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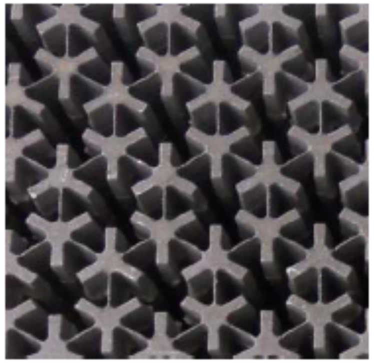
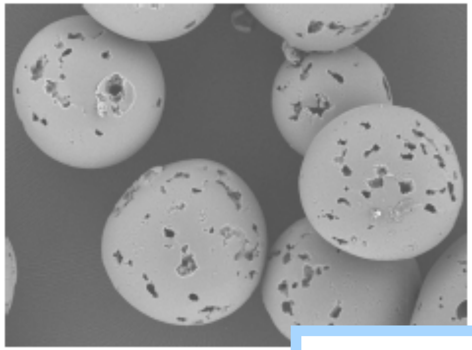
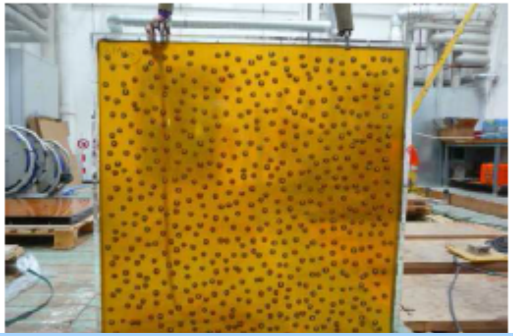
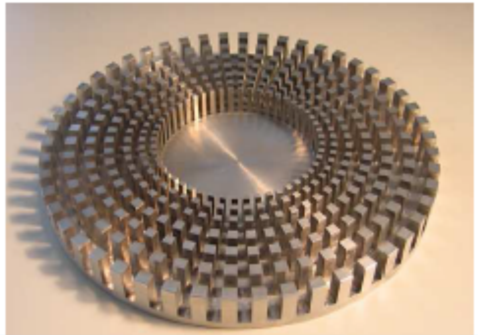
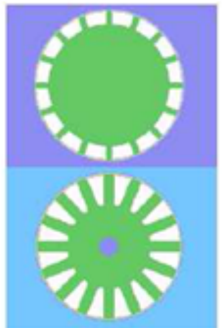


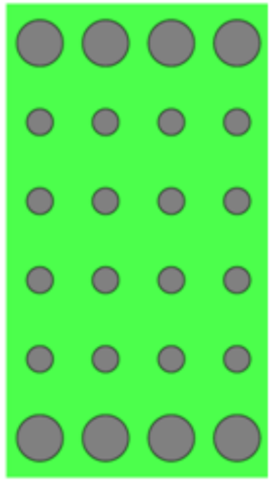


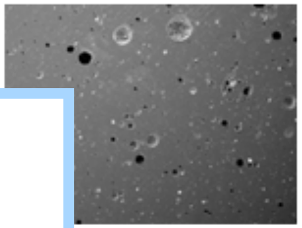


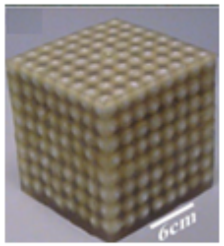


Metagenierie – Oléron – July 2017
Acoustic metamaterials and underwater acoustics applications









Christian Audoly
DCNS Research

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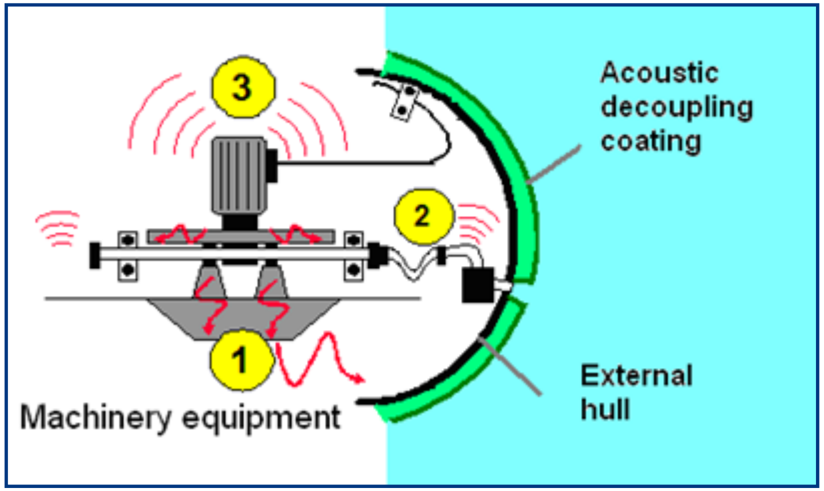
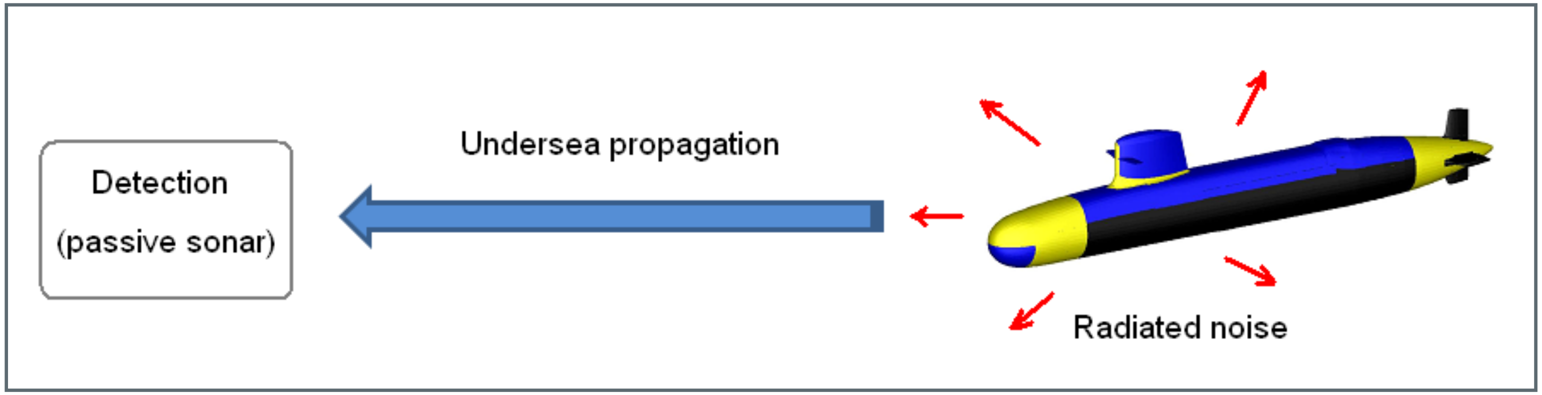
Contents

Materials for underwater acoustics – What applications ?

Underwater radiated noise

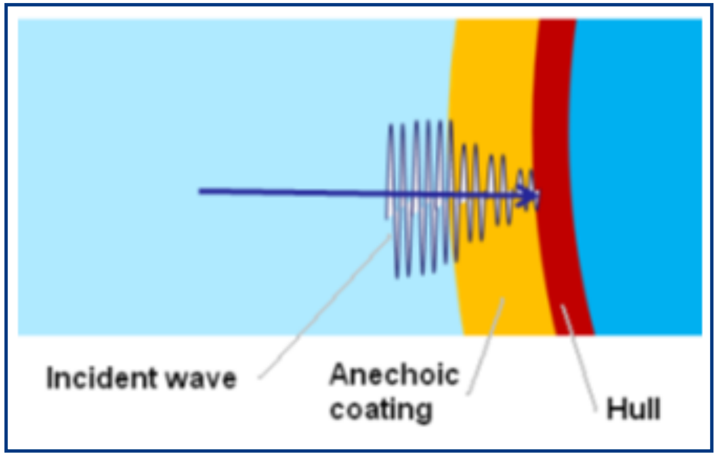
- Most of marine systems, structures or vehicles are equipped with machinery and with propellers, producing noise and vibration, radiating underwater noise or sound
- Emitted underwater noise can be detected by adverse passive sonars
- External hull acoustic decoupling coatings is an efficient solution for reduction of radiated noise

