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Experimental study of an tunable acoustic phase-shifter

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The paper presents the results of a numerical and experimental study of an acoustic phase-shifter based on a chain of rectangular Helmholtz resonators. Phase regulation of the transmitted acoustic wave is made by simultaneously changing the resonators volumes with the stepper motor. As a result of the experiment it was found that the developed acoustic phase-shifter allows to manipulate the wave phase within the range of $0-2\pi$ in the frequency range of 2000-2500 Hz. The transmittance factor is not less than 0.7. The phase-shifter can be used as a unit cell of tunable acoustic metasurface.

Keywords: acoustics, wave control, phase-shifter, metasurface.

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Acoustic metasurfaces are a topical issue in modern research since they allow for efficient refraction [1], reflection [2], focusing [3], absorption [4] and change of the wave front [5] of acoustic waves. A metasurface is usually made up of a set of cells that allow for changing the phase of a propagated wave by a specified value, e.g., from a discrete set $n\pi/4$, where $n = 0-7$. The main drawback of the considered phase-shifters is their static design, therefore, metasurfaces based on them can perform a single function only (e.g., refracting a normally incident fixed-frequency wave by a specified angle). Due to this, tunable acoustic phase-shifters are being actively studied. The paper [6] considers a tunable metasurface where the cells are screw phase-shifters. Changing of the screw screwing-in depth made it possible to change the phase of propagated radiation by 2π. In this case, the transmittance factor is heavily resonant and does not exceed 0.8. In [7] segments of thin-walled hollow cylinders are used as metasurface cells. Focusing and defocusing of a wave with a focal distance equal to about the cross dimension of the metasurface are shown. Tunable metasurfaces based on Helmholtz resonators are often considered. In [8], liquid is supplied into the resonator for returning, in [9] the resonator volume and waveguide tube cross-section are changed simultaneously. Both papers show a good agreement between the experimental data and numerical modeling results by the example of wave focusing and refraction. It should be noted that the resonator volume in [9] is changed manually. The main problem of modern controlled metasurfaces is the complexity and low speed of retuning of their phase-shifters. The use of liquid cells [8] requires a complex hydraulic control system and increased leak-tightness, while the geometry of the designs in papers [6,7] complicates the use of electrically controlled movement systems. Moreover, in paper [8] a full phase revolution requires ~ 25 s. Now let us consider an acoustic phase-shifter based on Helmholtz resonators that allow for prompt changing of resonator volume by means of a stepper motor.

The experimental setup for an acoustic phase-shifter is schematically shown in Fig. 1. An acoustic wave was excised using a small-sized electrodynamic loudspeaker CNS3508A075BER (CANOPUS) with an elliptical diffusor. An acoustic wave is transmitted from the loudspeaker to the phase-shifter and the load through a rectangular acoustic waveguide having the inner cross-section of 33×19 mm. The load of the output waveguide is a catenoidal horn of rectangular cross-section having the length of 160 mm and the mouth sizes of 160×160 mm with the boundary cutoff frequency of ~ 900 Hz, that matches the waveguide impedance and the open space impedance. The input and output waveguides have two flanges each for connection of measuring microphones; the flanges are located at the distance of 20 and 60 mm from the phase-shifter. Numerical simulation has shown that only the piston mode will be present in the waveguide at the specified distances in the frequency range of $1-10$ kHz. The phase-shifter consists of a rectangular waveguide tube with the inner cross-section of 10×19 mm, wall thickness of 2 mm, and length of $L_p = 100$ mm. Five rectangular-shaped Helmholtz resonators with the cross-section of 17.5×19 mm and the depth of 35 mm are connected to the tube via a rectangular neck having the cross-section of 2.5×19 mm. The numerical simulation has shown that the use of fewer resonators in the specified design does not allow for reaching the phase shift of 2π. Papers [1,9] show that a reduction of the cross-section of the waveguide tube while keeping the unchanged height of the Helmholtz resonators results in an increased phase shift introduced by the phase-shifter. However, the impedance jump present at the waveguide junction leads to increase of the wave reflected from the phase-shifter, which, in its turn, reduces the transmittance factor. With the dimensions used in the design, the change in output pressure amplitude does not exceed 30%. Interconnected

