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ABSORBING AND MANIPULATING SOUND WITH METAMATERIALS

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We present some recent acoustic metamaterial topics of experimental study at Exeter. The first is a thin acoustic metamaterial absorber, comprised of only rigid metal and air, which gives rise to near unity absorption of airborne sound on resonance. This simple, easily fabricated, robust structure comprising a perforated metal plate separated from a rigid wall by a deeply subwavelength channel of air, is an ideal candidate for a sound absorbing panel. The strong absorption in the system is attributed to the thermo-viscous losses arising from a sound wave guided between the plate and the wall, defining the subwavelength channel. In the second part of this talk, we explore a trapped acoustic surface mode on line of holes in a rigid material. The mode's propagation along a line of holes and a ring of holes is explored. The existence of the mode for a curved line, the circle, illustrates the potential for manipulating sound propagation by the simple use of lines of patterned holes on a rigid surface.
Keywords: metamaterial, absorber, surface-wave, losses, viscous

1. Metamaterial Absorber

In recent years, acoustic metamaterials, structures patterned on a subwavelength scale that exhibit novel properties not observed in nature for the control of sound, have been the focus of research interest. Pioneering work investigating these exotic structures has led to new ideas and concepts for the attenuation of low-frequency airborne sound, challenging the performance of more traditional structures such as those utilising fibrous or porous materials [1] or micro-perforated panels [2]. Structures that have been studied include membrane-type acoustic metamaterials [e.g., 3], which for example, may consist of an elastic membrane supported by a rigid grid and "decorated" with masses or rigid disks [e.g., 4]; plate-type metamaterials [5], for example consisting of a periodic arrangement of tungsten/silicone rubber cylindrical stubs; anisotropic porous lamella structures; and arrays of coiled or labyrinthine resonators [6].

In this work we report the remarkable absorption properties, on resonance, of an acoustic metamaterial structure of subwavelength thickness that comprises a perforated plate, separated from a rigid boundary by a deeply subwavelength narrow channel of air. This simple, easily fabricated, robust structure demonstrates a near complete absence of specular reflectance at selective frequencies, achieved through thermo-viscous loss and tuned by the air channel thickness.

The near-normal incidence specular reflectance (reflectance, R), from the entire panel as a function of frequency, for different values of the spacing between the perforated plate and rigid wall (g), is

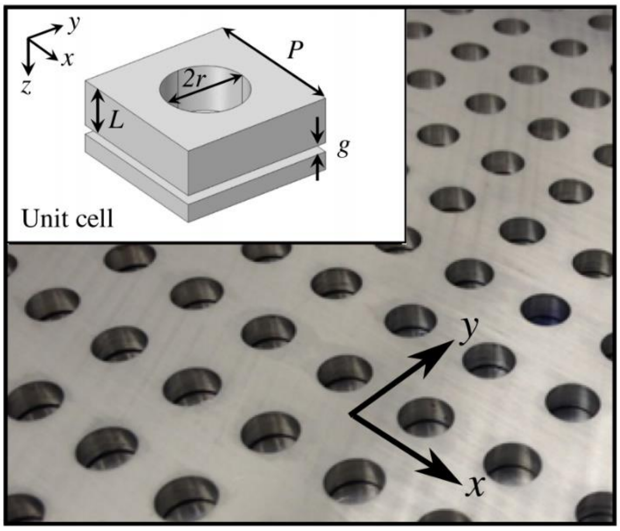

Figure 1: Photograph of the top perforated plate of the metamaterial absorber sample, of cross section 450 mm square. Inset: schematic representation of the sample unit cell (not to scale) with pitch, P = 16.5 mm. The plate perforations are pipes of radius r = 4.4 mm and length L = 5.07 mm. The thickness of the channel of air, g, is defined as the separation of the two plates.

