STRONG ATTENUATION USING SUBWAVELENGTH APERTURES IN A PHONONIC PLATE

Aliyasin El Ayouch, Mahmoud Addouche, Morvan Ouisse, Abdlekrim Khelif

Institut FEMTO-ST, Université de Franche-Comté, CNRS, 32 avenue de l'Observatoire 25044 Besançon Cedex, France

Philippe Lasaygues, Younes Achaoui

Laboratoire de Mécanique et d'Acoustique, UPR CNRS 7051, 31 chemin Joseph Aiguier, 13402 Marseille cedex 20 – France

e-mail: aliyasin.elayouch@femto-st.fr

The aim of this study is to demonstrate an acoustic screening in a periodically perforated plate. The phononic structure is constituted of sub-wavelength slit arrays, of the order of λ/10, in an aluminium plate that is immersed in water. These arrays act as Fabry-Pérot acoustic resonators, and through the coupling effect between them, we obtain a series of asymmetric shape peaks in the transmission spectra. This leads to an enhanced transmission at the resonance frequencies as well as to improve the attenuation significantly at the anti-resonance frequencies. Therefore, the composition between these anti-resonance frequencies, through the geometrical features, enables to reach an attenuation up to 23 dB, with a relative bandwidth of 11% and a center frequency of 175 kHz.

1. Introduction

The phononic crystals idea originally states that a strong periodic modulation in density and elastic constants can create band gaps that prohibit wave propagation in certain frequency ranges. In this Bragg-based band gap mechanism, the spatial modulation must be of the same order of the wavelength, which is a strong limitation that is imposed to the acoustic screening structures operating at low frequency regime. Indeed, the structure would have to be the size of few meters in order to shield environmental noises. Therefore, the sonic band gap structures are not relevant to other standard structures that use the "mass law" prediction, which describes the sound transmission loss in homogeneous plates. To overcome this limitation, Ping Sheng introduced a new class of phononic films. These new structures exhibit spectral gaps in an expected range two orders of magnitude smaller than the relevant sonic wavelength. These materials are based on locally resonant structural units. One membrane can be decorated with weights attached to the surface, or can be simply pierced as holes. [2] From here, these locally resonance-based structures can be subject to two physical conditions. Firstly, the acoustic resonators are isolated, with no crossing-over between them. It means that resonators are under conditions that prevent from a possible interaction between each other. For instance, one can separate the unit-cells by using a rigid grid[3,4]. In The numerical analysis, one can consider a solid rigid in the solid/fluid structures with slit arrays or holes[5,6]. Then, sharp peaks come out in the transmission spectra, highlighting thus an extraordinary transmission where the acoustic wave crosses the slab through sub-wavelength apertures at discrete frequencies of such resonators. In the second case, the locally resonators can weakly interact together by exchanging energy[7]. This occurs for fluid to solid finite impedance ratio[8,9]. Cells of the structure are thus linked to each other in such a way that the behavior of one affects the other one. This lead to a drastic change of the acoustic transmission shape as presented hereinafter.

In this article, we study acoustic transmission properties of sub-wavelength apertures. More precisely, we explore experimentally and through finite element simulations, the case of a plate periodically decorated with slit arrays, highlighting the combination of both Fabry-Pérot cavities and the coupling solid/fluid.

2. Geometry

The structure consists on a plate decorated with periodically distributed slit arrays. The system's period is "a" along the x-axis, the width of slit arrays is "d", and the plate thickness is "t", as represented in the figure 1. Those structure dimensions are expressed according to the system period "a". The perforated plate, constituted by aluminium, is immersed in water. Physical properties are listed in the table I.

Table 1. Materials properties

Material	**Density**	**c_l (m/s)**	**c_t (m/s)**	**K**
Aluminium	2700	6420	3040	11.6
Water	1000	1480	-	-

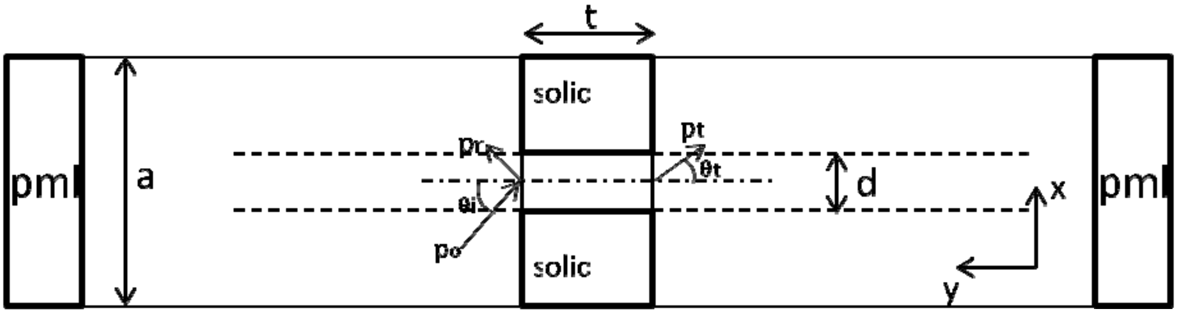

Figure 1. Diagram of the perforated plate unit-cell cross-section. In the fluid, we distinguish incident P_0, reflected P_r and transmitted P_t pressures.

