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MetaMAPP

Executive summary

In the field of waves and vibrations, Metamaterials (MMs) are artificial structures that allow the manipulation of electromagnetic, acoustic or elastic waves in exotic ways, giving rise to unexpected effects (e.g, negative effective refractive index, cloaking, focusing or filtering). These exceptional properties, not encountered in conventional materials, derive largely from the geometric structure rather than from material composition. This means that they can be realized and replicated in any material (or at any size scale), maintaining the same or very similar effects, apart from frequency/wavelength shifts. Although their characteristics can lead to practical advantages in many applications involving elastic and acoustic wave manipulation (e.g., advanced sensing, vibration damping in structures, acoustic noise abatement, etc.), the understanding of their properties constitutes an open and widely unexplored research field in many and diverse disciplines involved. Thus, despite their promise, MMs remain scarcely utilized in advanced technological fields, mainly due to the lack of a systematic approach in designing optimized, lightweight, practically-oriented structures.

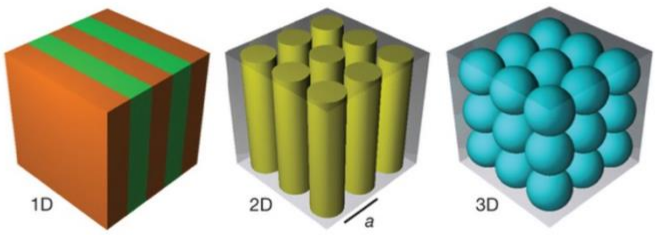
The project MetaMAPP (MetaMaterials APPlications) aimed to contribute to bridge the gap between theory and applications in MM research, by devising effective MM-based solutions to address practical issues encountered in the aeronautical industry. MetaMAPP adopted a research-oriented approach to:

- provide optimized design criteria for MM structures, using numerical algorithms and semi-empirical approaches;
- assessing the possibility to implement tunability of MM properties in response to an external optical stimulus;
- exploit the optimized MM structures for possible applications in the fields of Non Destructive Testing (NDT) and acoustic noise abatement;
- design, manufacture and prototype two devices: a metasensor together with a measurement protocol for NDT of composite aircraft components and an acoustic insulation panel to be applied in the nacelles and the fuselage of aircrafts;

As a long-term goal, the project aimed to bring the innovative potential of MMs to the market, fostering research and development of MMs-based products.

Key Words

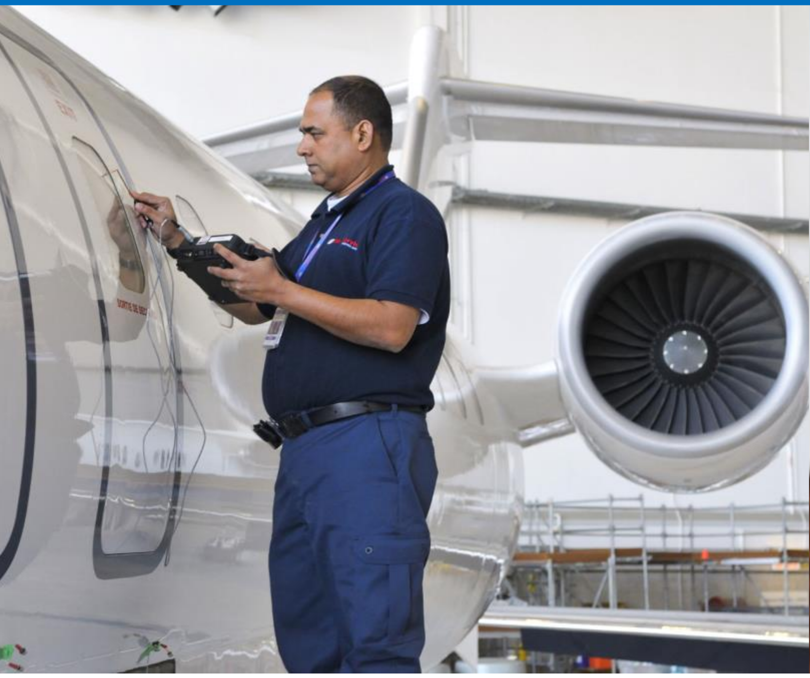
Metamaterials, elastic waves, acoustics, noise control, non-destructive testing.