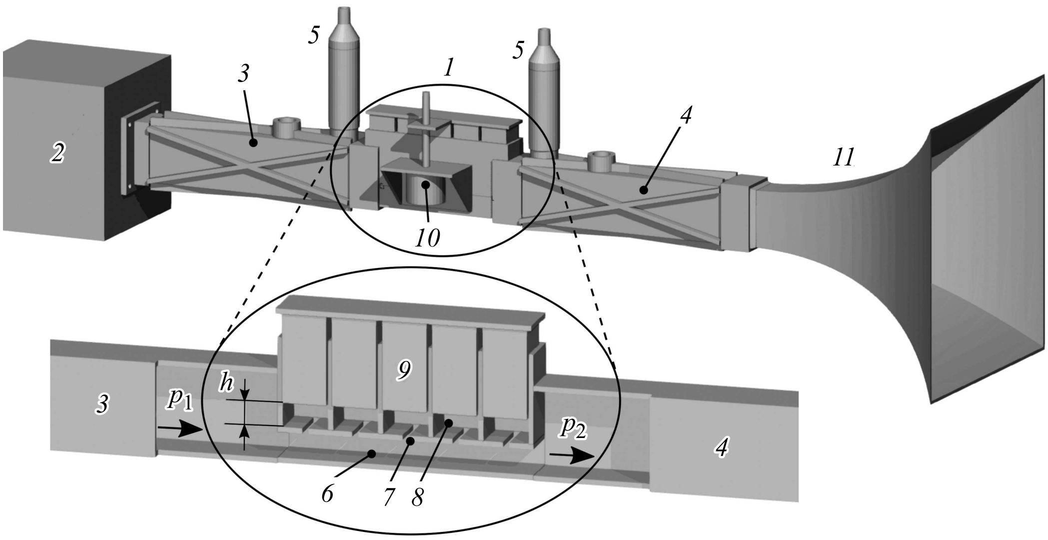

Figure 1. Schematic representation of the experimental setup. *1* — phase-shifter assembly; *2* — enclosed emitter; *3*,*4* — input and output waveguides; *5* — microphones; *6* — phase-shifter waveguide; *7* — resonator neck; *8* — resonator cavity; *9* — moving pistons; *10* — stepper motor; *11* — matching horn.

pistons 35 mm high are positioned inside each resonator. The position of the phase-shifter piston is set by the drive screw $M5 \times 0.8-50$ using a 25GBC12 bipolar stepper motor with a 1:12 gearbox. The space between the piston and the cylinder is filled with grease, which ensures smooth movement of the piston and somewhat compensates for the loose fit of pistons to the cylinders. When using the motor in the half-step mode, the angular step is 0.625°. Thus, the maximum resolution upon changing of resonator height h is $\sim 1.4\,\mu$m, while positioning accuracy is limited mainly by backlash of the stepper motor gearbox shaft.

The measuring unit is controlled by a personal computer. The UMC1820 (Behringer) audio interface performs signal conditioning and acquisition. ECM-66 (Sony) condenser electret capsules are used as measuring microphones, for which a preliminary amplifier with phantom power supply of 48 V was made. The phase-shifter is controlled by the stepper motor driver developed on the basis of the STM32F100C4T6 microcontroller (STMicroelectronics) and the FT232RL interface converter. The interface program, which fully automates the measurement process, is written in Python using the PySerial and SoundDevice libraries. All phase-shifter elements, waveguides, microphone housings and the horn are made of PLA-plastic (density $1.24\,g/cm^3$) by 3D-printing to the accuracy of 0.2 mm. Numerical simulation of the response of the developed phase-shifter cell was performed using the COMSOL Multiphysics software package. When constructing the modeling geometry, it was assumed that the walls of the waveguide and phase-shifter elements are absolutely rigid. A boundary condition in the form of a perfectly matched layer was set at the output cross-section of the second waveguide. Fig. 2 shows the dependences of the normalized amplitude of the pressure of the wave exiting from the phase-shifter cell p_2 (a) and the phase difference between the incident and the exiting waves $\Delta\varphi$ (b) on resonator height h and frequency f. It follows from these dependencies that the developed phase-shifter cell allows for shifting the passing wave phase by any value within $0-2\pi$ in the frequency range of 2500−3000 Hz. Fig. 2 shows the dependencies of the normalized amplitude of pressure of the wave exiting the phase-shifter cell p_2 (c) and phase difference between the incident and exiting waves $\Delta\varphi$ (d), obtained in the experiment. It can be seen that the operating range of the made phase-shifter has displaced to a lower-frequency region and efficient phase control is performed in the range of 2000−2500 Hz. This discrepancy can be explained by the insufficiently high accuracy of making of the phase-shifter elements. Firstly, cross-sections of resonator necks are slightly lower than the specified ones and may differ from the specified ones by 0.2 mm due to thermal deformation of the material and the use of technological „supports“, necessary during 3D-printing by the FDM method. Secondly, given the loose fit of the movable pistons to the resonator walls despite the present lubricant, the active component of resonator impedance, related to radiation losses, increases. Nevertheless, the experiment results agree well qualitatively with the numerical simulation results and the required phase shift has been obtained in the range of interest. The developed and studied phase-shifter can be used as a cell of a tunable acoustic metasurface. The developed design allows for a full revolution of the acoustic wave phase. The cell retuning rate is not less than 1 rad/s. It can be anticipated that proportional scaling of waveguide size and number of cells will make it possible to form an operationally tunable acoustic metasurface for random control of the acoustic wave front.

