Acoustic characteristics evaluation of an innovative metamaterial obtained through 3D printing technique

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Abstract. The reduction of interior noise level in the transportation sector is a big problem to cope with in view to increase the comfort of passengers. For this reason a great emphasis from the research community is devoted to develop new technology which are able to satisfy the mechanical requirements with concrete benefits from the acoustic point of view. Currently, it does not exist a solution for wideband range of frequency. Indeed, porous materials are characterized by outstanding dissipation in the high frequency range but they exhibit poor performance in the low and medium frequency range, where instead resonant cavities systems have the best performances but with narrow-band sound absorption. For this reason, the design and development of new materials which offers a good acoustic absorption over a wide range of frequencies is requested. In this paper, a hybrid metamaterial is designed, by coupling resonant cavities with micro-porous material and obtained through additive manufacturing technique which enables to model complex geometries that could not be feasible with classical manufacturing. Numerical and experimental studies have been conducted on the manufactured samples of PLA, with an interesting focus on the effect of each parameter which affects the absorption properties.

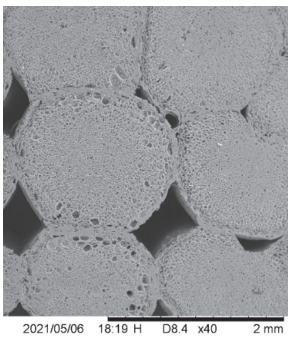
Introduction

Materials have been used to control wave propagation for centuries. The evolution of these are the metamaterials: artificial structures, typically periodic, composed of small meta-atoms that, in the bulk, behave like a continuous material with unconventional effective properties. Acoustics Metamaterial are classified by the mechanism of sound absorption, i.e. how they can manipulate and control sound waves in ways that are not possible in conventional materials. Metamaterials with zero, or even negative, refractive index for sound offer new possibilities for acoustic imaging and for the control of sound at subwavelength scales [1].

In literature it is possible to find three macro-classes: porous metamaterials, membrane resonators and cavity resonators. The first acoustic meta-atoms were spherical metal cores coated with a soft rubber shell packed to a simple-cubic lattice in a host material, which could exhibit a Mie-type resonance frequency far below the wavelength-scale Bragg resonance frequency of the lattice [2]. Other architectures for acoustic metamaterials involve segments of pipes and resonators in the form of open and closed cavities. In 2006, these configurations composed a metamaterial characterized by a waveguide loaded with an array of coupled Helmholtz resonators [3]. At their collective resonance frequency, a low-frequency stopband is formed. Several other metamaterial-based approaches for realizing unusual acoustic refraction have been demonstrated, as example by coiling up space with labyrinthine structures [4], the sound propagation phase is delayed such that band folding with negative dispersion. Most of the acoustic metamaterial designs described above make use of periodic structures, but given that the concept of acoustic metamaterials is based on the local, internal mechanical response of the structure, there is no reason why metamaterials cannot be made from aperiodic architectures. This idea is beginning to be explored using metamaterials composed of a soft matrix containing an unstructured array of bubbles of a second material. This is the main idea of the concept that has been realized in the laboratory. The subject of this work is a hybrid metamaterial composed by resonant cavities and porous material obtained through 3D printing technique. The 3D printing technique has given to the researcher the possibility to invent different geometry that could be impossible to realize with classical manufacturing. The work will firstly illustrate the technical evolution that has led to the construction of the different type of metamaterials that nowadays are subject of study. In the middle it will be introduced the technique of 3D printing used to create the sample, and in the end the numerical simulation and the experimental results will be reported.

3D printing of porous materials

The samples in additive manufacturing used in this research have been obtained using a printer based on Fused Deposition Modeling (FDM) technology. FDM technology consists in depositing on a printing surface several layers of a material that, layer after layer, form a three-dimensional object. The raw material is usually a filament of a certain diameter, which is found on the market in the form of a coil. The filament is pushed by an extruder and passes into the heated nozzle at a temperature above the glass transition temperature of the material in use. The technology used during the realization phase consists in solubilizing the blowing agent in the print blanks, so that the material is expanded during printing. Unlike foaming the piece by solubilizing an expanding agent inside in a post-printing phase, this methodology, obtaining the desired morphology by controlling a rapid jump in pressure and temperature, allows you not to face problems related to the control of the geometry of the workpiece, because the high residual stresses due to printing deform the workpiece during foaming [5]. The production of polymer foams consists of several stages listed: (a) selection of granules and fibres; (b) extrusion of filament; (c) solubilization of the blowing agent in the filament; (d) AM foam printing. By controlling parameters such as the solubilization time, speed and temperature of the extrusion, it is possible to block filaments and then the foams at different densities (Fig. 1) [6]. In the case of study, in the realization of the specimens it was chosen to proceed with medium density foams. The versatility of this process has allowed the realization of the metamaterial of which it has been chosen to characterize the absorption.



