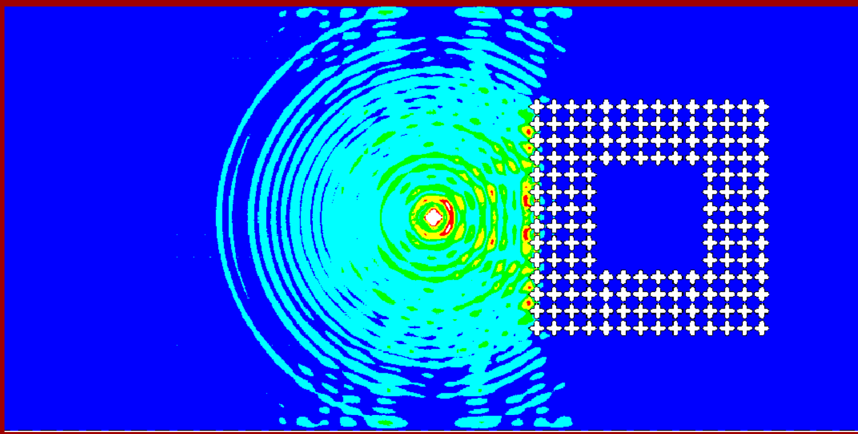

1st International Workshop on: "Advances in mechanical metamaterials"

10-11 October 2016, University of Trento, Italy

Organisers: Marco Miniaci & Anastasiia Krushynska

Local organisers: Davide Bigoni & Nicola Maria Pugno

sponsored by:

EU Horizon 2020 research and innovation programme (Marie Sklodowska-Curie grant N.658483)

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First International Workshop on:

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https://sites.google.com/site/metamikr2015/events

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We would like to express our deepest gratitude to all the participants who made possible the realization of this workshop.

A special thanks goes to Dr. Federico Bosia, Profs. Davide Bigoni, Bruno Morvan and Nicola Maria Pugno for their continuous and excellent guidance throughout the whole event organization.

We are grateful as well to Irena Jatro and Faroudja Hadjaz for their prompt help with the bureaucratic help.

Marco & Anastasiia

Trento, 10 - 11 October 2016

Contents

Part I

Monday 10th October

1.1 Independent Tuning of Elastic Metamaterial Properties: Theory and Applications

***Y. Y. Kim*[1], *J. H. Oh*[2] *and H. Lee*[1]**

[1] Seoul National University

[2] Ulsan Institute of Science and Technology

Abstract

We present the first realization of a single-phase elastic metamaterial allowing independent tuning of effective negative density and stiffness for elastic waves in a plate that propagate along a designated direction. In spite of apparent similarity between elastic waves and electromagnetic/acoustic waves, the independent negativity tuning in elastic metamaterials has not been realized earlier. For the realization, we use local-resonance phenomena occurring in the parallel and perpendicular directions to the wave propagation direction. As an application of the resulting elastic metamaterials, we explore to adjoin the frequency band of negative density and that of negative stiffness, which opens a fully continuous widened stop band. An interesting phenomenon happening at the band-adjoining frequency is also investigated. Another application is the realization of an elastic hyperbolic metamaterial lens exhibiting total-transmission sub-wavelength imaging in which an extreme stiffness value along the wave propagation direction is realized. The experimental results will be also presented.

Contact details

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Talk time: 09:50 - 10:40

1.2 Locally Resonant Metalenses for Lamb and Rayleigh Waves in Plates and Half-spaces

A. Colombi[1]

[1] Department of Mathematics, Imperial College London, South Kensington Campus, London, UK

Abstract

We present our recent work on a metamaterial made of a sub-wavelength collection of resonators (vertical rods) on a finite (plate) or semi-infinite (half-space) substrate that allows for controlling the A0 mode in the plate or Rayleigh waves in the half-space. The dispersion properties of this metamaterial are characterized by bandgaps and slow group velocity branches. We show how these latter can be used to build gradient index devices such as Maxwell, Eaton and Luneburg lenses for both the plate and the half-space case.

For the case of the half-space we also show that a particular hybrid branch of the dispersion curves allows an efficient conversion from Rayleigh to S waves that propagates on along the half-space. The conversion is enhanced when a graded array of resonators is used resulting in a broadband "metawedge" to mode convert or trap Rayleigh waves.

These devices are presented using results from time domain numerical simulations and laboratory experiments at various scales to highlight the broad applicability of these concepts across the wavelength spectrum. Potential applications span from optomechanics (nanoscale) and structural vibration control (microscale) to geophysics (mesoscale).

