Physical acoustics

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1 Introduction to elastic waves

What is a wave?

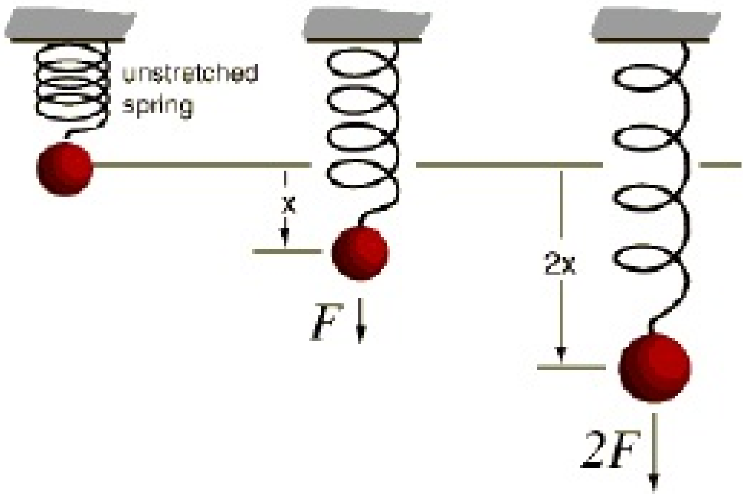
This is a rather fuzzy concept and several answers are possible.

- Answer 1 (signal processing): a wave is a (mathematical) model describing the propagation of a long distance signal as a function of time. Whatever it physically is, information (the signal) carried by the wave matters most.
- Answer 2 (applied mathematics): a wave is the solution to a wave equation, an elliptic partial differential equation of time and space. What matters is existence and unicity of the solutions, depending on boundary conditions.
- Answer 3 (physics): a wave is a propagating (small) perturbation of the state of equilibrium of a medium or a material. When locally and temporarily placed out of equilibrium, the medium reacts so as to return to its preferred state: rest! The perturbation propagates from a point to the next causally. The simplest approach is to consider the perturbation so little that the response is elastic; i.e. nonlinearities are neglected.

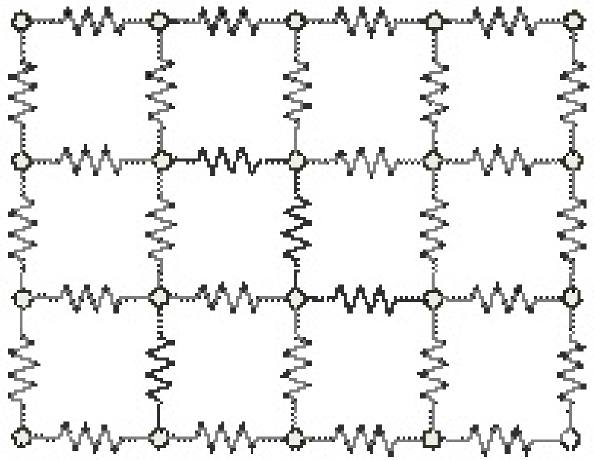
In this lecture, the physical point of view will be our main concern, but of course the two other points of view can't be neglected!

2 Elasticity

The simplest model of the elastic behavior of a medium subjected to a deformation is the spring.



1D



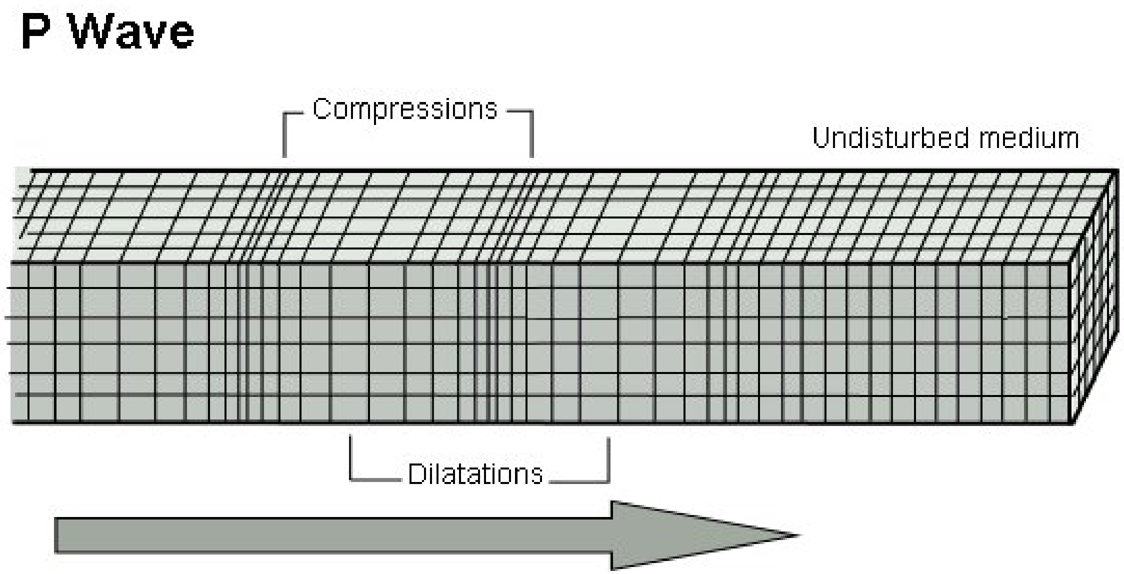
2D

3 What are the different types of elastic waves?

3.1 Longitudinal or pressure waves (P)

They propagate in any homogeneous medium: they are bulk waves.

