Control of sonic metamaterial stopband

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Abstract

The acoustic transmittance of two closely spaced rigid plates perforated with a square array of circular holes is studied both experimentally and numerically. The system exhibits a band of acoustic attenuation originating from hybridization between a two-dimensional resonance in the gap between the plates, and pipe modes in the holes. Misalignment of the holes in either one or both lateral dimensions shifts the centre frequency of the stop band to maintain the conditions required for zero transmission.

1. Introduction

The acoustic double fishnet (ADF) structure comprises two rigid plates, each perforated with a square array of circular holes, with the holes on one plate perfectly aligned with the holes on the other. Previous studies have shown how when the two plates are separated by a sub-wavelength gap, the system exhibits a band of near-perfect acoustic attenuation [1-3]. The present study investigates the influence of plate misalignment on the acoustic transmittance. Figure 1 shows a schematic of the misaligned ADF structure.

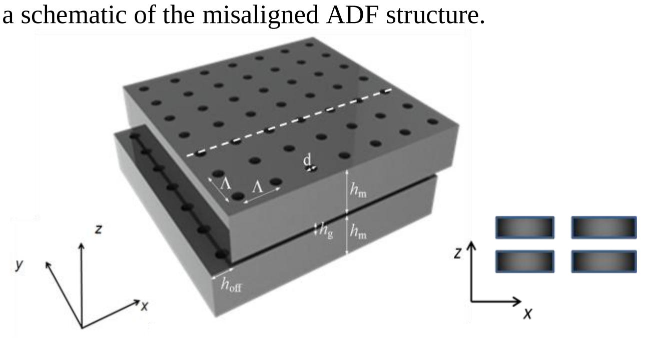

Figure 1: Schematic diagram of ADF structure, with plate thickness h_m, and gap size h_g. The circular holes, of diameter d, are arranged in a square array with pitch Λ. The lateral displacement between the plates is h_{off}. The right-side inset illustrates a cross section of a unit cell (shown with no lateral displacement) taken along the dashed white line.

The presence of a small gap between the two plates leads to the hybridisation of the two-dimensional resonance in the gap between the plates with the pipe modes in the holes leading to frequency shifts of the resulting transmission peaks. Moreover, the presence of the gap also leads to near-perfect suppression of sound transmission across a frequency band dictated by the pitch Λ.

When the holes in the two plates are aligned (i.e. each pair of aligned holes behave as a long pipe with a the gap at its mid-length), odd-order modes (exhibiting a pressure antinode in the region of the gap) are strongly perturbed in frequency, due to volume flow leakage into the gap, whereas even-order modes (exhibiting a pressure node in the region of the gap) are largely unaffected. The frequency at which sound blockage occurs corresponds with a resonance of the two-dimensional mode in the gap. Considering a symmetrical unit cell centred over one of the holes, the pressure must be maximal along the (square) boundary in the gap at the frequency of the “gap resonance”. As the plates are misaligned, the condition for zero transmission changes. Using symmetry arguments, there must still be a pressure antinode at the boundary of a square unit cell located centrally over the input hole, however for no sound to be transmitted there must be a pressure node located at the output hole. In this case, there is no pressure variation at the output hole and therefore no coupling between the holes in the two plates, and thus no transmission of sound. When the pressure wave in the gap satisfies these conditions, the sound field is no longer a simple resonance of the gap. It follows that the frequency of sound blockage should increase with misalignment of the plates, as the pressure node in the gap at the output hole spatially approaches a pressure antinode at the unit cell boundary, effectively forcing a quarter-wave into a smaller distance. It is clear that the case when the holes are aligned is a special case that satisfies the conditions for zero transmission.

2. Modelling

Figure 2 (a) and (b) show theoretical transmission spectra modelled with a modal matching technique (described in Ref. 3) for the cases of lateral and diagonal misalignment respectively. The technique involves matching the acoustic pressure and velocity functions at the each of the interfaces through the structure. Both plots clearly show the increase in frequency of the stop band as the plates are misaligned. Preliminary results from an analytical model (to be described in a future article) also agree well with these findings.