Contact details

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Talk time: 11:00 - 11:30

1.3 High-Contrast Resonators and 3D-Periodic Foundations Endowed With Wide Band Gaps for the Seismic Protection of Fuel Storage Tanks (part 1)

G. Carta[1], *A. B. Movchan*[1], *L. P. Argani*[1], *O. S. Bursi*[2], *V. La Salandra*[2]

[1] Department of Mathematical Sciences, University of Liverpool, UK

[2] Department of Civil, Environmental & Mechanical Engineering, University of Trento, Italy

Abstract

Fluid-filled tanks in tank farms of industrial plants can experience severe damage and trigger cascading effects in neighbouring tanks due to the large vibrations induced by strong earthquakes. In order to reduce tank vibrations, we have explored innovative strategies based on metastructures, designed by metamaterial based concepts.

Along these lines, we conceived a system of high-contrast resonators, consisting of chains of masses - connected by light beams - which are attached both to the top and to the tank foundation. When the tank is subjected to a ground acceleration, most of the external energy is channelled into the chains of resonators, which start to oscillate, while the tank undergoes smaller stresses and deformations. The design of the system of resonators was based on the Floquet-Bloch approach, which leads to an analytical expression of the dispersion relation that defines the wide low-frequency range in which the system of resonators works. The efficiency of this isolation device has been verified both in the frequency domain for different fluid levels, and in the transient regime under realistic seismic records. The Floquet-Bloch method has also been used to study a large cluster of containers connected by a common foundation. Even in this scenario, the resonators have proved to be capable of mitigating the vibrations of the containers. The analytical model was complemented by numerical simulations and examples

based on the data from the Northridge earthquake of 1994 and the Athens earthquake of 1999. Moreover, we have investigation 3D periodic foundations with effective attenuation zones conceived as vibration isolation systems for storage tanks. Based on common construction materials, concrete and rubber, the three-component periodic foundation cell has been developed. Frequency band gaps, computed using the Bloch-Floquet's theorem, have been found to be wide and in the low-frequency region, i.e. below 10 Hz. A parametric study has been also conducted to illustrate the influences of the geometrical and material parameters on the frequency band gaps. Based on the frequency band gaps analysis, numerical simulations have been performed to verify the efficiency of the periodic foundation. Harmonic analysis results have shown that periodic foundations can effectively reduce vibrations in the frequency band gap. Finally, a transient analysis of the whole 3D structure-foundation model has pointed out that 3D periodic foundations can also effectively isolate realistic seismic waves.

Contact details

A. B. MOVCHAN: Abm@liverpool.ac.uk

Talk time: 11:30 - 12:00

1.4 High-Contrast Resonators and 3D-Periodic Foundations Endowed With Wide Band Gaps for the Seismic Protection of Fuel Storage Tanks (part 2)

G. Carta[1], *A. B. Movchan*[1], *L. P. Argani*[1], *O. S. Bursi*[2], *V. La Salandra*[2]

[1] Department of Mathematical Sciences, University of Liverpool, UK

[2] Department of Civil, Environmental & Mechanical Engineering, University of Trento, Italy

Abstract

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Talk time: 12:00 - 12:30

1.5 Large Scale Metamaterials as Seismic Shields

M. Miniaci[1], *A. Krushynska*[2], *F. Bosia*[2] *and N. M. Pugno*[3,4,5]

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[5] School of Engineering & Materials Science, Queen Mary University of London, Mile End Road, London, E1 4NS, UK

Abstract

Earthquakes represent one of the most catastrophic natural events affecting mankind. At present, a universally accepted risk mitigation strategy for seismic events remains to be proposed. Most approaches are based on vibration isolation of structures rather than on the remote shielding of incoming waves. In this work, we propose a novel approach to the problem and discuss the feasibility of a passive isolation strategy for seismic waves based on large-scale mechanical metamaterials, including for the first time numerical analysis of both surface and guided waves, soil dissipation effects, and adopting a full 3D simulations. The study focuses on realistic structures that can be effective in frequency ranges of interest for seismic waves, and optimal design criteria are provided, exploring different metamaterial configurations, combining phononic crystals and locally resonant structures and different ranges of mechanical properties. Dispersion analysis and full-scale 3D transient wave transmission simulations are carried out on finite size systems to assess the seismic wave amplitude attenuation in realistic conditions. Results reveal that both surface and bulk seismic waves

can be considerably attenuated, making this strategy viable for the protection of civil structures against seismic risk. The proposed remote shielding approach could open up new perspectives in the field of seismology and in related areas of low-frequency vibration damping or blast protection.

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Talk time: 12:30 - 13:00

1.6 Towards the Design of Highly Dissipative Low-Frequency Metamaterials: the K-Damping Concept

I. Antoniadis[1]

[1] Dynamics and Structures Laboratory, School of Mechanical Engineering - National Technical University of Athens

Abstract

The terms "acoustic/elastic meta-materials" describe a class of periodic structures with unit cells exhibiting local resonance or possibly other traits that may bring about similar effects. An intuitive description of such designs is by using a simple "mass-in-mass" lumped parameter model. This localized resonant structure has been shown to result to negative effective stiffness and/or mass at certain frequency ranges close to the local resonances. As a result, these structures present unusual wave propagation properties at wavelengths well below the regime corresponding to bandgap generation based on spatial periodicity, (i.e. "Bragg scattering"). Therefore, acoustic/elastic meta-materials can lead to applications, especially suitable in the low-frequency range.