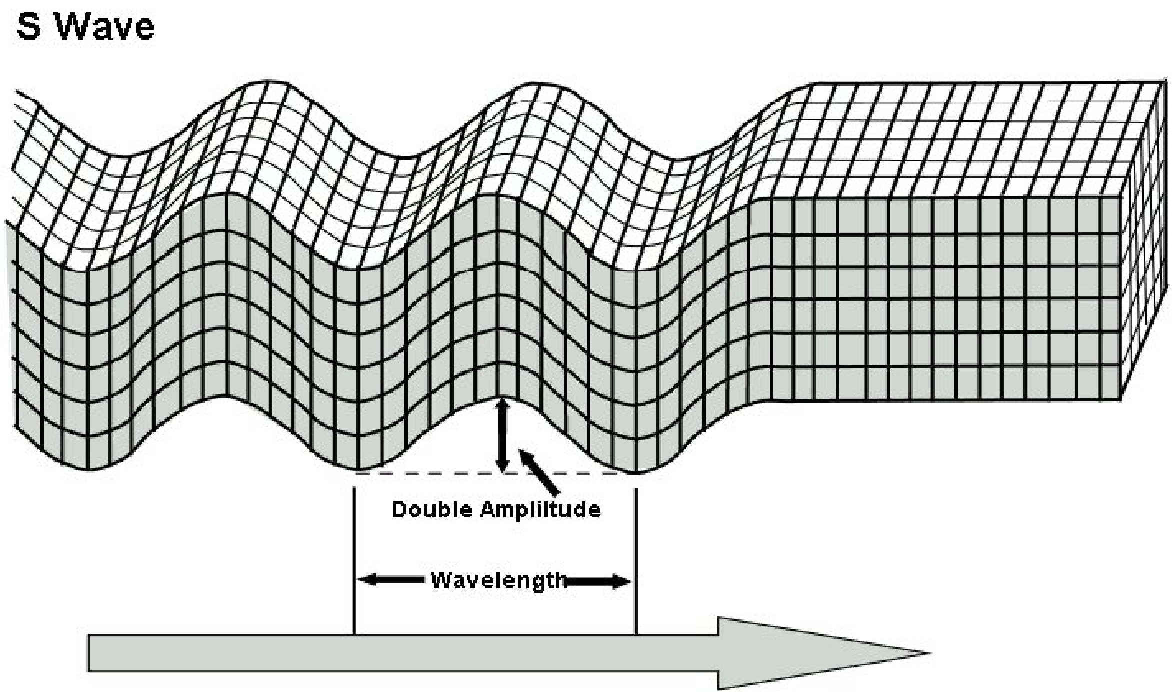
They exist is any kind of material state (fluid or solid). They are compressional waves (any variation of the local volume is related to a variation of pressure). The polarization is longitudinal.



3.2 Shear (transverse) waves (S waves)

Shear waves propage in a homogeneous medium: they are bulk waves.

They don't exist in non-viscuous fluids (ideally, they don't exist in air or water). There are always 2 shear waves in solids. The velocities can be degenerated (same direction of propagation, but orthogonal polarization). Displacements are not related to a change in the local volume.

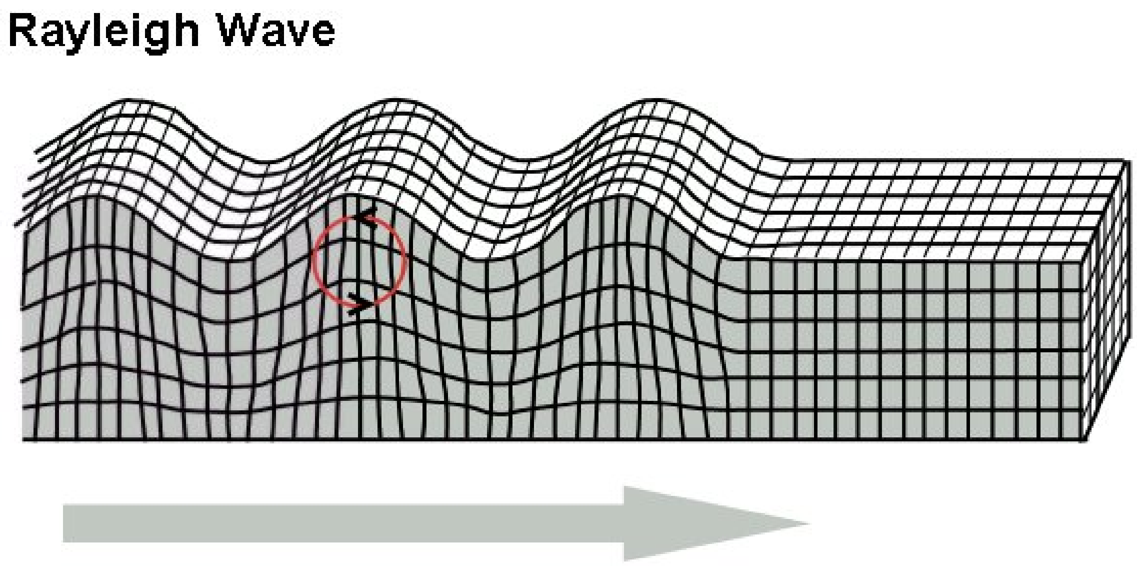


3.3 Rayleigh surface waves (R)

Surface waves propagate at the surface of a medium or at the interface between two media (interface waves).

