Features of amplitude frequency characteristics of ABS plastic 3D printed metamaterial sample

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Abstract. In this study, we investigated the acoustical properties of custom-designed phononic crystal-like acoustic metamaterials 3D printed from ABS plastic. The elastic properties of these metamaterials were studied experimentally and numerically. The metamaterial consisted of a set of plane parallel lattices the number of which could vary in different samples. Each lattice in the sample consisted of 16 parallel square rods. The amplitude-frequency characteristics (AFC) of the fabricated metamaterial sample were measured in the frequency range (35-100) kHz using longitudinal acoustic waves both in air and water. The propagation velocities of longitudinal and shear acoustic waves of ABS plastic itself were measured prior to the experiment. The band gaps (stop bands) were detected and investigated while measuring AFC of the metamaterials. We have found that the increase in the number of lattice layers in the sample led to the band gap acoustic wave attenuation coefficient increase along with the band gap narrowing, while the central frequency of the band gap remained the same. The numerical simulation of the sample frequency response was carried out in COMSOL. The results of experimental studies and numerical simulations were in satisfactory agreement. We have also investigated the ultrasound scattering diffraction pattern of the sample. The obtained results can be used in solid-state physics and material science, to create materials with controlled frequency-dependent acoustic properties.

Key words: Acoustic metamaterial, ABS-plastic, elastic properties, acoustic scattering

1. Introduction
Metamaterials are composite materials with properties determined not much by the properties of their individual constituent elements, but by the periodic structure which they form. Interest in metamaterials with a negative refractive index was raised in 1967 with the work of Veselago at el. [1]. But in fact, these materials were created and demonstrated much later [2-4]. One of the special cases of acoustic metamaterials is phononic crystals. They have an artificial periodic structure with a period slightly shorter than the acoustic radiation wavelength.

Phononic crystals have several unusual properties. In particular, the propagation of acoustic waves through them has a zone structure [5]. Recently, there was an increased interest in designing various structures with the properties of phononic crystals [6]. The first calculation of the band structure in periodic elastic composites was carried out by Kushwaha et al. in 1993 [7]. For the transverse elastic wave, "phonon" band gap was obtained, which continues to the boundary of the Brillouin zone. Sigalas et al. [8] have calculated the band structure of the elastic waves propagating in two-dimensional periodic liquids and solids. Vasseur et al. [9] have studied theoretically and...
experimentally the band structure of a two-dimensional phononic crystal, consisting of steel cylinders placed in an epoxy matrix. Experimental measurements and numerical simulations have proved the existence of two forbidden stop bands, independent of the bulk acoustic waves (BAW) propagation direction in this structure. Li et al. have proposed a method for creating phononic crystals with a large bandwidth [10]. They have been shown by numerical simulation the gap between two bands in the plane (longitudinal and shear) mode can be formed by using a certain number of rods embedded in the matrix material. Krushynska et al. have analyzed [11], a solid metamaterial with quasi-resonant Bragg gaps. It was shown that these gaps were achieved by overlapping the Bragg band gap with local resonance modes of the metamaterial. Bobrovnikii et al. demonstrated for a one-dimensional model of metamaterial, a new approach to the description of an arbitrary type acoustic media, based on the representation of media as periodic structures with periodicity cells having internal (hidden) degrees of freedom [12]. This approach was feather extended by them for two-dimensional models of the metamaterial [13].

A significant number of works devoted to acoustic metamaterials have been completed, however, the properties of periodic structures of acoustic metamaterials are still not fully understood there is a number of unsolved problems that complicate the design of acoustic metamaterials with given wave properties. These include the lack of simple and convenient methods for analyzing their wave properties, adequate methods for determining their effective parameters, etc. Despite a large number of developed structures with the properties of phononic crystals, modern 3D printing technology is not widely used to create phononic crystals. The purpose of this work was to create metamaterials (phononic crystals) by 3D printing and experimentally study their elastic properties, to evaluate their amplitude-frequency characteristics (AFC) in the ultrasonic frequency range.

2. Experimental setup and sample description
The test samples were made by Fused Deposition Modelling (FDM) 3D printing from 2.85 mm ABS plastic filament (eSUN, China) with 100% filling using 3DQ Mini 3D printer (3Dquality, Russia) with 0.05 mm nozzle. To determine the elastic properties of the ABS polymer, a test sample in a cubic shape was printed out similarly, and the velocities of the longitudinal and shear BAW were measured by the pulsed ultrasound method. The measurements have been conducted with UD2V-P45 universal ultrasonic flaw detector (Kropus, Russia). The acoustic coupling between piezoceramic transducers of the flaw detector and the sample was carried out using silicone oil, which has both longitudinal and shear elastic properties. The measurement of the velocity of elastic waves \( V \) was carried out by the impulse method for "transmission" according to the formula \( V = L/\tau \), where \( L \) is the length of the sample, \( \tau \) is the time of BAW pulse passage through the sample. The measurements were carried out at a frequency of 100 kHz. Based on the measurements, all independent components of the second-order elastic tensor were calculated (\( C_{11} \) and \( C_{44} \)).

\[
C_{11} = \rho(V_L)^2 = (2,86*10^6)N/m^2, \quad C_{44} = \rho(V_s)^2 = (6,9*10^6)N/m^2
\]

(1)

The test samples BAW velocity dispersion and anisotropy were not found in the conducted ultrasonic measurements. Additionally, the acoustic impedance was calculated for the lattice material, as well as filling materials (air and water):

\[
Z = \rho c
\]

(2)

The main elastic characteristics of the investigated materials are shown in Table 1.

