# Design and Fabrication of Acoustic Rotator Based on Extremely-anisotropic Metamaterials

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**Abstract**— The field rotator is a fascinating device which can be regarded as a special kind of acoustic illusion, with the capability of making the object covered by it appears like a rotated one. By exploiting acoustic metamaterials with extremely anisotropic parameters, we have theoretically designed and experimentally realized an acoustic field rotator that can be employed to rotate the acoustic wave front by a certain angle. For airborne sound, the designed field rotator simply comprises an array of identical plates made of acrylonitrile butadiene styrene plastic (ABS). Both the numerical and experimental demonstrations of the rotation effect illustrate that the resulting device has a broadband functionality. A nearly perfect agreement is observed between the numerical simulation and experimental results. The influence of the structural parameters on its performance has also been investigated. Moreover, we inspect the frequency dependence of rotation effect and it shows that the designed device can work effectively within a broad band, as long as the effective medium approximation is valid. In addition, it turns out that by elongating each plate the increase of anisotropy of metamaterial can be conveniently attained, which contributes to enhance the rotation effect. With the known relationship between the rotated angle and the structural parameters, the rotation angle can be manipulated conveniently. The application of the proposed device for non-plane wave has also been discussed and the possibility of extending the proposed scheme to three-dimensional cases has been considered. With the capability of rotating acoustic wave front in a controlled manner, the realization of acoustic field rotator has open up a new avenue for the versatile manipulations on the acoustic waves and may have potential application in various situations that require special acoustic controls.

Recently, transformation optics [1, 2] as well as transformation acoustics [3] has aroused great attention. Numerous fantastic devices have been designed and fabricated in experiment, such as invisibility [4] and illusion cloaks [5], etc.. In this letter, we present the theory design and experimental realization of an acoustic field rotator, which can rotate the wave front a preset angle in the center, and it can be regarded as a special acoustic illusion.

We established the mapping between the virtual system and the physical system, and the mass density $\rho^{-1}$ in the physical system should be as follows:

$$\rho^{-1}=\rho_0^{-1}\begin{pmatrix} 1+2t\cos\theta'\sin\theta'+t^2\sin\theta' & -t^2\cos\theta'\sin\theta'-t\left(\cos^2\theta'-\sin^2\theta'\right) \\ -t^2\cos\theta'\sin\theta'-t\left(\cos^2\theta'-\sin^2\theta'\right) & 1-2t\cos\theta'\sin\theta'+t^2\cos\theta' \end{pmatrix}$$

Here the background medium is chosen as air and $t=\theta_0 r/(b-a)$, which is related to the rotated angle $\theta_0$ in the inner cylinder [6].

We proposed a reduced model for the implementability in experiment as showed in Fig. 1. The cylinder is divided into several "fanlike" cells, and a rectangle made of acrylonitrile butadiene styrene plastic (ABS) is inserted in each cell, with its macro-axis titling an angle $\tau/2$ with respect to the tangential direction of the cell. The effective mass density in two different directions $\rho_u$ and $\rho_v$ can be obtained.

The experimental scheme is showed in Fig. 2, where an experimental system is established by two paralleled Plexiglass plates. An array of 188 rectangles was fabricated with thermoplastics via 3D printing to meet the theoretical requirement. We detected acoustic pressure in the inner region of the device in three particular frequencies, 3400 Hz, 5700 Hz and 6700 Hz, and compare the measured results and the simulations as showed in Fig. 3. Throughout the paper, the software COMSOL MULTIPHYSICS is used for the numerical simulations. It can be clearly observed that it has an excellent agreement between the experimental result and the simulation under any particular driving frequency. The wave front inside the rotator remains a plane, almost identical as the incident wave, and it has been rotated by a certain angle as if the wave is propagating from the top-left direction.

