**Continuous Manipulation of Acoustic Wavefront Using a Programmable Acoustic Metasurface**

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Abstract

Conventional passive acoustic metasurfaces (AMSs) can hardly reconfigure their topologies or structural parameters, which limits their wide applications. In this paper, a programmable AMS which contains an array of reconfigurable subwavelength unit cells, regulated by a set of stepper motors with lead screws and a cost-effective control system is presented. The unit of the AMS is composed of a parallel one-dimensional daisy-chained slit with five Helmholtz resonators. The phase shift of the transmission wave through the AMS units can be precisely controlled over the full phase range and continuously tuned by varying the slit width at high transmission efficiency. Benefitting from such a mechanism, the designed AMS is able to achieve continuous versatile wave manipulation functions in simulation and in experiment by engineering the phase and amplitude of transmission waves, including tuneable acoustic refraction, tuneable acoustic focusing and tuneable acoustic self-bending. Thus, this proposed AMS holds a great potential for a wide range of applications including diagnostic sonography, active non-destructive evaluation, acoustic holography, noncontact micro-particles manipulation and energy harvesting.

Keywords: acoustic metasurface, programmable control, tuneable manipulation

1. Introduction

The past decade has witnessed a dramatic growth of research interest in acoustic metasurfaces (AMSs) which are regarded as a two-dimensional (2D) equivalent of acoustic metamaterials [1–5]. More recently, the AMSs with subwavelength thicknesses have enabled many extraordinary manipulations of acoustic waves such as anomalous refraction [6, 7], acoustic cloaking [8, 9], acoustic coding [10, 11], asymmetric acoustic transmission [12, 13] and energy harvesting [14, 15]. Previous developments of AMSs mainly focused on the design and manufacturing of innovative structures including space-coiling AMSs [16, 17], membrane-type AMSs [18–20], Helmholtz resonator (HR)-based AMSs [21, 22]. However, there was a lack of attention to their practical applications. In fact, most AMSs only consist of passive structures, which limit their working frequency ranges and functional diversity for a long period of time [23]. Therefore, being able to conduct tuneable or programmable control of acoustic waves is beneficial for further and distinctive applications of AMSs.

To overcome the limitations of the conventional passive AMSs, considerable researches have been conducted to achieve tuneable acoustic steering by introducing changes of the acoustic phases and frequency ranges [23]. Asymmetric transmission has been achieved by rotating the HR-based AMS to adjust the angle of incidence wave [24] or adjusting the gap of the bilayer HR-based AMS [25]. In addition to these bodily movements of the AMSs, there has been a growing interest in exploring new tuneable AMSs by tuning their inherent geometric parameters of the AMS units in recent years. Space coiling-up structures have shown extraordinary ability in tuneable acoustic reflection [26, 27] and tuneable acoustic transmission [28, 29]. However, a relatively high transmission efficiency may only be achieved around the resonance frequencies [28, 29], which will affect the transmission efficiency when continuously changing the structural parameters. Although a helicoid metasurface unit with gradient pitch was designed to modulate acoustic wavefront with near perfect transmission, this structure may lack tuneability due to the gradient pitch [30]. HR-based AMSs have been proven to possess the capabilities of full phase controlling (2π range) by adjusting the structural parameters [22]. On the other hand, HR-based AMSs can also achieve relatively high transmission efficiency due to Fabry-Pérot resonance in the duct coupled with the resonance of HRs [21]. Benefitting from these advantages, tuneable acoustic transmission has been achieved by tuning structural parameters which are perpendicular to the transmission direction in 2D space, including the slit width [31] and the ratio of the slit width to the HR width [32]. More practically, the volumes of the HRs of a programmable AMS can be tuned by pumping in (or out) water to the cavities of the HRs [33]. However, to quickly and conveniently realise phase shifting is very useful for continuous wave control including active non-destructive evaluation and noncontact micro-particle manipulation.

This study presents a programmable HR-based AMS which can realise various continuous acoustic wave manipulations. Theoretical analyses and numerical simulations show that the phase shift of the AMS units can be precisely controlled over the full phase range and continuously tuneable by varying the slit width. The AMS uses impedance matching in full phase range, which ensures the relatively high transmission efficiency. Several typical acoustic focusing situations with different focusing parameters are implemented by this type of AMSs with a certain distribution of slit width according to the generalized Snell’s law. The finite element method (FEM) model with thermoviscous consideration is employed to simulate these wave manipulations. Subsequently, the simulation results are compared with the experimental results. The designed AMS is shown in numerical simulations and experimental validations to have excellent performance in active wave engineering.

2. Results and discussions

2.1 Design principle and structure

Figure 1(a) shows a schematic diagram of how the designed programmable AMS manipulates the transmitted acoustic field. The light red part is formed by a number of AMS units. Each unit consists of five HRs and can independently, dynamically and continuously move along the z-axis. The light blue part is a fixed support structure. Each AMS unit is linked with a lead screw driven by a four-phase stepper motor. All stepper motors are programmably controlled by a cost-effective control system, as shown in Figure 1(b). The control system is formed by several microcontroller boards, a



**Figure 1** (a) Schematic diagram of the designed programmable AMS. (b) The schematic diagram of the control system (indicated by the dashed box) and its connection with the upper level system and the motors (*N*=20).(c) The schematic diagram of the sectional view of the designed AMS unit with fundamental parameters of the elementary units. (d) The normalized phase shift *ϕ* and transmission efficiency |*p*t/*p*i| of thermoviscous simulation results of the AMS unit as a function of the slit width *d*.