Lattices shape samples have been made of ABS plastic by 3D printing as well as a test sample to investigate the features of BAW propagation through the acoustical metamaterial.

Lattices were printed as rectangular elements square in cross-section - sample \#1.n, where \( n \) is the number of lattices, that could vary between 1 and 5 (Figure 1). Each lattice in the sample consisted of 16 parallel \( d=1.02 \) mm width by \( H=45 \) mm length square rods with a period \( l=2.51 \) mm. The amplitude-frequency characteristics (AFC) of the fabricated metamaterial sample placed in the air were measured in the frequency range (35-100) kHz using longitudinal acoustic waves. In this
frequency range, the wavelength in the air varies from 3.4 mm to 9.7 mm. Sample #2, n which was used in the water had the following dimensions: d=0.8 mm, H=50 mm, period l=2.8 mm, and D=2 mm. The number of elements in the lattice was also 16, the number of layers n in the lattice could vary from 1 to 5. Accordingly, with these parameters, plastic samples can be considered as metamaterials in the entire investigated frequency range. When investigating in a liquid medium (water), the measurements were carried out in the frequency range from 400 kHz to 1.5 MHz. In this frequency range, the wavelength in water was varying from 0.99 mm to 3.7 mm. Two ABS plastic lattices were tested in water. Accordingly, a lattice with a period of 2.51 mm can be considered as metamaterial at frequencies below 577 kHz, and a narrower lattice with a period of 1.28 mm - up to 1.13 MHz.

![Figure 1. A) Schematic diagram of sample #1, n and #2, n (top view), B) schematic diagram of sample #1, 5, #2, 5 consisting of 5 parallel arrays.](image)

The lattice layers in the sample were placed in parallel. During the study, a series of experiments were carried out, including ultrasonic wave amplitude measurements passed through an acoustic metamaterial in its various configurations.

|                          | ABS polymer | Air       | Water     |
|--------------------------|-------------|-----------|-----------|
| $\rho$, kg/m$^3$         | 1000        | 1.28      | 1000      |
| $V_L$, m/s               | 1690±50     | 330       | 1490      |
| $V_T$, m/s               | 830         | -         | -         |
| $C_{11}$, N/m$^2$        | 2.86*10$^9$ | -         | -         |
| $C_{44}$, N/m$^2$        | 6.9*10$^8$  | -         | -         |
| $Z$, N·s/m$^5$           | 1.69*10$^6$ | 4.2*10$^2$| 1.49*10$^6$|

A specialized ultrasonic setup was assembled to measure the resonant and nonlinear elastic properties of the metamaterial. The probing signal supplied from the lock-in amplifier SR850 (Stanford Research System, USA) was amplified using a Behringer Europower 2500 power amplifier and fed to a broadband electrostatic emitter (Figure 2). This configuration of the transmitting path made it possible to achieve high constancy of the signal power in a wide frequency range. To eliminate the undesirable effect of sound reflection from hard surfaces, a quasi-continuous mode was chosen with a pulse duration sufficient to establish oscillations with a constant amplitude in the system, but insufficient for sound to be reflected from the walls, floor, and ceiling to enter the microphone. The sample itself was fixed on a turntable covered with sound-absorbing material. After passing through the sample the ultrasound was detected by the microphone, and its amplitude was recorded in the device memory.

The turntable was adjusted in a way that the sample was located perpendicular to the ultrasound propagation line, after that the frequency response of the system was recorded. In this configuration, several experiments were carried out with different numbers of layers in the metamaterial.
To carry out the experiment in water, a specially designed measuring cell was used, which consisted of a metal guide-rod, to which piezoelectric sensors were attached using two small steel rods, pressed by the end to it. Piezoelectric sensors were inserted into plastic rings fixed with a screw to the steel rods so that the sensor could be rotated along with the ring, which was used to calibrate the sensors. The test sample was mounted on a thin metal rod screwed into the guide-rod. The rod holding the lattice was equipped with a limb drawn in degrees and a fixed arrow indicating the direction of propagation of the BAW. This design of the measuring cell made it possible to measure the dependence of the amplitude of the transmitted BAW signal on the angle of incidence of the BAW on the sample of the studied acoustic metamaterial. The experimental setup is schematically shown in Figure 3. Table 2 lists the typical dimensions and distances in the measuring cell.