They exist in fluids, in particular at the interface of water and air (water waves on the sea) but also in solids. The polarization (the displacement vector) is (mostly) elliptical. Displacements are related to a local volume change.

The displacement amplitude decreases exponentially away from the surface or interface.

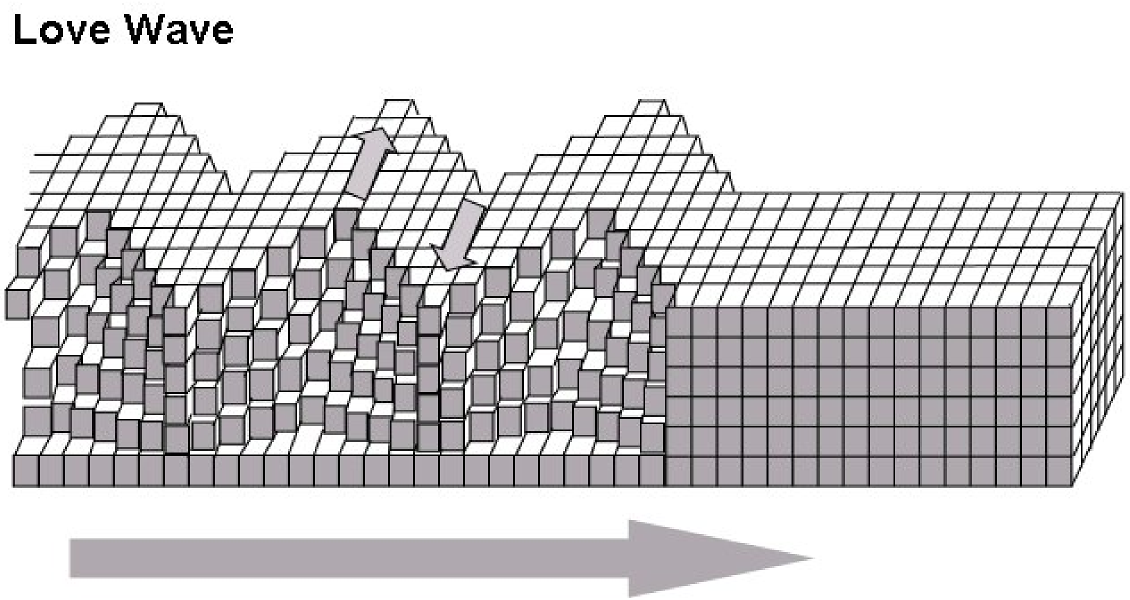


3.4 Shear (or transverse) surface waves

They propagate at the surface of a medium or at the interface between two media (interface waves).

They are referred to as Love waves in seismology (a Love wave is a surface mode of a composite substrate in ultrasonics). The polarization is purely transverse. Displacements are not related to a change in the local volume.

The displacement amplitude decreases exponentially away from the surface or interface.

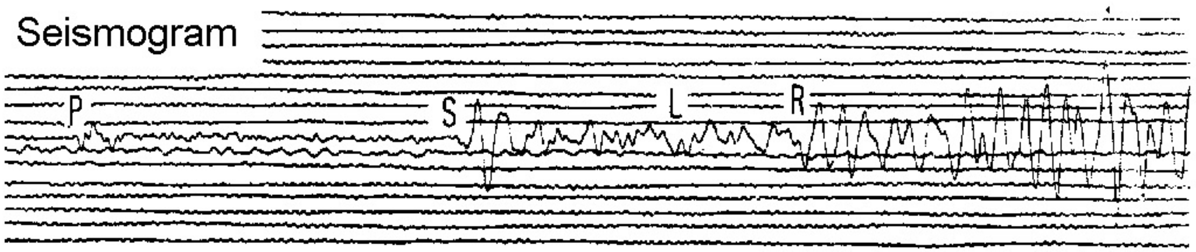


4 Earthquakes

In seismology, elastic waves propagate inside the crust of the Earth. Shear waves (S) cause the largest damage to buildings...

before  after.... 

