A NUMERICAL STUDY ON THE BEHAVIOR OF PARTITION PANELS WITH MICRO-RESONATOR-TYPE METAMATERIALS

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ABSTRACT

The usual measures adopted to increase the acoustic performance of partition panels are based on the increase weight or on the superposition of layers of different materials. More recently, new concepts are being considered, with the behaviour of such structures being improved by additional dynamic effects, such as the incorporation of internal micro-resonant elements. Therefore, an adequate response of these elements can be sought, to mitigate the weaknesses in the sound insulation over the perceptible frequency range.
A numerical study is proposed, to analyse the dynamic effect of incorporating different kinds of metamaterials in the design of partition panels.

RESUMO

As medidas habitualmente adotadas para aumentar o desempenho acústico de painéis de separação em edifícios são baseadas no aumento de peso ou na sobreposição de camadas de diferentes materiais. Mais recentemente, têm sido considerados novos conceitos, com o comportamento de tais estruturas a ser incrementados por efeitos dinâmicos adicionais, tais como a incorporação de elementos micro-ressonantes internos. Portanto, pode-se procurar uma resposta adequada destes elementos para mitigar os pontos fracos no isolamento acústico na gama percetível de frequências.
Propõe-se um estudo numérico para analisar o efeito dinâmico da incorporação de diferentes tipos de metamateriais no projeto de painéis de separação em edifícios, assim como algumas formas possíveis de materialização destes conceitos.

1. INTRODUCTION

Noise reduction in many building systems can be attained with the incorporation of different types of acoustic metamaterials, namely, plate-type acoustic metamaterials, spring-mass resonators, phononic crystals, elastic metamaterials, membranes in perforated plates or in honeycomb structures, locally resonant sonic materials, metasurfaces, perforated plates, arrangements of Helmholtz resonators or discrete sets of scatterers arranged as sonic crystals. The usage of local resonant elements, periodically displaced in a regular grid of elements, permits the blocking of sound waves beyond the limit of the conventional mass density law [1].

Liu et al. [2], based on the concept of localized resonant structure, have designed a 2 cm slab with embedded sonic crystals and showed that it was possible to surpass the conventional mass-density law of sound transmission by one or more orders of magnitude, at 400 Hz. On the other hand, Schwan and Boutin [3] presented the results of the reflection phenomena in an elastic half-space exhibiting a "resonant surface" over which linear oscillators are distributed. The authors have demonstrated that the surface motion comes to zero in the resonating direction around the oscillators' eigenfrequency and that the surface impedance may be isotropic or anisotropic, depending on the type of oscillator.

A periodic structure of cells with local resonant structures was numerically designed by Claeys et al. [4] and the stop band behaviour and consequent improvement of the acoustic performance were experimentally validated. The stop bands were numerically estimated through unit cell modelling and then a finite element model was applied to predict the insulation performance of the 3D printed demonstrator. The stop band behaviour was also explored in plates with tuned resonators, on both a vibration and an acoustic level. It has been shown that care should be taken in designing stop bands for vibro-acoustic applications since the characteristic mode split, in resonance based stop band materials, can drastically influence the radiation efficiency of those materials. Therefore, in order to achieve an interesting acoustic stop band behaviour, adjusted resonators have to be designed in accordance to the plate's coincidence effect [5].

In the present work, some innovative solutions are illustrated and, according to their main characteristics and theoretical acoustic behaviour, they are grouped in different sets of systems. The introduction of new concepts in the design of partition panels envisages the maximization of their performance, with increased application flexibility without compromising the operability with higher weights. Making use of a general and versatile numerical method, as the Finite Element Method (FEM), and profiting from the benefits of the periodicity observed in many metamaterials, a numerical conceptual study is then briefly presented on the noise reduction achieved by periodic partition panels. In the last part of the paper, some ideas and examples on the possible materialisation and prototyping of these innovative metamaterials are discussed and illustrated with small-sized samples already produced in the scope of an ongoing R&D project.

2. INNOVATIVE ACOUSTICAL SOLUTIONS WITH INCREASED PROPERTIES

Mainly in the last decade, some innovative concepts have been theoretically explored for acoustical solutions, through analytical studies and numerical analyses. Complemented with laboratory tests, under controlled conditions, the combined use of different materials in specific types of periodic arrangements has demonstrated to exhibit peculiar features regarding the acoustic properties of these systems, namely increased noise abatement and acoustic absorption. These recent acoustic materials and solutions can be grouped in the following types of systems, as represented in Figure 1: the metamaterials, the metasurfaces, the sonic crystals, the multilayer systems and other alternative solutions.

