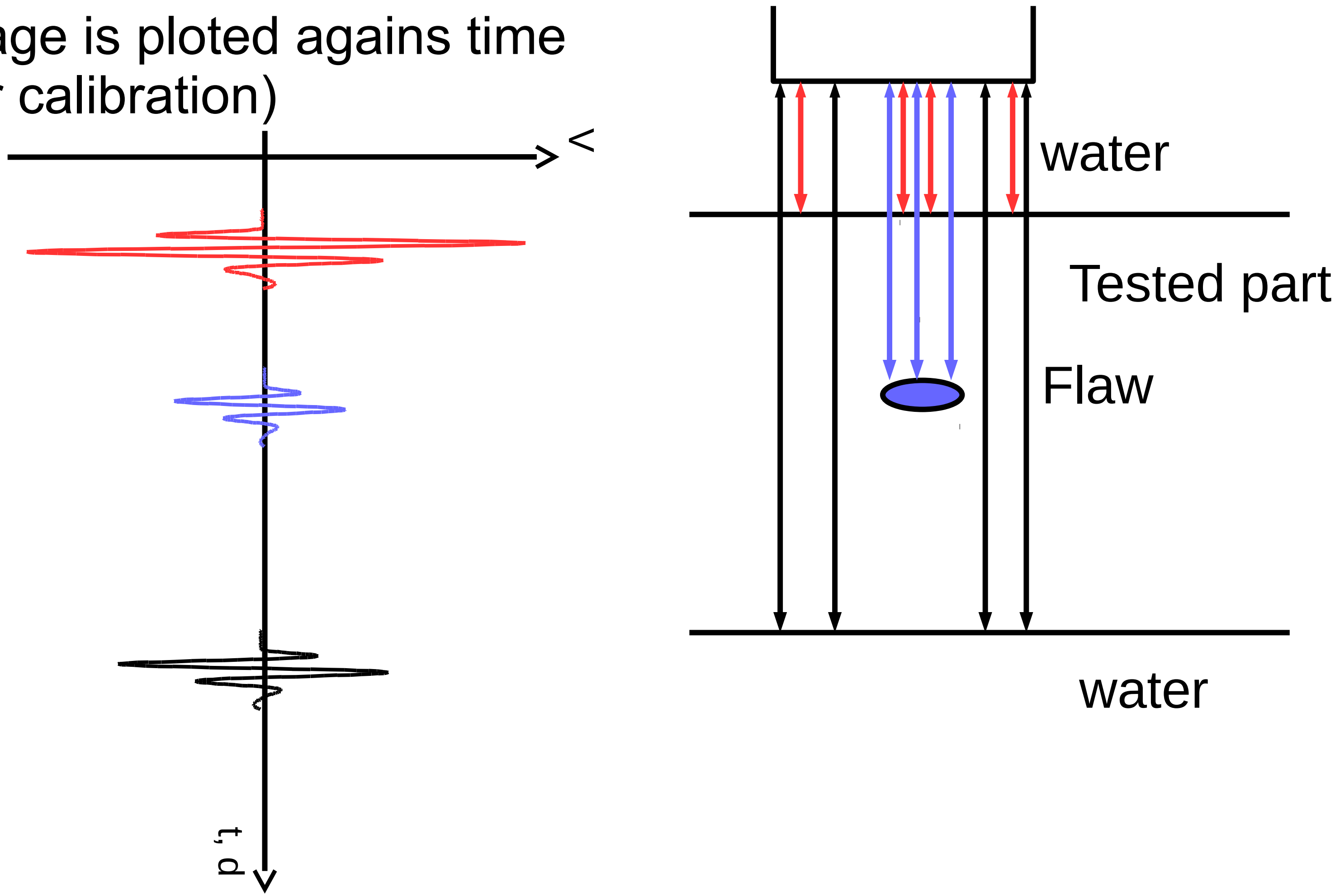
Validity of the results

- **Any discard to the perfect conditions will lead to an under evaluation of the size.**

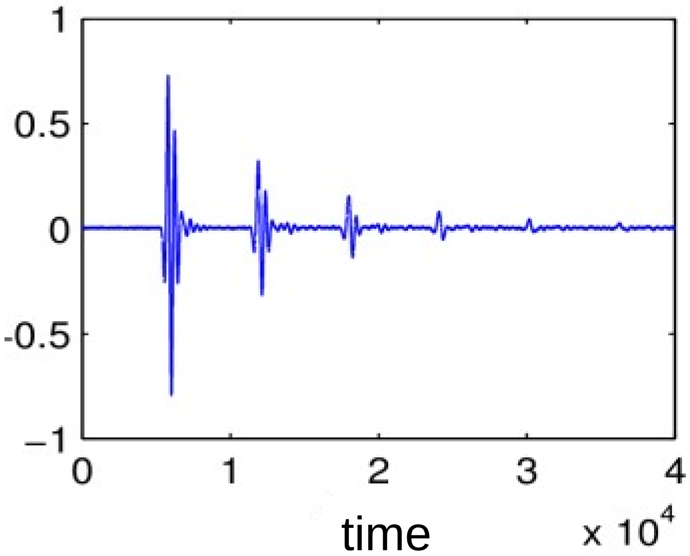
Data presentation

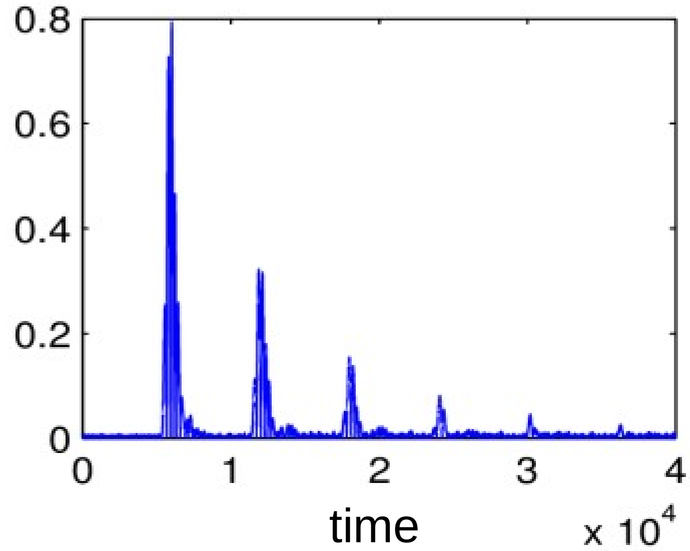
A-scan presentation

Point measurement
The receive voltage is ploted agains time
(or distance after calibration)

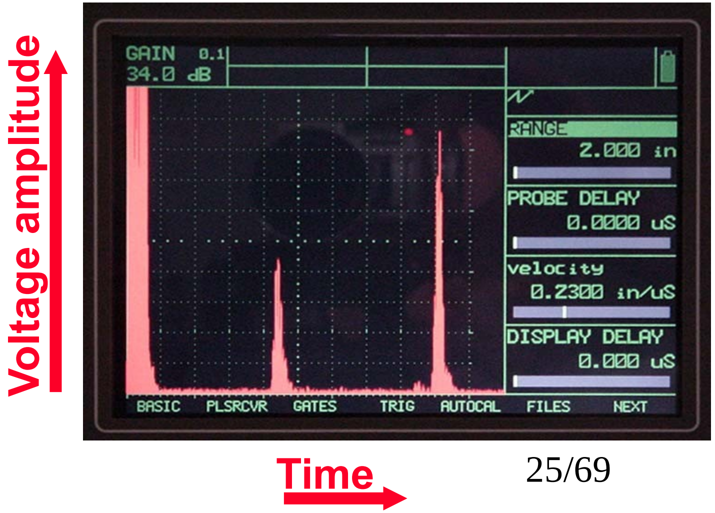


A-scan data presentation





- The depth of a flaw can be estimated directly



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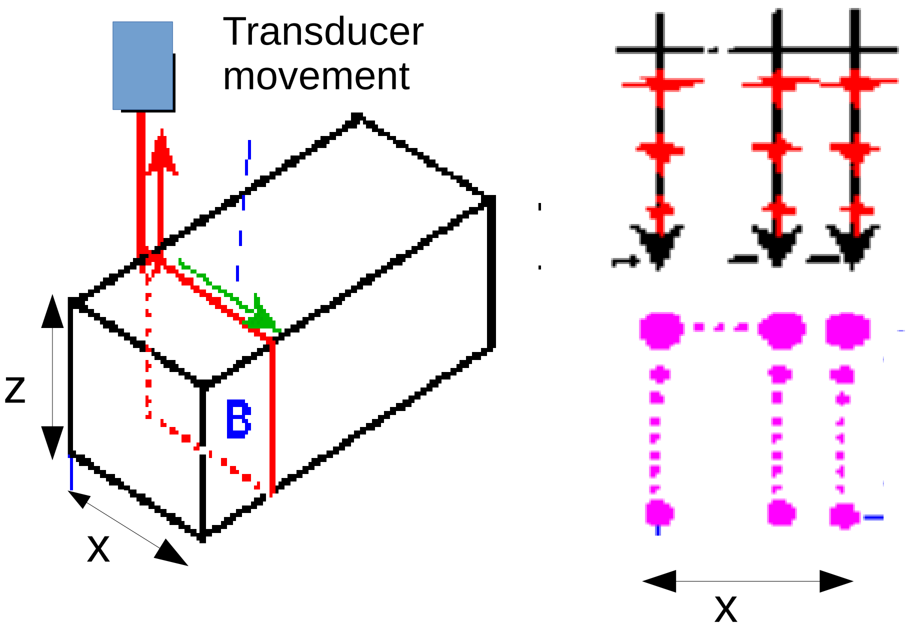
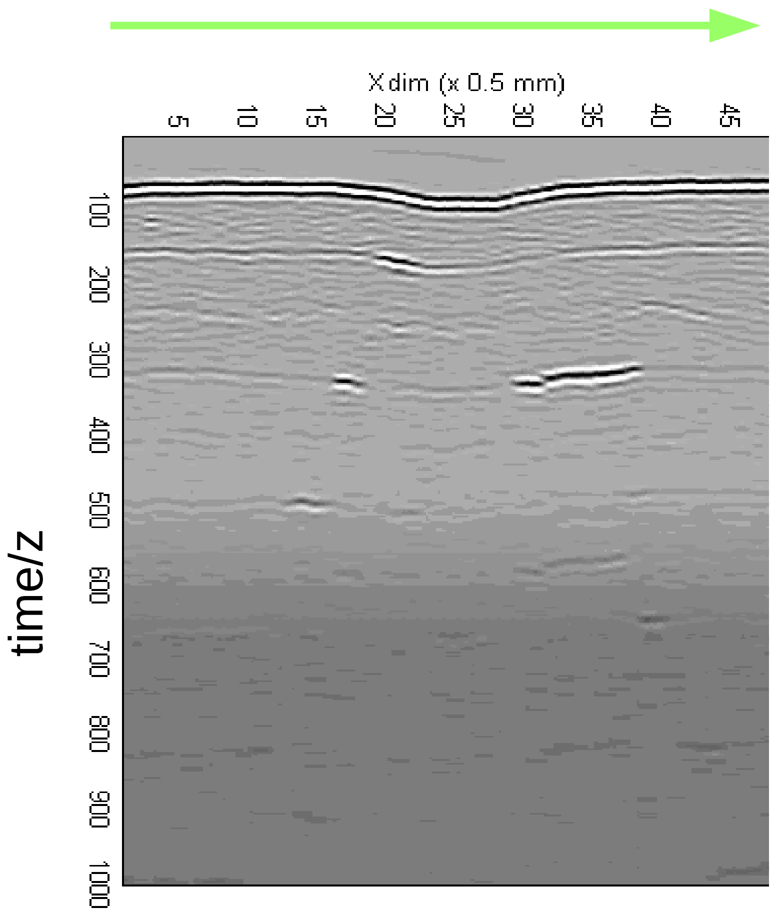
B-scan presentation

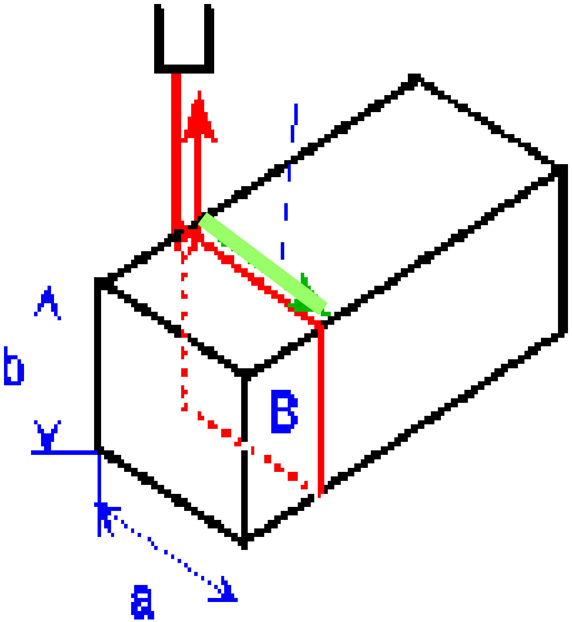
The B-scan presentation is a cross-section of the tested part.

