EUROPEAN MECHANICS SOCIETY

Colloquium Final Report

N. 649 – Metamaterials and Architected Materials for Novel Energy Harvesting Solutions

Dates and location: **07/05/2024 - 09/05/2024, London, UK**

Chairperson **Jacopo M. De Ponti**

Co-Chairperson **Gregory J. Chaplain, Richard V. Craster, Andrea Colombi**

Conference fees

- Regular registration **400.0 €**
- PhD student registration **200.0 €**

What other funding was obtained? **We have received financial support from the H2020 FET-proactive European project "Metamaterial Enabled Vibration Energy Harvesting (MetaVEH)" under Grant Agreement No. 952039**

What were the participants offered? **The registration fee included:**

- 1 conference bag, 1 block notes, 1 pencil;
- 8 coffee/pastries breaks;
- 3 lunches;
- 1 drink reception;
- 1 social dinner;

Number of members of Euromech (reduced registration fee) **15**

Number of non-members of Euromech (full registration fee) **27**

Applicants (members)

- Sondipon Adhikari
- Cristian Cassella
- Alberto Corigliano
- Richard Craster
- Jacopo Maria De Ponti
- Amir Gat
- Chiara Gazzola
- Mahmoud Hussein
- Muamer Kadic
- Varvara Kouznetsova
- Anastasiia Krushynska
- Sofia Kuperman

- Michael Leamy
- Massimo Ruzzene
- Richard Wiltshaw

Applicants (non members)

- Ricardo Alcorta Galván
- Andres Arrieta
- Federico Bosia
- Gregory Chaplain
- Bryn Davies
- Robyn Edge
- Alper Erturk
- Annachiara Esposito
- GOLSHAN FARZI
- Antonio Gliozzi
- Sebastien Guenneau
- Luca Iorio
- Oksana Koplak
- Vincent Laude
- Mario Lázaro
- Federico Maspero
- MARCO MOSCATELLI
- Fabio Nistri
- Raj Kumar Pal
- Luca Rosafalco
- Giuseppe Rosi
- Nevena Rosić
- Marc Serra-Garcia
- Tim Starkey
- Serife Tol
- Bart Van Damme
- Benjamin Vial

Scientific Report

The aim of the EUROMECH Colloquium 649 was to bring together world-leading, complementary expertise in the theory, simulation, manufacturing, and experimental realisation of metamaterials and architected materials for novel energy harvesting solutions.

Altogether there were 39 participants and 32 presentations. The list of participants, the full programme and the book of abstracts are available on the Colloquium website (https://649.euromech.org/). Most importantly, there was ample time for informal discussions among the participants during coffee breaks, lunches and social activities.

This report includes the relevant scientific topics discussed during the Colloquium. A detailed and more exhaustive description is reported in the book of abstracts.

Phononic crystals, acoustic and elastic metamaterials for energy confinement - Metamaterials (MMs) and Phononic Crystals (PCs) offer unique opportunities to manipulate elastic and acoustic waves, stimulating the research for new avenues in energy harvesting. Several solutions to concentrate elastic/acoustic energy at the harvester spatial position have been discussed. These includes: (a) gradientindex (GRIN) and Luneburg lenses, (b) multifunctional metastructures, (c) graded MMs involving adiabatic spatial modulation, (d) double-negative local resonance on negative group velocity dispersion curves, (e) elastic metasurfaces, (f) beyond-nearest-neighbour coupling (nonlocality), (g) localized modes in periodic and quasi-periodic media, (h) bound modes in the continuum (BICs).

Nonlinear elastic metamaterials - Nonlinear phenomena in elastic metamaterials have been discussed to overcome the performance degradation of resonant-based energy harvesters operating away from the resonant frequencies of the vibrating structures, especially for low-frequency applications. A new class of strongly nonlinear interactions in metamaterials that sustain soliton propagation has been discussed. The particle-like nature of solitons offers a fundamentally different mechanism to achieve effective dynamics that break the strong link between unit cell size and operating frequency.

