Vortex-sound diffusers using spiral metasurfaces

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Abstract – **Metamaterials allow the accurate control of the acoustic scattering using subwavelength thickness panels. In this work, we report the scattering of spiral-shaped metasurfaces with practical application to sound diffusers. We analytically, numerically and experimentally show that bipolar spiral-shaped metasurfaces produce broadband non-specular reflection. We observe that the reflected energy can be scattered at higher diffraction orders and, due to the spiral geometry, the phase of the scattering field rotates producing a vortex in the near field. Thus, the specular component at normal incidence vanish. This produces a perfect correlation-scattering coefficient when comparing to a rigid flat reflector of same dimensions. In particular, the scattering of an Archimedes spiral metasurface is presented. We show that the scattering pattern corresponds to a high-order Bessel beam. The use of binary locally reacting surfaces with chiral geometry produce non-specular reflected patterns, allowing the use of these structures use as sound diffusers.**

I. Introduction

The control of the acoustic scattering can be achieved using a broad range of materials. On the one hand, inclined flat surfaces and pyramidal or curved reflectors provides simple way to control acoustic reflections, however, their performance for low frequencies is limited due to diffraction and its temporal response is instantaneous[1]. On the other hand, locally reacting flat-surfaces composed of resonators, i.e., metasurfaces, offer broader range of possibilities to tailor the reflected wavefront using subwavelength building blocks. The use of locally resonating structures to control the acoustic scattering dates from the late 70's[2], when arrangements of quarter-wavelength resonators, called phase grating diffusers, where introduced to generate diffuse reflections. These materials, called sound diffusers, have found practical application in room acoustics and are broadly used in most broadcast studios, modern auditoria, music recording, control and practice rooms[1]. Recently, metamaterials allowed the design deep-subwavelength sound diffusers using slow-sound waves [6] or by using Helmholtz resonators [7]. Normally, the building blocks of diffusers are arranged in a square matrix, although hexagonal patterns have been suggested. In this work, we present the scattering properties of spiral-shaped structures to be used as sound diffusers. We make use of spiral curves to produce a binary (bipolar) pattern, being each zone of the pattern tailored using metamaterials to achieve phase inversion between the two zones. In particular, we present the scattering properties of regular Archimedes spiral structures, showing chiral symmetry.

Spiral patterns have been applied to generate diffraction plates producing vortex beams in both, acoustics and optics. In electromagnetism, Vogel's spiral lattices have been applied to design aperiodic photonic structures and plasmonic nanoparticle arrays whose scattering presents discrete orbital angular momentum. In acoustics, Archimedes' spiral gratings have been recently studied in transmission, showing that transmitted waves are locally diffracted producing conical wavefronts with phase dislocations, producing high-order Bessel beams[18]. These structures produce vortex beams in the near field, where its topological charge is equal to the product of the diffraction order and the number of arms of the spiral. Spiral lattices have been also used to distribute the active elements of phase arrays for biomedical ultrasound therapy and imaging applications. However, the acoustic scattering of spiral structures has been much less explored.

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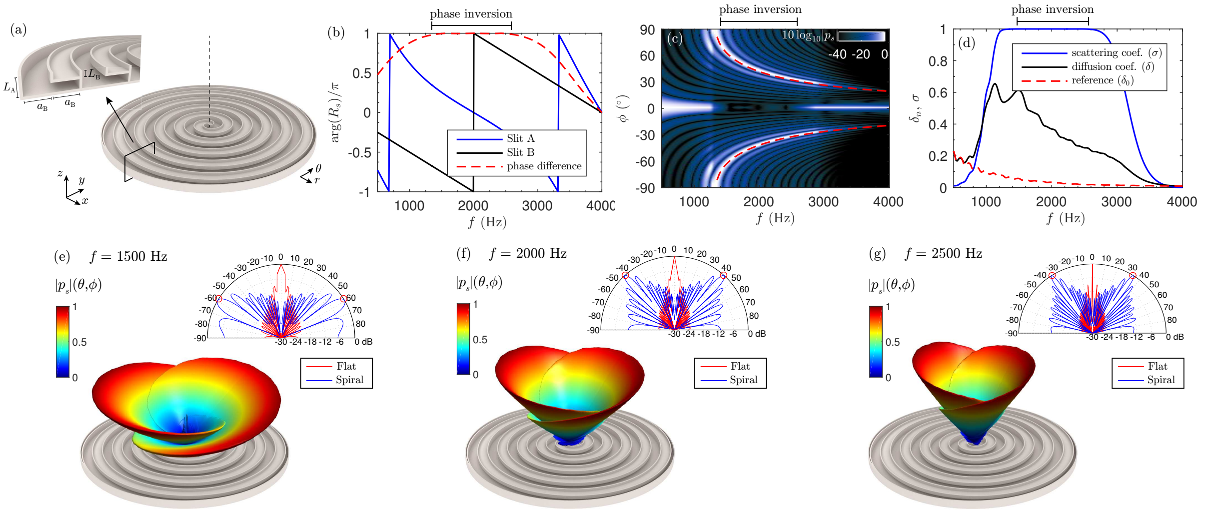

