# Classification of non-conventional phenomena involved in meta-materials
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**Abstract**: Meta-materials have been a subject of great interest in the field of acoustic materials for several years. The term « meta » is used to emphasize that at least one non-conventional phenomenon is used. These meta-materials could also be called multiple dynamic materials. A large number of works are published every year in this field and it may be difficult to distinguish if these works present new concepts or combine several existing concepts.

This presentation attempts to synthesize the different phenomena involved in meta-materials. These non-conventional phenomena such as double porosity, multiple-scattering, acoustical resonance, permeo-elasticity will be presented and a classification of the involved effects will be drawn. In addition, it will be shown that the periodicity of the inclusions, often encountered in meta-materials, can be seen as an additional phenomenon which is not mandatory to take advantage of other phenomena. The main idea of this work is to classify the non-conventional effects in order to have a toolbox when designing an acoustical material with multiple dynamics.

**Keywords**: meta-materials, multiple-dynamics, porous media, non-conventional phenomena, double porosity, solid inclusions, porous inclusions, sorption, acoustic resonators, membranes, periodicity

### 1. Introduction

Porous materials are widely used in automotive sound packages. Usual porous media (fibrous, foams) are generally considered homogeneous. The new trend to target the low-frequency acoustical performance is to investigate non-conventional phenomena. These materials including non-conventional phenomena are often called meta-materials. These non-conventional phenomena add additional dynamics and additional dissipation.

### 2. Classical porous materials

Porous materials are widely used for acoustic applications for their ability to dissipate acoustic energy via viscous and thermal effects. The porous materials are said to be good acoustic materials. They are particularly good sound absorbers and they can also be used to add visco-thermal dissipation for transmission applications when assembled in multi-layers.

Acoustic porous media can be divided in three categories: fibrous, foam and granular. These materials are made of a solid phase and a fluid phase (usually air). They exhibit an open network with a high porosity (volume fraction of air) usually greater than 90%. Two porous microstructures are illustrated in Figure 1 for a fibrous material and an open cell foam. These materials are widely used because they have a relative low cost. Even if they exhibit different microstructures, the acoustic dissipation mechanisms are identical. The visco-thermal dissipation can be accurately predicted [1-5].

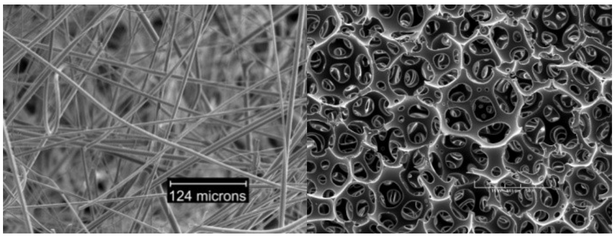


Figure 1: Example of porous microstructure, left: fibrous medium, right: open-cell foam.

When the elastic frame is considered, the structural effect and the coupling with the visco-thermal dissipation has to be considered using the Biot's model [6-7]. The elastic behaviour can be of primary importance for the transmission applications using a (bonded) porous material. If the poro-elastic medium is used for absorption applications or decoupled from other layers, it can usually be considered as rigid and motionless. Figure 2 shows a typical comparison of the sound absorption under normal incidence of a foam modelled with a rigid or an elastic frame for a moderate airflow resistivity of $\sigma$ = 25 000 N.s.m$^{-4}$ and a Young modulus of E = 200 000 Pa. The elastic effect (quarter wave resonance) is limited and localized in the frequency range.

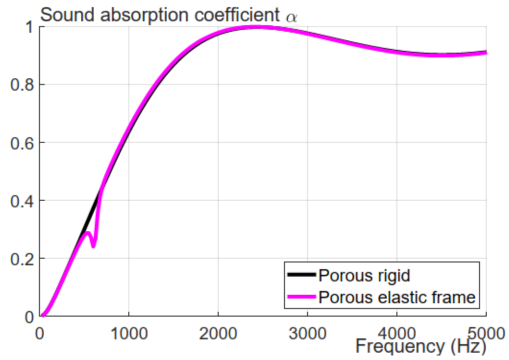


Figure 2: Comparison of the sound absorption under normal incidence of a 30 mm thick foam with a weak elastic coupling (σ = 25 000 N.s.m-4 and E = 200 000 Pa).

The porous materials enabling visco-thermal dissipation and elastic frame can be seen as “classical porous materials”.

Nevertheless, Figure 3 shows that a strong effect of the poro-elastic coupling can be achieved while adjusting the properties of a “classical” poro-elastic material.

