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ULTRASONIC HOLOGRAM FOR BI-DIRECTIONAL DIFFUSION BY PHASE CONTROLLING THE SCATTERING COEFFICIENTS

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ABSTRACT

In this work, we present a bi-directional asymmetric ultrasonic hologram that can simultaneously control both the reflected and transmitted wave-fields. To do that we design a surface made of a discrete spatial distribution of monolithic elements with different properties than the surrounding medium. This allows to compress two identical or different wavefield scattering patterns (for transmission and reflection) into a single monolithic object. We report an ultrasonic hologram based on Quadratic Residue sequences encoded with resonant building blocks behaving as an ideal Lambertian scatterer from both sides, with spatial autocorrelation coefficients of 0.7 each one, therefore diffusing waves in both transmission and reflection.

Keywords: *Acoustic hologram, Acoustic diffusers, Ultrasonic imaging, Acoustic scattering*

Research in ultrasounds covers a broad range of fields as non-destructive testing, underwater acoustics and imaging among others. Recently, there is an increasing interest in biomedical applications, such as non-destructive medical imaging [1, 2] and non-invasive controlled medical therapy [3, 4]. In this work we design of a bi-directional asymmetric ultrasonic hologram that works simultaneously in transmission and reflection. The design framework of such hologram follows a multi-objective optimization procedure which minimizes the difference in reflection and transmission phase values for a given length of polymer material, allowing the creation of a phase-space representing the total phase combinations between the two interfaces, the building blocks of which can be used to replicate any desired reflection and transmission phase profiles. In the work herein, the case of an ideal Lambertian scattering hologram made out of a Quadratic Residue sequence has been demonstrated, where high scattering values with a spatial auto-correlation coefficient around $\delta = 0.7$ have been reported [5].

We consider an ultrasonic hologram composed of a discrete spatial distribution of building blocks made of a monolithic polymer blocks with different height embedded in water. The working frequency is chosen at 1.1 MHz. An example layout can be seen through the artistic impressions in Figs. 1(a,b). We consider first a 1D problem for each constituting building block of the hologram. The building block is made of a monolithic polymer block of length l surrounded by two water blocks of length d_1 and d_2 respectively as shown in Fig. 1(c). The sound pressures, p, and normal particle velocities, v_z, at $z = 0$

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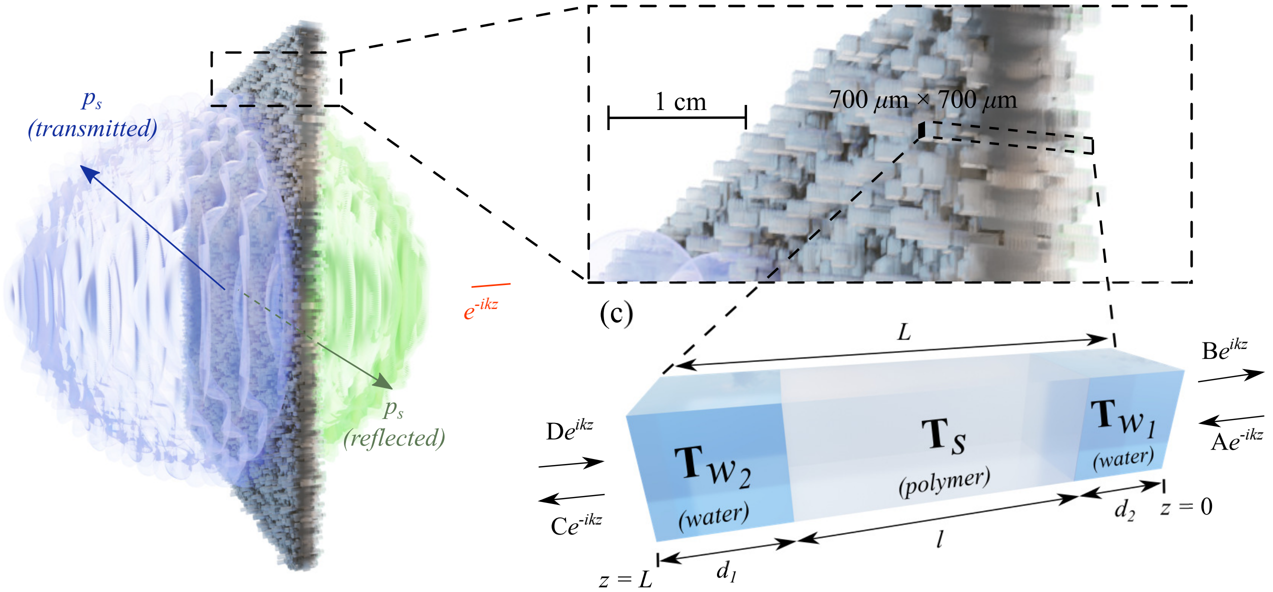