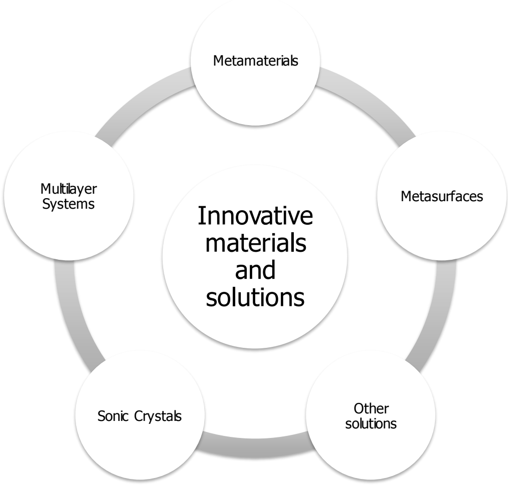

Figure 1. Innovative acoustical materials and solutions.

In the first group, corresponding to the metamaterials, we can include various configurations with plates or thin plates complemented with resonant elements, such as periodically distributed masses whose vibration modifies the sound reduction provided by the plates (Figure 2a, [5]). In the same group, we can also observe different types of resonant strucutures, with periodic arrangements of resonators (e.g. periodic resonators arranged or embedded in plate-like structures, or thin plates with designed cuts leading to periodic vibrating elements) (Figures 2b-2e, [6], [4], [7], [8]). The use of membranes separating rigid structures with periodic configurations and the use of elastic material covering discrete spherical masses disposed in periodic matricial arrangements have also been documented in the technical literature [9], [2].

The second group of solutions, entitled metasurfaces, is more focused on the improved superficial sound absorption registered on the exposed part of covering materials. Labyrinth structures are characterized by panels or structures with perforated surfaces connected to small volumes of air trapped in labyrinth paths and resonating in tuned frequencies (Figure 2f, [10]). Perforated panels usually exhibit periodic perforations (Figure 2h), connecting the surface to airgaps behind the panels, and recently more complex transversal geometries have been studied [11], as well as the use of sub-milimetric holes in microperforated panels. Also in this group, we can mention the periodic arrangement of arrays of Helmholtz resonators, with the resonant frequencies also depending on the spatial arrangement of the individual resonators and on the possible presence of sound absorbent material in the backing of the structure (Figure 2i).

Sonic crystals are periodic arrangements of acoustic scatterers, known to exhibit peculiar attenuation effects in ranges of forbidden frequencies or stop bands (Figure 2g, [12]). In these type of acoustic systems, the geometric spatial arrangement of the elements of the crystal is very important in the acoustic behaviour of the solution, as well as the selected material of the scatterers. Despite some degree of transparency of these kind of crystaline structures, the sound attenuation registered in selected ranges of frequencies can lead to interesting devices for loud electro-mechanical equipment protection that requires ventilation of the enclosure ([13]).

The combination and superpostion of layers of different materials has been used for sometime with interesting acoustic performances attained [14], and recently these multilayer or sanwich systems have been proposed to be combined with internal resonant elements (Figure 2d, [7]).

As can be observed, a great research effort has been recently dedicated in the pursuit of innovative acoustic solutions with increased properties, which is now complemented with an emerging interest of the industry in the application and materialisation of these concepts.