Next we inspect the frequency dependence of rotation effect. A slice with a nearly negligible width is placed in the center of the rotator, stretching across the inner circular region. A minimum

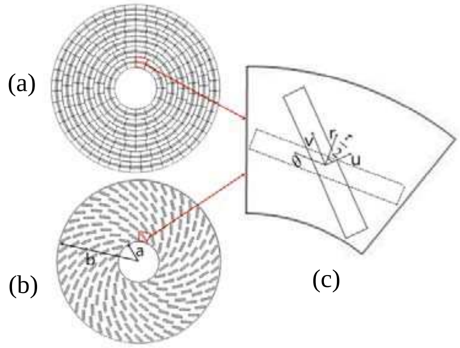


Figure 1: The pattern of the reduced model. In (a) picture the rectangle's macro-axis is parallel to the tangential direction. In (b) picture each rectangle is rotated by $\tau/2$. (c) Picture is the enlarged view of a "fanlike" cell before (dashed line) and after (solid line) rotation.

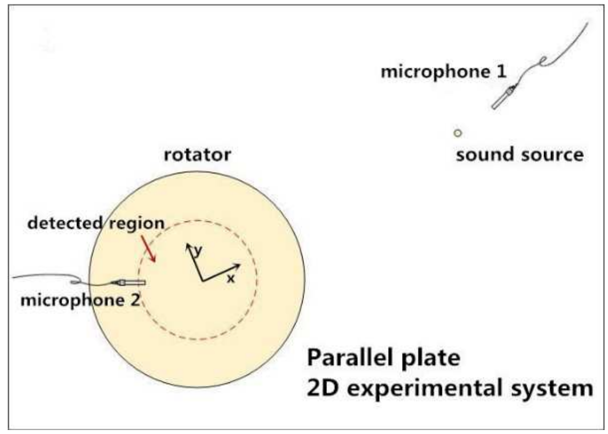


Figure 2: Schematic illustration of the experimental system. The field rotator is put 1 m away from the sound source, and the pressure in the center region (red dotted circle) is measured.

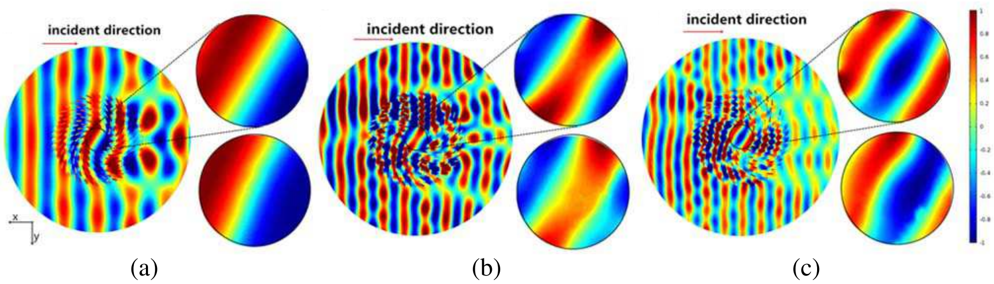


Figure 3: The comparison between the simulated and measured pressure field at (a) 3400 Hz, (b) 5700 Hz, (c) 6700 Hz. The left figure is the simulation around the rotator, the enlarged views of the simulated and measured results in the center are shown in the top-right and bottom-right figures respectively.

scattering caused by the slice can be reached when the slice is parallel to the direction of propagation. The parameter $\sigma$ is defined as the integral of the scattering caused by the slice of the inner circular region. In group A, the inner radius and outer radius of the device are 3.5 cm and 14 cm, and the size of the rectangles are $2.8\,\text{mm} \times 16.8\,\text{mm}$. The relationship between the scattering index $\sigma$ and the frequency in these structural parameters is illustrated in Fig. 4, the green cycle indicates the critical frequency, and it is 6800 Hz in this group. Another two group B and C have also been carried out, in which the structural parameters are twice and half of those in group A, and the critical frequencies are 3400 Hz and 13600 Hz, respectively. We can draw a generalized conclusion that the working standard of the field rotator is $kb \leq 17.4$, with $k$ being the wavenumber and $b$ being the outer radius. The acoustic field rotator should have a broadband functionality due to the absence of acoustic resonance element, and the rotation effect holds within a considerably broad spectrum as long as the effective media theory is valid.

