PRINCIPAL ACADEMIC TUTOR
Louena Shtrepi, Dept. of Energy, PoliTO

ACADEMIC TUTORS
Federico Bosia, Dept. of Applied Science and Technology, PoliTO
Antonio Gliozzi, Dept. of Applied Science and Technology, PoliTO
Alberto Corigliano, Dept. of Civil and Environmental Engineering, PoliMI
Raffaele Ardito, Dept. of Civil and Environmental Engineering, PoliMI
Francesco Braghin, Dept. of Mechanical Engineering, PoliMI
Riccardo Mereu, Dept. of Energy, PoliMI
Alessandro Daga, Dept. of Mechanical and Aerospace Engineering, PoliTO

EXTERNAL TUTORS
Stefano Izzo
Andrea Merulla
Patrizio Moruzzi

TEAM MEMBERS

Lorenzo De Santis,
Mechanical Engineering,
Politecnico di Milano

Alessandro Veca,
Mechatronic Engineering,
Politecnico di Torino

Matteo Dall'Ora,
Aeronautical Engineering,
Politecnico di Milano

Niccolò Michelotti,
Space Engineering,
Politecnico di Milano

Daniele Cassano,
Aerospace Engineering,
Politecnico di Torino

Francesco Alice,
Aeronautical Engineering,
Politecnico di Milano

Mario Nuzzi,
Aerospace Engineering,
Politecnico di Torino

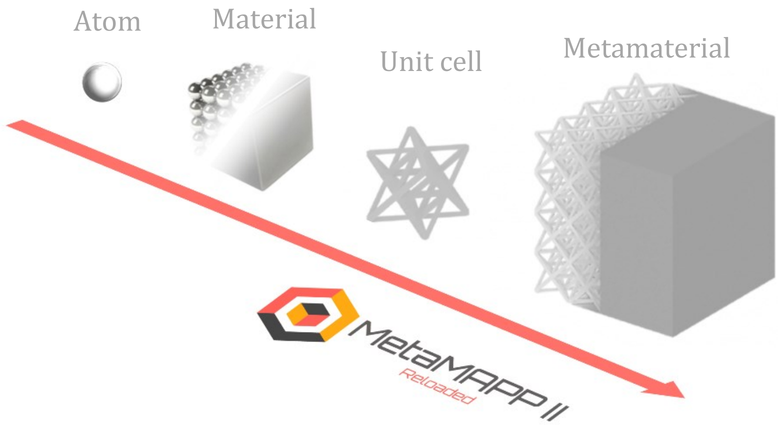
MetaMAPP II
Reloaded

Executive summary

Metamaterials have proven effective in addressing multiple technological issues, such as selective sound absorption in the automotive/aeronautical field, enhancing speech recognition in acoustic devices and damping vibrations in civil engineering, Despite their potential, a formalized set of recognized design principles with predictable output properties, quality, scalability, etc. has been lacking, limiting their widespread adoption in applications.
MetaMAPP II - Reloaded aims to develop a metamaterial-based solution to reduce the noise level inside a car cabin, particularly targeting a specific range of medium-high frequencies.
The development of the prototype has involved extensive research and literature analysis on the different families of currently studied and employed meta-materials, with the aim of laying the foundations for the proper product design process.
A substantial part of the workflow has been devoted to the identification of plausible unit cell geometries to meet the fixed requirements. Acoustics finite element simulations have been adopted to assess the properties of unit cells and unit cell clusters. These numerical models are essential to determine the influence of variable design parameters. A subsequent printing and testing phase has been adopted to validate numerical results and choose the best candidate unit cells for the final products.
A step-by-step process involving research and subsequent confrontation with stakeholders has led to a greater focus on transmission properties of the metamaterial panel (referred to as Sound Transmission Loss, or STL), compared to absorption ones. Additional working mechanisms of the labyrinthine cells have consequently been explored, combining purely acoustic absorption effects of the cavities with the elastic behaviour of the cell walls and structure itself.
The final outcome of *MetaMAPP II – Reloaded* consists of two types of prototypes, a cube and a panel made of metamaterial cells, that demonstrate and certify the acoustic performance of the designed acoustic metamaterial solution.

