A phase-matching approach for ultrasound hologram generation

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***Abstract*—Ultrasound holography has emerged as a promising technique for non-invasive brain therapies, enabling precise targeting of specific regions. In this context, acoustic holograms can be generated using low-cost 3D-printed acoustic lenses, where the wavefront is encoded into the height of the pixels of a lens. Traditionally, holograms are designed to focus at a planar surface in front of the transducer, resulting in a hyperbolic phase profile under the thin lens approximation. However, when the physical lens thickness exceeds this approximation, aberrations occur. In this work, we propose a phase-matching approach that aligns the phase of the field produced at the exit of the lens with the target phase across a holographic volume. This method is validated through analytical and simulation techniques, demonstrating improved focusing performance compared to traditional methods.**

***Index Terms*—Acoustic holograms, Acoustic lenses, Transcranial ultrasound.**

I. Introduction

Acoustic hologram are a rising technology that enables the generation of complex acoustic fields by encoding phase and/or amplitude information onto a surface, allowing for precise control over acoustic wave propagation [1]. This technology has found applications in various fields, including acoustics [2], [3], biomedical ultrasound [4]–[6], and advanced techniques such as contactless micromanipulation or biofabrication [7], [8].

Traditionally, phase-only acoustic holograms are designed by encoding the desired phase distribution onto a planar surface, known as the holographic plane, positioned at a set distance parallel to the surface of the transducer. This approach relies on the thin lens approximation, where the phase shift imparted by each pixel is determined by its height and the acoustic properties of the lens material [1], [6]. While effective for simple configurations, this method does not account for complex wave phenomena such as refraction, diffraction, and internal reflections, which become significant beyond the thin-lens approximation. As a result, aberrations may arise, limiting the accuracy and focusing performance of the generated acoustic field; and thus, more advanced design strategies are required that consider the full wave physics involved in hologram synthesis. On this work, we propose a novel *phase-matching* technique to overcome some of these limitations.

II. Materials and Methods

Currently, holographic lenses are designed under the assumption that each pixel behaves as a Fabry-Perot resonator, where each pixel induces a phase shift that matches the recorded phase at a location called the holographic surface, set at a fixed distance from the transducer [6]. This procedure, referred to as the *single-plane* method, assumes plane wave propagation through every pixel. However, this behavior does not fully capture the complex wave phenomena present in practical scenarios, such as refraction, diffraction, and internal reflections, especially when the lens thickness exceeds the thin lens approximation. These effects can lead to aberrations and reduced focusing accuracy.

To address these limitations, we propose a *phase-matching* strategy that extends the design process beyond a single plane. Instead of matching the phase at a fixed holographic surface, our method records the target phase across a holographic volume, comprising multiple planes parallel to the transducer. The lens geometry is then calculated so that the phase of the field produced at the exit of the lens matches the target phase throughout this volume. This approach leverages a physics-based model to account for wave propagation effects, enabling more accurate synthesis of the desired acoustic field and improved focusing performance.

To validate the proposed phase-matching approach, in-silico experiments were conducted using the k-Wave MATLAB toolbox [9]. Simulations employed a 50-mm aperture, 1.1 MHz planar transducer submerged in a homogeneous $25\,^\circ$ C medium ($c_0 = 1496.9$ m/s). Holographic lenses were generated using the single-plane and phase-matching approaches using rigid ($c_L = 2599.3$ m/s) and soft ($c_L = 973.6$ m/s) materials. Additionally, the angular spectrum method was also used as a baseline for comparison between the methods.

The ability of both methods to focus at different distances ranging from 10 to 120 mm in steps of 5 mm was tested (*F*-number values 0.2 to 2.4), as well as their ability generate complex acoustic patterns using a set of MNIST images for numbers one to five for focusing distances 10 to 90 mm (*F*-number values 0.2 to 1.8). For the latter, the generated acoustic patterns are compared using the Structural Similarity Index Measurement (SSIM) [10].