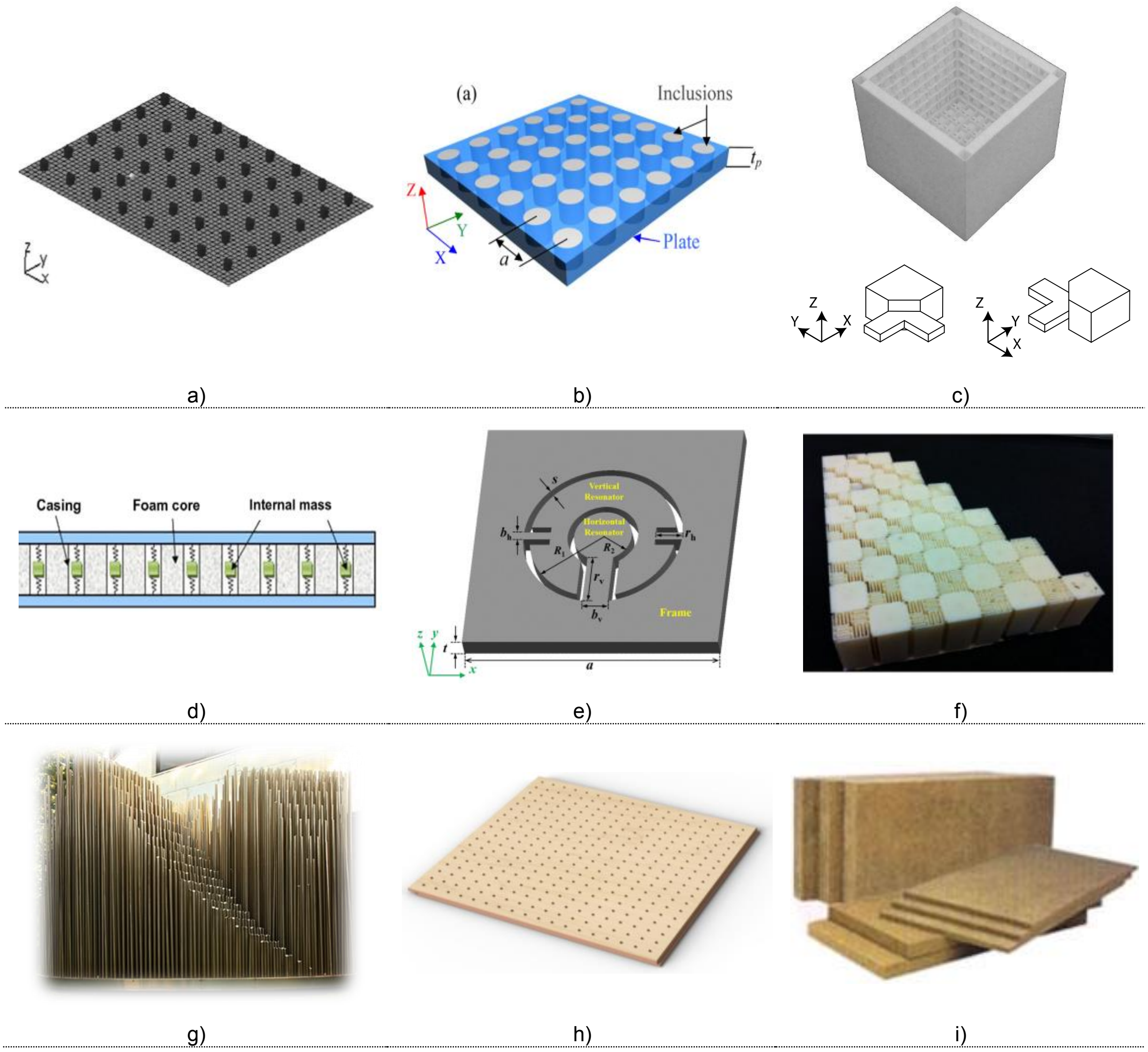

Figure 2. Examples of innovative acoustical materials and solutions: a) finite plate with tuned resonators [5], b) 2D finite phononic plate [6], c) 3D printed box with periodic resonators [4], d) sandwich beam with internal resonators [7], e) cut plate resonant structure [8], f) labyrinth acoustic metasurface [10], g) sonic crystals [12], h) perforated wooden panels, i) mineral wools / fibrous materials.

3. CONCEPTS AND METHODOLOGY IN THE DEFINITION OF MICRO-RESONATOR-TYPE METAMATERIAL

Noise reduction of a single partition panel, along the range of frequencies of interest in building acoustics, is known to be controlled by the stiffness of the panel, at the lowest frequencies, by the mass of the panel, in the mid frequencies range, and by the presence of critical frequencies due to the coincidence effect, at higher frequencies. In current partition panels, this last effect can be particularly penalizing for the global noise reduction. Therefore, making use of metamaterials related concepts, we seek for panel configurations that could minimize this effect. The use of local resonant elements and their periodic distribution, has demonstrated to be a valid approach to enhance the insulation properties of already proposed acoustic materials, allowing blocking sound waves beyond the limit of the conventional mass density law and addressing other limiting physical phenomena.

3.1 Numerical model

In this work, a simple uncoupled numerical model, based on the Finite Element Method (FEM) [15], has been implemented with the purpose of estimating the sound reduction of a partition panel and numerically verify the effects observed when periodic resonant elements are added to the panel surface. The benefits of the periodicity identified in many metamaterials are here considered, which enables very fast and efficient computations since a full spatial discretization of the system is no longer needed, when modeling periodic partition panels.

