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Acoustic Metamaterials

Negative Refraction, Imaging, Lensing and Cloaking

Springer

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Foreword

by Prof. Andrew Norris, Rutgers University, USA

What are Acoustic Metamaterials? The term Metamaterial has been in use for a little over a decade, introduced in 2000 by R.M. Walser [1]. His and subsequent definitions emphasize the requirements that metamaterials are artificial, i.e. man-made, heterogeneous devices that display new responses precluded by physical constraints from occurring in the constituent materials. In this sense it is clear that acoustic metamaterials must be capable of performing unusual acoustical feats, whether it is sound in air or water, bulk or surface elastic waves in solids, or other types of mechanical wave motion. Interest in acoustic metamaterials has grown rapidly with the realization that the concepts underlying the wave physics of electromagnetic metamaterials, concepts such as negative index of refraction, sub-wavelength imaging, time reversal techniques, transformation optics, etc., have counterparts in acoustics. The subsequent rapid increase of research activity has resulted in numerous special sessions at acoustics conferences, and several special issues of journals devoted to acoustic metamaterials and related topics. However, it is difficult for the researcher, let alone the newcomer, to keep abreast of developments in this new and fast moving field.

The present volume is therefore especially welcome as it is the first comprehensive survey of the state of the art in acoustic metamaterials research. The book is particularly recommended for scientists, engineers and mathematicians with no prior knowledge of acoustic metamaterials. The twelve chapters, written by some of the best people working in the field, are generally written at the level of review articles. This format allows the reader with some background in theoretical and applied acoustics to quickly appreciate and understand the variety of phenomena, applications, and theory at play. The editors, Richard Craster and Sébastien Guenneau, are deeply involved in the subject, having made significant theoretical and experimental contributions to the development of acoustic metamaterials research. As they themselves became acquainted with this rapidly evolving subject, they realized the need for a single source where the interested scientist could quickly get up-to-speed with the wide range of topics involved, such as dynamic homogenization, sub-wavelength acoustic imaging, and transformation acoustics. Prior to this there was no existing text where one could find all of this information. The editors are to be congratulated for assembling in one volume survey articles that together provide a fairly thorough overview of current acoustic metamaterials research.

The field of acoustic metamaterials combines a wide variety of disciplines and subjects, providing a wealth of interesting and challenging problems: Take, for instance, the topic of transformation acoustics and its most well known application, cloaking. The problems involve differential geometry, partial differential equations, acoustic experimentation, continuum mechanics, anisotropy, homogenization, multiple scattering, numerical simulation, material fabrication, etc., and researchers with background in any of these areas will find something of interest. I have found breadth of subject matter to be the most stimulating and rewarding aspect of acoustic metamaterials, and I hope the reader will share my enthusiasm for the subject after reading this book.

1. R.M. Walser, Metamaterials: What are they? What are they good for? APS March Meeting Abstracts, p. 5001, 2000

Rutgers University, Piscataway, NJ, USA Prof. Andrew Norris

Foreword
by Prof. Ross McPhedran, The University of Sydney, Australia

The study of metamaterials is often considered to relate only to the construction of devices and systems for controlling in unprecedented ways the propagation of electromagnetic waves and light. Indeed, it was with his radical ideas relating to these types of wave that Sir John Pendry ignited the interest of scientists, mathematicians and engineers worldwide.

However, it has gradually become evident that the new concepts and techniques emerging from the study of metamaterials are not restricted just to electromagnetism: indeed, we are witnessing a revolution in the whole field of wave science. This is no more evident than in this timely book, which is the first comprehensive study of the impact of metamaterial concepts on the control of acoustic and elastic waves.

Those who are already knowledgeable about the interaction of acoustic or elastic waves with structured systems will not need convincing as to the value of this book. For those who are thinking about taking up the field, there are a number of good reasons why they should commence, with *Acoustic Metamaterials* as an indispensable guide. First among these is Sir Edmund Hillary's classic reason: "Because it's there". The field of acoustic metamaterials is relatively underexplored, with compensating rich challenges and opportunities. Secondly, many of the aspects which make optical metamaterials research difficult do not apply to acoustic metamaterials. For example, to achieve strong contrast in optical properties generally requires use of metals, which are accompanied by strong and undesirable dissipation or loss of energy. The combination of strong contrast and weak energy dissipation is easily achieved in acoustics and elastodynamics. Fabrication of acoustic metamaterials can also be much easier than for their optical counterparts. Other motivational reasons abound in the comprehensive chapters comprising this book.

