4$^{\text{th}}$ Symposium on Acoustic Metamaterials

15-18 May 2024, Aegina, Greece

Organised by: Young Researchers in Acoustic Metamaterials

Web: yram.org
Web: sam-2024.sciencesconf.org/

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General information

Welcoming words

We are delighted to welcome you all to Aegina for the fourth symposium on acoustic metamaterials.

This symposium, dedicated to early career researchers and doctoral students coming from numerous European and overseas countries, reflects the international nature of the research activity developed in the field of acoustic metamaterials. It aims at sharing new advances and breakthroughs as well as fostering the community of young researchers in this research field. The fourth SAM will feature six distinct sessions, each consisting of 20-minute talks, along with four plenary lectures delivered by

- Agnès Maurel, DR, CNRS, Institut Langevin, ESPCI (FR)
- Ada Amendola, Prof, University of Salerno, Salerno (IT)
- Michael Haberman, Prof, The University of Texas, Austin (US)
- Kosmas Tsakmakidis, Prof, National and Kapodistrian University of Athens (GR)

This is an exciting time to be working in the field of acoustic metamaterials. During the symposium, we will have the opportunity to see and hear a lot about emerging applications and their impact on sound transport, wave absorption, noise control and much more.

You will also have the opportunity to get an insight into the great history of Greece with the social and cultural visit to the temple of Aphaia on Thursday afternoon, and Athens and the Acropolis on Saturday.

We wish you a warm welcome, and we hope you enjoy the symposium!

Best wishes from the organisers.

Venue

The symposium will be held in Danae Hotel, located at walking distance from Aegina port: Nikou Kazantzaki, Aegina 180 10, Greece.

Information

For practical reasons, we have created a WhatsApp community for the symposium where we will be able to announce updates or last minute changes during the symposium, as well as facilitating the organisation of social gatherings outside the program.

We strongly recommend you join this group to get all the fresh info.

Organizing Committee

Young Researchers in Acoustic Metamaterials (YRAM)

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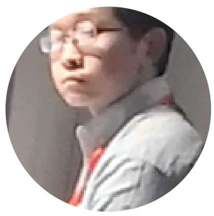

Yang Meng
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France

Sarah Tessier
IEMN
France

Should you have any questions, do not hesitate to come to us!

Breaks & Catering

The morning and afternoon coffee breaks will be offered at the conference venue "Danae Hotel". The lunches are planned around 13:00 at the conference venue and the dinners at 20:00 in restaurants close to the conference venue.

Wednesday May 15$^{\text{th}}$:

- Lunch: Restaurant in "Danae Hotel"
- Dinner: Restaurant "Kappos Etsi" at Panayi Irioti 9

Thursday May 16$^{\text{th}}$:

- Lunch: Restaurant in "Danae Hotel"
- Dinner: Restaurant "Dromaki" at Akti Totti Chatzi 30

Friday May 17$^{\text{th}}$:

- Lunch: Restaurant "Danae Hotel"
- Dinner: Restaurant "Kappos Etsi" at Panayi Irioti 9

Saturday May 18$^{\text{th}}$:

- Lunch: Restaurant To be announced

Social events

Cultural visit - guided visit to Aphaia Temple

Credits: en.wikipedia.org/wiki/Temple_of_Aphaia. This photo was taken by user Paweł "pbm" Szubert and it is released under CC-BY-SA-3.0 license.

Practical information

On Thursday afternoon, we will have the opportunity to visit the famous temple of Aphaia, one of the treasures of the island of Aegina.

We will leave the conference venue by bus at **2.30 pm on Thursday, meeting at the hotel entrance**.

A guide will be on the bus to explain the history of the temple and the island. It will take us around 30 minutes to get to the temple. We plan to return to the conference venue at around 5.30 pm.

Information about the temple

Aegina is home to one of Greece's most captivating archaeological sites: the Temple of Aphaia. This ancient temple, dedicated to the goddess Aphaia, is nestled within a sanctuary complex on a 160-meter hilltop overlooking the Saronic Gulf. The temple, with its stunning Doric architecture, dates back to around 500 BC and represents a unique piece of Greece's ancient history.

One interesting curiosity about the Temple of Aphaia is its triangular relationship with the Parthenon in Athens and the Temple of Poseidon at Sounion. If you draw lines on a map connecting these three temples, you create a perfect equilateral triangle, suggesting an intriguing link between these sacred sites. This geometric alignment has fascinated scholars and visitors for years, raising questions about the possible reasons behind such precise placement.

While exploring the temple grounds, you will find remnants of previous structures and an array of artifacts, including Late Bronze Age figurines. The pedimental sculptures, which adorn the east and west ends of the temple, depict scenes from two different Trojan wars. These impressive sculptures are known for their intricate details and dynamic postures, with many now displayed in Munich's Glyptothek museum.

As you walk through this ancient site, take a moment to appreciate the history, mythology, and artistic legacy that have been preserved over millennia. The Temple of Aphaia offers a captivating glimpse into Greece's rich past and is sure to inspire wonder and curiosity among all who visit.

Visit of Athens

The Parthenon on the Acropolis hill in Athens. Credits: en.wikipedia.org/wiki/Athens This image was originally posted to Flickr on 2 November 2011.

Practical information

On Saturday, we are offering an optional extra social day, aimed at continuing the formation of the community in a more informal waywith a visit to the Acropolis and its museum.

To enable people leaving on Saturday to attend this event, we plan to do the visit in the morning, and therefore leave Aegina by the **first ferry of the morning, i.e. at 9:00 am**.

The journey from Piraeus (arrival port in Athens) to the Acropolis takes around 45 minutes (with the metro). We will arrange for luggage to be deposited in a **secure locker located at Athinas 2 street, (Monastiraki station) https://lockers4all.com.gr**.

After the visit, we will organize the **lunch around 13:00**.

This extra day costs € 40 and includes the visit to the Acropolis and the locker. Please note that the ferry and metro must be taken separately.

If you did not book yet, but are still interested in joining, please let us know as soon as possible.

Information about Acropolis

In Athens, the iconic Acropolis rises above the city as a symbol of ancient Greece's rich history. This hilltop complex is home to some of the most revered and well-preserved classical structures, including the Parthenon, the Erechtheion, and the Temple of Athena Nike.

One intriguing aspect of the Acropolis is its transformation through time. While it is known as a temple complex dedicated to Greek deities, the site has served different purposes over the centuries. The Parthenon, originally dedicated to Athena, was later repurposed as a Christian church, then a mosque during the Ottoman Empire, and even as a gunpowder storage during a siege in 1687, which caused significant damage. This varied history reflects the changing cultural and political landscapes of Athens over the centuries.

As you explore the Acropolis, you will be captivated by the grandeur of the Parthenon, with its towering Doric columns and detailed friezes. The Erechtheion, known for its Porch of the Caryatids, and the Temple of Athena Nike, perched on a high bastion, add to the site's allure.

A visit to the Acropolis Museum at the base of the hill reveals artifacts and sculptures from the site, offering deeper insights into the history and significance of this remarkable place. Walking among these ancient ruins, you will witness the craftsmanship and engineering prowess of the ancient Greeks, making the Acropolis of Athens not just a historic site but an enduring source of inspiration.

List of sponsors

We warmly thank the sponsors of this 4th edition of the Symposium on Acoustic Metamaterials

- European Acoustics Association
- Acoustic Metamaterial Group (AMG, Hong-Kong)
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- Groupement de Recherche Archi-Meta
- Swiss Federal Laboratories for Materials Science and Technology (Dubendorf, Switzerland
- Sil&Add (Le Mans, France)

European Acoustics Association

The European Acoustics Association (EAA) is a non-profit entity established in 1992 that includes in its membership societies predominantly in European countries interested in to promote development and progress of acoustics in its different aspects, its technologies and applications. EAA gathers 33 societies of acoustics and serves more than 9000 individual members all over Europe. The European Acoustics Association (EAA) is an Affiliate Member of the International Commission for Acoustics (ICA) and of Initiative of Science in Europe (ISE).

