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Design and Experimental Validation of a Resonant-Cavity Acoustic Metasurface for 23 kHz Ultrasonic Focusing

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Abstract: *Acoustic metasurfaces are a class of artificial structures capable of precisely modulating sound wave propagation at subwavelength scales, offering significant potential in sound field manipulation and wavefront reconstruction. To address the limitations of traditional ultrasonic focusing methods, such as structural complexity, bulkiness, and insufficient modulation flexibility, this paper proposes an ultrasonic focusing modulation method based on a resonant-cavity acoustic metasurface. By constructing a subwavelength resonant unit model combined with finite element numerical simulations, the relationship between unit structural parameters and the amplitude-phase response of transmitted sound waves is systematically analyzed, achieving continuous phase modulation within the 0–2π range. On this basis, a discrete phase unit library is established, and a planar metasurface structure consisting of 18 units is designed to realize wavefront reconstruction and spatial focusing of 23 kHz incident ultrasound. Furthermore, the sound field distribution and focusing characteristics are analyzed through numerical simulations. The results indicate that the designed metasurface can produce significant sound pressure enhancement in the target area. Experimentally, an ultrasonic testing platform was constructed to scan and measure the sound field distribution. The experimental results show good agreement with the simulation results regarding focal position and sound pressure distribution characteristics. This study demonstrates that the proposed method enables efficient modulation of ultrasonic waves and holds practical value for acoustic computational modeling and the design of miniaturized acoustic devices. Compared with existing studies, the proposed structure achieves efficient focusing of low-frequency airborne sound waves while maintaining a compact size and structural simplicity, and its feasibility is further validated through experiments.*

Keywords: *Acoustic metasurface, Ultrasonic focusing; Phase modulation, Acoustic field measurement, Experimental Validation*

1. Introduction

Ultrasonic focusing is a critical research direction in acoustics, with extensive applications in medical imaging, non-destructive testing (NDT), and particle manipulation. However, traditional ultrasonic focusing devices typically rely on bulky transducers or acoustic lenses, which face challenges such as structural complexity, large footprints, and limited modulation flexibility. Therefore, developing compact and efficient methods for ultrasonic focusing is of great significance. Acoustic metasurfaces[1-2] are artificial structures that manipulate sound wave propagation through subwavelength unit cell arrays, enabling the precise design of acoustic phase, amplitude, and impedance. Compared to traditional bulk structures, metasurfaces achieve equivalent wavefront modulation capabilities with millimeter or even submillimeter thicknesses. This makes them highly advantageous in fields such as telecommunications, medical ultrasound, NDT, acoustic holographic imaging[3], and the design of acoustic cloaking structures.

Through the customized design of unit cell phases, acoustic metasurfaces enable the precise manipulation of ultrasonic waves within subwavelength scales, providing a novel technical approach for constructing compact difference-frequency sound field systems. Previous studies have demonstrated that acoustic metasurfaces based on coiling-up-space structures[4-5], labyrinthine cavities[6] and generalized acoustic impedance[7]can achieve complex wavefront modulation while maintaining high transmission

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efficiency. Furthermore, by flexibly arranging subwavelength units, acoustic metasurfaces can implement various modulation functionalities, such as beam steering[8], asymmetric transmission[9], and high-resolution acoustic imaging[10].

By introducing spatial phase gradients, acoustic metasurfaces can realize arbitrary reconstruction of the sound wavefront, offering a transformative pathway for ultrasonic focusing. In particular, resonant-cavity-based metasurfaces can achieve continuous phase modulation by simply adjusting geometric parameters, offering the benefits of structural simplicity and ease of implementation. Building upon these principles, this paper proposes a resonant-cavity acoustic metasurface structure designed for 23 kHz ultrasonic focusing. By constructing subwavelength units with continuous phase modulation capabilities, the incident wavefront is precisely reconstructed. A metasurface consisting of 18 units is then designed to achieve sound wave focusing in the target region. Combined with finite element simulations and experimental characterization, the sound field modulation performance is systematically analyzed, verifying the feasibility and effectiveness of this method for compact ultrasonic modulation devices. Compared with existing studies, the structure proposed in this paper achieves efficient focusing of low-frequency airborne sound waves while maintaining a compact size and structural simplicity, with its feasibility further verified through experimental validation.

