High sound screening in low impedance slit arrays

2011 New J. Phys. 13 043009

(http://iopscience.iop.org/1367-2630/13/4/043009)

New Journal of Physics
The open-access journal for physics

High sound screening in low impedance slit arrays

Héctor Estrada[1,2,3], **José María Bravo**[1] **and Francisco Meseguer**[1,2]

[1] Centro de Tecnologías Físicas, Unidad Asociada ICMM-CSIC/UPV, Universidad Politécnica de Valencia, Av. de los Naranjos s/n, 46022 Valencia, Spain

[2] Instituto de Ciencia de Materiales de Madrid (CSIC), Cantoblanco, 28049 Madrid, Spain

E-mail: hector.estrada@icmm.csic.es

New Journal of Physics **13** (2011) 043009 (7pp)
Received 22 December 2010
Published 8 April 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/4/043009

Abstract. We report on the key role of the acoustical impedance ratio between the solid and the host fluid in the transmission properties of slit arrays. Numerical calculations predict huge sound screening effects up to 60 dB for low impedance ratio values. The screening band appears over a broad frequency region and is very robust against dissipative losses of the material as well as against the sound incident angle. This counterintuitive result is discussed in terms of the hydrodynamic short circuit, where the fluid and the solid at the radiating interface vibrate out of phase, resulting in a huge sound blocking effect.

S Online supplementary data available from stacks.iop.org/NJP/13/043009/mmedia

The behaviour of waves interacting with periodic structures has been a subject of intensive research in recent years. In particular, the transmission of light through periodically perforated metal films [1] has attracted considerable attention not only due to their intriguing physics [2], but also because it promises several applications [3] in the field of nanophotonics. For sound waves, specifically for airborne sound, the use of periodically perforated panels or slit arrays is within common practice in acoustical engineering [4, 5]. Their acoustical properties are well understood in most cases, as the sound wavelength in air is far larger than the geometrical parameters that define the array (the period, aperture size and plate thickness). This knowledge has been extended by the latest studies performed on this kind of structure [6]–[12], which deal with phenomena that appear when the wavelength λ is comparable to at least one of the geometrical parameters of the array. Recent experimental and theoretical studies focus on the

[3] Author to whom any correspondence should be addressed.

resonant full transmission peaks [6]–[10]. The sound transmission features of hole and slit arrays are governed by Fabry–Perot resonances similarly to transverse magnetic (TM) polarized light transmission through slit arrays [7, 13] under the perfect conductor (rigid solid) assumption for light (sound). This resemblance is no longer valid for electromagnetic wave transmission through hole arrays owing to the strong cutoff of the holes and the appearance of extraordinary transmission, even for an infinitely thin holey film [14].

Recently, Estrada *et al* [11] reported on quite a counterintuitive result where, by means of the Wood anomaly, drilling holes in a homogeneous plate decreases the transmission of sound by several decibels at certain frequencies, well below the prediction of the mass law. Also, a strong interaction between periodicity-induced modes and leaky Lamb modes for finite impedance ratio between the fluid and the solid was demonstrated in [15, 16], whereas surface plasmons can couple and interact with Fabry–Perot modes when light is transmitted through metallic nano-slit arrays [17, 18]. However, our results reveal that for slit arrays having a finite impedance ratio, no leaky Lamb modes are present in its sound transmission features as occurs with hole arrays. These features make sound transmission through hole or slit arrays unique compared to light.

In this paper, we will report on the key influence of the impedance ratio K between the solid and the fluid in slit-array systems. Contrary to what should be expected, our results show that finite impedance ratios would produce a far larger sound screening than an infinite impedance ratio.

We performed calculations by means of finite elements using Comsol multiphysics software. A unit cell of the slit array having a period a, a slab thickness $t = 0.6a$ and an aperture of size $d = 0.28a$ is modelled using periodic boundary conditions and perfectly matched layers (PML) in the transmitted and reflected far sides for time-harmonic plane wave excitation. In the solid slab, the out-of-plane components of the strain tensor and the displacement are assumed to be zero, which allowed us to deal with a two-dimensional (2D) problem for an isotropic solid. The transmitted and reflected sound power are then obtained integrating the component of the time-averaged intensity that is normal to the array right before the PML. Convergence is achieved for an element size around $\lambda/15$ and is confirmed through the balance of the total sound power in the system.