In theory, the parameters of $\rho_u$ and $\rho_v$ satisfy the relationship $\rho_v^{-1} - \rho_u^{-1} = t\sqrt{t^2+4}$, and $t$ is related to the rotated angle $\theta_0$ in the center of the rotator. Therefor we are able to manipulate $\theta_0$ by changing the discrepancy between $\rho_u$ and $\rho_v$, which can be obtained by using two kinds of different materials or simply by enlarging the respect ratio of the inserted rectangles. Here we keep the width unchanged and adjust the length of the rectangles, and illustrate the relationship between $\theta_0$ and the aspect ratio of the rectangles Fig. 5 is the relationship between $\theta_0$ and the length of the rectangles, it shows that the rotated angle increase with the increase of the length, and it has a nearly linear relationship.

It is worth noting that although the rotation performance has only been exemplified in plane

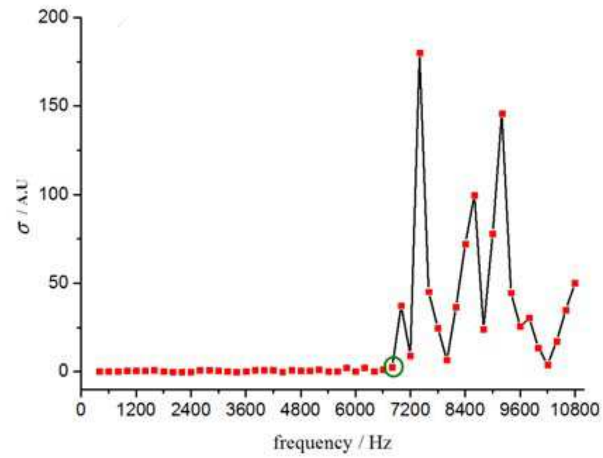


Figure 4: The relationship between the scattering index $\sigma$ and the frequency in group A. The green circle indicates the critical frequency, it is 6800 Hz in these particular structural parameters.

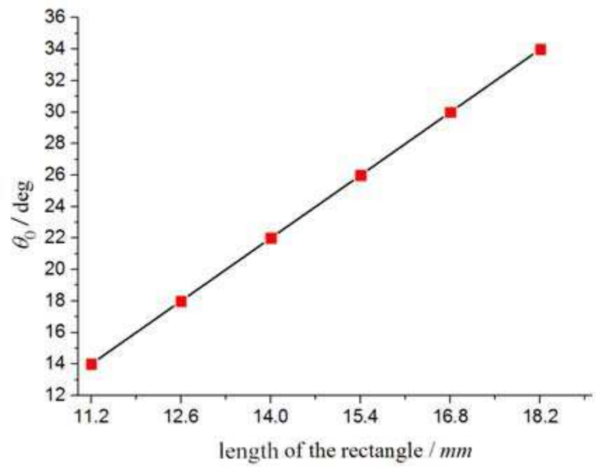


Figure 5: The rotated angle increase with the increase of the length of the rectangles.

wave, its performance should be irrelevant to the type of wavefront. Further simulations proved that it can work well in cylindrical wave. Moreover, the possibility of designing a field rotator for spherical wave in three dimensions will be anticipated in the future.

In summary, we have designed an acoustic field rotator capable of rotating the wave fronts inside it at a certain angle. It has an excellent agreement between the experimental results and simulation. We have also inspected the frequency dependence of rotation effect, it demonstrates that the device has a good performance as long as the effective media theory is valid. In addition, the rotated angle increases with the increase of the length of the rectangles, and is has a nearly linear relationship. The designed acoustic field has open a new avenue to the special manipulation of acoustic wave.

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