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Deep Sub-wavelength metamaterials for sound absorption for the reflection and ventilation problems.

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Abstract – **The absorption of sound constitutes a prominent research line in audible acoustics. Acoustic absorbers developed up to now are efficient in the high frequency range with sizes comparable to the wavelength of the frequency to be absorbed. Contrary, in the low frequency regime huge dimensions leading to oversized treatments and high manufacture costs arise. In this talk we discuss acoustic metamaterials showing efficient absorption at low frequencies with deep subwavelength dimensions. On the one hand, by exploiting the slow sound effect, the resonance frequencies of the system can be shifted down to the low frequency range and the phase shift of the reflection coefficient can be perfectly tuned. On the other hand, the critical coupling conditions are introduced to achieve a perfect impedance matching allowing perfect absorption conditions. We will show in detail the design of the ultra-thin absorbers working in the low frequency regime.**

I. Introduction

Acoustics metamaterials have recently revolutionized the field of acoustics and mechanics due to their extraordinary functionalities giving rise to breakthroughs in the material design strategy. Common wall treatments are made of flat panels with poor efficiency at low frequencies to attenuate, absorb or diffuse acoustic waves. In order to be efficient at low frequencies a complex problem must be solved: reducing the geometric dimensions of the structure while increasing the density of states at low frequencies and finding the good conditions to match the acoustic impedance of the surrounding medium.

Acoustic metamaterials have been proposed as a successful approach for increasing the density of states at low frequencies with reduced dimensions. Recently, several possibilities based on these systems have been used to design sound absorbing structures or efficient diffusers which can present simultaneously sub-wavelength dimensions and very good efficiency. On one hand, the design of sub-wavelength structures can be achieved by using different strategies. One of them consists of using space-coiling structures [1, 2]. Another way is to use sub-wavelength resonators as membranes [3, 4] or Helmholtz resonators (HRs) [5]. Recently, a new type of sub-wavelength metamaterials based on the concept of slow sound propagation has been used for the same purpose [6]. This last type of metamaterials makes use of its strong dispersion for generating slow-sound conditions inside the material [7] and, therefore, drastically decreasing working frequency. Hence, the structure thickness becomes deeply sub-wavelength. On the other hand, the impedance matching of such open, lossy and resonant structures can be achieved by the well know critical coupling condition [8, 9, 10]. These open systems, at the resonant frequency, are characterized by both the leakage rate of energy (i.e., the coupling of the resonant elements with the propagating medium) and the intrinsic losses of the resonator. The balance between the leakage and the losses activates the condition of critical coupling, trapping the energy around the resonant elements and generating a maximum of energy absorption. In the case of transmission systems, degenerate critically coupled resonators with symmetric and antisymmetric resonances should be used to perfectly absorb the incoming energy by trapping the energy in the resonant element, i.e., without reflection or transmission [11]. In the case of purely reflecting system, either symmetric or antisymmetric resonances that are critically coupled can be used to obtain perfect absorption of energy by a perfect trapping of energy around the resonators [9, 10].

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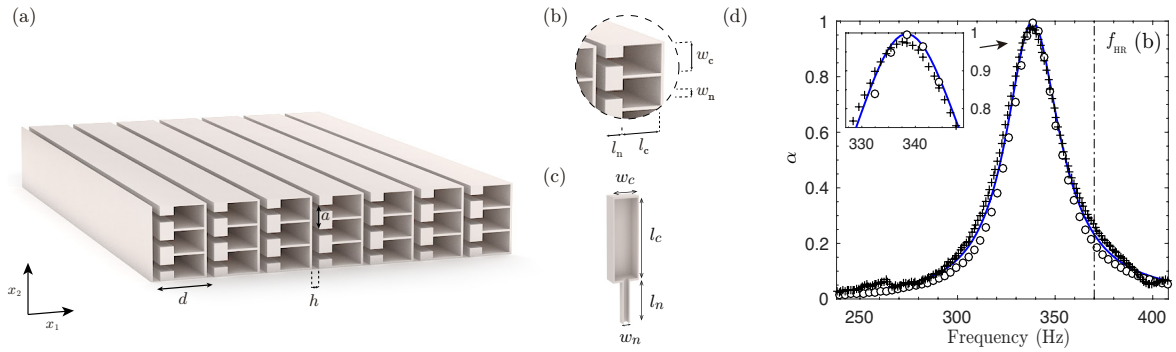


Fig. 1: (a) Conceptual view of the thin panel placed on a rigid wall with three layers of 2D Helmholtz resonators. (b) and (c) conceptual views of a 2D and 3D HRs respectively. (d) Absorption of the system measured experimentally (crosses), calculated by the transfer matrix method (continuous blue) and finite element method (circles).

In this talk we discuss the acoustic metamaterials, based on slow sound and critical coupling conditions, showing efficient absorption [8, 9, 10, 12, 13] at low frequencies with a deep subwavelength size. We notice that this kind of structures has been also exploited for efficient sound diffusion with deep sub-wavelength structures [14]. The analyzed system will consist of a 2D flat panel composed of a periodic distribution of slits loaded by a finite array of HR (see Fig. 1(a-c)). By exploiting the slow sound effect, the resonance frequencies of the system can be shifted down to the low frequency range and the phase shift of the reflection coefficient can be perfectly tuned. The critical coupling conditions are introduced to achieve a perfect impedance matching allowing perfect absorption conditions. We will show in detail the design of both monochromatic and broadband ultra-thin acoustic absorbers.

II. Building blocks

We consider a 2D flat panel composed of a periodic distribution of slits of width h separated a distance d and distributed in the x_1 direction as shown in Fig. 1 (a). Each slit is loaded by a finite array of M Helmholtz resonators (HRs) separated with lattice constant (distance between HRs) a. The HRs considered in this work can be either 2D (Fig. 1 (b)), made of combination of slits squared cross-section neck and a cavity with length and width dimensions $l_{\mathbf{n}}$ and $w_{\mathbf{n}}$, $l_{\mathbf{c}}$ and $w_{\mathbf{c}}$ respectively, or 3D (Fig. 1 (c)), made of square cross-section tubes, with a neck and a cavity widths w_n and w_c, and lengths l_n and l_c respectively. The system made by the slit with the loaded HRs is considered as the building block of the acoustic metamaterial described in this work.

III. Results

One of the main results discussed in this talk is shown in Fig. 1(d). Figure 1 (d) shows the absorption coefficient at normal incidence calculated with the transfer matrix method (TMM), predicted numerically by FEM and measured experimentally. At $f = 338.5$ Hz, perfect absorption can be observed. Therefore, the structure presents a peak of perfect with a thickness $L = \lambda/88$. The maximum absorption measured experimentally was $\alpha = 0.97$, as shown in the inset of Fig. 1 (d). This small discrepancy between the measurements and the models can be caused by experimental reasons including the non perfect fitting of the slit on the impedance tube and the excitation of plate modes of the solid medium that composes the metamaterial.

IV. Conclusion

Realistic panels made of bricks with Helmholtz resonators for sound perfect absorption with sub-wavelength sizes are discussed in this talk. The sub-wavelength feature of the presented structures provides perfect absorption for a wide range of incident angles. This almost omnidirectional sound absorber can be employed in practical applications where the omnidirectional feature is mandatory. These promising results have been used to study different configurations producing broadband perfect absorption with deep sub-wavelength structures, named rainbow trapping absorbers, that will be also described in detail.

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