As a first case, the implementation of locally resonant meta-materials in seismic isolation applications is discussed by investigating their potential feasibility in the [0.5, 5.0] Hz frequency band. To this end, via adoption of both Bloch's theory and classical vibration analysis, the one-dimensional mass-in-mass lattice is analyzed in three overlapping sub-bands and corresponding relations for the structural parameters are derived. Initial numerical simulations on finite-dimensional lattices reveal significant potential in the proposed solution and encourage further investigation. Preliminary sizing of such meta-materials resulted to dimensions in the order of 0.1 m up to 1.0 m. Such dimensions present opportunities for the efficient design of unit lattice concepts in the infra-sound range, since they can be equipped with an efficient internal structure. However, the low frequency range of seismic waves requires very heavy internal moving masses, and may im-

pose constraints at the amplitudes of the internally oscillating locally resonating structures.

Further-more, the K-Damping concept will be analyzed. According to this concept, the acoustic/elastic meta-materials are designed to include negative stiffness elements instead of internally resonating added masses. This concept removes the need for the heavy locally added heavy masses, while it simultaneously exploits the negative stiffness damping phenomenon.

Application of this concept to a flexible beam indicated exceptional properties in attenuating the flexural waves of the beam and provided evidence of a drastic increase of several orders of magnitude for the damping ratio of the flexural waves propagating within the structures.

Contact details

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Talk time: 13:00 - 13:30

1.7 Dissipative Acoustic Metamaterials with Sub-wavelength Band Gaps

A. Krushynska[1], *V. G. Kouznetsova*[2] *and M. G. D. Geers*[2]

[1] Department of Physics and Nanostructured Interfaces and Surfaces Centre (NIS), University of Torino, Via Pietro Giuria 1, I-10125, Torino, Italy
[2] Department of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands

Abstract

This talk presents a numerical framework for investigating dispersion properties of phononic materials with dissipative components. Starting from an overview of existing approaches to analyse energy dissipation effects in phononic crystals and acoustic metamaterials due to viscous and viscoelastic material losses, we proceed with considering key aspects of the proposed framework based on the finite-element method and suitable for dealing with various well-known mechanical model describing viscoelastic models. To illustrate the framework capabilities, as an example, we analyze the dispersion and transmission characteristics of a 3-phase acoustic materials made of stiff circular resonators with a soft coating embedded in a polymeric matrix. Viscoelastic material losses present in the matrix and/or the resonators coating are introduced by either an artificial Kelvin-Voigt model with 1 viscosity parameter or a generalized Maxwell model with a number of parameters required to fit experimentally measured data. The analysis of dispersion properties of a corresponding infinite structure is performed by exploiting 3D band structure diagrams including imaginary and complex-values branches of dispersion curves. The interpretation of the obtained results is facilitated by using attenuation spectra and wave transmission for finite-size metamaterial structures. Two mechanisms of the wave energy attenuation, i.e. due to local resonances of inclusions and dissipative effects in the materials, are discussed separately.

Contact details

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Talk time: 14:30 - 15:00

1.8 Pillar Structures for Acoustic Metamaterials and Phononic Crystals

Y. Pennec[1], *Y. Jin*[1], *S. Hémon*[1], *B. Bonello*[2], *B. Djafari Rouhani*[1]

[1] Institut d'Electronique, de Microélectronique et de Nanotechnologie, UMR CNRS 8520, Université de Lille Sciences et technologies, 59650 Villeneuve d'Ascq, France

[2] Institut des NanoSciences de Paris, UMR CNRS 7588, Campus de Jussieu, 75005, Paris, France

Abstract

Among the large varieties of phononic crystals, pillar structures have received a great deal of attention. Indeed, periodic structures of pillars on a thin plate or on a substrate can exhibit both Bragg band gaps as well as low frequency gaps associated with local resonances of the pillars. Thus, they have been studied for different perspectives, either as a phononic crystal or as an acoustic metamaterial. In this presentation, we give a review of our contributions in this field and their most recent progress. First, we describe the mechanism for the opening of the band gaps and their trends as a function of the geometrical parameters as well as material parameters ranging from common materials to soft materials such as rubber. We show the evolution of the band structure when the thickness of the plate is increased until reaching the case of a thick substrate, thus showing the existence of band gaps among the surface localized modes. We review the effect of the pillars shape (cylindrical, conical, double pillars with a neck) and of some additional structures (combined holes and pillars, pillars attached to the plate with thin bars). In a second part, we describe our recent study of whispering gallery modes (WGM) in hollow pillars where confined modes can be obtained both in the Bragg and in the low frequency gaps. In particular, when the hollow part of the pillars is separated from the plate by a cylindrical basis, the confinement of the WGM can be significantly increased, thus opening to functionalities such as filtering and multiplexing by the introduction of waveguides