Fig. 1: (a) Scheme of the geometry for the Archimedes' spiral sound diffuser, the binary panel is composed of 2 slits (A,B), one well resonating at its QWR and other slit resonating at its Helmholtz resonance. (b) Phase of the reflection coefficient of both areas (blue and black), and phase difference (dashed red). (c) Scattered far-field pressure as a function of frequency and elevation angle. Red dashed line marks the first axisymmetric diffraction grating angle. (d) (blue) Scattering coefficient, (black) diffusion coefficient of the spiral panel, and (red dashed) diffusion coefficient of a reference reflector of same area. (e-g) Angular distribution of the scattered pressure for 1500, 2000 and 2500 Hz, respectively.

II. Archimedes spiral sound diffusers

The Archimedes spiral is a particular case of the family of Archimedean spirals which are given by the polar curve $r(\theta) = a\theta^{\gamma}$, where r is the radial coordinate, θ the polar angle and a the growth parameter. The exponent γ defines the rate of growth: for $\gamma > 1$ the spiral diverges while for $0 < \gamma < 1$ the spiral converges to a given radius and the distance between successive turns decreases with each turn. For the Archimedes spiral, $\gamma = 1$, i.e., the distance between successive turns remains constant. The binary structure is composed of a circular flat panel where the Archimedes spiral curve is used to separate 2 zones, as Fig.1(a) shows. Two wells were placed into the surface. We consider the surface as locally reacting. Into the first area, a straight well as a quarter wavelength resonator. In the other zone, a Helmholtz resonator is designed. Fig 1(a) shows the geometry of the designed metasurface, while in 1(b) we show the frequency-dependent phase of the reflection coefficient. We can observe that the first resonator inverts the phase of the reflection coefficient with respect to the second resonator over a broad range of frequencies. This allows the generation of the binary metasurface. The far-field scattered pressure is shown in Fig 1(c). As the distance between turns is constant, a, waves are locally diffracted with an angle $\beta = \sin^{-1} na/\lambda$ being λ the wavelength of the impinging wave and n the diffraction order. This produces a conical wavefront that in the far field generates the characteristic rings of a Bessel beam. Fig 1(e-f) shows the scattering for frequencies 1500, 2000 and 2500 Hz, where the characteristic ring is clearly visible. In addition, the phase of the scattered field rotates with each turn: the scattered field transports angular orbital momentum.

Important attention should be taken to the zero-th diffraction order: the specular component. The first component of the spatial Fourier transform of the spatially dependent reflection coefficient is zero, therefore, this binary structures present no specular reflection. To quantify its performance, it is useful to calculate the correlation-scattering coefficient, σ_{ϕ} as as usually in room acoustics and sound diffusers design[1]. This coefficient measures the correlation between the scattering of the strucnure and those of a flat panel of same dimensions. Thus, values close to zero indicate that the reflection is mostly specular while values close to the unity indicates the energy spreads in other directions rather than specular. The retrieved frequency-dependent correlation-scattering coefficient is shown in Fig 1(d). We observe that the absence of specular reflection makes this index being the unity, this occurring for frequencies where there exist a difference of phase between the two zone od the spiral, i.e., when the reflection coefficient of the quarter-wavelength resonator is $R = -1$. Other way to quantify the performance of the acoustic structure is to calculate the diffusion coefficient, which is important in practical applications of these metasurfaces such as in room acoustics. This coefficient measures the uniformity of the scattering, being the unity when there is not a privileged reflection direction, and zero when all the energy is reflected in only one direction. The diffusion coefficient normalized to that of a flat plane is shown in Fig 1(d). The diffusion coefficient reaches values below, which are moderate, because the energy is scattered in a small range of elevation angles. This is caused due to the uniformity of the Archimedes spiral whose separation distance between successive turns is constant.