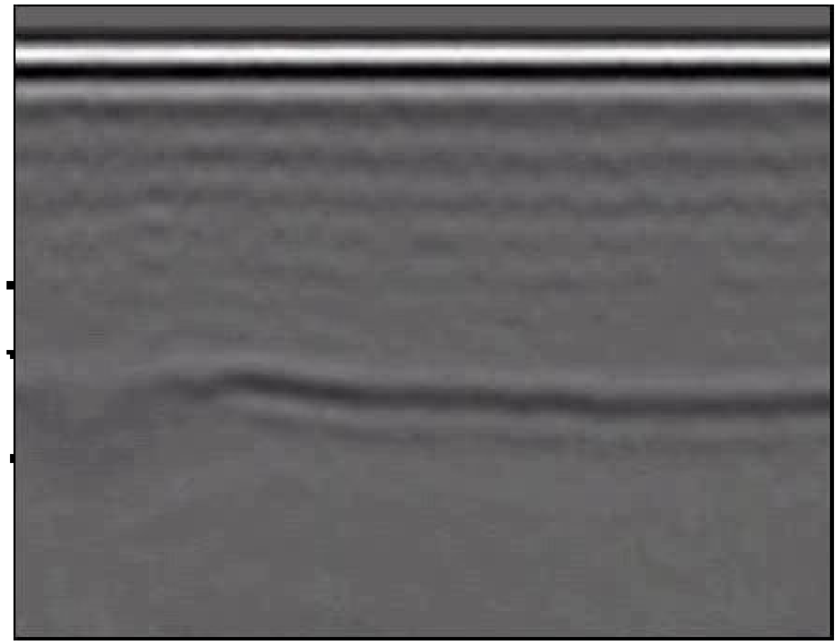
Seuls l'épaisseur et les dimensions latérales des défauts peuvent être estimés.





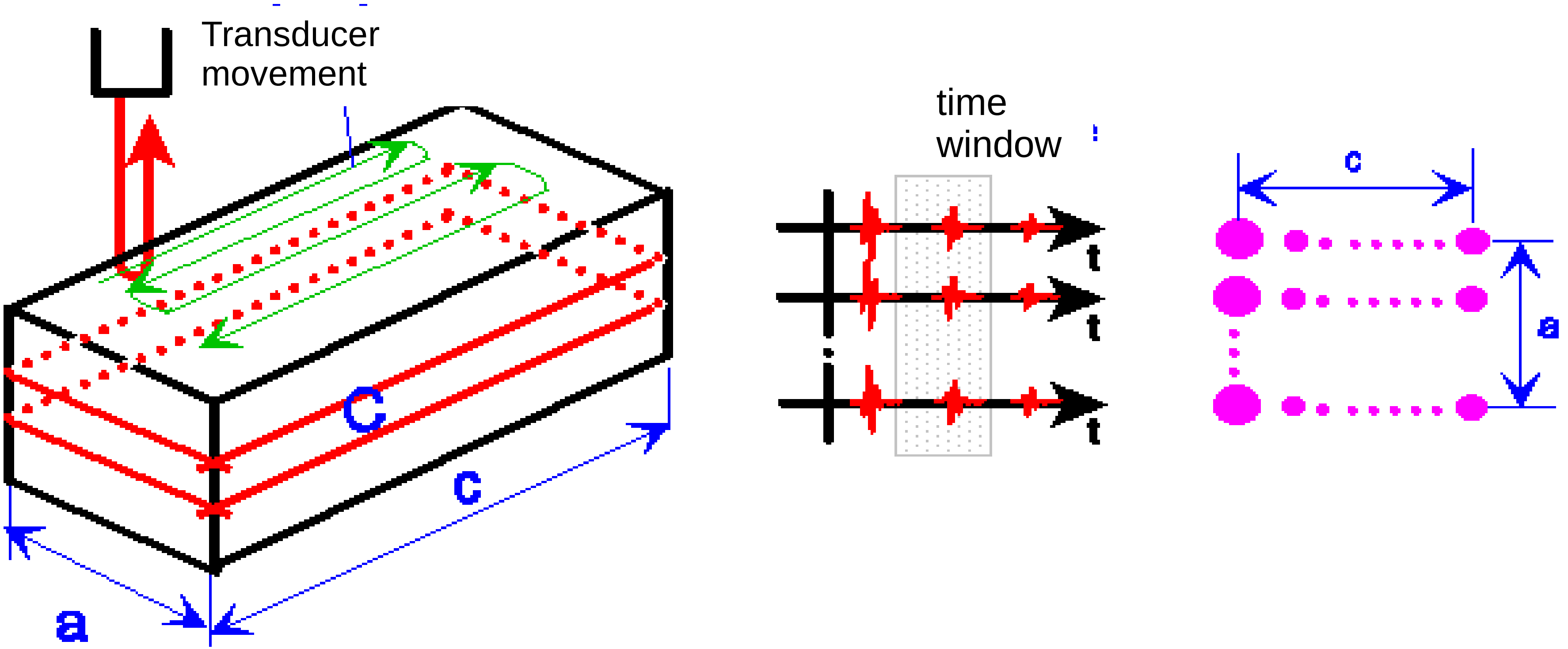
B-scan presentation





C-scan presentation

The C-scan presentation is a plan-type view parallel to the scan pattern of the transducer. C-scan are produced with computer controlled scanning systems. Typically, a data collection of A-scan is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded.



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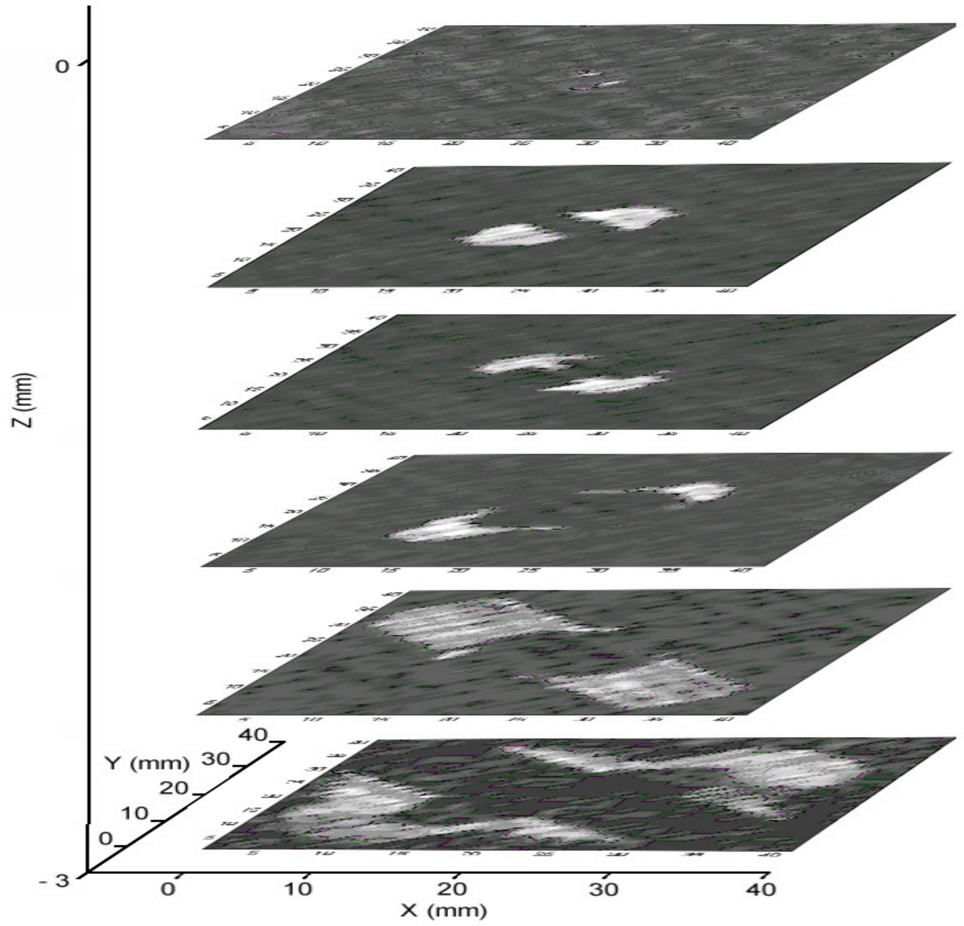
C-Scan presentation

C-Scan composite

C-scan recalé



5

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Ultrasound propagation

Modelization tools

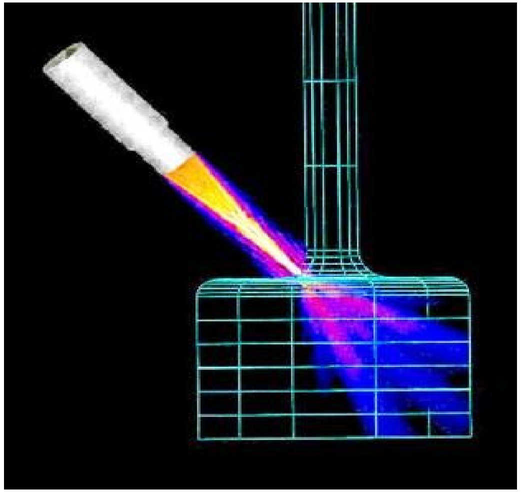
Principles of Ultrasonic Testing

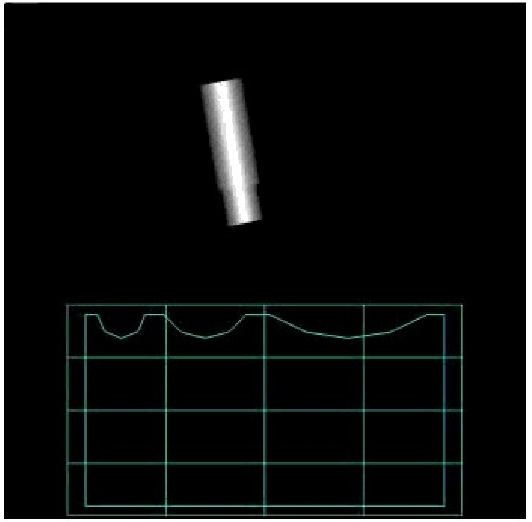
Ultrasonic waves are introduced into a material where they travel in a straight line and at a constant speed until they encounter a surface.

At surface interfaces some of the wave energy is reflected and some is transmitted.

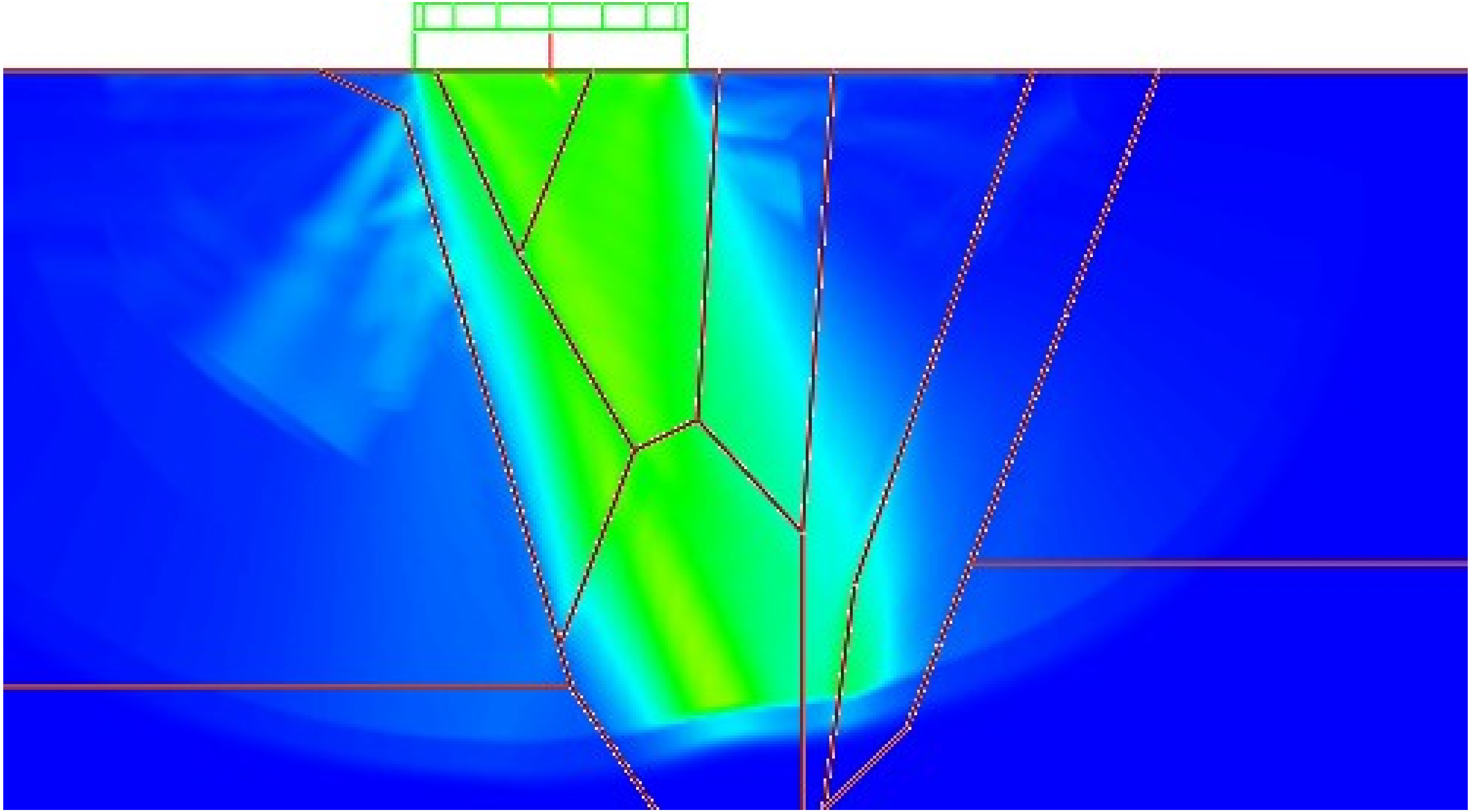
The amount of reflected or transmitted energy can be detected and provides information about the size of the reflector.

The travel time of the sound can be measured and this provides information on the distance that the sound has traveled.