Figure 1. (a) Artistic impression of a $10 \times 10 \times 1$ cm ultrasonic bi-directional hologram diffusing an incident plane wave in a uniform scattering profiles for each direction; reflection in green, transmission in blue. (b) Close-up of the lens; each monolithic block has a lateral size of $\Delta l_x \times \Delta l_y$=700$\mu$m×700$\mu$m. (c) Representative 1D Transfer Matrix diagram of a monolithic block of total length L composed of a solid element (e.g., polymer) and an exterior medium (here, water). The local phase and amplitude of the reflection and transmission coefficients depend on d_1, d_2 and l.

and at $z = L$ can be modelled by means of the Transfer Matrix Method (TMM). Due to the lateral dimensions of the building blocks ($\Delta l_x \times \Delta l_y$=700$\mu$m×700$\mu$m) we can assume plane wave propagation. Therefore, the transfer matrix $\mathbf{T}$ of the building block can be derived and the reflection, R, and transmission, T, coefficients calculated. This implies that we consider each building block is independent from each other in the structure and considered as an equivalent fluid. Such approximation can be made due to the low difference in impedance between the water and polymer media, with a polymer-to-water impedance ratio $Z_p/Z_w = 1.67$, coupled with the fact that shear waves can also be neglected due to the system being considered under normal incidence.

Following Fraunhofer's diffraction theory, the scattered sound pressure distribution over a surface with an anisotropic phase distribution, such as a reflection or transmission coefficient in this case, can usually be resumed as a spatial Fourier transform of the corresponding complex surface coefficient. In this case, the far-field pressure distribution, $p_s(\theta, \phi)$, where θ and ϕ are the azimuthal and elevational angles, respectively, of a radiating rectangular surface with a spatially dependent phase distribution coefficient, $\xi(x, y)$, of size $2a$ and $2b$ in the x and y directions respectively, can be calculated using the Fraunhofer integral [6]

$$p_s(\theta, \phi) = \int_{-a}^{a} \int_{-b}^{b} \xi(x, y) e^{ik(x \sin\phi \sin\theta + y \sin\phi \cos\theta)} \mathrm{d}x\mathrm{d}y. \quad (1)$$

The subindex $s = R, T$ represents the reflection and transmission problem respectively, and $\xi(x, y) = R(x, y)$ ($\xi(x, y) = T(x, y)$) for the reflection (transmission) problem.

In order to design a hologram that can behave as an ideal diffuser in both reflection and transmission sides, we look for a spatial phase distribution for the both the reflection and transmission coefficient such that the spatial Fourier transform of said distribution approximates a flat angular response. There are many number theoretic sequences that can help design such phase distribution, such as the maximum length or quadratic residue sequences [7].