controller area network (CAN) and several motor drives (A4988). The master controller (Arduino UNO R3) receives the control signal from the upper level system (e.g. a personal computer, PC) and then sends the signal to the CAN send module (MCP-2515). CAN send module distributes the signal by sending high and low voltage signal to each CAN receive module (MCP-2515) which connects with a slave controller (Arduino Nano). When a slave controller receives the signal, it goes through a pre-stored program to output the control signal required by each motor drive. Consequently, the stepper motor can receive the signal to manipulate the slider of the lead screw. In this design, each AMS unit can modulate the phase shift by continuously adjusting the slit width and then shape the phase of the wavefront of the transmission waves travelling in the xy-plane.

Figure 1(c) shows a schematic diagram of the sectional view of the designed AMS unit, which is composed of a parallel one-dimensional daisy-chained slit with five HRs. The geometric parameters are *a* = 7.5 mm, *b* = 7.5 mm, *w* = 4.4 mm and *h* = 1 mm, which denote the cavity and the width and height of the neck of the HRs, respectively. The width *W* of an HR of the AMS is 8.5 mm and the total thickness of the AMS *T* is 43.5 mm. The length of the AMS unit in x-direction is 20 mm and there is a 1mm partition between the two adjacent units. Besides, the height between the upper and lower plates of the inlet (and outlet) *H* is 9.5 mm. The resonant angular frequency *ω*0 of the HR can be given by , where  and  are the acoustic compliance of the cavity and the acoustic mass of the neck, respectively. In consideration of the correction due to the neck height of the HR associated with end effects, *h*eff is the effective height of the neck, which can be expressed as [34]. The above equations yield the resonant angular frequency *ω*0 = 44064 rad/s and the resonant frequencyof the HR.

The principle of modulating the phase shift of acoustic wave with angular frequency *ω* is based on tuning the effective bulk modulus *E*eff, which can be expressed as [35]:

, (1)

where  is the bulk modulus of the medium (i.e. air) and *F*=*S*cavity/*S*slit=*ab*/*Wd* is an adjustable geometrical factor. *Γ* = 2π×1400 Hz is the dissipation loss in the HR units, which is determined empirically by making the inflection point (at *d* ≈ 2.75 mm) of the phase shift curve calculated from eq. (2) coincide with that of the numerically simulated curve (the phase shift curves are discussed in the following content). When the frequency of the incident acoustic wave (i.e. working frequency) *f* < *c*0/*T* (i.e. *f* < 7885 Hz), the wavelength of the acoustic wave *λ* > *T*, which means that the thickness of the AMS is in the range of subwavelength. Under this condition, the AMS could be regarded as a homogeneous medium with an effective velocity  of the acoustic wave throughout the AMS. Therefore, the phase shift of the incident acoustic wave throughout the AMS could be expressed as . Hence, *ϕ* could be expressed as a function of *f* and *d* below:

, (2)

which shows the relationship between the phase shift *ϕ* and the slit width *d* as well as the working frequency *f*. Owing to the fact that the transmission efficiency will be considerably low due to the thermoviscous effect of long and narrow pipes when the working frequency is relatively low, we choose 5000 Hz as the working frequency for a suitable range of the slit width to cover the 2π span of the phase shift. Figure 1(d) shows the spectrum of the normalized phase shift (red dashed curve for analytical results and red circles for simulative results) of the designed AMS unit with variable *d* and *f* based on eq. (2). It can be inferred that the slit width *d* plays the dominant role in determining the value of phase shift *ϕ* when the working frequency *f* is fixed. The slit width from 1.504 to 9.052 mm (corresponding to deep subwavelength of 0.022 ≤ *d*/*λ* ≤ 0.132) is selected to realise the phase shift of the AMS units over the 2π range. The analytical and simulation results of phase shift show good agreement within this range of slit width.

Transmission efficiency is a key aspect in the design of an AMS for acoustic transmission including acoustic refraction, acoustic focusing and acoustic self-bending. The value of the slit width *d* directly influences the interface between the AMS units and the air. It is crucial to keep the impedance matched, which affects the transmission efficiency of the AMS. For this reason, the transmission efficiency of the AMS unit is checked in the numerical simulation with a thermoviscous models and is shown as the blue solid curve in figure 1(d), which illustrates the relative high transmission efficiency with *d* varying from 1.504 to 9.052 mm.

The numerical simulation throughout this paper is carried out by the FEM in commercial software COMSOL Multiphysics. The material of the medium of the simulation models is air at 20 degrees Centigrade (*ρ*0=1.21 kg/m3, *c*0=343 m/s). In order to totally absorb the outgoing waves, the periphery of the transmitted field is surrounded by perfect matched layers (PMLs). Considering that the air thermoviscous effect may cause energy loss and transmission efficiency drop, we adopt a thermoviscous model and add a boundary layer mesh in the numerical simulation. Moreover, the thickness of the viscosity boundary layer is discussed in Supplementary material S1.

