DOI: 10.61782/fa.2025.0420

FORUM ACUSTICUM EURONOISE 2025

GENERATING ACOUSTIC HOLOGRAMS BEYOND THE HYPERBOLIC APPROXIMATION

Víctor Vegas-Luque[1*] **Diana Andrés**[1] **Alba Eroles-Simó**[1]
Juan J. Rodríguez-García[1] **Francisco Camarena**[1] **Noé Jiménez**[1]
[1] Instituto de Instrumentación para Imagen Molecular (i3M), Universitat Politècnica de València (UPV) – Consejo Superior de Investigaciones Científicas (CSIC), Spain

ABSTRACT

Transcranial focused ultrasound has proven to be an effective method for the treatment of neurological disorders, offering a non-invasive and highly precise approach for the targeting of specific brain regions. In this context, ultrasound holograms have been shown to be capable of focusing through the human skull using low-cost 3D-printed acoustic holographic lenses, where a wavefront is encoded into the height of the pixels of a lens. When the coding is performed at the holographic plane, i.e., a planar surface in front of the transducer, the reconstructed wavefront is approximated by a hyperbolic phase profile in the thin lens approximation. However, as the thickness of the physical lens is beyond the thin lens approximation, this results in aberrations. In this work, a new strategy is proposed matching the phase of the field produced at the exit of the lens to the target phase in a whole holographic volume. The method is validated using analytic and simulations techniques. Results show that this phase-matching approach provides better focusing performance over traditional methods and, therefore, might be used for accurate hologram synthesis in practical applications.

Keywords: *Acoustic holograms, transcranial ultrasound, phase-matching*

**Corresponding author*: *vvegluq@i3m.upv.es.*

1. INTRODUCTION

Acoustic holograms are intricate lenses designed to encode customized phase distributions onto their surface, enabling the formation of specific acoustic pressure patterns within a medium [1]. Essentially, an acoustic hologram produces a three-dimensional acoustic field, providing precise control over pressure waves at a target region [1, 2]. It operates on the principles of interference and diffraction, akin to optical holograms, but adapted for sound waves. This technology has gained prominence for its versatility, finding applications in many fields such as in acoustics [3, 4], biomedical ultrasound [5, 6] and advanced techniques such as contactless micromanipulation or biofabrication [7, 8].

In particular, acoustic holograms hold significant promise in ultrasound therapy, particularly in transcranial ultrasound [6], where they have demonstrated great potential to enhance treatment effectiveness. Applications include improving hyperthermia treatments [9, 10], facilitating targeted drug delivery by opening the blood-brain barrier [11, 12], neuromodulation [5, 13] or the creation of customized cavitation patterns [14]. Beyond therapy, acoustic holograms can also be utilized for imaging and monitoring therapeutic ultrasound treatments [15].

Current holographic methods are based on the recording of a phase and/or amplitude of the desired wavefront [1]. In particular, phase-only acoustic holograms aim to build a *holographic lens* that allows the phase of the wavefront coming out of the lens to match that of the recorded wavefront. However, existing lens design methods fail to precisely encode the target phase distribution, primarily due to the complex topology of these lenses, which introduces intricate wave physics often overlooked in the design process [16]. As a result, physical lenses generate suboptimal acoustic images. In this work, we propose a method for designing acoustic holograms and lenses that accurately reproduce a desired target field. This approach uses a *phase-matching* strategy to ensure that the phase of the field produced at the exit of the lens matches the target phase across the entire holographic volume. We validate this method through analytical and simulation techniques, demonstrating its superior performance in focusing acoustic waves compared to traditional methods.

2. METHODS

In current hologram design methods, the target field is defined in a transverse plane and it is assumed that the lens produces a phase shift at the transverse plane location [6]. This results in a simple linear relationship between the lens height and the phase of the field. However, this approach assumes plane wave propagation, and thus, does not account for other wave phenomena such as refraction and diffraction at discontinuities. To address these limitations, we propose a *phase-matching* strategy to match the field at the exit of the lens to better match that of the target field.