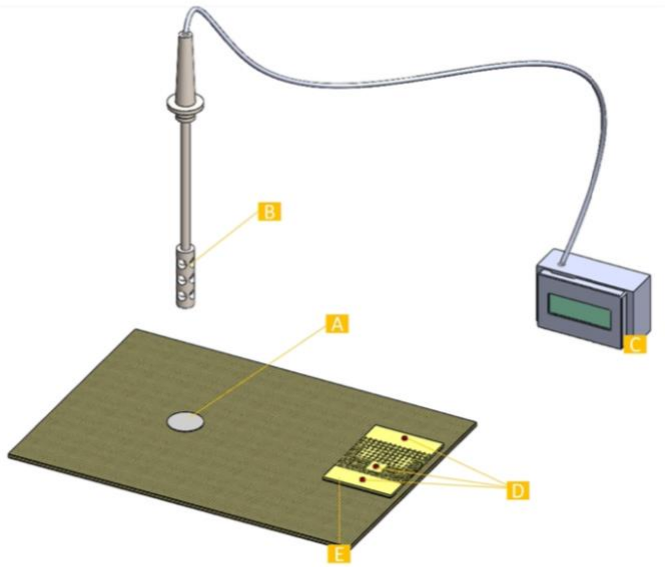


Phonic cristals .

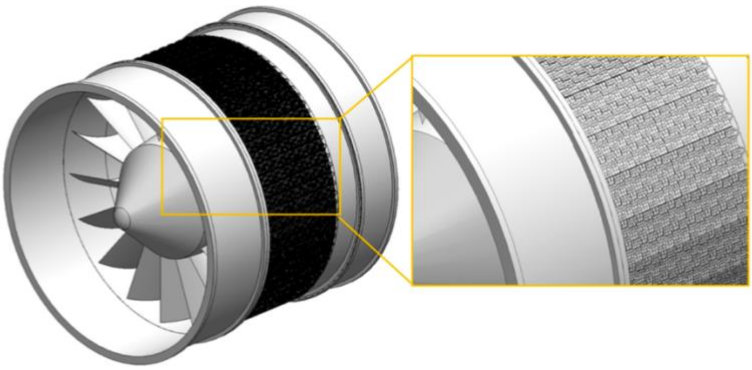
MEASURMENT PROTOCOL FOR NDT

ACOUSTIC NOISE CONTROL

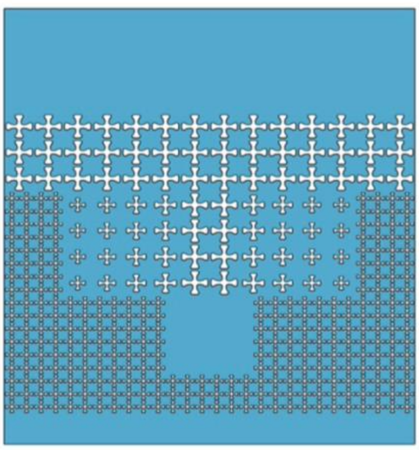




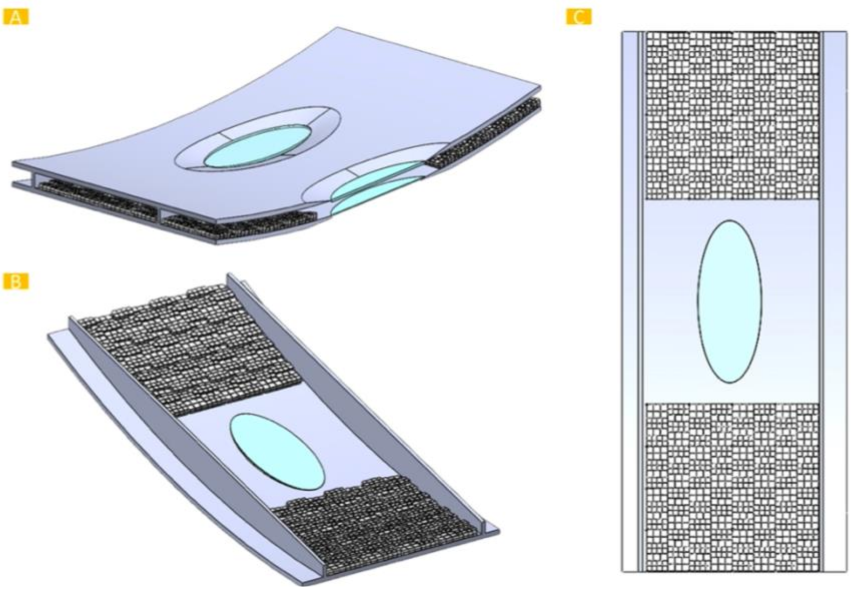
***Concept of the solution for NDT damage identification**. (A) Acquisition point (input); (B) Airprobe trasducer; (C) Electronic signal processor connected to the transducer; (D) Acquisition points (Output); (E) Metasensor*



***Acoustic panel** mounted on aircraft engine*



Metasensor



***Acoustic panels on an airplane fuselage**. (A) Side view of the mounted acoustic panels; (B) Cropped fuselage to show the acoustic panel configuration on the inner surface; (C) Top view of the cropped airplane fuselage.*

Project description written by the Principal Academic Tutor

Research on metamaterials has experienced considerable growth in recent years, producing concepts that could potentially be exploited in practical applications. This is because metamaterials allow to manipulate acoustic and elastic waves at various size scales and in unconventional ways, e.g. for focusing or filtering effects (band gaps), with advantages compared to traditional solutions in terms of reduced thickness and weight or parts, and increased functional versatility. However, systematic design criteria are lacking, and correspondingly, theoretical concepts encounter difficulties in finding their way to the market. The METAMAPP project aimed to reduce this gap, and demonstrate how metamaterial designs can be optimized, adapted and exploited to address specific technological challenges in applied engineering fields, and specifically in aeronautics.