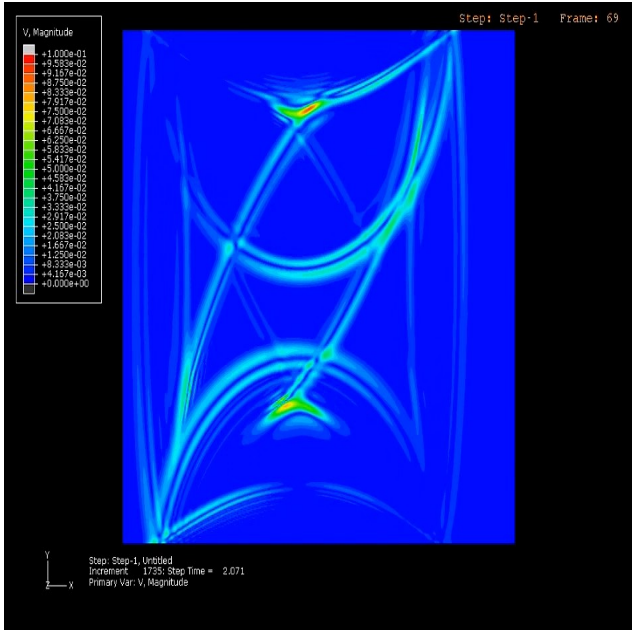




Is ultrasound propagation always simple ?



Propagation in an anisotropic medium



Observed phenomena :

- Anisotropic propagation
- Multimodes
- Reflections

Source : http://wn.com/Anisotropic_Elastic_Wave_Propagation

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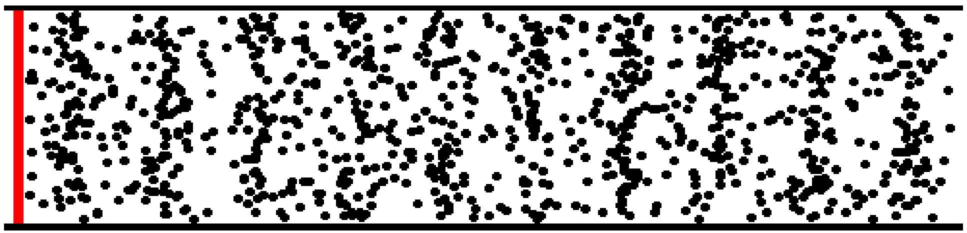
Wave polarisation

polarisation

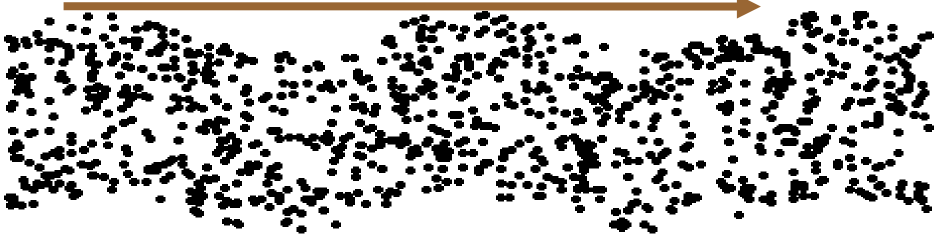
Propagation direction

longitudinal wave



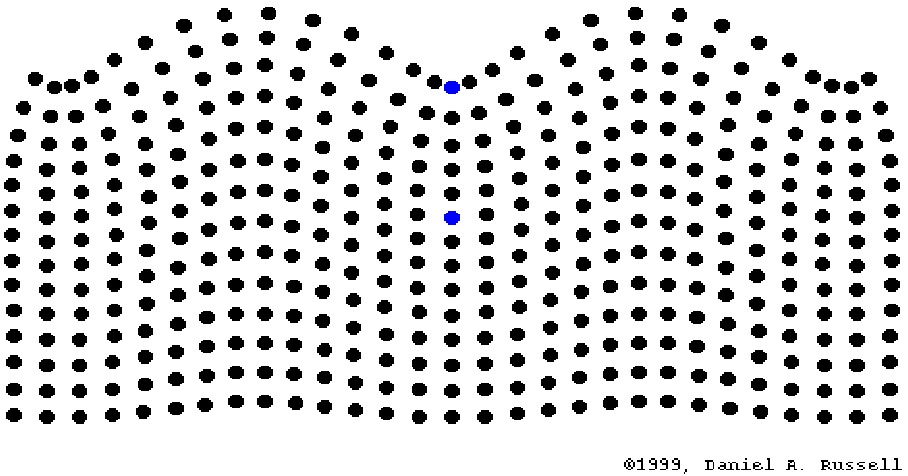
polarisation

Propagation direction



shear wave

Propagation direction

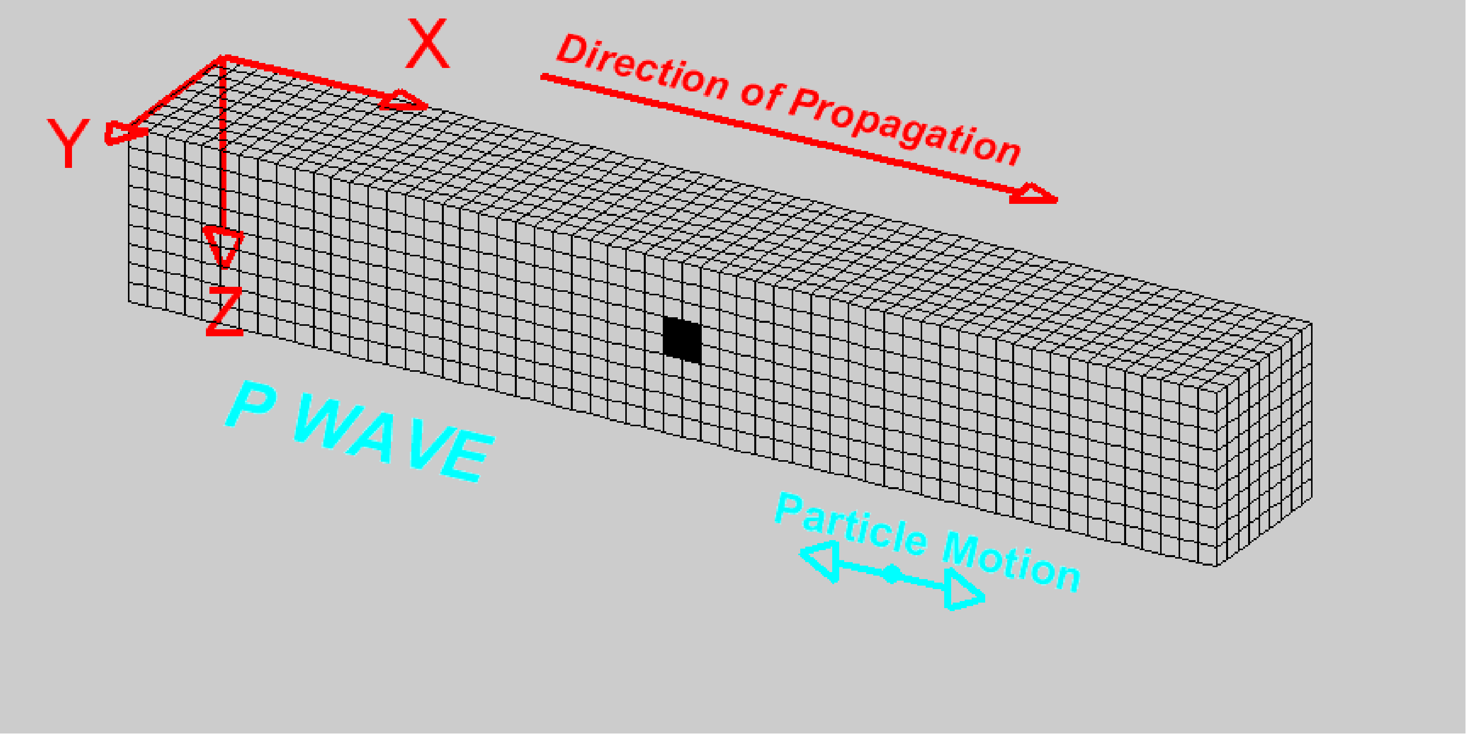


Surface or Rayleigh wave
(elliptic pol. = longitudinal + shear)

Animation courtesy of Dr. Dan Russell, Grad. Prog. Acoustics, Penn State
http://www.acs.psu.edu/drussell/demos.html

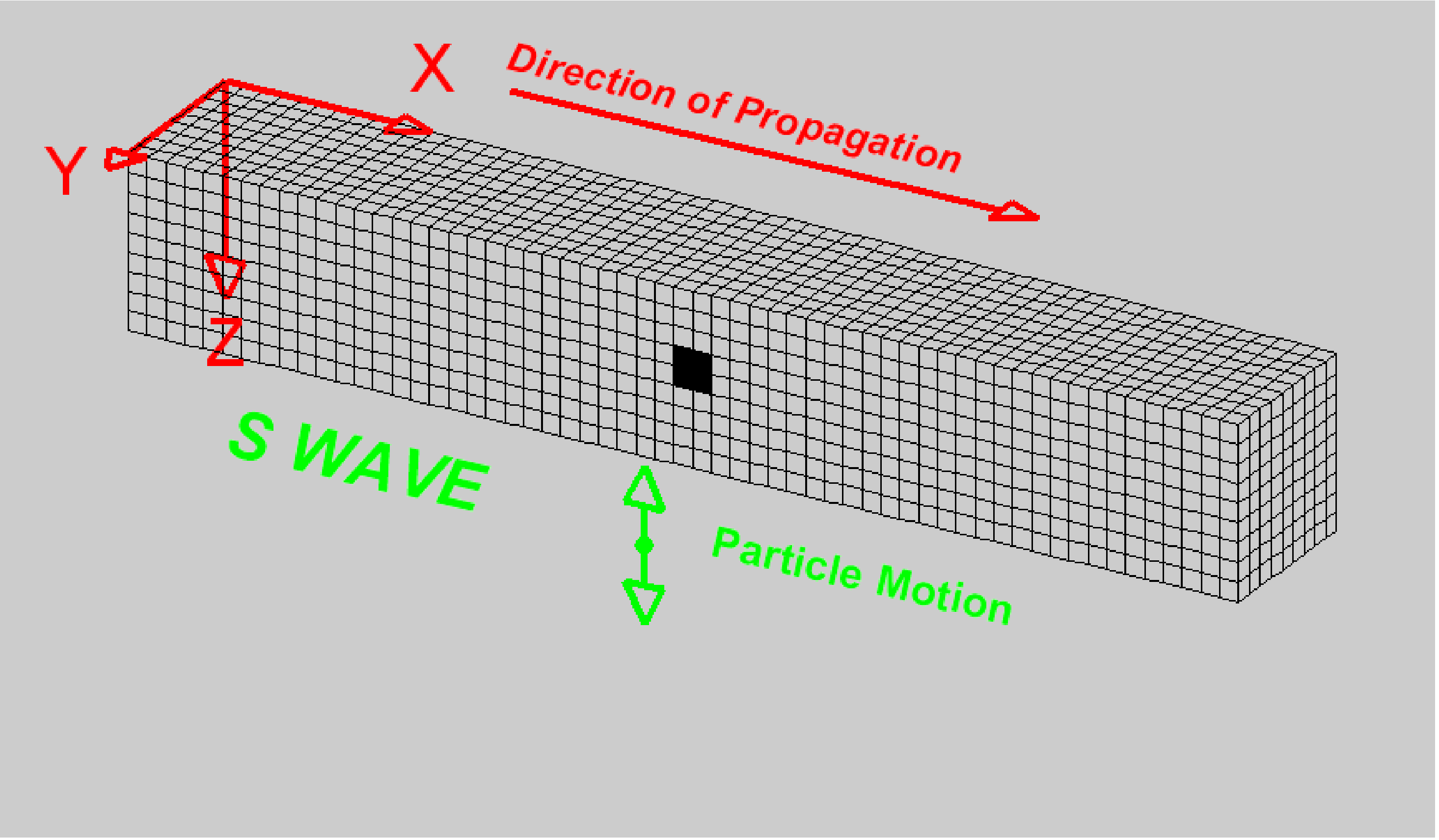
Bulk waves : Longitudinal

- Longitudinal
- Compressionnal
- Primary (P Wave)