The characteristic acoustic impedance in a fluid is given by $z_0 = \rho_0 c_0$, where ρ_0 is the fluid density and c_0 the wave velocity. For a given solid of density ρ, longitudinal wave velocity c_l and transverse wave velocity c_t, the impedance ratio between the solid and the fluid is defined as $K = z_s/z_0 = \rho c_l/\rho_0 c_0$. This ratio controls the sound transmission through a fluid–solid interface at normal incidence. On the other hand, the c_t/c_0 ratio determines whether the wave motion of a homogeneous plate is governed by leaky Lamb waves and one Scholte–Stoneley mode ($c_t/c_0 > 1$) [19] or mainly by Scholte–Stoneley waves as it occurs in a fluid–solid interface ($c_t/c_0 < 1$) [20]. The transverse wave velocity in the solid is chosen as $c_t = 0.7c_l/\sqrt{2}$, thus satisfying $c_l^2 - 2c_t^2 > 0$.

Figure 1(a) reveals the key role of K for slit arrays compared to homogeneous plates. The sound power transmission coefficient τ has been calculated as a function of the normalized frequency fa/c_0 at normal incidence. The features described in several papers assuming $K = \infty$ [6]–[11], namely the resonant full transmission peaks and the Wood anomaly, appear almost unchanged for $K = 15$ at $fa/c_0 = 0.6$ and 0.99 for the first and at $fa/c_0 = 1$ for the latter. However, when $K = 8$, huge unexpected transmission dips appear. To retain a more global picture of the effect of K, it has been varied between $2 \leqslant K \leqslant 15$ following five different

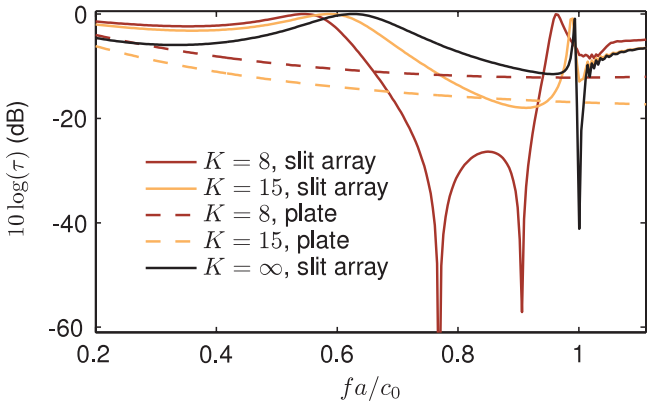

Figure 1. The transmitted sound power coefficient τ in dB as a function of the normalized frequency fa/c_0 for slit arrays and homogeneous plates having different K.

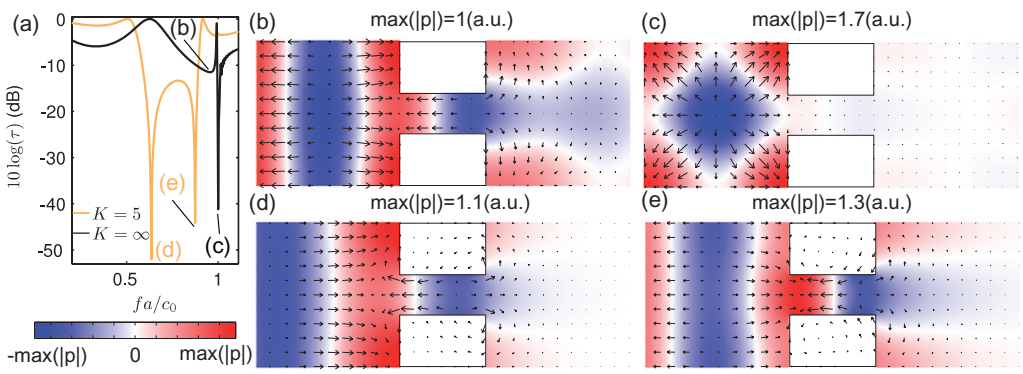

Figure 2. (a) The transmitted sound power coefficient in dB for slit arrays of different K as a function of the normalized frequency at normal incidence. For each peak indicated by labels (b)–(e), the pressure (colour online) and displacement (arrows) fields are shown at the slit-array unit cell. The incident wave travels from left to right having the same amplitude in all cases. Differences in the range of the colour scale arise due to the existence of constructive interference in the pressure field. Arrow scaling is also different for each plot.

slopes $m = (c_l/c_0)/(\rho/\rho_0)$. The transmission features evolve with decreasing K in agreement with what is reported in [11] for aluminium-perforated plates immersed in water ($K \approx 11.8$, $c_t/c_0 \approx 2$) and the theoretical prediction in [21] for PMMA-perforated plates in water ($K \approx 1.8$ $c_t/c_0 \approx 0.7$).[4]

The physical origin of this phenomenon can be understood by comparing the pressure and displacement fields for finite and infinite K values, as shown in figure 2 when a plane wave coming from the left side impinges on the slit array. Two points for each transmission curve in figure 2(a) corresponding to $K = 5$ (light curve) and $K = \infty$ (black curve) are shown and labelled in figures 2(d)–(e). The moderate transmission of –12 dB obtained for $K = \infty$

[4] See supplementary data (available online at stacks.iop.org/NJP/13/043009/mmedia) for the whole set of calculations and a detailed description.