SAM 2024 is co-organized by the EAA's Technical Committee on Acoustic Material.

Institut d'Acoustique - Graduate School

Led by Le Mans University and the CNRS, the "Institut d'Acoustique - Graduate School" university research school was launched in 2018. Inspired by the Anglo-Saxon model of "graduate schools", the Institute aims to become an international reference center for research and training in the field of acoustics.

Acoustic Metamaterials Group

We are a smart materials and acoustics company that is changing the way we interact with sound and providing noise control solutions in conditions conventional materials cannot address. Coupling applied physics with intelligent design and manufacturing, we are pioneering a new class of multifunctional materials - called metamaterials.

Arenberg Doctoral School

The Arenberg Doctoral School aims at training doctoral researchers both as future scientists and as scientifically trained professionals. The core of the doctoral training is doing research. In addition to research as an instrument for training and development, doctoral researchers also follow more formal training via seminars, workshops, summer schools, and other course components. In order for doctoral researchers to be employable in a broad range of highly qualified positions, transferable skills are a necessary part of the doctoral training program.

Insitut d'electronique, de microélectronique et de Nanotechnologie

With 450 employees of 40 different nationalities, the IEMN brings together most of the research in Hauts-de-France, from nanoscience to instrumentation in the field of microtechnology. It has 5 supervisory bodies and a budget of €28m to develop miniaturised technologies with high added value in electronics, photonics, telecommunications, health technologies, electrical energy, the Internet of Things and transport..

Leuven Mecha(tro)nic System Dynamics

Active since the late sixties, the Noise and Vibration Research Group is still playing an essential role in researching many relevant and advanced industrial applications in the noise and vibration engineering field.

Groupement de Recherche Archi-Meta

GdR ARCHI-META intends to seize this spontaneous convergence and act as a catalyst to go beyond the specificities linked to acoustics and mechanics, bringing together a new community around architected metamaterials. The objective is to get communities (mechanics and acousticians) to identify and resolve common scientific issues highlighted in recent years and to share the theoretical tools specific to the two communities to establish a common language.

EMPA

EMPA is a Swiss Federal research institute within the ETH domain with 1000 employees including 150 PhD students. As part of the Swiss Federal Institutes of Technology Domain, it is an institution of the Swiss federation. For most of the period since its foundation in 1880, it concentrated on classical materials testing. Since the late 1980s it has developed into a modern research and development institute. According to its vision – Materials and technologies for a sustainable future – Empa aims at developing solutions for current problems facing industry and society in areas such as energy, the environment, mobility, health and safety.

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Tailor-made acoustic solutions. When silence is a necessity and ready-to-use solutions don't meet your expectations, turn to Sil&Add! Our expertise, based on the latest advances in aeronautics, is deployed to develop the custom acoustic solution you need.

15 May 2024

Plenary talk - Acoustic analog of Autler-Townes Splitting and application to perfect resonant absorption of guided water waves

Agnès Maurel[1] *†

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Abstract: Our talk will focus on the acoustic analogue of the Autler-Townes splitting, in a configuration where two channels supporting quarter-wave resonances are closely spaced and interact via the evanescent field. We will present the scattering properties of this unique resonator connected to a waveguide in the cases where the two channels are tuned (identical) and detuned (slightly asymmetric). In the detuned case, we will demonstrate that by adjusting the geometry of the resonator, one can easily bring the reflection and transmission zeros to the same position (in the complex plane of wave numbers). An application of this property to the perfect absorption of surface waves will be presented.

Curriculum vitae: Agnès Maurel is a research director at CNRS and conducts her research at the Langevin Institute in Paris. She studies wave propagation in complex media in the fields of waves covering acoustics, electromagnetism, elasticity, and water surface waves. In recent years, her research has focused on the modeling of microstructured materials, which includes metamaterials and metasurfaces.

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Metamaterials for sound absorption

Linear and Nonlinear Thermoviscous Losses of a Helmholtz Resonator

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In this work, we study the absorption effects of linear and nonlinear losses of an acoustic Helmholtz resonator. For a single resonator, the scattering coefficient can be approximated by a pair of isolated zero and pole together with a local phase. From a single pair of complex zeros and poles, we can reconstruct the local scattering coefficient along the real frequency axis. In the lossless case, the poles and zeros are complex conjugated due to time reversal symmetry. When the intrinsic thermal and viscous losses are considered, the zero is shifted towards the real frequency axis and toward lower frequencies as the effective neck length is increased. By tuning the geometry of the resonator, one can obtain Coherent Perfect Absorption when the zero is a purely real value in the linear case and the wave is absorbed along the neck. If one turns to the nonlinear case, the fluid flow is no longer irrotational. A second lossy effect is now possible as the acoustical waves energy is converted into kinetic rotational energy. This is due to the appearance of small vortices located at the vicinity of the neck as the amplitude is increasing. At higher amplitude, larger vortices are blown away from the neck. We present preliminary results as we cary out numerical computation in the linear and nonlinear lossy case. We track the path of the poles and zero and observe the generation of higher harmonics. We illustrate the occurence of Coherent Perfect Absorption through the use of high amplitude waves.

Keywords: Helmholtz resonator, Nonlinear absorption, Coherent perfect absoprtion

*Speaker

Mosaic design strategy: from underwater sound absorbers to air sound insulation metamaterials

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The lightweight design of acoustic metamaterials for low-frequency manipulation has always been a scientific challenge. The limitations of causality and mass density law pose obstacles to acoustic metamaterials' ultra-thin and lightweight design for the absorption and blocking functionalities. In this talk, we propose a mosaic design strategy for acoustic metamaterials, which replaces uniform design with periodic discrete elements by utilizing the characteristics of discrete elements to achieve novel acoustic phenomena. This strategy is shown to be successful in the design of underwater acoustic absorbers. For underwater acoustics, we use slender solid rods as discrete elements, which are made of an impedance-matched composite1. By applying a pressure release boundary condition on the sidewalls of the elements, we can regard Young's modulus as longitudinal wave modulus to tune the effective bulk modulus of the absorber, thereby reducing the minimum thickness under the causality constraint. By combining elements with 9 different lengths as a unit according to the integration scheme2 and arranging the units periodically, we have successfully obtained our underwater sample with ultra-thin thickness (averaged thickness only 8.9mm), realizing high sound absorption (> 0.9) in the frequency range of 4-20 kHz, where the wavelength is much larger than its dimension. The result is demonstrated by both simulations, as well as experiments carried out in a large water pool. New approaches will be introduced in the talk based on the extension to a mosaic design strategy for the realization of a zero-bandgap metamaterial plate that can insulate low-frequency air-borne sound. Previous works on this topic include the analytic works of Movchan and MacPhedran3 on a solid plate with periodically perforated holes, in which the boundary condition of zero displacements was imposed on the holes' edges. There were also some 1D chain designs in which a zero bandgap was defined in the absence of a transmitted signal over a finite low-frequency regime4-5. Preliminary discussions on the mosaic design strategy presented will show in this talk that it can significantly reduce the size or weight of sound-absorbing/insulating metamaterials, thereby providing

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a novel direction for the design of ultra-thin/lightweight acoustic metamaterial with significant practical applications. *This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 101106904 - MDS-APP-UAF. P.S. acknowledges the support of RGC grant A-HKUST601/18 and AoE/P-502/20-3 for this work. J.-P.G. and V.R.-G. acknowledge the support of the ANR-RGC METARoom project (ANR-18-CE08-0021) for this work. V.R.-G. acknowledge support from Grant No. CIAICO/2023/052 of the "Programa para la promocion de la investigacion cientifica, el desarrollo tecnologico y la innovacion en la Comunitat Valenciana" funded by Generalitat Valenciana.*

Keywords: underwater sound absorber, sound insulating metamaterials, causality, mass, density law

Characterisation of metamaterials for underwater acoustics using the 5-point method.