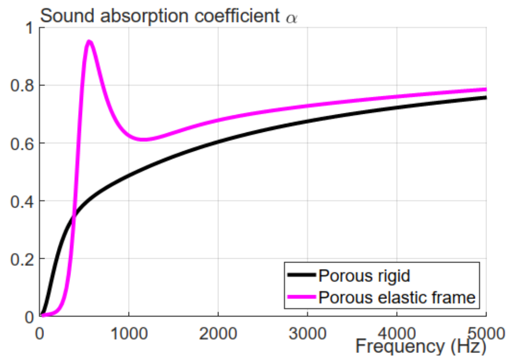


Figure 3: Comparison of the sound absorption under normal incidence of a 30 mm thick foam with a strong elastic coupling (σ = 200 000 N.s.m-4 and E = 5 000 Pa).

At low frequency, the wavelength being large compared to the material morphological dimensions and its thickness, these classical porous materials suffer from a lack of dissipation. This explains the large interest in studying meta-materials, or in other words, how to add additional dynamics or dissipation phenomena. Even if there is a plethora of work concerning meta-materials, they mainly deal with few concepts which are generally combined.

The subwavelength dissipation is often pointed out in meta-material works. It has to be recalled that the maximum dissipation of a rigid-backed material appends at the frequency f=c/4L, L being the thickness of the sample and c the speed of wave in the porous medium. The acoustic wavelength in air is $\lambda = c_0/f$. The velocity of the waves “propagating in the fluid phase” of a porous medium depends on the frequency and is lower that the one in air $c(f) < c_0$. Thus, the comparison of with the acoustic wavelength in air has to be considered with caution.

## 3. Non-conventional phenomena

This section attempts to present and to classify the non-conventional phenomena involved in meta-materials.

### 3.1 Multi-scale material with diffusion processes

This first category of meta-materials is based on the use of multiple scales. It can be a porous matrix with air, solid or porous inclusions. By adjusting the sizes of the inclusions and the properties of the porous matrix, additional dissipation effects, especially diffusion effects, can be achieved.

#### *3.1.1Double porosity media*

Adding meso-perforations or air inclusions in a carefully chosen porous medium can lead to an enhancement of the sound absorbing performance in a given frequency range. This kind of material is called double porosity medium and is illustrated in Figure 4. This double porosity media add a pressure diffusion effect when there is a strong permeability contrast between meso (i.e., the meso-perforations) and micro scales (i.e., the porous matrix) [8-9].

Porous media with air inclusions enable a weight reduction and can take advantage of additional pressure diffusion effects as depicted in Figure 4.

| | $\phi$ | $\sigma$ | $\Lambda$ | $\Lambda'$ | $\alpha_\infty$ | $k_0'$ |
|---|---|---|---|---|---|---|
| Materials | | (N.s.m$^{-4}$) | (μm) | (μm) | | (1e$^{-10}$ m²) |
| Porous A | 0.95 | 120 000 | 12 | 72 | 1.08 | 11 |
| Porous B | 0.98 | 17 500 | 106 | 151 | 1.00 | 56 |

Table 1: Material parameters

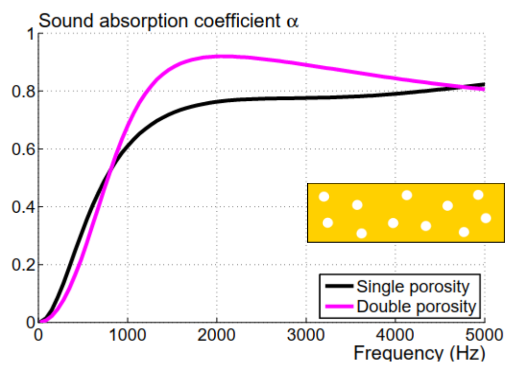


Figure 4: Potential effect of the double porosity on the sound absorption coefficient (20 mm-thick-sample of Porous A with 11% of 10 mm-diameter-holes).

*3.1.2 Solid inclusions*

This type of heterogeneous porous media with solid inclusions enables to take advantages of a tortuous effect at the mesoscopic scale as shown in Figure 5. Porous materials with solid inclusions can also add multiple scattering effects while not being necessary periodic [10].

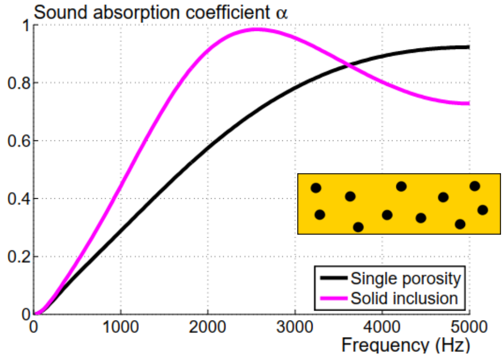


Figure 5: Potential effect of the solid inclusions on the sound absorption coefficient (20 mm-thick-sample of Porous B with 12.6% of rigid inclusions).

