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Labyrinthine Acoustic Metamaterials with Space-Coiling Channels for Low-Frequency Sound Control

A. O. Krushynska[1)], F. Bosia[1)], N. M. Pugno[2)]
[1)] Department of Physics and Nanostructured Interfaces and Surfaces, University of Torino, Via Pietro Giuria 1, 10125 Torino, Italy. akrushynska@gmail.com
[2)] Laboratory of Bio-Inspired and Graphene Nanomechanics, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123 Trento, Italy. nicola.pugno@unitn.it
Also at:
(i) School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
(ii) Ket Labs, Edoardo Amaldi Foundation, Italian Space Agency, Via del Politecnico snc, 00133 Rome, Italy

Summary
We numerically analyze the performance of labyrinthine acoustic metamaterials with internal channels folded along a Wunderlich space-filling curve to control low-frequency sound in air. In contrast to previous studies, we perform direct modeling of wave propagation through folded channels without introducing effective theory assumptions. We reveal that metastructures with channels that allow wave propagation in the opposite direction to incident waves, have different dynamics as compared to those for straight slits of equivalent length. These differences are attributed to tortuosity effects and result in 100% wave reflection at band gap frequencies. This total reflection phenomenon is found to be insensitive to thermo-viscous dissipation in air. For labyrinthine channels generated by recursive iteration levels, one can achieve broadband total sound reflection by using a metamaterial monolayer, and efficiently control the amount of absorbed wave energy by tuning the channel width. Thus, the work contributes to a better understanding of labyrinthine metamaterials with potential applications for reflection and filtering of low-frequency airborne sound.
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1. Introduction

Acoustic metamaterials are composites with an engineered structure providing remarkable functionalities, e.g. acoustic cloaking, transformation acoustics, and subwavelength-resolution imaging [1, 2]. Apart from unusual effective properties, metamaterials offer various possibilities to control propagation of sound or elastic waves at deep sub-wavelength scales [3, 4, 5]. This can be achieved by incorporating heavy resonators [3], Helmholtz resonators [6, 7], tensioned membranes [8, 9], and sub-wavelength perforations or slits [10, 11, 12, 13] in a material structure. A class of acoustic metamaterials with internal slits is also known as "labyrinthine". These have recently attracted considerable attention due to their abilities to exhibit an exceptionally high refractive index and to efficiently reflect sound waves, while preserving light weight and compact dimensions [12, 13, 14].

Labyrinthine metamaterials enable to slow down the effective speed of acoustic waves due to path elongation by means of folded narrow channels [13, 15]. Their high efficiency in manipulating low-frequency sound has been experimentally demonstrated for various channel geometries. For example, Xie *et al.* have shown the existence of a negative effective refractive index at broadband frequencies for labyrinthine metastructures with zig-zag-type channels [16]. For the same configuration, Liang *et al.* have demonstrated extraordinary dispersion, including negative refraction and conical dispersion for low-frequency airborne sound [15]. Frenzel *et al.* have used the zig-zag channels to achieve broadband sound attenuation by means of three-dimensional labyrinthine metastructures [17, 18]. The issue of poor impedance matching for labyrinthine metamaterials has been addressed by exploiting tapered and spiral channels [19] and hierarchically structured walls [20]. Cheng *et al.* have proven almost perfect reflection of low-frequency sound by sparsely arranged unit cells with circular-shaped channels that support generation of strong artificial subwavelength Mie resonances [12]. In our previous work, we have proposed a simple modification to the latter design (by adding a square frame) to achieve a wider bandwidth tunability

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