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Experimental characterization of underwater metamaterial-based acoustic panels remains essential to reveal their actual efficiency in terms of reflection, transmission and absorption, since numerical experiments (i.e. simulations) tend to neglect potentially critical effects such as mechanical assembly imperfections or variations in material properties. However, the development of precise measurement procedures giving access to the intrinsic reflection and transmission properties of a finite size panel in an acoustic tank is still a challenge. When insonified by plane waves, these panels typically generate strong edge-diffracted waves. Combined with signals coming from successive reverberations on the water tank walls, they produce a complex wave field in the vicinity of the panel. To tackle this issue, the 3-point method has been developed by L. Roux et al. (J. Acoust. Soc. Am. 147, 2 (2020) 1104-1112). It exploits pressure measurements from several points in space to separate the contributions of these diffracted waves in order to extract the incident, reflected and transmitted pressures. However, for metamaterial designs based on periodic arrays of inclusions in the panel transverse directions, there exists a cut-off frequency above which non-zero array diffraction orders become propagative in water and thus lead to the apparition of additional beams with frequency-dependent propagation directions in the reflected and transmitted fields. Above this cut-off frequency, the 3-point method must be extended to take into account these additional waves. This extension is named 5-point method since it exploits five hydrophones measurement positions instead of three to determine the reflection and transmission coefficients. This method has only been in use for a short time and further tests are needed to prove its validity and make improvements. Tests were carried out on a panel where the lattice constant of the array could be modified. The pressure field was mapped on the reflection and transmission sides to test the robustness of the 5-point method and to prove its utility compared to the 3-point method.

Keywords: Measurement, metamaterials, reflection, transmission, coefficients, periodic arrays

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Modified Helmholtz resonators for sub-wavelength and broadband noise absorption: theory and experiments

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Sound absorption at low frequencies is an everlasting concern in modern acoustics, pushing researchers toward the conception of increasingly compact designs. In this work, we propose a Helmholtz resonator geometry coupled with a micro-perforated panel for sub-wavelength and broadband noise absorption. A lumped model employing the transfer matrix method is developed to analyze the resonance mechanisms of the structure, which determine its absorption performance.
Numerical simulations using the Finite Element Method are carried out to validate the theoretical framework. Measurements are conducted in an impedance tube to confirm the efficacy of the proposed structure.

Keywords: absorption, Helmholtz resonator

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Minimum-phase reflection in passive acoustic system for optimal broadband absorption

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This work shows that, among the possible designs of a 1D system achieving a target absorption spectrum, the one with minimum-phase reflection displays the minimum total volume, making this design optimal for practical use. Minimum-phase reflection implies that all the zeros and poles of the reflection coefficient lie in the same half complex-frequency plane. A dimensionless optimality factor is theoretically derived on the basis of two sum rules of the 1D system: the more optimal the system, the closer this factor approaches unity. Illustrative examples using coupled Helmholtz resonators for broadband sound absorption are provided. These examples show theoretically and numerically that when employing two resonators in parallel, 4 distinct systems can be designed to achieve identical absorption spectrum. The optimal design for minimum-phase reflection features a 40% reduction in total volume compared to its maximum-volume counterpart, while both configurations achieve an absorption coefficient of 0.95 in the frequency range between 900 and 1400 Hz.

Keywords: Broadband absorption, Sum rules, Minimum phase system

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Plenary talk - Acoustic wave interaction with spatiotemporally modulated metasurfaces and domains

Michael Haberman[1] *†

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Abstract: Acoustic and elastic metamaterials with space- and time-dependent material properties have recently received significant attention as a means to realize systems that induce nonreciprocal wave propagation in the bulk or enable frequency and mode conversion of fields scattered from metasurfaces. This work will introduce the fundamentals of acoustic wave propagation in spatiotemporally modulated (STM) materials including space-symmetry breaking of the dispersion relations for freely propagating waves, reflection and transmission at time boundaries, and frequency and wavenumber conversion at interfaces between unmodulated and STM media. The talk will include specific examples of the use of STM to control scattered acoustic waves, namely diffusive and nonreciprocal scattering from flat surfaces via STM of the input admittance and a coupled-mode technique to determine scattering from finite inhomogeneity whose properties are general functions of space and time. In the latter example, we will consider canonical geometries where the analytical solution is known for the unmodulated case which can be used as basis functions to construct the fields within the STM domain. Computations of the scattered field directivity pattern will then be carried out as a function of the modulation parameters to determine cases that yield a large degree of control over the scattered field directivity pattern for each generated frequency harmonic.

Curriculum vitae: Dr. Haberman is an Associate Professor in the Walker Department of Mechanical Engineering at the University of Texas (UT) at Austin with a joint appointment at the Applied Research Laboratories UT Austin. He received his Ph.D. and Master of Science degrees in Mechanical Engineering from the Georgia Institute of Technology in 2007 and 2001, respectively, and received a Diplôme de Doctorat in Engineering Mechanics from the Université de Lorraine in Metz, France in 2006. His undergraduate work in Mechanical Engineering was done at the University of Idaho, where he received a B.S. in 2000. Dr. Haberman's research interests are centered on elastic and acoustic wave propagation in complex media, acoustic metamaterials, new acoustic transduction materials, ultrasonic nondestructive testing, and vibro-acoustic transducers. He has worked extensively on the modeling and characterization of acoustic metamaterials, composite materials, and the multi-objective design of acoustical materials. His research finds application in technical areas that include the absorption and isolation of acoustical, vibrational, and impulsive energy using negative stiffness and Willis coupling, devices that make use of non-reciprocal acoustic and elastic wave phenomena, and condition monitoring of lithium-ion batteries using ultrasonic methods.

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Acoustic metasurfaces

Isospectral open cavities and gratings

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Open cavities are often an essential component in the design of ultra-thin subwavelength metasurfaces and a typical requirement is that cavities have precise, often low frequency, resonances whilst simultaneously being physically compact. To aid this design challenge we develop a methodology to allow isospectral twinning of reference cavities with either smaller or larger ones, enforcing their spectra to coincide so that open resonators are identical in terms of their complex eigenfrequencies.
For open systems the spectrum is not purely discrete and real, and we pay special attention to the accurate twinning of leaky modes associated with complex valued eigenfrequencies with an imaginary part orders of magnitude lower than the real part. We further consider twinning of 2D gratings, and model these with Floquet-Bloch conditions along one direction and perfectly matched layers in the other one; complex eigenfrequencies of special interest are located in the vicinity of the positive real line and further depend upon the Bloch wavenumber. The isospectral behaviour is illustrated, and quantified, throughout by numerical simulation using finite element analysis. This work is published in (1).
(1) S. Cominelli et al. "Isospectral open cavities and gratings." arXiv preprint arXiv:2401.06136 (2023). To be published in Proceedings of the Royal Society A,

Keywords: Geometric transform, Spectral problems, Effective medium, Finite elements, Metamaterials

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Computing the dispersion relations of guided waves in multilayer structures with spectral methods

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Energy dissipation effects are used in the design of poroelastic-based surfaces and interfaces. To date, this topic has received little attention in the literature. Therefore, we propose in this work to study a multilayer arrangement of elastic and poroelastic layers and investigate its modal behavior. Further development would include firstly joint mitigation of both acoustic and elastic waves by exactly matching the losses with the leakage of the structures; and secondly surface acoustic waves manipulation notably by confining the elastic energy in various resonant periodic structures, thus developing a poroelastic metasurface. (T. Weisser et al., JASA 139.2 (2016))
The computation of complex dispersion relations of metaporoelastic configurations typically involves an algorithmic search of complex roots of a numerically computed determinant. This usually requires computationaly intensive methods, with no strong assurance to find all roots. To overcome the limitations of root-finding, a spectral collocation method, already used to evaluate the dispersion relations of elastic waves, is first developed to configurations involving poroelastic layers in the absence of periodic inclusions.
The classical elasticity equation is used for elastic layers, while the (u, p) governing equations formulation is used for poroelastic layers (N. Atalla, R. Panneton and P.Debergue, JASA 104.3 (1998)). In each layer, the appropriate set of equations is written as a linear differential operator, discretized along a set of nodes distributed on the transverse direction of the structure. (F. Quintanilla, M. Lowe, R. Craster, JASA 137.3 (2015)), (L. Trefethen, Spectral Methods in MATLAB, SIAM (2000)). At each interface, coupling operators are provided. Further algebraic manipulations allow to write the system as a generalized eigenvalue problem which eigenvalues are the complex wavenumbers and which eigenvectors are the constructed physical fields in the layers (D. Kiefer et al., JASA 145.6 (2019)). These results are studied with regards to the semi-analytical results obtained from the root-searching procedure. The latter can be extended so that the amplitudes of the propagating waves are also solved, thus allowing to reconstruct the mode shapes and put to perspective the numerical physical fields obtained with the SCM.
The method is applied on a bilayer structure composed of a melamine foam layer coated by an aluminum plate on one side and rigid backed on the other side. The results are validated against those calculated by the root-finding Müller method, and experimental results obtained

*Speaker

with SLaTCoW method (A. Geslain et al., JAP 120.13 (2016)). Results are found in good agreement. The proposed method allows for a quick and accurate way to compute dispersion relations of such systems. This work also paves the way for the generalization of such method to tackle periodic structures in a poroelastic host.