The first, more theoretical part of the project, focused on exploiting optimization algorithms and semi-empirical approaches to improve the performance of existing metamaterial architectures, and to explore the possibility of achieving tunability using photo-responsive polymers.
The second part of the project concentrated on specific applications for the developed metamaterial designs, in the fields of nondestructive testing and noise control.

In the first case, an experimental protocol was developed to highlight, exploiting nonlinear elastic response, the presence of defects or delaminations in composite plates; a 3D printed-metasensor was then designed, optimized, numerically simulated and experimentally validated to isolate harmonic frequencies in the detected signal, thus enhancing signal to noise ratio.

In the second case, a lightweight sound absorbing metamaterial panel was designed, fabricated and tested, exploiting the so-called "rainbow" effect, i.e. the use of spatially distributed metamaterial unit cells of variable dimensions and thus resonance frequencies, giving an overall absorption spectrum over the desired frequency range.

In both chosen applications, a proof of concept experiment was performed with 3D-printed prototypes of the designed metamaterial structure, demonstrating the feasibility of Metamaterial Applications in diverse fields.

Team description by skill

The multidisciplinarity of the team was an important strength of the project, because it allowed to merge competences from different subjects, related both to basic scientific research and engineering. The team included students with background in physics and material science (with computing and laboratory experience) students with past experiences of project management and students with field-specific competences (mechanical, civil and aeronautical engineering). This composition allowed to diversify tasks and prioritize objectives. Those more proficient in theoretical aspects contributed to numerical simulations, physical modelling and understanding; those with proficiency with coding dealt with the optimization procedures, while the more industry-oriented students were responsible for Computer Aided Design (CAD) and manufacturing. All the students participated in the experimental work, which involved quick assimilation of new techniques, coding, data analysis and reporting.

Student role division

Goal

MetaMAPP seeks to exploit the properties of metamaterials to enhance the sensitivity of ultrasonic nondestructive testing techniques for damage detection in fibre-reinforced polymer(FRP) composite panels. More specifically, the technique exploits nonlinear elastic effects, whereby the presence of material defects/inhomogeneities generates higher harmonics of the fundamental signal. Since these harmonics are often small in amplitude, it is necessary to filter out both the noise and the contribution of the fundamental frequency. Thus, MMs can provide a passive tool to increase the spatial and temporal precision of damage detection through the selection (filtering) and amplification (energy focusing) of the defect-related signals. The second goal is to develop a sound absorption panel to be applied on engine nacelles and on the fuselage of an aircraft in order to reduce the acoustic noise radiated in the environment and inside the airplane, by exploiting the rainbow effect in MMs. This allows to produce a device which is able to absorb the noise in the desired frequency range, with :1) a reduced thickness and weight of the panel compared to existing solutions; 2) flexibility in the choice of the material; 3) possibility of exploiting sub-wavelength band gaps that can be tuned to occur at low frequencies where the acoustic wavelength is large compared to the material, and where the performance of traditional passive noise control treatments is limited.

Understanding the problem

MetaMAPP project targets the application of MMs in the aeronautical industry in which two main issues have been identified. On the one hand, current methods and techniques aimed at assessing the structural health of aircrafts components are inefficient, require high maintenance downtimes, and cannot be performed in real-time or in situ. Undetected damage in aircrafts can jeopardize the safety of the crew and the passengers, while inefficiencies in the maintenance chain are costly from an environmental standpoint and economically for airline companies. Preventing and addressing this problem provides a decisive step forward in non-destructive testing (NDT). On the other hand, aircraft noise pollution in the vicinity of airports constitutes a serious health concern, and significant improvements in noise abatement technologies by conventional approaches have been scarce. This problem can be tackled by improving acoustic noise attenuation.

