From metaporous materials to subwavelength absorbers: some recipes to design perfect sound absorbers

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Abstract— **A perfect absorber, i.e., a structure which absorbs 100% of the incident acoustic energy, of very small thickness is of great scientific and engineering interest. Until now, porous or fibrous materials have been the common choice for noise passive control due to their ability to dissipate sound through thermal and viscous losses. This results in limitations: to absorb low frequency sound, bulky and heavy treatments are required even when optimized multilayer or graded materials are used. For many years the development of noise reducing treatments has been the subject purely of acoustics research. However, recent scientific advances provide a unique and timely opportunity to bring about significant improvements in the design of noise treatments. This presentation aims at giving an overview of some solutions that have been recently developed in LAUM to tackle the problem of sound absorption by rigidly backed subwavelength structures.**

***Index Terms*—Perfect absorption, metaporous material, slow sound, deep-subwavelength absorber, critical coupling.**

I. Introduction

The ability to perfectly absorb an incoming wave field in a sub-wavelength material is advantageous for several applications in wave physics as energy conversion[1], time reversal technology[2], coherent perfect absorbers[3], or sound-proofing[4] among others. The solution of this challenge requires to solve a complex problem: reducing the geometric dimensions of the structure while increasing the density of states at low frequencies and finding the good conditions to match the impedance to the background medium.

Until now, sound absorption has been achieved by using porous materials or microperforated materials. These materials attenuate sound waves through viscothermal losses arising from the interaction of the sound wave with usually motionless solid elements. Perfect absorption requires impedance matching with the surrounding medium. This condition might be realized thanks to the critical coupling condition, which relies on the analysis of the reflection coefficient in the complex frequency plane. This analysis provides the balance between the energy leakage of the system and the attenuated energy. When these two energies exactly counterbalance, the critical coupling condition is fulfilled and perfect absorption is achieved.

The present presentation is organized as follows. First, the limitation of regular acoustic porous materials will be assessed. Then, metaporous and metaporoelastic materials will be presented. These materials represent an efficient alternative to purely porous materials in the inertial regime, in the sense that they provide broadband perfect absorption for wavelength smaller than 10 times the thickness of the materials. Finally, some structures constituted of slow sound based resonators will be critically coupled to the surrounding medium and will provide prefect absorption for wavelength 88 times larger than the structure thickness.

II. Usual absorption by rigid frame porous materials

Acoustic wave propagation in rigid frame porous materials is usually modeled through semi-phenomelogical fluid models[5,6]. These equivalent fluid models rely on complex and frequency dependent equivalent density and compressibility, which respectively accounts for viscous and thermal losses. Different regimes might be considered and of particular interest are the viscous and inertial regimes. These two regimes are separated by the Biot frequency. Below this frequency, the density is mainly imaginary and the pressure field satisfies a diffusion equation, while above this frequency, the density is mainly real and the pressure field satisfies a Helmholtz equation with losses. The lowest frequency absorption peak corresponds to the so-called quarter-wavelength resonance. By first order Taylor expanding the numerator of the reflection coefficient of a rigid frame porous plate rigidly backed around this frequency, we end with an optimal length which reads as $L^{opt} = iZ_0/\rho_{eff}\,\omega + \pi c_{eff}/2\omega$, where Z_0 is the characteristic impedance of the air medium, and ρ_{eff} and c_{eff} are respectively the effective density and sound speed in the rigid frame porous material. Therefore, it imposes a purely complex value of the effective density and a purely real value of the effective sound speed. In other words, this might only be achieved for a frequency which is slightly above the Biot

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frequency. Therefore, this results in two limitations: (1) rigidly backed porous materials could only absorb sound for wavelength smaller than 4 times their thickness, and (2) rigidly backed porous materials could only perfectly absorb sound for frequencies larger than the so-called quarter wavelength resonance when the latter corresponds to the Biot frequency. Below this frequency, attenuation is too large, while above this frequency, attenuation is too small. Therefore, bulky and heavy structures are required to absorb sound at low frequency and very low frequency cannot be absorbed by homogeneous porous materials.

