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Bianisotropic Acoustic Metafluids in an Aqueous Environment

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14. ABSTRACT

Recent research has shown that fluids embedded with subwavelength scatterers can be described as an effective fluid, or metafluid, with dynamic effective properties. If the scatterers exhibit asymmetry and/or if multiple-scattering betweenscatterers is not negligible, bianisotropy emerges. Acoustic bianisotropy is characterized by coupling between the effective stress-strain and velocity-momentum relations of the metafluid. Theoretical homogenization schemes have demonstrated emergent acoustic bianisotropy for an infinite array of subwavelength scatterers in a fluid matrix. Experimental studies demonstrated individual asymmetric scatterers and metasurfaces that exhibit acoustic bianisotropy. However, previously proposed scatterers were not suitable for an aqueous environment, and previous experiments were limited to one and two dimensions. This report summarizes the approach and accomplishments of the work performed by Caleb F. Sieck with the support of a Karles Fellowship towards designing and experimentally testing a three dimensional aqueous bianisotropic metafluid.

15. SUBJECT TERMS

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CONTENTS

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BIANISOTROPIC ACOUSTIC METAFLUIDS IN AN AQUEOUS ENVIRONMENT

1. OBJECTIVE

The objective of this project was to design and explore the application of bianisotropic acoustic scatterers in an aqueous environment for the extraordinary redirection of acoustic waves. Bianisotropic acoustic scatterers enhance control of acoustic waves through the coupling of monopole and dipole scattering moments, enabling the realization of acoustic properties beyond the range of traditional materials.

2. NAVAL S&T BENEFIT

Development of novel underwater acoustic materials with enhanced capabilities has a high potential payoff to the Navy and is a topic of interest with Codes 32 and 33 of the Office of Naval Research. In addition to significant improvements in acoustic metafluid design, the realization of these materials for aqueous environments provides for the potential expanded functionality over a wide range of underwater acoustic applications, including acoustic coatings and sensors.

3. BACKGROUND

Acoustic and elastic metamaterials have emerged as a novel means to go beyond the bounds of traditional composite materials and achieve extreme effective mechanical properties such as negative, near zero, or very large dynamic mass-density and stiffness. These extreme properties are achieved through subwavelength microstructures that create hidden degrees of freedom and can be predicted by performing dynamic homogenization on a representative unit cell. In the 1980s, J. R. Willis mathematically showed that the dynamic homogenization of elastic composites results in coupling between stress-strain and momentum-velocity relations, which requires additional effective material parameters beyond mass-density and stiffness tensors [1]. This coupled mechanical response has become known as Willis coupling and is analogous to bianisotropy in electromagnetism. While bianisotropy has been studied in electromagnetism for over 200 years due to the natural occurrence of optical activity in some crystals, engineered bianisotropic effects such as asymmetric absorption and reflection, one-way transparency, and anomalous refraction have recently received renewed interest thanks to electromagnetic metamaterials [2]. Despite Willis' results and observations of "acoustical activity," the idea of bianisotropy in acoustic and elastic systems received little attention until decades later [3]. In 2006, Milton et al. demonstrated mathematically that although the conventional elastodynamic equations lack transformation invariance, the equations describing a Willis material are invariant to coordinate transforms, which enabled the adaptation of transformation optics to elastodynamics [4]. At the most fundamental level, Willis coupling accounts for spatial dispersion, which is inherent to all composites, and can be enhanced with asymmetric microstructure leading to novel wave phenomena such as deeply subwavelength impedance-matching between dissimilar media [5], optimal anomalous reflecting and transmitting metasurfaces [6–8], and surface bound acoustic modes, which traditional fluids cannot support [9]. Additionally, neglecting Willis coupling in models has been shown to result in simulations and experiments

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that appear to violate passivity and causality [3, 5]. Previous studies of acoustic bianisotropy have been limited to airborne acoustics and have considered only single scatterers [5, 7, 10] or metasurfaces [6, 8].

4. RESULTS AND ACCOMPLISHMENTS

This work extended the investigation of acoustic bianisotropy to aqueous environments through the development of analytical and numerical predictive tools necessary to design and characterize a finite sized bianisotropic sample underwater. Two research paths continued in parallel throughout this effort: the bianisotropic response of small acoustic scatterers and the observation of bianisotropy in a finite acoustic metamaterial.

Acoustically small scatterers are well characterized by monopole, dipole and coupled polarizabilities. The coupled polarizability characterizes the scatterers ability to convert monopole excitation to dipole scattering or vice versa [3, 7, 10]. Analytical models of acoustic scatterers were developed demonstrating that sectored cylinders result in bianisotropic scattering, and numerical techniques were developed to extract the polarizabilities of geometries of interest. Higher order scattering modes had to be taken into account due to elastic coupling between water and the solid scatterers; these modes were neglected in previous studies because solids appear acoustically rigid compared to air [7, 10]. A method of numerically extracting bianisotropic scattering was developed using commercial finite element software. In Fig. 1(a), the coupled polarizability divided by its theoretical maximum value [7] is shown for the resonant acoustic scatterer that appears in the insert of panel (b). The chosen scatterer, which is made of stainless steel and immersed in water, exhibits strong Willis coupling for a wide range of opening angles θ, as evident by the normalized coupled polarizability above 0.8. The opening angle $\theta = 60^\circ$ was chosen for future analysis due to wide range of coupled polarizability values at wavelengths significantly larger than the size of the scatterer, highlighted in panel (b). The dispersion curves for an infinite array of the C-shaped scatterers for acoustically rigid scatterers (black ‘o’) and for stainless steel scatterers (blue ‘x’) that are elastically coupled to water, the surrounding fluid, are presented in Fig. 1(c). When the lattice period L is approximately a quarter wavelength and larger, the effects of elastic coupling significantly contribute to the effective response of the array. This highlights the importance of accounting for elastic coupling in aqueous acoustic metamaterials.