The numerical simulations have been conducted with commercial FEM software, COMSOL Multiphysics in Pressure Acoustics Frequency Domain. A two-dimensional simplified model consisted of squares with the side equals to the side of the sample lattice ($d=1.02$ mm) was used for simulation. The elements of the lattice were assumed to be rigid, and a linear elastic fluid with the properties of air was used in the models. The number of the elements and their physical properties were the same as in experimental samples.
Table 2. Dimensions and distances in the measuring cell.

| Distance from | Distance to | Value      |
|---------------|-------------|------------|
| transducer    | lattice     | 120 mm     |
| lattice       | receiver    | 130 mm     |
| center of rail| center of sensor | 160 mm |
| center of sensor to water surface | 90 mm |
| Piezo sensor body diameter | 60 mm |
| Piezo plate diameter         | 40 mm |

3. Results

3.1. Propagation of longitudinal BAW in a metamaterial sample in the air

The amplitude-frequency characteristics of metamaterial samples with different numbers of parallel lattices in the sample (\#1, \#n) were experimentally studied in the air in the frequency range of 35-100 kHz (Figure 4a). The non-transmission bands (forbidden zones) for the considered lattices in the air were experimentally investigated. It was possible to obtain a clear pass band in the region of 52-65 kHz in this case. An increase in the number of lattice layers led to an increase in the absorption coefficient in the considered range of the non-transmission band. Additionally, the numerical simulation in the COMSOL environment of the two-dimensional ABS lattice with a period of 2.51 mm showed qualitatively similar results (deviations from the experiment can be explained by simplifications made in the simulation) (Figure 4B). The amplitudes of the transmitted signals in Figure 4 are normalized to their values at 35 kHz and a single lattice layer.

![Figure 4A](image1.png)

![Figure 4B](image2.png)

**Figure 4.** Passbands of ABS plastic lattice with a period of 2.51 mm in the air A) experiment; B) numerical modeling.
3.2. Propagation of longitudinal BAW in a metamaterial sample in the water

For samples \#2.\textit{n} in the form of multilayer lattices made of ABS plastic with the number of lattice layers (\(n\)) from 1 to 5, the amplitude-frequency characteristics of the transmitted bulk acoustic wave (BAW) in water through the sample were experimentally obtained.

The received signal normalization of the BAW passed through the sample was normalized to the previously measured result for the BAW that passed through the experimental cell with a fixing box without a sample. Thus, the amplitude-frequency characteristic shown in Figure 5, was only influenced by metamaterial itself.

As seen from AFC-characteristic on Figure 5, with an increase in the number of lattice layers in the metamaterial, the frequency response becomes more indented, the sample starting to act as a bandpass filter, passing the signal in the ranges from 670 kHz to 880 kHz, from 975 kHz to 1140 kHz, and also from 1260 kHz to 1400 kHz.

![Amplitude-frequency characteristic of samples](image)

**Figure 5.** Amplitude-frequency characteristic of samples \#2.1 (1 layer), \#2.3 (3 layers), \#2.5 (5 layers) in the water.

The measurements were also carried out for sample \#2.5 in the form of 5 layers lattice with the angle of rotation between the normal to the plane of the lattices and the direction of propagation of the BAW. The measurements were carried out with a step of 1 degree in the range from -60° to 60° of rotation of the sample relative to the direction of propagation of the BAW for two fixed frequencies 526 kHz and 712 kHz, which were the frequencies with the highest amplitude for the sample under study.

![Amplitude-frequency characteristic of samples](image)

**Figure 6.** Dependence of the amplitude of the transmitted BAW on the angle of rotation related to the direction of propagation of the BAW for sample \#2.5 for a frequency of 526 kHz and a frequency of 712 kHz.

Figure 6 shows the symmetric pattern at both considered frequencies with respect to the lattice rotation angle, and in the case of propagation of the wave with a frequency of 526 kHz, 2 maximums can be observed at 21° and 39°.

For the 712 kHz wave, there are 3 maximums: a small maximum at 3–7°, 17°, and 29°, which are clearly visible at positive roll angles and shift to the side in the region of negative roll angles. This corresponds to the theoretical distribution of the intensity of the transmitted signal, obtained in the
case of a plane wave incidence on a screen with several identical rectangular holes since the patterns formed by each individual hole overlap and the shadow zones disappear. The maximums on the dependence of the amplitude of the transmitted acoustic wave for a frequency of 712 kHz are closer to the axis than for a frequency of 526 kHz since a shorter wavelength corresponds to a higher frequency, which corresponds to a smaller coordinate for the first minimum, which means that the whole picture becomes more compressed.

4. Conclusions
We have developed and characterized new metamaterial structures consisted of a variable number of parallel lattices. The samples were made of ABS plastic by 3-D printing. We have measured the velocities of compressional and shear waves and calculated the elastic moduli of the second order for the ABS material. The amplitude-frequency characteristics were measured for bulk acoustic waves transmitted through metamaterial samples with different numbers of lattices in the sample placed in gas and liquid media. It was found that the frequency response depends on the number of elementary lattices in the sample and the angle between the direction of propagation of bulk acoustic waves and the normal to the plane of the lattices. Thus, we have proven that it is possible to create new metamaterials acting as band-pass amplitude-frequency filters for longitudinal acoustic waves based on the diffraction of several lattices.

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