2.2 Tuneable acoustic refraction

To realise control of the acoustic characteristics and switch between different acoustic functions, tuneability is a key property required for applications such as B-scan in diagnostic sonography [36] and active non-destructive evaluation [37]. Sweeping the inspection angle can not only increase the detectability of the target such as cracks which can occur over a range of angles, but also increase coverage from a particular location [38]. For a long time, such angular sweeps can be carried out only with complex directly coupled arrays which require a high-end and expensive post-processing system to independently control the phase delay of each transducer in the phased array. Although considerable researches have been conducted to achieve tuneable acoustic steering by programmable AMSs, there remains a limitation in rapidly and continuously shaping the wavefront.

Here, we demonstrate the tuneable acoustic refraction for angular sweeps using the designed programmable AMS. Firstly, by assuming the total duration time of the modulation *t*0 is much larger than the period of acoustic wave *T*0 (), the process of continuous adjusting of the AMS unit is quasi-static and adiabatic. Thus, time-harmonic dependence exp(j*ωt*) of the acoustic waves does not need to be considered in this work. By means of the discontinuous local phase shift along the *x*-axis in the suitable range of deep subwavelength, it is easy to shape the wavefront for forming a desired transmitted field using the designed AMS. According to the generalized Snell’s law, the transmission wave through the AMS with incident angle distribution *θ*i(*x,t*) and refraction angle (i.e. transmitted angle) distribution *θ*t(*x,t*) could be expressed approximately as [39, 40]:

, (3)

where  and *ϕ*(*x*,*t*) are the wave factor of air and the phase shift distribution (PSD) over time along the *x*-axis, respectively. As shown in figure 2(a), the acoustic plane wave propagates in the direction perpendicular to the surface (along *y*-axis) of the AMS and refracts with an initial refraction angle *θ*1 = −π/6. Then The designed refraction angle is steered to *θ*2 = π/3 with a uniform angular velocity *ω*r= (*θ*2−*θ*1) / *t*0. It is obvious that neither the incident angle nor refraction angle is affected by the position of AMS units along the *x*-axis, which can be expressed as:

, (4a)

. (4b)

By substituting eqs. (4a, 4b) into eq. (3) and then integrating the resulting equation along the *x*-axis, we can obtain the phase shift *ϕ*(*x,t*) as:

, (5)

where *ϕ*0 is the integration constant of the indefinite integral. The total length of the AMS along the *x*-axis is 0.421 m (6.14*λ*) with 20 corresponding units to form the whole AMS, which will be the same in following cases. The corresponding tuned slit widths for the tuneable acoustic refraction at 0 s and *t*0 are shown in Supplementary material S2.

To investigate the dynamic status of the designed AMS units, figure 2(b) shows the change of the slit widths of the 20 AMS units over time. Firstly, we number the AMS units from left (−*x* direction) to right (+*x* direction) from 1 to 20. The two curves whose numbered sum is 21 show the symmetry at *t* = *t*0/3, where the refraction angle becomes 0. Each slit width of



**Figure 2.** (a) Schematic diagram of the tuneable acoustic refraction realised by the designed AMS. (b) The change of the slit widths of the 20 AMS units over time. The PSDs over 2π range for the ideal AMS (blue line) and the units of the designed AMS (red circle) for the (c) initial and (d) final states, respectively. The normalized pressure field of the tuneable acoustic refraction realised by the designed AMS for the (e) initial and (f) final states, respectively.

the 20 AMS units has gone through the entire range of 1.5 to 9.0 mm since the full phase shift (2π span) is needed. It is worth noting that the slit width suddenly varies from 1.5 to 9.0 mm (or from 9.0 to 1.5 mm) for several times. This indicates the importance that the methods for moving the AMS units should be as fast as possible to decrease the system error. Moreover, it can be observed that all the curves change monotonously between two adjacent sudden changes.

Figure 2(c, d) illustrates the PSD over 2π range for the ideal AMS (blue line) and the units of the designed AMS (red circle) with *ϕ*0 equals to 0. The distributions of the AMS are designed using a numerical method with eq. (2) and eq. (5), which makes the midpoints of each AMS unit along *x*-axis meet the ideal phase shift desired. Based on the generalized Snell’s law [39], the incident waves can be refracted by introducing a linear phase gradient to the AMS. The normalized acoustic pressure fields (normalized with respect to *p*i) of the designed AMSs as shown in figure 2(e, f) demonstrate the tuneable phase shift ability to shift the designed refraction angles (see video of the dynamic manipulation in Supplementary material). The refraction angles of each transmission wave are coincident with the designed refraction angles *θ*1 = −π/6 and *θ*2 = π/3, respectively, which display the good performance of the designed AMS to realise tuneable acoustic refraction. Moreover, the overall transmissions of the designed AMS are around 72% and 86% for the initial and final states, respectively, which show relatively high efficiency of the proposed AMS.

2.3 Tuneable acoustic focusing

Acoustic focusing is of interest for a wide range of applications including acoustic trapping [41], acoustic tweezer [42] acoustic holography [43] and energy harvesting [44, 45]. Although conventional AMSs are able to realise passive control of acoustic focusing, these AMSs with fixed configurations face the problem of lacking manoeuvrability in steering the focus point. Thus, AMSs that can be reconfigured to generate tuneable acoustic focusing beams within one design are highly advantageous, and have potential value for the aforementioned applications.

