ÉCOLE D'HIVER

GDR ARCHI META
DN METACMED

24-28 FÉVRIER 2025 - IEMN/JUNIA

INFORMATIONS ET CONTACTS

Site web : https ://gdr-archi-meta.univ-lille.fr

LISTE DE DIFFUSION

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PARTENAIRES ET TUTELLES

cnrs GDR Groupement de recherche
ARCHI-META
Architectured Metamaterials

MetacMed
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- Bruno **MORVAN**, LOMC
- Vincent **PAGNEUX**, LAUM
- Julien **POITTEVIN**, NAVAL GROUP
- Martin **PONCELET**, LMPS

GROUPES DE TRAVAIL

- **GROUPE 1** - Théorie : outils théoriques pour le métamatériaux - Vincent **PAGNEUX** (LAUM) et Christelle **COMBESCURE** (IRDL)

- **GROUPE 2** - Géométrie : organisation spatiale et temporelle des métamatériaux - Fabrice **LEMOULT** (ESPCI), Muamer **KADIC** (FEMTO-ST), Cédric **BELLIS** (LVA)

- **GROUPE 3** - Matière : fabrication, essais et durabilité des métamatériaux - Bruno **MORVAN** (LOMC), Martin **PONCELET** (LMPS), Kerem **EGE** (LVA)

- **GROUPE 4** - Applications : applications en ingénierie des métamatériaux Justin **DIRRENBERGER** (PIMM), Laetitia **ROUX** (Naval groupe) Fabien **CHEVILLOTTE** (MATELYS)

INTRODUCTION

The last 20 years have seen a remarkable growth in scientific interest in (elastic and mechanical) metamaterials. One of the reasons for this is the great potential that this subject area has in itself as a "link between different disciplines", particularly acoustics and solid mechanics. In addition, through a better mastery of architecture, it makes it possible to create complex engineering systems with unconventional dynamic and quasi-static behavior.

However, the literature seems to show that since its introduction in the early 2000s, two almost independent macro-communities have formed around this subject: that of acousticians, more focused on phenomenology, and that of mechanics, more focused on methodology.

However, it is clear that 1) these two communities are dealing with the same scientific problem, and that 2) certain differences in purpose and language have given, and still give, the impression that these are two loosely coupled fields of research. This has made intercommunity dialogue insufficient until now. However, it is easy to see that the subjects investigated and the methodologies used are generally complementary. The time has come for a new community to emerge, particularly at the international level.

In this context, the ARCHI-META GdR proposes to seize this spontaneous convergence and act as a catalyst to go beyond the specificities related to acoustics and mechanics, and thus to bring together a new community around architectured metamaterials. The overall objective is to get the communities (mechanics and acousticians) to work together to identify and resolve the common scientific issues that have come to light in recent years and to share the theoretical tools specific to the two communities in order to establish a common language. This synergy will make it possible to address more effectively the scientific issues limiting the development of these promising technologies.

PRÉSENTATION

Les 20 dernières années ont vécu une remarquable croissance de l'intérêt scientifique autour des métamatériaux (élastiques et mécaniques). Une des raisons est le grand potentiel que cette thématique porte en elle-même en tant que « trait d'union à travers différentes disciplines », notamment l'acoustique et la mécanique des solides. De plus, elle permet, par une meilleure maîtrise de l'architecture, de réaliser des systèmes d'ingénierie complexes à comportement dynamique et quasi-statique non conventionnel.

Cependant, la littérature semble montrer que depuis leur introduction, au début des années 2000, la formation de deux macro-communautés, presque indépendantes, a eu lieu autour de ce sujet : celle des acousticiens, plus axée sur la phénoménologie et celle des mécaniciens, plus axée sur la méthodologie.

Toutefois, il apparaît clairement que 1) ces deux communautés traitent de la même problématique scientifique, et que 2) certaines différences de finalité et de langage ont donné, et donnent toujours, l'impression qu'il s'agit de deux champs de recherches faiblement couplés. Cela a rendu le dialogue intercommunautaire jusque-là insuffisant. Cependant, on s'aperçoit facilement que les sujets investigués et les méthodologies utilisées sont généralement complémentaires. Il est l'heure qu'une nouvelle communauté puisse voir le jour, ce qui est en particulier le cas à l'internationale.