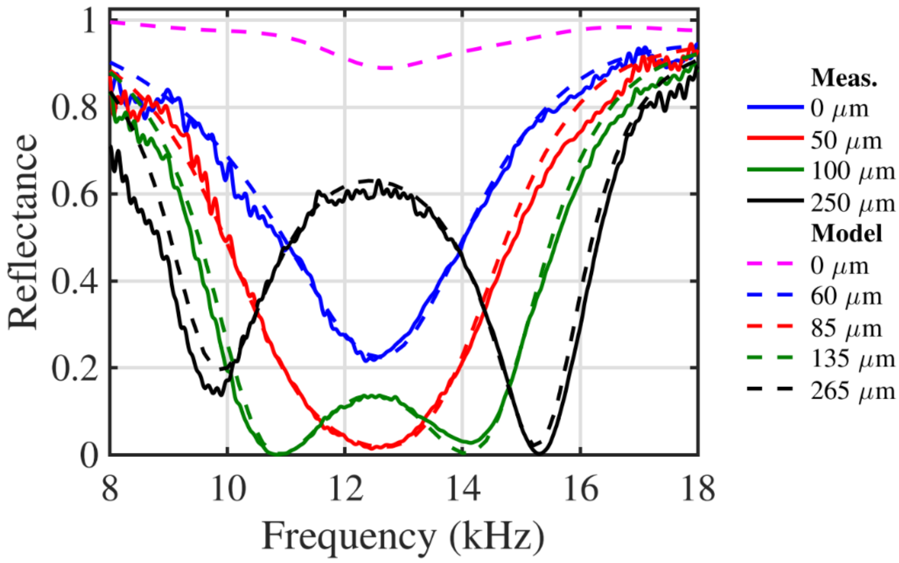

Figure 2: Measured (solid lines) and numerically modelled (dotted lines) normal incidence reflectance spectrum for different values of the thickness of the channel of air between the two plates, g. The difference between the value of g set using small spacers in the experiment, and that which provides the best 'fit' via modelling, is attributed to air gaps arising from the flatness tolerance of the perforated plate above the rigid boundary, which is caused during the fabrication process. Note the sample is non-diffracting for normal incidence sound across the studied frequency range.

obtained experimentally using a pulse-measurement technique in a free-space environment. The experimental data are compared to numerical simulations obtained using COMSOL Multiphysics 5.2a (which simulates the response of the structure to a normally incident plane wave). In the numerical simulations, both viscous and thermal loss contributions are considered due to their significant effect in narrow cavities [7].

The optimum coupling condition (i.e., zero in reflectance) is achieved when the radiative and non-radiative losses in the system are balanced. Upon introducing a gap between the two plates, a narrow channel of air is introduced that is bound largely by acoustically rigid walls at which the "no-slip" boundary forces the tangential particle velocity to zero. This exerts a frictional shear force on the overlying fluid and a viscous boundary layer is formed (of characteristic length $\delta_{\mathrm{v}} \approx \sqrt{\frac{\upsilon}{\omega}}$, where ν is the coefficient of shear viscosity). Simultaneously, thermal conduction allows heat transfer to take place between the fluid (air) and the walls, and a thermal boundary layer is formed (of characteristic length $\delta_{\kappa} \approx \sqrt{\frac{\kappa}{\omega}}$,, where κ is the thermal conductivity). The losses associated with these boundary layers (with thicknesses on the order of tens of microns at these frequencies) are advantageously used to tune the absorption in the system, by varying the thickness of the gap between the two plates, such that a near-complete absence of reflectance can be obtained.

The numerical model is utilised to explore the pressure field profiles on resonance in order to gain a deeper understanding of the behaviour of the system. While in reality the mode in each hole is able to interact with its neighbours via the narrow air channel (and also diffracted evanescent fields above the structure), for normal incidence sound, we can define ‘cavities’ by considering only the unit cell because the symmetry planes can be treated as rigid walls. For the lowest frequency mode, strong pressure fields are localised within the gap between the two plates, falling to zero along the length of the hole, with a pressure minimum close to the entrance of the hole, i.e., an approximate quarter wavelength resonance is supported by the entire ‘cavity’. For the higher frequency mode, two pressure nodes are observed in the resonant fields, one within the gap between the two plates and one close to the entrance of the hole, i.e., an approximate three-quarters wavelength resonance is supported by the entire cavity.