Here, we demonstrate the tuneable acoustic focusing for focal point steering using the designed programmable AMS. The acoustic plane wave propagates in the direction along *y*-axis and focuses at the point *F*1(*x*1 = 0.1, *y*1 = 0.3) as shown in figure 3(a). The designed focal point is then moved to the point *F*2(*x*2 = −0.1, *y*2 = 0.2) at a uniform velocity *v*, which could be obtained by . Thus, the *x*-axis and *y*-axis components of *v* follow as:

, (6a)

. (6b)

Then, the angular component in the eq. (3) can be expressed as:

, (7a)

, (7b)

where the coordinates of the focal point over time follow:

, (8a)

. (8b)

By substituting eqs. (7a, 7b) into eq. (3) and then integrating eq. (3) along the *x*-axis, we can obtain the phase shift *ϕ*(*x,t*) as:

. (9)

The corresponding tuned slit widths for the tuneable acoustic focusing at 0 s and *t*0 are shown in Supplementary material S2.

Figure 3(b) shows the change of the slit widths of the 20 AMS units over time. It can be observed that part of the curves no longer changes monotonously between two adjacent sudden changes as in the previous case of tuneable acoustic refraction. Figure 3(c, d) illustrates the PSD over 2π range for the ideal AMS (blue line) and the units of the designed AMS (red circle) with *ϕ*0 equals to 0. When phase shifts are set to values indicated in figure 3(c), the acoustic wave focused at (0.1, 0.3) as shown in figure 3(e, g) (see video of the dynamic manipulation in Supplementary material). Then, the focal point can be tuned to (−0.1, 0.2) as shown in figure 3(f, h) by gradually changing the phase shifts to values indicated in figure 3(d). Figure 3(b) shows the change of the slit widths of the 20 AMS units over time.

Figure 3(i, j) show the normalized acoustic intensity distribution (normalized with respect to *p*i2) at the focal points along the *x*-axis and *y*-axis for the initial and final states, respectively, which reveal the energy amplification factor |*p*fp/*p*i|2 at the focal points. It has been proved that the transmission efficiency of the structure of the designed AMS units can reach a high level as shown in figure 1(d). Owing to the high transmission efficiency and the fine discrete resolution of phase shift, the energy amplification factors of the aforementioned AMSs reach 5.48 and 6.87 at the initial and final states, respectively. Moreover, the extent of the energy concentration of the transmitted acoustic focusing can be characterized by the transverse full width at half the maximum (FWHM) of the acoustic intensity of the focal point. The corresponding FWHMs of the initial and final states are 0.056 m (0.81*λ*) and 0.044 m (0.64*λ*), respectively, which are considerably smaller than the focal size formed by using traditional piezoelectric transducers. As a result, the designed AMS can continuously refocus acoustic waves, which is a promising way of active tuneable acoustic focusing.



**Figure 3.** (a) Schematic diagram of the tuneable acoustic focusing realised by the designed AMS. (b) The change of the slit widths of the 20 AMS units over time. The PSDs over 2π range for the ideal AMS (blue line) and the units of the designed AMS (red circle) for the (c) initial and (d) final states, respectively. The normalized pressure field of the tuneable acoustic focusing realised by the designed AMS for the (e) initial and (f) final states, respectively. The normalized intensity field of the tuneable acoustic refraction realised by the designed AMS for the (g) initial and (h) final states, respectively. Normalized acoustic intensity distribution along (i) *x*-axis and (j) *y*-axis for the initial and final states, respectively.

2.4 Tuneable acoustic self-bending

Self-bending (also self-accelerating) beam provides a possibility to form a beam to propagate along any prescribed arbitrary convex trajectories in a two-dimensional setting, which is critical for applications in acoustic beam engineering such as bottle beams [46] and acoustic tweezers [47].

Here, we demonstrate the tuneable acoustic self-bending using the designed programmable AMS. In this case, the acoustic wave is shaped to a nonparaxial beam for guiding the acoustic energy along a desired convex trajectory. The acoustic plane wave propagates along the *y*-axis and the transmitted acoustic beam follows an arc of a circle, of which the centre is *O*1(*x*1 = 0.1995, *y*1 = 0.3) and the radius *r*1 = 0.3 m as shown in figure 4(a). The designed centre of the circle is then moved to the point *O*2(*x*2 = −0.1995, *y*2 = 0.4) at a uniform velocity . At the same time the radius shifts to *r*2 = 0.4 m. Thus, the *x*-axis and *y*-axis components of *v* also follow eqs. (6a, 6b). The shift speed of the radius follows . At the self-bending regime, the refraction wave should be a tangent line of the designed circle. The detail of the formula derivation of the acoustic self-bending is discussed in Supplementary material S3. Then, the angular component in eq. (3) can be expressed as:

, (10a)

, (10b)

where the time-dependent *x* and *y* coordinates of the centre of the circle and the radius follow eqs. (8a, 8b) and:

. (11)



**Figure 4.** (a) Schematic diagram of the tuneable acoustic self-bending realised by the designed AMS. (b) The change of the slit widths of the 20 AMS units over time. The PSDs over 2π range for the ideal AMS (blue line) and the units of the designed AMS (red circle) for the (c) initial and (d) final states, respectively. The normalized pressure field of the tuneable acoustic self-bending realised by the designed programmable AMS for the (e) initial and (f) final states, respectively. The normalized intensity field of the tuneable acoustic self-bending realised by the designed AMS for the (g) initial and (h) final states, respectively. The green dash lines indicate the designed convex trajectories.

By substituting eqs. (10a, 10b) into eq. (3) and then integrating the resulting equation along the *x*-axis, we can obtain the phase shift *ϕ*(*x,t*) as:

. (12)

The corresponding tuned slit widths for the tuneable acoustic self-bending at 0 s and *t*0 are shown in Supplementary material S2.

