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Design strategies for amplitude and phase acoustic holograms in biomedical ultrasound

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***Abstract* – Current approaches for acoustic hologram generation are focused on phase-only methods. The few alternatives proposed for amplitude and phase holograms becomes cumbersome or not suitable for biomedical ultrasound applications. In this work, we present several topologies for phase-and-amplitude acoustic holograms based on metamaterial and phononic crystals suitable for biomedical ultrasound. These approaches go beyond traditional phase holograms and produce sharper acoustic images for non-invasive and localized preclinical and clinical therapeutic applications like neuromodulation, drug delivery or surgery, or biomedical ultrasound imaging. Several application examples are provided.**

I. Introduction

Passive acoustic structures like metamaterials can be used to engineer wavefronts in many practical applications. By tuning its topology, the local refraction, scattering or inner resonances can be tailored for a particular functionality. Among them, acoustic holograms can generate highly complex acoustic fields [1] . These high-performance lenses are emerging as a low-cost technology to produce therapeutic acoustic images of arbitrary shape, with applications ranging from 3D printing [2] to biomedical ultrasound [3]. Using a 3D-printed phase-only hologram, single focal spot, multiple focus and arbitrary acoustic images, or even vortex beams [4]. In addition, by exploiting time-reversal symmetry of the wave equation acoustic holograms can encode complex wavefronts compensating the aberrations of stiff layers, enabling the focusing of ultrasound into the human brain [5]. By shaping the acoustic field, holograms have been used for non-invasive drug delivery in the brain through the disruption of the blood-brain barrier[6]. Moreover, holograms can also modulate the thermal pattern induced by heat deposition to tissue under the action of the ultrasound beam [7]. Holograms can generate thermal patterns with arbitrary spatial distribution, thermal patterns matching the shape of a target, e.g., a tumor for hyperthermia applications, and they can be tuned to compensate for heat transport mechanisms and achieving uniform thermal dose over several targets [8].

However, acoustic holograms are usually designed to only encode the phase of the beam, neglecting the amplitude information of the time-reversed wavefront. There exist some strategies to produce magnitude and phase holograms, but most of the design strategies are valid for sound waves in air [9] and, therefore, they are not suitable for biomedical ultrasound applications, which are generally water-coupled. Only some strategies have been proposed to produce phase and magnitude holograms, such as using multiple holographic plates or stackable holograms [10], reflection modes or pixel-modification strategies [11]. None of these strategies has been applied in biomedical ultrasound applications, as they are not well suited for biomedical ultrasound devices.

Moreover, even considering phase-only holograms, current implementations of holographic lenses can only approximate the objective phase distribution. Assumptions like the thin-lens approximation for refracting surfaces, and physical phenomena like absorption or diffraction at phase jumps, in addition to beam diffraction by finite apertures, produce a phase distribution at the exit plane that does not match the target phase distribution [12]. Therefore, the retrieved acoustic images produced by the current implementations of phase-only holograms are sub-optimal.

In this work, we propose metasurfaces with internal resonances to encode the full-wave information in a 3D-printed structured material. In particular, we report the use of metasurfaces to synthesize wavefronts by tuning subwavelength 3D-printed elastic resonators for ultrasonic frequencies, as shown in Fig. 1. These structures are

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shown to be remarkably flexible for spatially-coding arbitrary phase-conjugated fields corresponding to the ones used for selected biomedical ultrasound applications.

II. Results

The basic building blocks are based on an elastic resonator composed of a narrow elastic column connecting two wide columns, as shown in Fig. 1(a-b). In this way, by tuning the geometrical parameters of each building block, a phase and magnitude distribution can be obtained. A parametric study was performed using a theoretical 1D model for each building block, and a 3D elastic Finite Element Method. The results, shown in Fig. 1(c-g) show that by varying the width of the central narrow column and its length, the longitudinal resonance can be activated and its phase controlled. At the resonance, wave are reflected and transmission drops, and by tuning the parameters the phase can also be tuned. It is worth noting here that when considering the full elastodynamics, bending and torsional modes can appear. Therefore, special care must be taken when selecting in set of geometric parameters to avoid structural motions that are not longitudinal.