III. Results

Simulation results for single-plane and phase-matching techniques are shown in Fig. 1. The phase matching technique provides a mean focal deviation of 4.2 ± 3.7 mm across both materials, while it is 5.8 ± 3.5 mm the single-plane method. In

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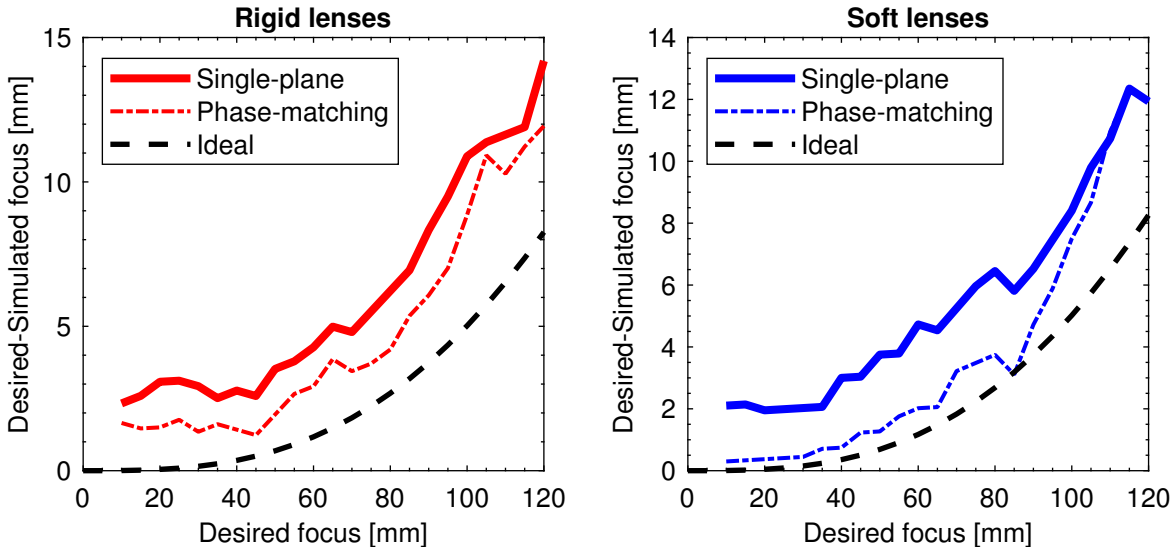


Fig. 1. Simulated focal distance for single-plane and phase-matching techniques for rigid (left) and soft (right) materials.

this way, the phase-matching approach systematically outperforms the traditional method for the studied range of focusing distances. This effect is particularly noticeable for F-number values below 0.5, where soft phase-matching lenses performed really close to the results provided by the angular spectrum method, with a mean 0.35 ± 0.05 mm deviation on this range.

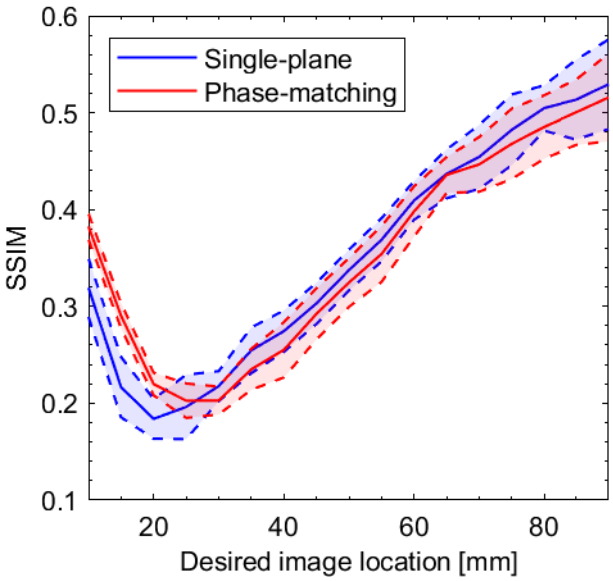


Fig. 2. Mean Structural Similarity Index Measurement (SSIM) for MNIST number images one to five obtained through single-plane and phase-matching acoustic hologram techniques.

The ability of both methods to generate arbitrary acoustic patters was studied using the MNIST patterns. Results from this study can be observed in Fig. 2. For F-number values above 0.5, the phase-matching approach provided an average 19.6% increase in SSIM over the single-plane, proving the ability of this novel method to generate more faithful acoustic patterns for low F-number. For F-number values above 0.5 however, the results for both methods were indistinguishable, as proven by a two sample Kolmogorov-Smirnov test ($p > 0.99$).

IV. Conclusions

In this work, we have provided a novel phase-matching approach for the design of acoustic holograms, enabling improved synthesis of complex acoustic fields for transcranial ultrasound applications. By matching the phase of the field produced at the exit of the lens to the target phase across a holographic volume, the proposed method overcomes limitations of traditional single-plane techniques, which rely on the thin lens approximation and neglect important wave phenomena. Simulation results demonstrate that the phase-matching strategy achieves superior focusing accuracy and enhanced pattern fidelity, particularly for low F-number configurations and soft lens materials.

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