ULTRASONIC INSULATION USING A HELMHOLTZ-LIKE PHONONIC CRYSTAL WITH A SLIGHT FILLING FACTOR

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ABSTRACT
Metamaterials are artificial materials designed to control and manipulate waves. They present the advantage to prohibit acoustic propagation in some frequency ranges called Band Gaps. In this paper, we present a series of Helmholtz-like resonators shaped for ultrasonic insulation purposes. This host plate is made of silicon in which the unit cell represents a phononic membrane formed by a sub-wavelength aperture and two Helmholtz resonators facing each other and immersed in water. The finite element simulations are performed between frequencies 1.7 MHz and 2.95 MHz. It is shown that such configuration exhibits a large band gap exceeding 1000 kHz and an attenuation up to -35 dB.

CCS Concepts
• **Smart Building and Home Automation → Green and Intelligent Construction.**

Keywords
Sound comfort, Phononic crystals; Acoustic Metamaterials, Helmholtz resonators.

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1. INTRODUCTION
In the recent years, there has been an increasing interest in studying acoustic wave propagation in periodic media. Phononic crystals are periodic structures made of at least two materials that enables perfect reflection of waves under Bragg scattering[1] [2]. Soon after, studies have been extended to acoustic metamaterials with localized resonances to control long waves using sub-wavelength elements [3]. Many intriguing phenomena have been put forward, including ultrasonic insulation and acoustic absorption followed by the design and engineering of materials with negative acoustic refraction (observed when both mass density and bulk modulus are negative), acoustic invisibility cloak, or acoustic induced transparency [4] [5].

Preexisting works on the topic have focused on generating ultrasonic opacity by coupling modes through Fabry-Perot reflection. In this work, we couple slits to Helmholtz resonators highly to constitute a phononic membrane. Through a 2D numerical simulation, we demonstrate how hybridization broadens the acoustic attenuation range.

2. SETUP
In this paper, an acoustic device supporting Helmholtz-like resonance is proposed using an array of apertures periodically etched in a thin membrane previously published in [6]. The design consists on a 3D sub-wavelength unit cell, in which a pair of Helmholtz-like resonators is shaped facing each other and immersed in water (fig.1). They are made of a rigid acoustic material (Silicon) with physical properties used for simulation described in Table 1. The structure has a solid domain thickness of 1 mm, a period of 0.5 mm, and rectangular Helmholtz cavity with

parameters (t=0.775 mm, l=0.2 mm, m=0.125 mm, n=0.2 mm, d=0.05 mm) with a filling factor of about 18%.

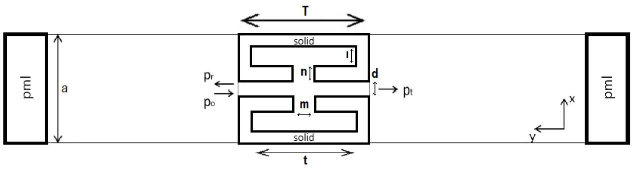


FIG. 1. Schematics of the unit-cell used in the phononic insulation, we distinguish incident Po, reflected Pr, and transmitted Pt pressures.

Calculations are realized using Comsol Multiphysics; a finite element analysis software. In order to be consistent with the experimental conditions, an acoustic plane wave is generated in one side of the structure. The transmission loss is evaluated by comparing the signal that crosses the phononic structure to the source. Thanks to periodicity, we limited the model to one-unit cell and applied periodic boundary conditions along the x-axis, as illustrated. Perfectly Matched Layers (PMLs) are placed on both sides to reduce reflections on the system boundaries.

Material	Density	C_L (m/s)	C_T (m/s)
Silicon	2.329	8433	5843
Water	1.0	1480	-

Table 1. Physical characteristics of materials.