Keywords: numerical method, spectral collocation method, guided wave, poroelastic medium, dispersion relation, multilayer

Elastic metasurfaces

Numerical simulations of the interaction between elastic waves and a single layer of resonant spherical particles

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Interaction between longitudinal waves and a single layer of spherical inclusions have already been well described both theoretically and experimentally (1–3) when the layer is a periodic array of spherical inclusions. In this work we aim to investigate the interaction between any kind of elastic wave (longitudinal or transverse) and a single layer of spherical inclusions that can be both periodically or randomly distributed. This is done by using the code MuScat 3D (4), adapted here to the case of elastic waves, allowing us to solve the multiple scattering equations for large distributions of spherical scatterers. Experimental and numerical results from the literature are retrieved to demonstrate the validity of our numerical approach before using it to explore the behaviour of other distributions of scatterers presenting sub-wavelength translationnal and rotationnal resonances. In particular, we are able to exploit the resonant properties of the inclusions to obtain a band gap behaviour for transverse waves. We also show that, for both longitudinal and transverse waves, random distributions of particles with long-range correlations can reproduce the behaviour of a periodic layer around the region of interest. This opens interesting perspectives to control the propagation of elastic waves with more robustness.

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Keywords: elastic waves, multiple scattering, planar array, space correlations, hyperuniformity

*Speaker

Embedded Periodic Structures for Antiseismic design: A Numerical Study

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The study of surfaces with periodic structures for the purposes of antiseismic design is an area of growing interest in the community of elastic metamaterials. Currently, antiseismic design focuses on structural decoupling (1), where structures are designed such that, in the event of an earthquake, the energy transferred from the ground to the critical structural elements is minimised. This design is, by its nature, bespoke to each structure and its specific needs.

An alternative solution would be to impede the seismic waves from reaching the structure in the first place. In previous studies, it has been shown that pillars placed on the surface of a material (2) or holes drilled within the material (3), with periodic spacing and suitable height/depth variation, reduce the amplitude of surface waves travelling on said surface. Depending on the distribution of the heights of the pillars, or the depth of the holes with respect to the surface wave propagation direction, this is either due to the energy of the wave being "trapped" in the features, or to the mode conversion of the surface wave to a bulk wave travelling away from the surface, or to Bragg-like scattering mechanism, in the latter case.

Such an approach minimises the anti-seismic design costs of a structure, but mainly, can shield entire areas rather than individual buildings. However, in terms of realistic applications, it may be undesirable to populate the perimeters of areas to be protected with arrays of tall pillars or deep holes. Here, we are proposing a solution where we achieve this amplitude reduction effect with pillars embedded in the material, rather than on its surface.

We present numerical validation of our design - numerical modelling of such problems provides useful insight for optimising the design of the metamaterial and for the behaviour of the design in a realistic application. However, due to the inherent low frequency, and hence, large wavelength, nature of seismic waves, generating finite element results quickly becomes infeasible, due to the singificant computational cost of generating, assembling and solving the models. Here, we discuss methods for the efficient creation of large scale meshes (3x10^9 degrees of freedom in 3 dimensions). By using the GPU-based finite element package Pogo (4), we demonstrate the ability to solve these meshes and obtain accurate and reliable results. Our numerical results show that the embedded pillar design is indeed able to reduce the amplitude of a surface wave, both verifying our theoretical calculations and providing useful insight for further validation via experimental design.

*Speaker

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Keywords: antiseismic design, FE modelling, numerical modelling, embedded structures

Simulating structured materials with regular and singular Green's functions in elasticity

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I will discuss the problem of wave scattering by arrays of inclusions in one-dimensional elastic waveguides. I shall demonstrate how the problem can be posed as a regular perturbation to the empty waveguide and tackled through the Green's function. I shall also demonstrate how this method can be applied to the problem considering arrays of elastic beams atop a two-dimensional elastic plate. Here, a beam can be thought of as a singular perturbation to the elastic plate – the perturbation being a monopole and dipole point source term within the elastic plate. Consequently, the solution can be expressed in terms of the Green's function and the gradient of the Green's function; these functions contain singularities, and I will briefly explain how to deal with these singularities to obtain converged solutions for scattering simulations or Floquet-Bloch eigensolutions.

Keywords: metamaterials, regular and singular perturbations, multiple scattering problems, Floquet, Bloch theory

*Speaker

Temporal and space-time modulated media

Scattering by a periodically time-modulated spherical particle

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We examine the scattering of light by a homogeneous spherical object characterized by a periodically time-modulated isotropic permittivity. The inelastic scattering T matrix, which describes the dynamically evolving particle, is evaluated using a rigorous time Floquet method. In the slow-modulation regime, our results are in excellent agreement with the quasistatic adiabatic approximation and the limits of its validity are established. At higher modulation frequencies, we discuss some remarkable phenomena. In particular, the time modulation leads to strong inelastic scattering and frequency conversion, accompanied by energy transfer between the scatterer and the light field, when the difference of the incident wave frequency to a particle optical resonance matches an integer multiple of the modulation frequency. Our insights into this simple system can be extended to more complex ones, such as periodic arrays of time-modulated spherical and non-spherical particles.

Keywords: Scattering, time, modulation

*Speaker

Dispersion properties of time modulated Klein-Gordon media

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In recent years, wave systems with periodically varying properties have attracted increasing interest due to their unique features, such as the formation of wavevector gaps analogous to the frequency gaps of spatially periodic systems. In particular, time-modulated systems are seen as a promising platform for novel wave applications such as magnetless nonreciprocity, multimode shaping, parametric amplification and ultrafast switching. Despite considerable attention to wave systems without frequency gaps in the unmodulated limit, inherently gapped systems, such as propagation of electromagnetic/acoustic waves in waveguides and periodic media, have received less attention. In this context, we study the dispersion properties of Klein-Gordon media and show that such systems have very rich dispersion properties not found in gapless systems, including Dirac dispersion relation with exceptional point of degeneracy, isolated in-gap states, and tunable wavevector gaps.

Keywords: Klein, Gordon, time modulated, exceptional points

*Speaker

16 May 2024

Plenary talk - An analytic study on the properties of solitary waves traveling on tensegrity-like lattices

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Abstract: This study develops an analytic study on the existence and properties of solitary waves on 1D chains of lumped masses and nonlinear springs, which exhibit a mechanical response similar to that of tensegrity prisms with locking-type response under axial loading. Making use of the Weierstrass' theory of 1D Lagrangian conservative systems, I will show that such waves exist and that their shapes depend on the wave speed. A progressive localization of the traveling pulses in narrow regions of space is observed as the wave speed increases up to a limit value. A comparative analysis illustrates that this study is able to capture the wave dynamics observed in previous numerical results on tensegrity mass-spring chains.

Curriculum vitae: Pr. Ada Amendola is an Associate Professor at the University of Salerno, Department of Civil Engineering.

