



RESEARCH PAPER

Design of one-dimensional acoustic metamaterials using machine learning and cell concatenation

Rih-Teng Wu¹ · Ting-Wei Liu² · Mohammad R. Jahanshahi^{1,3} · Fabio Semperlotti²

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Abstract

Metamaterial systems have opened new, unexpected, and exciting paths for the design of acoustic devices that only few years ago were considered completely out of reach. However, the development of an efficient design methodology still remains challenging due to highly intensive search in the design space required by the conventional optimization-based approaches. To address this issue, this study develops two machine learning (ML)-based approaches for the design of one-dimensional periodic and non-periodic metamaterial systems. For periodic metamaterials, a reinforcement learning (RL)-based approach is proposed to design a metamaterial that can achieve user-defined frequency band gaps. This RL-based approach surpasses conventional optimization-based methods in the reduction of computation cost when a near-optimal solution is acceptable. Leveraging the capability of exploration in RL, the proposed approach does not require any training datasets generation and therefore can be deployed for online metamaterial design. For non-periodic metamaterials, a neural network (NN)-based approach capable of learning the behavior of individual material units is presented. By assembling the NN representation of individual material units, a surrogate model of the whole metamaterial is employed to determine the properties of the resulting assembly. Interestingly, the proposed approach is capable of modeling different metamaterial assemblies satisfying user-defined properties while requiring only a one-time network training procedure. Also, the NN-based approach does not need a pre-defined number of material unit cells, and it works when the physical model of the unit cell is not well understood, or the situation where only the sensor measurements of the unit cell are available. The robustness of the proposed two approaches is validated through numerical simulations and design examples.

Keywords Acoustic metamaterial · Phononic crystal · Machine learning · Reinforcement learning · Neural network

1 Introduction

1.1 Motivation and relevant works

Acoustic metamaterials are artificial functional materials that offer unique dynamic properties. Either acoustic or elastic waves propagating through a metamaterial could experience effects including, just to name a few, frequency

band gaps (Vasseur et al. 2001; Wu et al. 2005; Oudich et al. 2011; Liu et al. 2014a), anomalous refraction (Sukhovich et al. 2009; Zhang and Liu 2004; Xie et al. 2014; Zhu and Semperlotti 2016), lensing (Lin et al. 2009), cloaking (Cummer and Schurig 2007; Chen and Chan 2007; Popa et al. 2011; Zhu and Semperlotti 2017), and robust waveguiding (Wang et al. 2015; He et al. 2016; Mousavi et al. 2015; Liu and Semperlotti 2019). These effects are typically not achievable in ordinary (i.e., non-engineered) materials. Acoustic metamaterials are typically assembled based on a combination of spatially distributed subwavelength scatterers that can span a variety of materials, shapes, and dimensions (Huang et al. 2009). Most classes of metamaterials typically exhibit spatial periodicity, i.e., translational symmetry in space, and can be designed based on their frequency-wavevector band structure. Acoustic metamaterials can also be non-periodic. Examples include functionally graded materials (Cummer and Schurig 2007), graded index phononic crystals (Lin et al. 2009), and acoustic black holes (Zhao et al. 2014;

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Study Of One Dimensional Multifunctional Acoustic Metamaterials

Jiangyi Zhang



Study Of One Dimensional Multifunctional Acoustic Metamaterials:

Acoustic Metamaterials Hong-Xiang Sun, Yong Ge, Shou-Qi Yuan, 2025-07-23 This book explores the rapidly evolving field of acoustic metamaterials focusing on their ability to manipulate sound waves through asymmetric transmission acoustic focusing and acoustic asymmetric focusing It introduces innovative research methods and achievements such as the use of underwater plate like metamaterials airborne metamaterials and phase controlled metamaterials to achieve precise control over sound propagation in 2D and 3D spaces Readers will be particularly interested in the novel applications of these materials in medical ultrasound underwater detection acoustic communication and noise reduction as well as the development of advanced devices like broadband AF lenses and thermoacoustic phase controlled metamaterials The book is enriched with detailed illustrations tables and clear theoretical explanations making complex concepts accessible It provides valuable insights into the design and modulation of high performance acoustic devices offering both foundational knowledge and advanced techniques for practical applications This work is particularly beneficial for researchers engineers and graduate students in acoustics materials science and related fields as it bridges the gap between theoretical research and real world applications