2. Acoustic Metasurface Design

2.1. Unit Cell Design

The unit cell structure of the acoustic metasurface designed in this study is illustrated in Figure 1. The unit cell consists of a main air channel and a localized resonant cavity, with its phase modulation mechanism based on the adjustment of local acoustic impedance. By varying the key structural parameter h_1/h, the transmission phase of the unit cell can be tuned to achieve a full $0\text{-}2\pi$ phase modulation range. The geometric parameters of the unit cell are set as follows: w=6.85 mm，h=2.7 mm， w_1=0.3 mm， w_2=1.4 mm, and a wall thickness of 0.25 mm. This specific configuration exhibits high transmission efficiency and stable phase response characteristics at an operating frequency of 23 kHz.

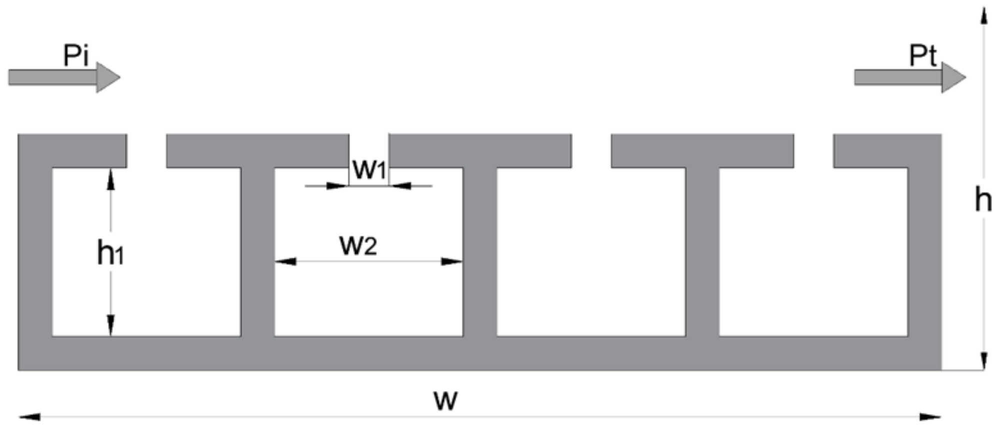

Figure 1: Schematic diagram of the metasurface unit cell.

2.2. Amplitude and Phase Response Analysis

In this study, the transmission characteristics of the unit cell were numerically analyzed using the Pressure Acoustics module in COMSOL Multiphysics 6.2. Figure 2(a) and Figure 2(b) present the simulation results of the transmission coefficient and phase response, respectively, obtained by adjusting the structural parameter ratio h_1/h. As shown in Figure 2(a), the unit cell maintains a consistently high transmission amplitude at 23 kHz within the specified parameter range, providing a robust amplitude foundation for subsequent beam manipulation. As illustrated in Figure 2(b), the continuous adjustment of h_1/h enables a full $0\text{-}2\pi$ continuous phase modulation at 23 kHz. This capability establishes the necessary conditions for achieving wavefront reconstruction and ultrasonic focusing at the target frequency.

