Accurate synthesis of acoustic holograms using field matching

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***Abstract*—Current methods for hologram design do not accurately encode the target phase distribution, mainly because the complex topology of these lenses results in a rich wave physics which is usually not considered in the design. In this work, we present a method to design acoustic holograms and lenses that accurately synthesize a target field using a phase-matching approach. Rather than producing a phase distribution over a holographic plane, the method matches the phase of the field produced by the lens to the target phase in a whole volume. For simple focused lenses, we theoretically demonstrate that classical methods result in a hyperbolic lens profile for higher-than-one refraction index materials, while the present method results in elliptic profiles, which are optimal. For lower-than-one refraction index, both methods result in hyperbolic profiles, but field matching method produces sharper focal spots, larger gain, and lower focal shifts, especially for low f-numbers. Finally, we observe that the structural similarity index of complex acoustic images produced at shorter distances is larger for the current method. The present technique goes beyond traditional methods to design acoustic holograms and might be used in emerging therapeutic ultrasound applications where an accurate control of the acoustic beam is needed.**

I. Introduction

Acoustic holograms are complex lenses that encode tailored phase distributions on their topology and can create specific patterns of acoustic pressure within a medium [1]. Acoustic holograms have emerged as a versatile technology with multiple applications in fields such as biomedical ultrasound [2], acoustics [3], or contactless micromanipulation and biofabrication [4], [5]. An acoustic hologram is a three-dimensional representation of an acoustic field that allows precise manipulation of pressure waves. This technology is based on principles of interference and diffraction, similar to optical holograms, but applied to sound waves.

One of the most promising areas for acoustic holograms is their application in ultrasound therapy, and in particular in transcranial ultrasound [2], [6], where acoustic holograms have shown immense potential to improve the efficacy of treatments such as hyperthermia [7], [8] and localized drug delivery by opening the blood-brain barrier [9], neuromodulation [10], or opening new avenues for transcranial particle trapping [11] and generation of arbitrary cavitation patterns [12]. They can also be applied for imaging [13] and monitoring therapeutic ultrasound treatments [14].

However, current methods [1], [2], [6] for lens design do not accurately encode the target phase distribution, mainly because the complex topology of these lenses results in a rich wave physics that is usually not considered in the design [15]. This results in physical lenses that produce sub-optimal acoustic images. In this work, we present a method to design acoustic holograms and lenses that accurately synthesize a target field.

II. Methods

In classical hologram design, the target field is defined in a transversal plane. These holographic lenses are designed to mimic the phase of the field at this location. In the case of perfect impedance matching between the lens and the exterior media, this result in an explicit linear relation between the height of the lens and the phase of the field. In case of mismatch, the height of the lens can also be found using a simple interpolation. However, the usual implementation using phase plate lenses cannot exactly synthesize the phase due to the lack of plane wave propagation, refraction, and diffraction at discontinuities.

We propose the use of a novel approach, where the field is first acquired in a volume instead of a plane. Instead of matching the phase of the field at a given distance, this method matches the phase of the field produced at the exit of the lens to the target phase in a whole volume. This phase-matching approach, analytical solution is found for simple cases, like for focused beams. For other situations, like complex holograms, the solution is can be found numerically.

The method is validated using analytic, simulation and experimental results, illustrated using several examples. First, a single focal lens is presented, using a 1-MHz circular aperture source and several 3D printing materials. A parametric study of the focusing performance is detailed and a comparison with traditional methods is presented. Second, a steered high-order Bessel beam is synthesized, and its angular spectrum is analyzed. Finally, several complex acoustic images produced at different depths are produced, and their structural similarity index measure (SSIM) is estimated.