Dans ce cadre, le GdR ARCHI-META se propose de saisir cette convergence spontanée et d'agir comme catalyseur pour aller au-delà des spécificités liées à l'acoustique et la mécanique, et donc de regrouper une nouvelle communauté autour des métamatériaux architecturés. L'objectif global est de faire travailler ensemble les communautés (des mécaniciens et des acousticiens) pour identifier et résoudre les enjeux scientifiques communs mis en évidence ces dernières années et de partager les outils théoriques propres aux deux communautés pour établir un langage commun. Cette synergie pourra permettre d'aborder de façon plus efficace les enjeux scientifiques limitant le développement de ces technologies prometteuses.

PROGRAM

Monday, February 24

09H00 : Welcome with coffe and pastery

09H15 : Welcome from the direction of the IEMN, the director of the GDR ARCHI-META and the coordinator of the MetAcMed project. Moment of gathering to remember the recent sad passing of Sarah Benchabane - Vincent **LAUDE**

09H45 : **Lecture 1 :** *Anisotropic elasticity, symmetry classes, tensor bases and Kelvin decomposition*
Speaker : Marc **FRANÇOIS** (Univ. Nantes)

11H15 : Coffee Break

11H30 : **Lecture 2 :** *Basic elements for investigating periodic structures (example of wave propagation in a 1D mass-spring chain, crystallography, reciprocal lattice, Brillouin zones)*
Speaker : Jérôme **VASSEUR** (Univ. Lille)

13H00 : Lunch Break

14H00 : **Lecture 3 :** *Basics of wave propagation, Band diagram calculation (Bloch theory, 1D analytical approaches, scalar and vector waves, boundary conditions, classical and complex band structures)*
Speaker : Vincent **LAUDE** (FEMTO-ST - CNRS)

15H30 : Coffee Break

15H50 : **Lecture 4 :** *Methods of calculation of the dispersion diagrams: Plane Wave Expansion Method (PWEM)*
Speaker : Jérôme **VASSEUR** (Univ. Lille)

17H20 : End of the day

Tuesday, February 25

09H00 : Welcome with coffe and pastery

09H15 : **Lecture 5 :** *Introduction to the Finite Element Method (FEM)*
Speaker : Yann **PENNEC** (Université de Lille)

10H45 : Coffee Break

11H15 : **Lecture 6 :** *Calculation of dispersion diagrams in Comsol Multyphisics*
Speaker : Marco **MINIACI** (IEMN - CNRS)

12H30 : Lunch Break

14H00 : **Lecture 7 :** *Multi-physics coupling in periodic systems (piezoelectricity and fluid-structure interaction)*
Speakers : Charles **CROËNNE,** Bertrand **DUBUS** (IEMN - CNRS)

15H30 : Coffee Break

15H50 : **Lecture 8 :** *Phononic crystals and elastic metamaterials: State of the Art and applications*
Speaker : Marco **MINIACI** et Yann **PENNEC**

17H20 : End of the day

Wednesday, February 26

09H00 : Welcome with coffe and pastery

09H30 : **Talk 1 :** *Sound and light: differences and similarities. Bringing acoustic metamaterials to real life scenarios*
Speaker : Gianluca **MEMOLI**

10H45 : Coffee Break

11H15 : **Talk 2 :** *Adaptive Materials: Looking beyond the horizon of mechanics*
Speaker : Andrea **BERGAMINI**

12H30 : Lunch Break

14H00 : **Talk 3 :** *Metal additive manufacturing and its challenges for the years to come*
Speaker : Éric **CHARKALUK** (Institut Polytechnique de Paris)

15H30 : Coffee Break

15H50 : **Talk 4 :** *Dynamics of flexible mechanical metamaterials: robust nonlinear waves, travelling reconfiguration fronts and their mutual interactions*
Speaker : Vincent **TOURNAT**

17H20 : End of the day

Thrusday, February 27

09H00 : Welcome with coffe and pastery

09H15 : **Lecture 9 :** *From microscopic to multi-scale dissipation in poro-elastic materials : characterisation, modeling and implementation*
Speaker : François - Xavier **BÉCOT**

10H45 : Coffee Break

11H15 : **Lecture 10 :** *Soft skills in research (for PhD and early stage post-docs)*
Speaker : Skills4Science