Springer Handbook of Aerogels Michel A. Aegerter, Nicholas Leventis, Matthias Koebel, Stephen A. Steiner III, 2023-10-01 This indispensable handbook provides comprehensive coverage of the current state of the art in inorganic organic and composite aerogels from synthesis and characterization to cutting edge applications and their potential market impact Built upon Springer's successful Aerogels Handbook published in 2011 this handbook features extensive revisions and timely updates reflecting the changes in this fast growing field Aerogels are the lightest solids known to man Up to 1000 times lighter than glass and with a density only four times that of air they possess extraordinarily high thermal electrical and acoustic insulation properties and boast numerous entries in Guinness World Records Originally based on silica R D efforts have extended this class of materials to incorporate non silicate inorganic oxides natural and synthetic organic polymers carbon metal and ceramic materials Composite systems involving polymer crosslinked aerogels and interpenetrating hybrid networks have been developed and exhibit remarkable mechanical strength and flexibility Even more exotic aerogels based on clays chalcogenides phosphides quantum dots and biopolymers such as chitosan are opening new applications for the construction transportation energy defense and healthcare industries Applications in electronics chemistry mechanics engineering energy production and storage sensors medicine nanotechnology military and aerospace oil and gas recovery thermal insulation and household uses are being developed Readers of this fully updated and expanded edition will find an exhaustive source for all aerogel materials known today their fabrication upscaling aspects physical and chemical properties and the most recent advances towards applications and commercial use This key reference is essential reading for a combined audience of graduate students academic researchers and industry professionals

Architected Multifunctional Materials: Volume 1188 Yves J. M. Brechet, J. David Embury, Patrick R. Onck, 2009-10-07 The MRS Symposium

Proceeding series is an internationally recognised reference suitable for researchers and practitioners **Proceedings of ICOVP and WMVC 2025** Zuzana Dimitrovová, Paritosh Biswas, Tiago A. N. Silva, 2026-01-01 This book gathers select proceedings of the 16th International Conference on Vibration Problems ICOVP 11th International Conference on Wave Mechanics and Vibrations WMVC held in Lisbon Portugal on September 2 5 2025 It covers recent developments and cutting edge methods in wave mechanics wave propagation and vibrations applied to a wide range of engineering problems It presents analytical and computational studies in structural mechanics vibrations of transport systems vehicle dynamics seismology and earthquake engineering structural health monitoring acoustics aeronautics robotics and nuclear engineering among others *Nanomaterials, Metamaterials, and Smart Materials: Synthesis and Characterization* Kamal I. M. Al-Malah, 2025-07-02 Nanomaterials Metamaterials and Smart Materials Synthesis and Characterization explores the science and technology behind nanomaterials metamaterials and smart materials focusing on their synthesis characterization and applications It bridges fundamental concepts with cutting edge research covering material classification size dependent properties fabrication challenges and real world applications in energy healthcare and electronics Societal and ethical considerations are also discussed providing a well rounded perspective on material advancements Key Features Comprehensive Coverage Explores nanomaterials metamaterials and smart materials from foundational principles to advanced applications Practical Learning Tools Includes prerequisite concepts video resources and end of chapter problems for self assessment Interdisciplinary Approach Connects physics chemistry and engineering to real world applications Extensive References Provides citations for further exploration and deeper learning *Dynamics of Lattice Materials* A. Srikantha Phani, Mahmoud I. Hussein, 2017-07-17 Provides a comprehensive introduction to the dynamic response of lattice materials covering the fundamental theory and applications in engineering practice Offers comprehensive treatment of dynamics of lattice materials and periodic materials in general including phononic crystals and elastic metamaterials Provides an in depth introduction to elastostatics and elastodynamics of lattice materials Covers advanced topics such as damping nonlinearity instability impact and nanoscale systems Introduces contemporary concepts including pentamodes local resonance and inertial amplification Includes chapters on fast computation and design optimization tools Topics are introduced using simple systems and generalized to more complex structures with a focus on dispersion characteristics