Figure 4(b) shows the change of the slit widths of the 20 AMS units over time. Similar to the previous case of tuneable acoustic focusing, some of these curves are not monotonic between two adjacent sudden changes. Figure 4(c, d) illustrate the PSD for the ideal AMS (blue line) and the gradient AMS (red circle) of the designed AMS with *ϕ*0 equal to 0. When phase shifts are set to values indicated in figure 4(c), the acoustic wave follows the arc of a circle with centre *O*1(*x*1 = 0.1995, *y*1 = 0.3) and radius *r*1 = 0.3 m as shown in figure 4(e, g). Then, the arc of the circle can be tuned to the arc with centre *O*2(*x*2 = −0.1995, *y*2 = 0.4) and radius *r*1 = 0.4 m as shown in figure 4(f, h) by gradually changing the phase shifts to values indicated in figure 4(d) (see video of the dynamic manipulation in Supplementary material). Figure 4(b) shows the change of the slit widths of the 20 AMS units over time. The transmitted beams of the initial and final states are coincident with the designed convex trajectories as the green dashed line shown in figure 4(g, h), respectively, which demonstrate the good performance of the designed AMS to realise tuneable acoustic self-bending.

Beyond shaping the acoustic wavefront to realise various acoustic manipulations, our designed AMS possesses a unique advantage which can also realise “Off” switching or total reflection of acoustic waves easily by closing the channel (i.e. tuning the slit width *d* to 0) with lower duration time compared with previous HR-based AMS with tuneable HR cavities [33], which has not been detailed in this paper. Therefore, the incident waves will be totally reflected after hitting onto the solid surface of the AMS. This advantage also makes it easy to “close” certain AMS units to realise complex acoustic wave engineering.

2.5 Experimental validations

Experimental validations are presented below to demonstrate the functions and effectiveness of the designed programmable AMS. The experimental apparatus of the programmable AMS is shown in figure 5(a). The AMS units and their support structure are fabricated by stereo lithography appearance (SLA) with a commercial 3D printer, which is made of acoustically rigid plastic (photosensitive resin 9400). Each AMS unit is assembled with a linear actuator formed by a four-phase stepper motor and a lead screw as shown in figure 5(b), while these motors are independently controlled by the designed control system introduced in Section 2.1 as shown in



**Figure 5.** (a) The experimental apparatus of the programmable AMS. (b) The 3D printed AMS unit and its connection to the motor with lead screw. (c) Part of the control system formed by several microcontrollers.



**Figure 6.** (a) Schematic diagram and (b) the photo of the experimental apparatus to measure the acoustic transmitted field of the interested scanning area.

figure 5(c). It is worth mentioning that the maximum speed of the slider of the lead screw driven by the motor is 154 mm/s, which ensures that the slit width of the AMS unit can be quickly adjusted between 1.5 to 9.0 mm. Several breadboards are used to build the circuits of the slave controllers and motor drives. Then, the AMS units and the motors are arranged in an array along the *x*-axis and are mounted vertically on the lower layer of the planar waveguide. Different from the structure in the schematic diagram shown in figure 1(a), each 3D printed AMS unit is reinforced by support ribs to avoid undesired deformation. The control programs written in Matlab and Arduino software are pre-transferred to the corresponding slave controllers. The control system is powered by a 5 V and a 12 V regulated power supplies as shown in figure 5(a). Moreover, two support rods are used to prop up the lower layer of the planar waveguide to prevent its deformation. See video of the experimental dynamic manipulation of the programmable AMS in the Supplementary material.

To measure the transmitted acoustic field manipulated by the programmable AMS, a measuring system is added to the experimental apparatus shown in figure 6(a, b), including a planar loudspeaker (BMS 4508ND), a power amplifier (BSWA PA50), a data acquisition instrument (Donghua DH5922D) and two 1/4-inch microphones (BSWA MPA416). One microphone is fixed near the loudspeaker as a reference while another one is movable to scan the interested area of the transmitted field point by point (0.1 m × 0.1 m with 1 cm spacing). Wedge-like sound-absorbing foam surrounds the entire test field between the planar waveguide to prevent reflected waves from affecting the experimental results. A virtual audio cable software package is used to provide a sinusoidal signal at 5000 Hz to the power amplifier.

To obtain the acoustic field of the scanning area, the amplitude ratio *A* and phase difference *φ* of the signals measured by mic. 1 and mic. 2 at these test points are calculated. The normalized instantaneous acoustic pressure *p* of each test point is obtained as. Then, the whole experimental acoustic field is constructed via bi-cubic interpolation of these pressure data points (on a 11 × 11 grid of the scanning area). The experimental acoustic fields of the interested areas indicated by white square in the simulation results of the corresponding acoustic fields are shown in figure 7. To be specific, these results correspond to the simulation results of the (a) initial and (b) final states of tuneable acoustic refraction (indicated by white squares shown in figure 2), the (c, e) initial and (d, f) final states of tuneable acoustic focusing



**Figure 7.** The experimental acoustic field of the interested area indicated by white square in the simulation results of the corresponding acoustic field. To be specific, these results correspond to the simulation results of the interested areas of the (a) initial and (b) final states of acoustic refraction, the (c, e) initial and (d, f) final states of acoustic focusing and the (g, i) initial and (h, j) final states of acoustic self-bending, respectively.

