Ultrasound Transmission Bands Through Perforated Plates with Two Periodic Arrays of Subwavelength Apertures

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Abstract
Both theoretical and experimental results on ultrasound transmission through perforated plates with two periodic arrays of subwavelength holes are presented. Multiple transmission peaks and dips can be achieved by a single perforated plate. The locations of the transmission peaks and dips can be tuned independently by the periodicities of the individual hole arrays. The locations of the transmission peaks and dips produced by the double periodicity device result from the sum of the transmission peaks and dips of the individual hole arrays. Prospective applications of this structure can be anticipated, such as in ultrasonic filters and ultrasonic medical instrumentation.

Keywords: subwavelength perforated plate, ultrasound transmission, double periodic array

1. Introduction

The pioneering work of Ebbesen et al. [1] demonstrated that periodic square arrays of subwavelength holes on a metal plate can transmit much more light per hole than expected by Bethe’s theory [2] for a single hole. Since then, the extraordinary optical transmission has attracted much interest and has been intensively analysed with the purpose of understanding the physical origin of the phenomenon and to explore its possible applications in optics and optoelectronics. The ideas and studies developed for the optical case have been transferred to the acoustic case. In the last years, sound transmission through one and two dimensional aperture gratings has been studied, reporting extraordinary effects in sound transmission through subwavelength apertures either in slit or hole geometries. The first works to appear were theoretical studies that demonstrated the extraordinary acoustic transmission through subwavelength holes [3-5]. Another study of acoustic wave transmission through a one-dimensional periodic array of subwavelength slits was reported both theoretically and experimentally [6].

In the bi-dimensional periodic array of subwavelength holes, Hou et al. [7] had found that diffraction evanescent waves play an important role in tuning the Fabry-Perot resonances. Estrada et al. had shown [8] that the extraordinary acoustic transmission is not only observed in plates perforated with a periodic array of holes, since it is also observed when plates were perforated with a random distribution of holes. On the other hand, they also show that Wood anomalies [9] lead to extraordinary sound screening in perforated plates well beyond that predicted by the well known “mass law”. The role of the filling fraction of holes and the lattice geometry in the transmission features of perforated plates were studied in Estradas’ works [10,11] showing that both the position and the width of the transmission peak can be tuned changing geometrical parameters.

The purpose of this work is to show through both theory and experiment that multiple transmission peaks and dips can be achieved by a single perforated plate with two periodic arrays of subwavelength holes, and their frequency positions were controlled independently by the periodicities of the individual hole arrays.
2. Experimental Setup

To perform the ultrasonic transmission measurements, the experimental setup based on the well known ultrasonic immersion transmission technique was used. The sample was placed in a water tank and the alignment and positioning were provided by an automated positioning system built around a water tank, which is capable of sweeping the receiver transducer through a 3D grid of measurement points located at any trajectory inside the tank. A couple of transmitter/receiver ultrasonic immersion transducers with 32 mm in active diameter and -6 dB bandwidth (155-350 kHz). Each transducer was located at a distance longer than that of its near-field distance (43 mm) from the plate and aligned with respect to the plate. A pulser/receiver generator (Panametrics model 5077PR) produces a pulse which is applied to the emitter transducer that launches the signal through the inspected plate. Then, the signal is detected by the receiving transducer, acquired by the pulser/receiver, post amplified and digitalised by a digital PC oscilloscope (Picoscope model 3224). Time domain data is finally analysed after averaging 100 different measures and deleting unwanted reflections by means of a time window. The transmission spectrum is then calculated as

\[ |T(\omega)|^2 = \frac{|H(\omega)|^2}{|H_0(\omega)|^2} \]  

(1)

from the power spectrum of the signal \( H(\omega) \) normalised with the reference signal power spectrum \( H_0(\omega) \) measured without the sample plate. Scan measurements using synthetic aperture technique [12] were made to avoid finite size effects.