Exploring the opportunities

In NDT, the proposed metasensor could address various needs of end users, depending on the application, e.g. the maintenance division of airline companies or wind turbine blades manufacturers, as well as many other companies involved in advanced manufacturing and maintenance of FRPs parts. In a broader perspective, which takes into account the interplay between aircraft industries and society, other requirements impact can be addressed, namely: applicability to FRPS, integrability in damage-tolerant design concept (i.e. the sensor design should be easily integrable in existing protocols), reduction in maintenance downtime, portability in situ and resilience and sustainability of aircrafts. In the field of acoustic noise reduction in aeronautics, when considering the broad range of options which are presently employed to the purpose of acoustic noise abatement, the main requirements are mostly motivated by the need to develop competitive metamaterial-based solutions, as well as by the ambition to achieve a higher level of sustainability and low-environmental impact, improving the performance of the pre-existing solutions. More specifically, the developed innovative sound absorption device should have the following properties: a reduced thickness, a comparison with current technologies suggests that keeping a thickness lower than 2.5 cm would outperform rock wool, modularity, lightness, eco-sustainability, durability and easy maintenance.

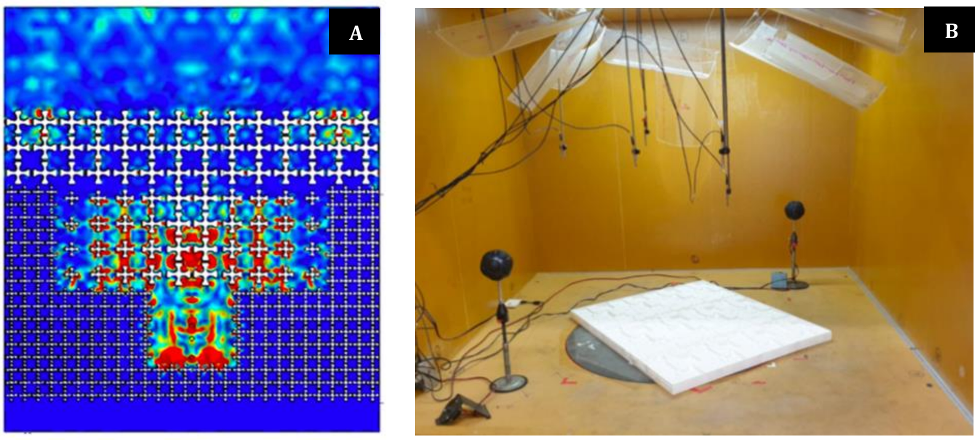
Generating a solution

The main building block of MMs is their unit cell (UC). The properties of MMs emerge when multiple UCs are periodically arranged in space. Therefore, the design of optimized MM solutions begins with the study of suitable unit cells.

As a starting point, 6 UCs were optimized starting from existing designs in the literature. Three of these were numerically optimized through an evolutionary algorithm: this step generated a "four-leaf clover" (FLC) geometry, which was selected for the NDT device. Other three UCs were experimentally optimized through a semi-empirical approach, among which the "simple Wunderlich labyrinth" (SWL) UC was selected and used for acoustic noise insulation. Given the two application fields of the project (i.e., NDT and acoustic noise insulation), two devices were designed and implemented.

- The first device, to be employed in NDT, consisted of a prototype of a MMs-based sensor ("meta-sensor") together with a measurement protocol for assessing and monitoring the structural health of composite aircraft components. The meta-sensor design employed a graded spatial arrangement of FLC unit cells. When the metasensor is applied to a defected testing sample, it filters unwanted frequencies and enhances and focuses the nonlinear elastic response generated by the interaction of a test signal (provided by the user) with defects and/or inhomogeneities potentially present in the sample. These non-linearities, which carry information on the position and the nature and the defect, are focused by the metasensor to a single acquisition spot. Therefore, the signal quality at the output is enhanced, and can be retrieved by a laser vibrometer (or, alternatively, a piezo- electric sensor) pointing to the metasensor focus. The outlined procedure allows to reconstruct the location of the damage.
- The second prototype consists in an acoustic panel to be applied in the nacelles and the fuselage of the aircraft for noise absorption. Following the requirement of being competitive with the other state-of-the-art technologies while fully utilizing MMs properties, our acoustic panel has many advantages: it is thin, lightweight, modular and easily maintained. The design of the acoustic panel exploits an appropriate spatial configuration of many SWL optimized unit cells, each tailored to function in a specific frequency range. The overall effect is the acoustic attenuation over the desired range of frequencies.

For ease of fabrication and precision, both devices were manufactured through polymeric 3D printing. Tests on both prototypes yielded promising results. The metasensor succeeded in selectively focusing specific frequencies, while attenuating undesired ones. Although the filtering capacity remains to be fully implemented, the results retain a high level of scientific interest, due to the novel design criterion (a graded-refractive index, still largely unexplored in the scientific literature) and the numerical optimization procedure based on evolutionary algorithms - a novel powerful approach for MMs.



Prototypes. *(A) Metasensor; (B) Acoustic absorption panel*

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