12H30 : Lunch Break

13H30 : **Lecture 11 :** *3D prinitng, metamaterials and biomedical applications*
Speakers : AMAZEMET et G. **HANNEMA**

15H00 : Coffee Break

15H30 : **Lecture 12 :** *Soft skills in research (for PhD and early stage post-docs)*
Speaker : Skills4Science

17H20 : End of the day

Friday, February 28, in Junia

09H00 : Welcome with coffe and pastery

09H15 : **Lecture 13 :** *Soft skills in research (for PhD and early stage post-docs)*
Speaker : Skills4Science

10H45 : Coffee Break

11H15 : **Lecture 14 :** *Soft skills in research (for PhD and early stage post-docs)*
Speaker : Skills4Science

12H30 : Lunch Break

13H30 : **Lecture 15 :** *Applications of ultrasonic waves, PCs & MMs*
Speakers : S.**LAURETI** et D. **HUTCHINS**

15H00 : Coffee Break

15H30 : *Guided tour of the Acoustics laboratories : Underwater acoustic measurements – acoustic test basin*

Speaker : Monique **POUILLE-FAVRE** et Florian **Allein**

16H50 : End of the day

ABSTRACTS

Anisotropic elasticity, symmetry classes, tensor bases and Kelvin decomposition

Marc FRANÇOIS

University of Nantes, France

The successive revolutions in composite and now architectural materials, as well as the consideration of natural materials (biological or geological), oblige the engineer to deal with anisotropic behavior. In the latter case, the natural basis (in which components exhibit simple relationships) is not always known.

Linear elasticity is the simplest mechanical behavior, which occurs at least at low levels of deformation for any solid material but is also of interest for nonlinear behaviors when the tangent relationship is considered.

Anisotropic elasticity involves the fourth order elasticity tensor with its major and minor index symmetries. The eight possible distinct symmetry classes were rather recently (1997) proved by Forte & Vianello. With four indices, the classical canonical basis is not the best for representing the properties of the elasticity tensor.

On the contrary, the use of a 6 dimensional second order tensor basis allows a simple matrix representation and the preservation of the vector space structure. Among these bases, the Kelvin eigenbasis allows elasticity to be considered as a sum of weighted projectors, separating modes and energy.

2D elasticity offers great simplifications: firstly, an analytical determination of the natural basis and secondly, the existence of a set of five invariants that separate the symmetry classes (Verchery, 1982). Other properties, such as how to calculate the monoclinic case, Herman's theorem (1934) and Cauchy elasticity are also shown

Basic elements for investigating periodic structures (example of wave propagation in a 1D mass-spring chain, crystallography, reciprocal lattice, Brillouin zones

Jérôme VASSEUR

University of Lille

The purpose of Lecture 2 is to revisit fundamental concepts from the theory of crystalline solids, including the direct lattice, unit cell, reciprocal lattice, reciproc al lattice vectors, and the Brillouin zone, among others. These concepts will be introduced in a pedagogical manner, starting with simple periodic structures, such as one-dimensional infinite atomic chains. Key elements of crystallography relevant to the study of periodic structures will be reviewed and illustrated with several examples.

Basics of wave propagation and dispersion relations

Vincent LAUDE

CNRS, Insitut FEMTO-ST, UMR CNRS 6174, Université Marie et Louis PASTEUR, Département Micro Nano Sciences & Systèmes (MN2S)

In this lecture, I will first introduce the basic equations for acoustic waves in fluids and elastic waves in solids. The main purpose will be to highlight the many common features of scalar and vector wave equations, but also to signal the differences between them. I will discuss the main boundary conditions that are encountered and what they imply for dispersion relations. Then the Bloch theorem will be introduced and will be applied to simple 1D periodic systems, such as sinusoidal gratings.

The case of the 1D mass chain will be revisited to introduce analytically the concept of complex band structure and evanescent Bloch waves. All the aforementioned topics relate implicitly to Bragg type crystals. We will next introduce the concept of local resonance from a simple system of resonators grafted periodically along a waveguide. Finally, I will introduce to the dispersion of waves guided by coupled resonators inside phononic crystals.