Key Words

Acoustic MetaMaterials, Sound Transmission Loss, Sound Absorption, Automotive.



POLITECNICO MILANO 1863 · ALTA SCUOLA POLITECNICA · Politecnico di Torino

Project description written by the Principal Academic Tutor

Metamaterials are artificial structures that allow to manipulate acoustic/elastic waves in exotic ways, giving rise to cloaking, focusing or filtering effects (band gaps), with advantages such as reduced material thickness/weight and design versatility, i.e. opening new opportunities to pursue sustainable solutions. The project fits in the field of smart technologies and aimed to tackle challenging aspects on real case studies working on frontier technology for the automotive industry. Specifically, it addressed noise control issues by innovative design of labyrinthine acoustic metamaterials to overcome the limitations of traditional materials. Besides the design aspects and laboratory characterizations, the approach aimed to create the bases for a solid application of these innovative materials in the future at a broader scale. Moreover, new methodologies for component design and testing procedures were explored to provide students with a rich experience and higher sensitivity towards the physical simulated/measured quantities and to create a solid know-how.

After a first explorative phase of the state-of-the-art solutions, metamaterials design, optimization techniques, a second phase of investigation of possible performance characterization at different scales was developed, going beyond traditional methods and including efficient baseline lightweight and thin noise insulating and damping materials. Several challenges were faced using dedicated simulation methods, numerical optimization, material and geometrical development, fabrication technology (3D printing) and specialized characterization setups. Prototyping at different scales led to a more tangible overview of the problem and applicable solutions.

The team of students was challenged to collaborate, bringing together competences in physics, mechanics, computing, digital fabrication, acoustics, civil engineering, materials science, design and management.

The whole team had the opportunity to increase possibilities of exploitation of competences in collaboration with industry.

Team description by skill

The project was carried out through the collaborative efforts of a team comprising students from *Politecnico di Milano* and *Politecnico di Torino* with distinct engineering backgrounds and technical knowhow. This diversity allowed the group to approach the research problem with different perspectives and combine the strengths of each individual's expertise. The allocation of roles within the team naturally evolved according to each person's unique interests and preferences, often resulting in the creation of temporary sub-groups addressing a specific research activity throughout each phase of the project.

The team composition and main tasks allocation have been performed as follows:

- Lorenzo De Santis (Mechanical Engineering): team leader, unit cell design and testing.
- Alessandro Veca (Mechatronic Engineering): elastic metamaterials design and numerical simulation.
- Matteo Dall'Ora (Aeronautical Engineering): acoustic metamaterials design and testing.
- Niccolò Michelotti (Space Engineering): elastic metamaterials design and numerical simulation.
- Daniele Cassano (Aerospace Engineering): acoustic metamaterials design and testing.
- Francesco Alice (Aeronautical Engineering): acoustic metamaterials design and numerical simulations.
- Mario Nuzzi (Aerospace Engineering): acoustic metamaterials design and testing.

Goal

MetaMAPP (MetaMaterials APPlications) - *II Reloaded* pushes forward the work and builds on the knowledge acquired in the previous ASP project, *MetaMAPP I*, whose primary scope was to design and optimise a metamaterial sample, exploring its application feasibility in the aeronautical field, thus paving the way to a future thorough and detailed prototyping of such products. The main target of *MetaMAPP II - Reloaded* is to devise a metamaterial-based solution to employ in automotive applications, to selectively reduce noise levels inside a car cabin, close to set target frequencies. A second parallel aim of the collaborative project is to reduce, as much as possible, the mass of the panel/s to be implemented, while keeping the shape and structural constraints into consideration. These goals stem from the strong push for technological innovation in the automotive industry, in the attempt to overcome the average performance conventional materials offer in the same application area, which turns out to be unsatisfying in some applications, and to pursue sustainability goals, reducing material quantities employed for the fabrication and component weight. The main constraint to the design is to respect strict geometrical and structural requirements of the panel. A further limitation on the product manufacturing techniques is given by 3D printing architectures and cutting machinery, adding a complexity degree to the design process. To measure success, a performance index that looks at how well the product can block sound for each unit of weight is considered.

