Slit-array transmission loss feasibility in airborne sound

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Recent experiments conducted in water at ultrasonic frequencies showed the possibility of overcoming the transmission loss provided by homogeneous plates at certain frequencies by drilling periodically distributed holes on it. In this letter, the feasibility of using slit arrays to increase the transmission loss at certain frequencies for airborne sound is studied. Numerical results predict a) very low transmission loss for a slit array in comparison with a homogeneous plate in air and b) the transmission loss of a slit array can overcome that of a homogeneous plate if the impedance mismatch is low enough.

In recent years, the study of the acoustical properties of hole and slit arrays in finite plates has been boosted by the promising and interesting findings in the field of optics [1, 2] and the development of metamaterials for both, acoustic [3, 4] and electromagnetic waves [5]. However, the use of hole and slit arrays in the field of acoustics is not new. The main difference between the already well known acoustic properties of slit or hole arrays [6, 7] and the latest research on such structures [8–13] lies in the size of the wavelength with regard to the periodicity, aperture size, and plate thickness. Although for light it is very interesting to increase the transmission through metal plates by inserting subwavelength holes arrays, for sound is always challenging to decrease the transmission. For finite thickness plates or walls in the long wavelength regime, the transmission is controlled by the mass per unit area of the plate or wall [14]. Thus, sound screening at long wavelength values is difficult to achieve in thin plates. Towards this direction different strategies have been considered for hole arrays [13, 15–17]. Wood-anomaly sound screening is reported in [13] for periodically perforated Aluminum plates immersed in water at ultrasonic frequencies. On the other hand, two layers of periodically perforated plates have been theoretically proposed to reduce the sound transmission for low impedance mismatch [15] (water-PMMA) and for infinite impedance mismatch [16, 17] (rigid solid).

One key issue in hole-array sound screening is whether it can be applied for the case of airborne sound at audible frequencies [18–20]. In this paper we will show that due to the high impedance contrast at the solid/air interface, Wood-anomaly induced sound screening of perforated plates does not overcome the high transmission loss attained for the case of homogeneous plates. Numerical simulations also show that transmission loss for the slit arrays, are effective only when the impedance mismatch is low, as in the case of Aluminum and water [13].

The transmission problem has been solved numerically by means of finite elements implemented in Comsol Multiphysics software for frequency domain. A unit cell of the slit array (see Fig. 1a)) having a period a, a slab thickness t = 0.6a, and an aperture of size d = 0.28a constitutes the geometry of the problem. The slab is modeled as an elastic domain having zero out-of-plane components of the strain and displacement to keep the problem in two dimensions. A fluid domain is used to model the slit and the surrounding media. The pressure in the fluid is decomposed as the sum of incident (known) and scattered (unknown) pressures, the first being a plane wave.

FIG. 1. a) Diagram of the slit-array geometry having a periodicity a, a slit size d, and a slab thickness t. The unit cell is delimited by vertical dashed lines. b) Transmission loss in dB for a slit array (solid curve) and a homogeneous wall (dashed curve) both made of concrete in air as a function of the normalized frequency at normal incidence.
at normal incidence. The fluid-structure interaction is ensured by imposing continuity of both, the normal displacement and the normal stress at the fluid-solid interfaces. The periodicity enters through the lateral limits of the unit-cell via periodic boundary conditions. Finally, to satisfy the Sommerfeld radiation condition at infinity, perfectly matched layers (PML) are used at top and the bottom of the unit-cell. Wavelength-dependent scaling is applied to the mesh, the thickness of the PML, and the vertical size of the unit-cell. The transmitted and reflected sound power is calculated by integrating the vertical sound intensity along the unit-cell width right at the interface between the fluid domain and the PML. Convergence is achieved for a mesh element size around $\lambda/15$ and has been tested through the balance of the total sound power.