Topological elastic metamaterials - In recent years, dispersion topology has emerged as a principle governing unique wave transport phenomena through interface or edge modes that are impurity-immune. In this setting, curvature has been explored as a route for the design of topological mechanical metamaterials and waveguides in the context of periodic minimal surfaces. Curvature has been explored as an alternative mean to induce spatial variations of the effective refractive index of waveguides. By operating within the short wavelength limit, homogeneous curved waveguides can be designed by relating the refractive index to the Gaussian curvature. Consequently, the wave trajectories can be predicted by means of geodesic analysis of the surface followed by a classical ray tracing approach. Such approach supports the vision of topological interfaces and curved surfaces as general frameworks where geometrical modulations and symmetries can be introduced to achieve novel and unusual mechanical and acoustic functionalities. These include the ability to localize waves at specified locations, which can find applications in the conversion of elastic and acoustic energy into usable forms. The concept of topological rainbow trapping has also been discussed, amalgamating the classical Su-Schrieffer-Heeger (SSH) model with graded elastic metasurfaces, so-called metawedges. The resulting structures form one-dimensional graded-SSH metawedges that support multiple, simultaneous, topologically protected edge states. These robust, enhanced localized modes are leveraged for applications in elastic energy harvesting using the piezoelectric effect.

Tuneable elastic metamaterials - Metamaterial tuneability and reconfigurability are key requirements to target real applications. One potential means for achieving reconfigurability employs shunted piezoelectric (PZT) disks in which a unit cell's mechanical impedance is altered using negative capacitance circuits. Dynamic reconfigurability and programmability of such material platforms can then be obtained through simple on/off switching. In this vein, an electroacoustic Topological Insulator (TI) which exhibits programmable topologically protected edge states for acoustic multiplexers, demultiplexers, and transistors has been discussed. Photoresponsive polymers have also been discussed to tune the topological properties of phononic crystals. The photo-responsive nature of the azo-polymer material allows the reduction of its Young's modulus through laser stimulation, targeting the central interface region of a topological interface. This variation depends on the intensity of the laser, and results in a dynamic and reversible frequency shift in the localized mode. This concept can be also extended to two-dimensional lattices made of interconnected SSH chains, giving rise to a variety of possible topological phases such as higher-order topological insulators and Weyl semimetals.

Energy harvesting methods - The prevailing approach for characterization of the energy harvesting devices is to consider a finite structure operating under forced vibration conditions. An alternative framework has been discussed, whereby the intrinsic energy-harvesting characteristics are formally quantified independently of the forcing and the structure size. In doing so, the notion of a piezoelectric material has been considered rather than a finite piezoelectric structure. With this new metric, the intrinsic energy harvesting availability of piezoelectric metamaterials, chosen to be statically equivalent to a given piezoelectric phononic crystal (Piezo-PnC), has been discussed, leading to a so-called metaharvesting phenomenon. Such discussion have shown that the intrinsic energy harvesting availability is enhanced by local resonances, and enhanced further by inertial amplification. Parallel to this, another approach as been considered, targeting the inefficiency from mechanical to electrical energy conversion. The traditional approach towards battery-less energy harvesting edge devices involves converting ambient vibrations into electricity, that is then used to power conventional electronic circuits. This approach is very convenient, as it can be realized by merely replacing the battery by an energy harvester. However, it has two significant sources of inefficiency. First, there is a conversion from mechanical to electrical energy (and subsequent signal rectification) that contributes to energy losses, and second, electronic systems are notoriously power hungry – requiring a significant amount of energy. A new paradigm in self-powered devices has been proposed, where tasks such as sensing or processing are directly powered by mechanical energy – without any mechanical-electronic transduction, leveraging the very low energy dissipation in micromechanical systems, and eliminating conversion losses entirely. Four components underpinning this vision have been introduced. First, passive elastic signal processing, consisting in performing signal classification using the energy contained in the signal itself. Second, mechanical digital computing, where computations are directly powered by mechanical oscillations instead of electrical energy. Third, mechanical-to-mechanical energy harvesting, where stochastic ambient vibrations are converted into deterministic mechanical oscillations that can be directly used to power digital computations. Finally, mass-spring model to geometry conversion, that allows to translate complex designs into metamaterial geometries.