III. METAPOROUS AND METAPOROELASTIC MATERIALS

An efficient way of designing broadband and thin sound absorbing materials is to combine viscothermal losses arising from porous materials with periodic resonant elements. The role of the former is to attenuate sound, while the role of the latter is to trap the sound energy inside the structures at frequency much lower than the quarter-wavelength one as well as to modify the system attenuation. The periodic embedment of rigid inclusions in a porous plate, whose first absorption peak is not unity in the inertial regime, leads to an enhancement of the absorption of the structure at low frequency. This enhancement is due to the excitation of a trapped mode, which traps the acoustic energy between the inclusion set and the rigid backing. For a given filling fraction and position of the inclusions, the energy leakage of the structure might be exactly compensated by the attenuation and a perfect absorption peak might be reached for frequency much lower than the so-called quarter wavelength frequency[7]. The Bragg interference arising from the interaction of the inclusions with their image with respect to the rigid backing unfortunately leads to a large reflection of the structure and therefore a lower absorption. At higher frequencies, the absorption might be enhanced at the resonance frequencies of the porous plate, which are discretely excited thanks to the periodicity. These modified modes of the plate corresponds to Wood anomaly in presence of the porous plate. Note that the required filling fraction for perfect absorption is larger for three dimensional inclusions than for two dimensional ones[8]. This implies that perfect absorption might be impossible to achieve for some porous materials with some three dimensional inclusion shapes, typically sphere inclusions arranged on a cubic lattice. The absorption might be further enhanced at low frequencies by embedding resonant inclusions, like split ring[9] or Helmholtz[10] resonators. At their resonance frequency, the acoustic energy is trapped in the resonant inclusions and attenuated by viscothermal losses. Split ring resonators (Helmholtz resonators as well but to a lower extend) might be coupled with the rigid backing. Therefore, broadband absorption might be achieved by considering a supercell composed of various split ring resonators with different slit orientations. It is worth noting here, that perfect absorption can only be achieved when the resonance of the inclusion lies in the inertial regime of the porous matrix. When it lies in the viscous regime, absorption peaks are usually noticed but cannot be unity either because the acoustic energy cannot travel to the resonators or because the resonator cannot resonate when filled with a porous materials. Whilst the effect of the Bragg frequency might be erased by adjusting the resonance of resonant inclusions at this frequency, it might be more efficient to structure the rigid backing by adding quarter wavelength resonators or Helmholtz resonators[11,12]. Therefore, the embedded resonant inclusions leads to perfect absorption at low frequencies while the structured rigid backing erased the associated absorption loss at higher frequencies in optimized structures.

Accounting for the possible motion of the skeleton paves the way to remove the limitation of the metaporous materials to the inertial regime. Beside the apparent rigidification of the poroelastic structure by the embedment of purely elastic inclusions, elastic resonators usually resonate at lower frequencies than acoustic ones. As for example, a preliminary study[13] has shown that the periodic embedment of viscoelastic shells enables the enhancement of the poroelastic plate absorption coefficient thanks to the excitation of the trapped mode, the volume mode of the shell but also the higher order modes of the shell which occur at much lower frequency than the Biot frequency. If optimally excited, elastic resonances might offer new possibilities for the design of subwavelength metaporoelastic materials.

IV. DEEP SUBWAVELENGTH ABSORBERS BASED ON SLOW SOUND RESONANCES

A successful approach for increasing the density of states at low frequencies with reduced dimensions is the use of metamaterials. Recently, several possibilities based on these systems have been proposed to design sound absorbing structures which can present simultaneously subwavelength dimensions and strong acoustic absorption[14].

Slow sound metamaterials make use of strong dispersion in ducts when loaded by resonators (quarter wavelength[15,16] of Helmholtz[17] resonators) for generating slow-sound conditions inside the material and, therefore, drastically decrease the frequency of the absorption peaks. Hence, the structure thickness becomes deeply sub-wavelength with regards to the wave in the air. Slow sound was till recently achieved by considering sound propagation in ducts loaded by detuned resonators in the induced transparency band[18]. The associated dissipation was usually considered as a side effect of an unexpected adverse reaction. However, slow sound can be observed below the resonances of the loading resonators and the associated attenuation may be useful to design sound absorbers. Such a metamaterial may consist of a thin panel perforated with a periodic arrangement of slits, the upper wall of which being loaded by identical Helmholtz resonators[17] (HRs). The presence of the HRs introduces a strong dispersion in the slit producing slow sound propagation, in such a way that the resonance of the slit is down shifted: the slit becomes a deep subwavelength resonator. The visco-thermal losses in the system are considered in both the resonators and the slit by using effective complex and frequency dependent parameters. Therefore, by modifying the geometry, the intrinsic losses of the system can be efficiently tuned and the critical coupling condition can be fulfilled to solve the impedance matching to the exterior medium.

In the complex frequency plane, the reflection coefficient has pairs of zeros and poles that are complex conjugates one to another in the lossless case. Under the $e^{-i\omega t}$ sign convention, the zeros are located in the positive imaginary plane. The imaginary part of the complex frequency of the poles of the reflection coefficient represents the energy leakage of the system into the free space. Once the intrinsic losses are introduced in the system, the zeros of the reflection coefficient move downwards to the real frequency axis. For a given frequency, if the intrinsic losses perfectly balance the energy leakage of the system, a zero of the reflection coefficient is exactly located on the real frequency axis and therefore perfect absorption can be obtained[19,20]. This condition is known as critical coupling. An example will be shown where the sample was designed in this way and manufactured using stereolithography techniques. The structure presents a peak of perfect absorption at $f = 338$ Hz (different than that of the HR, $f_{HR} = 370$ Hz) with a thickness $L = \lambda/88$.

V. Conclusion

This presentation depicts an overview of some recent advances concerning the design of thin sound absorbing materials. First, metaporous and metaporoelastic materials are presented as an efficient solution in the inertial and possibly in the viscous regime of the porous matrix. Then, deep-subwavelength absorbers based on slow sound are proposed. These materials paved the way of the design of deep subwavelength broadband sound absorbing materials.

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