Her current research activities are devoted to the computational design, modeling and manufacturing of multiscale innovative materials and structures in engineering fields where current knowledge of such systems is only partial. She studies lattice structures at different scales, to form cellular solids; devices; fibers and fabrics; and building-scale structures.

A modeling research line of her research project studies the effects of internal and external prestress on nonlinear lattice mechanics, with the aim of designing arbitrary lattice behaviors. Material-scale applications of multiscale lattices deal with novel dynamic devices and hierarchical composite materials. A structure-scale application exploits lattices with morphing abilities to design adaptable envelopes for energy efficient buildings.

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Non-linear, non-hermitian and topological acoustic/elastic systems

Bifurcation and stability analysis of a topologically nontrivial Kagome lattice

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The discovery of higher-order topological insulators (HOTIs) in condensed matter physics has motivated researchers to explore analogous materials in the fields of acoustics and elastic systems, opening up new avenues for understanding and manipulating wave phenomena in diverse mechanical systems. In recent times, there has been a surge of research in this field; however, a significant portion of these studies has primarily focused on linear dynamics. Our current research represents a noteworthy step toward understanding the impact of nonlinearity on the topological characteristics of an elastic HOTI. We investigate a mechanical Kagome lattice that supports topological states, such as edge states and corner states. A nonlinear continuation technique is employed to obtain the nonlinear periodic solutions by providing linear corner and edge states as the initial conditions. The stability of these nonlinear solutions is determined using Floquet theory. We find that by incorporating onsite nonlinearity into the lattice, the frequency and stability of topological states are varied. We observe a new type of stable corner states within the bandgap when the linear corner state is continued in the nonlinear regime. Interestingly, the linear edge state also evolves into nonlinear corner states as the lattice energy is increased. Different types of bifurcations, such as pitchfork and Neimark-Sacker, are noticed in the lattice during the nonlinear continuation of the linear edge state. Moreover, edge breathers are also observed from linear edge states as more lattice energy is supplied. These findings highlight the impact of nonlinearity on the characteristics of topological states and reveal the existence of new types of states not present in linear lattices.

Keywords: Higher order topological insulators, Mechanical Kagome lattice, Nonlinear dynamics, Bifurcations.

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Control of nonlinear waves in non-Hermitian topological systems

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Topological and non-Hermitian (NH) systems offer promising avenues for advanced wave control devices, showcasing unique phenomena such as robust topological and skin states. Recent research has increasingly focused on exploring the interplay between these two types of waves. In this context, we introduce a one-dimensional NH model: a non-reciprocal variant of the Su-Schrieffer-Heeger (SSH) chain. We first demonstrate the exceptional properties of this NH SSH chain in the low-amplitude regime. We then, look at the system's behavior as it transitions into a finite-amplitude regime where nonlinear effects cannot be neglected. We demonstrate that just by incorporating on-site Kerr effects, we can greatly enhance the range of wave phenomena achievable beyond what is observed in its Hermitian counterpart.

Keywords: Non Hermitian systems, Non reciprocal Networks, Nonlinear dynamics, Topological edge modes, Non, Hermitian Skin Effects

*Speaker

Bistability via buckling: from static to dynamic forcing

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In recent years, bi-stable systems, as for instance a buckled beam, are gaining a lot of interest due to their wide field of applications in the quasi static regime, for instance mechanical fuses and mechanical actuators in soft robotics, and in the dynamic regime, for instance energy harvesting devices and nonlinear energy sinks.
Bistable systems typically present a double well potential with an unstable state in between two stable regions, which results in an energy barrier able to store mechanical energy.
Such potential is inherently nonlinear, leading to amplitude dependent stiffness, which can even be negative.
In this context, we focus on the mechanical behaviour of a buckling beam made of a 3D printed soft material in both static and dynamic regime.
The static response is determined using traction compression test machine to measure the force, the deflection and input energy, coupled with camera-based displacement field measurement to resolve the local deformation of the beam.
These two measurements are connected through the Euler-von Kármán beam model, relating the deformation to the bending and compressive energies.
In addition, we aim at describing the deformation in terms of decomposition over the stable and unstable buckling modes.
The dynamic response, which relies on a typical Duffing-like softening behaviour in the weakly nonlinear regime, is determined via amplitude dependent frequency response function using a shaker and accelerometers, in addition to the camera-based instantaneous local deformation measurement of the beam.
We aim at getting better understanding by relating the static and dynamic observations via the camera-based field measurement, in particular.

Keywords: Bistability, nonlinearity, buckling, video processing, vibration

*Speaker

Competing Forces in Nonlinear Waves

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Coherent structures such as steadily propagating waves in open channel flow, necessarily owe their existence and their very stability to a balance of all forces acting on the system or, in other words, to two or more competing mechanisms.
In this talk we focus upon the case of the so-called monoclinal flood wave, and we show that its characteristic shape is the outcome of a hierarchy of pairwise near-balancing forces.
Finally, we demonstrate that the monoclinal flood wave owes its stability to a delicate balance between two competing mechanisms: nonlinearity vs. anomalous diffusion.

Keywords: Saint, Venant equations, monoclinal flood wave, nonlinear stability, open channel flow, balance of forces

*Speaker

Energy transport and chaos in a one-dimensional nonlinear stub lattice

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We numerically study the dynamics of propagating waves in a one-dimensional stub chain in the presence of disorder and nonlinearity. We theoretically predict and numerically observe three different dynamical regimes induced by chaos: weak chaos, strong chaos and self-trapping regimes. Our numerical simulations show subdiffusive spreading for relatively larger disorder strengths for both the weak and strong chaos regimes, with the second moment following the power laws $m_2 \propto t^{-0.33}$ and $m_2 \propto t^{-0.5}$ respectively. In addition, the time evolution of the finite time maximum Lyapunov exponent Λ diminishes to zero by following the power laws $\Lambda \propto t^{-0.25}$ and $\Lambda \propto t^{-0.3}$ respectively for the weak and strong chaos regime. Additionally, decreasing the disorder strength leads to gaps in the frequency spectrum. Simulations taken with disorder in that region show no influence of the gaps on the dynamics of the wave packet spreading in the weak chaos regime. On the other hand, in the regime of strong chaos, our findings remain inconclusive.

Keywords: Numercial Methods, Symplectic integrators, Chaos, Nonlinear, Lattice Structures

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Experimental realization of Van der Pol oscillators

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Self-sustaining oscillations of a non-conservative system with nonlinear damping are commonly described by the Van der Pol (VdP) equation. Here we experimentally realize the VdP oscillators using airflow-driven whistles. We derive the linear growth rates of such whistles by direct measurements and by system identifications assuming a VdP oscillation law, respectively. A good agreement is found between the different estimation results in both the linearly stable (no whistling) and unstable (whistling) regimes. This allows us to quantitatively identify the nonlinear damping of the oscillators and adjust it over a wide range of magnitudes through the inject flow rates. The designed whistle can thus serve as a basic nonlinear meta-atom to explore a variety of nontrivial wave phenomena and meta-structures, such as exceptional-point encircling, PT-symmetry metamaterials, and nonlinear topological insulators.

Keywords: Van der Pol oscillators, nonlinear damping, system identification

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Nonlinear propagation in 2D acoustic networks

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Nonlinearity, dispersion and dissipation are widely recognised as pivotal factors in wave propagation, often coexisting in physical systems. One of the most interesting phenomena which stems from the balance of dispersion and nonlinearity is the emergence of solitons, namely robust localized waves propagating undistorted in nonlinear dispersive media. In this work we study the propagation of high-amplitude sound waves in acoustic waveguide networks. Specifically, we analytically and numerically demonstrate the existence of anisotropic cylindrical solitary waves two dimensional square network of connected waveguides. Furthermore, we illustrate that the inclusion of Helmholtz resonators in the network "heals" its inherent anisotropy, consequently transforming the anisotropic cylindrical solitons to isotropic ring solitons.