The characteristic acoustic impedance $z_0$ is given by the product between the fluid density $\rho_0$ and the phase velocity $c_0$. The impedance mismatch between a solid and a fluid will be simple considered as $K = z_s/z_0 = \rho c_0/\rho_0 c_s$, where $\rho$ is the solid density and $c_0$ is the longitudinal wave velocity in the solid. In the case of concrete ($\rho = 2400 \text{ kg/m}^3$, $c_0 = 2996 \text{ m/s}$) and air ($\rho_0 = 1.12 \text{ kg/m}^3$, $c_0 = 343 \text{ m/s}$) the impedance mismatch yields $K = 1.7 \times 10^4$. The results of this high impedance mismatch in the transmission loss (TL) of the slit array compared with the homogeneous wall of the same thickness and material is showed in Fig. 1(b) as a function of the normalized frequency $fa/c_0$ at normal incidence. Resonant full transmission peaks and the Wood anomaly are present in the slit array spectrum, as expected from previous results using rigid-solid assumption [8–13]. It is clear that the slit array doesn’t provide any advantage at any frequency in terms of TL over the homogeneous plate. The homogeneous plate TL (dark solid curve) is nearly 55 dB below that for concrete-air (Fig. 1b)).

For simplicity, one can define the slit array insertion loss as $IL = 10 \log(\tau/\tau_0)$, where $\tau$ is the transmitted sound power coefficient of the slit-array for finite impedance mismatch and $\tau_0$ is the transmitted sound power coefficient of the homogeneous layer having the same material and thickness than the slit array. One can see the insertion loss (IL) of the slits in a homogeneous plate will be everywhere negative. Changing the fluid to water ($\rho_0 = 1000 \text{ kg/m}^3$, $c_0 = 1480 \text{ m/s}$) and the solid to Aluminum ($\rho = 2700 \text{ kg/m}^3$, $c_0 = 6500 \text{ m/s}$) lowers the impedance mismatch up to $K = 1.2 \times 10^4$, which is 3 orders of magnitude lower than the previous case. The TL for Al-water slit array and homogeneous plate as a function of the normalized frequency at normal incidence is showed in Fig. 2. Between $0.7 < fa/c_0 < 0.98$, the slit array TL overcomes the plate TL reaching a maximum of 21 dB. The differences in the slit array transmission for concrete in air and Al in water can be extracted comparing Fig.1(b) and Fig. 2. The first resonant full transmission peak $fa/c_0 \approx 0.6$ is slightly shifted to lower frequencies with regard to the concrete-air case, while the Wood anomaly minima is almost absent for the Al-water slit array. The TL maximum at $fa/c_0 \approx 0.9$ is almost 10 dB larger for the Al-water array compared to the concrete-air array. This results explain the results reported in [13] for Al-water mismatch at ultrasonic frequencies, although hole arrays where studied instead of slit arrays.

The previous results preclude the use of the slit array sound screening in airborne conditions due to the huge impedance mismatch between the air and most solids ($K > 10^3$). In order to establish a proof-of-concept we performed further calculations replacing the solid by a fluid having different acoustic impedances. The results of the IL in dB for different $K$ are shown in Fig. 3 and set a clear distinction between the phenomena observed.
with solid slabs and fluid slabs. An homogeneous fluid slab can only sustain Fabry-Perot modes and in all cases the TL provided by the homogeneous slab is several decibels higher than that of the slit array. Therefore, the IL is almost always negative and decreases as $K$ increases. There are, however, porous materials capable of showing low impedance and certain amount of sound absorption as well. This kind of materials could be suitable candidates to show interesting properties when they are arranged periodically, as several authors have reported in previous studies for airborne sound [21, 22]. Porous materials are, however, more complex and are out of the scope of this study. The possibility of overcoming the homogeneous plate transmission loss by inserting slits in a low impedance material is unfortunately not realistic for airborne sound because no conventional solid has such a low acoustic impedance. Replacing the solid by a fluid, i.e. another gas, could be more feasible in the practice but, as our calculation predicts, will be useless in terms of transmission loss. Also low impedance metamaterials [23] working in the effective media regime could be appropriate to provide the low impedance mismatch required. We hope this study stimulates more research on slit arrays made of low-impedance porous materials or metamaterials.

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