(indicated by white squares shown in figure 3) and the (g, i) initial and (h, j) final states of tuneable acoustic self-bending (indicated by white squares shown in figure 4), respectively. Considering that the programmable AMS would have assembly errors and stroke errors bigger than a passive AMS, the agreement of these experimental results with the simulation results in the previous section is impressive, which proves that the designed programmable AMS has excellent performance in active wave engineering.

3. Conclusions

A programmable AMS which contains an array of reconfigurable subwavelength unit cells, regulated by a set of stepper motors with lead screws and a cost-effective control system is presented. Each unit of the AMS is composed of a parallel one-dimensional daisy-chained slit with five Helmholtz resonators. The phase shift of the transmission wave through the AMS units can be precisely controlled over the full phase range and continuously tuned by varying the slit width with high transmission efficiency. Benefitting from such a mechanism, the designed AMS is able to achieve continuous versatile wave manipulation functions by engineering the phase of transmission waves. Several typical wave manipulation functions including tuneable acoustic refraction, tuneable acoustic focusing and tuneable acoustic self-bending are demonstrated by both numerical simulations and experimental validations. Due to its tuneability, the designed programmable AMS holds a great potential for a wide range of applications including diagnostic sonography, active non-destructive evaluation, acoustic holography, noncontact micro-particles manipulation and energy harvesting.

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References

[1] Ma G and Sheng P 2016 Acoustic metamaterials: from local resonances to broad horizons *Sci. Adv.* **2** e1501595

[2] Cummer S A, Christensen J and Alù A 2016 Controlling sound with acoustic metamaterials *Nat. Rev. Mater.* **1** 16001

[3] Xu Y, Fu Y and Chen H 2016 Planar gradient metamaterials *Nat. Rev. Mater.* **1** 16067

[4] Lee D, Nguyen D M and Rho J 2017 Acoustic wave science realized by metamaterials *Nano Converg.* **4** 3

[5] Assouar B, Liang B, Wu Y, Li Y, Cheng J-C and Jing Y 2018 Acoustic metasurfaces *Nat. Rev. Mater.* **3** 460–472

[6] Tang K, Qiu C, Ke M, Lu J, Ye Y and Liu Z 2015 Anomalous refraction of airborne sound through ultrathin metasurfaces *Sci. Rep.* **4** 6517

[7] Chiang Y K, Oberst S, Melnikov A, Quan L, Marburg S, Alù A and Powell D A 2020 Reconfigurable acoustic metagrating for high-efficiency anomalous reflection *Phys. Rev. Appl.* **13** 064067

[8] Faure C, Richoux O, Félix S and Pagneux V 2016 Experiments on metasurface carpet cloaking for audible acoustics *Appl. Phys. Lett.* **108** 064103

[9] Esfahlani H, Karkar S and Lissek H 2016 Acoustic carpet cloak based on an ultrathin metasurface *Phys. Rev. B* **94** 014302

[10] Xie B, Tang K, Cheng H, Liu Z, Chen S and Tian J 2017 Coding acoustic metasurfaces *Adv. Mater.* **29** 1603507

[11] Fang X, Wang X and Li Y 2019 Acoustic splitting and bending with compact coding metasurfaces *Phys. Rev. Appl.* **11** 064033

[12] Cao S and Hou Z 2019 Angular-asymmetric transmitting metasurface and splitter for acoustic waves: combining the coherent perfect absorber and a laser *Phys. Rev. Appl.* **12** 064016

[13] Wang X, Fang X, Mao D, Jing Y and Li Y 2019 Extremely asymmetrical acoustic metasurface mirror at the exceptional point *Phys. Rev. Lett.* **123** 214302

[14] Liu G-S, Peng Y-Y, Liu M-H, Zou X-Y and Cheng J-C 2018 Broadband acoustic energy harvesting metasurface with coupled Helmholtz resonators *Appl. Phys. Lett.* **113** 153503

[15] Jin M, Liang B, Yang J, Yang J and Cheng J-C 2019 Ultrathin planar metasurface-based acoustic energy harvester with deep subwavelength thickness and mechanical rigidity *Sci. Rep.* **9** 11152

[16] Li Y, Liang B, Tao X, Zhu X and Zou X 2012 Acoustic focusing by coiling up space *Appl. Phys. Lett.* **101** 233508

[17] Yuan B, Cheng Y and Liu X 2015 Conversion of sound radiation pattern via gradient acoustic metasurface with space-coiling structure *Appl. Phys. Express* **8** 027301

[18] Ma G, Yang M, Xiao S, Yang Z and Sheng P 2014 Acoustic metasurface with hybrid resonances *Nat. Mater.* **13** 873–878

[19] Huang T-Y, Shen C and Jing Y 2016 Membrane- and plate-type acoustic metamaterials *J. Acoust. Soc. Am.* **139** 3240

[20] Langfeldt F and Gleine W 2019 Membrane- and plate-type acoustic metamaterials with elastic unit cell edges *J. Sound Vibr.* **453** 65–86

[21] Li Y, Jiang X, Liang B, Cheng J and Zhang L 2015 Metascreen-based acoustic passive phased array *Phys. Rev. Appl.* **4** 024003

[22] Lan J, Li Y, Xu Y and Liu X 2017 Manipulation of acoustic wavefront by gradient metasurface based on Helmholtz resonators *Sci. Rep.* **7** 10587