3. RESULTS

The numerical simulations show that basically, the coupling of these resonances' mechanism induces an enhancement of the transmission at discrete frequencies, in which the acoustic energy of the incident wave is totally transmitted through the apertures. In this case, sharp peaks can be observed in the transmission spectra,

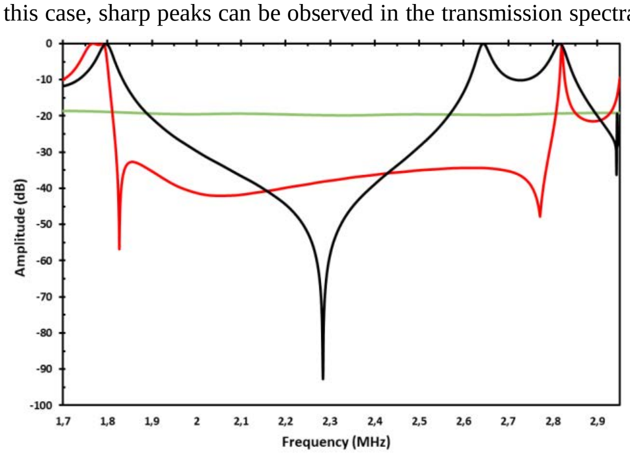
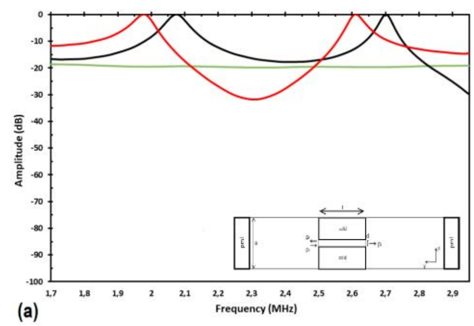


FIG. 2. The black and the red lines represent the amplitude transmission spectra, obtained by finite element method, related to the membrane in Figure 1. The red line corresponds to the case of silicon, and the black line to a fictive rigid solid. The green curve represents the amplitude transmission through a homogeneous silicon membrane.

thus highlighting an extraordinary transmission. In the other case, the local resonators can weakly interact together by exchanging energy.

The physical origin of those phenomena can be obviously shown when using solid rigid conditions on boundaries for the perforated plate Figure 2 (black line), the Fabry-Perot effect is clearly identifiable by resonances of the transmission at frequencies 1.8 and 2.65 MHz, moreover an antiresonance reaching -95 dB is observed, due to Helmholtz-like resonators.

Once applying solid rigid conditions for each component of the structure Figure 1 separately. We can isolate the effect generated by Fabry-Perot resonance through the aperture Figure 3(a), furthermore, the specific Helmholtz effect appears in Figure 3 (b). However, when we remove rigid solid conditions on the boundaries and apply silicon characteristics to the solid (see Table I), we create a finite acoustic impedance ratio between fluid and solid. This



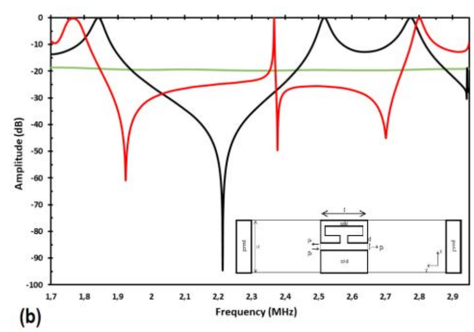


FIG. 3. Amplitude transmission spectra, obtained by finite element method (a) related to a membrane perforated (red line). (b) related to a membrane perforated with one side Helmholtz-like resonator (red line). The black line in (a) and (b) represents the rigid solid conditions used on boundaries. The green curve represents the amplitude transmission of a homogeneous silicon membrane.