Basics of wave propagation and dispersion relations

Jérôme VASSEUR

University of Lille

Lecture 4 focuses on the Plane Wave Expansion method which is an usual tool allowing the calculation of band structures of periodic composite materials such as phononic crystals. Basic principles of the method are first presented and its application to two-dimensional bulk phononic crystals i.e. structures of infinite extent, is reported with many details. Advantages and drawbacks of the PWE method are then discussed. It is also shown that the method can be used for calculating the band structure of phononic crystals of finite thickness and for analyzing the evanescent waves within the phononic band gaps.

Introduction to the finite element method (FEM)

Yan PENNEC

University of Lille, France

Initially, the Finite Element Method (FEM) is a numerical technique that was developed with the aim of finding approximate solutions to differential equations defined in geometric domains where the boundary values are known.

This method was first used in structural mechanics and has a history of about 70 years, as it was first applied to aircraft design in the 1950s. It is now used in many areas of physics, such as electromagnetism (solving Maxwell's equations), acoustics (Helmholtz equation), elasticity (Hooke's law),thermal analysis (Fourier equation), fluid mechanics (Navier-Stokes equations), etc.

This presentation serves as a brief introduction to this powerful method for solving d'Alembert's equations. The first reading introduces its basics through a simple example of solving a 1D differential equation. Two classic methods are introduced: (i) the method of weighted residuals, and (ii) the weak formulation and variational method. These two methods form the foundation of the modern finite element version.

Reading 2 deals with presenting the technique along with meshing a structure, the nodal formulation, and the various elements in 1D, 2D, and 3D spaces. The objective is to set up the finite element equations in 1D for solving the following differential equation :

$$\alpha \frac{d^2\phi}{dx^2} + \beta \frac{d\phi}{dx} + \gamma\phi = f(x)$$

Finally, we will introduce a generalization through the matrix formulation of the problem in a domain Ω consisting of N finite elements.

Calculation of dispersion diagrams in Comsol Multiphysics

Marco MINIACI

University of Lille, France

In this talk, I will explore how to calculate dispersion diagrams of periodic structures using COMSOL Multiphysics.

The session will begin with revising the concepts of dispersion relations (i.e., the relationship between wave frequency and wave vector) seen in previous lectures. I will then walk through the process of setting up a simulation model, including defining the material properties, geometry, and boundary conditions for a periodic structure, such as a phononic crystal or waveguides. Using the built-in physics interfaces, we will demonstrate how to calculate the dispersion curves by solving for the eigenfrequencies of the system.

The talk will also cover key considerations such as mesh refinement, the choice of solvers, and interpretation of the resulting diagrams, with practical examples of how dispersion diagrams can inform the design of acoustic and elastic devices. Additionally, part of the lecture will be dedicated to an exercise where attendees will be asked to independently develop and calculate their own band diagrams, reinforcing the concepts discussed and providing hands-on experience.

Multi-physics coupling in periodic systems (piezoelectricity and fluid-structure interaction)

Charles CROËNNE et **Bertrand DUBUS**

IEMN - CNRS

Multi-physical couplings can generate new physical phenomena when used in the design and production of phononic crystals and acoustic metamaterials. When this coupling is strong, it can significantly modify the desired dispersion properties but also provide new functionalities, useful in the design of acoustic metamaterials. This presentation illustrates these issues with two examples: electromechanical coupling used in piezoelectric acoustic metamaterials and mechano-acoustic coupling associated with heavy fluid-structure interaction and acoustic radiation in metamaterials for underwater acoustics.

Phononic crystals and elastic metamaterials: State of the Art and applications

Marco MINIACI et Yan PENNEC

IEMN - CNRS - University of Lille

In this talk, we will explore some of the diverse possible applications of phononic crystals and elastic metamaterials. We will start from "seismic metamaterials", which have shown good promise in mitigating ground-born vibrations and the stabilization of structures. Moving on, we will discuss noise reduction applications, where phononic crystals and metamaterials are used to attenuate unwanted sound across a wide range of frequencies, significantly improving acoustic environments in both industrial and urban settings.

We will then explore a key aspect of this technology which is "waveguiding", which can be achieved through both trivial and topologically protected unit cell designs. These designs enable efficient wave propagation, even in the presence of defects, and open exciting possibilities for energy harvesting by converting mechanical vibrations into usable electrical energy. Finally, we will explore the use of phononic crystals in non-destructive testing (NDT) applications, specifically through time reversal techniques.