*3.1.3 Porous inclusions*

Considering porous inclusions in a porous matrix enables to control the permeability contrast which mainly controls the overall dissipation level. This heterogeneous porous media can still benefit from additional mesoscopic tortuosity and pressure diffusion effect as presented in section 3.1.1 [11-12] (see Figure 6).

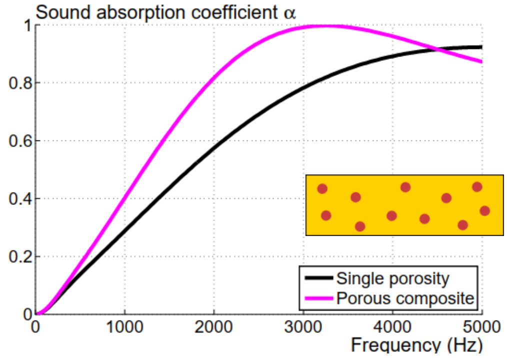


Figure 6: Potential effect of the porous inclusions on the sound absorption coefficient (20 mm-thick-sample of Porous B with 12.6% of Porous A inclusions).

*3.1.4 Sorption*

The diffusion process can be enhanced by using sorption (adsorption/desorption) phenomena. These effects are generally introduced through a third scale (nano) of porosity. This can be achieved with activated carbon for instance [13-14].

In addition to improve the dissipation, this phenomenon enables to reduce the bulk modulus of the heterogeneous material. It is very useful for shifting the resonance of a cavity towards low frequencies.

3.2 Acoustical resonators

The use of acoustical resonators (Helmholtz [15] or quarter wave length resonators) is not recent and their use coupled to porous media has gained some interest in the last decades [16-18]. The resonators can be embedded in the porous matrix while acting as rigid inclusions and adding dissipation at the resonance frequency as depicted in Figure 7. The acoustical resonators can also be positioned on the sides or at the rear of the material [18].

Several resonators can be combined with different dimensions and resonance frequencies. This type of combination tends to a Schroeder diffuser [19].

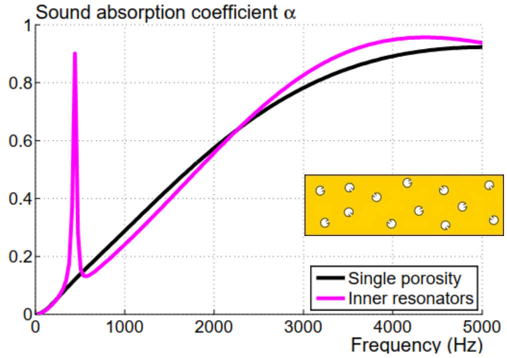


Figure 7: Potential effect of inner resonators on the sound absorption coefficient (20 mm-thick-sample of Porous B with 20% of inner resonator set at 423 Hz).

3.5 Soft membranes

The effect of rigid membranes in porous materials is well known. They allow to increase the airflow resistivity and the tortuosity [20].

The effect of soft membranes has been less studied despite their high potential [21] (see Figure 8). The coupling of the soft membranes with the visco-thermal dissipation is called the permeo-elasticity concept and has been studied thanks to a homogenization method [22]

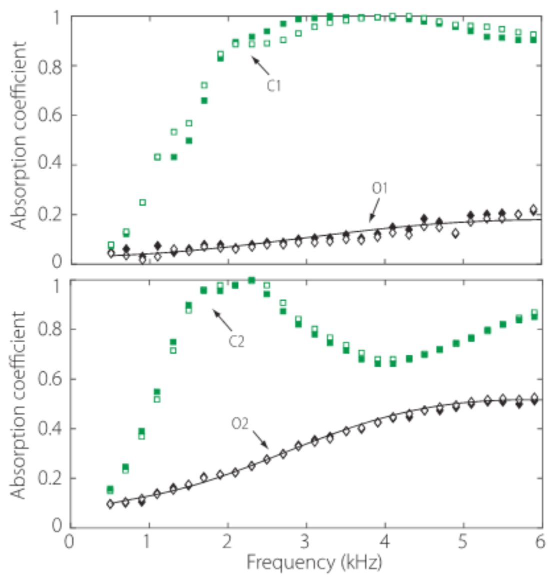


FIG. 3. Measured absorption versus frequency for open cell foams (O1 and O2, black symbols) and closed-cell foams (C1 and C2, green symbols). Samples were 2 cm thick. Reproducibility was tested by measuring 2 samples of each type (solid and open symbols). Solid black lines show JCAL model for the open-cell foams.