and cavities in the phononic crystal. We discuss also the possibility of sensing applications when the hollow parts are filled with a fluid. In the last part of the presentation, we investigate the scattering of an incident Lamb wave in the plate by a single or a line of pillars in comparison with the experimental laser generation and detection of acoustic waves and the measurements of the vibrations at the top of the pillars and in the plate by a Michelson interferometer. We study the excitations of the bending and compressional modes and show that the pillar behaves like a local resonator that re-emits the excitation with some phase delay. The amplitude and phase of the re-emitted waves are studied as a function of the characteristics of the pillars and the value of the frequency close to a resonance. The transmission across one line of pillars drops to zero at the frequency of a resonance while it becomes again possible when the frequencies of two different resonances are pushed to coincide with each other. We also show the possibility of Acoustically Induced Transparency (AIT) when a resonance is squeezed between the zeros of transmission of two successive line of pillars. These investigations open the way to tune the transmission and scattering properties by making the pillars active by means of an external excitation.

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Talk time: 15:00 - 15:30

1.9 Bio-Inspired Mechanical Metamaterials

M. Miniaci[1], **A. Krushynska**[2], **F. Bosia**[2], **A. B. Movchan**[3] **and N. M. Pugno**[4,5,6]

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[6] School of Engineering & Materials Science, Queen Mary University of London, Mile End Road, London, E1 4NS, UK

Abstract

Hierarchical structures with constituents over multiple length scales are found in various natural materials like bones, shells, spider silk and others, all of which display enhanced quasistatic mechanical properties, such as high specific strength, stiffness and toughness. At the same time, the role of hierarchy on the dynamic behaviour of metamaterials remains largely unexplored. This study assesses the effect of bio-inspired hierarchical organization as well as of viscoelasticity on the wave attenuation properties of continuous mechanical metamaterials.

In the first part of the talk, we consider single-phase metamaterials formed by self-similar unit cells with different hierarchical levels and types of hierarchy. Results highlight a number of advantages through the introduction of structural hierarchy. Band gaps relative to the corresponding non-hierarchical structures are mostly preserved, while additional "hierarchically-induced" band gaps appear, with novel properties with respect to known local resonance or Bragg scattering

mechanisms. Additionally, some hierarchical configurations allow the tuning of the band gap frequencies of regular metamaterial to lower frequencies, with a simultaneous significant reduction of the global structural weight. We show that even small viscoelastic effects, not treated in the current literature, are essential in determining this behaviour. The approach we propose allows the addition of hierarchical elements to existing metamaterial configurations, with the corresponding improvement of the wave damping properties, thus providing indications for the design of structures for practical applications. Some preliminary experimental results based on SLDV (Scanning Laser Doppler Vibrometer) acquisitions are also provided.

In the second part, inspired by the Nephila spider orb web architecture, we propose a design for mechanical metamaterials based on its periodic repetition. We demonstrate that spider-web metamaterial structure plays an important role in the dynamic response and wave attenuation mechanisms. The capability of the resulting structure to inhibit elastic wave propagation in sub-wavelength frequency ranges is assessed, and parametric studies are performed to derive optimal configurations and constituent mechanical properties. The results show promise for the design of innovative lightweight structures for tunable vibration damping and impact protection, or the protection of large scale infrastructure such as suspended bridges.

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Talk time: 15:30 - 16:00

1.10 Modeling Wave Propagation in Non-Local Band-Gap Metamaterials Via the Relaxed Micromorphic Model

A. Madeo[1]

[1] LGCIE, INSA-Lyon, Université de Lyon, 20 avenue Albert Einstein, 69621, Villeurbanne cedex and IUF, Institut universitaire de France, 1 rue Descartes, 75231 Paris Cedex 05, France

Abstract

Generalized continuum models are nowadays recognized to be a useful tool for the macroscopic description of the mechanical behaviour of materials with heterogeneous microstructures showing unorthodox properties and/or size effects. In particular, a recently introduced generalized continuum model, which we called relaxed micromorphic, has been shown to be well-adapted to describe very exotic behaviours of micro-structured materials in the dynamic regime. In particular, a relaxed micromorphic model is, to our knowledge, the only non-local, generalized continuum model which is able to describe complete band gaps with respect to wave propagation. We study dispersion relations for the considered relaxed medium and we are able to disclose precise frequency ranges for which propagation of waves is inhibited (frequency band-gaps). We explicitly show that band-gaps phenomena cannot be accounted for by classical micromorphic models of the Mindlin-Eringen type as well as by Cosserat and second gradient ones. We finally present some results concerning wave reflection and transmission at a Cauchy/relaxed-micromorphic interface outlining possible interesting applications in vibration and noise control.