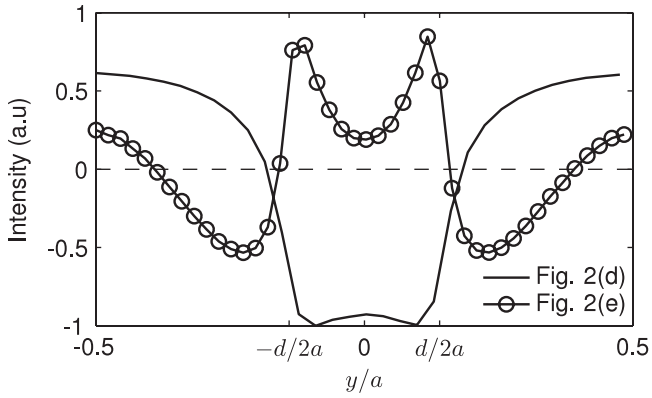

Figure 3. Time-averaged intensity normal to the aperture at the right side of the slit array referred to in figures 2(d) and (e), as a function of the normalized vertical coordinate y/a. The hole is centred at $y/a = 0$ and the positive side of the intensity points towards the outside of the slit.

at $fa/c_0 = 0.95$ is distinguishable from figure 2(b). Some portion of the incident wave coming from the left passes through the slit and is transmitted to the right. The interfaces at the right side of the solid cannot move, i.e. they act as a rigid baffle. This behaviour differs from that of the Wood anomaly minimum at $fa/c_0 = 1$ (see figure 2(c)). As expected, the incident wave is almost completely reflected at the left side of the array, precluding the wave to enter the slit. Thus, even if the plate thickness is enlarged up to infinity [22], the same phenomenon occurs. On the other hand, when $K = 5$, the solid can vibrate and it couples to the fluid. How this coupling contributes to decreasing the transmission through the slit array can be inferred from figures 2(d) and (e), which correspond to the minima in figure 2(a) at $fa/c_0 = 0.64$ and 0.87, respectively. At first glance, the fields for $K = 5$ are more similar to those of figure 2(b) than to the Wood anomaly ones. However, in these cases, the incoming wave penetrates not only the slit but also the solid in such a way that the outward displacement at the slit right side is compensated for by the inward displacement of the solid right face. Thus, an evanescent wave appears at the transmitted side of the slit array, yielding sharp dips beyond –40 dB in transmission. This phenomenon is well known in the sound radiation of structures and it is called the hydrodynamic short circuit [23]. Also the field inside the slit is affected by the solid deformation. Small gradients in the vertical direction distort the otherwise straight displacement field.

To further understand the differences between both transmission minima for $K = 5$, we can analyse time-averaged quantities related to the sound radiation as the sound intensity normal to the aperture at the right side of the slit array unit cell (see figure 3). Surprisingly, at the first minimum (regarding figure 2(d)), the solid is attempting to transmit energy to the fluid, but the fluid within the slit inhibits it, resulting in an overall sound blocking effect, as shown at the minimum (d) of figure 2(a). The intensity at the second minima (regarding figure 2(e)) behaves in the opposite way, mainly concentrated at the edges of the slit. This shape is presumably induced by the solid deformation because the cavity sustains a standing wave and little energy is carried through the slit. In addition, the intensity at the solid presents more gradients due to the shorter wavelength of the incoming wave.

Previous results for normal incidence can be broadened, considering nonzero parallel to the array wavenumber $k_{\parallel}$ such that for the incident wavenumber in the fluid k_0, the angle of