The conceptual numerical model is illustrated in Figure 3, with the partition panel being excited by incident plane waves and being modelled as infinite in a longitudinal (vertical) direction, with the incorporation of periodic discrete resonators represented by a vibrating mass-spring element.

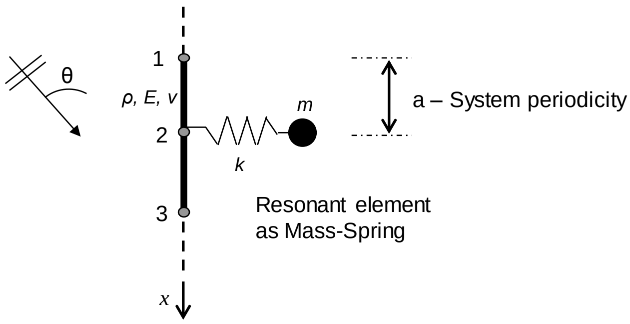

Figure 3. Schematic representation of the numerical modelling concept with periodic system and mass-spring resonant elements.

Thus, the following equation of motion is solved by a classical 1D formulation of the FEM [15], computing the displacement vector, $\mathbf{u}$, while the panel is being discretized by Timoshenko beam elements (incorporating shear deformations),

$$\mathbf{K}\,\mathbf{u} - \boldsymbol{\omega}^2\mathbf{M}\,\mathbf{u} = \mathbf{F} \quad (1)$$

with $\mathbf{K}$ and $\mathbf{M}$ representing the usual FEM stifness and mass matrices, $\mathbf{F}$ representing the external forces and $\boldsymbol{\omega}$ the angular frequency, $\boldsymbol{\omega}=2\pi\mathrm{f}$.

Applying periodic boundary conditions, based on the Floquet-Bloch theory ([5], [16]), enables modeling only a unitary (isolated) cell of the periodic system, greatly optimizing computation times, with the following relations between displacements of adjacent nodes being imposed:

$$u_1 = u_2.\,\mathrm{e}^{-\mathrm{i}k_x a} \quad (2)$$

$$u_3 = u_2 . \mathrm{e}^{\mathrm{i}k_x a} \tag{3}$$

with a representing the spatial periodicity of the system and k_x representing the wavenumber in the periodic direction, given by $k_x = \omega/c \cos\theta$, and c is the sound propagation speed.

3.2 Numerical results

After obtaining the solution of the FEM model in terms of nodal displacements of the vibrating surface, the radiated noise by the elastic panel can approximated by:

$$|p| = \rho c |v| \tag{4}$$

with p representing the radiated sound pressure, ρ the air density, and v the velocity of the vibrating panel.

Figure 4 illustrates the sound pressure level radiated by the panel for the complete set of incidence angles, from θ=0 to θ =π/2, with the latter corresponding to normal waves exciting the panel. On the left side, the behaviour of a homogeneous panel, without resonant elements, can be observed, with the increase of sound pressure level corresponding to the coincidence effect at each incident angle. The other three figures exhibit the modified radiated pattern after adding resonant elements to the vibrating surface, with the interference of the characteristic resonance frequency of these elements being clearly visible. In these cases, different parameters (stiffness and mass) have been used in order to properly adjust the resonance frequency of the periodic resonant elements.