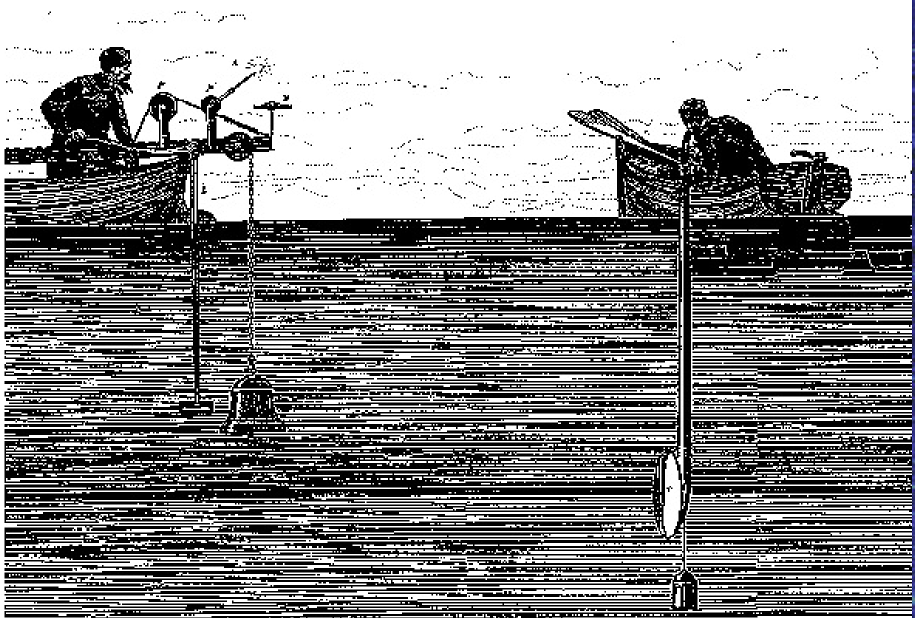
Seismogram showing the successive arrival of 4 type of waves

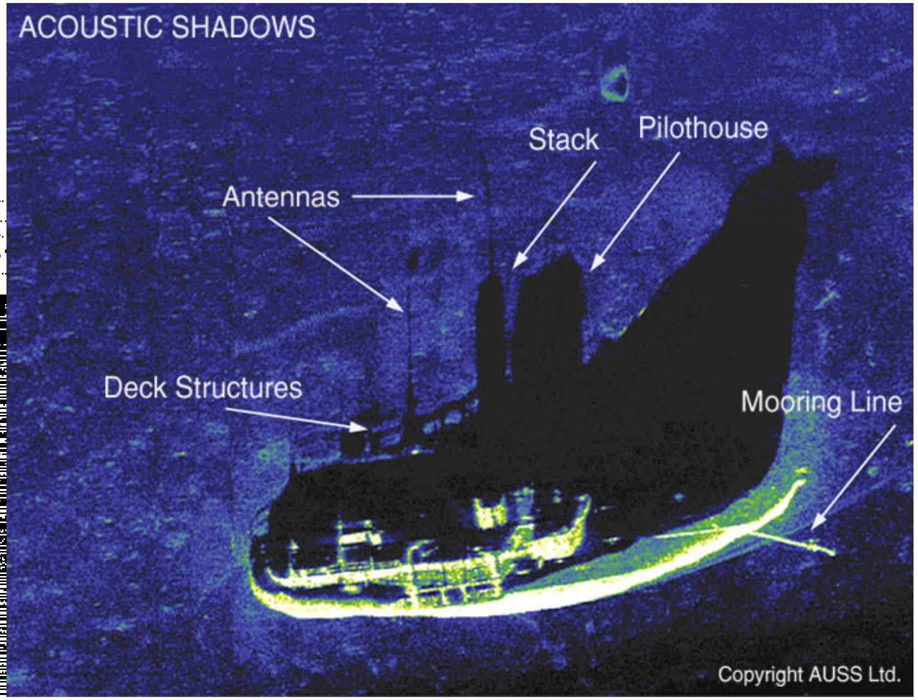


5 Applications of waves in fluids?

5.1 The sonar

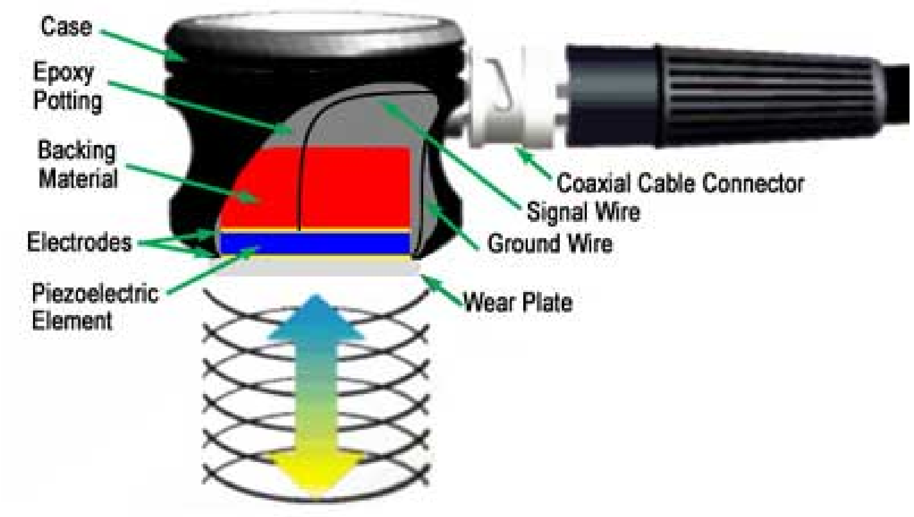
The sonar is a technique related to the Radar, but for underwater detection. Acoustic frequencies are relatively low, limiting the spatial resolution but increasing the reach.