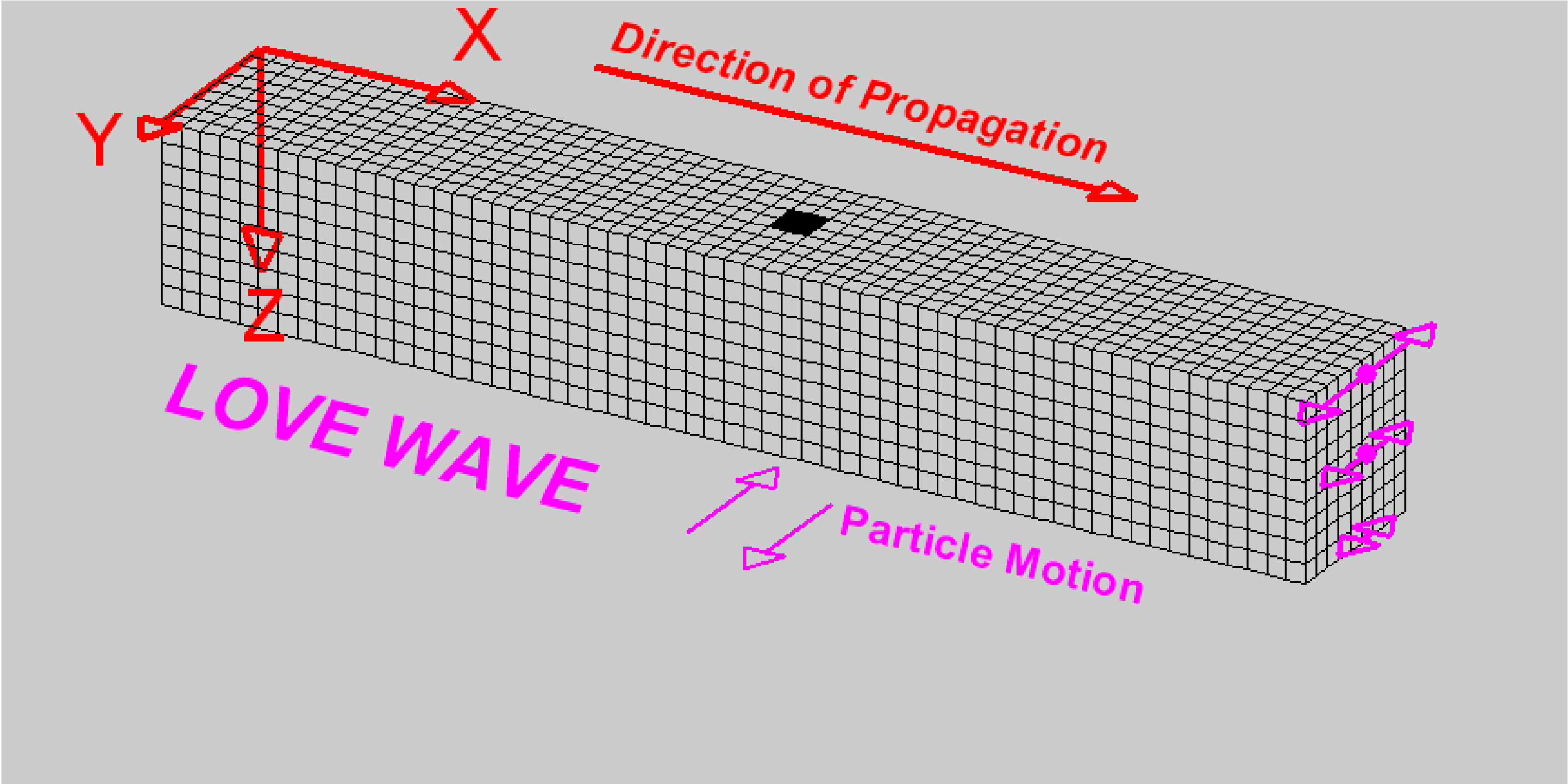


Bulk waves : Shear

- Transverse
- Shear
- Secondary
- S Wave



Surface waves : Love



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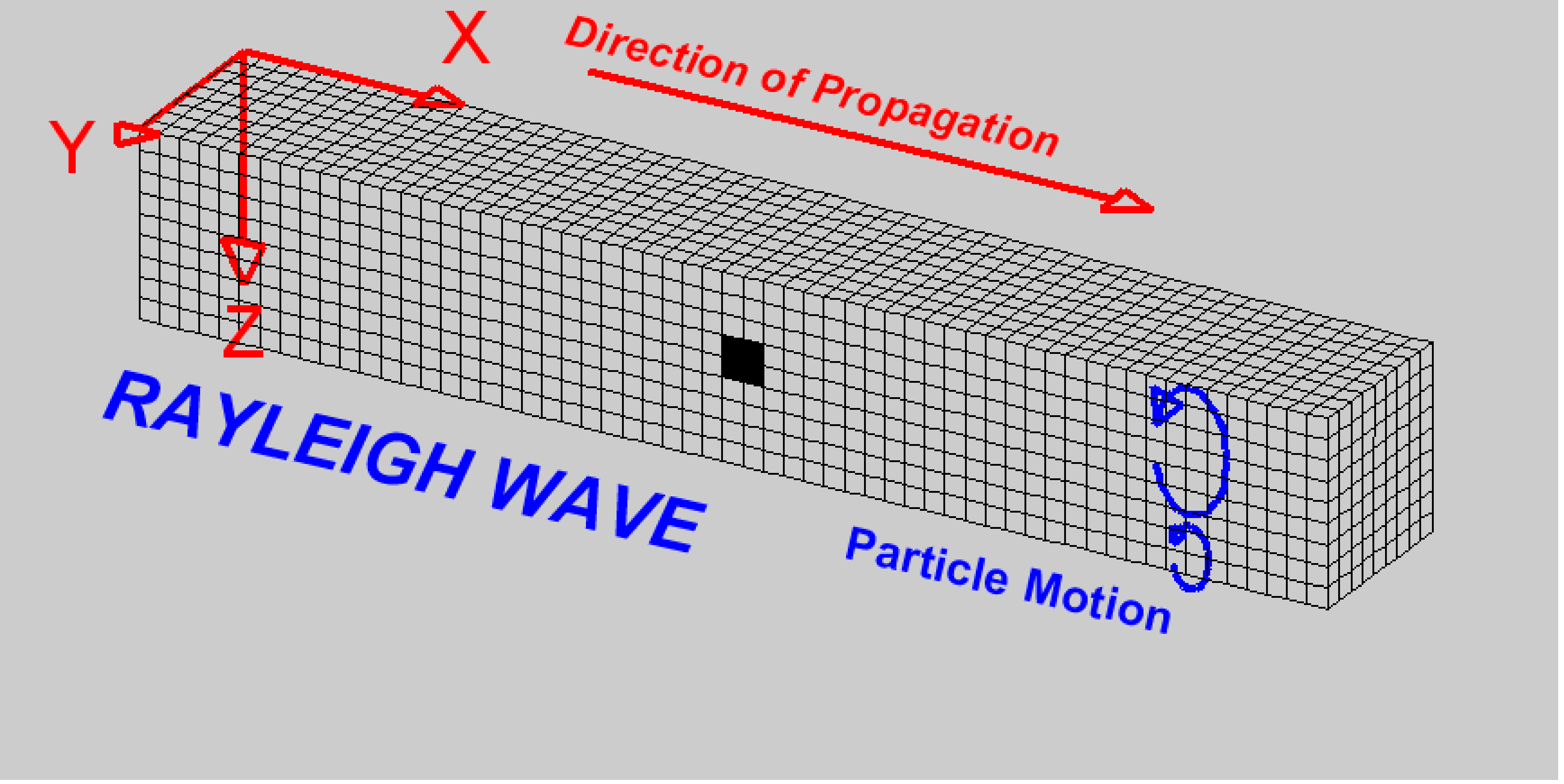
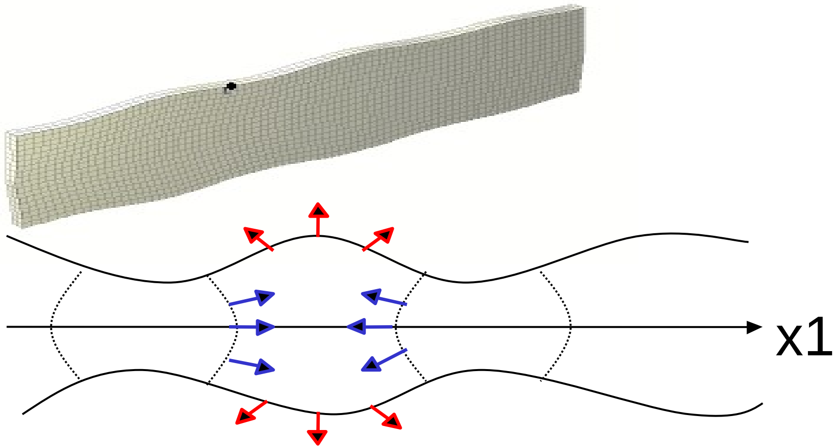
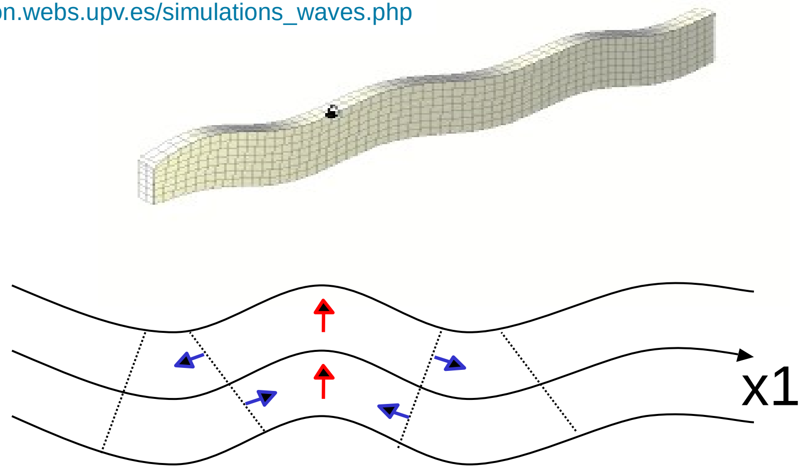
Surface waves : Rayleigh

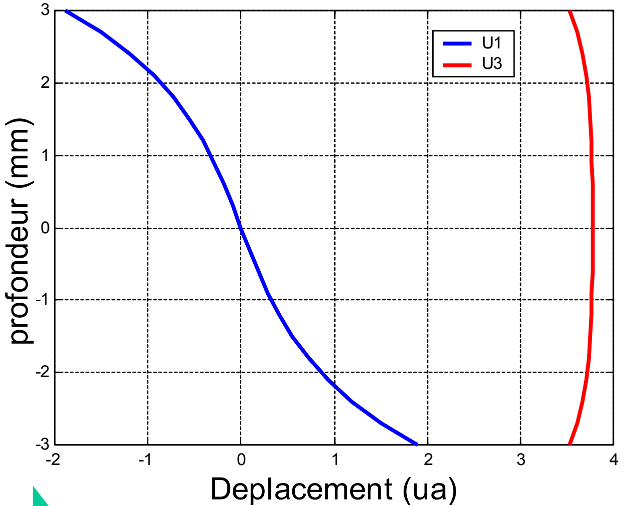


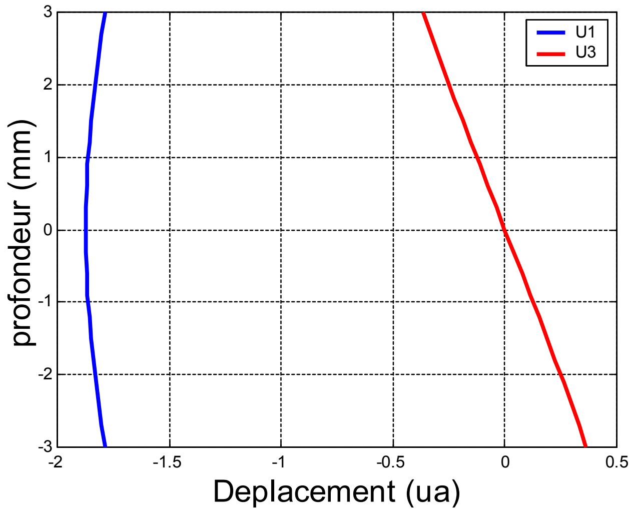
Guided waves – Lamb Waves – Plate waves

source : https://nojigon.webs.upv.es/simulations_waves.php





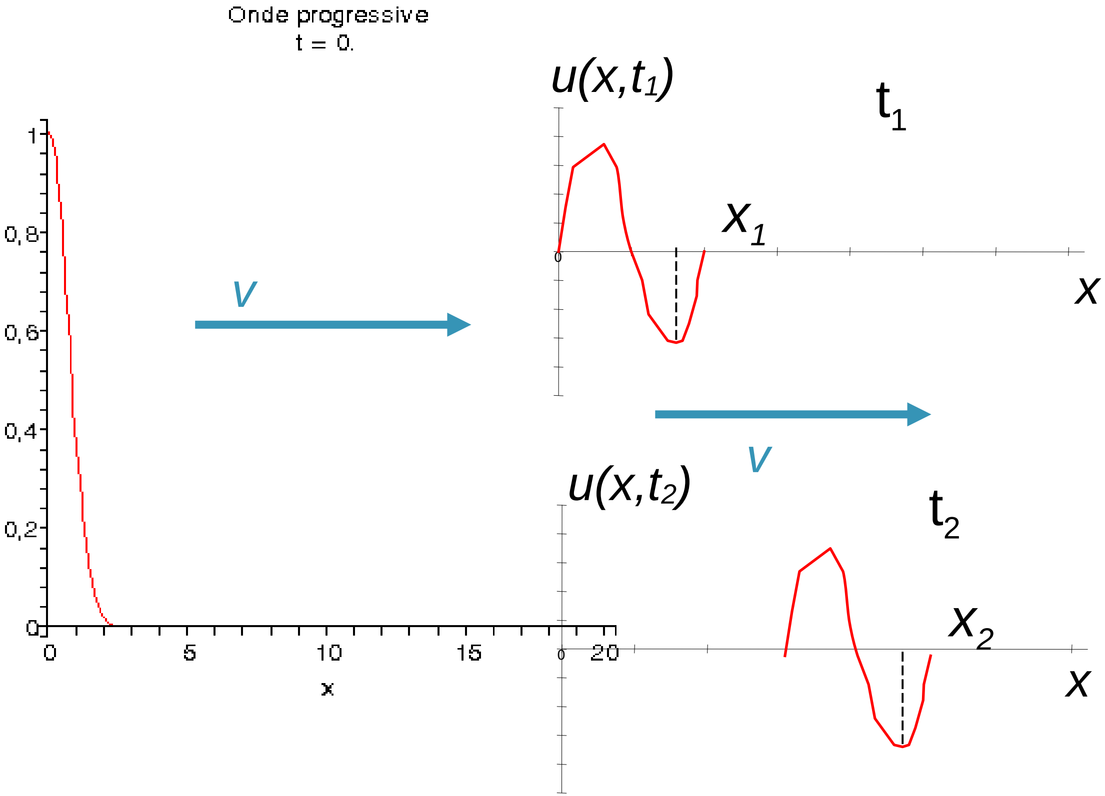




Different sensitivity to each kind of flaw

Click here for animation please
http://www.ndt.net/ndtaz/files/lamb_a.gif

Modelisation and analysis tools : propagating plane waves PPW (1/2)