In contrast with conventional single plane methods, where the phase of the field is matched at a holographic plane at a set distance from the transducer, our proposed phase-matching method matches the phase of the field produced at the exit of the lens to the target phase in a whole holographic volume, that is, in successive planes parallel from the transducer location up to a desired distance. The height of each pixel in the lens is determined such that its transmission coefficient phase aligns with the recorded phase originating from the virtual sources at some point in the holographic volume.

The proposed method is validated through analytical mean and simulations using a 1.1-MHz circular 50-mm aperture transducer. Simulations were performed using k-Wave toolbox (MATLAB) for simulating acoustic wave propagation [17]. The transducer was modeled as a circular piston with a Gaussian distribution of the amplitude and a uniform phase distribution. Simulation are performed in a uniform water medium at a temperature of $25\,^{\circ}\mathrm{C}$ with a resolution of $\lambda/6$, where $\lambda \approx 1.4\,\mathrm{mm}$ is the wavelength water at the working frequency; in which the lens is placed on top of the planar source.

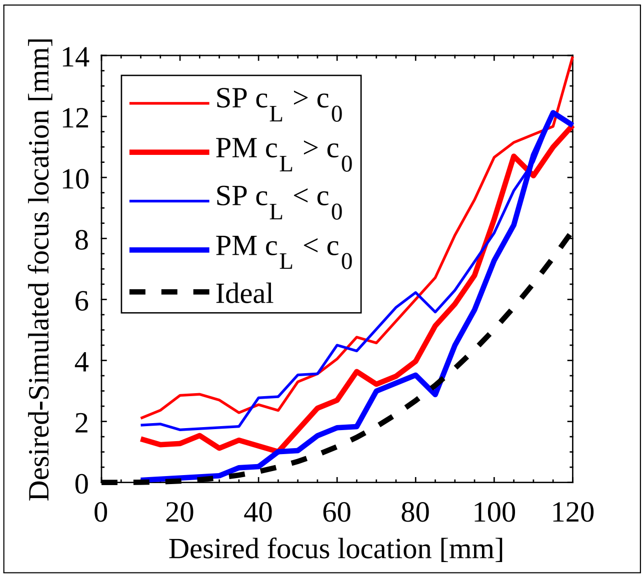

Figure 1. Simulated focus for single plane (SP) and phase matching (PM) lenses for rigid and soft materials.

The performance of the phase-matching approach is compared to traditional methods, comparing its focusing capabilities at multiple distances and its hability to create complex acoustic images at different depths via the estimation of their structural similarity index measure (SSIM) of the obtained acoustic fields for MNIST number images one to five [1]. The fields obtained via propagation through the lens will be compared againts the ideal pattern obtained via the Rayleigh-Sommerfeld integral using a back and forth propagation of the original MNIST images.

3. RESULTS

Simulation results in Fig. 1 in which both methods were compared against an ideal focused transducer. It can be observed that phase-matching hologram lenses outperform traditional methods for both rigid ($c_L > c_0$) and soft ($c_L < c_0$) lenses, producing focal spots closer to the ideal case for all studied focal distances. In particular, soft

[1] The SSIM index is a perceptual metric that quantifies the similarity between two images, ranging from 0 to 1, with 1 indicating perfect similarity [18].