allows a sort of cross talk between resonators (Figure 4), which leads to a drastic change in the transmission. In these conditions, we observe an enhancement of the transmission at the resonance frequencies of 1.8 MHz and 2.8 MHz. Between these two frequencies, a broadband attenuation occurs. This attenuation exceeds the limits of the conventional mass-density law, characteristic of the homogeneous plate. Figure 4(b, c) show the elastic displacement field distributions at the anti-resonance mode. Waves operating at 1.82 MHz and 2.77 MHz are visualized through the elastic displacement and pressure distribution in the unit cells and the host fluid, which reveals a high degree of cross-talk

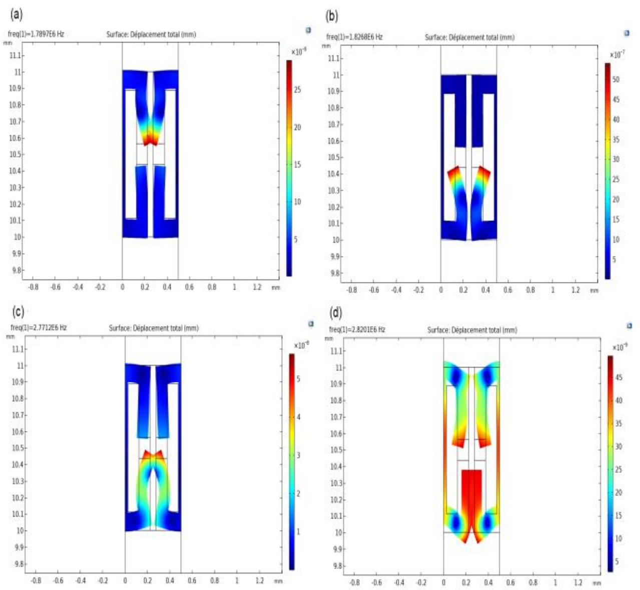


FIG.4. Displacement field of the membrane unit cell corresponding to the modes of vibrations, at resonance (panels (a) and (d)) and antiresonance (panels (b) and (c)) frequencies.

between them. The effect of the structure parameters and thickness on the resonance frequencies and bandgap is presented in Figure 5. Indeed, it is possible to shift the transmission and the attenuation by varying the Helmholtz cavity parameters or the aperture width of the unit-cell.

4. CONCLUSION

In conclusion, we have obtained transmission losses up to 35dB, on a large bandwidth exceeding 1000 kHz, with a filling factor smaller than previously proposed in [6] ($ff = 95\%$), through periodically perforated silicon wafer. Our analytical description provides a thorough understanding of the phenomenon that is based on the coupling of Fabry-Pérot interference and Helmholtz resonance through a fluid-solid interaction. Thus, asymmetric shapes of resonances and anti-resonances enable to create an area of huge acoustic blocking effect. This should therefore motivate the development of many potential and practical applications, particularly in controlling the phononic properties of materials for a green and intelligent construction.

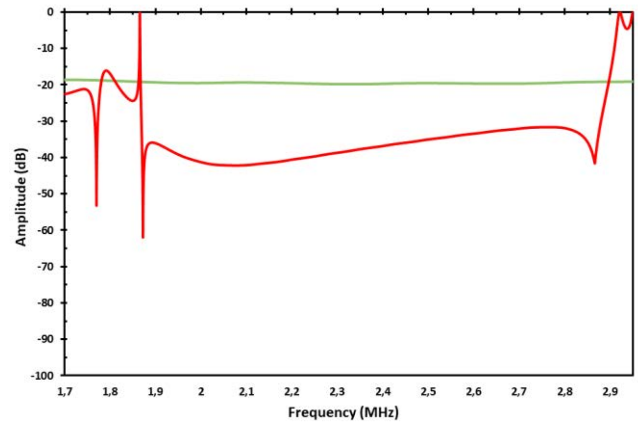


FIG. 5. The red line represents the amplitude transmission spectra, obtained by finite element method, related to the membrane Figure1 structure, with Helmholtz cavity of (t=0.7 mm, l=0.225 mm, m=0.1 mm, n=0.2 mm). The green curve represents the amplitude transmission of a homogeneous silicon membrane.

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