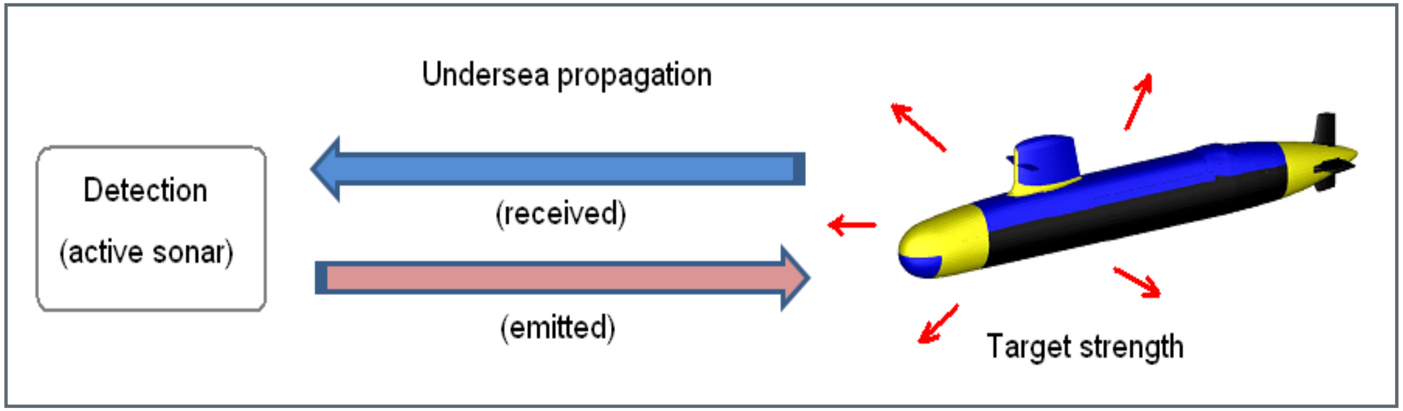




Acoustic target strength

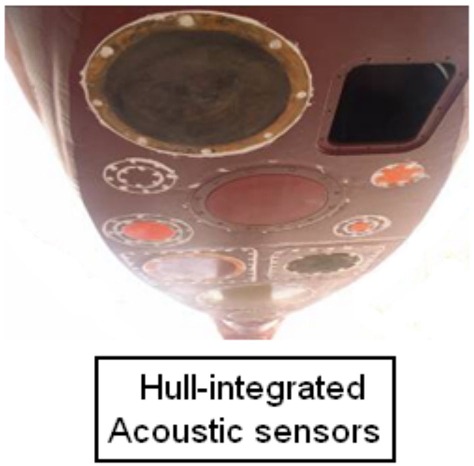
- When submitted to an acoustic wave, a submerged platform produces an echo characterized by the target strength, depending on hull shape and characteristics, frequency and direction
- The echo can be detected by adverse active sonars
- External hull acoustic deflectors and anechoic coatings allow reduction of target strength

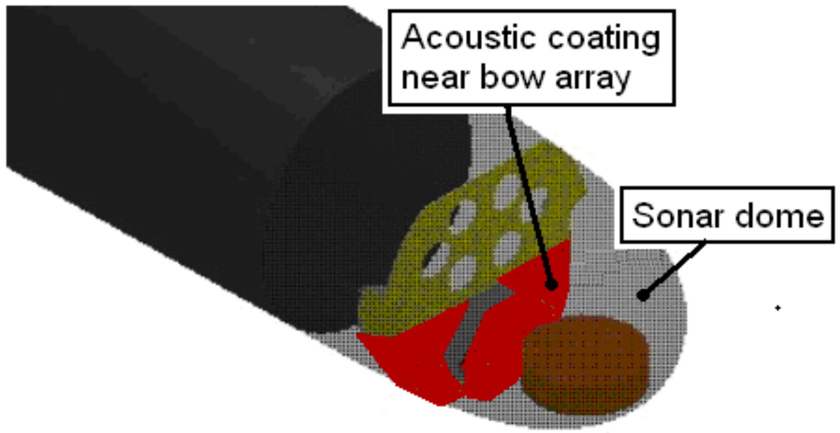




Integration of acoustic detection systems

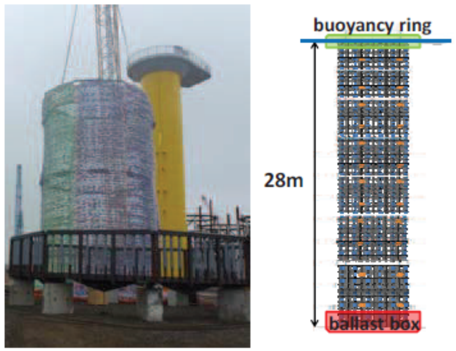
- Acoustic systems, integrated on board, are used for navigating, sensing the environment, or detecting underwater objects
- Acoustic materials can be used to improve the performance of the systems or prevent disturbances such as spurious wave reflexions or self noise
- Examples:
  - Installation of acoustic systems under the hull of a research vessel
  - Integration of a bow submarine array: absorption of waves on the backing plate and self noise reduction with the sonar dome



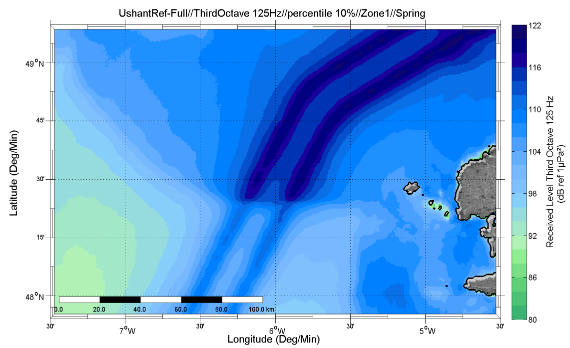


Underwater acoustics environmental issues

- Growing concern among the scientific community for the impact of anthropogenic activity regarding underwater acoustics and its adverse effect on marine life
- The European Community adopted in 2008 the MSFD, requiring Member States to take measures to achieve a good environmental status. Different criteria, including underwater noise, are taken into account
- Examples of current topics:
  - Curtains for the reduction of pile driving underwater noise
  - Mitigation measures for commercial shipping noise footprint (cf. AQUO Project)
- Acoustic materials can be considered for noise control solutions