This approach allows for enhanced detection of material defects, making it a valuable tool for quality control and structural health monitoring. Each of these applications demonstrates the powerful capabilities of phononic crystals and elastic metamaterials in transforming the way we manage waves across various engineering domains.

Sound and light: differences and similarities. Bringing acoustic metamaterials to real life scenarios

Gianluca MEMOLI

University of Sussex

Sound and light have many similarities from the physical point of view. But also some crucial differences. When it comes to devices, for instance, it is clear that we live in a world designed for sight. Why is that? When did it start? And, more importantly, can metamaterials bridge the gap? In this talk, the speaker will describe how the quest for these answers underpins both his user-driven research and his commercial activities.

Adaptive Materials: Looking beyond the horizon of mechanics

Andrea BERGAMINI

Empa

The design of mechanical systems such as structures or elastic metamaterials is, more often than not, based on the assumption that the elastic response of the system is time - invariant, because the geometry of the structure and the physical properties of the constituting materials are constant over time. In cases, where the operational conditions of the system substantially vary over time, matching all demands set to the object at hand may represent a very challenging task.

Next to complex systems with mechanisms and actuators, the integration of so called smart or adaptive materials promises to expand the solution space available to us.

In this talk, I will introduce you to adaptive materials and their ability to exchange energy between the mechanical domain (where energy density is represented in the elastic strain field) and other energy domains (such as thermal, chemical or electrical) allowing for a better management of mech nical energy and the implementation of exciting functions such as mechanical actuation or stiffness change.

Metal additive manufacturing and its challenges for the years to come

Éric CHARKALUK

Institut Polytechnique de Paris

Dans ce cours, la fabrication additive métallique sera présentée à travers ses principaux process et applications. Principalement basée sur l'interaction entre le laser/le faisceau d'électrons et la matière, la physique de ces process et ses conséquences sur le matériau et sur les composants ou éprouvettes construites seront présentées. L'accent sera ensuite mis sur le cas des « matériaux » architecturés. Les particularités de telles structures de parois/poutres minces seront décrites : rugosité, précision, variabilités, microstructures, etc. La caractérisation mécanique et la modélisation de tels matériaux architecturés seront ensuite détaillés. Ce cours proposera enfin quelques défis pour les années à venir.

In this course, the metal additive manufacturing will be introduced through its main processes and applications. Mainly based on the interaction between laser/electron beam and matter, the physics of the processes and its consequence on the material and on the built components or specimens will be presented. A focus on the case of architected "materials" will then be proposed. The particularity of such thin walls/beams structures will be described: roughness, precision, variabilities, microstructures, etc. The mechanical characterization and the modeling aspects of such architected materials will then be detailed. This course will finally proposed some challenges for the years to come.

Dynamics of flexible mechanical metamaterials: robust nonlinear waves, travelling reconfiguration fronts and their mutual interactions

Vincent TOURNAT

CNRS, Le Mans Université, Institut d'Acoustique–Graduate School, LAUM UMR 6613

In this presentation, I will recall the fundamentals of the dynamics of flexible mechanical metamaterials, and particularly the propagation of robust nonlinear waves in this class of architected materials. I will then describe in more detail some recent results on the dynamics of multi-stable metamaterials, composed for example of bistable mechanical units elastically coupled to their nearest neighbors. Such multi-stable metamaterials can support progressive fronts, also called transition waves, switching sequentially its multi-stable units front one equilibrium to another, and resulting in the local or global reconfiguration of the medium. In addition, these nonlinear metamaterials are also known to support a rich variety of nonlinear waves, as
vector solitons, breathers, conical waves, among others.

We will address such questions as how they can be triggered, what can be their propagation properties, and how they interact with other nonlinear waves. In general, these reconfiguration fronts obey nonlinear reaction - diffusion equations and show specific properties not necessarily found in other waves supported by periodic and/or nonlinear media, e.g., strong nonreci-pro city, robustness, extreme amplitude dependent behavior … The presentation will be concluded with a discussion on their potential implementation for applications involving local or global reconfiguration of a medium, manipulating mechanical memory, controlling waves in space and time, mechanical computing or be the vector for material embedded intelligence.

