Sound blockage through closely spaced perforated layers

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Abstract

The transmission of sound through a pair of rigid plates each perforated with a sub-wavelength square array of small circular holes is experimentally explored in air. The holes in the plates are aligned with one another and the plates are separated by a gap significantly smaller than the wavelength of the incident sound. This so-called "Acoustic Double Fishnet" (ADF) structure [J. Christensen, L. Martín-Moreno and F. J. García-Vidal, App. Phys. Lett. **97** 134106 (2010)] is characterised by a band of near-perfect blockage of sound at a frequency dictated by the periodicity of the hole array. Comparison of experimental data with the predictions of analytical and numerical models provides understanding of the observed phenomena, which is discussed in terms of a hybridization of the Fabry-Perot modes with the mode supported in the gap between the plates. The experimental transmission data matches the theoretical models well, with small differences arising due to viscous drag, which is particularly significant in narrow structures. Such a structure may find use for limiting acoustic transmission in applications where ventilation is required.

1. Introduction

The past couple of decades have seen a large amount of research invested in the study of metamaterial structures. Sub-wavelength features that change the effective properties of a substrate have been used to remarkable effect such as enhancing the transmission properties of a structure so that significantly more incident radiation is transmitted than is directly incident upon the transparent regions [1]. Another structure has been designed to guide acoustic waves around a central region allowing an object placed within the central region to remain hidden [2]. The desire for thin, lightweight structures capable of suppressing sound transmission has led to novel structures being proposed, including the negative dynamic mass membrane [3] and the acoustic double fishnet (ADF) structure [4]. The latter

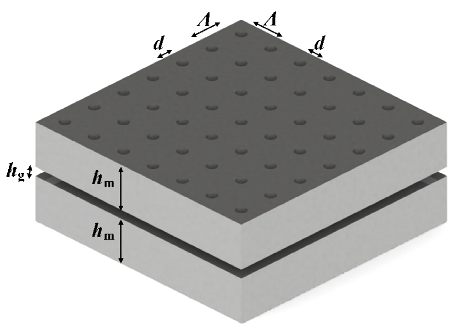

Fig. 1: Diagram of the ADF structure showing structural dimensions. Λ is the array pitch, d is the hole diameter, h_g is the gap thickness and h_m is the plate thickness.

is explored further in this work to provide more in depth undertanding of the modes supported, and the first experimental evidence of its acoustic performance. The ADF structure is essentially two perforated plates in close proximity and offers the possibility of suppressing the transmission of sound within a frequency band prescribed by the periodicity of the square array of holes. Fig. 1: shows a schematic of the ADF structure.

2. Theory of the ADF structure

Single holey plates support Fabry-Perot resonant modes when the wavelength of the incident sound is a unit fraction of the effective length of the pipe created by the presence of the holes. Fig. 2: shows this resonant behaviour for a plate 12 mm thick with 2.4 mm diameter holes in an 8 mm square array. The red line represents the finite element method (FEM) predictions [6] and the black line is experimental data. The ADF structure introduces a sub-wavelength gap between two single plates and the mode supported in this region hybridizes with the Fabry-Perot modes. The convergence and divergence of the resonant modes at the gap resonance (Fig. 3:) allows for a band bounded by two odd-order Fabry-Perot modes, i.e. those with pressure antinodes at the gap. These modes interfere destructively within this band, leading to significant suppression of the transmitted sound. In this lossless model, complete destruction occurs only at a singular frequency with the black region corresponding to levels below 0.5% amplitude transmission.

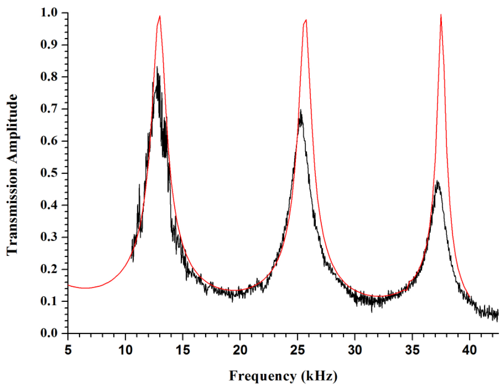

Fig. 2: Transmission plot for a single holey plate with thickness $h_m = 12$ mm and hole diameter $d =$ 2.4 mm. The red line is FEM modelling and the black line is data captured with the experimental set up.

3. Experimental Results

The experimental set-up consists of a loudspeaker and microphone with two parabolic mirrors, one to ensure a plane wave is incident on the ADF structure and the other to refocus the transmitted the frequency is swept. The experiment is undertaken in air. The black lines on the graphs of Fig. 4: are the experimentally measured transmissivity of the ADF structure. The model dimensions are matched to those used in the experimental arrangement (h_m = 5.96 mm, h_g = 0.94 mm, $\Lambda = 8$ mm and hole diameter d = 2.4 mm). The most noticeable difference between the model predictions and the experimental data is in the magnitude of the peak transmitted signal. This arises because viscous drag is not correctly incorporated within the FEM anaylsis (red lines). There is also a small variation in the plate thicknesses (±50 μm) that is not represented in the model. Where the resonant peaks lie within ~1 kHz of one another, the noise within the data makes it difficult to resolve the two peaks.