Keywords: nonlinear propagation, 2D lattices, solitons, shock waves

*Speaker

17 May 2024

Plenary talk - Topological trapped-rainbow and nonreciprocal guides beyond the time-bandwidth limit

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Abstract: Topologically protected wave transport has recently emerged as an effective means to address a recurring problem hampering the field of 'slow light' for the past two decades: Its keen sensitivity to disorders and structural imperfections. With it, there has been renewed interest in efforts to overcome the delay-time–bandwidth limitation usually characterizing slow-light devices, on occasion thought to be a 'fundamental limit'. Our talk will overview latest developments and point out important new functionalities that overcoming the limit can enable.

Curriculum vitae: Kosmas L. Tsakmakidis obtained his Diploma degree in Electrical & Computer Engineering from the Aristotle University of Thessaloniki, Greece (2002), his Master of Research (MRes) in Electronic Engineering from the 5*A-ranked Advanced Technology Institute (ATI) of the University of Surrey, UK (2003), and his Doctorate degree (PhD) in Applied Physics and Engineering from ATI, University of Surrey (2009).

During 2008-2013 he was a Royal Academy of Engineering/EPSRC research fellow, first at the ATI, University of Surrey (2008-2010), and then in the Condensed Matter Theory Group, Department of Physics, of Imperial College London (2011-2013). He subsequently worked as a senior postdoctoral research fellow in the Department of Mechanical Engineering of the University of California, Berkeley (2014-2015), a Eugen Lommel postdoctoral fellow at the Max Planck – University of Ottawa Center for Extreme and Quantum Photonics & the Department of Physics, University of Ottawa (Canada, 2015-2016), and as an EPFL Fellow in the Bioengineering Department, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne (Switzerland, 2017-2018). Since March 2018 he is an assistant professor (tenured since Nov. 2021) in the Department of Physics, Section of Condensed Matter Physics, of the National and Kapodistrian University of Athens (NKUA), Greece.

He specializes in condensed matter photonics, nanophotonics, metamaterials, plasmonics, 'slow' and 'fast' light, active/lasing nanostructures, computational physics, invisibility cloaking, and light-based chiral sensing schemes, where he has made a number of seminal contributions and introduced key concepts and results in the fields [e.g., K. L. Tsakmakidis, et al., Nature 450, 397 (2007); K. L. Tsakmakidis, et al., Phys. Rev. Lett. 112, 167401 (2014); K. L. Tsakmakidis, et al., Science 356, 1260 (2017); K. L. Tsakmakidis, et al., Science 358, eaan5196 (2017)]. He is the originator of the broad, multidisciplinary applied-physics research topic known as the 'rainbow effect,' referring to broadband slow and stopped waves. For his work, he has received awards by the Royal Academy of Engineering (UK, 2008), the Institute of Physics (best PhD Thesis prize,

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2010), the UK Parliament (2010), the University of Surrey (Researcher of the Year, 2010), the Academy of Athens (Lycurgus Award, 2021), and the National and Kapodistrian University of Athens (2023) [1, 2]. His work is often covered by physics-dedicated and general-media outlets (e.g., APS Physics, Physics World, Physics Today, BBC, The Economist).

Metamaterials for sound insulation

Complex Band Structure Calculations via the FEM Method for Characterizing Immersed Acoustic Metamaterials

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The noise generated by offshore maritime activities is a significant concern due to its impact on marine species. To mitigate these noise disturbances, the design of acoustic metamaterials offers a promising solution. These materials can manipulate the propagation of acoustic waves, thereby providing the ability to control and reduce radiated noise in water. In this study, we address the finite element solution of the propagation equation in periodic arrays consisting of a solid within a fluid medium. The eigenvalue problem is solved by imposing a real frequency and calculating the associated complex wave number. This approach allows us to examine propagation modes within the structure under realistic conditions of sound sources, by imposing a real frequency and searching for the associated mode. The method is initially applied to 2D periodic arrays of steel wires in a nylon matrix, and it is compared with the plane wave expansion method. Next, the analysis is extended to 3D solid/solid and solid/fluid periodic arrays and results are confronted with those obtained by the Layer Multiple Scattering method. The solid/fluid model is finally enriched by introducing losses in the solid part, before turning to more complex geometries such as split tubes. The developed method thus allows the characterization of more complex geometries, thanks to finite element modeling. This approach would notably enable, in the long term, the comparison of dispersion curves calculated at real frequencies with transmission loss curves of acoustic metamaterials adapted to underwater noise reduction.

Keywords: FEM method, Complex Band Structure, Immersed Metamaterials

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Multi-modal resonator design for maximized broadband vibroacoustic attenuation in metamaterial panels through topology optimization

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Resonant metamaterials can achieve exceptional vibroacoustic attenuation by subwavelength local resonators attached to a host structure. In lightweight thin panels, resonant metamaterials improve vibration attenuation by stopping the propagation of free bending waves in specific resonance-based bandgaps, and enhance sound insulation by increasing the effective inertia of forced bending waves excited by an acoustic load. One of the main limitations of conventional metamaterial panels is that they employ single-mode transversal resonators, which vibrate perpendicular to the host plate and achieve vibroacoustic improvements only in a narrow frequency band. Furthermore, the mass added to the host structure by the resonators does not always fully contribute to the desired transversal mode, since a significant portion may remain static or inactive, particularly near the points where the resonators are attached.
Recently, multi-modal metamaterial panels have been proposed, which achieve broadband attenuation by exploiting multiple translational and rotational modes within a single resonator. Translational resonator modes transfer transversal forces to the host structure and create omnidirectional bandgaps with finite bandwidth. Rotational resonator modes transfer bending moments and create directional zero-bandwidth bandgaps in the direction perpendicular to the rotation axis. Both types of resonator modes correspond to a sound transmission loss (STL) peak at resonance, and broadband STL improvements can be achieved by combining multiple modes. Despite the interesting potential offered by this concept, only preliminary resonator designs have been so far proposed, exploiting a limited amount of modes within each resonating unit. Effective methodologies are still lacking to systematically design manufacturable multi-modal metamaterial resonators that achieve an appropriate amount of resonances across the target frequency range, with an adequate participating mass.
In this work, we develop a methodology to design adequate multi-modal resonator layouts for metamaterial panels by topology optimization. Topology optimization is an advanced structural optimization technique that is able to foster enhanced, non-intuitive structural layouts by allowing for free material distribution within the available design space, and therefore does not require any preliminary design choices or user-defined layout parametrizations. The method can therefore generate from scratch the full topology of the resonator design, including the shape,

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size, and location of structural features and holes. The proposed topology optimization method leverages an effective medium model of the metamaterial panel, i.e., a homogenized metamaterial representation through an equivalent dynamic effective mass density. This provides accurate vibroacoustic predictions while significantly reducing computational costs with respect to more conventional techniques, based on detailed (periodic) finite element modelling. The optimization objective is to maximize the broadband STL of the metamaterial panel for diffuse sound incidence, while constraining the maximum resonator mass. To avoid weak structural connections in the designed layouts, additional connectivity constraints are imposed. The formulated topology optimization problem is solved through the method of moving asymptotes (MMA) as a gradient-based optimizer, for which the necessary adjoint sensitivities of objective and constraints are derived.

The efficacy of the proposed topology optimization approach is demonstrated by targeting the suppression of coincidence STL dips in orthotropic host plates. For narrowband coincidence dips, the optimized resonator exhibits maximized mass participation in one single mode of interest. For broadband coincidence dips, the method effectively generates multi-modal resonators with up to 6 resonances distributed across the target frequency range, surpassing the maximum performance ideally achievable by single-mode resonators.