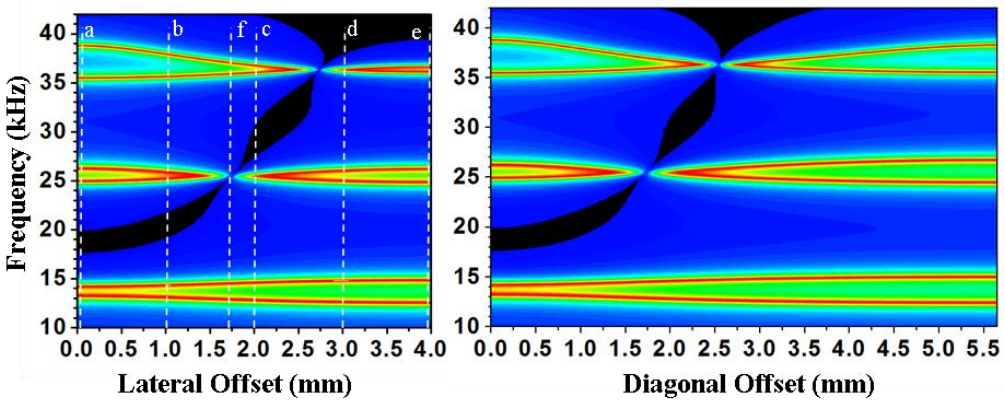

Figure 2: (a) Predicted transmission spectra using a modal matching technique [3], showing the resonant modes of two h_m = 12 mm thick perspex plates separated by h_g = 0.94 mm at increasing lateral plate offsets. Red shading indicates regions of strong transmission, and black indicates transmission amplitudes of less than 0.5%. (b) Similiar transmission spectra as (a) with plates offset diagonally.

3. Experiment

The experimental sample consists of two perspex (Lucite) plates, with thickness h_m = 12 mm and perforated with circular holes of diameter d = 2.4 mm in a square array of pitch Λ = 8 mm. The square plates have sides of length 200 mm (corresponding to a 25×25 array of holes), and are separated by an air-filled gap with h_g = 0.94 mm. A plane sound was normally incident in air on to the sample. The experiments were undertaken with frequencies ranging between 10 and 40 kHz. A series of sample geometries were studied with 1 mm incremental offsets of the plates and an additional data set obtained at an offset of 1.69 mm to demonstrate the strong suppression of a transmission resonance (Figure 3). The experiments utilised a pair of parabolic mirrors, one to produce the plane wave from point source and the other to focus the transmitted sound wave into the detector.

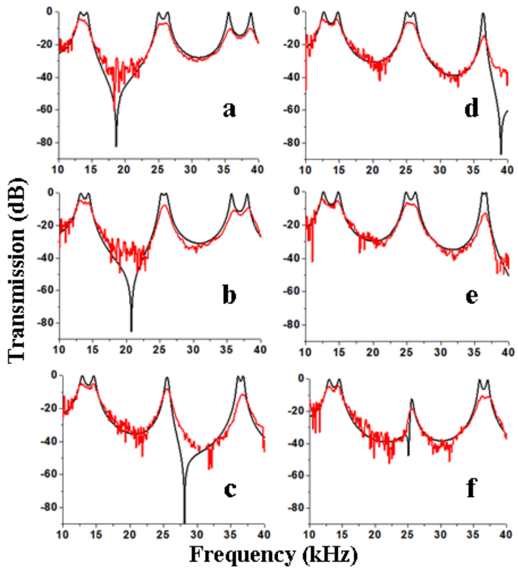

Figure 3: Experimental (red line) and theoretical modelled (black line) transmission results through the ADF structure in air. Graphs (a)-(e) show the transmission for h_{off} = 0 mm, 1 mm, 2 mm, 3 mm, and 4 mm respectively. Graph (f) shows the transmission for h_{off} = 1.69 mm.

4. Discussion

The data presented (Fig. 3) shows generally good agreement with the theoretically predicted transmittance of the ADF structure. Note, that in comparison with the model, the experimental results exhibit non-unity transmittance on resonance, and imperfect sound blockage. It is proposed that this error is associated with the failure to fully account for viscous losses within the narrow pipes in the system. As shown in Bell *et al.* [3] the magnitude of sound suppression is significantly greater than that provided by a single holey plate of equivalent total thickness. Offsetting the plates provides a reasonably simple method of tuning the location of the stop band and as shown in Figure 3 (f), the stop band can be used to significantly reduce the strength of transmission resonances that are otherwise present, thus producing a broader frequency band with significant sound suppression.

Acknowledgements

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5. References

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