Metamaterial devices - The advancement of sensor technology has ushered in the era of the Internet of Things (IoT), yet the challenge of charging sensors remains unsolved. Chemical batteries possess a finite lifespan, and their replacement may be difficult. For this reason, reducing the power consumption of sensors is nowadays a key factor for enabling successful IoT applications. Metamaterials enables the localisation of elastic waves and the amplification of local fields. Such enhancement can be used to simultaneously harvest energy and perform sensing operation. In this context, a machine learning model that leverages an encoder-decoder scheme has been discussed to sense mechanical signals, aiming at realising (nearly) autonomous sensors for vibration monitoring. Moving to the microscale level, an acoustic metamaterial (AM) structure based on a forest of locally resonant rods attained by corrugating thin AlN/AlScN films has been discussed to maximize the piezo-generated mechanical energy. Such AM structure in the active region of a bulk-acoustic-wave (BAW) resonator has been demonstrated to led to a new class of resonators, labeled as Two-Dimensional-Resonant-Rods (2DRRs), with an augmented electromechanical coupling coefficient. When such a metamaterial structure is instead applied in an acoustic delay line structure, it has been shown to generate passbands and stopbands that alter the acoustic dispersion characteristics of plate modes propagating in single-plate un- corrugated devices. This provides the opportunity to generate a new class of filtering structures that can be used for communication, for instance in the self-interference cancellation networks of SPAR radios. Such acoustic filtering

structures can be even leveraged to prevent any energy leakage from the active region of AlN/AlScN resonators, while ensuring an easier heat flow to the substrate in favor of a higher power handling.
Metamaterial optimisation - The ability to steer acoustic waves to desired locations is quintessential for holography, focusing, imaging, data processing, computing, etc. It can be realized using rationally architected media – elastic metamaterials. Yet, most of existing metamaterials have a lattice architecture and achieve wave steering along pre-defined paths formed by modified unit cells, which connect an input to output(s). Other promising approaches are nonperiodic spatiotemporal metamaterials that enable non-reciprocal features and control of scattered wave field. In both cases, however, the locations of the input and outputs cannot be changed without modifying the metamaterial architecture, and the wave amplitude at the output(s) is governed by a metamaterial architecture and the mechanical behavior of constituents. A new concept for architecture-controlled wave steering have been discussed. This was inspired by the rich functionalities of aperiodic, spatially textured designs and the "allosteric" behavior of disordered networks when an excitation applied at one location yields a predefined response at a distant location. In this context, a successful implementation of rational pruning strategy to steer acoustic waves in disordered networks has been discussed, demonstrating that wave energy can be guided to different locations depending on the excitation frequency without changing the network architecture. Parallel to this other a Reinforcement Learning (RL) procedure has been discussed as an alternative way to guide the metamaterial optimisation. To do that, the design problem has been formalised as a Markov Decision Process (MDP). This assumption consists in splitting the optimisation into a sequence of decisions that modify the current design. Similar concepts were initially discussed in the field of computational design synthesis and were recently applied to truss optimisation. Adopting such a framework enables addressing design requirements encountered during both device fabrication and operation. The potential of the proposed approach to manage an optimisation process under stochastic operational conditions is assessed by comparing it with the results of a genetic algorithm optimisation.

Analytical and numerical methods for metamaterials - The reduction of computational time is key in designing and optimising elastic and acoustic metamaterials for specific applications. Analytical solutions based on singular Green's functions and their derivatives have been discussed to enable efficient computations of scattering simulations or Floquet–Bloch dispersion relations for waves propagating. Moreover, analytical and semi-analytical formulations for wave propagation along elastic plates, waveguides and half-spaces have been discussed to describe topological phenomena and quasi-normal modes.

Number of participants from each country

COUNTRY	PARTICIPANTS
Italy	13
United Kingdom	9
United States	8
Serbia	1
Netherlands	3
Switzerland	1
Israel	2
France	4
Spain	1
TOTAL	**42**

Please send this report in electronic form to the Secretary General of EUROMECH, within one month after your Colloquium.