The principal authors and architects of *Acoustic Metamaterials* are internationally-known and respected researchers in this new field. They have used their wide knowledge and excellent range of contacts to assemble a prestigious team of authors. The result is a beautifully written and well illustrated volume, which exposes the reader to the whole range of techniques necessary to comprehend this field and its emerging applications, ranging from the basic ideas to the latest striking research developments.

Acoustic Metamaterials does more than capture an expanding research field at an exciting stage of its development. Its survey of ideas and techniques will make it an indispensable element of any wave scientist's library for years to come.

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Preface

In 1931, on the centennial of Maxwell's birthday, Albert Einstein described the work of the Scottish physicist and mathematician as *the most profound and the most fruitful that physics has experienced since the time of Newton.* Einstein kept a photograph of Maxwell on his study wall, alongside pictures of Michael Faraday and Newton. James Clerk Maxwell is best known for formulating classical electromagnetic theory: This united all previously unrelated observations, experiments and equations of electricity, magnetism and optics into a consistent theory summarized by four partial differential equations. Importantly, Maxwell's equations retain their form under coordinate changes and gave rise to the Einstein field equations of general theory of relativity. Einstein's equations, published in a compact form in 1915, are a set of 10 (coupled and non-linear) equations describing the fundamental interaction of gravitation as a result of spacetime being curved by matter and energy. These tensor equations are also preserved when they undergo geometric transformations. In generalized coordinate systems, e.g. non-Euclidean metrics, they express that light follows curved trajectories along geodesics. In this way, the flow of light in spacetime is detoured around massive cosmological objects such as heavy planets or black holes (in the latter case, light is ultimately absorbed if it enters the so-called event horizon, but that's another story). The *tour de force* of British physicist Sir John Pendry was to recognize in 2006 that one can markedly enhance control of light trajectories on the scale of the human laboratory by designing metamaterials whose permittivity and permeability curve the electromagnetic space, whereby the time variable only plays the role of a parameter. This original proposal opened new vistas in photonics, e.g. with the fast growing field of cloaking.

However, James Clerk Maxwell is also known for other seminal works, such as for presenting the first durable colour photograph (using the principle of three-colour analysis and synthesis, the basis of nearly all subsequent photochemical and electronic methods of colour photography) during an 1861 Royal Institution lecture on colour theory. Moreover, Maxwell is also recognized for his foundational work on the rigidity of rod-and-joint frameworks like those in many bridges. The latter scientific legacy is maybe less well known, but is of foremost importance as it underpins the parallel developments in electromagnetic and acoustic metamaterials. The foundations of continuum mechanics were lain in Sir Isaac Newton's *Philosophiæ Naturalis Principia Mathematica*, published in 1687, that is over two centuries before Maxwell's work on solid mechanics; it lays the foundations for most of classical mechanics. In this groundbreaking work, Newton described universal gravitation and the three laws of motion. However, Newton was also interested in the theory of light: He built the first practical reflecting telescope and developed a theory of colour based on the observation that a prism decomposes white light into the many colours that form the visible spectrum. In mathematics, Newton shares the credit with Gottfried Leibniz for the development of differential and integral calculus, which are central to modern analysis.

Newton's first Law (the law of inertia) states that an object at rest tends to stay at rest and that an object in uniform motion tends to stay in uniform motion unless acted upon by an external force. The meaning of this law is the existence of reference frames (called inertial frames) where objects not acted upon by forces move in uniform motion (in particular, they may be at rest). This law is central to Galilean and Lorentzian mechanics. In Chap. 1, we draw some useful analogies between governing equations of electromagnetic and mechanical waves allowing for control of their trajectories in transformed coordinates. The field of transformational optics and acoustics is actually a very topical subject and will be further discussed in Chaps. 7–12. The second of Newton's laws further states that a force applied on a particle equals its mass times its acceleration. In the case of a rigid solid, this law is still valid, in which case one considers the center of mass (or gravity) of the solid. In Chap. 1, we stress that it is this very precise law, which bridges electromagnetic and acoustics metamaterials, since it allows one to approximate them as a discrete set of masses connected by springs. The detailed analysis of very unusual dynamic averaged properties of locally resonant structures consisting of split ring resonators (associated with effective negative magnetism or density upon resonance) is carried out using the concept of multi-structures developed by Kozlov, Movchan and Mazy'a in the late nineties. The asymptotic analysis involves Newton's second law at junctions between thin bridges and rigid bodies. Another way to achieve a genuine negative refractive index is to consider a high-contrast in material parameters, modelled using classical low-frequency homogenization. In contradistinction, the origins of all-angle-negative refraction (AANR) in phononic crystals can be seen from the high-frequency homogenization approach recently introduced by Craster and Kaplunov which is also described in this chapter; AANR is based upon negative group velocity of waves propagating along certain crystallographic directions.

