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Space-coiling fractal metamaterial with multi-bandgaps on subwavelength scale

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ABSTRACT

Acoustic metamaterials are remarkably different from conventional materials, as they can flexibly manipulate and control the propagation of sound waves. Unlike the locally resonant metamaterials introduced in earlier studies, we designed an ultraslow artificial structure with a sound speed much lower than that in air. In this paper, the space-coiling approach is proposed for achieving artificial metamaterial for extremely low-frequency airborne sound. In addition, the self-similar fractal technique is utilized for designing space-coiling Mie-resonance-based metamaterials (MRMMs) to obtain a band-dispersive spectrum. The band structures of two-dimensional (2D) acoustic metamaterials with different fractal levels are illustrated using the finite element method. The low-frequency bandgap can easily be formed, and multi-bandgap properties are observed in high-level fractals. Furthermore, the designed MRMMs with higher order fractal space coiling shows a good robustness against irregular arrangement. Besides, the proposed artificial structure was found to modify and control the radiation field arbitrarily. Thus, this work provides useful guidelines for the design of acoustic filtering devices and acoustic wavefront shaping applications on the subwavelength scale.

1. Introduction

Acoustics is the branch of science that studies the propagation of sound and vibrational waves. Acoustic waves are virtually omnipresent in our daily lives and in engineering practice. However, acoustic waves are not always easy to control. New artificial structures/materials that have the ability to control acoustic waves as they propagate, are extremely desirable [1]. Thus, acoustic metamaterial, which is inspired from the developments in electromagnetism [2,3], is a typically periodic (but not necessarily so) artificial structures/materials, composed of small 'meta-atoms' with size scale that is larger than the ordinary atom and much smaller than the operation wavelength. Since the properties of the metamaterials are governed by the 'meta-atom' structures rather than their base materials, by elaborate designing and engineering the parameters of the 'meta-atom' structures such as shape, geometry, size or orientation, unconventional functionalities beyond the capability of conventional materials can be realized, such as forbidden bands [4–7], negative refractive index [8–13], acoustic cloaking [14–19], and subwavelength imaging [20–23]. So far, the strong frequency dispersion of the band structure in acoustic

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metamaterial has been ascribed to two mechanisms. The first one is the Bragg scattering in composites with periodic variations of density and sound velocity [4,5]. In such materials, the Bragg scattering occurs when the lattice constant of the acoustic metamaterial is of the order of half an operating wavelength or more. The second one is the 'local resonance' (LR), which works when the lattice constant is much smaller than its operating wavelength, and the forbidden bands exist in a narrow region around the resonant frequency [6,7]. Thus far, most acoustic metamaterials have been constructed based on the LR theory. Liu et al. [4] fabricated the first LR acoustic metamaterial with negative dynamic mass density by means of a high-density lead sphere and silicone rubber, for the elastic waves propagating in three-dimensional arrays. Subsequently, a further class of acoustic metamaterials with single or double negative effective parameters were proposed, consisting of Helmholtz resonators in the form of open and closed cavities [9–11,24,25]. A three-dimensional has been designed to obtain a strong wave attenuation band in the acoustic frequency range by Delpero et al. [26]. For resonant elements with different structures, a new type of metamaterial called membrane-type metamaterial, which possesses exotic physical properties, has been theoretically proposed and experimentally verified to possess the abilities for bandgap tunability and low-frequency sound attenuation [10,27–30]. Lai et al. [31] presented an elastic metamaterial with hybrid elastic unit cells that can generate multiple resonances with monopolar, dipolar, and quadrupolar characteristics. However, the structures, designed to possess extreme parameters, utilize locally resonant elements with considerable absorption losses and narrow operating bandwidth, which limit their practical applications. Ganghoffer et al. [32–37] studied the homogenization of network materials which used as acoustics metamaterials are widely used and their wave propagation properties with different lattices in the low frequency range. Recently, Cheng et al. [38] demonstrated that artificial Mie-resonance-based metamaterial (MRMM) provide novel acoustic characteristics. A common feature of the Mie resonance is the high refractive index compared to the background medium, especially for airborne sound [11,12,40–46]. The coiling up space of the MRMMs has a labyrinthine structure, and the fluid particles have an ultraslow propagation speed inside the structures. The structures open up a simple but versatile route for the design of acoustic metamaterials. The artificial MRMMs with a high refractive index have an extremely low absorption loss, which makes it promising for engineering applications [41,43,44]. The space coiling structures with zigzag channels are considerably simple in 2D, 2.5D [46], and 3D [40,45]. However, a generalized technique for the design of arbitrary space coiling, based on the self-similar fractal, to obtain a better control over the sound propagation has never been explored.