Keywords: Topology optimization, locally resonant metamaterials, rotational and multimodal resonators, effective medium modelling, broadband sound transmission loss

Advancement in metamaterial tuning for sound-proof and ventilated window

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Effective strategies to optimise façade sound insulation and ventilation have led to the development of distinct approaches within building design (Harvie-Clark et al., 2019). While providing visual connection and natural ventilation, traditional windows often force users to compromise between functions, impacting indoor environmental quality (IEQ) (Fusaro and Kang, 2021). Researchers have sought solutions to this dilemma through diverse methodologies, such as mechanical ventilation (Du et al., 2020) and noise control systems (Lam et al., 2018). Acoustic metamaterials (AMMs), specifically designed for noise and ventilation control, offer promising advantages, including low energy consumption and direct integration into windows (Kumar et al., 2020), fostering durability through solutions like microperforated panels (MPPs) and resonant cavities (Jiménez et al., 2017). However, challenges persist in this evolving field, including i) the need for a comprehensive multiphysical analysis from numerical and experimental perspectives, ii) ergonomic design considerations for Acoustic Metawindows (AMWs), capable of delivering natural ventilation and noise attenuation, and iii) the need of covering the gap which exists in standard regulations for noise façade insulation concerning open windows.
This study features a first step as a literature review on multiphysical methods for assessing the acoustic and fluid dynamic relationship in AMMs and a second step in developing a holistic method for assessing the physical, psychophysical, and ergonomic characteristics of a ventilated Acoustic Metawindow (AMW). The reviewed papers highlighted the scarcity of studies and methodologies surrounding aero-acoustic interactions and realistic multiphysical models (Fusaro et al., 2024.b). The review emphasises the importance of fluid dynamics, turbulence generation, and contamination over the acoustic field. Parameters like Transmission Loss (TL), absorption coefficient (α), Mach number (Ma), Acoustic Transmission (T), and Flow Velocity (v) dominate studies, primarily conducted as parallel mono-physics, with only a limited percentage combining multi-physical models. Finite Element Method (FEM) software, such as COMSOL Multiphysics, proves instrumental in simulating aeroacoustic interactions through a combined mesh method and linearised Navier-Stokes equations (Fusaro et al., 2024.b). This method incorporates thermal and viscous boundary layer resolution, turbulence attenuation, and Fluid-Structure Interaction (FSI) (Fusaro et al., 2023).
The ergonomic impact and optimisation of AMMs for noise and ventilation control were done by applying the filtering effect of the metamaterial-based system over environmental noise and then assessing it through psychoacoustic analysis, acoustic perception tests, and soundscape questionnaires (Fusaro et al., 2022). Experimental tests considered International regulations which predominantly address noise insulation for closed façades' partitions, combining them and extending their application to open systems for noise insulation (Fusaro et al., 2024.a).

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This study combined numerical and experimental approaches to determine the noise sound insulation index (SI), sound level difference (Dn,e , ISO 10140), and ventilation potential (blower door test method, ISO 9972) of the AMW. The results demonstrated the potential applicability of standard regulation methods for such prototypes.
The final design, featuring $\frac{3}{4}$ wavelength resonator elements and Fano-like interference, proves equivalent to superior traditional windows noise control, offering a Dn,e ranging from 30 to 40 dB (frequency range of 100-5000 Hz) with a fully open window, meeting EN 13779 standards for flow rate per person. These findings advocate for adopting advanced AMWs over traditional counterparts, promising enhanced ventilation and noise reduction benefits while urging the development of more inclusive regulations considering open sound-insulating devices as vertical partitions in the built environment.

Keywords: multiphysical analysis, destructive interference, ventilated window, acoustic metawindow, psychoacoustics

Case study: the use of acoustic metamaterials in the design of a window air intake silencer

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This presentation introduces the use of acoustic materials in the design of an innovative window air inlet silencer. The product is intended for exterior installation, tailored to match the standard dimensions of window air inlets, specifically the slot through the window. It is designed to complement internal window air inlet equipment. The silencer's design encompasses multiple functionalities. The main one is reducing external noise transmission (such as traffic, airport, and city center noise) from outside to inside the room equipped with the air inlet. Additionally, it minimally impacts air flow, ensures resistance to water and sunlight, offers washability for accumulated dust, and emphasizes aesthetics compared to other existing silencers. The development of the silencer involves a comprehensive approach, incorporating numerical simulations, optimizations, prototypes, and standard experimental tests. Silencer performance is compared according to the acoustic material of which it is made.

Keywords: Silencer, materials, building

*Speaker

Ventilated Hexagonal acoustic Metamaterial plate based on sided branches Helmholtz resonators with multiple local resonances

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The development and application of noise control strategies on subwavelength regimes have thus demanded a continuous effort by several researchers. In this context, the advent of acoustic metamaterials arose as a novel strategy for the manipulation and control of sound waves of subwavelength dimensions and the development of lightweight acoustic devices. Previously research has evidenced the capacity of symmetric-axially acoustic systems to achieve impressive acoustical absorption behaviours in broadband, enabled by the critical coupling of resonators with distinct resonances. Here, we further extend the idea of an acoustic metamaterial plate conceptualized to manipulate the front wave propagation and sound attenuation characteristics in a ventilated acoustic system comprising multiple subwavelength resonators in the form of a panel, herein named Acoustic Hexagonal Metamaterial (AHM), consequently, the high capacity to handle the sound transmission loss (STL) is theoretically (using dissipative fluid equivalent approach) and numerically (using boundary layer impedance method) reported. Thus, AHM is realized by expanding the theory of in-parallel coupling of tunned Helmholtz Resonators under grazing incidence into each unit cell section. The respective attenuation mechanism results from the compressive extensional movement, conducting to a negative effective bulk modulus value, therefore a bandgap is generated, shown by the respective dispersion curves, herein theorized as single, dual, and triple resonance, resulting from the organization of group and sets of Helmholtz resonators. Based on this, we initially demonstrate numerically and analytically the averaged transmission 20 dB around the audible range at approximately 800Hz until 3kHz, and achieving specific gaps around 50 dB at tunned frequencies. The obtained results are promising and expand the applicability of these axially symmetric devices in the development of novel compact attenuators with applications in different engineering contexts, especially in building environments.

Keywords: Acoustic metamaterial, Sound Transmission Loss, Helmholtz resonators, symmetric, axially, building environments.

*Speaker

Numerical Performance Investigation of a Ventilated Noise Barrier: from unit cell prediction to finite-size sound transmission loss

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Traffic noise pollution has represented a significant challenge for modern societies, requiring the development of innovative noise mitigation strategies. In the last decades, intensive research has been developed into the design and evaluation of noise barriers but there still lacks a simultaneous proper air ventilation for a comfortable environment and lower visual impact. This study presents a comprehensive numerical investigation into the design and performance of ventilated acoustic metamaterial noise barriers to mitigate urban noise while maintaining adequate ventilation. Considering the recent advancements in acoustic metamaterials and computational modeling techniques, we model the design and numerically investigate the periodically arranged noise barriers in open air which will also allow ventilation. For performance analysis, a finite-element approach has been applied to model the design of the barrier, and the Sound Transmission Loss (STL) of the unit cell has been computed numerically. To validate STL and study bandgaps, dispersion curves have been generated for the unit cells with varying configurations. A parametric analysis is also carried out to investigate the effects of the unit cell's geometric size and the acoustic incident angle on the effectiveness of noise reduction. Within the mid-range of frequencies, sound waves have been attenuated without disturbing the airflow for ventilation. Finally, evaluating the effect of finite size of the noise barrier on the STL, highlighting how in-situ performance may vary as compared to the predicted performance in idealized infinite conditions.

Keywords: Ventilated Noise Barriers, Acoustic Metamaterials, Phononic Crystals, Numerical Modeling, Sound Transmission Loss

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Phononic crystals

Improved manufacturability of 1D chiral phononic crystals for low-frequency vibration isolation.

