Engineered Materials for Acoustics: Metamaterials, Sonic Crystals and Calculated Microstructures

Raymond Panneton *[1]

[1]Centre de recherche acoustique-signal-humain de l'Université de Sherbrooke (CRASH-UdeS)

1 Introduction

For two decades, research on acoustic materials (absorbent and insulating) has largely translated into metamaterials and sonic crystals or, more generally, into engineered acoustic materials. A large number of scientific articles on these unconventional materials appear every week, even every day. While research is moving towards a more in-depth knowledge of these materials and new concepts, their applications are already numerous in several sectors of industry. Through all the research, it is sometimes difficult to fully define what acoustic metamaterials, sound crystals, and engineered acoustic materials really are. This extended summary presents the author's personal definition and classification of these different classes of materials, adding the class of optimized conventional materials (or calculated microstructures), and grouping them under the family of "engineered acoustic materials".

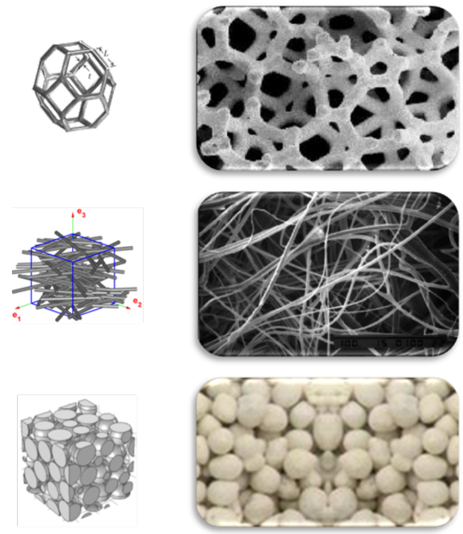

FIGURE 1 – Examples of conventionnal materials

2 Definitions

2.1 Conventionnal materials for acoustics

Conventional acoustic materials are notably foams, fibers and granular media. They are open-cell porous media with interconnected void spaces or pores saturated by air, see examples in Figure 1. They can be represented by a periodic unit cell (PUC) or a representative volume element (RVE) of characteristic size H. At audible frequencies, their characteristic size is much smaller then the wavelength $\lambda : H \ll \lambda$. When the motion of their solid phase is negligible, they are homogeneous equivalent dissipative fluids of effective density ρ_e and bulk modulus K_e. These two latter properties account for thermoviscous dissipation of the sound waves in these fluids. In the harmonic regime, the equation governing wave propagation is the Helmholtz equation $\Delta p + k^2 p = 0$. Here, the wave number is given by $k = 2\pi f / c_e$ and the effective sound speed by $c_e = \sqrt{K_e/\rho_e}$.

Such conventional acoustic materials generally offer low sound transmission loss (TL) per meter (db/m). Their TL is mainly governed by their resistance to airflow. On the other hand, they have good sound absorption coefficients at medium and high frequencies ; however, they exhibit asymptotic absorption. This limit cannot naturally be exceeded with increasing thickness. Moreover, their first absorption does not naturally exceed a wavelength-to-thickness ratio λ/L of 5. Consequently, they are of little use at low frequency in places of limited thickness.

*. raymond.panneton@usherbrooke.ca

2.2 Engineered materials for acoustics (EMA)

It may sound a little pompous, but while nature aims for energy minima in the manufacture of materials, Man aims for maximums in the performance of materials. Thus, by mastering the physics behind wave propagation and dissipation in air-saturated media, one finds complex optimal geometries that maximize, for example, sound absorption or transmission loss in a given frequency range. This is why such materials are called engineered materials or structured materials. The structuring of the materials may be at different scales : microscopic (much smaller than wavelength), mesoscopic (smaller than wavelength), and macroscopic (comparable to wavelength).

One of the first types of macroscopically structured acoustic materials was non-resonant sonic crystals (SC). A SC is a periodic arrangement of scatterers. They present band gap in the transmission of sound. The central frequency of the first band gap is given by the Bragg condition : $\lambda/H = 2$, where H is the size of the PUC of the SC. Since it requires at least two crystals to introduce Bragg diffraction, the size of the SC is of the order of the wavelength. It is used to block sound transmission and may require large dimensions at low frequencies.