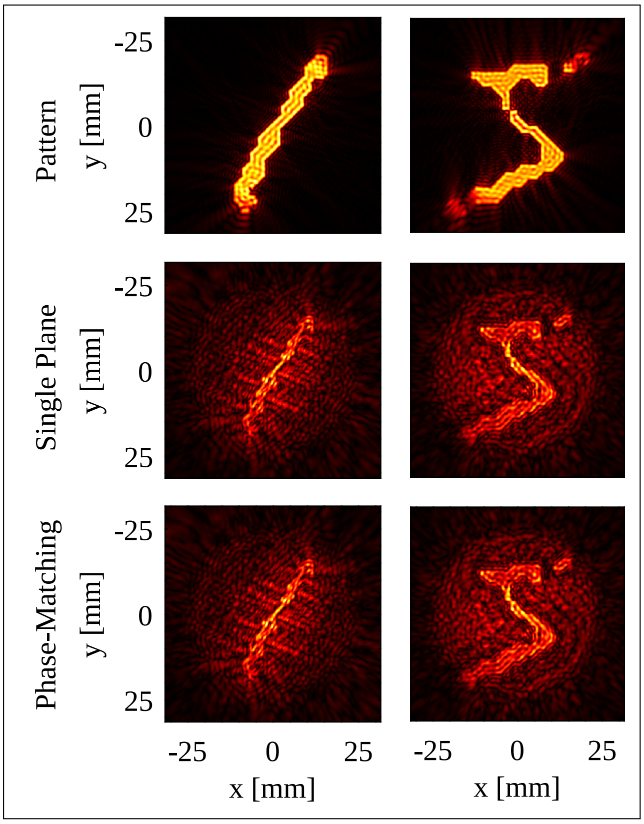

Figure 2. Acoustic patterns for MNIST iamges one and five obtained through Rayleigh-Sommerfeld propagation, traditional and phase-matching methods.

phase matching lenses appear to perform very close to an ideal focused transducer for nearer focus locations.

To study the performance of the phase-matching approach in creating complex acoustic images, we generated holograms to get the acoustic patterns for numbers one to five from the MNIST dataset. Due to the excelent focusing capabilities shown for soft lenses in Fig. 1 we have decided to work with soft lenses for this trial. An extract of theses images are shown in Fig. 2 for a focal distance of 15 mm. Since the prevalence of one method over the other cannot be easily ruled out, we evaluated the performance of these holograms at different focusing distances ranging from 10 to 90 mm in 5-mm steps using the Structural Similarity Index Method (SSIM), as shown in Fig. 3. The shaded error plot shows that both methods are pretty similar for this application, although we believe this may

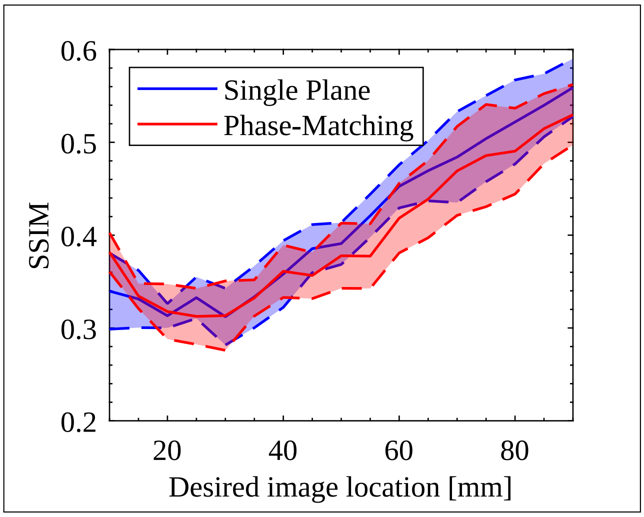

Figure 3. Average Structural Similarity Index Method (SSIM) for MNIST number images one to five obtained through traditional and phase-matching methods.

be to the existance of a critical angle that hinder the performance of the phase-matching approach. Still, for low focusing distances we can observe that the phase matching approach seems to outperform traditional methods.

4. CONCLUSIONS

In this work, we proposed a novel phase-matching approach for designing acoustic holograms that accurately reproduce the desired target field. This method aligns the phase of the field produced at the exit of the lens with the target phase across the entire holographic volume, resulting in superior focusing performance compared to traditional methods. We validated this approach through analytical and simulation techniques, demonstrating its effectiveness in focusing acoustic waves and creating complex acoustic images. Via simulations, we demonstrated that our approach outperfermorms traditional methods in terms of focusing capabilities at multiple distances, specially for soft lenses. The method also shows promise in generating complex acoustic images, with a slight advantage over traditional methods at lower focusing distances.

5. ACKNOWLEDGMENTS

This research has been supported thanks to grants RYC2021-034920-I, PID2022-142719OB-C21, and CNS2023-145707 funded by MCIN/AEI/10.13039/501100011033; Agencia Valenciana de la Innovació grants INNVA2/2022/11, INNVA1/2022/37, INNEST/2022/345, Generalitat Valenciana grant INVEST/2023/553 and Universitat Politècnica de València PAID-01-24.

6. REFERENCES

[1] K. Melde, A. G. Mark, T. Qiu, and P. Fischer, "Holograms for acoustics," *Nature*, vol. 537, pp. 518–522, 9 2016.