A **progressive wave** **u(x,t) is a disturbance, that travels without distorsion at constant velocity v.**

$$u(x_2,t_2) = u(x_1,t_1)$$

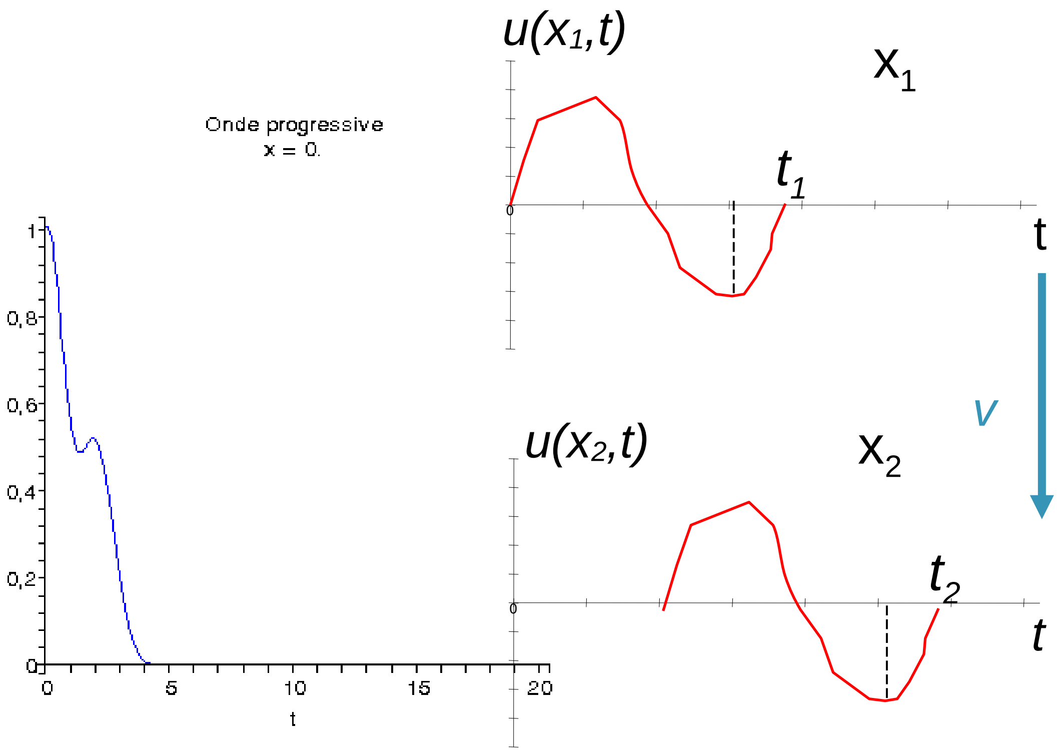
$$x_2 = x_1 + v(t_2 - t_1)$$

$$x_2 - v\,t_2 = x_1 - v\,t_1 = Cst$$

A progressive wave can be considered as a function f_x of the space variable, that is translated with time :

$$u(x,t) = f_x(x - v\,t) \text{ (along x increasing side)}$$

Modelisation and analysis tools : propagating plane waves (2/2)



A progressive wave u is a disturbance, that travels without distorsion at constant velocity v.

$$u(x_2,t_2) = u(x_1,t_1)$$

$$t_2=t_1+ (x_2-x_1)/ v$$

$$t_2-x_2/ v = t_1-x_1/ v = Cst$$

The progressive wave can be considered as a function f_t of the time variable, that is delayed with the observation position :

$$u(x,t) = f_t(t - x/v)$$

The basic kind of representation in a NDT measurement device.

Practice 1

- Derive the expression of a wave propagating along the **decreasing** direction

  1) In the case of a space function

  2) In the case of a time function

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Practice 2

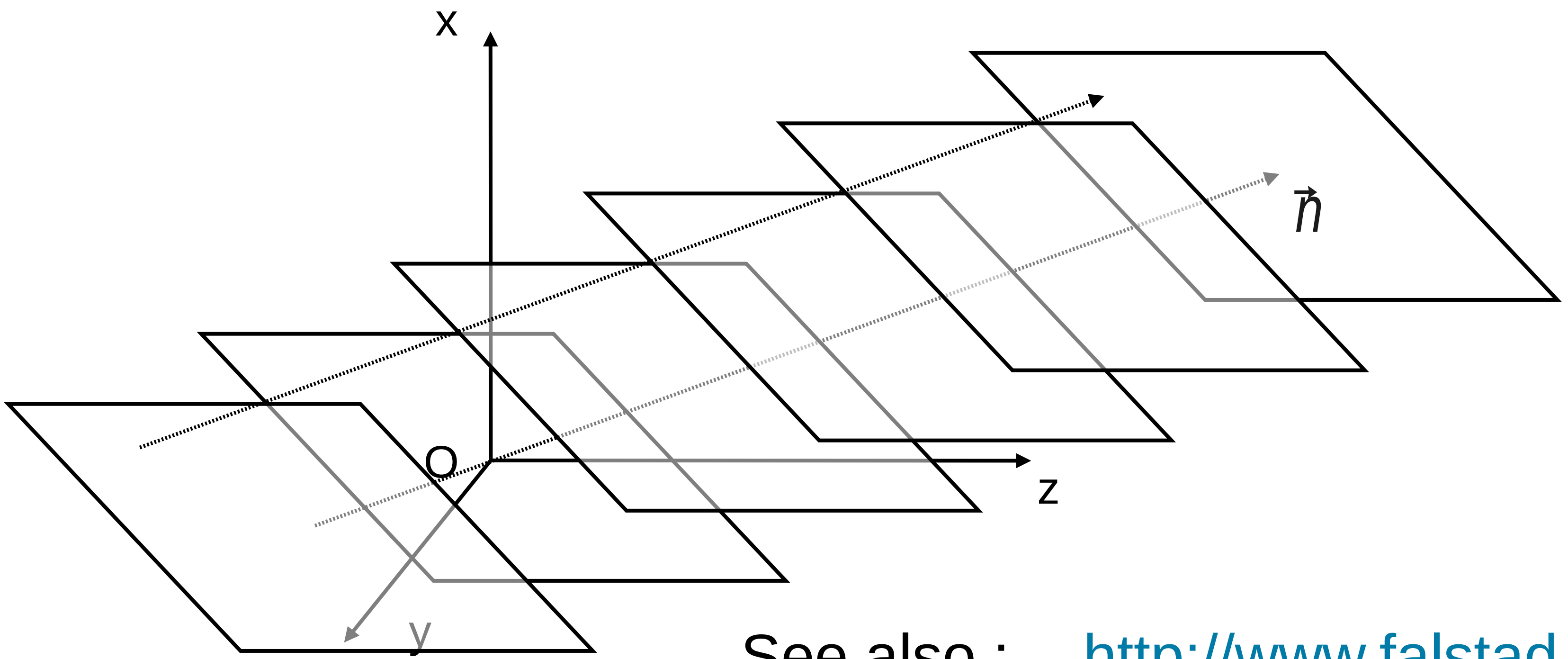
- The signal delivered in a 1D medium by a source, located at at $x = x_{A,}$ is given by :
$$u(x_A,t)=f(t)=U e^{\frac{-t}{\tau}}\sin\left(\frac{2\pi}{\tau}t\right) \text{ for } 0<t<\tau \text{ and } f(t)=0 \text{ elsewhere}$$

- For any position x, derive the expression of the progressive plane wave produced by the source, in a medium with propagation speed v.

- You will also plot :
  - $$\begin{cases} u(x_A,t) \\ u(x,t=3\tau) & x<x_A \\ u(x,t=3\tau) & x>x_A \end{cases}$$

Propagation of propagating plane waves in 3D

- A progressive plane wave is a wave that propagates in a well defined direction and takes the same values at any point of a plane perpendicular to the propagation direction.



See also : http://www.falstad.com/

Analytic expression of P. P. W in 3D

The general expression of a 3D PPW can be easily derived from the following figure :

$\vec{u}(P,t_0)=\vec{u}(O,t_0)$ Plane wave => same value in O and P

$\vec{u}(M,t)=\vec{u}(O',t)$ Plane wave => same value in O' and M

$t=t_0+\frac{\overline{PM}}{v}$ and $\overline{PM}=\overline{OO}$

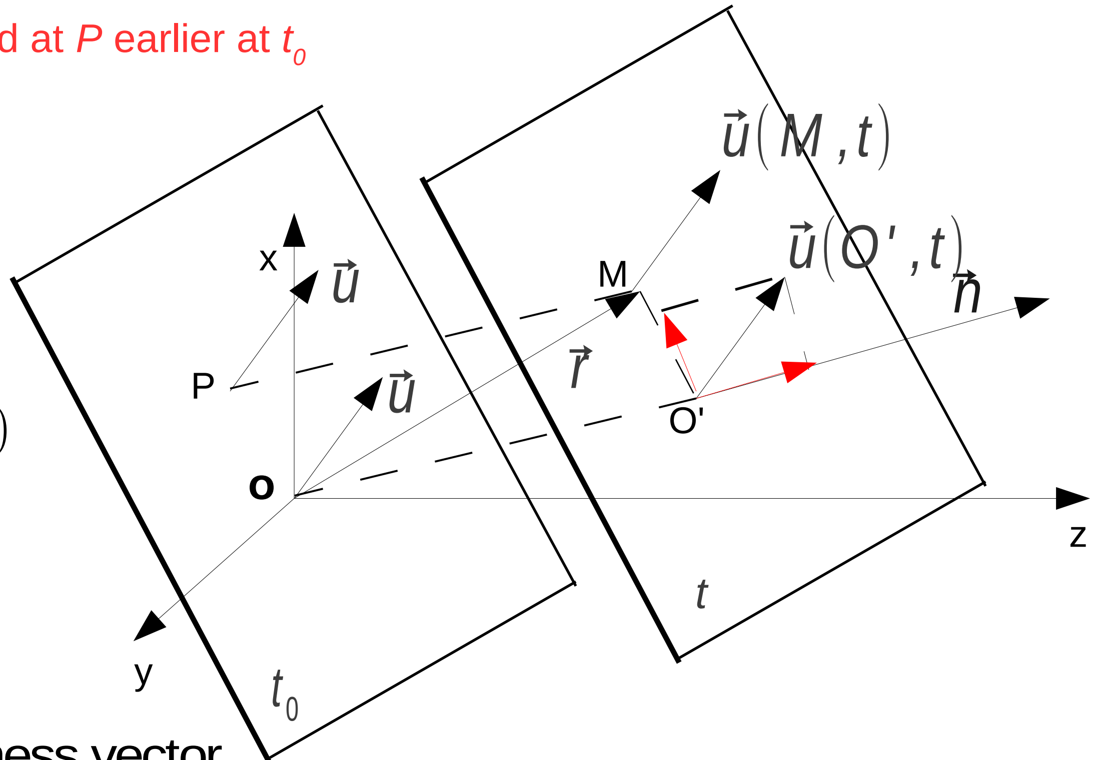
The wave observed at *M* at time *t* is the one we had at *P* earlier at t_0

$$\vec{u}(M,t)=\vec{u}(P,t_0)=\vec{u}(O,t_0)=\vec{f}(t_0)$$

$$t=t_0+\frac{\overline{PM}}{v} \quad \text{and} \quad \overline{PM}=\overline{OO'}$$

let's take : $\vec{r}=\overrightarrow{OM} \Rightarrow \overline{OO'}=\vec{n}.\vec{r}$

then $\vec{u}(\vec{r},t)=\vec{u}\left(O,t-\frac{\vec{n}.\vec{r}}{v}\right)=\vec{f}\left(t-\frac{\vec{n}.\vec{r}}{v}\right)$



the vector $\frac{\vec{n}}{v}$ is called the slowness vector

Practice 3

- From the previous slide, derive the expression of the general 3D PPW propagating along the x'x in the increasing x direction.

- From the previous slide, derive the expression f of the general 3D PPW propagating along the x'x in the decreasing x direction.

Practice 4

- Derive the expression of the general 3D PPW propagating in the <110> direction of a crystal.

- Derive the expression of the general 3D PPW propagating in the <111> direction of a crystal..