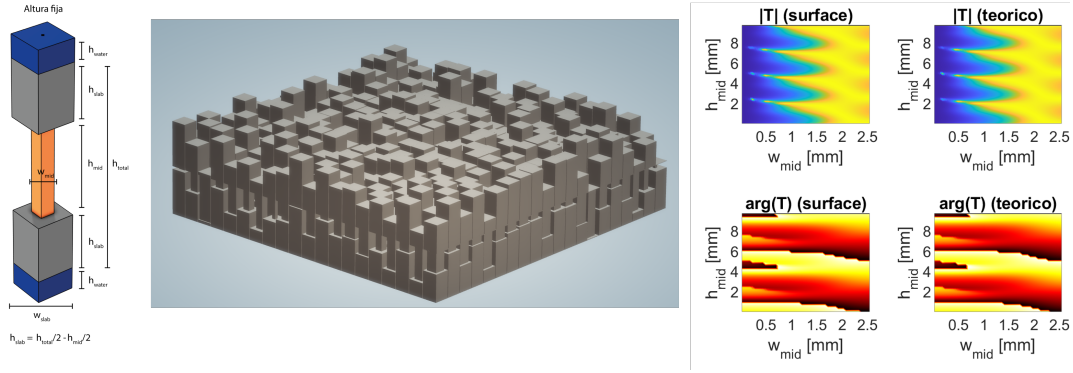


Fig. 1: Topology of an acoustic hologram using a metamaterial as a building block. Phase and magnitude can be controlled locally to generate accurate acoustic images.

Using these building blocks allows us to synthesize holograms that outperform only-phase designs. Figure 2 shows the target image and the images obtained by using the angular spectrum method [12] for an only-phase hologram and magnitude-and-phase hologram using the metasurface topology, considering a typical setup for biomedical ultrasound (aperture of 50 mm, frequency of 1 MHz, propagation in water with sound speed of 1500 m/s and density of 1000 kg/m^3, wavelength of 1.5 mm, and number of pixels 128^2.

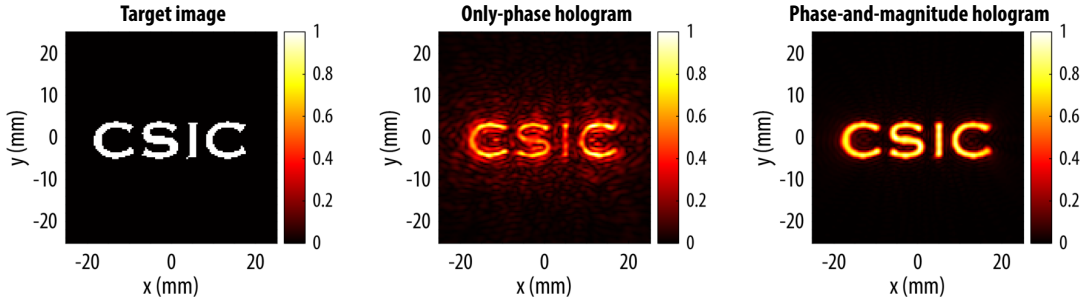


Fig. 2: Target image, and images obtained using the angular spectrum method for the only-phase topology and magnitude-and-phase topology using the metasurface approach.

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III. Conclusions

By mimicking phase-and-amplitude information, holographic metasurfaces can synthesize complex and arbitrary acoustic images with great accuracy. In this way, by tuning the hologram inner structure, we can synthesize high-intensity acoustic images with sharp resolution, which can be applied to focus therapeutic ultrasound beams and treat several diseases in a non-invasive, non-ionizing, localized and low-cost manner. This approach improves the targeting of ultrasound and paves the road for low-cost biomedical ultrasound applications.

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