Contact details

A. MADEO: angela.madeo@insa-lyon.fr

Talk time: 16:20 - 16:50

1.11 Homogenization of Structured Media

R. V. Craster[1]

[1] Department of Mathematics, Imperial College London, South Kensington, London SW7 2AZ, UK

Abstract

This talk will cover recent developments in the homogenization of structured media. In particular, I will concentrate on frame, truss, lattice media and how to treat them in 2D and 3D using homogenization theory. The talk will also look at dynamic anisotropy and methods to find Green's function behaviour.

Contact details

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Talk time: 16:50 - 17:20

1.12 Real Wave Propagation in Metamaterials

P. Neff[1]***, A. Madeo***[2]

[1] Fakultät für Mathematik, Universität Duisburg-Essen, Mathematik-Carrée, Thea-Leymann-Straße 9, 45127 Essen, Germany

[2] LGCIE, INSA-Lyon, Université de Lyon, 20 avenue Albert Einstein, 69621, Villeurbanne cedex and IUF, Institut universitaire de France, 1 rue Descartes, 75231 Paris Cedex 05, France

Abstract

We study the wave-propagation problem for isotropic generalized continuum models able to describe band-gap response observed in meta-materials. More precisely we investigate the recently introduced relaxed micromorphic model with respect to real wave speeds for a plane wave Ansatz. It is shown that positive definiteness of the energy always implies real wave speeds (positive definite acoustic tensor). Interestingly, rank-one convexity of the model does not imply real wave speeds (while it does in classical linear elasticity). Connections to strain gradient and Cosserat type material are hinted at.

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Talk time: 17:20 - 17:50

1.13 Transformation Cloaking for Flexural Waves in Thin Elastic Plates

M. Brun[1]

[1] Department of Mechanical Chemical and Material science Engineering University of Cagliari - Italy

Abstract

Cloaking transformations for flexural waves in thin elastic plates are considered. A model of broadband invisibility cloak channelling waves in thin plates around finite inclusions is given.

In contrast with the Helmholtz equation, the general form of the fourth-order partial differential equation describing flexural waves in thin plates is not invariant with respect to the cloaking transformation. Transformed equations can be interpreted in the framework of linear theory of plates in presence of longitudinal prestress. An asymptotic derivation provides a rigorous link between the model in question and elastic wave propagation in thin solids. This is discussed in detail to show connection with non-symmetric formulations in vector elasticity.

Contact details

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Talk time: 17:50 - 18:20

Part II

Tuesday 11th October

2.1 Topological Physics: an Adventure from Quantum Condensed Matter to Photonics and Classical Mechanics

I. Carusotto[1]

[1] INO-CNR BEC Center and Department of Physics, University of Trento, I-38123 Povo, Italy

Abstract

In this talk I will give a pedagogical and historical overview of how topological concepts naturally arise in our understanding of many branches of modern physics. Such topological concepts were originally invoked to explain surprising experimental observations in quantum condensed matter physics such as the integer and fractional quantum Hall effects.

In more recent years, they started being successfully applied in completely different contexts, such as photonics and classical mechanics. Key experiments will be illustrated and potential applications to devices and metamaterials with novel and intriguing properties will be highlighted.

Contact details

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Talk time: 09:30 - 10:00

2.2 Spin-Orbit Coupling in a Hexagonal Ring of Pendula

G. Salerno[1] *and* *A. Berardo*[2]

[1] Department of Physics, University of Trento, I-38123 Povo, Italy

[2] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano, 77, I-38123, Trento, Italy

Abstract

We consider the mechanical motion of a system of six macroscopic pendula which are connected with springs and arranged in a hexagonal geometry. When the springs are pre-tensioned, the coupling between neighbouring pendula along the longitudinal (L) and the transverse (T) directions are different: identifying the motion along the L and T directions as a spin-like degree of freedom, we theoretically and experimentally verify that the pre-tensioned springs result in a tunable spin-orbit coupling. We elucidate the structure of such a spin-orbit coupling in the extended two-dimensional honeycomb lattice, making connections to physics of graphene. The experimental frequencies and the oscillation patterns of the eigenmodes for the hexagonal ring of pendula are extracted from a spectral analysis of the motion of the pendula in response to an external excitation and are found to be in good agreement with our theoretical predictions. We anticipate that extending this classical analogue of quantum mechanical spin-orbit coupling to two-dimensional lattices will lead to exciting new topological phenomena in classical mechanics.