The self-similar fractal organizations/hierarchical structures are ubiquitous in biological territory, and all of which have been introduced to boost the mechanical performance [47–52]. Recently, illuminated by the fractal organizations, hierarchical photonic/phononic crystals with fractal architectures have been widely investigated. In the field of electromagnetics, a series of structures based on self-similar fractals that yield multiple bandgaps and passbands of electromagnetic waves have been presented [53–55]. In the field of acoustic waves, the applications of self-similar fractal techniques were verified numerically and experimentally, and then applied to the band structure of the phononic crystal and acoustic metamaterials [56–60], broadband wave filtering [59], noise attenuation [53], and focusing acoustic lenses [46].

In this paper, the self-similar fractal technique will be extended to the design of the MRMMs. We designed a new kind of space-coiling MRMMs with fractal geometry, and systematically investigated the effects of the fractal-inspired hierarchy on the band structure of the space-coiling MRMMs. Meanwhile, the sound wave propagation behaviors of space-coiling fractal MRMMs in a waveguide, including sound blocking and filtering were studied. In addition, the robustness of the developed higher order MRMM with respect to the irregular arrangement and wavefront shaping tunability of the fractal MRMMs were surveyed. Our results show that the self-similar properties of the MRMMs makes it a good candidate for new kinds of acoustic applications, and that they can be effectively used to tune the propagation of sound waves in acoustic metamaterials. This new strategy offers an alternate route to design novel materials and devices in acoustic engineering.

The rest of this paper is organized as follows. In Section 2, the evolution of a regular Hilbert into the space-coiling fractal MRMMs is illustrated. In Section 3, the finite element method (FEM) is briefly explained and applied to calculate the band structure and transmission coefficient of a space-coiling fractal MRMM. In Section 4, the sound wave propagation characteristics and applications of space-coiling fractal MRMMs are presented. It includes discussions on sound transmission loss (STL), sound blocking, robustness of the fractal MRMMs with higher order fractal, and wavefront shaping. The conclusion is drawn in Section 5.

2. Design of space-coiling metamaterials based on Hilbert fractal geometry

The two-dimensional (2D) unit cells of the first order, second order, and third order Hilbert fractal structures are respectively illustrated in Fig. 1(a)–(c). So far, the space-coiling metamaterials or folded channels have been employed for acoustic wave modulation [12,13,38–46]. This paper proposes an elaborate Hilbert fractal geometry design for the MRMM, which is different from prior artificial structure/materials. The fractal geometry was obtained from its inherent self-similarity and fractional dimension D_f. The dimension D_f is defined as the logarithmic ratio between the self-similarity unit number n and the reciprocal of the scale change rate s. It can be written as $D_f = \frac{\log(n)}{\log(1/s)}$. For simplicity, each order curve has a length $a/2$, and the feature segment (i.e., the shortest segment) length of the N-order Hilbert geometry is $a/2 \cdot (2^N - 1)(N \geq 1)$. Then going along the curve path from the initial position to the end, turning the curve path into a certain width liquid channel, in which the sound waves can propagate within it, the patterns of the Hilbert fractal structures are fabricated using a polylactic resin in a constant lattice $a/2$, displayed in Fig. 1(a)–(c). Namely, each order Hilbert structures made of resin plates with two