Chapter 2 by Khelif, Achaoui and Aoubiza focusses on the numerical analysis (using a finite time difference domain method coupled with Floquet-Bloch conditions to take into account the periodicity in the transverse direction and perfectly matched layers to account for the unbounded domain in the vertical direction) of elastic stop bands associated with periodic arrays of pillars evenly spaced on the surface of a semi-infinite substrate. Elastic waves propagating near the surface are sometimes evanescent in the upper and lower half planes (and therefore reminiscent of Rayleigh waves), and sometimes couple to body (pressure and shear) elastic waves. Depending upon the height of pillars, the physics is associated with either a locally resonant acoustic metamaterial type behaviour leading to low frequency stop bands (for high enough pillars, which can bend, rotate and so forth), or a phononic crystal behaviour leading to classical Bragg effects (for small pillars). The influence of crystal cladding symmetry upon the position and width of stop bands is used in order to distinguish between metamaterial and phononic crystal effects: In the former case, it is shown that stop bands are robust against symmetry changes, while in the latter case stop bands are wider for hexagonal than square lattices.

In Chap. 3, Gei, Bigoni, Movchan and Bacca investigate the effects of prestress on stop band and filtering properties of flexural waves propagating within periodic and quasi-periodic beams, as well as in periodic plates. In the first part, they model Floquet-Bloch propagation of flexural waves in prestressed periodic beams on an elastic spring foundation (Winkler type) which leads to a fourth order ordinary differential equation. They can then adjust the size of the periodic cell in order to introduce some quasi-periodic patterns (supercell approach), and this in turn leads to localization effects reminiscent of Anderson localization. Band gaps and self-similarity in quasiperiodic beams are also investigated. A transfer matrix model is used with the classical trace condition met in optics (whereas here the focus is on bending waves) in order to locate position of stop bands. In the second part, the authors consider plates prestressed through normal and shearing tractions (tensile prestress), and using a finite element model, the authors investigate tuning of stop band positions by varying prestress.

In Chap. 4, Estrada, de Abajo, Candelas, Uris, Belmar, and Meseguer explore extraordinary transmission of pressure waves through subwavelength holes in periodically perforated plates immersed in a fluid. In order to understand how pressure waves can squeeze into periodically arranged thin channels, the authors first use a scalar wave equation to model pressure waves in a fluid surrounded by rigid walls. But they also compare their numerical results with a full elasto-acoustic theory taking into account the transmission of sound waves from the fluid to the surrounding walls, within which pressure waves do couple to shear waves. Numerics are then shown to be in excellent agreement with experiments. Unlike for light, it is found that sound is transmitted through individual subwavelength holes in a perfectly rigid thin film approximately in proportion to their area. Moreover, hole arrays in perfectly rigid thin films do not exhibit full sound transmission due to the absence of lattice resonances responsible for the extraordinary transmission of light in Ebbesen's experiments. However extraordinary sound screening beyond that predicted by the mass law is observed. The authors also unveil a unique interplay between Wood anomaly minima and intrinsic plate (Lamb) modes.

In Chap. 5, Simonetti makes a very comprehensive survey of recent theoretical and experimental results on high-resolution imaging techniques for ultrasonic waves with fascinating applications in medical imaging, such as breast cancer detection. The author combines beamforming algorithms with inverse scattering theory in order to overcome the Rayleigh criterion, which limits the image resolution to about half the working wavelength, hence does not allow for shape reconstruction of subwavelength objects. His original approach involves the factorization of the far-field operator which encodes information about the subwavelength features of an object in the far-field pattern of the scattered wave. The basis of this approach is that to unlock the information about the distortion experienced by the probing wavefield as it travels within the object and which is caused by multiple scattering, it is necessary to approach image formation from an inverse scattering perspective. Recent advances in computer sciences underpin the fast and accurate mapping of the perturbation to the free propagation of ultrasound induced by the presence of an object, the maximum achievable resolution being only dictated by the dynamic range of the detector.

In Chap. 6, Fink, Lemoult, de Rosny, Tourin, and Lerosey review recent developments in time reversal techniques applied to subwavelength imaging for electromagnetic and acoustic waves. The authors explain how the time reversal symmetry of the wave equation allows for the refocussing of the far field emitted by a pressure source surrounded by a closed surface filled with transducer elements back onto the source. In this experiment, the heterogeneities of the medium inside the so-obtained time reversal cavity facilitate the imaging effect: the more complex the medium, the better the focussing. The authors come back to their famous broomstick experiment, whereby eight 2 mm long reactive antenna radiating an electromagnetic wave of about 2.5 GHz surrounded by a random collection of 3 cm long copper wires, and placed a distance of about one thirtiest of a wavelength apart are time reversed and refocussed on two antennas. A similar experiment is then devised for pressure waves with a periodic set of soda cans acting as Helmholtz resonators. With time reversal, the focal spots resolution is already one eight of the wavelength, whereas after the refined iterative time reversal technique, the resolution is far beyond.

