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Twisting acoustic reflections by spiral sound diffusers

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Abstract
We report broadband metasurfaces to control sound diffusion in the far field by the scattering of acoustic vortices. By encoding the holographic field of an acoustical vortex, these metasurfaces result in structures with spiral geometry. These metasurfaces inhibit specular reflections in the far field because all scattered waves interfere destructively in the normal direction. The scattering function is then unusually uniform because the reflected waves diverge spherically from the holographic focal spot. By triggering vorticity, energy can be evenly reflected in all directions except to the normal and, consequently, we observe a mean correlation-scattering coefficient of 0.99 (0.98 in experiments) and a mean normalized diffusion coefficient of 0.73 (0.76 in experiments) over a 4-octave frequency band. These spiral metasurfaces are good candidates to generate diffuse sound reflections for room acoustics, underwater acoustics, biomedical ultrasound, or particle manipulation devices.

Keywords: Vortex, sound diffusers, metamaterials, metasurfaces, scattering.

1 Introduction

Nowadays, research on acoustic metasurfaces is very active. However, the use of locally resonant structures to control sound diffusion in room acoustics dates to the late 70's, when arrangements of quarter-wavelength resonators, called phase-grating diffusers, were introduced by M. Schröeder to generate diffuse reflections [1]. These acoustic devices have found practical applications in room acoustics and are widely used in many broadcast studios, modern auditoria, music recording, control, and rehearsal rooms [2]. Recently, metamaterials were proposed to reduce the thickness of Schröeder diffusers by using Helmholtz resonators instead of quarter-wavelength resonators [3] or slow-sound metasurfaces with deep-subwavelength resonators [4], [5]. In this work, we study the scattering properties of spiral metasurfaces based on holographic acoustic vortices and make use of them to design broadband and non-specular sound diffusing surfaces [6].

2 Metasurface design

The proposed metasurface is sketched in Figs. 1 (a, b). The structure consists of a circular flat panel of radius a and thickness L and has N wells of spiral shape. The field of a spherically focused vortex source located at a distance $z = F$ on the metasurface plane $z = 0$ can be approximated in cylindrical coordinates $\mathbf{r} = \mathbf{r}(\phi, r, z)$ by a hyperbolic phase profile as [7]

$$p(\phi, r) = \frac{-ip_0}{k\sqrt{r^2 + F^2}} \exp\left(ik\sqrt{r^2 + F^2}\right) \exp(il\phi), \tag{1}$$

where F is the focal distance, $k = \omega / c_0$ is the wavenumber, ω is the angular frequency, c_0 is the sound speed, and p_0 is a constant. The time convention in this work is $\exp(-i\omega t)$. If a surface is set to radiate a time-reversed (or complex conjugate in the frequency domain) version of this field, a diffraction-limited vortex converging at the focal point $z = F$ will be observed, because of the time-invariance of the acoustic equations.

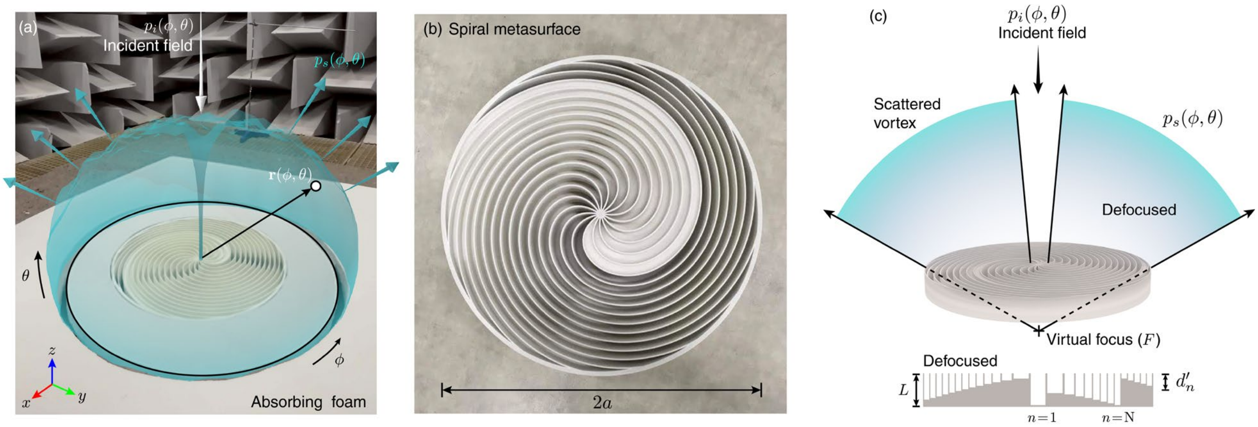

Figure 1 – (a) Scheme of the proposed spiral-shaped sound diffusing metasurface. (b) Geometry of the panel for the focusing configuration. (c) Spiral metasurface designed for the defocusing configuration using a virtual image of a vortex and its geometry.