At the mesoscopic scale, one can find materials formed of periodic resonant elements which are added along the path of acoustic propagation. Depending on the type of resonances, acoustic or elastic, they slow down the modulus of the speed of sound by decreasing the effective bulk modulus of air or increasing its density respectively. In this case,

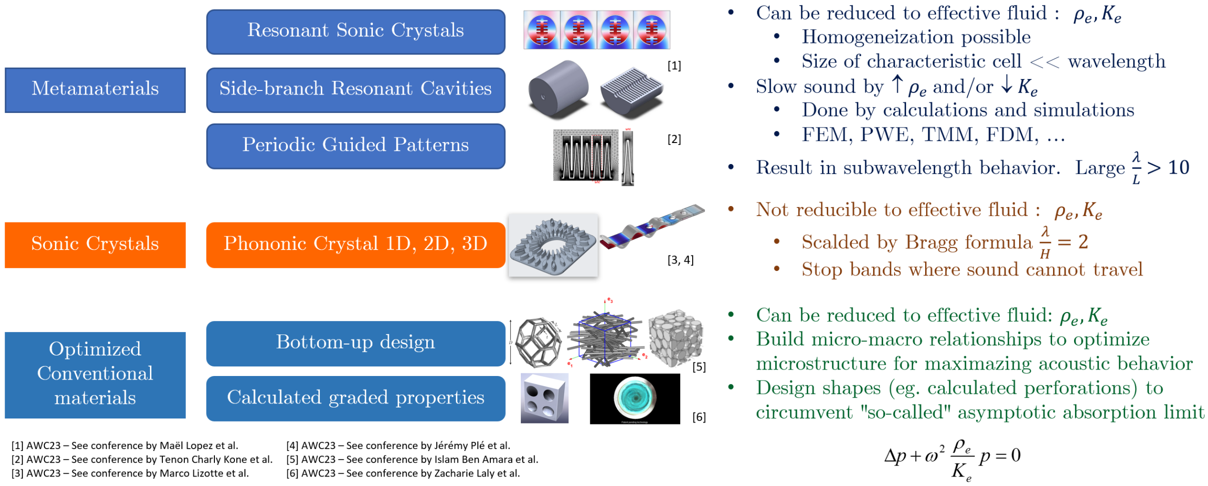

FIGURE 2 – Classification of engineered materials for acoustics.

they are also called sub-wavelength or slow sound materials. Much of the articles in the literature refer to these materials as metamaterials. Therefore, metamaterials shift the acoustic spectrum to lower frequencies and can achieve a wavelength-to-thickness ratio well over 10. Additionally, due to the resonances, their types and periodic arrangement, the wavenumber may be either positive real, imaginary, or negative real. This has the effect of creating band gaps of different natures.

Finally, at the microscale, one can find materials for which their microstructure and transport parameters are optimized by caculations to maximize thermoviscous dissipation. The author calls these materials optimized conventional materials. On the one hand, they may be conventional materials whose microstructure has been optimized by multiscale calculations (bottom-up approach). For example, sheets of fibers whose angular orientation and polydispersity of fiber diameters have been optimized to obtain the best acoustic absorption at low frequencies. In these cases, wavelength-to-thickness ratios as high as 10, even 20, can be achieved, which is more than twice the ratio of conventional materials. On the other hand, porous materials with graded properties can also be considered. The gradation can be continuous or stepwise.

3 Classification

As described in the previous paragraphs, three distinct classes emerge : sonic crystals (SC), metamaterials (MM), and optimized conventional materials (OCM). Since "Meta" in metamaterial is a Greek word meaning "beyond", for the author, metamaterials refer to materials for which the properties (speed of sound, density, bulk modulus, wave number, refractive index or other characteristic properties) are beyond those typically found in conventional materials. Therefore, according to the author's definition, SC and OCM should not be considered as metamaterials. However, since the shapes and matter organization of the three (SC, MM, and OCM) come from engineering calculations (whether simple or complex), they are all engineered materials or structured materials. Finally, the MM and the OCM being designed respectively at the mesoscopic and microscopic scales, they can also be homogenized at the macroscopic scale (wavelength scale) as for classical acoustic materials. Therefore, OCM and MM can be represented as equivalent fluids of effective properties for which the Helmholtz equation governs sound propagation.

Based on the previous short definitions, Figure 2 presents the classification proposed by the author. This classification and the underlying definitions are not the result of a consensus of the scientific community in acoustics. The author proposes here a classification that seems consistent with what is found in the literature. It remains to be debated and validated by peers. Its presentation at this conference is only one step.

4 Discussion and conclusion

As shown in Figure 2, the engineered materials for acoustics are divided in three classes : MM, SC and OCM. Note that reality is more complex than this simple classification. Indeed, acoustic solutions may imply combinations of many classes. For instance, a combination of SC with resonant MM elements, such as resonant sonic crystals, or a combination of side-branch resonant cavities embedded in a conventional porous materials. In this classification, the most important thing to keep in mind is the description given on the right side of the figure, or the wavelength-to-thickness ratio that each class can achieve. Based on this, an intelligent decision on the type of noise control elements for a given application can be made by acoustic engineers or architects.

Acknowledgments

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