III. Results

First, for simple focused lenses, we observe that the present method produces sharper focal spots, with a larger focusing gain, see Fig. 1(a-b). The focal spots are closer to the diffraction-limited estimations. For simple focused lenses, we theoretically demonstrate that classical methods for higher-than-one refraction index materials result in a hyperbolic lens

height profile, while the present method results in elliptic profiles, which indeed are the optimal solution, see Fig. 1(c). For lower-than-one refraction index materials, both analytical solutions result in hyperbolic phase profiles, see Fig. 1(c). However, only the profiles given by the phase-matching strategy are optimal. Solutions are different for highly focused sources (short focal distances). Phase matching holograms produces focal spots closer to the diffraction-limited ideal case. For low f-numbers, phase matching performs better than classical, while for moderate focused beams both methods converge.

Both models are limited by the existence of a critical angle during refraction. We illustrate this using Bessel beams and their angular spectrum. Critical angle reduces all phase-only holograms performance, limiting the maximum field steering. In practice, critical angle is more relevant for higher-than-one refraction index materials due to manufacturing constraints. Finally, we observe that the SSIM of complex acoustic images produced at shorter distances is larger for the current method, particularly for short focal distances. These images are produced without any optimization, as shown in Fig. 2(a-i).

IV. Conclusion

Phase-matching holograms can accurately synthesize the phase of a target field at the exit of the lens. In this way, the present technique goes beyond traditional methods to design acoustic holograms. This technique will find application in emerging therapeutic ultrasound applications where an accurate control of the acoustic beam is needed, and full-wave simulations are computationally expensive to use optimization methods.

Acknowledgment

This research has been supported by the MCI grant RYC2021-034920-I, AEI grants PID2022-142719OB-C21, and CNS2023-145707 and AVI grants INNEST/2022/345, and INNVA2/2022/11.

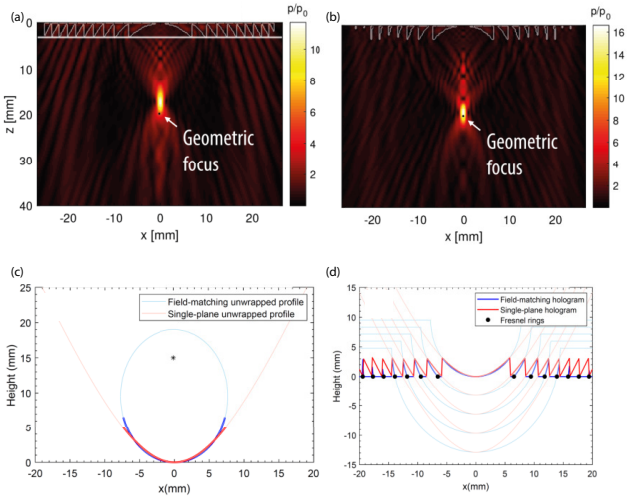


Fig. 1.

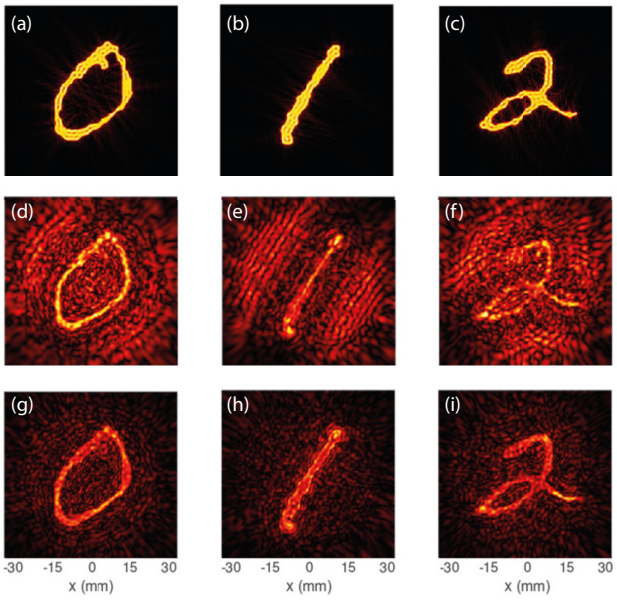


Fig. 2.

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