Net of bubble-like resonators for reduction of pile driving noise



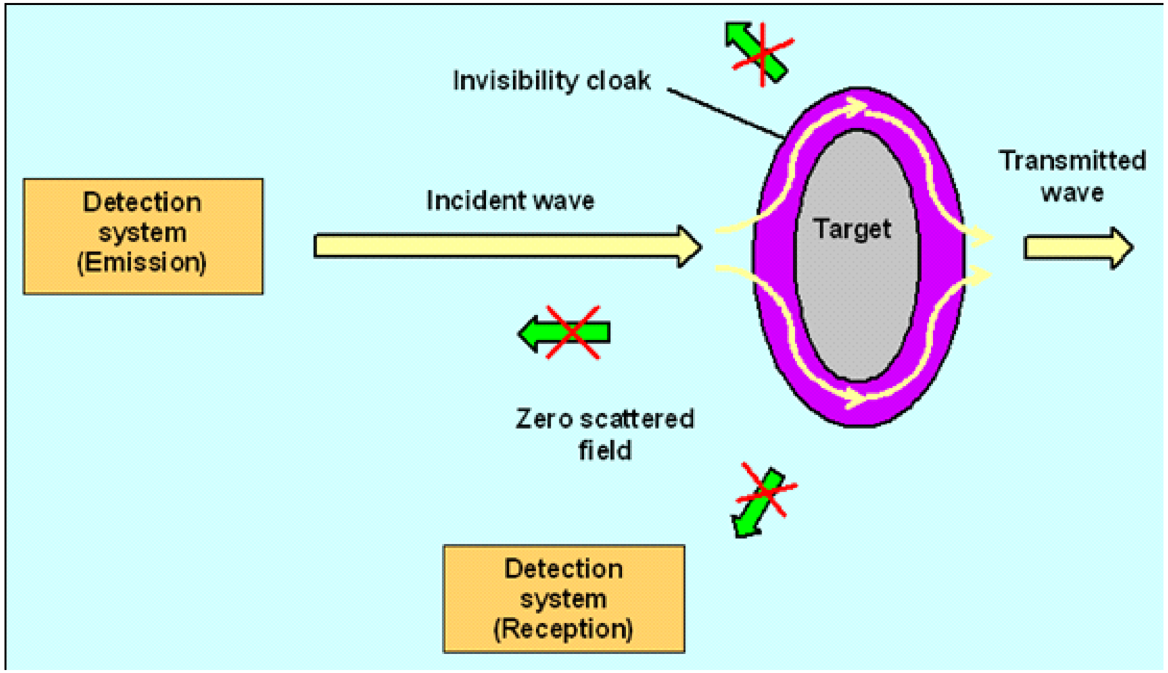
Definitions

Some definitions

- **Types of materials:**
  - Homogeneous / Inhomogeneous
  - Isotropic / Anisotropic
  - Dissipative
  - Dispersive (speed of sound varies with frequency)
- **An isotropic material is characterized by the volumetric mass and two sound speeds (longitudinal, transverse). If dissipative, they are complex-valued.**
- **Phononic crystal: inhomogeneous medium formed by a periodic arrangement of inclusions in a host medium (fluid or solid)**
  - Pass band: frequency band where propagation is not attenuated in a phonic crystal
  - Stop band: frequency band where there is no real solution for the wavenumber
- **Acoustic cloaking: concept for the achievement of a perfect stealth**
- **Metamaterial (not to be confused with acoustic cloak): Artificial composite materials whose acoustic characteristics are uncommon**
  - By comparison to natural materials or to its components
  - For example negative dynamic volumetric mass or sound speed, very high loss…
  - Can be made with periodic or random distribution of inclusions in a matrix

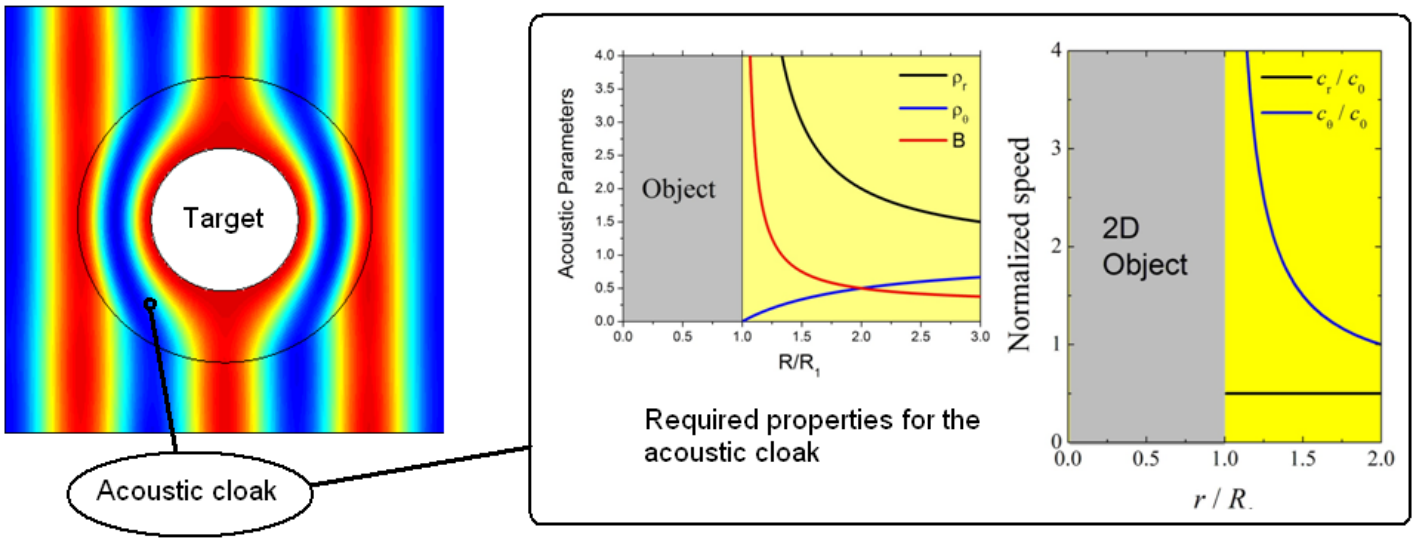
The acoustic cloaking concept

- The objective is to achieve a perfect stealth effect to hide an underwater object by controlling the propagation of waves around the object in a domain surrounding that object (the cloak)
- Two concepts : Transformational Acoustics and Scattering cancellation
- Metamaterials sould not be confused with acoustic cloaking
- DCNS point of view: unpractical concept for industrial UW applications



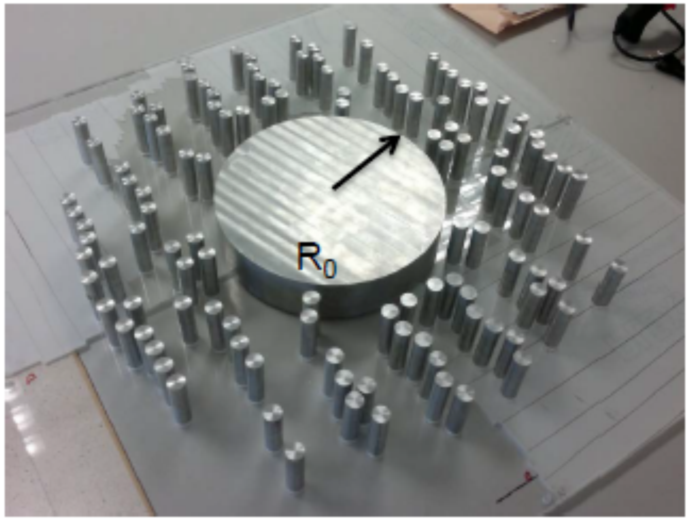
Acoustic cloaking based on TA (Transformation Acoustics)

- The acoustic properties of the invisibility cloak domain (density, speed of sound) are selected in order to allow the penetration of the incoming waves and the deviation of the wave path along the surface of the target.
- Although some works claim otherwise, the cloak is in general thick and requires heterogeneous and anisotropic materials with non-classical acoustical properties, such as very high densities or sound speeds, or using a combination of layers with very different properties.
- In any case, physical mechanisms making the phase velocity larger than that in the surrounded fluid must be introduced in order to make them feasible

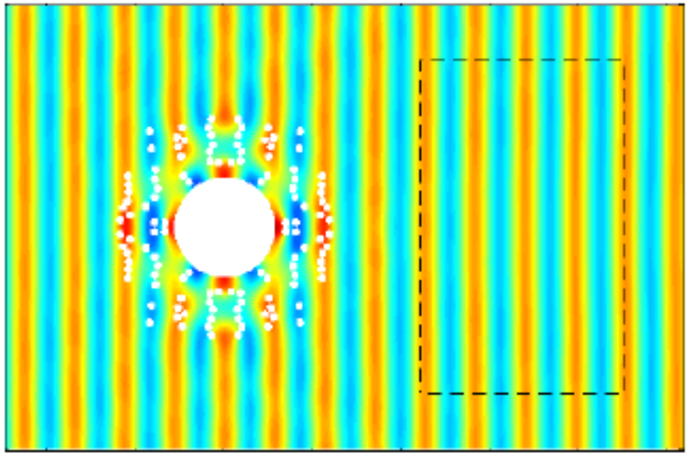


Acoustic cloaking based on SC (Scattering Cancellation)

- **The target is surrounded by small size secondary objects or structures whose acoustic scattered fields, combined with the target echo of the main body, produces an overall null scattered far field.**
- **Omni-directionally and broadband behavior remain as the challenges to address in the near future. Indeed, the scattering phenomena depend strongly on frequency and direction of incoming wave.**