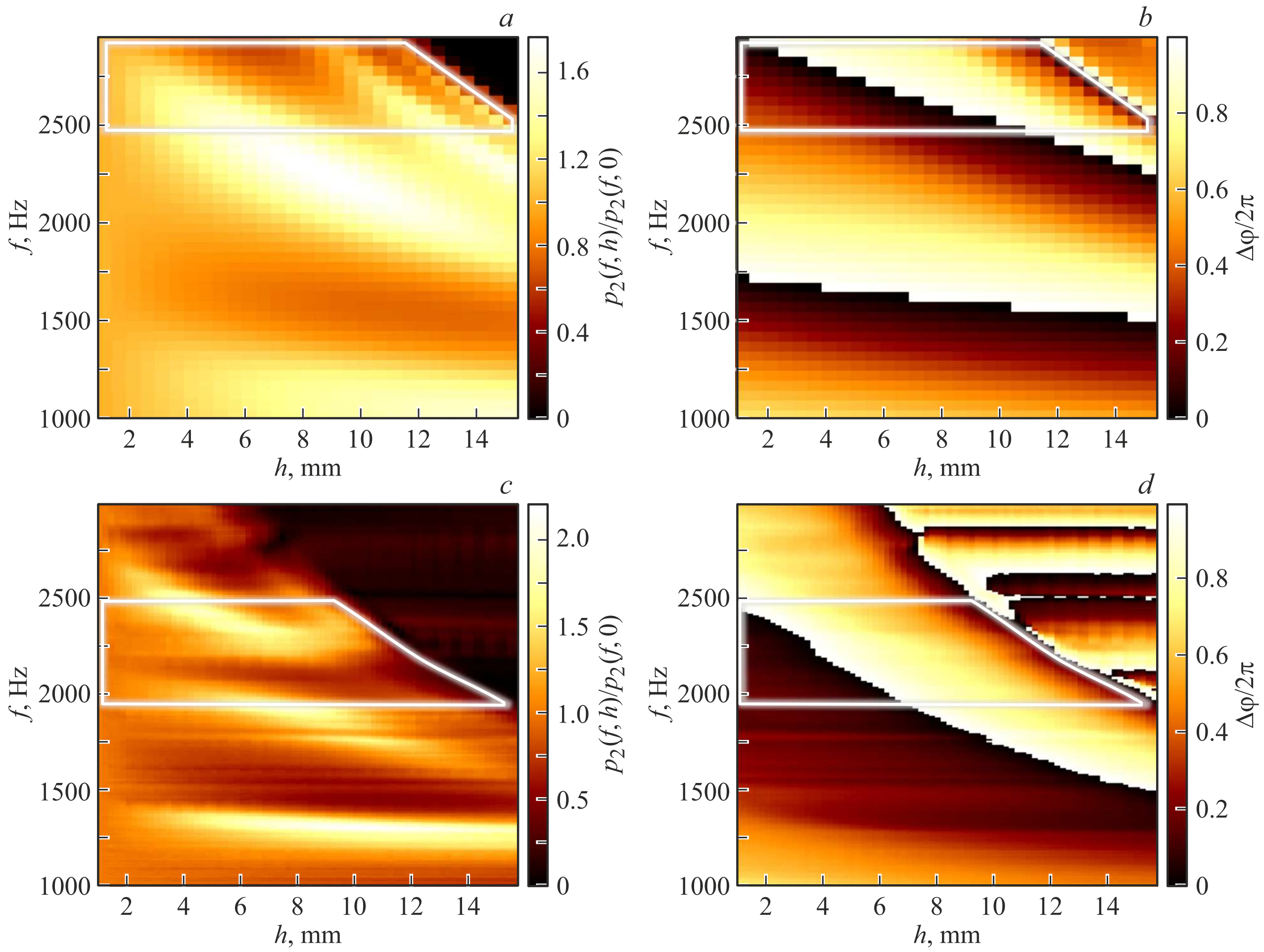

Figure 2. Dependencies of normalized pressure amplitude at the phase-shifter output (a, c) and the phase shift introduced by the phase-shifter (b, d) on acoustic wave frequency f and resonator height h, obtained by numerical simulation (a, b) and experiment (c, d). The bright line shows the region of phase regulation by 2π.

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Conflict of interest

The authors declare that they have no conflict of interest.

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