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Ultra Thin Acoustic Metamaterial Panels Based on Resonant Bricks for Perfect Absorption

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Abstract **– Perfect absorption by an ultra thin acoustic metamaterial panel working in reflection is theoretically and experimentally reported in this work. The system is made by a rigid panel with a periodic distribution of thin closed slits, the upper wall of which are loaded by Helmholtz Resonators (HRs). The propagation in the slit is highly dispersive due to the presence of the resonators, producing a slow sound propagation before the HRs resonance, and down shifting the resonance frequency to low values. By controlling the geometry of the HRs, the visco-thermal losses can be tuned in order to compensate the leakage of the system and fulfill the critical coupling condition so activating the perfect absorption of sound. Theoretical predictions and experimental results show the possibility to design simple structures with deep sub-wavelengths dimensions ($\lambda/88$).**

Perfect absorption (PA) is of particular interest for many applications such as energy conversion [1], time reversal technology [2], coherent perfect absorbers [3] or soundproofing [4] among others. For absorption applications, it is desirable to avoid bulky structures and design sub-wavelength structures.The recent advances in PA have motivated an increasing interest on the design of perfect absorbers which at the same time are sub-wavelength structures. Recently in acoustics, impedance matched sub-wavelength membranes [5] with broadband perfect absorption [6], quarter-wavelength resonators [7], unidirectional nearly perfect absorption systems based on Helmholtz resonator [8] have been proved as sub-wavelength perfect absorbers.

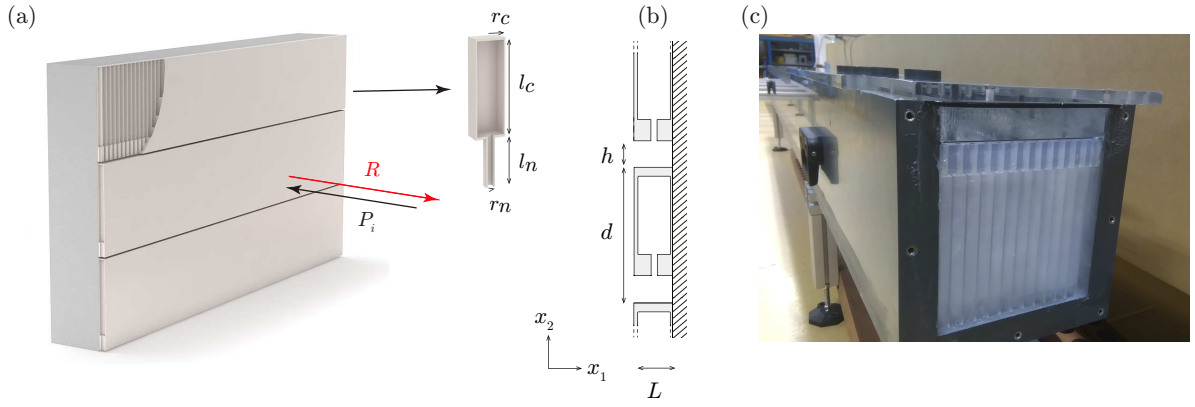


Fig. 1: (a) Conceptual view of the metamaterial panel. Inset shows the details of the Helmhotlz resonator. (b) Parameters of the sample. (c) Experimental set-up before closing the impedance tube. The panel was built by semi-optically transparent plastic.

In this work we go an step further and we consider the design of absorbing panels with the coupling between the exterior medium, i.e., considering the leakage of the resonant building blocks of the structure to the exterior medium. The system consists in a periodic arrangement of closed slits, of thickness h, in the x_2 direction with

periodicity d. The upper wall of the slit is loaded by identical Helmholtz resonators in an square array , as shown in Figs. 1(a-b). The Helmholtz resonators are characterized by a neck and cavity with radius r_n, and r_c and length l_n and l_c respectively [see Fig. 1(b)]. The visco-thermal losses in the system are considered in both the resonators and in the slit by using its effective complex parameters [9]. Therefore, by changing the geometry, the intrinsic losses of the system can be tuned.