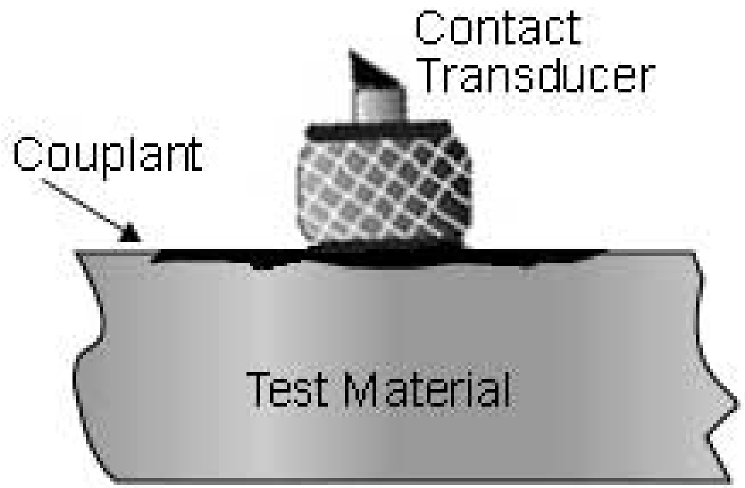
5.2 Medical echography

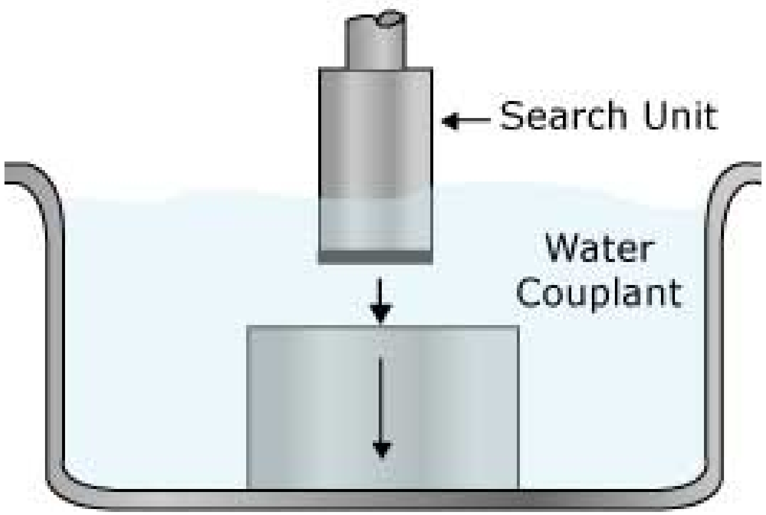
The human body looks much like water from the point of view of acoustic properties, except for certain parts such as bones. Ultrasonic waves (ultrasonic = the frequency of which is larger than what can be perceived by the human ear) are used for imaging the inside of the body or of organs.

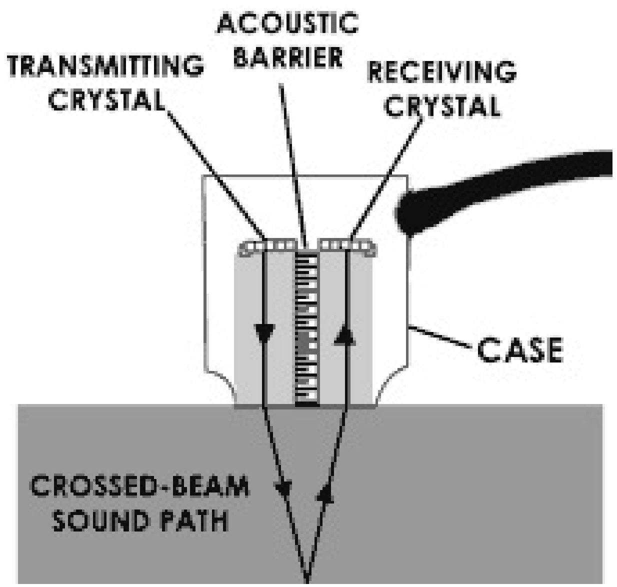


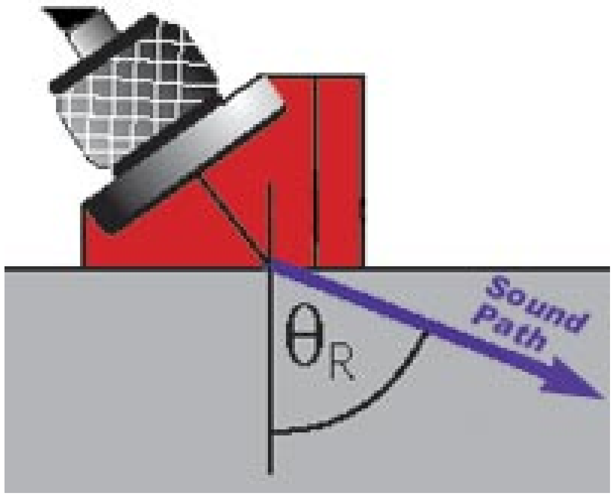
6 Applications of wave in solids?