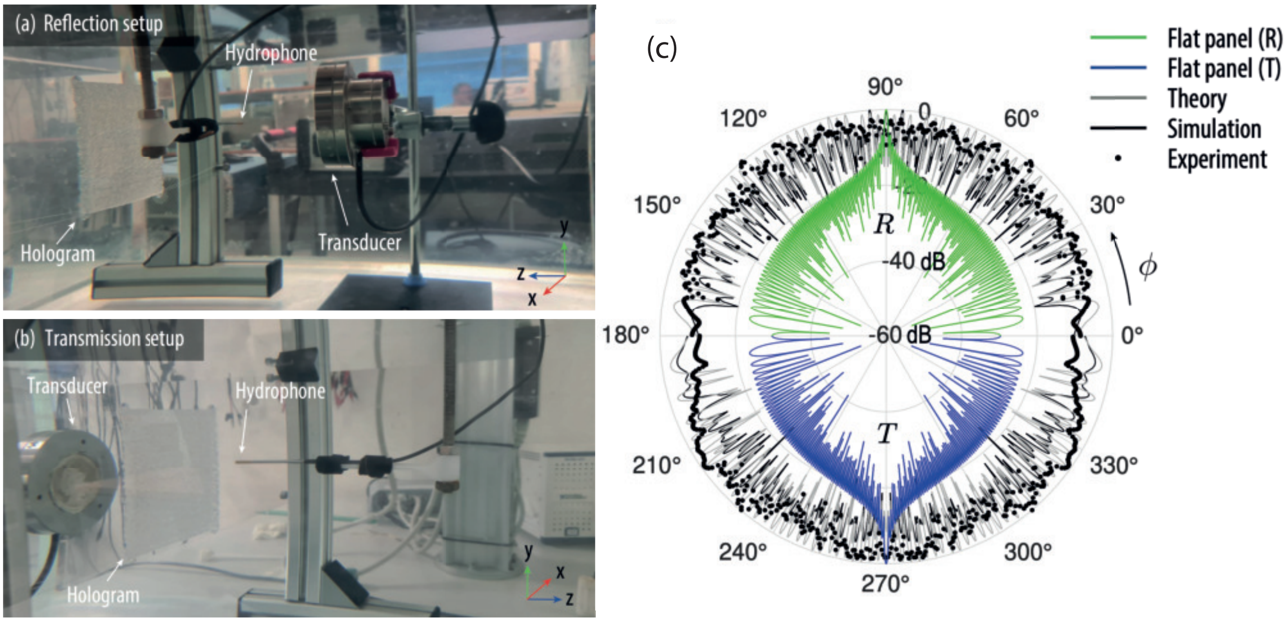

Figure 2. Experimental water tank measurement setup of the 3D-printed diffusing hologram in (a) reflection and (b) transmission situations. (c) Measured (dots) scattered polar pressure distribution in reflection (R) and transmission (T) compared to analytical (black line) values (QR) and the scattered field of a flat vibrating piston (blue and green lines).

Here, the quadratic residue (QR) sequence will be used, which when repeated in space, allows to generate evenly spaced diffraction lobes with even energy.

Experimental measurements of a 3D-printed hologram, with $N = 53$ repeated $M = 3$ times (see Fig. 1(a,b), were made in a water tank for the reflection and transmission configurations. Figures 2(c) show the polar scattered energy distributions measured from both sides of the hologram. It can be observed from Fig. 2(c) that both measured scattering fields are more uniform than the polar response of a planar vibrating piston, which outputs energy narrowly in the normal axis (0°), and are in good agreement with the predicted analytical curve. The Spatial Auto-Correlation Coefficient (SACC) of the polar distributions are $\delta^R = 0.65$ and $\delta^T = 0.71$ for the reflected and transmitted wave fields, respectively. Those can be considered quite high values due to the physical nature of the SACC where $\delta \to 0$ denotes a Dirac-like specular distribution and $\delta = 1$ a fully spherical one. Knowing than a SACC of unity is almost impossible to reach with traditional number theoretic sequences [8], there would be some diminishing returns in successfully increasing the SACC value when aiming closer to unity. A value around 0.7 thus already denotes a strong scattering behaviour, akin to one obtained through a Lambertian distribution.

In this work we have designed a bi-directional asymmetric ultrasonic hologram that can simultaneously control both the reflected and transmitted wave-fields. Depending on the applications, such hologram could be useful in situations where transmitted and reflected wave-fields need to be controlled at the same time, such as a bi-directional diffusing system emitting and receiving equally in and from all directions (equivalent of perfect optical diffusers in optics) or as a bi-directional beam directivity selector. Such hologram could also be used directly in reflection situations for minimizing unwanted specular reflections. This kind of tunable bidirectional hologram could be further optimized to create decollimating/collimating/focusing scattering wave fields for one or both directions, with potential applications ranging from ultrasound-guided medical procedures [9] to compressing sensing [10].

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Author contributions:

E.B, J-P.G, V.R-G, and N.J conceived the project, under the direction of N.J. E.B, V.R.-G and N.J wrote the code for the theoretical and numerical data. E.B performed the multi-objective optimization and provided the dimensions of the ultrasonic lens. J.R-S 3D-printed the sample and performed the experimental measurements along with N.J, as well as provided details on the experimental apparatus. N.J analyzed the experimental data. E.B, and N.J wrote the initial manuscript with input from all authors. E.B, V.R.-G and N.J prepared the revised version and the response to the referees with input from all authors. All authors have reviewed and commented on the final manuscript.

There are no competing interests to declare.

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