[2] D. Gabor, W. E. Kock, and G. W. Stroke, "Holography," *Science*, vol. 173, no. 3991, pp. 11–23, 1971.

[3] Y. Xie, C. Shen, W. Wang, J. Li, D. Suo, B. I. Popa, Y. Jing, and S. A. Cummer, "Acoustic holographic rendering with two-dimensional metamaterial-based passive phased array," *Scientific Reports*, vol. 6, 10 2016.

[4] S. Peng, A. Song, Y. Bai, C. Sun, and Y. Xiang, "Reconfigurable frequency-selective acoustic coding metasurface for multifunctional wavefront manipulation," *Applied Acoustics*, vol. 235, p. 110658, 5 2025.

[5] S. S. Yoo, A. Bystritsky, J. H. Lee, Y. Zhang, K. Fischer, B. K. Min, N. J. McDannold, A. Pascual-Leone, and F. A. Jolesz, "Focused ultrasound modulates region-specific brain activity," *NeuroImage*, vol. 56, pp. 1267–1275, 6 2011.

[6] S. Jiménez-Gambín, N. Jiménez, J. M. Benlloch, and F. Camarena, "Holograms to focus arbitrary ultrasonic fields through the skull," *Physical Review Applied*, vol. 12, 7 2019.

[7] Z. Ma, A. W. Holle, K. Melde, T. Qiu, K. Poeppel, V. M. Kadiri, and P. Fischer, "Acoustic holographic cell patterning in a biocompatible hydrogel," *Advanced Materials*, vol. 32, 1 2020.

[8] K. Melde, H. Kremer, M. Shi, S. Seneca, C. Frey, I. Platzman, C. Degel, D. Schmitt, B. Schölkopf, and P. Fischer, "Compact holographic sound fields enable rapid one-step assembly of matter in 3d," *Science Advances*, vol. 9, 2 2023.

[9] D. Andrés, J. Vappou, N. Jiménez, and F. Camarena, "Thermal holographic patterns for ultrasound hyperthermia," *Applied Physics Letters*, vol. 120, 2 2022.

[10] D. Andrés, I. Rivens, P. Mouratidis, N. Jiménez, F. Camarena, and G. ter Haar, "Holographic focused ultrasound hyperthermia system for uniform simultaneous thermal exposure of multiple tumor spheroids," *Cancers*, vol. 15, 5 2023.

[11] N. McDannold, C. D. Arvanitis, N. Vykhodtseva, and M. S. Livingstone, "Temporary disruption of the blood-brain barrier by use of ultrasound and microbubbles: Safety and efficacy evaluation in rhesus macaques," *Cancer Research*, vol. 72, pp. 3652–3663, 7 2012.

[12] S. Jiménez-Gambín, N. Jiménez, and F. Camarena, "Transcranial focusing of ultrasonic vortices by acoustic holograms," *Physical Review Applied*, vol. 14, 11 2020.

[13] K. Lee, T. Y. Park, W. Lee, and H. Kim, "A review of functional neuromodulation in humans using low-intensity transcranial focused ultrasound," 5 2024.

[14] J. Kim, S. Kasoji, P. G. Durham, and P. A. Dayton, "Acoustic holograms for directing arbitrary cavitation patterns," *Applied Physics Letters*, vol. 118, 2 2021.

[15] N. Lamothe, D. Andrés, A. Carrión, F. Camarena, J. A. Pineda-Pardo, and N. Jiménez, "Monitoring holograms for therapeutic ultrasound using passive cavitation beamforming," *Applied Acoustics*, vol. 224, 9 2024.

[16] D. Andrés, A. Carrión, F. Camarena, and N. Jiménez, "Methods to design and evaluate transcranial ultrasonic lenses using acoustic holography," *Physical Review Applied*, vol. 20, 10 2023.

[17] B. E. Treeby and B. T. Cox, "k-wave: Matlab toolbox for the simulation and reconstruction of photoacoustic wave fields," *Journal of Biomedical Optics*, vol. 15, p. 021314, 2010.

[18] Z. Wang, A. C. Bovik, H. R. Sheikh, and E. P. Simoncelli, "Image quality assessment: From error visibility to structural similarity," *IEEE Transactions on Image Processing*, vol. 13, pp. 600–612, 4 2004.