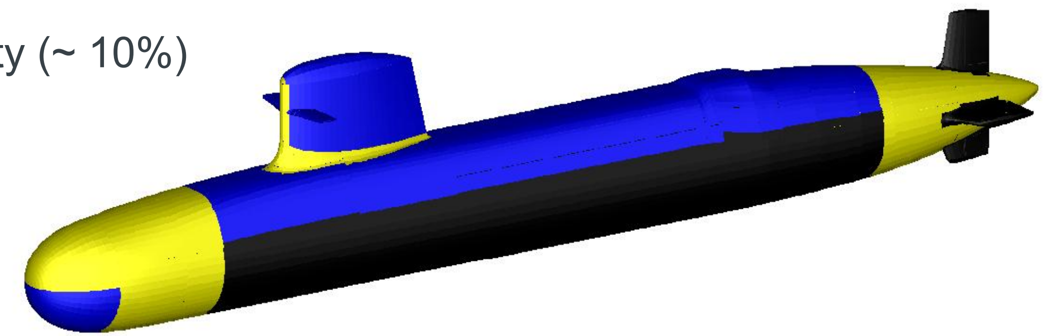


Experimental set-up (airborne acoustics)


Wave propagation with undisturbed pressure field in the downstream area

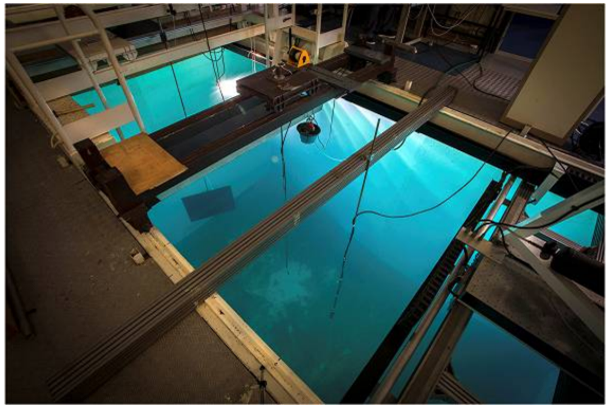
Integration of acoustic coatings

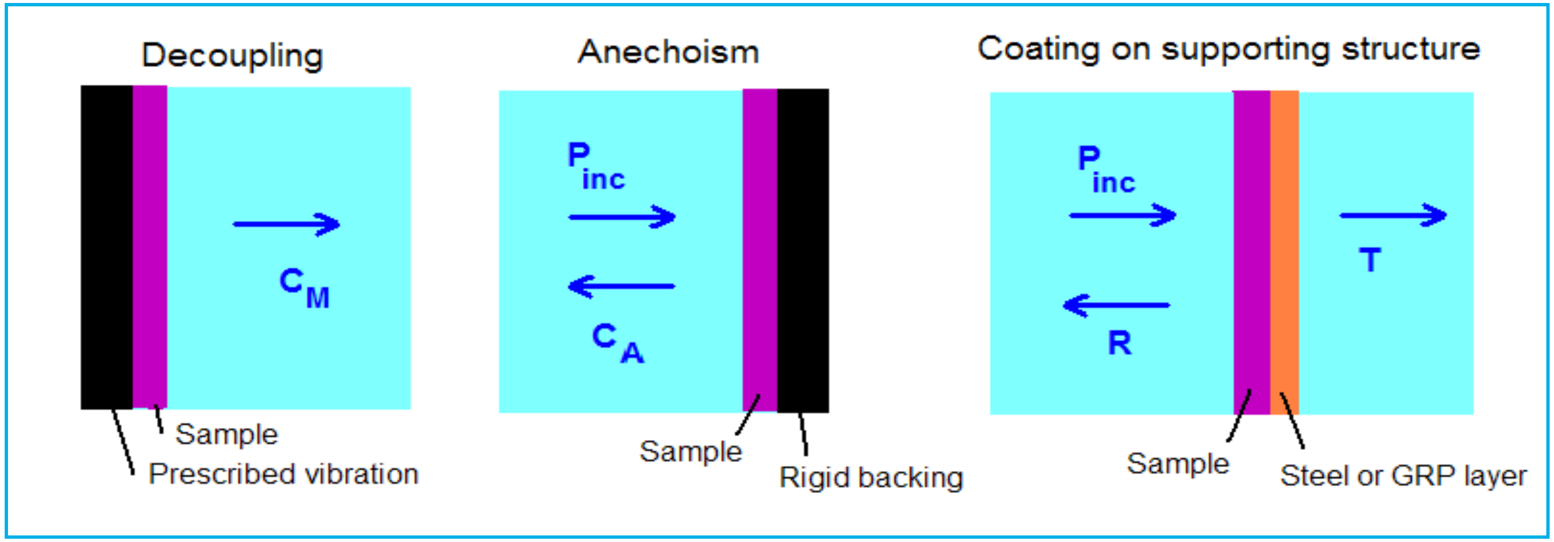
- **Depending on the needs, acoustic coatings can be put on differents parts of submarine hull**
  - Rigid pressure hull
  - Bridge fin
  - Bridge casing
  - Aft and bow frameworks
- **Note that the supporting structure is not necessarily the pressure hull, then is itself acoustically semi-transparent**
- **Also some integration requirements are prescribed by the naval architect :**
  - Maximum thickness (~ 50-100 mm)
  - Maximum density (~ 1.2)
  - Maximum static compressibility (~ 10%)
  - Thermal conductivity
  - Gluing process
  - Fire resistance
  - ….



Performances of acoustic coatings - Characterization

- **Depending on the application, relevant parameters for acoustic performance are**
  - Decoupling efficiency or attenuation
  - Reflexion and transmission coefficient
  - Anechoic coefficient (rigid backing)
- **Caracterization of coatings is usually done in acoustic tanks measurements using test panels, and post-processing where needed**

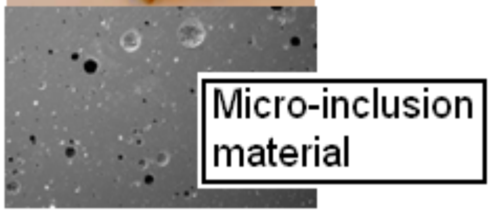




Technology overview

Classical technology : Micro-inclusion materials and coatings

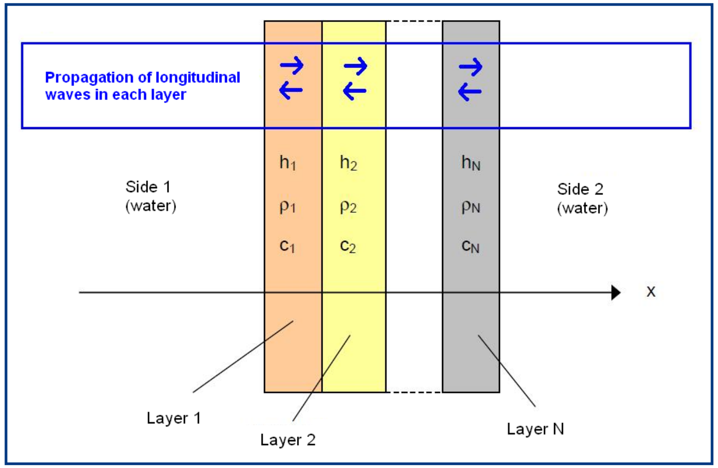
- **Material made with a viscoelastic matrix (generally polyurethane), micro-voids or air content (generally using micro-balloons with soft walls), and sometimes other inclusions (carbon black, minerals…).**
- **Possibility to design both decoupling and anechoic coatings, using one or several layers of materials. Matrix is generally polyurethane.**
- **These are not metamaterials. The performance is mainly by the ratio between thichness and sound speed in the material**
- **Note that one of the consequences of the presence of air is the variation of volume and acoustic properties with hydrostatic pressure**

