Diffusive Acoustic Metasurfaces for Single-element Photoacoustic Imaging

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Abstract: We present a novel strategy to generate high-resolution photoacoustic images based on spatiotemporal encoding by combining a single-element detector and a reflecting cavity with attached acoustic metasurfaces designed to maximize sound diffusion in reflection. Numerical results demonstrate the potential of this concept to develop low-cost photoacoustic imaging systems.

Photoacoustic tomography is an emergent medical imaging modality that utilizes laser-generated ultrasonic waves to create images driven by optical absorption of tissues thanks to the photoacoustic effect [1]. It combines the high spatial resolution of ultrasound images with the high-contrast and spectroscopic character of optical imaging. Image reconstruction in photoacoustics is typically based on the time-of-flight reading of acoustic waves registered at multiple positions, normally via multi-element ultrasonic arrays distributed along a certain surface. Hence, spatial resolution is strongly dependent on the geometry and aperture of the acoustic detector. Generally, optimal resolution is achieved if all emitted photoacoustic waves are captured, i.e., if the sample is surrounded by the measurement surface. Typical ultrasound probe configurations (linear, planar, arc-shaped, etc.) do not fulfill such condition, affecting the resolution, as multiple angular components are lost. This is known as the "limited view problem" and implies that high resolution systems are generally associated to large multi-element detectors which require dedicated electronics per channel, resulting in high cost and complexity.

An alternative to spatial encoding consists in carrying out the reconstruction process by temporal encoding of the received data in a single waveform. Here, the lack of spatially variant data is compensated by enlarging the received angular spectrum through the generation of replicas of the original signal via scattering [2], randomized reflecting elements [3] or reflecting surfaces enclosing the imaging sample [4, 5]. Temporal encoding solves the limited view problem and suggests that the number of detectors could be drastically reduced, replacing multi-element arrays with smaller single-element detectors, paving the way for the realization of low-cost advanced imaging systems.

In this work, we propose a novel strategy to generate photoacoustic images based on temporal encoding. Our approach utilizes a single-element detector and an acoustically reflecting cavity enclosing the imaging sample. To obtain an efficient reconstruction with high spatial resolution, acoustic metasurfaces are designed to maximize sound diffusion and attached to the cavity walls.

Numerical simulations have been carried out using a pseudo-spectral time-domain method using the k-wave toolbox [6]. We consider three closed cavities (rectangular, chaotic and rectangular with metasurfaces), a single-element detector and a set of circular targets with an initial pressure distribution to solve the forward acoustic wave propagation problem. Image reconstruction is performed using time-reversal, i.e., the registered waveform at the detector is time-reversed and back-projected into the domain, where the reconstructed image corresponds to the pressure values at the last temporal sample. The designed acoustic metasurfaces are composed of a set of quarter-wavelength resonators whose depth is set to maximize sound diffusion in reflection. In this

way, we have chosen a quadratic residue sequence to define the depths, as it provides a flat response in the angular spectrum.

The lateral resolutions for increasing simulation times have been calculated for the three tested cavities, being averaged over the nine sources, as shown in Figure 1. The rectangular cavity incorporating diffusive acoustic metasurfaces outperforms both the rectangular and chaotic cavities in terms of lateral resolution values, but also showing a reduced standard deviation, indicating a high uniformity in the representation of the acoustic sources along the space, as shown in Figs. 1(c-e). Numerical results demonstrate a remarkable enhancement in the spatial resolution with respect to existing closed-cavity configurations based in rectangular and chaotic cavities, indicating the potential of diffusive acoustic metasurfaces to achieve a high-quality reconstruction using a simple and affordable photoacoustic imaging system.

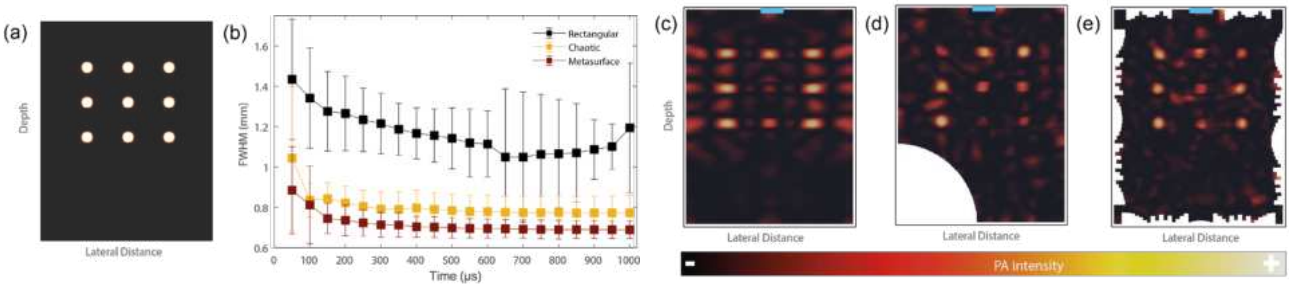


Figure 1. Photoacoustic image reconstruction scenarios: (a) Initial pressure distribution. (b) Lateral resolution for increasing simulation times. Reconstructed images for (c) rectangular, (d) chaotic and (e) rectangular cavity with metasurfaces.

Acknowledgments

We acknowledge financial support from Ministerio Español de Ciencia e Innovación grants "Ramón y Cajal" RYC2021-034920-I, Agencia Estatal de Investigación PID2022-142719OB-C21 and CNS2023-145707, to the Agencia Valenciana de la Innovació grants INNVA2/2022/11 and INNEST/2022/345, and by Generalitat Valenciana grant, CIAICO/2023/052, and IDIFEDER/2021/004.

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