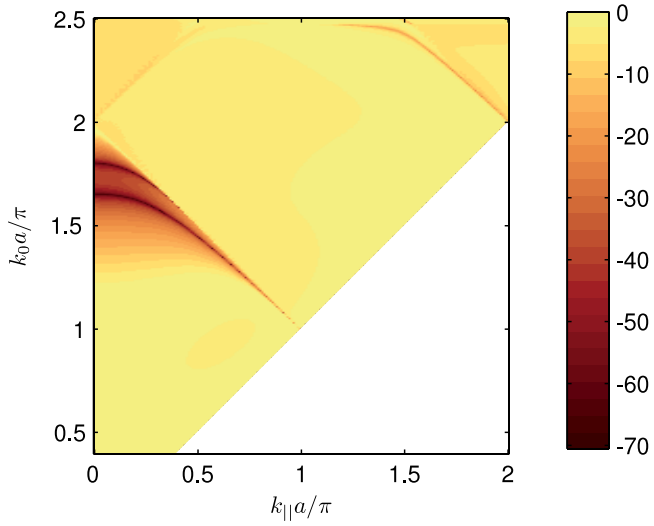

Figure 4. The transmitted sound power coefficient τ dispersion of a slit array for $K = 8$ (colour (grey) scale in dB) as a function of the parallel wavevector $k_{\|}a/\pi$ and the incident wavenumber k_0a/π.

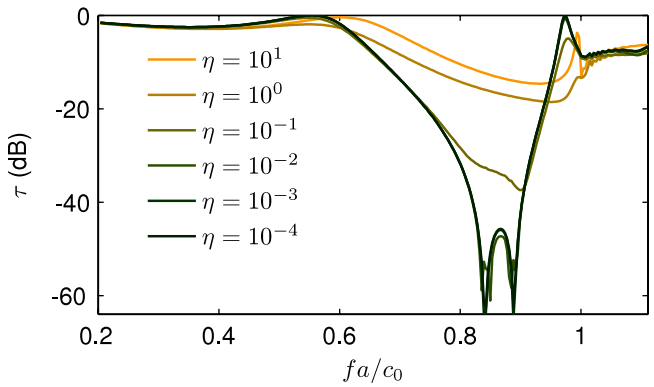

Figure 5. The transmitted sound power coefficient τ of a slit array for $K = 9$ in dB at normal incidence as a function of fa/c_0 for different values of the loss factor η.

incidence yields $\theta = \arcsin(k_{\|}/k_0)$. The sound power transmission coefficient τ is shown in figure 4 for $K = 8$ as a function of $k_{\|}$ and k_0. Dark regions below the Wood anomaly given by $k_0 = 2\pi/a - k_{\|}$ correspond to low transmission zones where both dips can be distinguished. Thus, an acceptable angular window of low transmission is provided.

One key difference between slit and hole arrays for finite impedance ratio is evident from a comparison of figure 4 to the experimental and theoretical results reported in [15, 16]. No leaky surface modes appear for slit arrays, because the solid slabs have no elastic connection between them as a perforated plate does.

The above-presented results were calculated without including any loss either in the host fluid or in the solid obstacle. To ensure the robustness of the huge transmission dips against dissipative losses present in the solid, we varied the loss factor η [24] through different orders of magnitude, as shown in figure 5. The transmission is quenched to 40 dB when $\eta = 0.1$ and

to less than 20 dB for $\eta \geqslant 1$. In real situations, the nature of the loss and its magnitude will depend enormously on the frequency range even for a single material[5]. Thus, it is expected that the choice of a material with $\eta < 10^{-1}$ would ensure very low transmission.

The nontrivial behaviour reported in this paper is even more outstanding than the already counterintuitive possibility of screening sound with slit (hole) arrays. The lowest transmission is not achievable with the highest impedance ratio, but with an optimum K. These results are consistent throughout the whole set of parameters included in this study (see footnote 4). As the impedance ratio for most solids in air is at least three orders of magnitude larger than those considered for this study, slit array sound screening is not suitable for airborne sound [25]. The physical mechanism involved in the transmission dips differs from the Wood anomaly. The solid vibrations allow normal intensity oscillation at the transmission face of the array, which produces very low radiated sound power. The existence of an optimum impedance ratio to obtain transmission losses up to 60 dB using slit arrays opens the door for a wide range of possible applications, mainly in underwater acoustics and underwater ultrasound. For sonar applications, it could be used as a reflector either to block signals coming from unwanted sources or for redirecting the launched sonar signal. In this aspect, a slit array can be a better option over a solid surface or a holey plate because of its hydrodynamic characteristics. Some similar applications, but at a smaller scale, could be thought of as well for underwater ultrasound.

Acknowledgments

We acknowledge financial support from the projects MICINN MAT2010-16879 and Consolider NanoLight.es CSD-2007-0046 of the Spanish Education and Science Ministry and from the project PROMETEO/2010/043 of Generalitat Valenciana. HE acknowledges support from a CSIC-JAE scholarship.