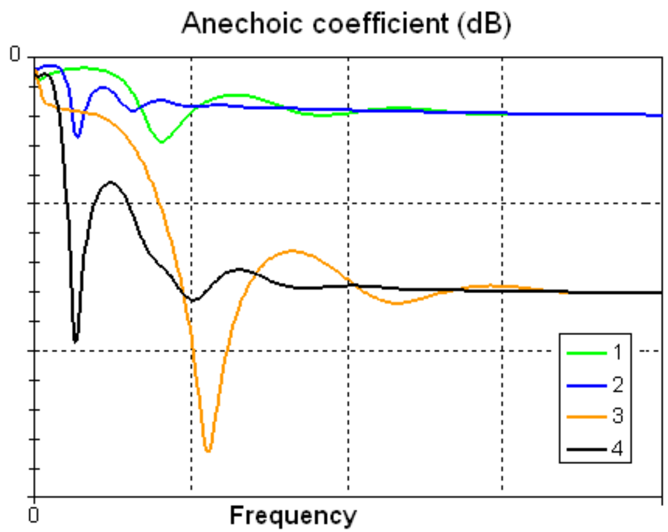


Coating with
three layers

Micro-inclusion technology - design

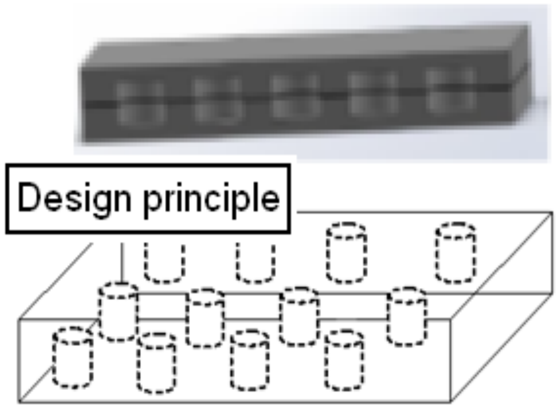
- **The acoustic performances of a coating using that technology depends mainly on :**
  - The number of layers and their thickness
  - The acoustic characteristics of each layer, more particularly the density and the complex celerity of longitudinal waves (which depend on frequency and temperature)
- **Prediction can be done using analytical models (general linear acoustics in a multilayer planar domain)**
- **Decoupling effect can be obtained with one layer of low impedance material**
- **Anechoïc effect is obtained using single or multiple layers of dissipative materials. There is a low frequency limit related to thickness/wavenumber**

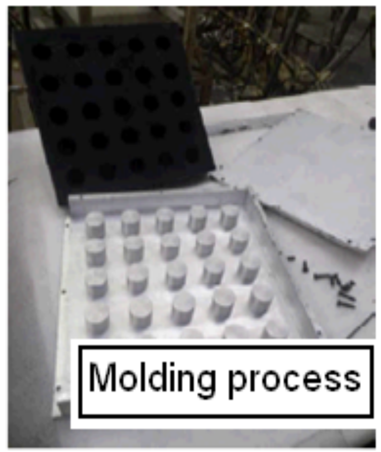




Classical technology : Alberich-type coatings

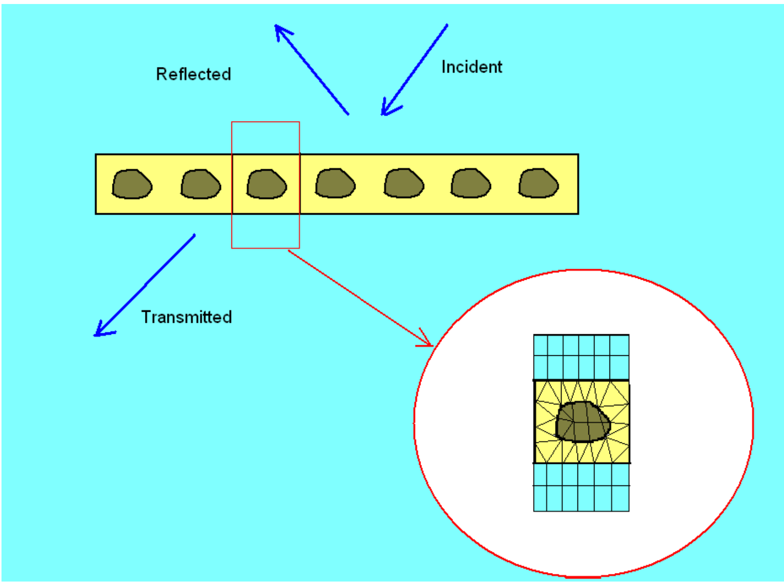
- **Molded air cavities, periodically spaced in a viscoelastic matrix, preferably in rubber**
- **The resonances of the cavities affect strongly the acoustic properties, with either a stop-band effect, either a high absorption.**
- **Possiblity for improved performance at lower frequencies, with applications for both decoupling coatings**
- **Due to resonant behaviour, limitations may appear for the bandwidth**
- **The presence of air leads to a dependency to hydrostatic pressure**

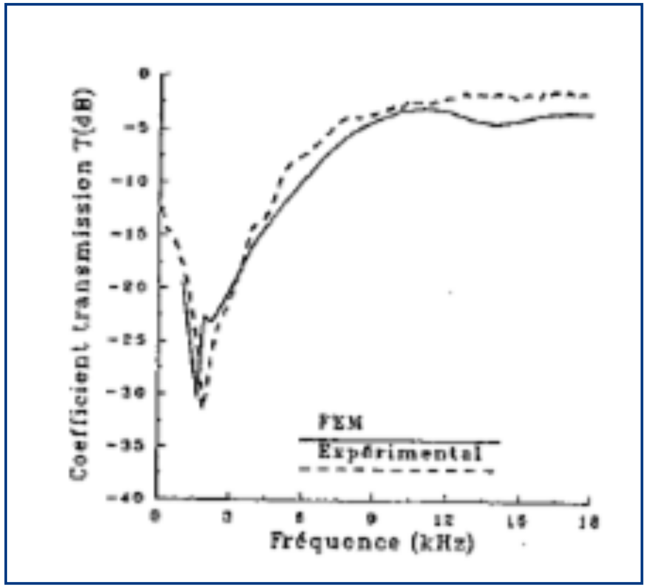




Alberich-type technology – design of periodic materials

- **Prediction of acoustic performance can be done using finite element models such as COMSOL or ATILA.**
- **Only one period (in 2D or 3D) is modelled and periodicity conditions are applied at boundaries**
- **A good knowledge of the physical properties of the base materials, in particular the matrix, is required**
- **Strong attenuation or absorption can be obtained around resonances**





Technology examples

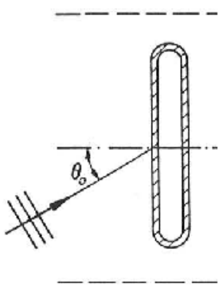
Historical « Alberich » coating

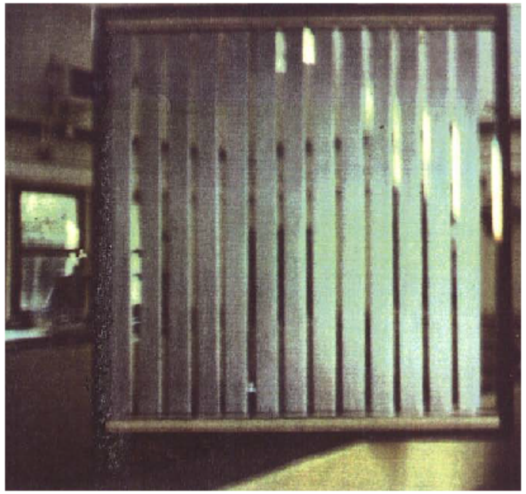
Experimental decoupling coating on a surface ship

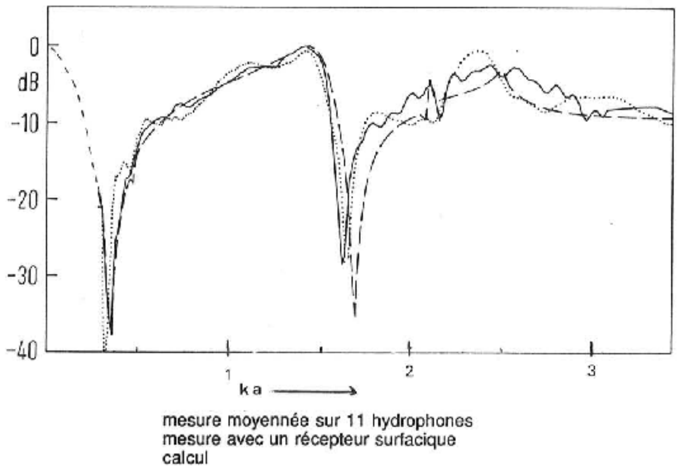
Acoustic coating on a modern submarine

Early research on acoustic materials exploiting resonant phenomena
Compliant tube gratings