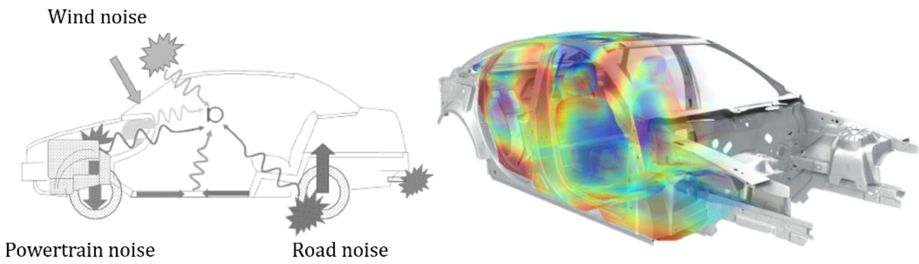


Figure 1: Car noise sources and example of noise map inside the vehicle cabin.

Understanding the problem

The *MetaMAPP II - Reloaded* project aims to increase the TRL of acoustic metamaterial solutions, reducing the distance between theory and practice and bringing AMMs closer to a practical industrial adoption in the automotive field. This has been pursued by means of the following steps:

- Setup and validation of acoustic/vibroacoustic numerical simulations.
- Experimental tests on 3D printed labyrinthine unit cells of different shapes and materials.
- Production of one or multiple prototypes of AMM panels based on the assembly of the best performing unit cells designs.

The main acoustic performance to be sought by the panel are both the Sound Transmission Loss (STL), namely the abatement of sound between two environments separated by the panel itself, and Sound Absorption (α), meaning the power of reducing the reflection of sound waves, converting sound energy into heat.

Due to the complexity of the problem, the whole project workflow was systematically organized in order to carry on multiple tasks at the same time by splitting the team into sub-groups. In any case, given the rather uniform background among the various members, it was decided not to proceed with a strict and permanent distinction of the roles. In this way, all the components of the team were substantially involved in the decision-making phases throughout the research project advancement, avoiding important choices to be undertaken by a sub-group only.