6.1 Non destructive evaluation





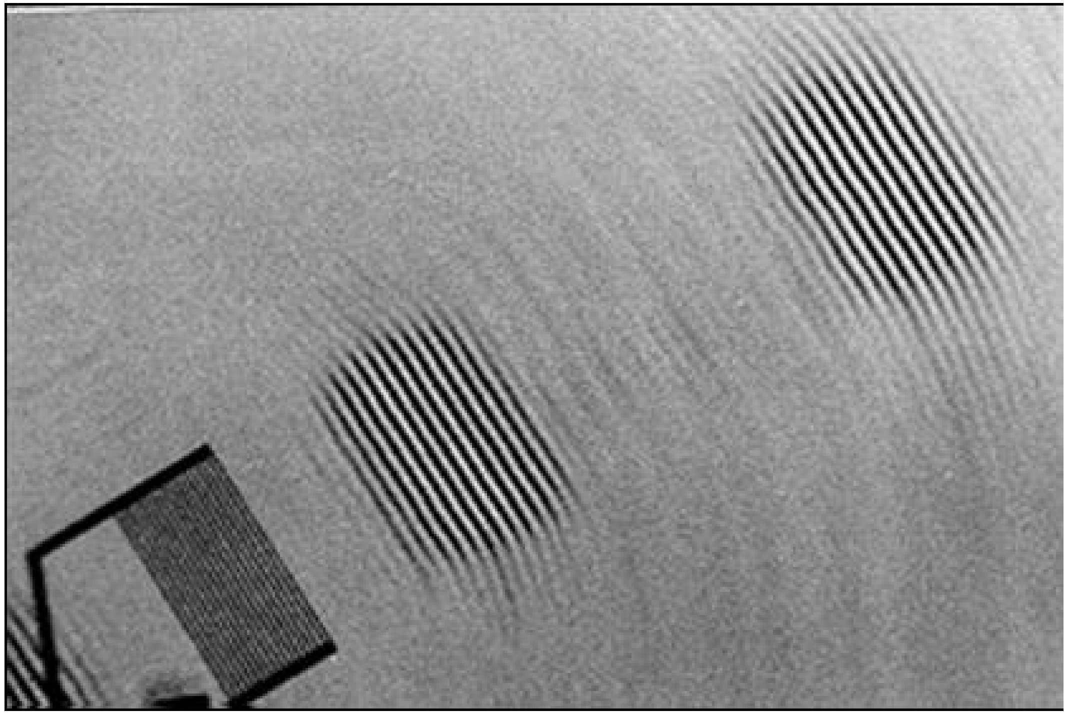




6.2 Surface elastic wave (surface acoustic waves, SAW)

There are presently several SAW filters in any mobile phones! Those filters are manufactured on piezoelectric substrates of quartz, lithium tantalate or others.

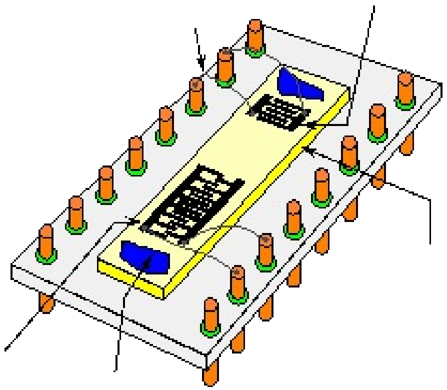
SAW are generated directly at the surface by interdigitated metal combs (interdigital transducer, IDT), having a periodicity of a few microns or less. The operating frequencies of SAW filters range from 50 MHz (television) to 2.5 GHz (UMTS).

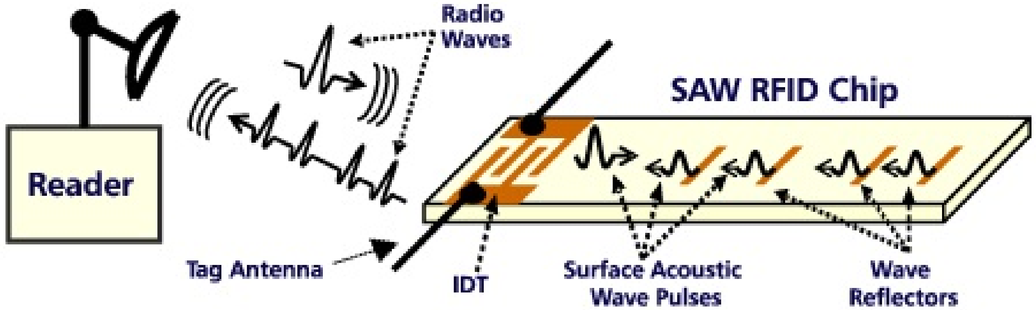


6.3 SAW sensors

Surface waves are quite sensitive to anything that changes local propagation conditions on the surface. They are furthermore quite sensitive to physical perturbations: temperature, pressure, stress, or else. As a matter of fact, SAW devices are the technological basis for very sensitive sensors, that can potentially be interogated from a distance when combined with a radio-frequency (RF) antenna.