- **Concept introduced in the USA as a solution for submarine flank array acoustic barriers (self noise reduction). Tubes have a flat shape and are designed in order to satisfy the maximum static pressure requirement. Theoretical models (partial domains method) first by Grinchenko (Ukraine) and then Radlinski (USA)**
- **PhD thesis by C. Audoly using two methods: partial domains and the multiple scattering theory). Multiple scattering applies to arbitrary configurations, not only periodic**
- **Result, checked with experiments: strong attenuation around some resonant frequencies**



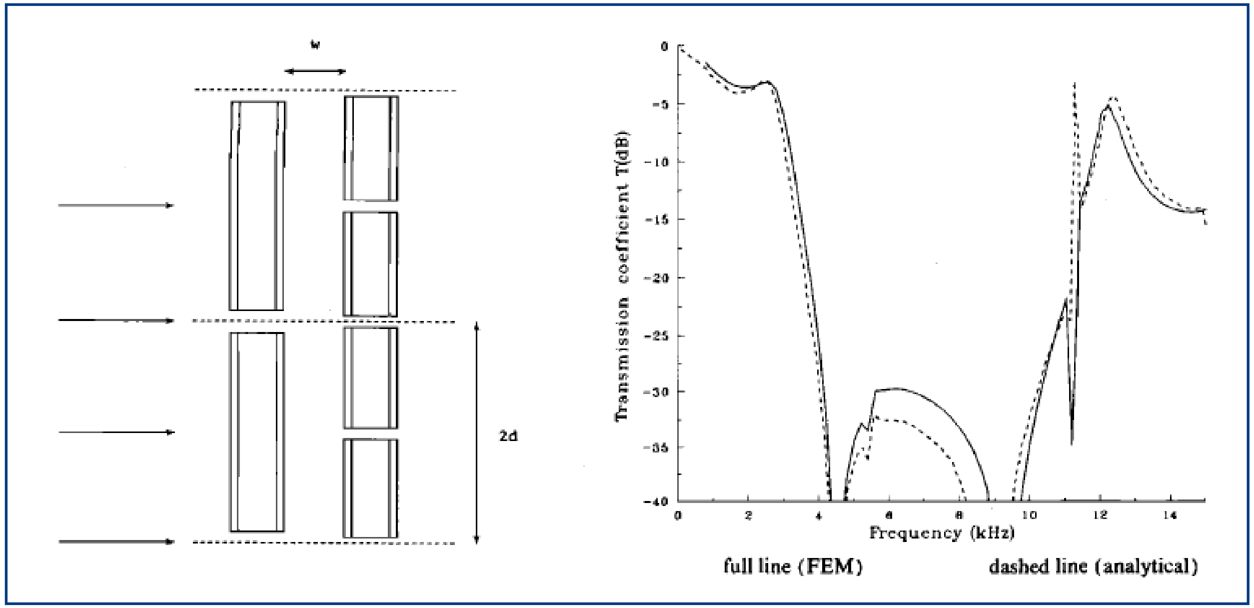




C. Audoly, G. Dumery, Modeling of compliant tube underwater reflectors.
J. Acoust. Soc. Am. Vol.87 N°5 p.1841-1846 (1991)

Early research on acoustic materials exploiting resonant phenomena
Compliant tube gratings

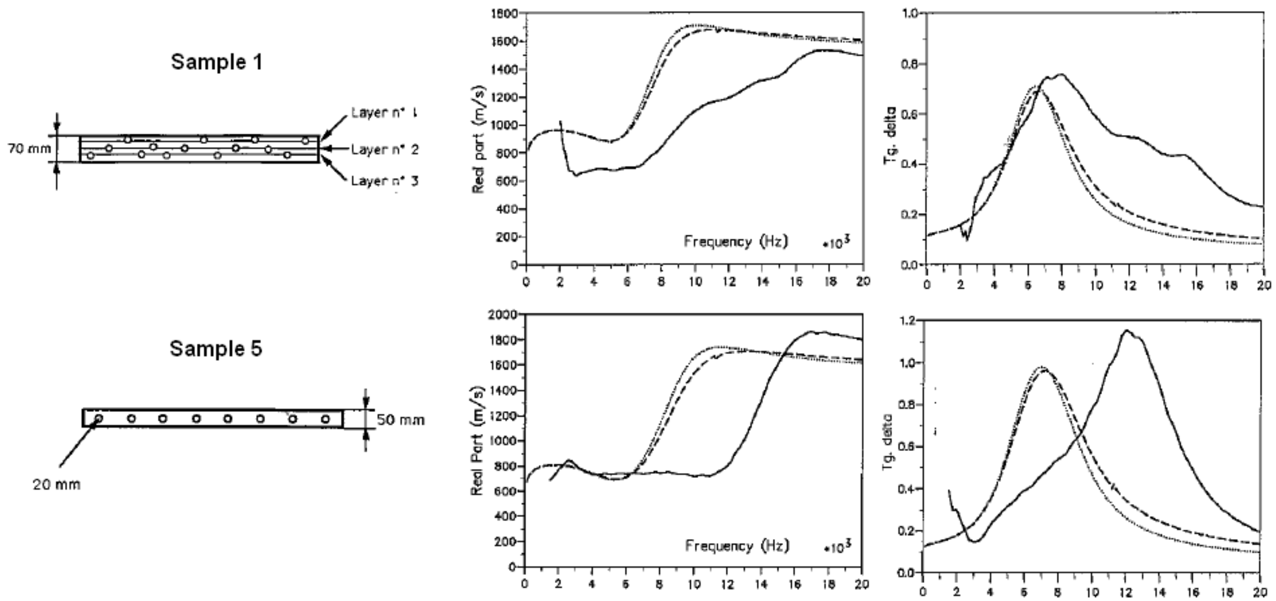
- **Extensions:**
  - Double layer compliant tube grating, allowing increasing the bandwidth of efficiency
  - Case of tube gratings embedded in a viscoelastic layer (partial domains method)



C. Audoly : Acoustic wave scattering from periodic gratings: Application to underwater acoustic baffles. UDT 1991 Conference (Undersea Defence Technology), Paris. Proceedings Microwave exhibition and publishers, p.1053-1058

Early research on acoustic materials exploiting resonant phenomena
Analysis of media containing resonant cavities (spherical)

- **The main objective was to investigate experimentally the phenomena using different test panels made on purpose with both periodic and pseudo-random arrangements**
- **The samples were tested in a water tank, with measurement of R and T along frequency**
- **An inversion is done to estimate the speed of sound along frequency, assuming volumetric mass constant and equal to the static one**
- **Results are compared to effective medium theories and FEM method**

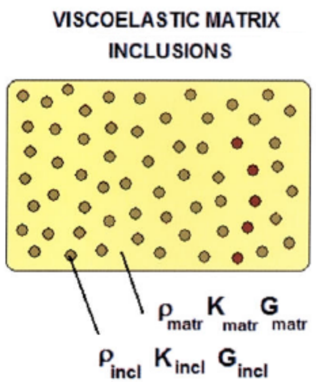


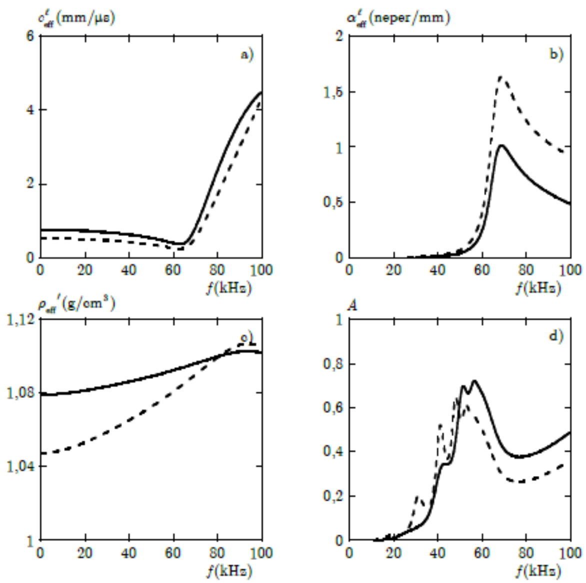
C. Audoly, Acoustic analysis of panels made with viscoelastic materials containing resonant cavities. Acta acustica, Vol. 2, N°5 (1994)