In Chap. 7, Li, Liang, Zhu and Zhang review theoretical and experimental properties of transformation based acoustic metamaterials. They explain how one can control pressure waves propagating in structured fluids by playing with the effective anisotropic density of a metamaterial immersed in the fluid. This is done using several examples: An acoustic carpet cloak consisting of curved brass plates flattens the wavefront of pressure waves scattered by a ground with a bump. A magnifying hyperlens consisting of 36 brass fins in air spanning 180 degrees radiates a pressure source field along three preferential directions. Finally, a holey structured metamaterial allows for a subwavelength image thanks to very large effective anisotropic density along some acoustic waveguides, which can be seen as the acoustic counterpart of the famous swiss roll experiment designed by the group of Pendry for electromagnetic radio frequencies.

In Chap. 8, Cummer draws analogies between transformation optics and acoustics, with in-depth explanations of what virtual (original medium) and physical (transformed medium) spaces are in terms of material parameters and wave phenomena. A beam shifter and an acoustic cloaking shell are designed through geometric transforms for pressure waves. Some examples of acoustic metamaterial structures are given and an experimental realization of an acoustic carpet based on perforated sheets of thin plastic stacked with thin air gaps in between is finally discussed.

In Chap. 9, Sánchez-Dehesa and Torrent make a survey of homogenization techniques applied to acoustic cloaking. These are based upon multilayered structures alternating fluids of different density and compressibility. The authors also propose to add some structural elements in fluid layers, such as cylindrical objects, thereafter called sonic crystals. They finally show an experimental realization of a corrugated metamaterial behaving as an anisotropic fluid and they explain what are the physical constraints on acoustic cloaking.

In Chap. 10, Haberman, Guild and Alù explain how one can design acoustic cloaks via scattering cancellation phenomena, based upon plasmonic and anti-resonance cloaking. They manage to cloak the pressure field for an isotropic sphere of stainless steel, aluminum and glass when it is surrounded by a thin shell of fluid. They also investigate such plasmonic shells with multilayers of fluids.

In Chap. 11, Kadic, Farhat, Guenneau, Quidant and Enoch make a survey of theoretical and experimental results on surface liquid and electron wave cloaking. The former is based upon effective anisotropic shear viscosity induced by a structured medium immersed in a fluid. The latter is associated with conformally mapped electromagnetic field at a metallic surface structured with dielectric pillars.

In Chap. 12, Guevara Vasquez, Milton, Onofrei and Seppecher make a very thorough survey of coordinate transformation techniques for Maxwell (electromagnetism), Helmholtz (acoustics) and Navier (elastodynamics) equations. They look at transformed mass-spring networks (what is called discrete transformation elastodynamics) with a Torque effect which could be used in elastic cloaking. They also discuss cloaking via active scattering cancellation devices not completely surrounding the cloaked region (exterior cloaking). The authors use a rich mathematical arsenal for zero frequency (Laplace in 2D) and finite frequency (Helmholtz in 3D) problems. Some theorems are stated for the conductivity equation in 2D making use of conformal transformation with an explicit polynomial solution and for active exterior cloaking for the Helmholtz equation in 3D with a remark on the Green's formula allowing for the explicit form of monopole and dipole sources needed for the cloaking device. The authors finally look at closely packed spherical exterior cloaks.

The twelve chapters constituting this book present an up-to-date survey of many aspects of acoustic metamaterials, including filtering effects, extraordinary transmission, subwavelength imaging via tomography or time-reversal techniques, cloaking via transformation acoustics and elastodynamics and even cloaking via acoustic scattering cancellation and active exterior cloaking. However, we do not claim that the topics covered in this book exhaust the acoustic wave phenomena to which suitably structured surfaces, solids or fluids could lead. Nonetheless, we hope the variety of subjects touched upon in this book, and the way to handle them (theoretically, numerically, experimentally) give a grasp of the richness of the emerging topic of acoustic metamaterials and will contribute to initiate even more research activity and applications in the near future.

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Finally, we wish to express our deepest gratitude to the authors for the thought and care they put into preparing their contributions, and to Professors Andrew Norris and Ross McPhedran whom kindly agreed to preface this book.

Marseille, France — Sébastien Guenneau
London, UK — Richard V. Craster

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