2. Acoustic Line Mode

In the second part of this paper we consider another metamaterial-inspired structure based on arrays of holes: we demonstrate that acoustic energy can be trapped and manipulated by surface structuring of a rigid material.

Surface patterning to control the propagation of *electromagnetic* energy can be traced back to the 1940s [8], However it was Ebbesen *et al.’s* work in 1998 [9] that is perhaps responsible for recent interest in this area. Then, with the realization by Pendry [10] that a simple holey metallic plate could support a surface localized surface-plasmon-like resonance (the ‘spoof-surface-plasmon’) even when the metal is perfectly conducting, came a reawakening - structures with scale lengths of order of, or less than that of the incident wavelength allow for novel manipulation of electromagnetic surface waves. Following this came the realization that a similar spoof surface acoustic wave may be likewise manipulated [11,12], breathing fresh life into the field. Notwithstanding extensive development in areas such as Enhanced Acoustic Transmission (EAT) [13-15], and subwavelength imaging [16,17], the simplest patterned structure which supports a surface-localized acoustic wave appears to have been overlooked. This structure, which lends itself easily to the manipulation and control of sound, is simply a line of identical holes drilled in a rigid solid.

In our results illustrated below, we have using a near-field measurement technique in which we directly image the localized acoustic field along on a single straight line of equi-spaced rigid-walled open-hole resonators, ‘The Acoustic Line Mode’ (ALM). Arranging this line of holes to form a closed ring demonstrates how the ALM follows readily around a curved path demonstrating how the ALM may be directed by design; opening up the potential for novel manipulation of acoustic energy.

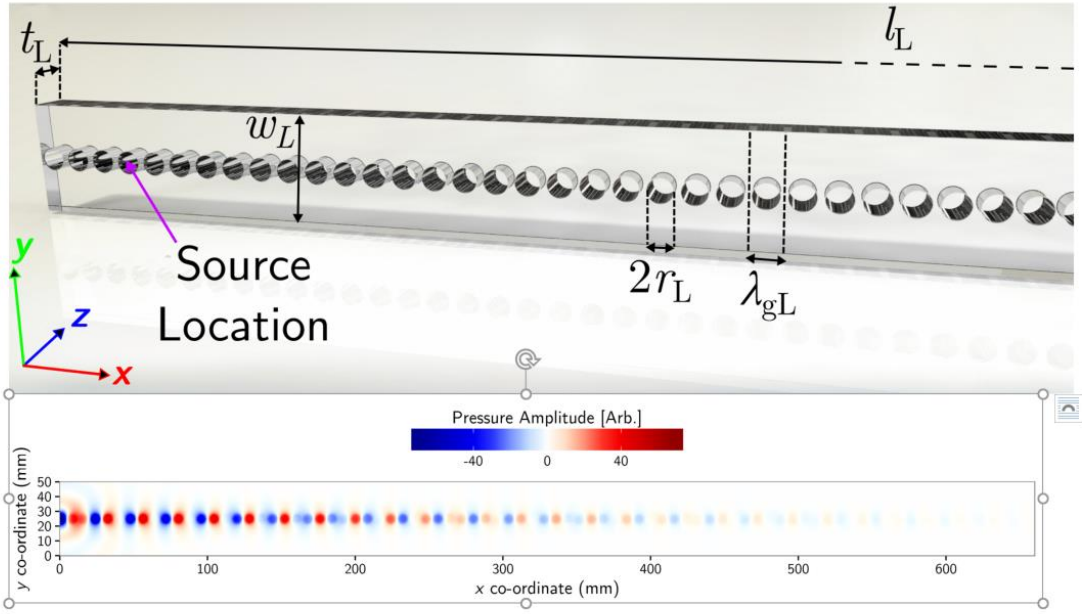

Figure 3: (top) Schematic of the line (L) sample. The acrylic plate has dimensions l_L = 840.00 mm (truncated in the figure) and w_L = 30.00 mm, with thickness (hole depth) t_L = 9.80 ± 0.10 mm. (bottom) Experimental data showing instantaneous pressure field Δp at frequency 12.31 kHz measured as a function of x and y coordinates along the surface of the line sample. The point-like source was located at x = 0 mm, y = 25 mm