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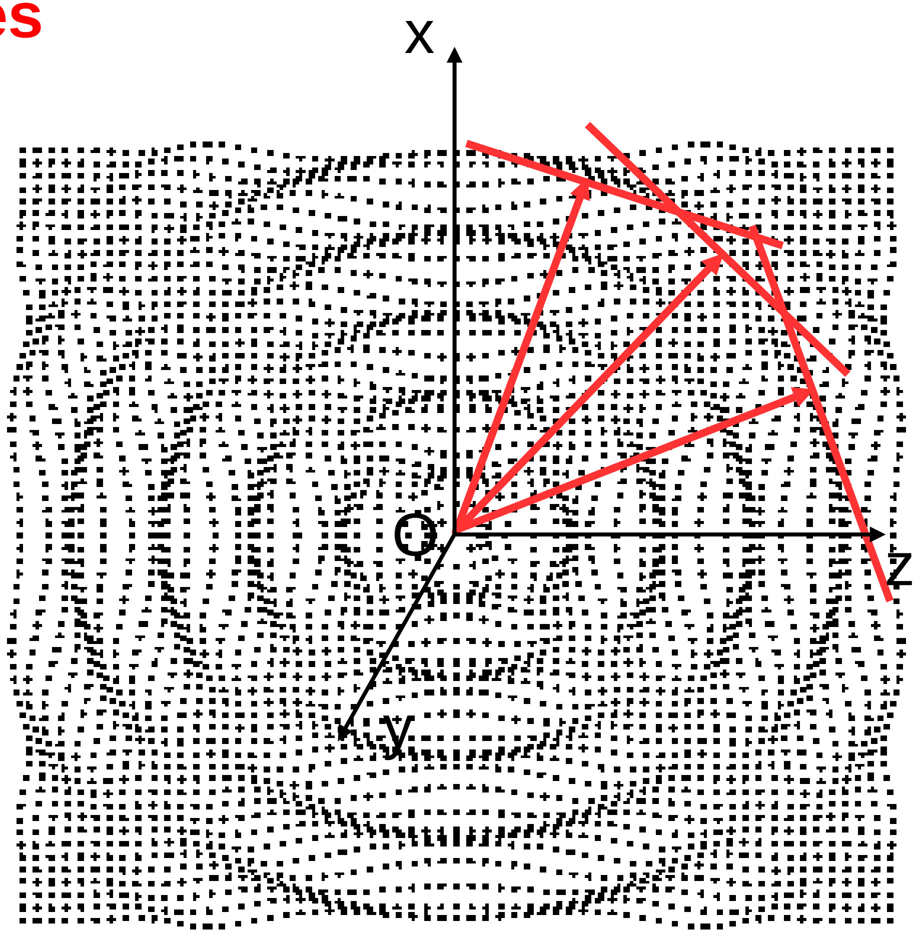
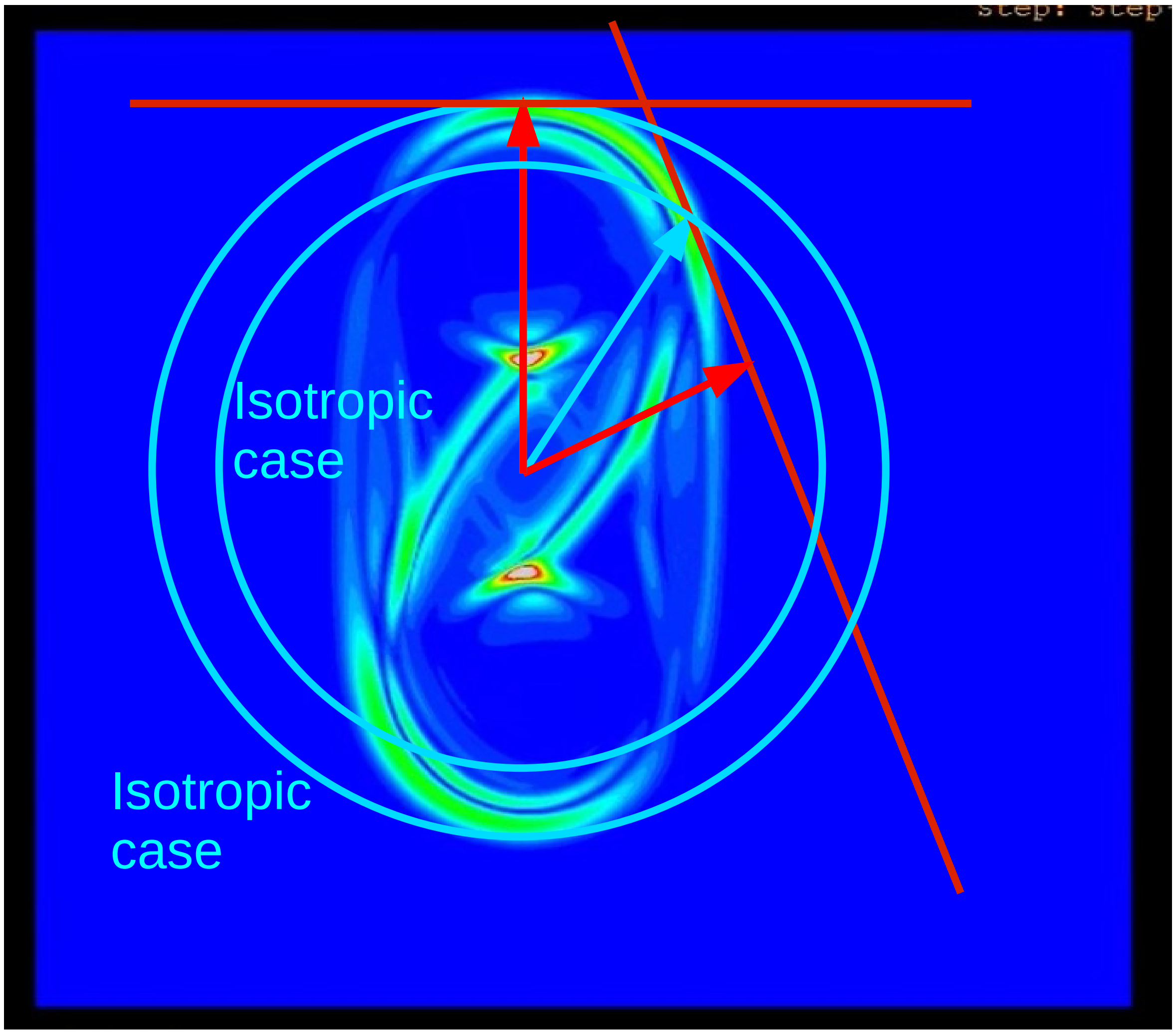
Are plane waves usefull ?

Any wave can be considered as a superposition of plane waves



Example

Any wave can be considered as a plane waves superposition



Energy velocity vector

Plane wave velocity vector

Wave equation characteristics
exemple of a fluid

$$\Delta\delta p - \frac{\rho_0}{\kappa}\frac{\partial^2 \delta p}{\partial t^2} = 0$$

One can remark that the constant (κ/ρ_0) is homogeneous to $(m.s^{-1})^{2}$,
Then the wave equation can be written as :

$$\Delta\delta p - \frac{1}{c^2}\frac{\partial^2 \delta p}{\partial t^2} = 0$$

- Where the constant c is a velocity
- The wave speed is related to the elastic modulii of the propagation medium

Relation between the propagation velocity and the medium properties

The elastic waves propagation velocity is directly linked to the material properties

$$v = \sqrt{\frac{\kappa}{\rho_0}}$$

Compression modulus

Propagation velocity

density

This relation can be exploited :

- To evaluate the distance of a "target" in a known medium (NDT)
- To evaluate the properties of an unknown material (NDE)

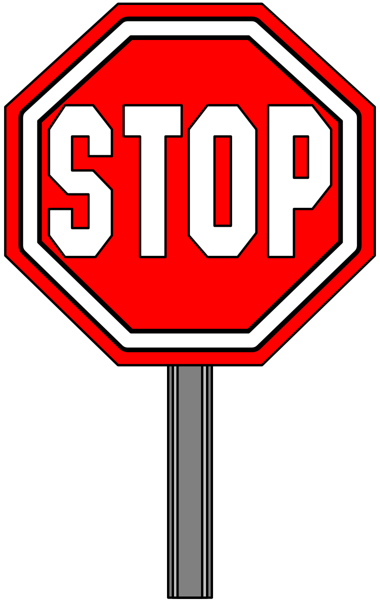
Ultrasonic velocities in an isotropic solid

$$C_L = \sqrt{\frac{E\left(1-\nu\right)}{\rho\left(1+\nu\right)\left(1-2\nu\right)}}$$

$$C_T = \sqrt{\frac{E}{2\rho\left(1+\nu\right)}}$$

Elastic waves in the harmonic regime

Progressive Plane Harmonic Waves with Linear Polarisation



In the following we'll only deal with linear polarisation waves : i.e. the polarisation remains constant during propagation.

All the other cases of polarisation can be considered as combinations of linear ones.

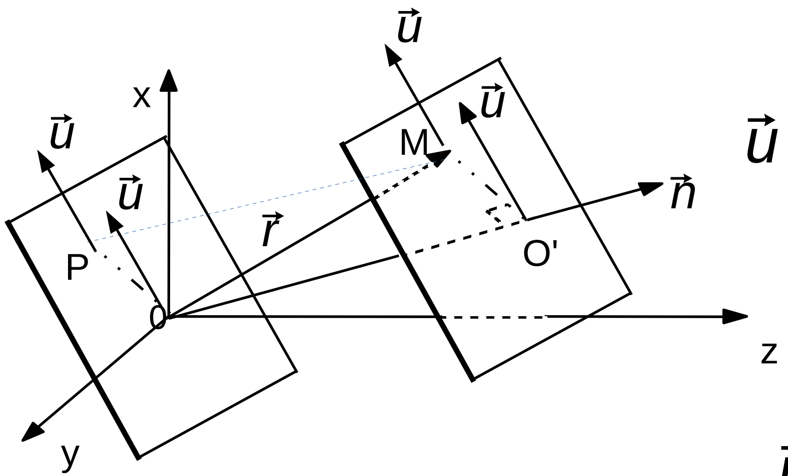
PPHL Waves

If a source located at O produces a signal s(t), it induces a disturbance :

$$\vec{f}(t) = \vec{u}_0 \cos(\omega t + \theta_0)$$

The observed disturbance at a point M is :

$$\vec{u}(M,t) = \vec{u}(O,t') = \vec{f}(t') \quad avec \quad t' = t - \frac{\vec{n}.\vec{r}}{v}$$



$$\vec{u}(M,t) = \vec{u}_0 \cos\left(\omega\left(t - \frac{\vec{n}.\vec{r}}{v}\right) + \theta_0\right)$$

And by distibuting ω into the parenthesis

$$\vec{u}(M,t) = \vec{u}_0 \cos\left(\omega t - \frac{\omega}{v}\vec{n}.\vec{r} + \theta_0\right)$$

$$\vec{u}(M,t) = \vec{u}_0 \cos\left(\omega t - \vec{k}.\vec{r} + \theta_0\right)$$

Quantities associated to PPHL Waves

$$\vec{u}(M,t)=\vec{U}_0\cos(\omega.t-\vec{k}.\vec{r}+\theta_0)=U_0\,\vec{p}\cos(\Psi(t))$$

U_0 : amplitude

$\vec{p}$: polarisation (unit vector)

$\Psi(t)$: instantaneous phase (rd)

θ_0 : phase at the space and time origin (rd)

$\omega=\frac{2.\pi}{T}$: angular frequency $(rd.s^{-1})$; T : time period (s)

$\vec{s}=\frac{\vec{n}}{v}$: slowness vector $(s.m^{-1})$: $\vec{k}=\frac{\omega}{v}.\vec{n}$: wave vector $(rd.m^{-1})$

$k=\frac{\omega}{v}=\frac{2.\pi}{\lambda}$: wave number or propagation constant $(rd.m^{-1})$

$\vec{n}$: unit vector (propagation direction)

λ : spatial period or wavelength (m^{-1})

v : propagation velocity $(m.s^{-1})$

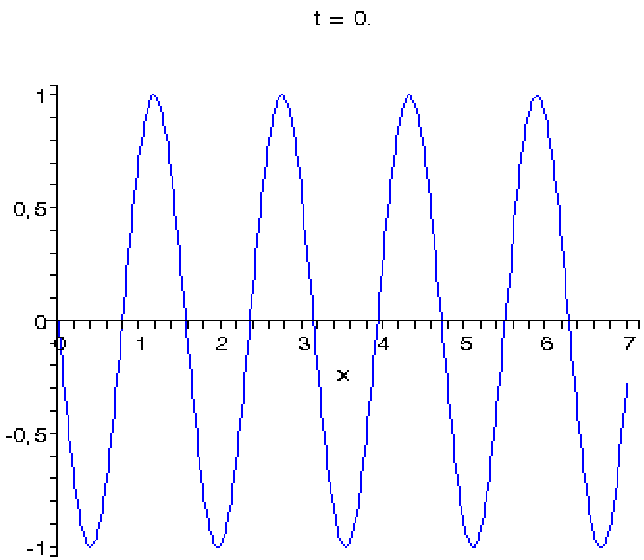
PPHL Waves

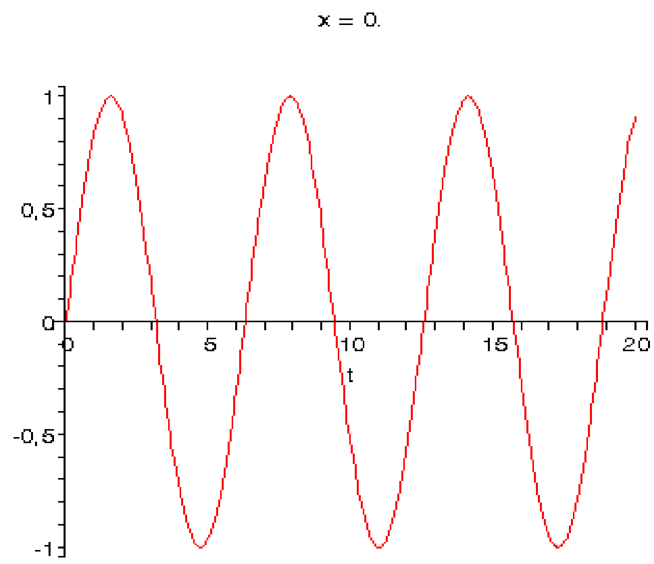
In the case of Uniform the isophase Ψ(t)=cte and isoamplitude U_0=cte surfaces are planes and are superimposed.

$$\vec{u}(M,t) = U_0 \vec{p} \cos(\Psi(t)) = \vec{U}_0 \cos(\omega t - \vec{k}.\vec{r} + \theta_0)$$