Proceedings of the 2nd International Conference on Electronic Engineering and Renewable Energy Systems Bekkay Hajji, Adel Mellit, Giuseppe Marco Tina, Abdelhamid Rabhi, Jerome Launay, Salah Eddine Naimi, 2020-08-14 This book includes papers presented at the Second International Conference on Electronic Engineering and Renewable Energy ICEERE 2020 which focus on the application of artificial intelligence techniques emerging technology and the Internet of things in electrical and renewable energy systems including hybrid systems micro grids networking smart health applications smart grid mechatronics and electric vehicles It particularly focuses on new renewable energy technologies for agricultural and

rural areas to promote the development of the Euro Mediterranean region Given its scope the book is of interest to graduate students researchers and practicing engineers working in the fields of electronic engineering and renewable energy The Journal of the Acoustical Society of America Acoustical Society of America,2007 Dynamic Equivalent Modeling of Acoustic Metamaterials Nansha Gao,Jie Deng,2022-10-17 This book derives physical models from basic principles studies the effect of equivalent models on the dynamic characteristics of phononic crystals and acoustic metamaterials and analyzes the physical mechanisms behind vibration and noise reduction It first summarizes the research status of vibration and noise reduction and research progress in phononic crystals and acoustic metamaterials Based on this one dimensional periodic beam two dimensional thin plate with circular hole and corresponding gradient structures are introduced and their dynamic characteristics are discussed in detail Therefore different equivalent methods for different models are proposed through theoretical analysis modal analysis and transmission rate analysis Finally a Helmholtz type acoustic metamaterial i e a multi layer slotted tube acoustic metamaterial is studied Aiming at the low frequency band gap of this model a theoretical model for solving the inverse problem of acousto electric analogue equivalent is proposed and the effect of structural parameters on the low frequency band gap is studied using this equivalent model This book closely revolves around how to conduct equivalent research on artificially fabricated periodic structures The methods and conclusions presented in this book provide a new theoretical basis for the application of artificial woven periodic structures in the field of low frequency vibration reduction and noise reduction and are also an innovation in the discipline of vibration and noise control This book is suitable for undergraduate students graduate students and teachers in vibration and noise majors in universities and can also provide references for engineering and technical personnel in related fields *Multiscale Lattices and Composite Materials: Optimal Design, Modeling and Characterization* Fernando Fraternali,Chiara Daraio,Julian J. Rimoli,2019-11-26 **Directory of Graduate Research** American Chemical Society. Committee on Professional Training,2005 Faculties publications and doctoral theses in departments or divisions of chemistry chemical engineering biochemistry and pharmaceutical and or medicinal chemistry at universities in the United States and Canada *Nonlinear Phenomena in 1D Acoustic Metamaterials* Jiangyi Zhang,2019 The subject of this PhD thesis is the propagation of nonlinear waves in 1D acoustic metamaterials More specifically we aim to study the interplay between nonlinearity loss and dispersion Our studies combine analytical calculations numerical simulations and experimental results In particular we focus our analysis on two main phenomena the second harmonic generation and the formation of solitary waves Two different acoustic metamaterials are studied i A waveguide loaded with a periodic distribution of side holes featuring negative effective bulk modulus and ii a waveguide periodically loaded with clamped elastic plates featuring negative effective mass density Relying on the electroacoustic analogy and the transmission line approach we derive a discrete lattice model for each system The corresponding long wavelength continuum approximation of the lattice models leads to a nonlinear dispersive and dissipative wave equation

From the latter by utilising a perturbation method we obtain analytical results regarding the second harmonic generation Furthermore with the use of a multiple scale analysis we find various envelope bright gap black and gray soliton solutions supported by the acoustic metamaterial The analytical predictions are corroborated by direct numerical simulations We finally perform experiments on an acoustic waveguide loaded with a periodic distribution of side holes and measure the second harmonic generation in close agreement with our theoretical predictions

Acoustic Metamaterials and Phononic Crystals Pierre A. Deymier, 2013-01-13 This comprehensive book presents all aspects of acoustic metamaterials and phononic crystals The emphasis is on acoustic wave propagation phenomena at interfaces such as refraction especially unusual refractive properties and negative refraction A thorough discussion of the mechanisms leading to such refractive phenomena includes local resonances in metamaterials and scattering in phononic crystals