These properties naturally extend to bulk elastic waves devices and thin-film devices.

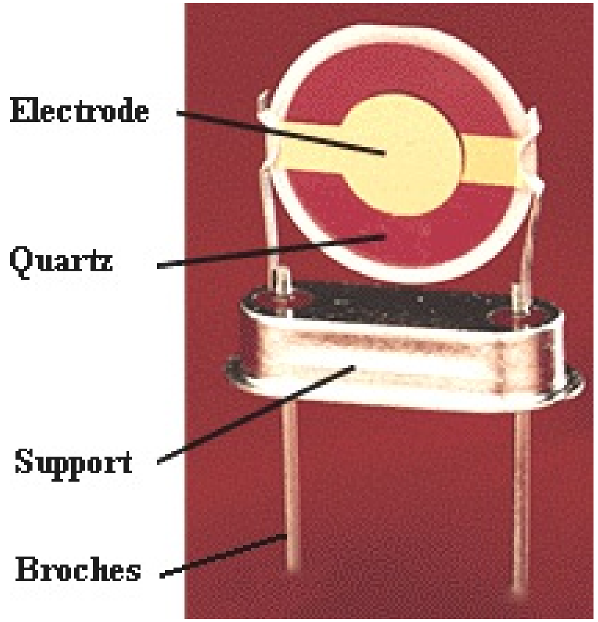




6.4 Bulk acoustic wave (BAW) resonators

There exist numerous types of resonators based on bulk waves, or more generally based on some acouctic mode, in a single-cristal. Among all materials, single-cristals have the smallest attenuation. It is thus possible to store elastic energy for a large number of wave oscillations, defining very pure frequencies. Control of a prescribed frequency leads to clockmaking, and hence to time measurement. Quartz crystals are widely used for this purpose.

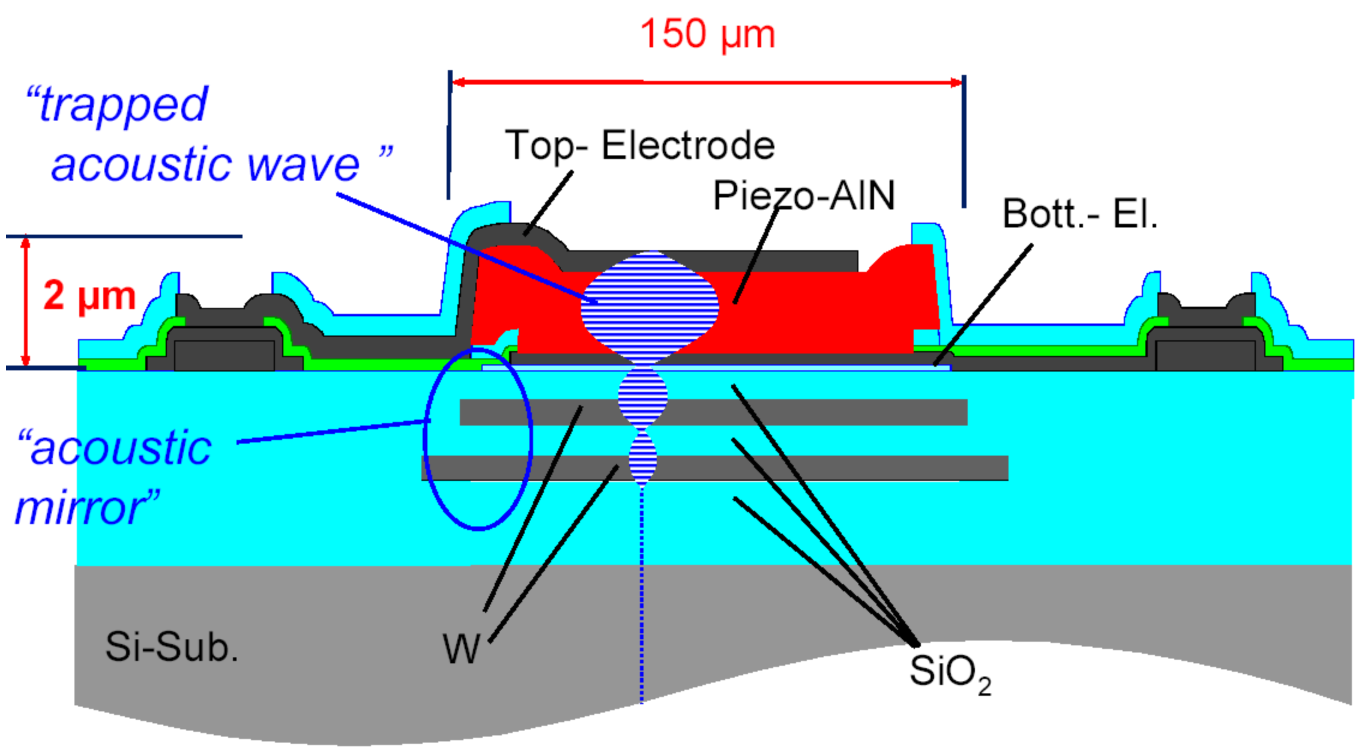
Useful frequencies range from a few 10 kHz to a few 100 MHz.