We carried out simulations of the acoustic transmission through the system. The outgoing signal from a source generating acoustic waves, placed in one side of the system, is compared to the signal that crossed the phononic structure. The acoustical transmission is function of normalized frequency, for plates perforated with periodically distributed sub-wavelength slits. Calculations are realized using Comsol Multiphysics; a finite element analysis software. Thanks to the periodicity of the system, we worked on the unit cell, presented in the figure 1a, and applied periodical conditions along the x-axis. Besides, perfectly matched layers (PML) are used, in order to reduce reflections on system boundaries, which simulate an artificial infinite domain.

3. Results and discussions

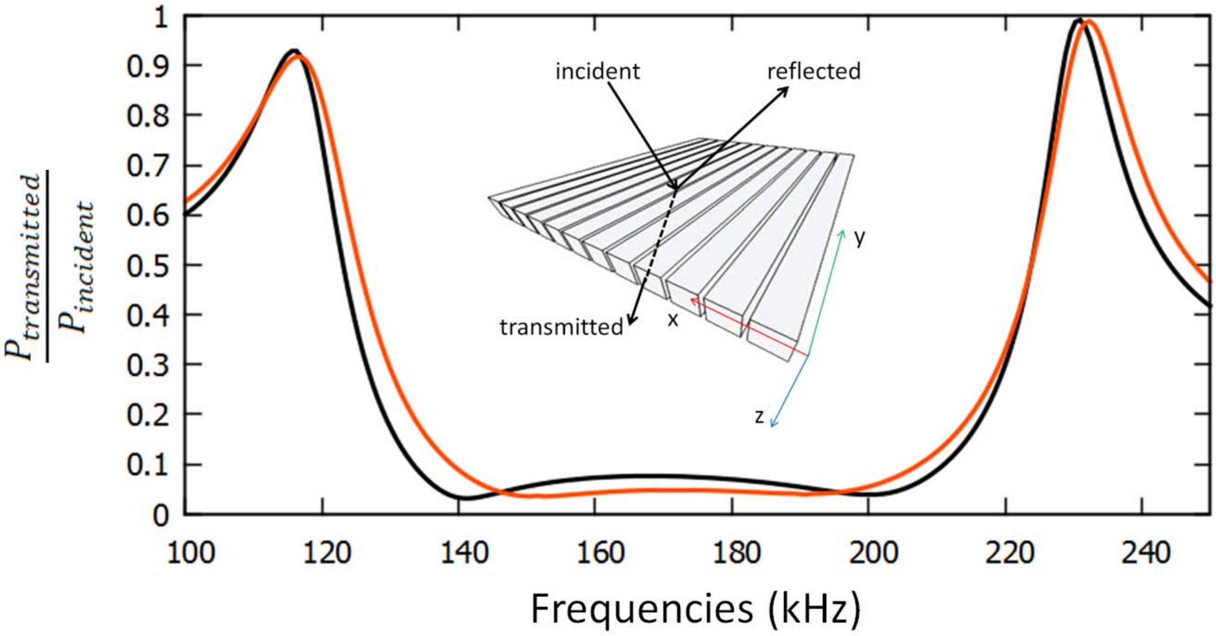

Figure 2. Amplitude transmission spectra, at normal incidence, related to a plate perforated with periodically distributed slit arrays. The plate thickness is equal to the system period "a", and apertures width are d=0.10a for the black line and d=0.12a for the orange line.

As previously presented, cavities of a perforated plate act as resonators for acoustic waves. At certain frequencies, an incident wave is totally transmitted through holes of a periodically perforated plate, which is also known as the Fabry-Perot effect. Resonance frequencies can be shifted by increasing the structure thickness. Here, the figure 2 depicts the acoustical transmission of a perforated plate of aluminium obtained by simulations using finite element analysis. Plate thickness is equal to the period "a", and aperture width is set to 0.1a. The transmission curve presented on figure 2 is however different from the classical Fabry-Pérot effect. We observe a resonance followed by an anti-resonance, and vice versa. Thus, finite impedance ratio between fluid and solid leads to resonances and anti-resonances that occur alternatively one after the other in the transmission spectra.

The finite impedance ratio between fluid and solid allows coupling between apertures that play the role of resonant cavities. This coupling contributes to increase or decrease the transmission through the slit arrays. Geometrical parameters have a direct effect on this coupling. More precisely, anti-resonance frequencies can be shifted by changing the width of apertures. Thus, the anti-resonance frequencies get closer when the aperture width increases, until a certain value of this parameter for which the anti-resonance frequencies merge. Then, increasing the aperture width makes the attenuation between the two resonance frequencies become ever less important.