Recent research in UW acoustics metamaterials and perspectives

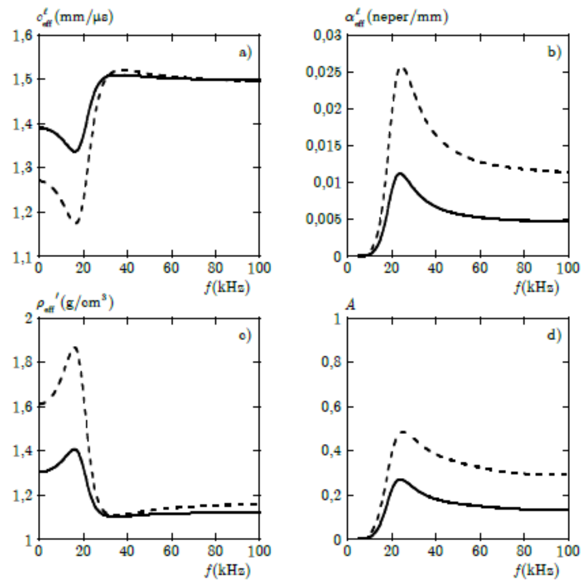
PhD thesis by G. Lepert – Metamaterials with randomly distributed resonant inclusions (2013)

- Numerical model for homogeneization derived from theory of Aristegui et al. , for spherical randomly distribued in a solid or fluid matrix
- Inclusions can be voids, fluid, solid of multilayer
- Both volumetric mass and sound speed are complex-valued and dispersive





Soft inclusions

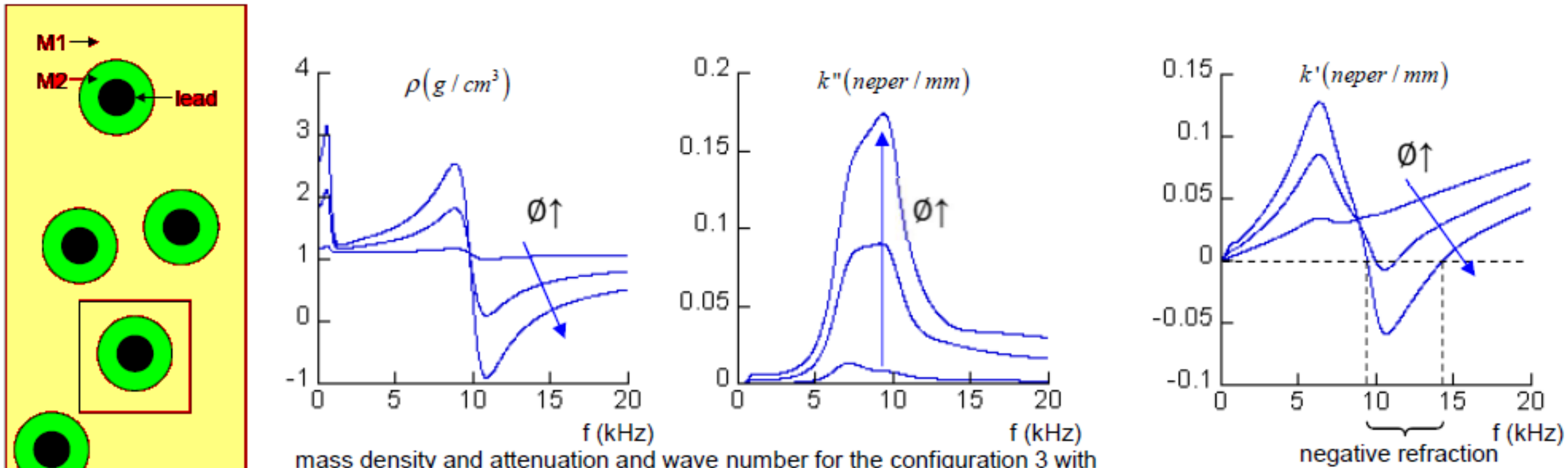


Massic inclusions

G. Lepert et al., Dimensionnement et caractérisation acoustique de matériaux fonctionnels formés d'inclusions résonnantes réparties aléatoirement . Congrès Français d’Acoustique, Poitiers, 22-25 Avril 2014.

PhD thesis by G. Lepert – Metamaterials with randomly distributed resonant inclusions

- **Comparison between theory and experiment was done using samples tested in a small tank at ultrasonic frequencies**
- **Additional studies were carried out with core-shell inclusions. In theory, negative values for dynamic density and sound speed can be obtained, but it was not observed experimentally**

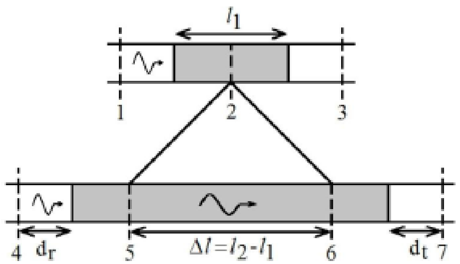


mass density and attenuation and wave number for the configuration 3 with different volume fractions (1, 10 and 20%)

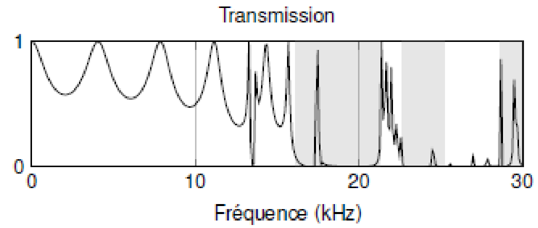
G. Lepert et al., Study of the acoustic behavior of materials with core-shell inclusions. 12th Anglo-French Physical Acoustics Conference, Fréjus, January 2013.

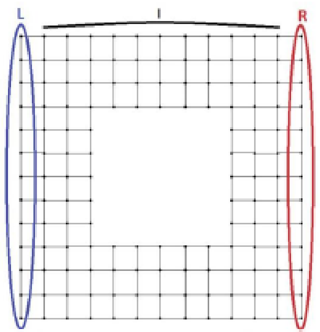
PhD thesis by P. Meresse – Absorbing materials with periodic structure and resonant inclusions (2015)

- **The first objective was to develop method allowing the determination of dispersion curves in a periodic material modelled by finite elements**
- **Two methods were developed, giving the same results:**
  - The « Bianco-Parodi » method using comparison of two fictive samples with different thicknesses
  - The « Transfer function » method, using a single elementary cell, more time-consuming but giving more information (all solutions, including transverse sound speeds)

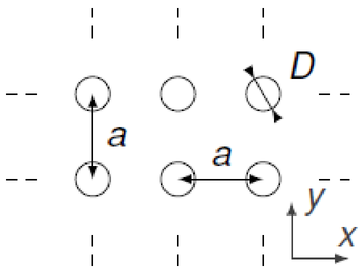


$$2\cos(k\Delta l) = \frac{T_1{}^2 + T_2{}^2 - (R_1 - R_2)^2 e^{2jkv(d_r - d_t)}}{T_1 T_2}$$

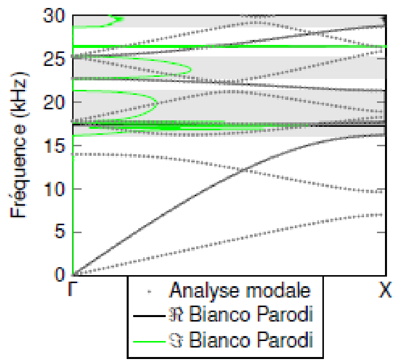




$$\left[T - e^{jk\Delta} I\right]\begin{pmatrix} U^j \\ F^j \end{pmatrix} = 0$$



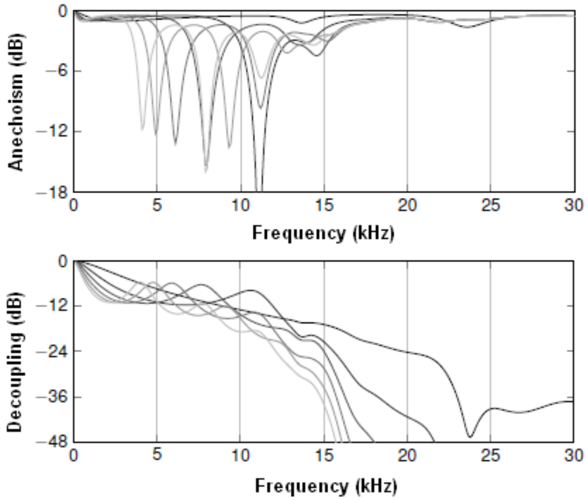
Example: 2D pores in a PU matrix, without losses