[23] Wang Y-F, Wang Y-Z, Wu B, Chen W and Wang Y-S 2020 Tunable and active phononic crystals and metamaterials *Appl. Mech. Rev.* **72** 040801

[24] Li Y, Shen C, Xie Y, Li J, Wang W, Cummer S A and Jing Y 2017 Tunable asymmetric transmission via lossy acoustic metasurfaces *Phys. Rev. Lett.* **119** 035501

[25] Liu B and Jiang Y 2018 Controllable asymmetric transmission via gap-tunable acoustic metasurface *Appl. Phys. Lett.* **112** 173503

[26] Fan S-W, Zhao S-D, Chen A-L, Wang Y-F, Assouar B and Wang Y-S 2019 Tunable broadband reflective acoustic metasurface *Phys. Rev. Appl.* **11** 044038

[27] Fan S-W, Zhao S-D, Cao L, Zhu Y, Chen A-L, Wang Y-F, Donda K, Wang Y-S and Assouar B 2020 Reconfigurable curved metasurface for acoustic cloaking and illusion *Phys. Rev. B* **101** 024104

[28] Zhao S-D, Chen A-L, Wang Y-S and Zhang C 2018 Continuously tunable acoustic metasurface for transmitted wavefront modulation *Phys. Rev. Appl.* **10** 054066

[29] Chen A-L, Tang Q-Y, Wang H-Y, Zhao S-D and Wang Y-S 2020 Multifunction switching by a flat structurally tunable acoustic metasurface for transmitted waves *Sci. China-Phys. Mech. Astron.* **63** 244611

[30] Liang S, Liu T, Chen F and Zhu J 2019 Theoretical and experimental study of gradient-helicoid metamaterial *J. Sound Vibr.* **442** 482–496

[31] Gong K, Wang X, Ouyang H and Mo J 2019 Tuneable gradient Helmholtz-resonator-based acoustic metasurface for acoustic focusing *J. Phys. D: Appl. Phys.* **52** 385303

[32] Chen Z, Shao S, Negahban M and Li Zheng 2019 Tunable metasurface for acoustic wave redirection, focusing and source illusion *J. Phys. D: Appl. Phys.* **52** 395503

[33] Tian Z, Shen C, Li J, Reit E, Gu Y, Fu H, Cummer S A and Huang T J 2019 Programmable acoustic metasurfaces *Adv. Funct. Mater.* **29** 1808489

[34] Kinsler L E, Frey A R, Coppens A B and Sanders J V 2000 *Fundamentals of Acoustics* 4th edn vol 4 (New York: Wiley) p 274

[35] Fang N, Xi D, Xu J, Ambati M, Srituravanich W, Sun C and Zhang X 2006 Ultrasonic metamaterials with negative modulus *Nat. Mater.* **5** 452–456

[36] Park S H, Kim S J, Kim E-K, Kim M J, Son E J and Kwak J Y 2009 Interobserver agreement in assessing the sonographic and elastographic features of malignant thyroid nodules *Am. J. Roentgenol.* **193** W416–W423

[37] Holmes C, Drinkwater B W and Wilcox P D 2005 Post-processing of the full matrix of ultrasonic transmit–receive array data for non-destructive evaluation *NDT E Int.* **38** 701–711

[38] Drinkwater B W and Wilcox P D 2006 Ultrasonic arrays for non-destructive evaluation: a review *NDT E Int.* **39** 525–541

[39] Yu N, Genevet P, Kats M A, Aieta F, Tetienne J-P, Capassp F and Gaburro Z 2011 Light propagation with phase discontinuities: generalized laws of reflection and refraction *Science* **334** 333–337

[40] Xie Y, Wang W, Chen H, Konneker A, Popa B-I and Cummer S A 2014 Wavefront modulation and subwavelength diffractive acoustics with an acoustic metasurface *Nat. Commun.* **5** 5553

[41] Yoon C, Kang B J, Lee C, Kim H and Shung K 2014 Multi-particle trapping and manipulation by a high-frequency array transducer *Appl. Phys. Lett.* **105** 214103

[42] Marzo A and Drinkwater B W 2019 Holographic acoustic tweezers *Proc. Natl. Acad. Sci. USA* **116** 84–89

[43] Zhang J, Tian Y, Cheng Y and Liu X 2020 Acoustic holography using composite metasurfaces *Appl. Phys. Lett.* **116** 030501

[44] Qi S and Assouar B 2017 Acoustic energy harvesting based on multilateral metasurfaces *Appl. Phys. Lett.* **111** 243506

[45] Qi S, Li Y and Assouar B 2017 Acoustic focusing and energy confinement based on multilateral metasurfaces *Phys. Rev. Appl.* **7** 054006

[46] Zhang P, Li T, Zhu J, Zhu X, Yang S, Wang Y, Yin X and Zhang X 2014 Generation of acoustic self-bending and bottle beams by phase engineering *Nat. Commun.* **5** 4316

[47] Meng L, Cai F, Li F, Zhou W, Niu L and Zheng H 2019 Acoustic tweezers *J. Phys. D: Appl. Phys.* **52** 273001

**Supplementary Material**

Continuous Manipulation of Acoustic Wavefront Using a Programmable Acoustic Metasurface

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**Contents:**

S1. The thickness of the viscosity boundary layer

S2. Detail parameters of the acoustic metasurface performed

S3. Formula derivation of the acoustic self-bending

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**S1. The thickness of the viscosity boundary layer**

The previous study has drawn attention to detrimental thermoviscous effects in subwavelength acoustic ducts [1]. Air viscosity of the designed acoustic metasurface (AMS) is taken into account in the numerical simulation in this study [2]. Boundary layer mesh is added to the surface of the AMS inner wall according to the thickness of the viscosity boundary layer *δ*visc, which can be expressed as, where *μ* is the dynamic viscosity which is a measure of a fluid’s resistance to shearing, *ω* is the angular frequency and the *ρ*0 is the equilibrium density. In this paper, *μ* = 1.983 × 10–5 Pa∙s, *ω* = 31416 rad/s, and *ρ*0 = 1.21 kg/m3. Thus, the *δ*visc in our simulation is 3.23 × 10–5 m.