Figure 8: Potential effect of thin and soft membranes of a 20 mm-thick sample. Fig 3. of ref [21]

### 3.6 Periodicity

When the inclusions are periodic, the heterogeneous material becomes a phononic crystal. In addition to the mesoscopic tortuosity and the multiple scattering effect (see section 3.1.2), interference phenomena appear (see Figure 9). These are called Bragg interferences.

This type of materials can create stop bands in transmission [22]. These periodic inclusions can also be embedded in porous media [23]

Figure 10 shows the increase of transmission loss around the Bragg frequency. Nevertheless, it corresponds to a decrease of the sound absorption coefficient. It confirms that the waves are reflected thanks to the periodic inclusions and not dissipated. The periodicity is thus of great interest for transmission purposes but not for sound absorption application.

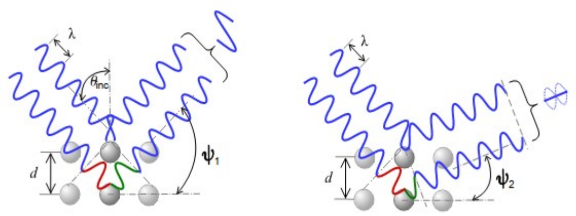

Figure 9: Illustration of Bragg interference for two diffraction angles Left: constructive interference, right: destructive interference (modified picture according license CC BY-SA 3.0 cdang)

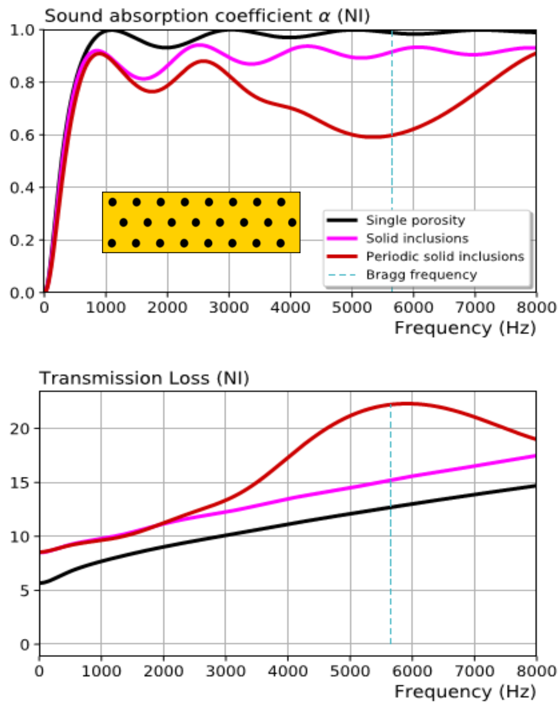


Figure 10: Potential effect of periodic solid inclusions. Top: sound absorption, Bottom: Transmission loss.

### 3.7 Impedance matching

The principle of impedance matching is to gradually modify the impedance to tend towards zero reflection [24]. The impedance matching is generally achieved by varying the topology of the material. This is the principle of the anechoic wedges and functionally graded materials for instance.

### 3.8 Alternative concepts

This work mainly focuses on concept directly integrated in porous materials. Nevertheless, mechanical resonators are also often used as well. Usually, they are directly coupled to the structure. They can be linear uni-axial spring-mass systems [25-26], bending mode resonators [27] as well as non-linear mechanical resonators [28-29]. Membrane type resonators can also be used [30].

The impedance matching concept can also be applicable for structural vibrations [31]. When applied on the structures, this concept is sometimes called "acoustic black hole" [32].

Finally, when dealing with underwater acoustics, most of the presented concepts cannot be used since the water impedance is very large compared to the air one. Most of meta-material solutions for underwater applications are based on solid visco-elastic matrix with soft inclusions.

## 4. Conclusions

Various concepts of non-conventional phenomena involved in acoustic meta-materials have been summarized. Despite the large amount of new published works every year, only few concepts are involved.

Most of the works combine some of these concepts, for instance:

- membranes and resonators [33],

- periodic solid inclusions and quarter wave length resonator backing [34],

- periodic inclusions and resonators [35].

These concepts can be seen as a toolbox for acoustician to design efficient solutions. It is important to note that the periodicity is not required for taking advantage of the presented non-conventional phenomena. The periodicity is an additional concept which can be combined with others.

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