Menger Fractal Acoustic Metamaterials with Double-Negative Property

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Abstract – **We construct new three-dimensional fractal acoustic metamaterials by adopting Menger structure, which have the double-negative property with a single structure. By adopting the finite element method and S-parameter retrieval method, the effective parameters of the acoustic metamaterials with different fractal orders are researched separately. The results show that with the increase of the fractal orders, the frequency ranges of negative effective parameters become wider. Furthermore, with the increase of the fractal order, the structure become lighter, which shows a promising application in engineering.**

I. INTRODUCTION

The appearance of locally resonant acoustic metamaterials provide a new way to control low-frequency sound waves for people [1]-[2]. In the frequency ranges of bandgaps, the effective parameter of acoustic metamaterials, such as effective mass density or effective bulk modulus is negative, which are also called single-negative acoustic metamaterials. Compared with single-negative acoustic metamaterials, double-negative acoustic metamaterials simultaneously with negative elastic modulus and negative mass density have more unique properties [3]-[4], such as negative refraction and acoustic focusing. However, in order to realize the double negative properties of acoustic metamaterials, two kinds of single-negative structures are usually combined together. Through the study of labyrinthine fractal structures, researchers have found there are multiple resonance modes appearing in them [5]-[7], which have the double-negative properties, high refraction indexes and show extraordinary physical properties, such as multi-bandgaps, negative refraction and acoustic focusing. Although the fractal structures with multiple resonance modes have the double-negative properties, most of the studies are limited to the two-dimensional fractal acoustic metamaterials, and the basic assumption of extending along the normal direction of the metasurface infinitely give rise to high reflection, which limit the practical application greatly. Therefore, it's meaningful to carry out the study of three- dimensional fractal acoustic metamaterials.

II. DESIGN OF FRACTAL ACOUSTIC METAMATERIALS

The Menger fractal structure has high symmetry and multiple resonant modes, which is the promising properties for the construction of double-negative metamaterials. In this text, the acoustic properties of three-dimensional Menger fractal metamaterials are studied and the three-dimensional unit cells of the first order, the second order and third order fractal structures are proposed in Fig1 (a)-(c).

The construction of the Menger structures can be understood as the following ways: firstly starting with a cube and dividing each face of the cube into nine squares, this way will divide the cube into 27 smaller cubes. Secondly, choosing the middle cube of each side and the most central cube as the acoustic tunnels, by this way, we construct the first order fractal metamaterials as shown in FIG.1.a. To construct the second order fractal acoustic metamaterials, taking the first order structure as the basis, a small unit similar to the first order structure whose dimension is d_2 occupy the rest cubes of the first order, which is shown in FIG.1.b. The construction of third order is similar to the second one, with the small unit whose size is d_3 occupy the rest cubes of the second order, which is shown in FIG.1.c. With the increase of the fractal order, there are more acoustic tunnels are introduced, which can effectively reduce the reflection of acoustic waves in the acoustic metamaterials surface and it's also a better way to construct light acoustic metamaterials, which show a promising application in engineering.

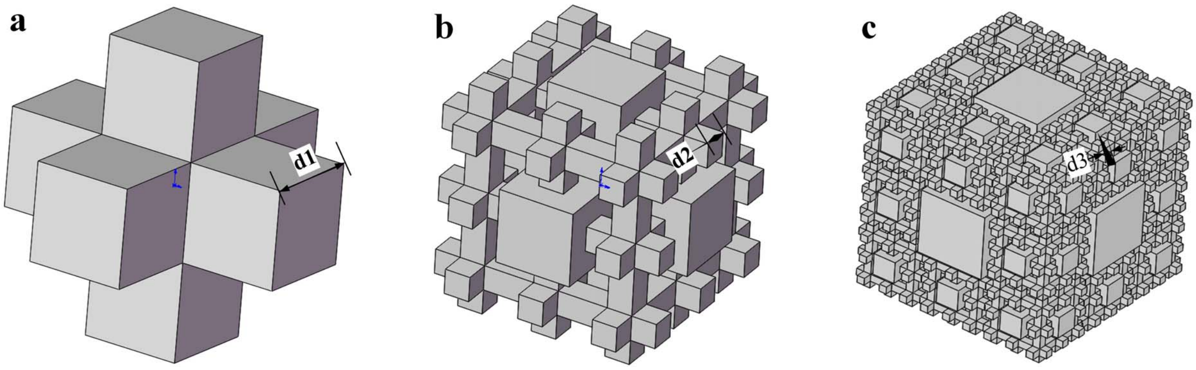

FIG.1. a-c The unit cells of the first-order to third-order fractal acoustic metamaterials (d_1=18mm,d_2=6mm,d_3=2mm)

III. CALCULATION OF EFFECTIVE PARAMETERS

In order to further understand the diagram of double-negative property formation, we calculated the effective parameters of the fractal acoustic metamaterials with the S-parameter retrieval method [8]. The effective mass density, bulk modulus are calculated with the COMSOL Multiphysics and plotted in FIG.3 a-c. The results show in the frequency range [3134Hz, 3152Hz], the effective parameters of the first order are negative, in the frequency range [2750Hz, 3450Hz], the effective parameters of the second order are negative, in the frequency range[2890Hz, 4420Hz], the effective parameters of the third order are negative, which prove that three-dimensional fractal acoustic metamaterials have excellent double-negative property.

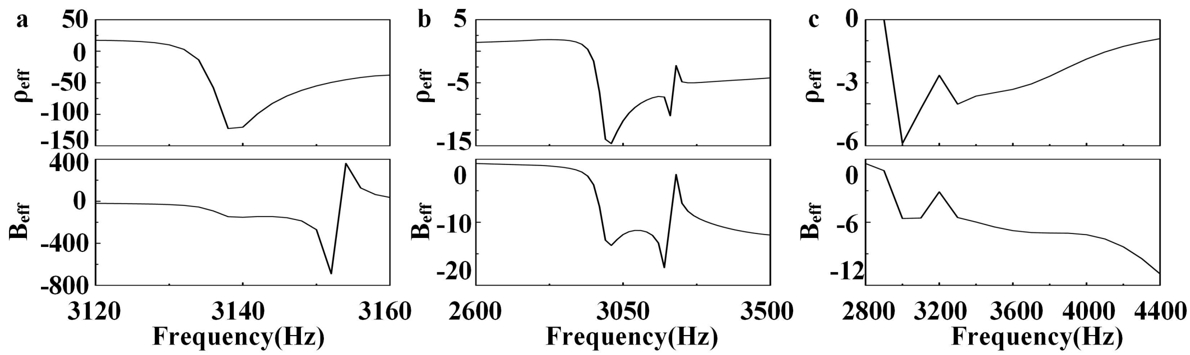

Fig.2. a-c Reflection and transmission coefficients of the fractal acoustic structures from first to third order

IV. CONCLUSION

In this text, three-dimensional Menger fractal acoustic metamaterials are proposed and their double-negative properties are systematically studied by the way of calculating their effective parameters. The results show that firstly, with the increase of the fractal order, the frequency ranges of negative effective parameters become wider, especially in the third order, it's excellent to have a broad range of double-negative. Secondly, with the increase of the fractal order, there are more acoustic tunnels are introduced, which can effectively reduce the reflection of acoustic waves in the acoustic metamaterials surface and it's also a better way to construct light acoustic metamaterials. The results strongly prove the three-dimensional Menger fractal acoustic metamaterials have the double-negative property and will be promising to be applied in engineering.

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