The measurements were made using brass plates with 350 mm in width and 450 mm in length (\( \rho = 7890 \text{ kg/m}^3, c_l = 5670 \text{ m/s}, c_t = 3230 \text{ m/s} \)) and 2 mm thickness, immersed in water (\( \rho = 1000 \text{ kg/m}^3, c_t = 1480 \text{ m/s} \)).

Figure 1 shows a schematic diagram of the three perforated plates considered.
onto the brass plate used. The second one had a square distribution of circular holes having a diameter of 3 mm and a unit cell period of 9 mm. The third one had a square distribution of circular holes having diameters of 1 mm and 3 mm and a unit cell period of 9 mm.

3. Results and Discussion

A calculation model in the hard-solid limit was used. An expansion of the acoustic field in terms of modes of a cylindrical cavity inside the hole and plane waves outside the hole was used to calculate the ultrasonic transmission. To determine the expansion coefficients, continuity of the parallel components of the pressure and velocity fields on both sides of the plate were imposed. The calculation procedure followed the scattering matrix techniques to derive analytical solutions for the transmission values in the small-hole limit, and which had been extended to arbitrary hole sizes relying on a fully converged numerical solution [13]. Figures 2(a)-2(c) show a comparison between measured and calculated transmitted ultrasound power coefficient, $\tau$, as a function of the frequency, $f$, in water at normal incidence for each of the three samples considered. The calculated results agree well with the experimental ones. Figure 2(a) shows the transmission spectra for the periodically square distribution of circular holes having a diameter of 1 mm and a unit cell period of 3 mm. At the frequency of around 280 kHz a transmission peak that corresponds to the Fabry-Perot resonance is observed. The transmission spectra of a perforated plate with circular holes having a diameter of 3 mm and a unit cell period of 9 mm, is shown in Figure 2(b). Two transmission peaks appear at the frequencies of around 280 and 160 kHz, corresponding to the Fabry-Perot resonances. Transmission dips are also observed at the frequencies of around 165 and 230 kHz, corresponding to the Wood anomaly of the array of the lattice period of 9 mm. The Wood anomaly for a normal incidence is given by:

$$\frac{\omega}{c} = \sqrt{\left(\frac{2\pi m}{p}\right)^2 + \left(\frac{2\pi n}{p}\right)^2}$$

(2)

where $p$ is the unit cell period, $m$ and $n$ are called Miller indices and $c$ is the speed of ultrasound in water. The positions of the Wood anomaly at frequencies around 165 kHz and 230 kHz correspond to Miller indices $(m,n) = (1, 0)$ and $(1, 1)$, respectively. The transmission spectra of the plate with two periodic holes arrays, having diameters of 1 mm and 3 mm and a unit cell period of 9 mm, is depicted in Figure 2(c). It could be seen that the transmission spectrum of this structure (2c) can be identified as a result of the sum of each of the simple periodic hole arrays (2a and 2b). The transmission peaks and dips of this new structure remain at the same frequencies as the simple arrays. Thus, this structure can be considered as a superposition of independent square hole array with a different lattice constant. This fact produces an overlapping of Fabry-Perot peaks at different frequencies.
Figure 2. Measured (solid curve) and calculated (dashed curves) transmitted ultrasound sound power coefficient at normal incidence as a function of the frequency for the three plates considered.
(a) Perforated plate with circular holes of a diameter of 1 mm and a unit cell period of 3 mm.
(b) Perforated plate with circular holes of a diameter of 3 mm and a unit cell period of 9 mm.
(c) Perforated plate with circular holes of diameters 1 mm and 3 mm and a unit cell period of 9 mm.

4. Conclusions

Sound transmission through perforated plates with two periodic arrays of subwavelength holes has been studied. The experimental results agree with the calculated ones. The results show that it is possible to achieve transmission peaks and dips at different frequencies simultaneously with the same sample because the perforated plate has the characteristic peaks and dips of each contributed array. Potential applications on ultrasonic technology, such as ultrasonic filters and ultrasonic medical instrumentation can be anticipated.

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References