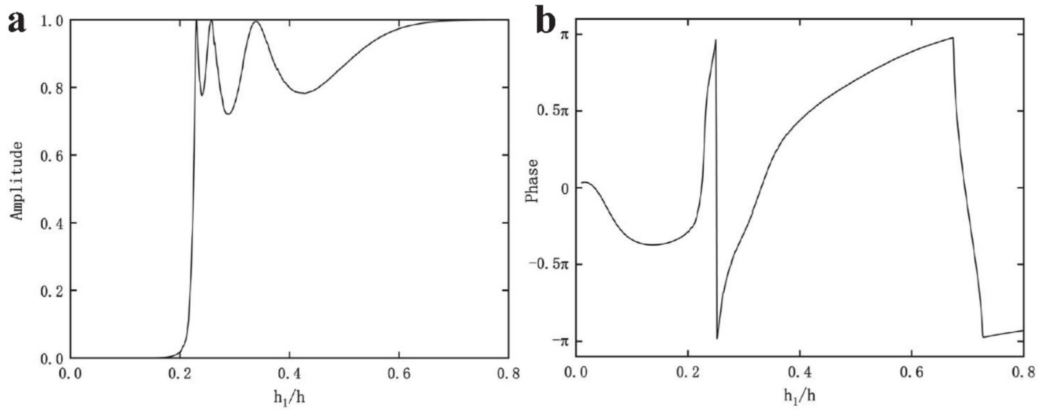

Figure 2: Simulation results of (a) transmission amplitude and (b) transmission phase of the metasurface unit cell.

2.3. Acoustic Focusing Phase Design

To achieve effective ultrasonic focusing, a specific spatial phase delay distribution must be introduced across the metasurface. In this study, the phase of each unit cell was designed based on the principle of wavefront focusing control. According to the target focal length, the required theoretical phase values at various positions along the metasurface were calculated using the focusing phase distribution formula and subsequently mapped to specific structural units.

The metasurface designed in this study consists of 18 subwavelength resonant units arranged uniformly along the transverse direction. Based on the Matlab simulation results, the theoretical continuous phase was designed and assigned to the structural units at their corresponding positions. The phase design is illustrated in Figure 3. The results indicate that the phase of the units exhibits a centrally symmetric distribution, with the overall phase gradually varying from the edges toward the center to form an approximately parabolic phase profile, thereby satisfying the requirements for wavefront convergence.

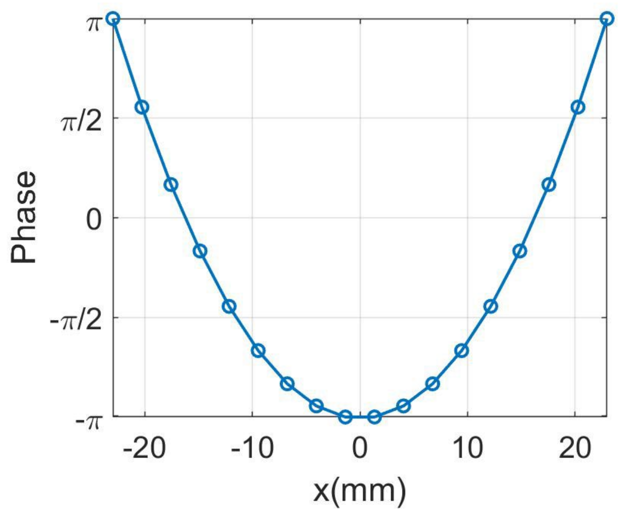

Figure 3: Phase design of the acoustic metasurface.

3. Acoustic Focusing Simulation Analysis and Experimental Validation

3.1. Simulation Results

A 2D simulation model was established in COMSOL Multiphysics 6.2, with an air domain size of 49 mm x 50mm. The incidence condition was set as a plane wave, while the metasurface and obstacles were modeled using acoustically rigid boundaries. A Perfectly Matched Layer (PML) was implemented to minimize boundary reflection interference. The mesh was refined to ensure at least 10 elements per

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wavelength, and frequency-domain solvers were employed at a frequency of 23 kHz. Figures 4(a) and (b) display the 2D acoustic pressure fields of the ultrasonic beam under metasurface modulation. Figure 4(a) corresponds to a uniform phase distribution with no focusing effect, whereas Figure 4(b) illustrates the focusing phase distribution. The simulation results demonstrate that after phase modulation, the sound waves form a distinct focus in the target region, characterized by a clear main lobe structure and concentrated energy.