III. Conclusion

We showed that using spiral-shaped metasurfaces High-order Bessel patters are produced. Due to diffraction grating effect waves spread in a discrete set of angles forming a conical wavefront. Due to chiral symmetry a vortex is produced in the near field, causing the specular reflection to vanish. This, we advance the potential application of these structures to design sound diffusers for room acoustic applications.

References

[1] T. J. Cox and P. D'antonio, *Acoustic absorbers and diffusers: theory, design and application*. Crc Press, 2009.

[2] M. R. Schröder, "Diffuse sound reflection by maximum- length sequences," *The Journal of the Acoustical Society of America*, vol. 57, no. 1, pp. 149–150, 1975.

[3] R. J. Hughes, J. A. Angus, T. J. Cox, O. Umnova, G. A. Gehring, M. Pogson, and D. M. Whittaker, "Volumetric diffusers: Pseudorandom cylinder arrays on a periodic lattice," *The Journal of the Acoustical Society of America*, vol. 128, no. 5, pp. 2847–2856, 2010.

[4] J. Redondo, R. Picó, V. Sánchez-Morcillo, and W. Woszczyk, "Sound diffusers based on sonic crystals," *The Journal of the Acoustical Society of America*, vol. 134, no. 6, pp. 4412–4417, 2013.

[5] L. Garcia-Raffi, L. Salmerón-Contreras, I. Herrero-Durá, R. Picó, J. Redondo, V. Sánchez-Morcillo, K. Staliunas, N. Adkins, A. Cebrecos, N. Jiménez *et al.*, "Broadband reduction of the specular reflections by using sonic crystals: A proof of concept for noise mitigation in aerospace applications," *Aerospace Science and Technology*, vol. 73, pp. 300–308, 2018.

[6] N. Jiménez, T. J. Cox, V. Romero-García, and J.-P. Groby, "Metadiffusers: Deep-subwavelength sound diffusers," *Scientific reports*, vol. 7, no. 1, p. 5389, 2017.

[7] Y. Zhu, X. Fan, B. Liang, J. Cheng, and Y. Jing, "Ultrathin acoustic metasurface-based schroeder diffuser," *Physical Review X*, vol. 7, no. 2, p. 021034, 2017.

[8] F. Lemoult, M. Fink, and G. Lerosey, "Acoustic resonators for far-field control of sound on a subwavelength scale," *Physical Review Letters*, vol. 107, no. 6, p. 064301, 2011.

[9] Y. Li, X. Jiang, R.-q. Li, B. Liang, X.-y. Zou, L.-l. Yin, and J.-c. Cheng, "Experimental realization of full control of reflected waves with subwavelength acoustic metasurfaces," *Physical Review Applied*, vol. 2, no. 6, p. 064002, 2014.

[10] S. Zhang, C. Xia, and N. Fang, "Broadband acoustic cloak for ultrasound waves," *Physical Review Letters*, vol. 106, no. 2, p. 024301, 2011.

[11] T. Wu, T. J. Cox, and Y. Lam, "A profiled structure with improved low frequency absorption," *The Journal of the Acoustical Society of America*, vol. 110, no. 6, pp. 3064–3070, 2001.

[12] V. Romero-García, G. Theocharis, O. Richoux, A. Merkel, V. Tournat, and V. Pagneux, "Perfect and broadband acoustic absorption by critically coupled sub-wavelength resonators," *Scientific reports*, vol. 6, p. 19519, 2016.

[13] N. Jiménez, W. Huang, V. Romero-García, V. Pagneux, and J.-P. Groby, "Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption," *Applied Physics Letters*, vol. 109, no. 12, p. 121902, 2016.

[14] N. Jiménez, V. Romero-García, V. Pagneux, and J.-P. Groby, "Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems," *Scientific Reports*, vol. 7, no. 1, p. 13595, 2017.

[15] M. Yang, S. Chen, C. Fu, and P. Sheng, "Optimal sound-absorbing structures," *Materials Horizons*, vol. 4, no. 4, pp. 673–680, 2017.

[16] P. D'antonio, "Planar binary amplitude diffusor," Oct. 6 1998, uS Patent 5,817,992.

[17] T. J. Cox, J. A. Angus, and P. D'Antonio, "Ternary and quadriphase sequence diffusers," *The Journal of the Acoustical Society of America*, vol. 119, no. 1, pp. 310–319, 2006.

[18] N. Jiménez, R. Picó, V. Sánchez-Morcillo, V. Romero-García, L. M. García-Raffi, and K. Staliunas, "Formation of high-order acoustic bessel beams by spiral diffraction gratings," *Physical Review E*, vol. 94, no. 5, p. 053004, 2016.