References

[1] Ebbesen W, Lezec H J, Ghaemi H F, Thio T and Wolff P A 1998 Extraordinary optical transmission through sub-wavelength hole arrays *Nature* **391** 667–9

[2] García de Abajo F J 2007 Colloquium: Light scattering by particle and hole arrays *Rev. Mod. Phys.* **79** 1267

[3] Genet C and Ebbesen T W 2007 Light in tiny holes *Nature* **445** 39–46

[4] Ingard U and Bolt R H 1951 Absorption characteristics of acoustic material with perforated facings *J. Acoust. Soc. Am.* **23** 533–40

[5] Müller G and Möser M 2004 *Taschenbuch der Technischen Akustik* (Berlin: Springer)

[6] Zhang X 2005 Acoustic resonant transmission through acoustic gratings with very narrow slits: multiple-scattering numerical simulations *Phys. Rev.* B **71** 241102

[7] Hou B, Mei J, Ke M, Wen W, Liu Z, Shi J and Sheng P 2007 Tuning Fabry–Perot resonances via diffraction evanescent waves *Phys. Rev.* B **76** 054303

[8] Lu M-H, Liu X-K, Feng L, Li J, Huang C-P, Chen Y-F, Zhu Y-Y, Zhu S-N and Ming N-B 2007 Extraordinary acoustic transmission through a 1d grating with very narrow apertures *Phys. Rev. Lett.* **99** 174301

[9] Zhou L and Kriegsmann G A 2007 Complete transmission through a periodically perforated rigid slab *J. Acoust. Soc. Am.* **121** 3288–99

[10] Christensen J, Martin-Moreno L and Garcia-Vidal F J 2008 Theory of resonant acoustic transmission through subwavelength apertures *Phys. Rev. Lett.* **101** 014301

[5] Note that $\eta \approx 2$–4×10^{-2} for Plexiglas, while for most common metals $\eta < 10^{-3}$ [24].

[11] Estrada H, Candelas P, Uris A, Belmar F, García de Abajo F J and Meseguer F 2008 Extraordinary sound screening in perforated plates *Phys. Rev. Lett.* **101** 084302

[12] Estrada H, Candelas P, Uris A, Belmar F, Meseguer F and García de Abajo F J 2008 Influence of the hole filling fraction on the ultrasonic transmission through plates with subwavelength aperture arrays *Appl. Phys. Lett.* **93** 011907

[13] Takakura Y 2001 Optical resonance in a narrow slit in a thick metallic screen *Phys. Rev. Lett.* **86** 5601–3

[14] García de Abajo F J, Estrada H and Meseguer F J 2009 Diacritical 2009 study of light, electrons, and sound scattering by particles and holes *New J. Phys.* **11** 093013

[15] Estrada H, García de Abajo F J, Candelas P, Uris A, Belmar F and Meseguer F 2009 Angle-dependent ultrasonic transmission through plates with subwavelength hole arrays *Phys. Rev. Lett.* **102** 144301

[16] Estrada H, Candelas P, Uris A, Belmar F, García de Abajo F J and Meseguer F 2009 Influence of lattice symmetry on ultrasound transmission through plates with subwavelength aperture arrays *Appl. Phys. Lett.* **95** 051906

[17] Lee K G and Park Q-H 2005 Coupling of surface plasmon polaritons and light in metallic nanoslits *Phys. Rev. Lett.* **95** 103902

[18] Kihm J E, Yoon Y C, Park D J, Ahn Y H, Ropers C, Lienau C, Kim J, Park Q H and Kim D S 2007 Fabry–Perot tuning of the band-gap polarity in plasmonic crystals *Phys. Rev.* B **75** 035414

[19] Viktorov I A 1967 *Rayleigh and Lamb Waves: Physical Theories and Applications* (New York: Plenum)

[20] Glorieux C, Van de Rostyne K, Nelson K, Gao W, Lauriks W and Thoen J 2001 On the character of acoustic waves at the interface between hard and soft solids and liquids *J. Acoust. Soc. Am.* **110** 1299–306

[21] Liu F, Cai F, Ding Y and Liu Z 2008 Tunable transmission spectra of acoustic waves through double phononic crystal slabs *Appl. Phys. Lett.* **92** 103504

[22] Norris A N and Luo H A 1987 Acoustic radiation and reflection from a periodically perforated rigid solid *J. Acoust. Soc. Am.* **82** 2113–22

[23] Williams E G 1999 *Fourier Acoustics: Sound Radiation and Nearfield Acoustical Holography* (New York: Academic)

[24] Cremer L, Heckl M and Petersson B A T 2005 *Structure-Borne Sound* 3rd edn (Berlin: Springer)

[25] Estrada H, Bravo J M and Meseguer F 2011 Slit-array transmission loss feasibility in airborne sound arXiv:1102.4960v1[cond.mat.other]