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Talk time: 10:00 - 10:30

2.3 Cloaking of Flexural Vibrations in a Structured Plate: Numerical and Experimental Proof-of-Concept

D. Misseroni[1], A. B. Movchan[2], N. V. Movchan[2]

[1] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano, 77, I-38123, Trento, Italy

[2] Department of Mathematical Sciences, University of Liverpool, Liverpool, UK

Abstract

The elastic invisibility cloak for flexural waves in a structured plate is validated through both numerical FE simulations and physical experiments. Experimental set-up and numerical simulation consider three different lattices, namely a homogenous lattice, a lattice with a hole, and a lattice with a cloaked hole. The lattices, constrained by clamps on the two shorter sides and having the other sides free, have been excited by using a Shaker connected to the left clamp. The considered mechanical and geometrical properties of the cloak are based on the regularised cloaking transformation and the theoretical design as reported Colquitt et al. for membrane waves and later for flexural waves in plates. The qualitative assessment of the efficiency of the cloak was provided experimentally by using the Hooke-Chladni-Faraday technique which shows the positions of the nodal lines of the vibrating plate

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Talk time: 10:30 - 11:00

2.4 An Innovative Metamaterial-based Device for the Passively Nonlinear Source Detection and Localization: Theoretical and Experimental Approach

M. Miniaci[1], *A. S. Gliozzi*[2], **B. Morvan**[1], **A. Krushynska**[3], **F. Bosia**[3], **M. Scalerandi**[2], **N. M. Pugno**[4,5,6]

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Abstract

In recent years, acoustic metamaterials have attracted increasing scientific interest for very diverse technological applications ranging from sound abatement to ultrasonic imaging, mainly due to their ability to act as band-stop filters. At the same time, the concept of chaotic cavities has been recently proposed as an efficient tool to enhance the quality of nonlinear signal analysis, particularly in the ultrasonic/acoustic case.

The goal of the present work is to merge the two concepts to propose a metamaterial-based device that can be used as a natural and selective linear

filter for the detection of signals resulting from the propagation of elastic waves in nonlinear solids, e.g. in the presence of damage, and as a detector for the damage itself in time reversal experiments. Numerical simulations and experimental measurements based on Scanning Laser Doppler Vibrometer demonstrate the feasibility of the approach and the potential of the device in providing improved signal to noise ratios and enhanced focusing on scatterer locations.

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Talk time: 11:20 - 11:50

2.5 Experimental Implementation of Tunable Piezoelectric Phononic Crystal

B. Morvan[1], **N. Kherraz**[1], **S. A. Mansoura**[1], **M. Miniaci**[1], **F. Levassort**[2], **L. Haumesser**[2], **P. Maréchal**[1], **P. Bénard**[1]

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Abstract

One of the most important properties of the phononic crystals (PCs) is their ability to prohibit the propagation of acoustic wave in some frequency ranges called Bragg gap (BG) or hybridization gap (HG). Recently, a growing number of works was devoted to the tunability of PCs and was particularly focused on tuning the position or the width of BG. Among the various methods proposed for the realization of tunable PC, the use of piezoelectric materials has proved its effectiveness.

Firstly, a 1D PC made of a stack of piezoelectric plates is considered in the presentation. The control of the effective properties of propagation of the ultrasonic waves in the structure is obtained through the Electric Boundary Conditions (EBCs) on each piezoelectric plate. The case of a negative capacitance impedance load is studied. Setting a negative capacitance shunt not only shifts the parallel resonance frequency of the piezoelectric plate, but also allows compensating the static capacitance of the piezoelectric plate. It has an effect on the effective value of the electromechanical coupling factor. After a brief description of the realization and characterization of the electronic device developed to simulate the negative capacitance, transmission measurements through the shunted PC are detailed showing frequency shifts in the band structure. In a second time, the presentation is focused on experiments with inductive impedance load. In this case, coupling are observed between an electric resonance and the elastic

propagation mode in the PC thanks to the piezoelectric effect. This leads to the opening of an hybridization gap in the band structure of the PC.

The second studied PC is a homogeneous piezoelectric plate covered by 1D periodic arrangement of thin metallic electrodes. The application of various EBCs on the electrode lattice allows changing periodically the effective properties of the piezoelectric plates. Using an optical set-up with a laser vibrometer, experimental dispersion curves are obtained and compared to the theoretical ones. Moreover, displacements and electrical potential fields calculated with a finite element method are used to analyze the BG. The application of periodic EBCs consisting in an alternation of SC electrodes and FP electrodes induces the opening of a frequency gap at the edge of the Brillouin zone for the fundamental symmetric Lamb mode S0. According to our chosen design, this Bragg gap appears around 400 kHz but can be shifted towards low frequency range. This is obtained by doubling the spatial periodicity of the lattice if the same EBC is applied on two consecutive electrodes. Finally, the use of Lamb waves with various dispersion properties and symmetries offer a large number of possibilities for band structure engineering. The device can be easily implemented in integrated electronic circuits and could be efficiently used for the realization of tunable frequency filters or resonators.