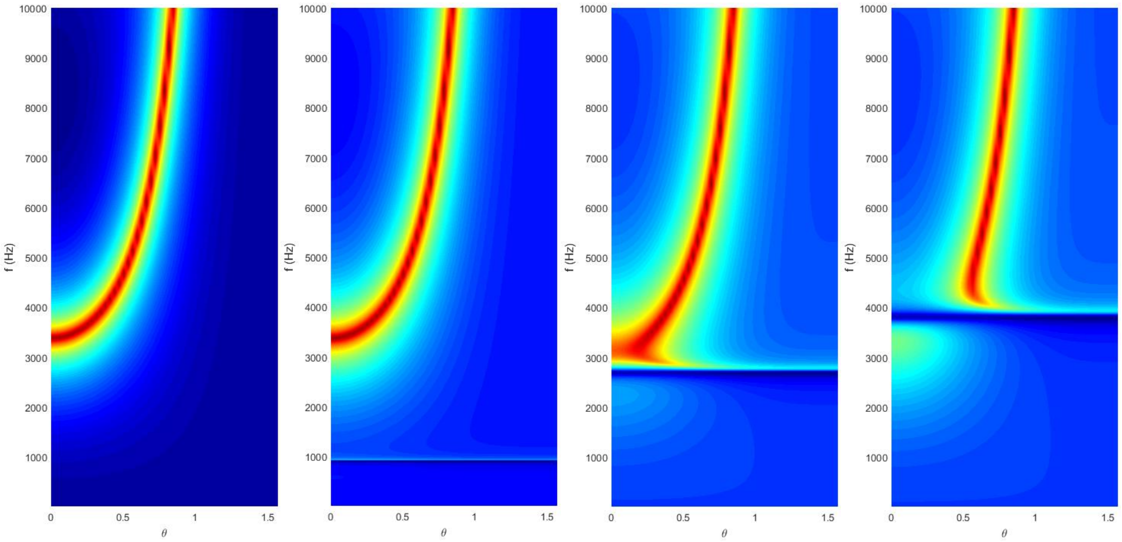

Figure 4. Radiated sound pressure level by the periodic panel with different arrangements of mass-spring resonant elements attached.

The sound reduction curve achieved by the periodic panel has been numerically evaluated by the difference of two sound pressure levels, namely the sound pressure level corresponding to the incident plane wave impinging the panel and the sound pressure level determined by the sound radiated by the periodic panel. In both cases, oblique incident waves have been taken into account, with inclination angles from θ=0 to θ =π/2, corresponding to varying directions from tangential incident waves to normal incident waves, respectively. Therefore, for the same four panel configurations referred above, the estimated sound reduction curves are presented in

Figure 5 and compared to the theoretical mass law in the frequency range from 100 to 5000 Hz. The influence of the presence of the mass-spring resonators placed over the panel, is clearly visible, with the coincidence effect being counterworked and the sound reduction dip at the critical frequency being mitigated.

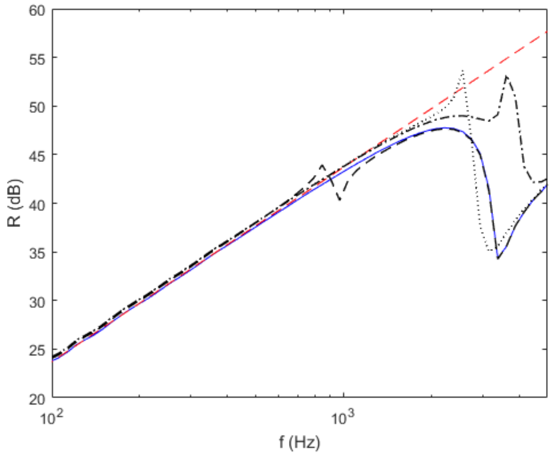

Figure 5. Estimated noise reduction achieved by the periodic panel with different arrangements of mass-spring resonant elements (red dashed line corresponds to the theoretical mass law).

4. MATERIALISING AND PROTOTYPING

4.1 Materials

In order to materialise and produce some real samples inspired by the concepts addressed in the previous section, a very large search for possible materials to be used has been achieved. In fact, the characteristics and requirements of the materials have been analysed, but also some materials and respective properties were identifed, so as to be able to numerically simulate the elastic behaviour of the samples prior to its production.

A set of materials that were identified correspond to very recent materials used in 3D printing technologies. This important technological field has successfully emerged in the last decade and has been presenting significative developments in the last years, regarding production techniques and equipments, product technical specifications, and costs and versatility of production. Different materials were identified (e.g. thermoplastics – polyamide, Nylon, ABS, polycarbonate -, photopolymers, etc.) and two additive manufacturing technologies were suggested (e.g. the fuel deposition modeling - FDM and the PolyJet technologies). Complementarly, the use of other materials has also been evaluated, such as, different types of plywood and medium density fiberboard (MDF) panels; wood, flax and cork particleboards; perforated and grooved panels; steel plates; various elastic materials (melamine foams, polyethilene and polyurethane foams, EPDM rubber, etc.).

4.2 Designing and prototyping of samples

After analysing the numerical results obtained with the described FEM model, a set of samples was designed and its materialisation was achieved. In all cases, the production material was first selected, and then the dynamic behaviour (through modal analysis determination) of a 3D unitary cell was computed using a commercial 3D finite element analysis package (Mecway). This step enabled performing geometric adjustments to the resonator dimensions. Then, 3D models of each of the samples were designed prior to the production phase.

Figure 6 illustrates the design and materialisation of a 3D printed sample in polyamide thermoplastic (FDM Nylon 12), with periodic resonant elements connected to vertical walls and being printed as small beam elements with a bigger mass in the extremety (the dimensions were estimated in a similar way as described in Section 3). In the 3D modal analysis performed (figures 6, on the left), the resonant frequency corresponding to the flexural mode of interest corresponds to 1075 Hz. The picture on the right of Figure 6 illustrates the 3D printed sample.