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Phononic crystals are intensively investigated as novel solution for vibration isolation of structures. Due to their typically complex geometry, however, they cannot be realized with conventional production processes, so that their fabrication involves 3D printing or a multitude of assembly steps. The aim of this study is to improve the manufacturability of a one-dimensional chiral phononic crystal for low-frequency vibration isolation. The design of this large-scale chiral phononic crystal aims to tangibly demonstrate the vibration isolation, tuning the bandgap to a frequency lower than 140 Hz – the maximum frequency that can be perceived by the human hand. The crystal consists of masses joined together by tilting connectors, which transform a translational excitation into a combined translation and rotation movement of the masses . Two relative arrangements of the tilting connectors in isotactic (all oriented equally) and syndiotactic (with alternating orientation) are compared to demonstrate the concept of tacticity.
In a first step of this work, an assembly designed to preserve the crystal's properties while reducing the number of mechanical components is presented. The geometrical limitations induced by the improved manufacturability of this chiral phononic crystal are analyzed. In a second step, a parametric study reflects on the influence of the connector's thickness and inclination on the crystal behavior. Applying the wave finite element method to a unit cell FEM model, the dispersion curves can quantify the impact of these parameters on the bandgap starting frequency. The design of the crystal components is optimized to achieve a bandgap starting at 60 Hz. Based on this optimized design, a two-unit cell model and a manufactured demonstrator in isotactic and syndiotactic configurations are produced.

Keywords: chiral phononic crystal, elastic waves, vibration isolation

*Speaker

Design of Pentamode Metamaterials for 3D Cloaking Application

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Invisibility has always fascinated people thoroughout history, felt as something magical. The early studies by Pendry and Leonhardt about electromagnetism opened up the possibility of turning this dream into reality. Since then, much work has been done to achieve this possibility in diverse fields, beyond electromagnetic waves. As far as acoustics is concerned, there exist examples of well-functioning cloaks, still limited in terms of working frequencies or directivity performance. The so-called *Pentamode* (PM) metamaterials play an important role to overcome such limits. These structures are also called *metafluids* since, similarly to common fluids, they can sustain only hydrostatic pressure, but with the advantage that they can be made anisotropic by correctly designing their geometry.
Despite the publication of several studies on cloaking with PM metamaterials, significant hurdles persist in achieving cloaking for 3D objects. A notable challenge arises from the fact that the analysis of PM properties often occurs within Cartesian coordinates, disregarding the distortions that arise when transitioning to the curved geometry surrounding a body, such as a sphere or a cylinder. Furthermore, the determination of the requisite properties for achieving perfect cloaking conditions is not standardized, rendering it a design parameter that requires meticulous consideration and selection.
This study aims to address these gaps by examining the PM structure proposed by Vipperman using analytical tools provided by Norris for the analysis of elastic networks. Through this approach, we derive analytical definitions for the effective quasi-static bulk modulus and mass density of the lattice, as dependent on geometric design variables. To account for deformations occurring in non-Cartesian domains, we introduce variations in the shape of the individual cell of the PM metamaterial, considering stretches in appropriate directions. Consequently, our analysis provides a close form that connects the cell properties to the geometric design variables. Once that an analytical formulation for the properties is found, it is still unclear how to choose them among the many possibilities. For this purpose, an optimization of the transformation function is implemented. This tool tries to find the best possible transformation function which requires properties to the cloak that fits inside the set of achievable properties, avoiding us the burden of the choice.

Keywords: Pentamode metamaterial, 3D acoustic cloaking, analitic properties definitions, geometry parameters optimization

*Speaker

On High-Bulk-Modulus Acoustic Pentamode Metamaterials: The Three-Dimensional Metal Water

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In the last couple of decades, a lot of effort has been spent on developing acoustic metafluids, engineered solid structures capable of mimicking the properties of a fluid domain, thus exploitable for manipulating and guiding sound waves. Among them, a leading role has been played by the so-called *pentamode metamaterials*, artificial crystals whose effective elasticity tensor is characterised by five out of six null eigenvalues; hence, they can withstand only hydrostatic stresses, as fluids do. In underwater applications, the design of a 3D isotropic PM metamaterial capable of replicating the behaviour of water, which is the quintessential PM, is an achievement of great interest; however, the 3D geometries of state-of-the-art ideal PMs, that are characterised by FCC or hexagonal lattices with thin double-cone links that are joined in such a way to decouple longitudinal and transverse waves since the resulting bulk modulus B of the unit cell is infinitely larger than its shear modulus G, do not allow to reach the required density and stiffness.

In this work, the PM lattice is introduced starting from some known results. Then, the idea of double cones is extended and the existing theoretical limitation in terms of effective bulk modulus that PMs based on this sort of links possess if a contained shear/bulk ratio is targeted, is presented. Afterwards, an alternative shape for the links composing the PM lattice is proposed in order to overcome such restrictions. The provided mechanism shows a significantly lower-shear and a higher-axial stiffness, eliminating the theoretical upper threshold on the attainable bulk-to-shear moduli ratio of a PM. On the other hand, such a complex metamaterial geometry implies introducing manufacturing issues.

The geometry of the primitive unit cell of the so-called *metal water* has been modelled using *Comsol Multiphysics*. Thanks to low-frequency homogenization, an effective elastic solid has been obtained by imposing the appropriate Floquet boundary conditions on the connection surfaces. Therefore, the quasi-static mechanical properties of the designed cell are extracted: a satisfactory absolute bulk modulus and a very small shear/bulk ratio have been achieved. On top of that, PMs possess even more interesting dynamic rather than static behaviour; hence, the Irreducible Brillouin Zone has been calculated and the dispersion relation has been displayed, highlighting the opening of two PM bandgaps where only compressional waves propagate.

Keywords: 3D metal water, pentamode metamaterial, anisotropic fluid

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Interdigitated comb piezoelectric phononic crystals for telecom applications

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In this presentation, piezoelectric phononic crystals (PPhC) made up of interdigitated combs of periodic electrodes are considered. In addition to Bragg bandgaps due to the presence of periodic electrodes, their interconnection results in an additional level of electrical periodicity opening supplementary bandgaps in the dispersion curves which correspond to electrical resonance/antiresonance of the comb pairs. The presence of bandgaps is also showcased by calculation of the reflection coefficient of finite size interdigitated comb PPhC for surface acoustic waves on a piezoelectric substrate, revealing the presence of high amplitude reflection coefficient lobes near these bandgap frequencies. Using these mirrors, single port SAW resonators operating around 1.6 GHz are designed to provide experimental verification of the mechanism for bandgap opening and a practical application in an electroacoustic device for signal processing.

Keywords: piezoelectricity, phononic crystal, radiofrequency, electrical Bragg bandgap

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Numerical and experimental investigations of wave propagation in Kelvin Cell-based periodic lattice architectures

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Engineered periodic materials are a promising solution for mitigating vibrations due to their ability to modulate and inhibit elastic wave propagation in targeted frequency bands. This filtering functionality depends upon the topology and periodicity of the material microstructure and is strongly related to the acoustic dispersion in the microstructure's constituent unit cells. Investigating the interplay between cell topology, underlying periodicity, and emerging dispersion properties is, therefore, a vital step in developing materials with customized filtering properties.
This contribution addresses the dispersion properties of periodic open-cell microstructures. A unit cell design strategy is introduced based on the Kelvin cell as a template geometry. The geometry is subsequently altered along three axis directions by imposing twists on the cell's square faces. The geometrical changes are independently applicable in three-axis directions, which offers the potential to adjust the microstructure's filtering characteristics based on the twist angle and choice of periodicity. Finite element models of twisted unit cells and Bloch's theorem for 1D periodicity are considered, and it is demonstrated that altering the template geometry by the twisting approach may enforce frequency band gaps stemming from coupled longitudinal-torsional modes and Bragg scattering. Band gaps of the latter type can be effectively tuned by adjusting the twist angle while keeping the material parameters unchanged.
While the band gap feature is directly linked to the assumption of infinitely extended periodic media, practically realizable structures are bounded by finite numbers of unit cells. Therefore, the contribution addresses the transition from infinite to finite-size periodicity through dynamic analyses of selected finite-size periodic structures. The vibration attenuation capabilities of samples manufactured from SLA printing are experimentally tested and compared to numerical results obtained from harmonically induced wave motions. Particular attention is directed to the conformity of the numerically predicted and experimentally determined attenuation region.

Keywords: elastic metamaterial, vibration control, dispersion, Bloch, Floquet wave propagation, experimental testing, 3D, printing, additive manufacturing

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