From microscopic to multi-scale dissipation in poro-elastic materials : characterization, modeling and implementation

François-Xavier BÉCOT

Matelys

Noise abatement solutions could have two different strategies: either re-directing the energy or dissipating it. This talk will mainly address the dissipation mechanisms which may occur at various scales of a structure, from the micro -structure of a poro-elastic material to the dissipation across the scales of a heterogeneous structure.

The dissipation occurring in a homogeneous medium will be reviewed and the main quantities representing visco-inertial and thermal losses will be introduced. A general implementation of Biot's poro-elasticity equations will be recalled, which allows us to describe a large variety of micro-structures. An analytical model will also be reviewed, which enables us to represent the interaction across multiple scales of heterogeneous media. Some examples of meta-materials taken from literature will illustrate these approaches.

The last part of the talk will address the practical design and implementation of such heterogeneous structures or meta-materials. How to retrieve the critical characteristics of the substrate? What type of dissipation to target? What are the corresponding industrial applications and what mechanisms are they exploiting?

Concluding remarks will be given from an industrial perspective about the expected outcomes of today's research and the main stakes of tomorrow's efforts.

3D prinitng, metamaterials and biomedical applications

AMAZEMET et G. HANNEMA

In this session, we will share insights with hands-on medtech startup founder's experience in developing regulated medical devices. We will explore the key steps in R&D, from early prototypes to clinical validations. We will focus on the importance of a robust quality management system and careful regulatory planning (under FDA & MDR). We will also cover practical do's and don'ts that can help new teams manage risk and ensure compliance. This path supports the creation of safe, effective products that meet clinical needs and regulatory requirements

Applications of ultrasonic waves, phononic crystals and metamaterials

S.Laureti, D. Hutchins

The presentation will start with the basics of ultrasound, namely the concept of acoustic impedance, transmission across a boundary, and refraction at an interface between two media. The types of common ultrasonic wave modes will then be discussed, as this is important when it comes to applications. Their main properties will be briefly outlined, including aspects such as dispersion, scattering and resonance. Thereafter, a review will be given of the main applications that exist using conventional approaches, concentrating on those of interest to members of MetacMed.

This will include nondestructive testing, medical imaging, other medical applications such as blood flow monitoring, and high-power applications such as HIFU. This is then followed by a description of how the particular properties of Phononic Crystals (PCs) and Acoustic Metamaterials (MMs) can be used to provide enhancement to existing technologies. This will include applications to biomedical diagnosis, imaging, energy harv esting and sound adsorption

Guided tour of the laboratories: Underwater acoustic measurements – acoustic test basin

Monique POUILLE-FAVRE, Florian ALLEIN

Université de Lille, CNRS, Université Polytechnique Hauts-de-France, Junia, UMR 8520-IEMN, OAE Department

Underwater acoustic measurements are essential, on the one hand, to characterize unitary or antenna sources, transmitting or receiving, and, on the other hand, to validate their performance and their implementation for industrial use in SONAR systems or metrology use for research.

Similarly, the acoustic properties or performance of composite/complex submerged structures must be verified experimentally. New structures are being studied and optimized for military or civilian applications, for example to improve the control of noise pollution at sea.

Before moving on to measurements in "real" in situ conditions (at sea), which can be logistically and financially burdensome, measurements in acoustic test basins offer a good evaluation of the performance of the systems, subject to taking into account the limitations they present given the finite space in which they are carried out and therefore adapting the techniques to these limitations if necessary.

Different types of measurements will be presented, recalling the conditions and assumptions to be verified through measurement benches developed at the acoustic test basin located at JUNIA ISEN Lille (*):

Taking pressure level measurements using hydrophones/standard transmitters for different applications, in particular for measuring the emission level (Sv/SPL) and directivity of transmitters to be qualified or for measuring the reception level (Sh/OCV) and directivity of receivers to be qualified. Measurement of reflection and transmission coefficients of acoustic panels (3-point/5-point methods and spatial averaging)

(*) The acoustic testing tank located in Lille, built in 1985, with dimensions (8m long, 6m wide and 7m deep), offers and allows measurements in an open academic environment, in the sense that the tank can be used for student projects, external services and research in the broad sense.

NOTES