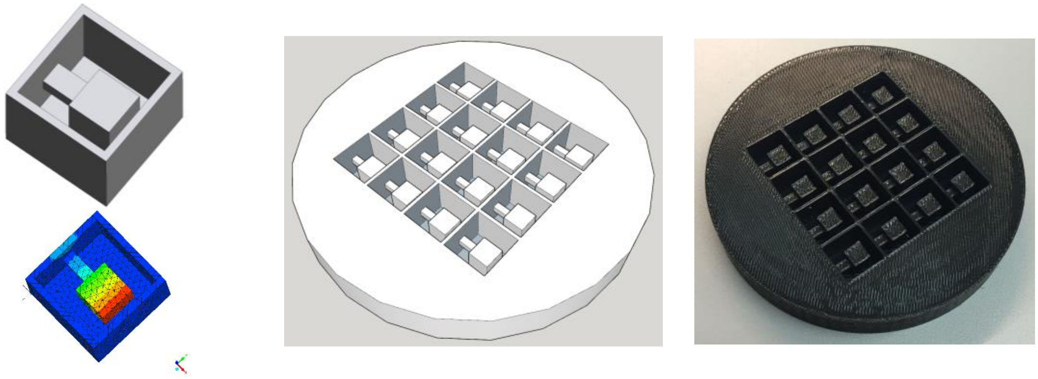

Figure 6. 3D printed metamaterial: on the left, 3D illustration of unitary cell and resonant mode; in the middle, 3D representation of sample; and, on the right, 3D printed sample in polyamide.

The second sample presented in this study adopted the 3D printing technology that enables the use of multiple photopolymer materials. In this case, the periodic resonant elements are being materialised by a vertical paralelepipedic element 3D printed in two different materials (PolyJet RGD 450 and PolyJet Rubber-Like), with the heavier and more rigid PolyJet RGD 450 material (the mass) being printed above the more elastic PolyJet Rubber-Like material (the spring), whose shore hard elastic constant was properly adjusted. In this case, the resonant frequency illustrated in Figure 7 on the left side corresponds to a vertical vibration mode for 1254 Hz. The final sample that was produced can be observed on the right side of Figure 7.

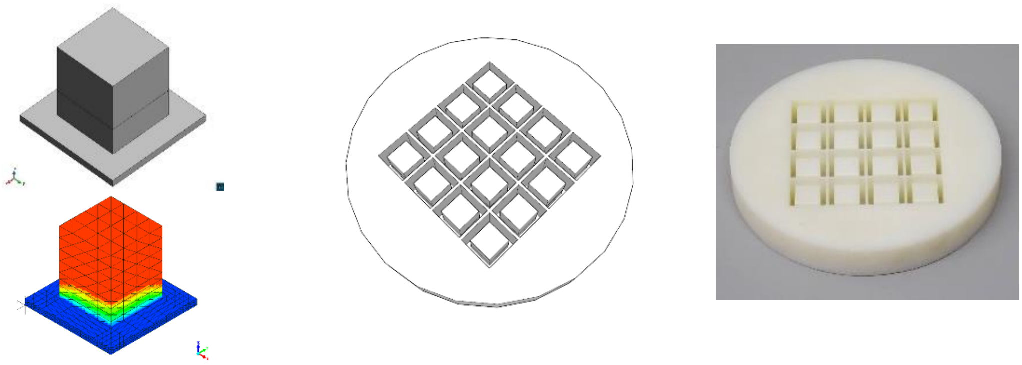

Figure 7. 3D printed metamaterial: on the left, 3D illustration of unitary cell and resonant mode; in the middle, 3D representation of sample; and, on the right, 3D printed sample in multiple photopolymer materials.

5. CONCLUSIONS

In this work, after presenting innovative materials and acoustic solutions described in recent technical and scientific literature, a very simple conceptual numerical model based in the FEM has been implemented for the computation of radiated noise by a simple panel. In fact, a very efficient model has been achieved, taking into consideration the periodicity of the physical system, with the objective of analysing the noise reduction by panels with distributed resonant elements and addressing their possible design. Some ideas regarding the prototyping of these lightweight metamaterial-type systems have been presented, for laboratorial testing at different reduced scales. The increase of acoustic attenuation due different acoustic phenomena has been identified.

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