Progress was made towards adapting homogenization techniques for an infinite array of scatterers [3] to a finite arrangement of scatterers [11]. The effective properties of the finite subwavelength arrangement of scatterers can strongly depend on the chosen boundaries and on the position within the domain, even when arrangement is periodic. Therefore, bianisotropic effects stemming from the finite extent of an experimental sample must be well understood to extract meaningful effective properties. Another significant limitation on the realization of acoustic metamaterials in aqueous environments is the ability to fabricate the designed structures. The fabrication of subwavelength dynamic microstructures as part of a large macrostructural component often requires precision across many orders of magnitude in size. This challenge is overcome using metal additive manufacturing for the 3D printing of the metal structure, such as the lattice of bianisotropic scatterers shown in Fig. 1(d). The sample shown was fabricated from stainless steel using selective laser sintering powder bed fusion with a GE Additive Concept Laser M2 system. A larger bianisotropic acoustic metamaterial was fabricated by the same technique and was experimentally tested. However, the data from this experiment is yet to be analyzed.

Results from this effort were presented at the 176th Meeting of the Acoustical Society of America [9, 11] and at Phononics 2019 [12].

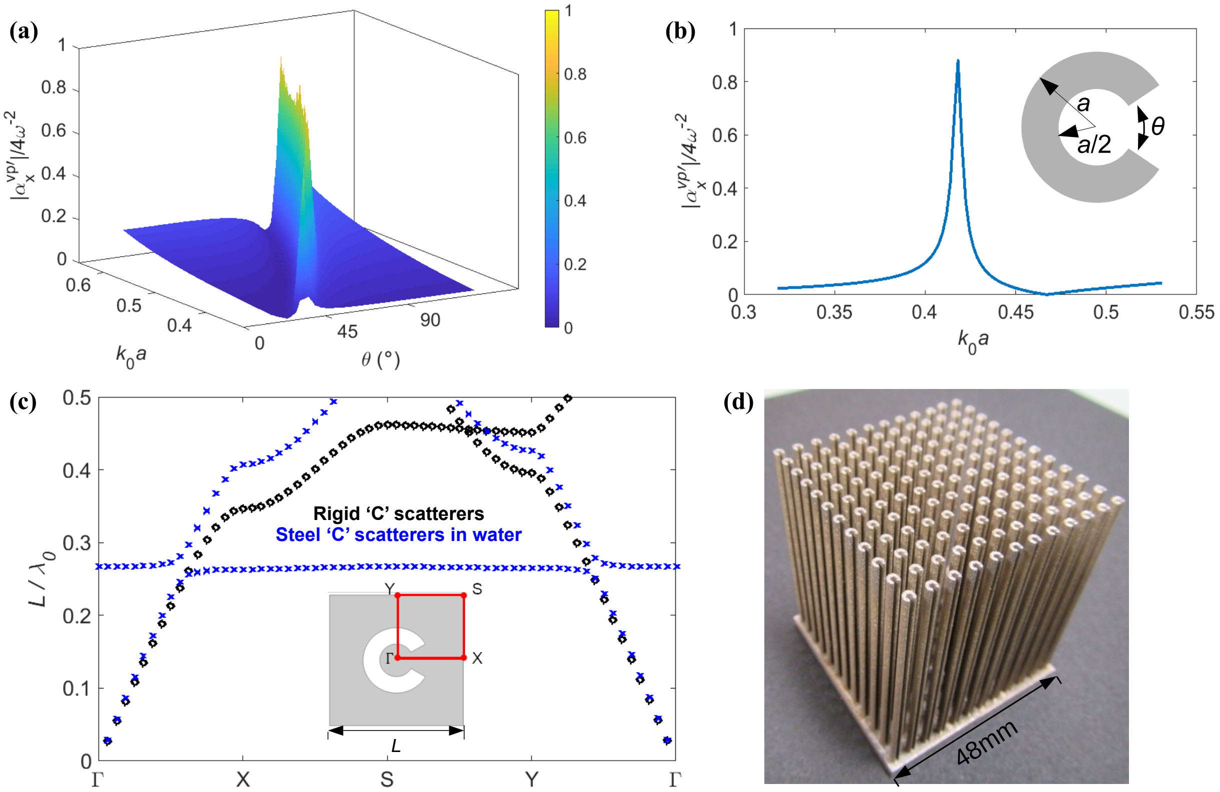

Fig. 1 — (a) Normalized coupled polarizability (vertical axis) of C-shaped bianisotropic acoustic scatterer plotted versus normalized frequency and opening angle. (b) Normalized coupled polarizability for $\theta = 60^\circ$ plotted versus normalized frequency. The C-shaped scatterer studied panels (a)-(d) is shown in the insert in panel (b). (c) Band diagrams of an array of C-shaped scatterers with $\theta = 60^\circ$ arranged in a square lattice with spacing $L = 4a$, for acoustically rigid scatterers (black 'o') and steel scatterers in water (blue 'x'). The vertical axis is the lattice spacing divided by the wavelength in the fluid surrounding the scatterers, and the wavevector path for the horizontal axis is indicated in the insert. (d) An array of bianisotropic scatterers printed from stainless steel powder using selective laser sintering technique: $a = 1\,\text{mm}$, $\theta = 60^\circ$, $L = 4a$, and 50 mm tall.

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