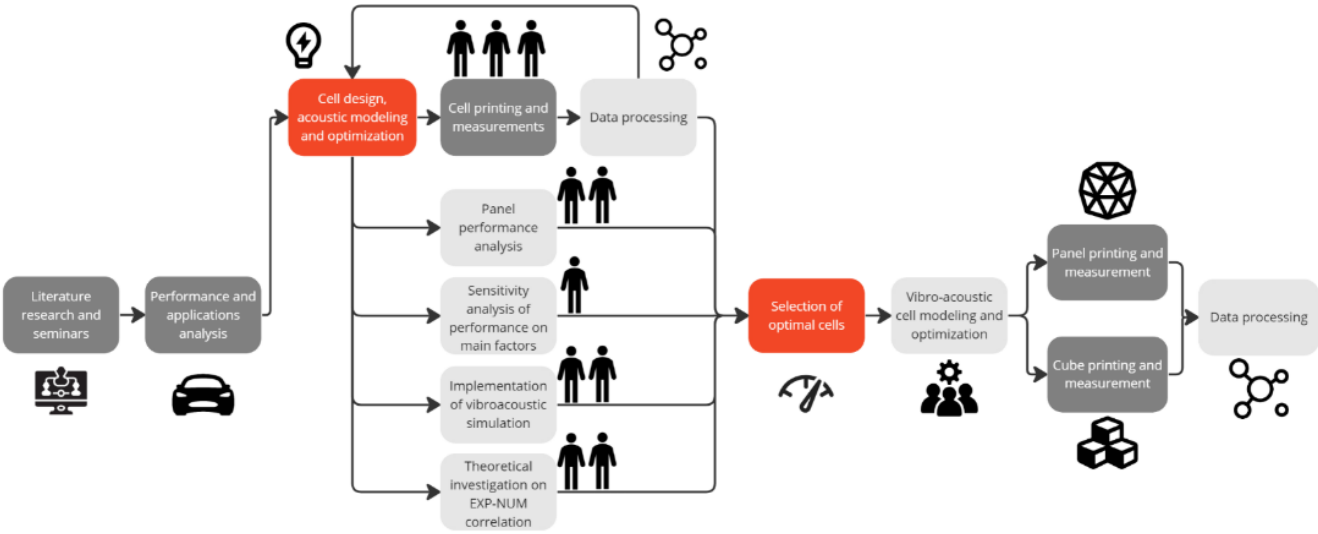


Figure 2: Project Workflow.

Exploring the opportunities

The first core part of the project involved a long and detailed process of study, analysis and design of metamaterial unit cells. To do so, several numerical simulations on the software COMSOL Multiphysics were carried out, both considering only the effect of air (acoustic simulations) and the interaction between air and flexible walls (vibroacoustic simulations).

Different options for internal labyrinth geometries, materials and dimensions were analyzed and compared. In particular, the performances investigated were the acoustic absorption and the acoustic transmission loss within the medium-high frequency range. These properties characterise the reduction of a specific range of undesired noise inside the vehicle cabin.

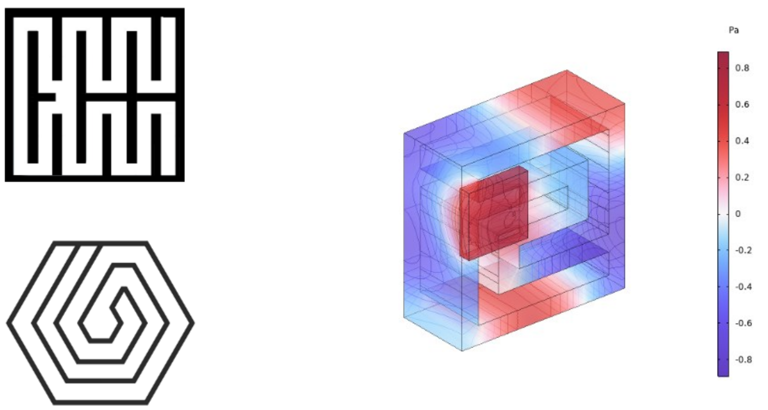


Figure 3: Examples of internal labyrinth geometries and 3D pressure acoustic numerical simulation.

Parallel to the numerical simulations, experimental measurement campaigns were conducted, the aim of which was to validate and confirm the results obtained numerically. For this purpose, samples of metamaterial cells with different geometries and dimensions were printed using 3D printing techniques. The measurements were carried out in the Kundt's tube experimental setup, which allows the quantification of both absorption and transmission loss.

Figure 4: Examples of 3D resin printed unit cells and Kundt's tube experimental setup.

Generating a solution

Following the analyses carried out on the unit cells, it was possible to design final prototypes in order to achieve the project's objectives. The first type of prototype consists of a cube with five walls made from metamaterial cells and one missing wall, so that a sound source can be inserted inside the cube.

This prototype makes it possible to calculate the insertion loss, and thus the reduction in sound pressure, once the cube is placed around the source. This prototype has numerous advantages, such as the relative simplicity in the experimental measurement of insertion loss. In addition, it provides an immediate qualitative understanding of the acoustic insulation capabilities of the cube made from metamaterials, when it is compared to a cube of equivalent mass and size but composed of flat walls. In particular, it resulted that the metamaterial cube showed an insertion loss 15% higher than the one of the non-metamaterial cube.