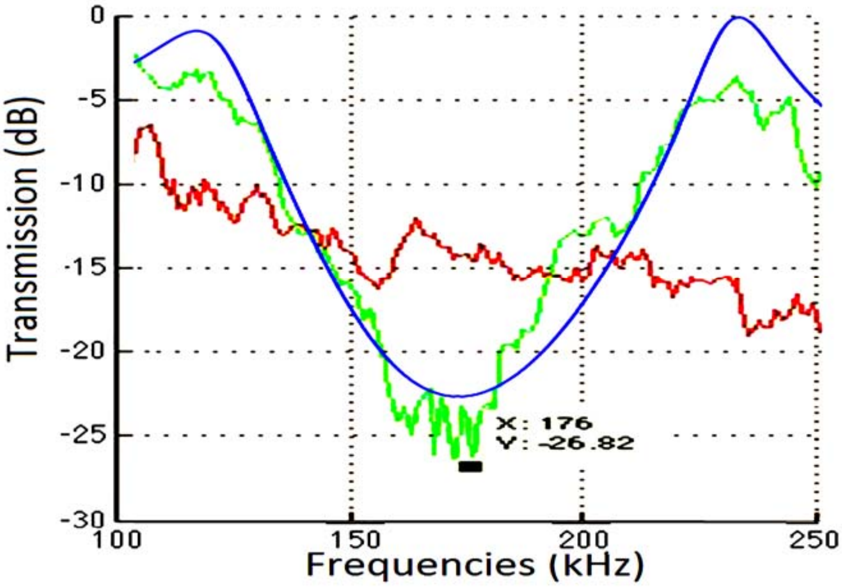

Figure 3. The curves depict the amplitude transmission spectra of a plate perforated with periodically distributed slit arrays, at normal incidence, obtained by simulation (blue) and experimentally (green). The plate thickness is equal to the system period "a", and width of apertures d=0.17a is optimized in order to obtain the maximal attenuation . The red line shows the mass law trend for a plate with the same thickness, obtained experimentally.

The experimental evidence of this screening had been conducted using a homogeneous and a perforated plate of aluminium having a thickness of 5 mm. There are apertures of 0.85mm (17% of the period) regularly disposed every 5mm. A transducer and a hydrophone had been used for the emission and reception of acoustic waves; everyone is placed on either side of the phononic structure. We studied the transmission of a pulse that cross the homogeneous plate on the one hand, and the perforated plate on the other hand. In order to compare the transmission spectra of each situation, we applied a Fourier transform on both temporal signals. The figure 3 is the transmission spectra of both structures, at normal incidence. We observe two enhanced transmission areas centered around 100 kHz and 230 kHz, between which there is an attenuation frequency band. This attenuation reaches 23 dB on a relative bandwidth of 11% with a center frequency of 175 kHz. We observe on the figure 3 an attenuation improvement, up to 10 dB compared to the homogeneous plate, in a certain frequency band.

Acoustic shielding that suppresses noise has always been searched out for many reasons, from comfort and practical convenience, to scientific and strategic issues. This simple and potentially cheap solution could be used as reflectors that block signals from undesirable noise, given its efficiency and its adaptability to materials.

4. Summary

In conclusion, we have obtained transmission losses up to 23 dB on a relative bandwidth of 11% with a center frequency of 175 kHz, through periodically perforated thin membrane. The physical mechanism that underpins such a behavior is based on the Fabry-Pérot resonators and the coupling fluid-solid. Finite impedance ratio between fluid and solid leads to asymmetric shape of peaks in the transmission spectra. Thus, asymmetric shapes of resonances and antiresonances, that are close together, permit to generate an area of huge acoustic blocking effect. This opens the way for many applications, particularly in underwater acoustics and underwater ultrasound.

5. Acknowledment

We acknowledge the financial support from the Region of Franche-Comté under the reference 2012C-08901.

REFERENCES

[1] Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan, and P. Sheng, *Science* **289**, 1734 (2000).
[2] Z. He, S. Peng, R. Hao, C. Qiu, M. Ke, J. Mei, and Z. Liu, *Appl. Phys. Lett.* **100** (2012).
[3] Z. Yang, J. Mei, M. Yang, N. H. Chan, and P. Sheng, *Phys. Rev. Lett.* **101**, 204301 (2008).
[4] J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, and P. Sheng, *Nature Comms.* (2012).
[5] J. Christensen, L. Martin-Moreno, and F. J. Garcia-Vidal, *Phys. Rev. Lett.* **101**, 014301 (2008).
[6] H. Estrada, P. Candelas, A. Uris, F. Belmar, F. Meseguer, and F. Javier García de Abajo, *Wave Motion* **48**, 235 (2011)
[7] Y. Pennec, B. Djafari, H. Larabi, A. Akjouj, and G. Leveque, *New Journal of Physics* 14 (2012).
[8] H. Estrada, J. M. Bravo, and F. Meseguer, *New Journal of Physics* **13**, 043009 (2011).
[9] C. Qiu, R. Hao, F. Li, S. Xu, and Z. Liu, *Appl. Phys. Lett.* **100** (2012).