Contact details

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Talk time: 11:50 - 12:20

2.6 The Layer-Multiple-Scattering Method Applied to Phononic Crystals Involving Complex Particles: Some Recent Advances

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Abstract

After a brief outline of the layer-multiple-scattering method, we present some new results concerning phononic crystals and related structures consisting of solid inclusions which exhibit additional degrees of freedom. In particular, two kinds of particles are considered here. First, porous fluid-saturated inclusions offering unprecedented possibility for shielding through high-level narrow- and wide-band absorption depending on the type of solid skeletal frame used. Second, solid scatterers with unusual (imperfect) boundary conditions applied on their surface, involving discontinuity of the displacement field through spring-type coupling, which lead to interesting tuning of localized modes and subsequent band gaps. The first system could be of interest for applications ranging from millimetre down to even micrometer scales; the second system has been recently used to mimic successfully the behaviour of nanostructured core-brush crystalline films operating in the GHz frequency range and fabricated through self-assembly techniques.

Contact details

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Talk time: 12:20 - 12:50

2.7 Large Amplitude Nonlinear Waves in Elastic Metamaterials

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Abstract

Wave motion lies at the heart of many disciplines in the physical sciences and engineering. For example, problems and applications involving light, sound, heat or fluid flow are all likely to involve wave dynamics at some level. In this talk, I will present our recent work on a class of problems involving intriguing nonlinear wave phenomena-large-deformation elastic waves in solids.

Specifically, we examine the propagation of a large-amplitude wave in an elastic one-dimensional medium that is undeformed at its nominal state. In this context, our focus is on the effects of inherent nonlinearities on the dispersion relation. Considering a thin rod, where the thickness is small compared to the wavelength, I will present an exact formulation for the treatment of a nonlinearity in the strain-displacement gradient relation. As an example, we consider Green Lagrange strain. The ideas presented, however, apply generally to other types of nonlinearities. The derivation starts with an implementation of Hamilton's principle and terminates with an expression for the finite-strain dispersion relation in closed form. The derived relation is then verified by direct time-domain simulations, examining both instantaneous dispersion (by direct observation) and short-term, pre-breaking dispersion (by Fourier transformations), as well as by perturbation theory. The results establish a perfect match between theory and simulation and reveal that an otherwise linearly nondispersive elastic solid may exhibit dispersion solely due to the presence of a nonlinearity. With this analysis framework established, I will then demonstrate a method for extending the theory to a continuous thin rod with periodically embedded local resonators, i.e., an elastic metamaterial. The method, which is based on a standard transfer matrix

augmented with a nonlinear enrichment at the constitutive material level,yieldsan approximate band structure that accounts for the finite wave amplitude. I will highlight the effects of the nonlinearity on a sub-wavelength band gap, among other intriguing outcomes.

This work provides insights into the fundamentals of nonlinear wave propagation in solids, both natural and engineered problem relevant to a range of disciplines including dislocation and crack dynamics, geophysical and seismic waves, material non-destructive evaluation, biomedical imaging, and, of course, the most intriguing topic of all and the focus of this workshop: elastic metamaterials.

Contact details

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Talk time: 12:50 - 13:20

2.8 Elastic Waves in Finitely Deformed Microstructured Materials

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Abstract

Acoustic metamaterials with periodic microstructures (also referred to as phononic crystals) have attracted considerable attention due to their remarkable properties such as negative elastic moduli, mass density, and refractive index stemming from their microstructures. Moreover, the ability of soft metamaterials to sustain large deformations opens rich possibilities for manipulating elastic wave propagation by deformation. Hence, elastic waves can be tuned by constructing microstructures, which can be further actively controlled by external stimuli, e.g., by mechanical loading, magnetic or electric fields.

In this talk, we will start with the discussion of the acoustic properties of the relatively simple homogeneous hyperelastic materials, and then we will turn to the materials with periodic microstructures. First, we will explore the influence of the deformation induced stiffening on the propagation of small-amplitude elastic plane waves. Second, we will show that electroactive homogeneous materials can be utilized to achieve acoustic functionalities such as disentangling of pressure and shear waves by application of an electric field. Next, we will proceed with the analysis of wave propagation in highly deformable layered materials. In particular, we will present the long wave estimates of the phase and group velocities for the waves propagating in finitely deformed layered media. Moreover, we will introduce the material compositions and loading conditions producing wide complete band gaps (i.e., frequency ranges where neither pressure nor shear waves cannot propagate) at low frequency ranges. Finally, we will discuss the anisotropy of elastic wave propagation in finitely deformed fiber-reinforced composites.