Acoustic Metamaterials with Controllable Transmission Laura Enrique Feliu, 2020 This project deals with the design and analysis of sound scattering in acoustic metamaterials with the aim to realize a controllable transmission response First a so called stealth acoustic metamaterial is studied This is a metamaterial with non periodic rigid scatterers that suppress acoustic scattering at predefined frequencies Although the literature reports a single stealth one dimensional configuration here we show that this configuration is not unique for the specified geometric parameters and that the sound transparent behaviour can be achieved by simply relocating the scatterers To optimize their positions we have developed four algorithms generating feasible configurations which are based on a random choice and three optimization procedures The algorithms are not restricted to the stealth behaviour but are shown to perform well to achieve any desired transmission value This opens bright perspectives to the development of non periodic acoustic metamaterials with controllable transmission In particular we show how a plane wave front can be changed to a half sin function form The acoustic characteristics of the proposed metamaterials have been studied analytically and the obtained results are verified by finite element simulations

Bianisotropy in Passive Acoustic Metamaterials Caleb Frederick Sieck, 2017 Metamaterials are composite materials whose dynamic microstructure results in macroscopically observable properties beyond those available in nature The emergence of metamaterials has enabled unprecedented control of electromagnetic elastodynamic and acoustic wave propagation and has led to technologies including invisibility cloaks super and hyper lenses and subwavelength bandgaps These effects are made possible through the hidden degrees of freedom afforded by the dynamic microstructure Analytically the macroscopically observed parameters are the result of a dynamic homogenization procedure using weighted field averages over a representative volume element of the composite After performing the homogenization procedure constitutive relations reveal the dependencies between macroscopic fields and metamaterial properties Recent research has demonstrated that dynamic homogenization results in constitutive relations that are coupled which is not the case for most traditional materials This general effect is well known in electromagnetism and is known as bianisotropy but the analogous effect in elastodynamics and acoustics was discovered

more recently and is also often referred to as Willis coupling. However, most current homogenization schemes are modeled to determine macroscopic properties in the same form as traditional materials and therefore do not account for coupled constitutive relations. Additionally, in the absence of embedded sources, metamaterial parameters are non-unique, which allows for macroscopic descriptions that only include traditional parameters or traditional parameters and coupling parameters. For acoustic metamaterials, the traditional properties are density and compressibility. The additional coupling parameters result in macroscopic momentum density and volume strain fields that are coupled due to both being dependent on macroscopic acoustic particle velocity and pressure fields. This dissertation explores the analogs between bianisotropy in electromagnetism, elastodynamics, and acoustics and the consequences of neglecting these effects on the physical interpretation of acoustic metamaterial parameters. The analogs are used to provide a qualitative understanding of the origin of coupling parameters, and a multiple scattering homogenization procedure is derived to demonstrate coupling due to asymmetry and nonlocal effects. Additionally, the restrictions of causality, passivity, and reciprocity on acoustic metamaterial parameters are derived, and it is demonstrated that macroscopic descriptions that neglect bianisotropy in one-dimensional acoustic metamaterials do not in general satisfy these restrictions.

Fundamentals and Applications of Acoustic Metamaterials Vicente Romero-Garcia, Anne-Christine Hladky-Hennion, 2019-08-09 In the last few decades, metamaterials have revolutionized the ways in which waves are controlled and applied in physics and practical situations. The extraordinary properties of metamaterials, such as their locally resonant structure with deep subwavelength band gaps and their ranges of frequency where propagation is impossible, have opened the way to a host of applications that were previously unavailable. Acoustic metamaterials have been able to replace traditional treatments in several sectors due to their better performance in targeted and tunable frequency ranges with strongly reduced dimensions. This is a training book composed of nine chapters written by experts in the field, giving a broad overview of acoustic metamaterials and their uses. The book is divided into three parts covering the state of the art, the fundamentals, and the real-life applications of acoustic metamaterials.