6.5 Film bulk acoustic resonators (FBAR)

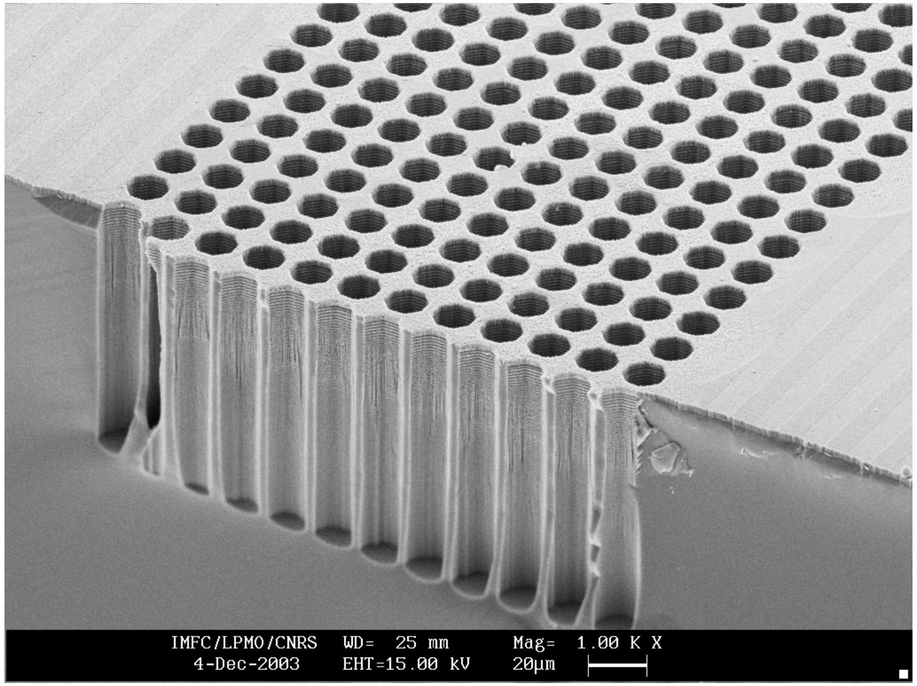
FBAR (film bulk acoustic resonators) are bulk wave resonators using piezoelectric thin-films with micron-size thickness. They have slightly larger loss than single-crystal resonators, but high frequency operation is possible (1 to 5 GHz). They complement SAW filters.

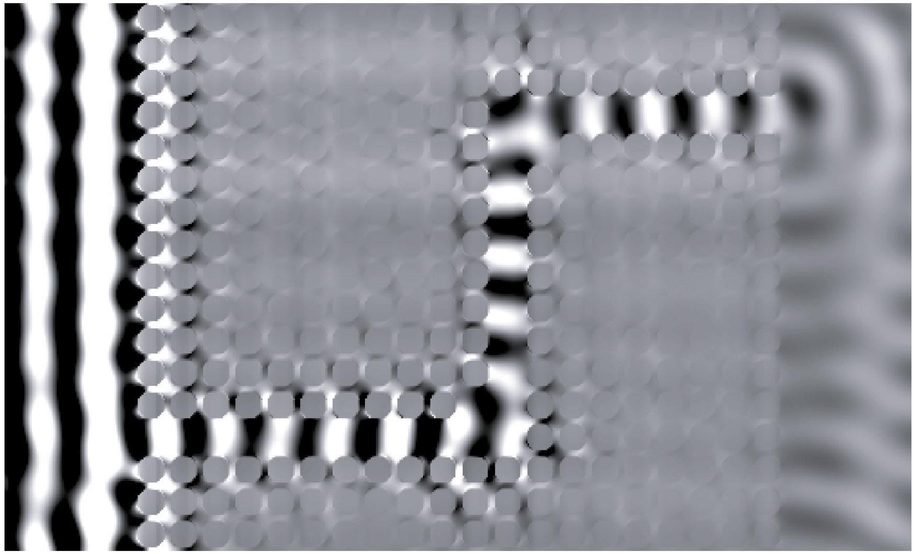
The figure depicts a SMR (solidly mounted resonator).



6.6 Phononic crystals

Phononic crystals are 1D, 2D, or 3D composite periodic structures similar to photonic crystals in optics/electromagnetism. A large material contrast is generally necessary to obtain complete band gaps, i.e. frequency ranges within which any wave is reflected, whatever the polarization or the direction of incidence.





7 Agenda

1. Introduction
2. Scalar acoustic waves

3. Cristals, tensors, elasticity and piezoelasticity (summary)
4. Plane waves in solids

5. Guided waves
Plate waves
Guided waves
Surface waves

Hands-on acoustic problems with Comsol