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Talk time: 14:30 - 15:00

2.9 Ultrasensitive Characterization of Gold Nanorods Mechanical Oscillations

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Abstract

Mechanical vibrational resonances in metal nanoparticles have been intensively studied as they can provide significant insight into nanoscale elasticity and potential applications to ultrasensitive mass detection. In this work, we use broadband femtosecond pumpprobe spectroscopy to study the longitudinal acoustic phonons of arrays of gold nanorods with different aspect ratios, fabricated by electron beam lithography. We follow in real time the impulsively excited extensional oscillations of the nanorods by measuring the transient shift of the localized surface plasmon band. Broadband and high-sensitivity detection of the time-dependent extinction spectra enables us to develop a model which allows to retrieve the time-dependent elongation of the nanorods with an ultrahigh sensitivity and to measure oscillation amplitudes of just a few picometers and plasmon energy shifts on the order of $10e2$ meV.

Contact details

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Talk time: 15:00 - 15:30

2.10 Folding and Faulting Waves in Cosserat Elasticity

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[2] School of Engineering & Computing Sciences, Durham University

Abstract

Elastic solids with extreme orthotropy and obeying the constrained Cosserat theory have been shown to provide examples of folding and faulting materials. The key to this behaviour is that the material has to work in a state near failure of ellipticity. In these conditions, the problem of wave propagation is analyzed through the derivation of a new Green function for time-harmonic concentrated load. Results show the existence of folding and faulting waves and may find applications in the channelling and filtering of mechanical signals.

Contact details

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Talk time: 15:30 - 16:00

2.11 On Other (non Meta) Extreme Materials Investigated in Trento

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Abstract

Nanomaterials like carbon nanotubes (CNTs) or graphene have been shown to exhibit outstanding mechanical properties. Unfortunately, transferring their superior characteristics from the nanoscale to macroscale, through their integration in polymeric or inorganic matrices, is a challenging task. Current graphene or CNT- based nanocomposites display characteristic strength and toughness values more than 10 times below the best biological structural materials. Moreover, current engineering materials are in general neither multifunctional, nor self-healing, nor self-cleaning, nor do they display stiffening or tunability in constitutive properties. All of these features however are defining properties of natural biological composites, such as spider silk, limpet teeth, beetle armours, gecko toes, or lotus leaves, to cite only few examples. Thus, bioinspired approaches can be pursued to mimic natural (usually hierarchical) materials and design novel synthetic ones with superior mechanical properties, artificially emulating the way Nature fabricates materials. Here, I will review some of the most promising results obtained in the course of our ERC Starting Grant on Bioinspired Hierarchical Super Nanomaterials and the 3 related ERC Proof of Concepts, involving strength/toughness optimization, smart adhesion, super-hydrophobicity, reduced friction, impact, damping and vibration control. I will also discuss emerging per-

spectives for future work, including the possibility of producing so-called Bionic composites obtained through direct/natural mixing of carbon-based nanoreinforcements into natural materials (e.g. spider or silkworm silk, yeast films, etc.), taking advantage of optimized natural mechanisms (e.g. spider or silkworm spinning, fermentation, etc.).

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Talk time: 16:00 - 16:30

1st International Workshop on:

"Advances in mechanical metamaterials"

In recent years, the study and design of novel materials with unconventional and advanced vibrational properties, often referred to as mechanical metamaterials, has opened up new research road-maps in the field of phononics due to their unique possibilities to control elastic waves. In a broad sense, these materials are heterogeneous media with various types of periodicity at different structural organization levels (from nano- to macro-scale). The structural periodicity, rather than material composition, governs the overall dynamic properties, leading to exotic physical properties, such as negative refraction, stop-band filtering, cloaking, energy harvesting etc., unachievable using continuous materials or traditional composites.

In parallel, recent advances in material science and technology have allowed the realization of a huge variety of metamaterials operating at very different frequency scales, leading to novel application proposals in the field of wave control, focusing and collimation, environmental noise reduction, or even earthquake protection. The fast growth of the topic and expanded interest in the field from researchers with expertise in the areas of acoustic and elastic waves, composite materials, material science, and related fields, provide the main motive for the organization of this event.

Contributions will concern the dynamics of mechanical metamaterials, comprising phononic crystals with direction-dependent frequency bands caused by Bragg scattering and acoustic/elastic metamaterials with the additional feature of local resonance giving rise to sub-wavelength phenomena. This Workshop is intended to provide a platform for researchers working in the field of metamaterials to disseminate their ideas on the design and characterization of new configurations, highlighting novel dynamic phenomena and exploring additional promising applications. The Workshop should also stimulate a cross-fertilization between researchers of the field with other scientists, providing a rapidly growing discipline with an opportunity to find new potential fields of application.

Marco Miniaci & Anastasiia Krushynska