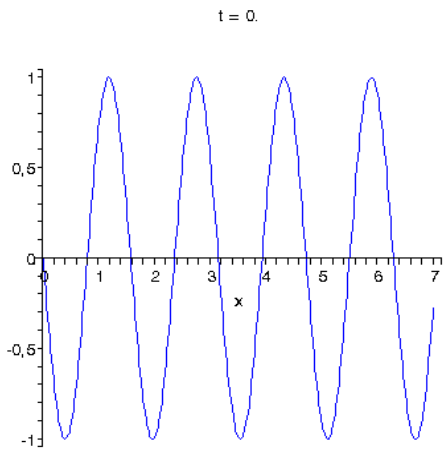
This function is periodic both in space and time

see Maple worksheet

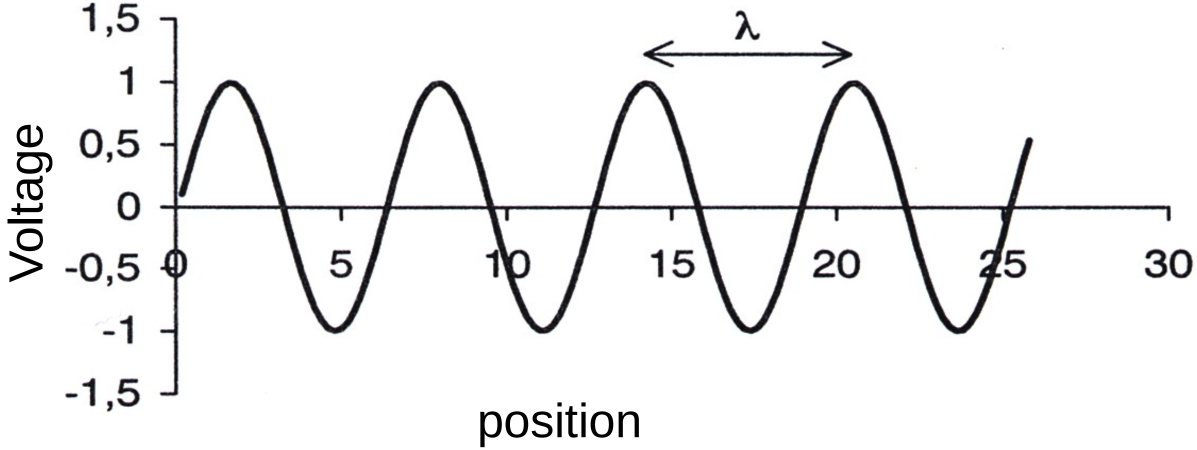


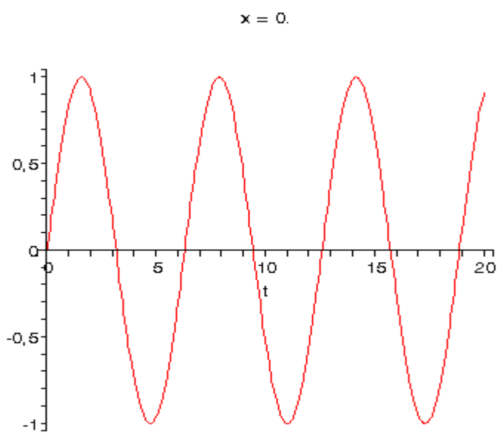


$$\vec{u}(M,t)=U_0\vec{p}\cos(\Psi(t))=\vec{U}_0\cos(\omega t-kx+\theta_0)$$

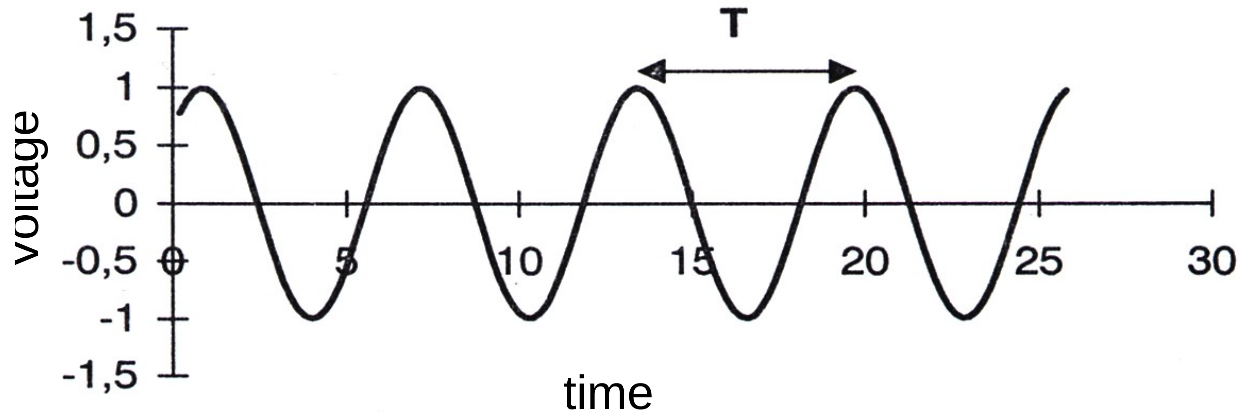


At a given moment





At a given position



Complex representation of UPPHL waves

$$\tilde{\vec{U}}(M,t)=\tilde{\vec{U}}_0\exp\left[j\left(\omega t-\vec{k}.\vec{r}+\theta_0\right)\right]=\tilde{U}_0\vec{p}\exp\left[j\left(\omega t-\vec{k}.\vec{r}\right)\right]$$

$$\tilde{U}_0=U_0\exp\left(j\theta_0\right) \qquad : \quad \text{complex amplitude}$$

$$\tilde{\vec{U}}(M,t)=\tilde{U}_0\vec{p}\exp\left[j\left(\omega t-\left(k_x x+k_y y+k_z z\right)\right)\right]$$

Let's express the space and time derivatives of this kind of function :

$$\frac{\partial\tilde{\vec{U}}(M,t)}{\partial x}=-jk_x\tilde{\vec{U}}(M,t)\;;\frac{\partial\tilde{\vec{U}}(M,t)}{\partial y}=-jk_y\tilde{\vec{U}}(M,t)\;;\frac{\partial\tilde{\vec{U}}(M,t)}{\partial z}=-jk_z\tilde{\vec{U}}(M,t)\Rightarrow\tilde{\vec{\nabla}}=-j\vec{k}.$$

$$\frac{\partial^2\tilde{\vec{U}}(M,t)}{\partial x^2}=-k_x^2\tilde{\vec{U}}(M,t)\;;\frac{\partial^2\tilde{\vec{U}}(M,t)}{\partial y^2}=-k_y^2\tilde{\vec{U}}(M,t)\;;\frac{\partial^2\tilde{\vec{U}}(M,t)}{\partial z^2}=-k_z^2\tilde{\vec{U}}(M,t)\;;\Rightarrow\tilde{\Delta}=-k^2.$$

as well

$$\frac{\partial\tilde{\vec{U}}(M,t)}{\partial t}=j\omega\tilde{\vec{U}}(M,t)\quad et\quad\frac{\partial^2\tilde{\vec{U}}(M,t)}{\partial t^2}=-\omega^2\tilde{\vec{U}}(M,t)$$

Wave equation in complex form

wave equation

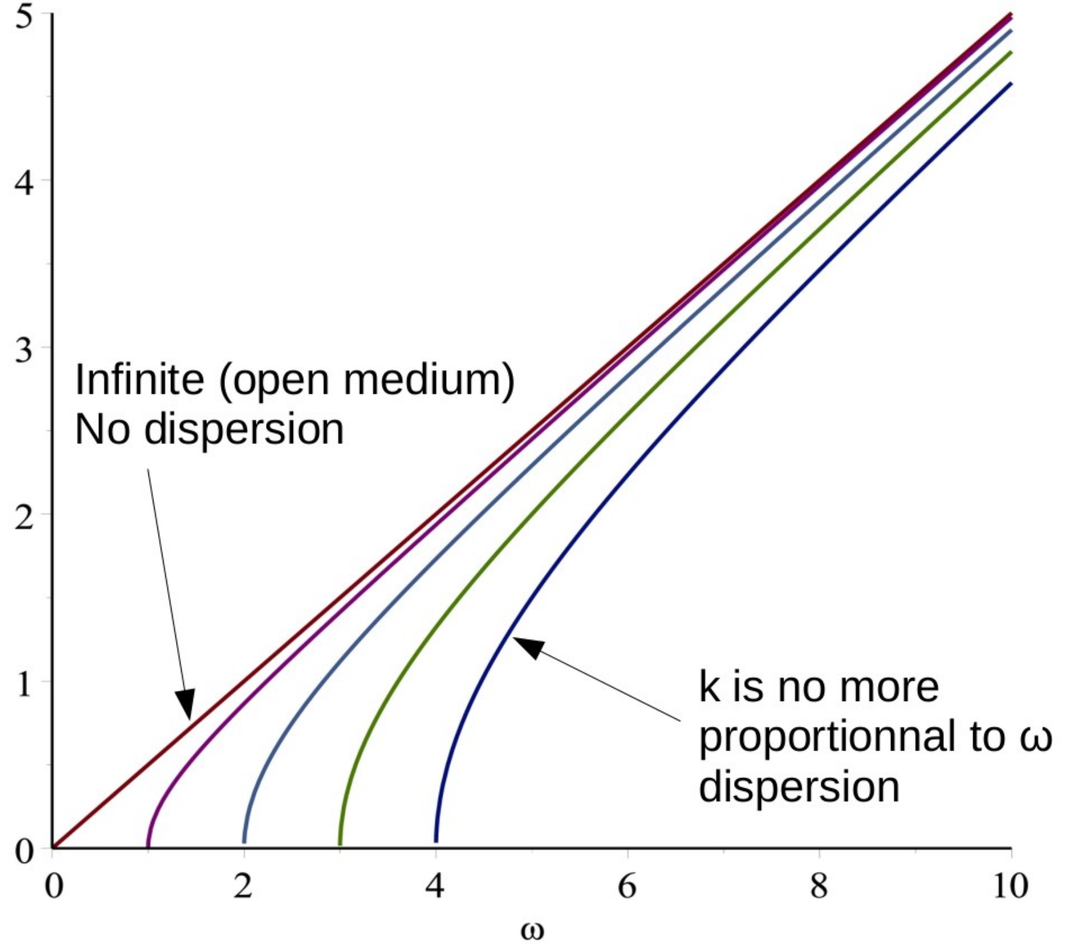
$$\left(\tilde{\Delta} - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}\right)\tilde{\vec{U}}(M,t) = 0$$

dispersion equation

$$\boxed{k^2 - \frac{\omega^2}{v^2} = 0}$$

dispersion equation

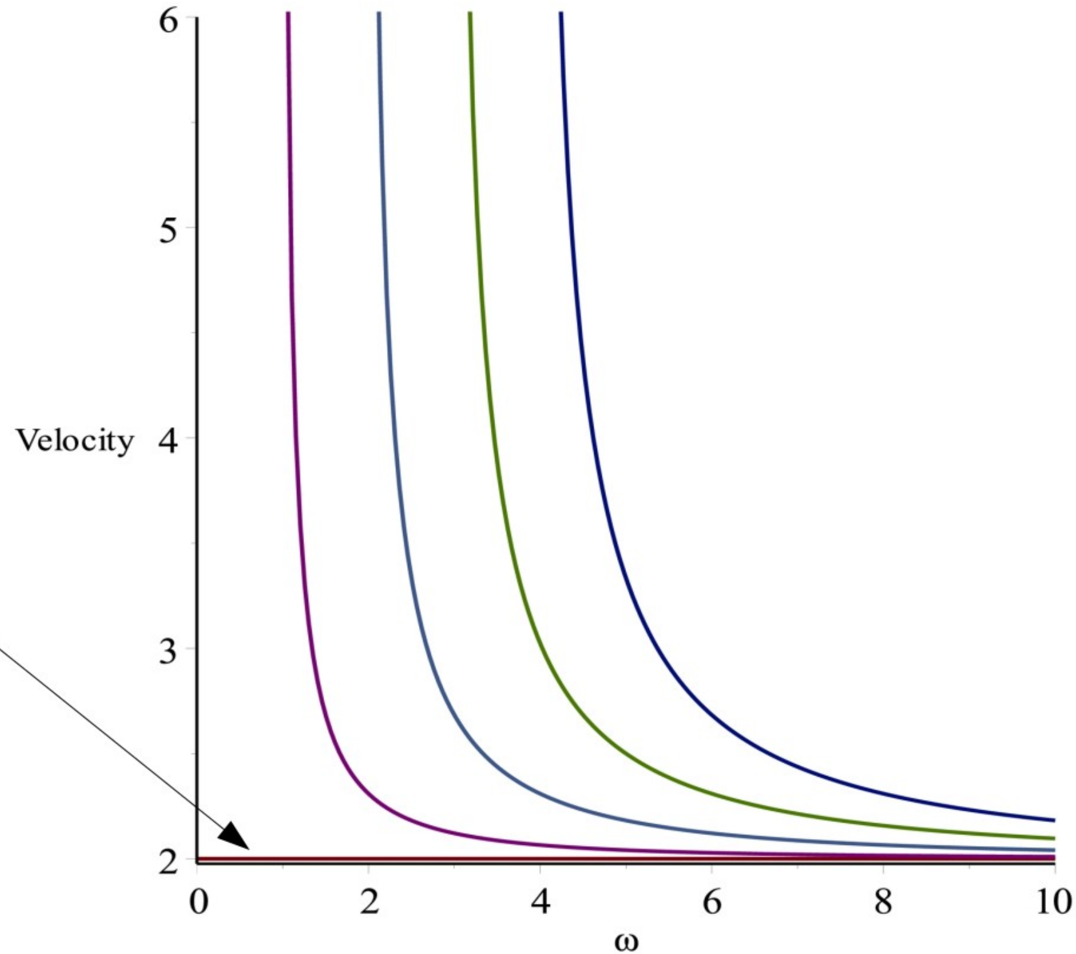
$$k^2 - \frac{\omega^2}{v^2} = 0$$



dispersion equation

$$k^2 - \frac{\omega^2}{v^2(\omega)} = 0$$

Infinite (open medium)
No dispersion v is independent of ω
(free space propagation)

