Acoustic and elastic metamaterials

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Abstract

We will review some of the recent advances in the field of acoustic and elastic metamaterials. These research fields became hot topics in last few years with an increasing number of papers that grows almost exponentially. The interest on these artificial structures arouses because of their potential application in designing novel devices for sound and vibration control. Their applications cover a broad spectrum such as noise attenuation, medical imaging, ultrahigh focusing or vibration isolation.

1. Introduction

Acoustic metamaterials refer materials with extraordinary acoustic properties that might be feasible using artificial structures of ordinary materials. Using the effective medium approach, the extraordinary properties appear only when the lattice separation is must smaller than the operating wavelength. In a first approach, acoustic metamaterials can be divided in two main types; one covers the ones with positive parameters but having anisotropic fluid-like behaviour and the other contains those with negative parameters. Type I metamaterials with anisotropic mass density are employed to produce fascinating functionalities like acoustic cloaks [1, 2], magnifying hyperlens [3] or gradient index lenses [4,5]. Analogous devices can be also possible using metamaterials based in a tensorial bulk modulus [6]. On the other hand, type II metamaterials with negative parameters have been proposed for a wide range of potential applications. From their initial proposal [7], experimental works have demonstrated the feasibility to obtain artificial structures with negative bulk modulus [8, 9], negative dynamical mass density [10] or both simultaneously [11]. Metamaterials with negative parameters can be used to design acoustic devices with negative index of refraction devices but their application encounters two main drawbacks; their narrow band operation and the associate losses due to their resonant operation.

Acoustic cloaking is perhaps one of the more fascinating phenomenon proposed in the acoustic realm since it allows, in principle, the shielding of any object from incident sound within a broadband region of frequencies and, moreover, it has the property of restoring the wavefront of the impinging wave. This phenomenon will be discussed as a paramount example of what are the current challenges in this research topic.

2. Acoustic cloaking based on anisotropic metamaterials

Acoustic cloaks require artificial structures behaving as fluid-like material with dynamical mass anisotropy. This property was predicted in arrays of non-isotropic solid cylinders embedded in a fluid background [12], but the given set of parameters predicting cloaking [1] can be only obtain by using

ISBN 978-952-67611-2-1

a multilayer of two isotropic fluid-like isotropic materials [13]: one with high density (ρ_+) and other with low density (ρ_-). These densities are functions of the distance r to the object to be concealed and their expressions are

$$\rho \pm (r) = \rho_r(r) \pm \sqrt{\rho_r^2(r) - \rho_r(r)\rho_\theta(r)}, \tag{1}$$

where $\rho_r(r)$ and $\rho_\theta(r)$ are the components of the tensorial mass density proposed in [1]. The corresponding sound speed is also a tensor with components

$$c_r(r) = \left(\frac{R_b - R_a}{R_b}\right)c_0 \text{ and } c_\theta(r) = \left(\frac{r}{r - R_a}\right)c_0, \tag{2}$$

indicating that within the cloak, with thickness R_b-R_a, the angular speed continuously increases and even diverges at distances near R_a. Fluid-like structures with cylindrical mass anisotropy have been recently demonstrated using 2D waveguides with corrugations [14]. However, within these waveguides, sound speed larger than c_0, the speed in the background, are impossible to obtain unless an additional physical mechanism is involved. In spite of this general conclusion an imperfect acoustic cloak was recently reported using sound waves propagating in a film of water deposited on top of a solid with a specifically designed corrugated surface [15]. Later on, a directional acoustic cloak based on an optimized distribution of 120 cylindrical rods surrounding a circular object was demonstrated in airborne sound [16].

To overcome the difficulties mentioned before, a "reduced acoustic cloak" in which the phase velocity tensor is equal to that of the ideal cloak but with different acoustic parameters has been proposed [17]. This can be obtained by using,

$$\widetilde{\rho}_r(r) = \alpha\left(\frac{R_b}{R_b - R_a}\right)^2 \rho_0; \quad \widetilde{\rho}_\theta(r) = \left(\frac{R_b}{R_b - R_a}\right)^2\left(\frac{r - R_a}{r}\right)^2 \rho_0; \quad \widetilde{B}(r) = \alpha B_0, \tag{3}$$

where α is a parameter taking values $\alpha \geq 1$. These parameters can be obtained by using a cluster of identical cylinders surrounding the object and heating or cooling the surface's cylinders according to their spatial position. This proposal involves the temperature as the physical mechanism producing the increasing of phase speed at distances close to the object. Figure 1 depicts, as an example, the proposed circular distribution of 20 layers of cylinders needed to create the required temperature dependence in a cloaking shell with R_b=3R_a.

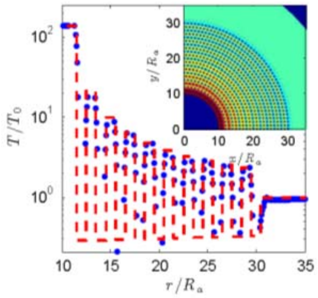

Figure 1: The temperature profile required for the realization of the reduced cloaking shell (red dashed line) is compared with the temperature profile obtained by heating or cooling each cylinder at the corresponding temperature (blue dots). The blue dots are obtained by full wave simulations.

3. Elastic metamaterials for cloaking and other device functionalities

Though the problem of acoustic cloaking has been widely studied by different groups and the experimental results are not yet conclusive, the problem of guiding elastic waves around a central region is rapidly growing because of its potential application on vibration isolation. In this regards, the design of a cylindrical cloak specifically design to control the bending waves propagating in isotropic thin plates [18, 19] was rapidly demonstrated experimentally by using a polymer plate 1 mm thick with concentring rings of different metamaterials [20].

Together with cloaking of elastic waves, many other devices can be envisaged from elastic metamaterials that can be designed using the great feasibility given by the elastic parameters of metals and composites. The effective medium theory has been already applied to get the parameters of certain elastic metamaterials and it has been predicted unusual wave propagation phenomena under different combination of signs in the effectic elastic parameters [21]. Particularly interesting are the elastic metamaterials exhibiting multiple resonances in its building blocks. Extraordinary behaviour of these "hybrid elastic solids" includes the case of "super anisotropy" in which compressional waves and shear waves propagate only along different directions [22].

4. Summary

We have reported the state of the art in some problems related with the rapidly developing field of acoustic and elastic/mechanical metamaterials. While the derivation of effective parameters for acoustic metamaterials without losses has been widely covered, the solutions including the material damping still remain a problem scarcely treated [23]. Though a theory for Bloch-wave propagation in damping elastic media has been already reported [24], the properties of elastic wave propagation in microstructured elastic or mechanical materials will be a topic of paramount interest in the near future because of their potential applications for vibration control.

Acknowledgements

Work supported by the Spanish Ministry of Science and Innovation under Grants TEC 2010-19751 and CSD2008-00066 (Consolider program) and by the U.S. Office of Naval Research. The authors acknowledge useful discussions with J. Carbonell, F. Cervera, A. Climente, A. Díaz-Rubio and R. Gracià-Salgado.

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