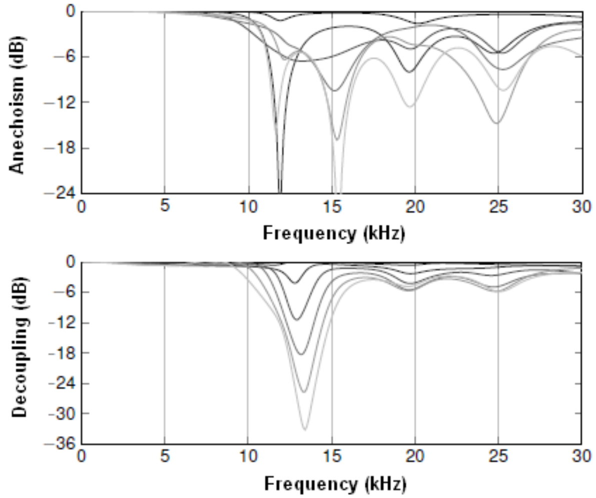
P. Meresse et al., Propagation number in periodic structures considering losses, J. Phys. : Conf. Ser. 581, 1 (2015) 012012

PhD thesis by P. Meresse – Absorbing materials with periodic structure and resonant inclusions

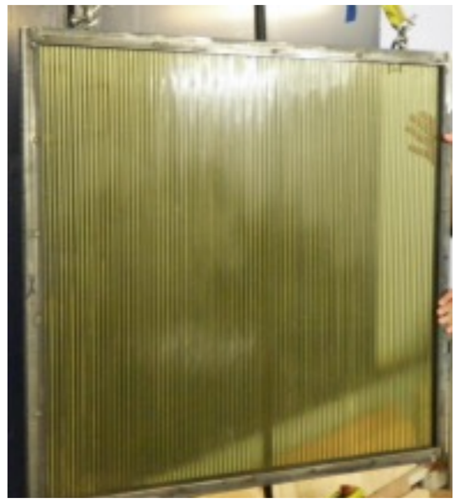
- **Parametric studies were carried out by varying the number of layers and the losses in the matrix for two cases: pores and steel rods**
- **When damping coefficient increases, it is more difficult to relate the stop band/pass bands and the curves of R & T coefficients, mainly in the case of pores**
- **One sample with steel rods in the form of a test panel was tested in a water tank and experimental results agree well with numerical prediction**



Lossy matrix with cylindrical pores

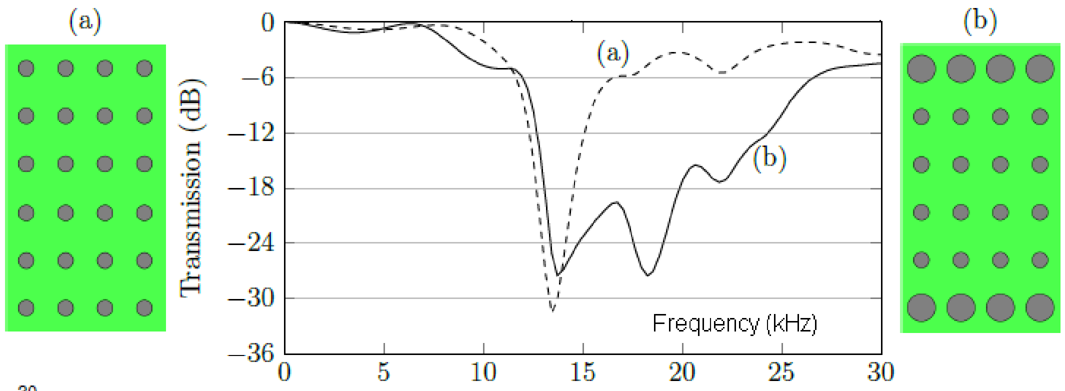


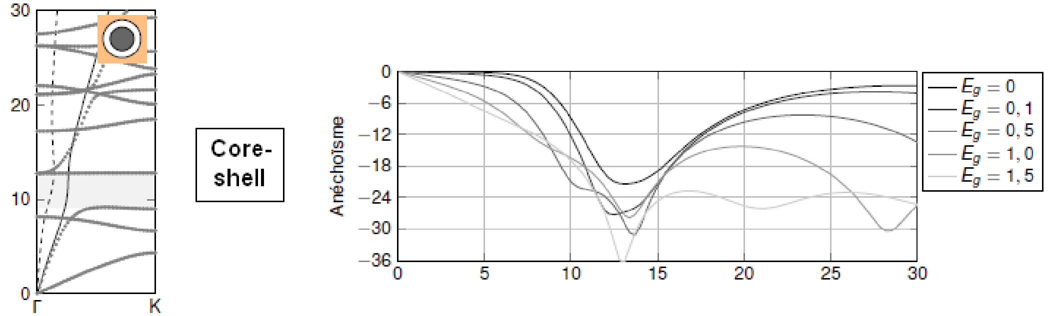
Lossy matrix with steel rods



PhD thesis by P. Meresse – Absorbing materials with periodic structure and resonant inclusions

- **Additional studies were done with the objective to define new concepts of metamaterials with acoustic properties of interest for naval applications**
  - Reflectors with steel rods in a matrix (without air, with potential applications for acoustic systems in very deep waters)
  - Anechoic materials using core-shell configurations





P. Meresse et al., Phononic crystal slab optimization by means of resonant interface layers, Proceedings of 44th International Congress on Noise Control Engineering, INTERNOISE, 9-12 August 2015, San Francisco, CA, USA

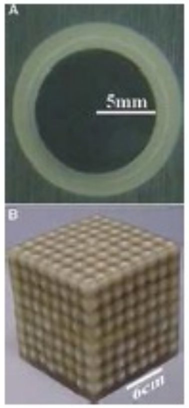
Summary

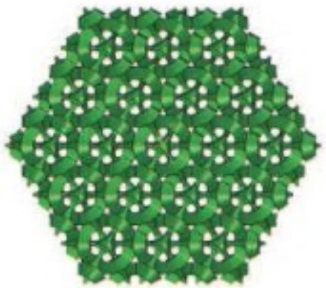
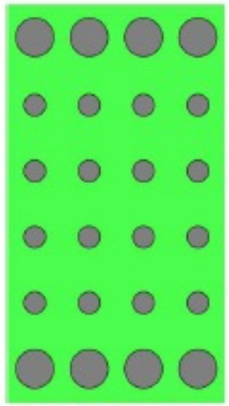
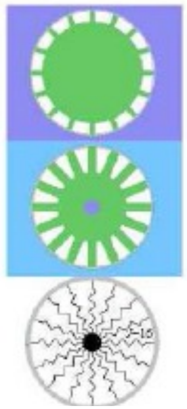
Naval applications - needs

- **Coatings for ship acoustic discretion and stealth**
  - Anechoism at low and very low frequencies
  - Decoupling at low and very low frequencies
  - Trade-off between acoustic performances and resistance/stability to hydrostatic pressure
- **Sonar domes and acoustic windows**
  - Trade-off between acoustic transparency and mechanical resistance
  - Windows with selective frequencies
- **Underwater detection systems**
  - Multipurpose materials optimized for sonar array integration
- **Civilian applications**
  - Commercial ships and MRE: low cost decoupling coatings
  - Acoustic materials for very deep waters
- **Note: the marine environment induces technology constraints**
  - Choice of basis materials
  - Transposition of solutions from airborne acoustics is not straightforward

Interest for research on metamaterials

- **Metamaterials have been studied for a long time, and has gained recently a « hot topic » status**
- **Possible exploitation of acoustical effects of metamaterials**
  - Efficiency with smal thickness to wavelength ratio
  - Exploitation of stop-bands, super-resonant effects, negative dynamic density and/or wavenumber
- **New types of inclusions and/or optimum repartition in one or several layers open new perspectives**
- **The practical use of these new concepts for underwater applications is still to be addressed**

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