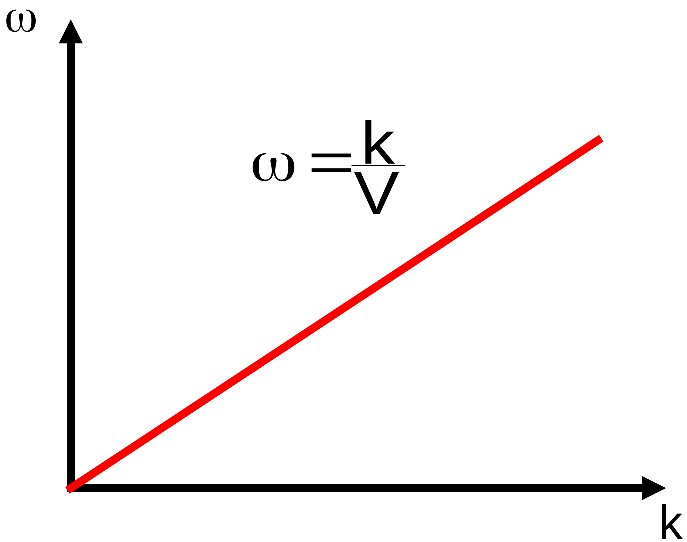


Dispersion curves

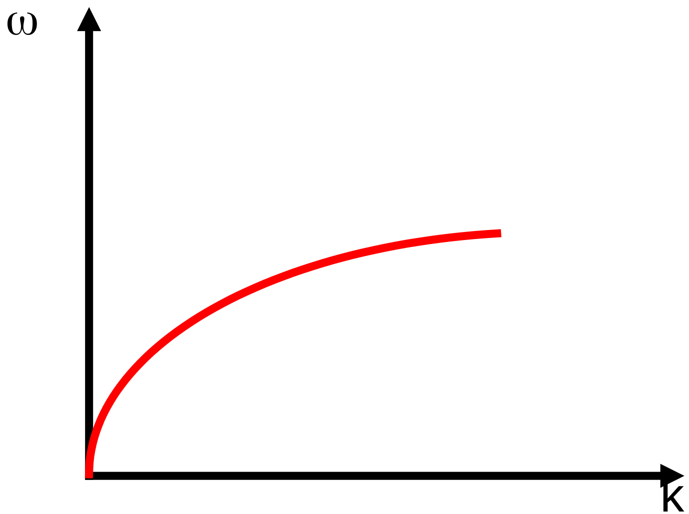
Dispersion curves are plots of the dispersion equation : namely ω(k) but also V(k) or V(f) or

- *non dispersif case*
  V = Cte

dispersive case
V = f (ω)



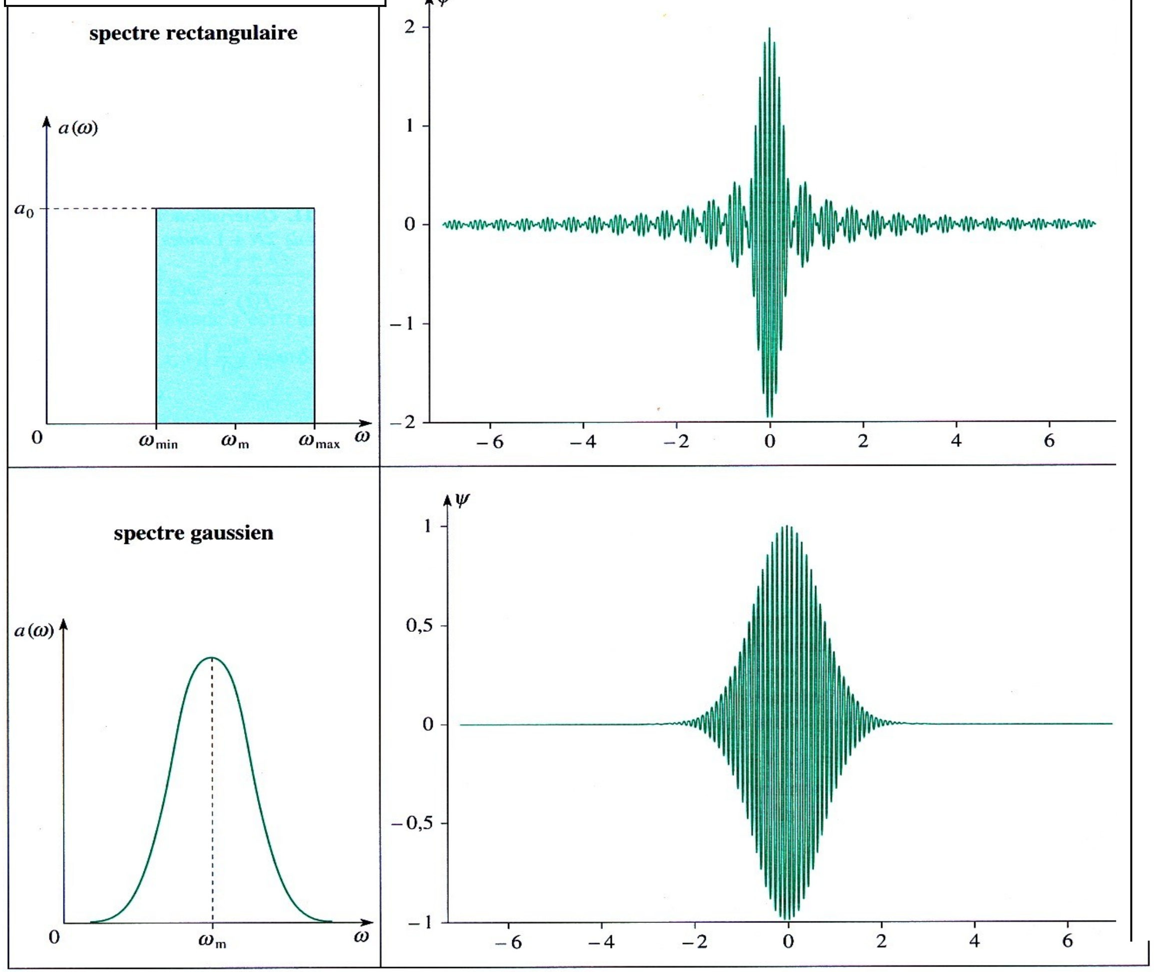
The dispersion curve is linear



The dispersion curve is non linear

Examples of wave packets

Frequency domain	Time domain (wave packet)

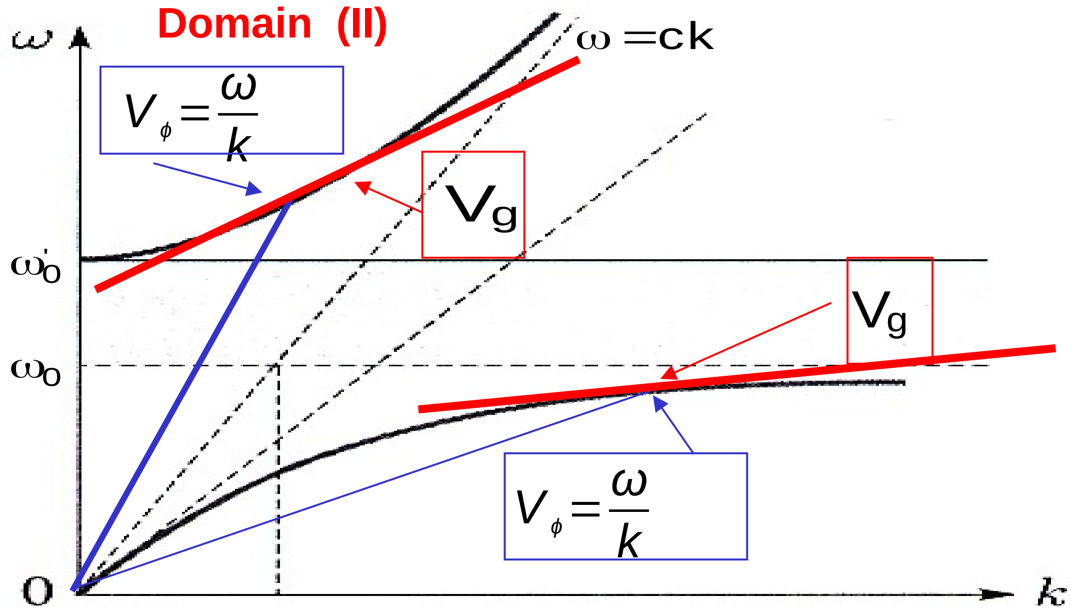


Group velocity of a wave packet

$$\delta\omega \ll \omega_m \quad \Rightarrow \quad \frac{\delta\omega}{\delta k} \approx \frac{d\omega}{dk}$$

The group velocity V_g is the slope at $\omega = \omega_m$ of the dispersion curve $\omega(k)$

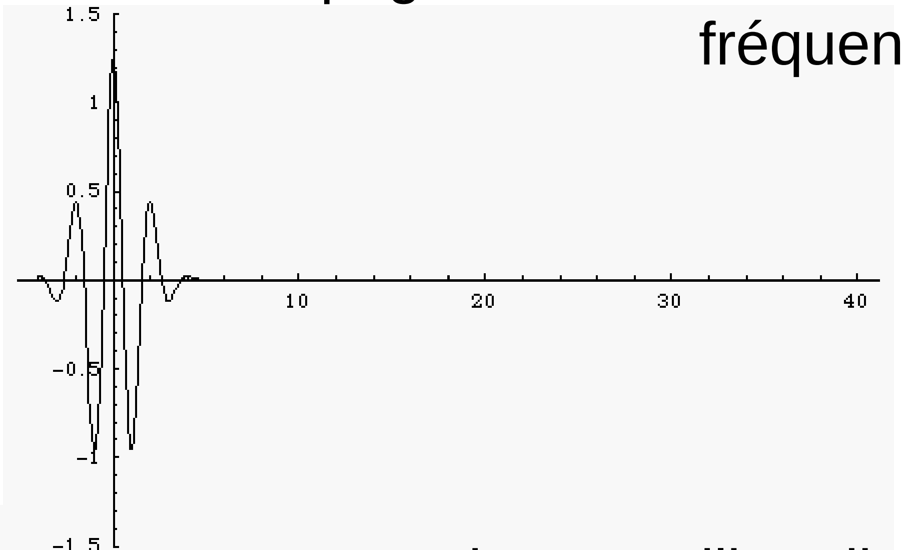
Example of a dielectric material (optics)



Conséquences sur la propagation des ondes

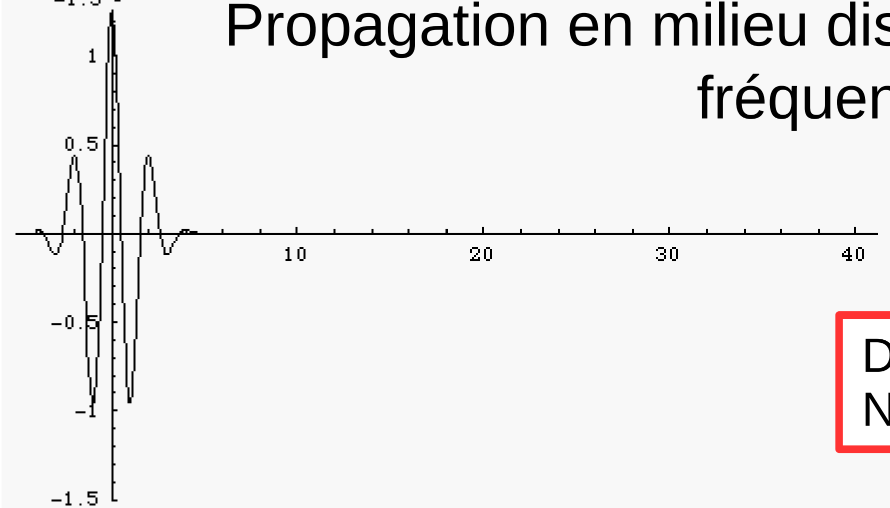
Propagation en milieu non dispersif : Toutes les composantes fréquentielles se déplacent à la même vitesse

PAS DE DISTORSION



Propagation en milieu dispersif : chacune des composantes fréquentielles se déplace à sa propre vitesse

DISTORSION DU SIGNAL



Difficultés à définir le temps de vol
Nécessité d’introduire la notion de vitesse de groupe

Concept of impedance

Let's consider a UPPL wave propagating along x increasing

direction (resp. decreasing) : $\delta p(x,t) = f\,(t \mp \frac{x}{v})$

$$\left.\begin{aligned} \frac{\partial \delta p(x,t)}{\partial t} &= f\,' \\ \frac{\partial \delta p(x,t)}{\partial x} &= \mp \frac{1}{v}\, f\,' \end{aligned}\right\} \Rightarrow \frac{\partial \delta p(x,t)}{\partial t} = \mp v \frac{\partial \delta p(x,t)}{\partial x}$$

From the state equation of the fluid :

$$\delta p(x,t) = -\kappa \frac{\partial u(x,t)}{\partial x} \Rightarrow \frac{\partial \delta p(x,t)}{\partial t} = -\kappa \frac{\partial \dot{u}(x,t)}{\partial x}$$

Then : $$\mp v \frac{\partial \delta p(x,t)}{\partial x} = -\kappa \frac{\partial \dot{u}(x,t)}{\partial x}$$

Impedance (cont)

By integration with respect to x variable

$$\delta p(x,t) = \pm\frac{\kappa}{V}\dot{u}(x,t) = Z\dot{u}(x,t)$$

with $$Z = \pm\frac{\kappa}{V} = \pm Z_c$$

where :

Z : acoustic impedance

Z_c : caracteristic impedance of the medium

Note that Z_c only depends upon the material properties

$$\boxed{Z_c = \frac{\kappa}{V} = \kappa\sqrt{\frac{\rho_0}{\kappa}} = \sqrt{\kappa\rho_0} = \rho_0 V}$$

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Some examples of impedance values

Unit : the Rayleigh - Ray - ($kg.m^{-2}.s^{-1}$)

Exemples

Fluid	Temperature (K)	Z_c (Mrayl)
water	298	1,49
méthanol	303	0,866
mercury	297	19,7
Air (1 Mpa)	331	$0,428.10^{-3}$
Air (1 Mpa)	343	$0,414.10^{-3}$
Argon (4 Mpa)	293	23.10^{-3}