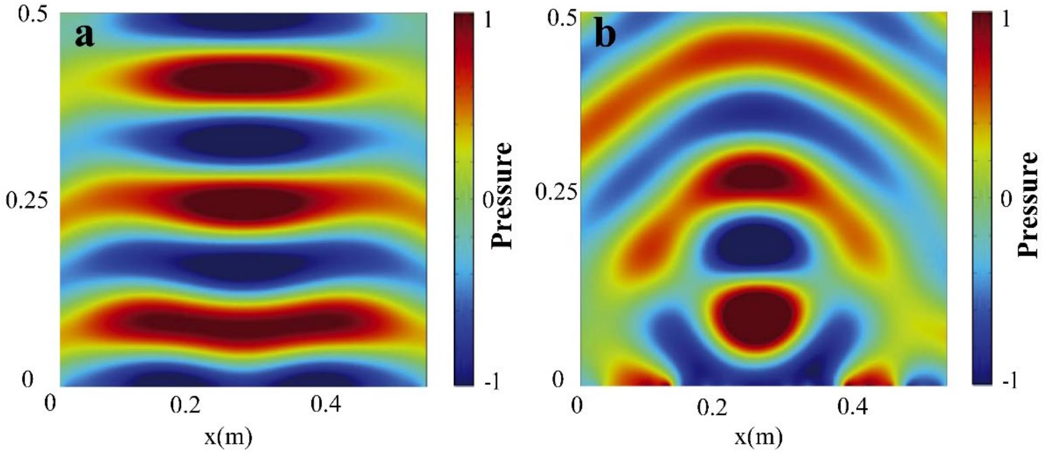

Figure 4: Acoustic pressure field distributions: (a) without focusing modulation and (b) with focusing phase distribution.

3.2. Experimental Validation

To verify the practical focusing performance of the designed resonant-cavity acoustic metasurface, an ultrasonic experimental platform was constructed to evaluate its sound field modulation capability. The experimental system primarily consists of an ultrasonic transducer, a signal generation and amplification module, a 3D motorized scanning system, and a data acquisition module. An ultrasonic transducer with a center frequency of 23 kHz was employed as the acoustic source. A sinusoidal excitation signal generated by a signal generator was used to drive the transducer to emit quasi-plane waves. To minimize the influence of boundary reflections on the experimental results, acoustic-absorbing materials were utilized throughout the testing process to suppress sound reflections.

The fabricated acoustic metasurface sample was positioned vertically at a specific distance in front of the acoustic source, ensuring the incident waves were at normal incidence to the metasurface structure. To obtain the spatial sound field distribution, a high-precision 3D motorized scanning system was used to perform point-by-point scanning in the region behind the metasurface. The scanning area covered the 2D plane near the focal point, with a step size set to 0.1 mm to ensure sufficient spatial resolution of the sound field distribution.

The experimentally measured sound field distributions are shown in Figure 5. From Figures 5(a–f), it can be observed that at different time cross-sections, the sound waves gradually undergo wavefront reconstruction during propagation. The acoustic energy continuously converges toward the pre-designed focal region, and the high-pressure zone progressively strengthens and stabilizes, clearly reflecting the dynamic focusing process of the ultrasonic waves. Under steady-state conditions, a significant acoustic pressure concentration area is formed at the focal position, with an amplitude markedly higher than that of the surrounding regions, demonstrating excellent spatial focusing characteristics.

Furthermore, a comparative analysis between the experimental results and numerical simulations reveals good agreement in terms of focal position, sound pressure enhancement trends, and main-lobe width, with only slight deviations in localized areas. These discrepancies primarily stem from the combined effects of fabrication tolerances and ambient noise. Overall, the experimental results corroborate the numerical predictions, fully validating the effectiveness and reliability of the designed resonant-cavity acoustic metasurface. The results demonstrate that the structure can achieve efficient focusing modulation of 23 kHz ultrasonic waves, showing strong feasibility and application potential in practical engineering scenarios.