Previous papers predicting the acoustic transmission properties of the ADF structure using modal matching techniques [4, 5] have suggested blockage of sound occurs across a substantial bandwidth. The data presented here, in the form of transmitted amplitude (as opposed to amplitude squared used in previous papers), makes the profile of the stop band more apparent.

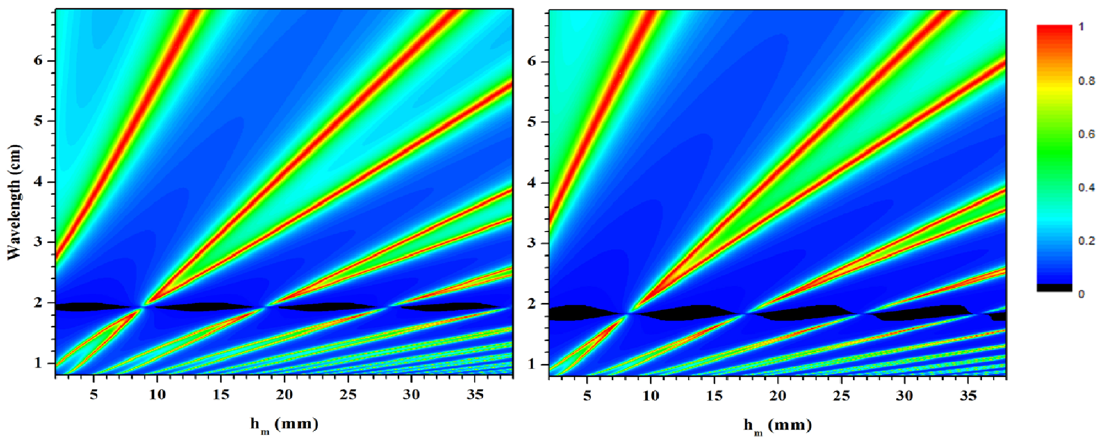

Fig. 3: Transmission spectra for the ADF structure as a function of wavelength and h_m. The left plot shows the spectra for a gap h_g = 0.47 mm and the right plot for h_g = 0.94 mm as used in the experiment. The plane sound wave is incident normal to the ADF structure. Black regions indicate a transmission amplitude < 0.5%.

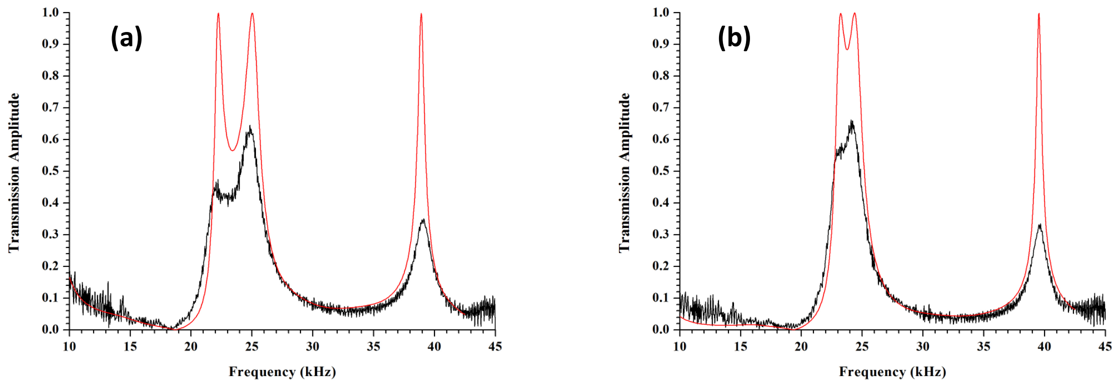

Fig. 4: Normalised amplitude transmission graphs for the ADF structure with a plate thickness, h_m = 5.96 mm and a gap size of (a) h_g = 0.47 mm and (b) h_g = 0.94 mm. The hole diameter is 2.4 mm. The red line indicates the transmission predicted by FEM modelling. The zero transmission occurs at (a) 18.3 kHz and (b) 19.2 kHz.

4. Conclusion

It is shown that the ADF fishnet structure transmits and blocks sound as predicted by the theory. The detailed behaviour arises from the interaction of two odd-order resonances located proximally to one another due to the hybridization of the Fabry-Perot modes with the gap mode that takes place. The ADF structure presents an attractive opportunity to suppress a band of sound prescribed by the periodicity of the structure in situations where the free flow of air through a solid boundary is required.

References

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