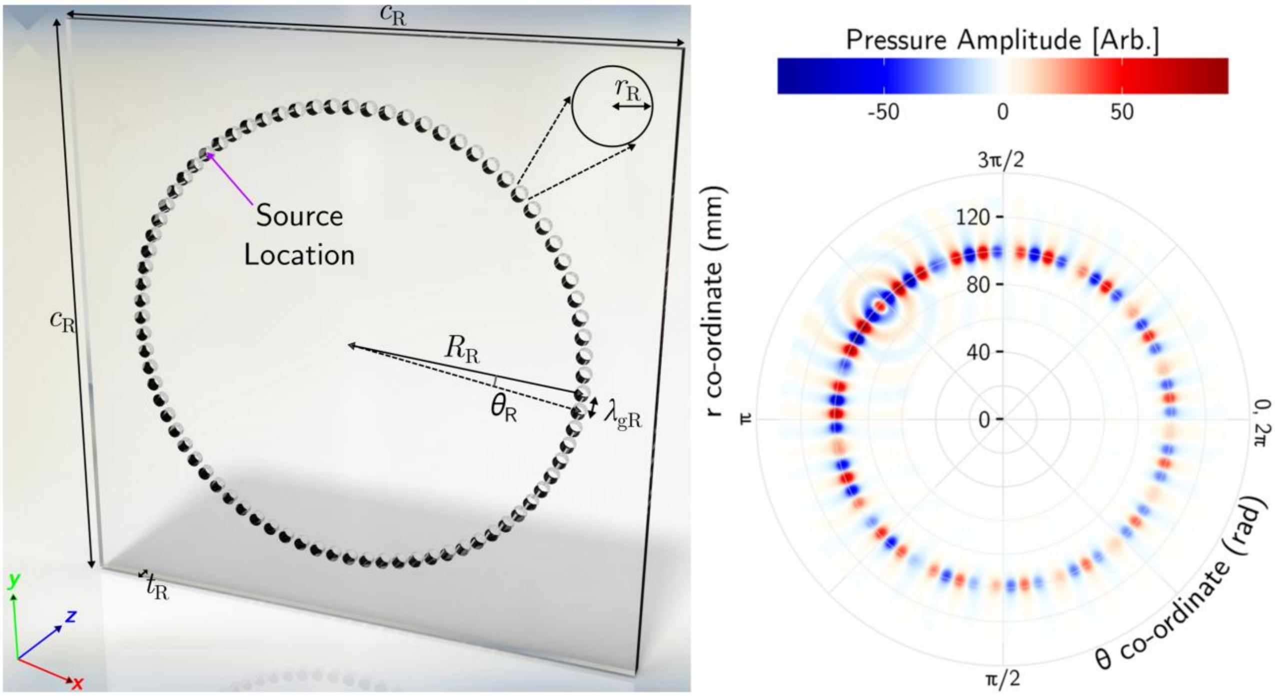

Figure 4: (left) Schematic of the ring (R) sample. The acrylic plate has a rectangular cross-section of sides c_R = 29 mm with thickness (hole depth) t_R = 7.51 ± 0.06 mm. There are 80 holes that make up the ring, which is of radius R_R = 10.1 ± 0.05 mm. Each of the holes is of radius r_R = 3.35 ± 0.005 mm, separated by arc $\theta_R = \frac{2\pi}{80}$. This gives them a central spacing (periodicity) $\lambda_{gR} \approx$ 8.00 mm in the θ direction, around the circumference of the ring R_R. (right) Polar plot of experimental data showing instantaneous pressure field Δp at frequency of 14.63 kHz measured as a function of r and θ coordinates along the line sample's surface.

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