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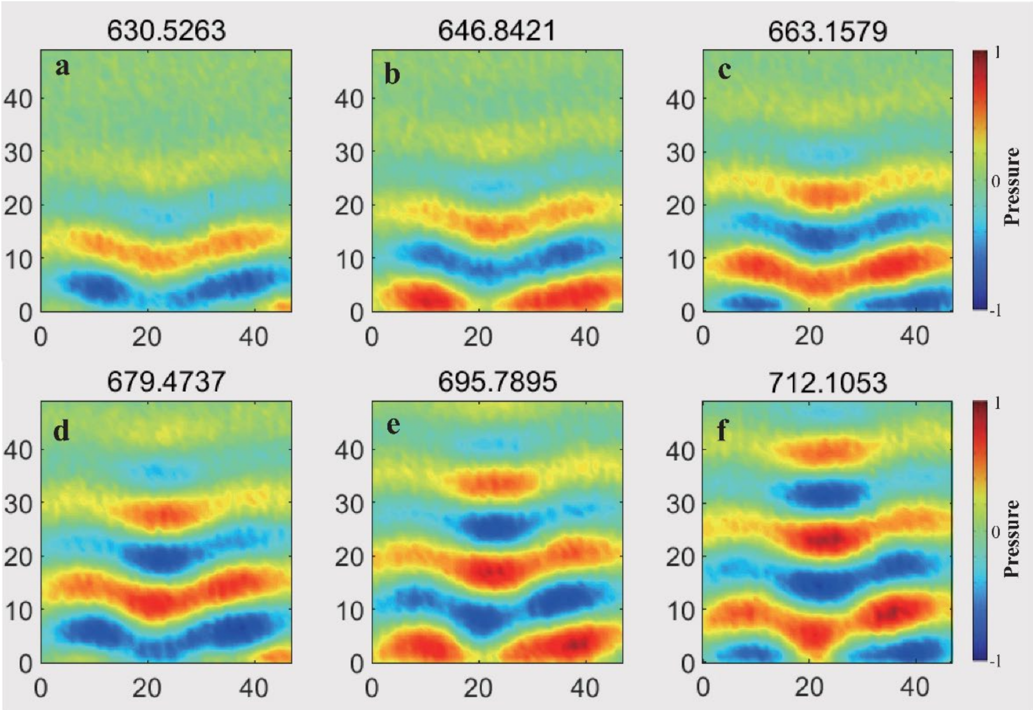

Figure 5: shows the experimentally scanned sound pressure distributions at time instants of 630.5263 μs, 646.8421 μs, 663.1579 μs, 679.4737 μs, 695.7895 μs, and 712.1053 μs, respectively.

4. Conclusion

Focusing on the precise modulation of ultrasonic waves, this paper proposes and implements an ultrasonic focusing method based on a resonant-cavity acoustic metasurface. By constructing subwavelength resonant units and optimizing their geometric parameters, continuous modulation of the transmitted acoustic phase is achieved. On this basis, a planar acoustic metasurface is constructed according to the target focusing phase distribution, realizing effective wavefront reconstruction of the incident ultrasound.

Through finite element numerical simulations, the phase response characteristics of the resonant cavity units and their influence on the overall focusing performance are systematically analyzed. The results indicate that the designed units can achieve full phase coverage while maintaining high transmission efficiency at the target frequency. Sound field simulations of the constructed metasurface verify its capability to form high-intensity acoustic pressure focusing at the pre-designed focal length. Experimentally, an ultrasonic testing platform was established, and sound field scanning tests were performed on the fabricated metasurface sample. The experimental results are not only consistent with the simulations in terms of spatial distribution, but also further reveal the process of gradual wavefront reconstruction and the dynamic convergence of acoustic energy toward the focal region through acoustic pressure scans at different time intervals. This intuitively reflects the time-domain evolutionary characteristics of focus formation. Significant acoustic pressure enhancement and stable spatial focusing were observed in the target region, verifying the feasibility and effectiveness of the proposed method. Meanwhile, the sources of error between experiments and simulations are analyzed, providing a reference for subsequent optimization designs.

The resonant-cavity acoustic metasurface proposed in this paper offers the advantages of structural simplicity, ease of implementation, and high modulation precision, providing a compact and efficient solution for ultrasonic focusing. This method holds promising application prospects in fields such as medical ultrasonic imaging, non-destructive testing (NDT), acoustic manipulation, and micro-scale particle manipulation. Future work will further explore broadband modulation, dynamically reconfigurable metasurfaces, and fine control of 3D acoustic fields to enhance its engineering applicability.

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