To design a metasurface with such phase profile, we follow a twostep procedure. The first step consists in spatially discretizing the metasurface with a geometry compatible with the phase profile of Eq. (1). This can be done by the expansion of the binary Fresnel-spiral zone plates [8] for the case of the N phase zones and l_0 arms. The boundary between the $n-1$ and n-th phase zone is then given by the following expression

$$r_{n,m}(\phi) = \sqrt{\left[F + \lambda_0\left(\frac{l_0\phi}{2\pi} + \frac{n}{N} + m\right)\right]^2 - F^2}, \tag{2}$$

where $n = 0, \ldots, N-1$ is the index of each wall, $0 < \phi < 2\pi$ is the azimuthal coordinate, $\lambda_0 = c_0 / f_0$ is the design wavelength with f_0 the design frequency, l_0 represents the topological charge at the design frequency, and $m = 0, 1, \ldots, l_0 - 1$ is the index of each arm. The second step consists in assigning to each phase zone the phase values given by Eq. (2). This is done by drilling spiral wells in the panel with a depth d_n and $d_n^{'}$ of the n-th well, for the focusing and defocusing panels respectively, set accordingly to

$$d_n = \frac{n\lambda_0}{2N} \quad \text{and} \quad d_{n'} = \frac{(N - n + 1)\lambda_0}{2N}, \tag{3}$$

where the design wavelength $\lambda_0 = 2L$ is associated to the lowest cut-off frequency of the structure and $f_0 = c_n / 2L$, and c_n is the sound speed inside the well.

3 Results

To quantify the performance of the metasurface, the correlation-scattering coefficient, $\sigma(f)$, is calculated as usual in room acoustics and sound diffusers design [2]. This coefficient measures the decorrelation between the scattered field by the structure and that by a flat panel of the same dimensions. Thus, a 0 value of $\sigma(f)$ indicates that the reflection is specular while a 1 value indicates that the scattered energy spreads in all directions other than specular. The retrieved frequency-dependent correlation-scattering coefficient is shown in Fig. 2 (a). A good agreement is found between theoretical predictions for the focusing and defocusing devices as in the far field both systems present similar scattering field. The experimental results for the focusing device validate this behaviour. We observe that the absence of specular reflection makes the correlation-scattering coefficient being almost unitary at frequencies that are multiples of the design frequency because vortices of integer charge are then generated. The correlation-scattering coefficient remains close to unity over the entire design frequency band ($\sigma(f) > 0.9$ for $f_0 < f < Nf_0$), taking a mean value of 0.98 (0.99 in theory) over the frequency range from 2 kHz to 16 kHz.

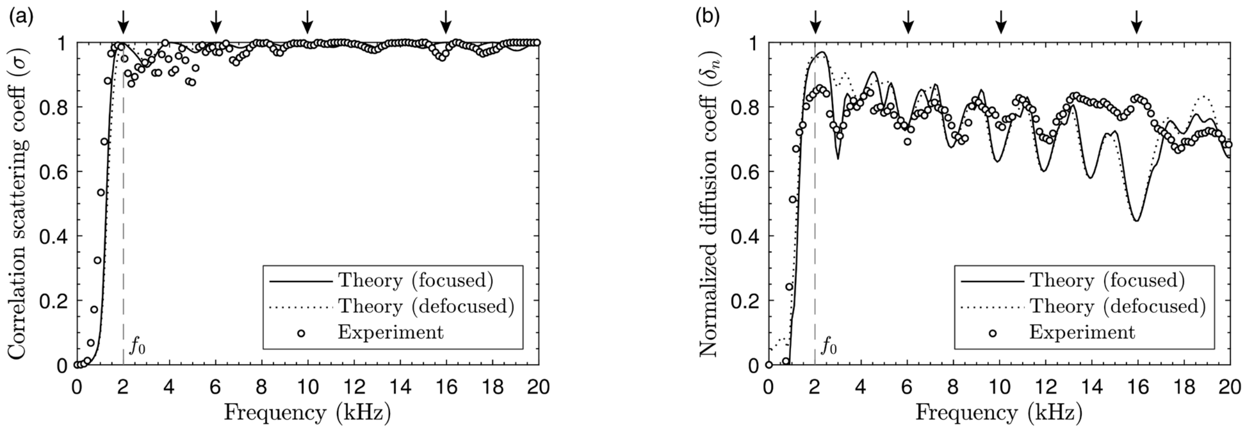

Figure 2 – (a) Correlation scattering coefficient, arrows indicate the frequencies 2 kHz, 6 kHz, 10 kHz, and 16 kHz. (b) Normalized diffusion coefficient.

A second important parameter to quantify the performance of the acoustic structure is the diffusion coefficient, $\delta(f)$ [2]. When all the energy is reflected in a single direction, $\delta(f) = 0$, while $\delta(f) = 1$ when there is no preferred direction of reflection, and the scattering function is uniform. The magnitude of the diffusion coefficient must be normalized by that of a perfect reflector of the same dimensions, namely the normalized diffusion coefficient $\delta_n(f)$. Figure 2 (b) shows the normalized diffusion coefficient calculated theoretically and measured experimentally for the focusing and defocusing metasurfaces. This coefficient presents a peak at the design frequency of amplitude $\delta(f_0) \approx 0.95$ theoretically and $\delta(f_0) \approx 0.85$ experimentally. This high value arises from the fact that the holographic vortex generates spherically diverging waves. However, the value of the normalized diffusion coefficient cannot reach unity because there is a lack of scattering in the normal incidence. As the topological charge of the scattered vortex increases with frequency a wider range of angles close to normal direction presents reduced scattering. Therefore, the response is less uniform, and the value of the normalized diffusion coefficient decreases with frequency. The normalized diffusion coefficient takes a mean value of 0.76 (0.73 in theory) over the frequency range from 2 kHz to 16 kHz.

4 Conclusions

Vortex beams present a null in the far field because the phase singularity of a vortex beam inhibits the propagation of waves along the axial direction. In this way, reflecting surfaces based on vortices only present off-axis reflections. In addition, these spiral metasurfaces can spread uniformly the energy over the entire angular spectrum by focusing (or defocusing) a vortex in the near field, thus, allowing the design of ultra-broadband acoustic diffusers with simultaneous high diffusion performance and non-specular reflections.

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