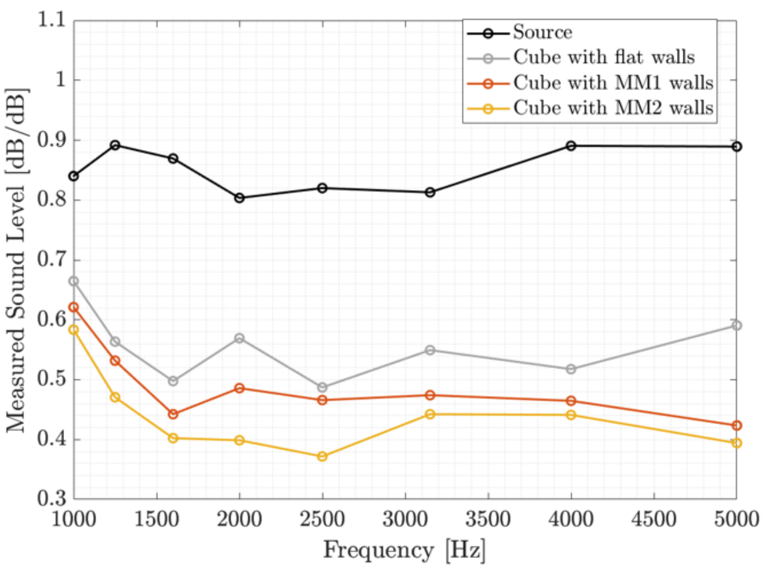


Figure 5: Normalized Sound Pressure Level comparison between the sound source, the cube with flat walls, and the metamaterial cubes.

However, the cube prototype is not suitable to certify the absorption and transmission loss of the metamaterial, and since this is of crucial importance in an industrial context, it was also necessary to produce a final prototype that would allow this. In fact, a panel composed entirely of metamaterial cells was designed and produced in order to achieve certifications of acoustic absorption and transmission loss using standard experimental methodologies.

Figure 6: Experimental setups for the cubes (insertion loss) and the panel (absorption) acoustic performance measurements.

Main bibliographic references

- V. Laude. “Phononics Crystals”, De Gruyter, 2015.
- R. Corradi. “Vibration and sound. Noise and Vibration Engineering”, 2023.
- P. A. Deymier. “Introduction to phononic crystals and acoustic metamaterials. Acoustic Metamaterials and Phononic Crystals”, 2012. doi: 10.1007/978-3-642-31232-8_1.
- M. Marco, C. Claudia, and A. Raffaele. “Locally resonant materials: wave propagation analyses and application to impact absorbers”. 2018.
- L. D’Alessandro, E. Belloni, R. Ardito, A. Corigliano, F. Braghin. “Modeling and experimental verification of an ultra-wide bandgap in 3D phononic crystals”, Applied Physics Letters, 109 (22), 221907 (2016).
- L. D'Alessandro, E. Belloni, R. Ardito, F. Braghin, A. Corigliano. “Mechanical low-frequency filter via modes separation in 3D periodic structures. Applied Physics Letters”, 111, (23), 231902 (2017).
- C. Gazzola, S. Caverni, A. Corigliano. “From Mechanics to Acoustics: Critical Assessment of a Robust Metamaterial for Acoustic Insulation Application. Applied Acoustics”, 183, 108311, (2021).
- Krushynska, A. O., F. Bosia, M. Miniaci, and N. M. Pugno. 2017. “Spider WebStructured Labyrinthine Acoustic Metamaterials for Low-Frequency Sound Control.” New Journal of Physics 19(10). doi: 10.1088/1367-2630/aa83f3.
- Krushynska, A. O., F. Bosia, and N. M. Pugno. 2018. “Labyrinthine Acoustic Metamaterials with Space-Coiling Channels for Low-Frequency Sound Control.” Acta Acustica United with Acustica 104(2):200–210. doi: 10.3813/AAA.919161.
- V. H. Kamrul, L. Bettini, E. Musso, F. Nistri, D. Piciucco, M. Zemello, A.O. Krushynska, D.Misseroni, N. Pugno, A.S. Gliozzi, M. Lott, L. Shtrepi, F. Bosia. “Proof of concept for a lightweight panel with enhanced sound absorption exploiting rainbow labyrinthine metamaterials” arXiv:2110.05026 (2022)
- L. Sangiuliano, C. Claeys, E. Deckers, B. Pluymers, and W. Desmet. “Force isolation by locally resonant metamaterials to reduce nvh.” SAE Technical Paper Series, 2018. doi: 10.4271/2018-01-1544.