Several theoretical models based on modal decomposition and on the transfer matrix method have been developed to analyze the reflection coefficient which is the scattering function of the system. Without loss of generality, in the lossless case, the representation of the reflection coefficient in the complex frequency plane provides pairs of zeros and poles that are complex conjugates one from another. In the $-\imath\omega t$ sign convention, the zero is in the positive imaginary plane. The system is open to the free field on one side, therefore the system itself presents energy leakage to the free field. The imaginary part of the complex frequency of the zero of the reflection coefficient represents this leakage. Once the intrinsic losses are introduced in the system, the zero of the reflection coefficient moves to the real frequency axis, in such a way that if the intrinsic losses perfectly balance the energy leakage, the zero of the reflection coefficient is exactly placed on the real frequency axis and perfect absorption, $\alpha = 1 - |R|^2 = 1$, can be obtained. This condition is known as critical coupling.

An optimized calculation using the transfer matrix method, provides structures with perfect absorption with deep-subwavelength sizes. Figure 2(a) shows the representation of the reflection coefficient in the complex frequency plane of one of these structures, that has a peak of perfect absorption at $f = 338.5$ Hz with a thickness $L = \lambda/88$. The color map corresponds to the case in which the critical coupling condition is fulfilled, i.e. the zero of the reflection coefficient is on the real frequency axis. As long as the intrinsic losses depend on the geometry of the resonators, we also represent the trajectory of this zero as the length of the neck of the HRs changes. The crossing of the trajectory with the real frequency axis implies that perfect absorption can be achieved by this system at this particular frequency.

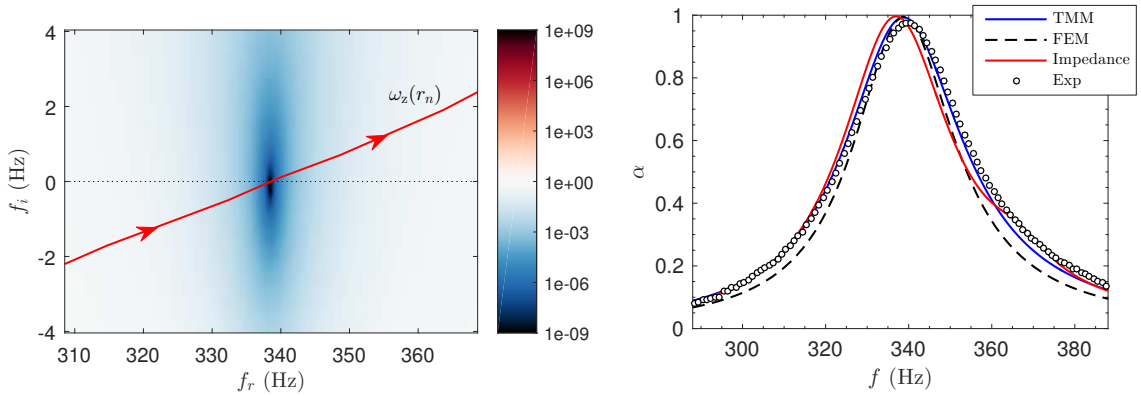


Fig. 2: (a) Representation of $|R|^2$ in the complex frequency plane. Continuous line represents the trajectory of the complex zero of the reflection as the radius of the neck, r_n, is changed. (b) Representation of the theoretical, numerical and experimental absorption coefficient for the configuration corresponding to the crossing of the trajectory in (a) with the real frequency axis.

Figure 2(b) shows the absorption coefficient at normal incidence calculated with the different semi-analytical methods, predicted numerically and measured experimentally for the configuration corresponding to the crossing of the trajectory of the zero with the real frequency axis. At this frequency, perfect absorption can be observed.

Realistic panels for sound perfect absorption with sub-wavelength sizes are designed in this work with simple structures made of bricks with Helmholtz resonators. Perfect absorption of sound is achieved at 338.5 Hz with a panel thickness of $L = \lambda/88 = 1.1$ cm. It is worth noting here that the total panel size in the vertical dimension is also sub-wavelength $d = \lambda/6.5 = 14.5$ cm. These promising results open the possibilities to study different configurations based on these structures to extend the results to broadband and omnidirectional perfect absorption with deep sub-wavelength structures, which remains a great scientific challenge.

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