**S2. Detail parameters of the acoustic metasurface performed**

For convenience and clarity, the corresponding tuned slit widths for the tuneable acoustic refraction, tuneable acoustic focusing and tuneable acoustic self-bending at 0 s and *t*0 are listed in Table S1.

**Table S1.** The corresponding tuned slit widths *dN* (mm) (*N*=1, 2, …, 20) for the tuneable acoustic refraction, tuneable acoustic focusing and tuneable acoustic self-bending at 0 s and *t*0.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| case (*t*) | *d*1 | *d*2 | *d*3 | *d*4 | *d*5 | *d*6 | *d*7 | *d*8 | *d*9 | *d*10 |
| refraction (0 s) | 3.2 | 4.2 | 5.9 | 1.5 | 1.8 | 2.2 | 2.8 | 3.6 | 4.9 | 7.1 |
| refraction (*t*0) | 3.0 | 2.0 | 8.7 | 4.4 | 2.7 | 1.9 | 7.2 | 3.9 | 2.5 | 1.8 |
| focusing (0 s) | 1.9 | 8.1 | 4.8 | 3.3 | 2.4 | 1.9 | 1.6 | 6.8 | 4.9 | 3.9 |
| focusing (*t*0) | 2.0 | 1.8 | 1.6 | 8.0 | 7.2 | 7.0 | 7.5 | 8.9 | 1.6 | 1.9 |
| self-bending (0 s) | 4.3 | 3.7 | 3.3 | 3.1 | 3.0 | 2.9 | 3.0 | 3.2 | 3.7 | 4.4 |
| self-bending (*t*0) | 9.0 | 4.2 | 2.5 | 1.7 | 5.3 | 3.1 | 2.1 | 1.6 | 5.4 | 3.5 |
| case (*t*) | *d*11 | *d*12 | *d*13 | *d*14 | *d*15 | *d*16 | *d*17 | *d*18 | *d*19 | *d*20 |
| refraction (0 s) | 1.6 | 2.0 | 2.4 | 3.1 | 4.1 | 5.8 | 8.9 | 1.8 | 2.2 | 2.7 |
| refraction (*t*0) | 6.1 | 3.5 | 2.3 | 1.6 | 5.3 | 3.1 | 2.1 | 1.5 | 4.6 | 2.8 |
| focusing (0 s) | 3.3 | 2.9 | 2.6 | 2.5 | 2.4 | 2.4 | 2.5 | 2.7 | 3.0 | 3.5 |
| focusing (*t*0) | 2.3 | 2.9 | 3.9 | 6.0 | 1.6 | 2.1 | 3.0 | 4.7 | 9.0 | 2.0 |
| self-bending (0 s) | 5.7 | 8.6 | 1.8 | 2.4 | 3.4 | 5.7 | 1.7 | 2.5 | 4.2 | 9.0 |
| self-bending (*t*0) | 2.6 | 2.1 | 1.7 | 8.9 | 6.6 | 5.4 | 4.7 | 4.3 | 4.0 | 4.0 |

**S3. Formula derivation of the acoustic self-bending**

We would like to show the formula derivation of the acoustic self-bending below. First, we suppose that the designed acoustic wave is tangent to an arc of a circle , whilst the designed AMS is placed along the *x*-axis as shown in Fig S2.



**Figure S2.** The schematic diagram of the acoustic self-bending in which the designed wave is tangent to an arc of a circle.

The wave from a certain position on the AMS (*x*, 0) should be tangent to the arc at (*x*0, *y*0). Thus, the following equations could be obtained:

 (S1)

 (S2)

By taking the derivative of the both sides of the eq. (S1), we can obtain:

 (S3)

After solving the eq. (S3), we can obtain the *y*0 as follow:

 (S4)

Considering −π/2 < *θ* < π/2, we should choose:

 (S5)

By substituting eqs. (S1) and (S5) into eq. (S2), we can obtain:

 (S6)

Then, (S6) can be rewritten as:

 (S7)

By substituting the relationship of sin*θ* with tan*θ* into eq. (S7), we can obtain:

 (S8)

**References**

[1] Ward G P, Lovelock R K, Murray A R J, Hibbins A P, Sambles J R and Smith J D 2015 Boundary-layer effects on acoustic transmission through narrow slit cavities *Phys. Rev. Lett.* [**115** 044302](https://doi.org/10.1103/PhysRevLett.115.044302)

[2] Jensen M H 2014 Theory of thermoviscous acoustics: thermal and viscous losses [*COMSOL Blog*](https://br.comsol.com/blogs/theory-of-thermoviscous-acoustics-thermal-and-viscous-losses/?setlang=1)