New Acoustics Based on Metamaterials Woon Siong Gan, 2017-12-10 This book highlights the acoustical metamaterials' capability to manipulate the direction of sound propagation in solids, which in turn control the scattering, diffraction, and refraction, the three basic mechanisms of sound propagation in solids. This gives rise to several novel theories and applications, and hence the name new acoustics. As an introduction, the book mentions that symmetry of acoustic fields is the theoretical framework of acoustical metamaterials. This is then followed by describing that acoustical metamaterials began with locally resonant sonic materials, which ushered in the concept of negative acoustic parameters such as mass density and bulk modulus. This complies with the form invariance of the acoustic equation of motion, which again exemplifies the symmetry property of acoustic fields.

Effective Acoustic Metamaterial Homogenization Based on Hamilton's Principle with a Multiple Scales Approximation Michael Boone Muhlestein, 2020 This paper derives and demonstrates a one-dimensional acoustic

metamaterial homogenization method The homogenization method uses a multiple scales approximation with Hamilton's principle a weak form representation of the dynamic equation While the multiple scales approximation makes the predicted effective material properties of this method inexact the method is shown to be highly versatile Analytical and numerical examples are given showing the ability of the homogenization method to account for viscosity and finite amplitude effects

Topics On The Nonlinear Dynamics And Acoustics Of Ordered Granular Media Yuli Starosvetsky, K R Jayaprakash, M Arif Hasan, Alexander F Vakakis, 2017-03-17 This research monograph provides a brief overview of the authors research in the area of ordered granular media over the last decade The exposition covers one dimensional homogeneous and dimer chains in great detail incorporating novel analytical tools and experimental results supporting the analytical and numerical studies The proposed analytical tools have since been successfully implemented in studying two dimensional dimers granular dimers on on site perturbations solitary waves in Toda lattices to name a few The second part of the monograph dwells on weakly coupled homogeneous granular chains from analytical numerical and experimental perspective exploring the interesting phenomenon of Landau Zener tunneling in granular media The final part of the monograph provides a brief introduction to locally resonant acoustic metamaterials incorporating internal rotators and the resulting energy channeling mechanism in unit cells and in one and two dimensional lattices The monograph provides a comprehensive overview of the research in this interesting domain However this exposition is not all exhaustive with regard to equally exciting research by other researchers across the globe but we provide an exhaustive list of references for the interested readers to further explore in this direction

Metamaterials with Extreme Properties for the Control of Acoustic Waves Matthieu Malléjac, 2020 Zero index metamaterials for which at least one of the effective parameters density or dynamic compressibility for acoustics vanishes have received considerable attention in recent years These materials have the particularity of inducing a considerable increase in the effective wavelength thus offering numerous application possibilities including among others propagation without phase change acoustic hiding of diffusers directivity control etc This PhD work focuses particularly on the near zero effective density regime in acoustic metamaterials made of thin plates in air Through an in depth study of a periodic arrangement of thin elastic plates embedded in a waveguide we have been able to explore analytically numerically and experimentally some of the above effects Particular attention is paid to the losses inherent to this type of system and their consequences on the expected behavior We begin by studying numerically and experimentally observing a phase change free propagation through the metamaterial at a frequency in a stopband of the finite system We then transpose the concept of photonic doping to acoustics The addition of an impurity here a well chosen Helmholtz resonator to the system allows to transform the regime of zero density into one where density and compressibility are simultaneously near zero Thus propagation without phase change is accompanied by a unitary transmission due to the impedance matching of the system with the surrounding air Finally we study the possibility of performing acoustic hiding or masking of an object using the

acoustic wavelength stretching offered by the zero density

The book delves into Study Of One Dimensional Multifunctional Acoustic Metamaterials. Study Of One Dimensional Multifunctional Acoustic Metamaterials is an essential topic that needs to be grasped by everyone, ranging from students and scholars to the general public. The book will furnish comprehensive and in-depth insights into Study Of One Dimensional Multifunctional Acoustic Metamaterials, encompassing both the fundamentals and more intricate discussions.

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 6. In chapter 5, this book will draw a conclusion about Study Of One Dimensional Multifunctional Acoustic Metamaterials. The final chapter will summarize the key points that have been discussed throughout the book.
- This book is crafted in an easy-to-understand language and is complemented by engaging illustrations. It is highly recommended for anyone seeking to gain a comprehensive understanding of Study Of One Dimensional Multifunctional Acoustic Metamaterials.

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