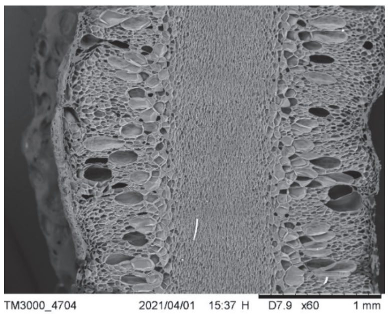


Figure 1 SEM Images of foamed filament (Tammaro et al., 2021)

Analyzed configuration

The tested specimens have the following geometrical data: height of 30mm and 19 holes with a diameter of 3mm, passed, arranged radially. A numerical analysis was immediately carried out using Comsol software to evaluate the acoustic performance of the identified geometry. Subsequently, the specimen were manufactured. In addition to the foaming parameter, it was also chosen to evaluate two possible printing logics: the first consists of printing the full cylinder and then drilling the holes using different techniques; the second, on the other hand, involves creating the holes during printing. This dual mode of realization showed how the production process clearly affects the behavior from the point of view of absorption.

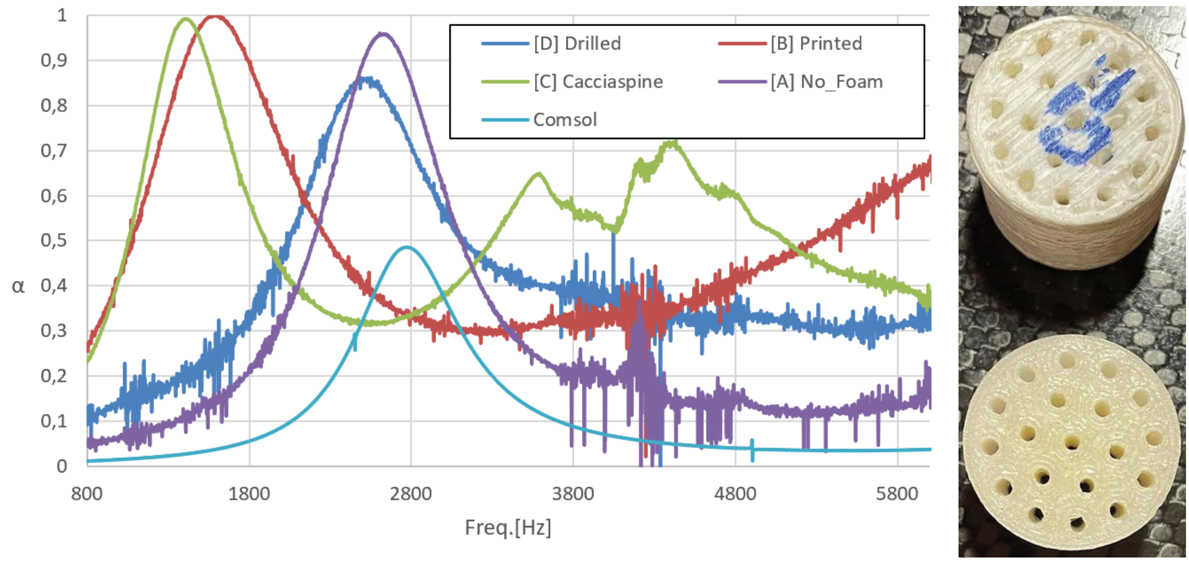


Figure 2: Absorption coefficient diagram

Several aspects are evident from the diagram in Fig. 2: 1) Validation of the numerical model: in order to obtain this comparison, the specimen was first printed using both modes mentioned above, then it was then tested in the impedance tube, complying with the regulations of test's standard, and finally after extracting the data, the curve of the numerical model (petrol) was compared with the experimental (violet). It is observed that the material (unfoamed PLA) is found to have a damping effect that amplifies the absorption curve at the frequency identified by the numerical model reaching almost unity. 2) Drilling method: it is interesting to note how the methodology used to make the holes alters the absorption behavior of the specimen. Three drilling methodologies were chosen to be analyzed. The first one is to drill the specimen in a cold running water bath by using a drill press. Despite the cold water immersion, the temperature reached between the drill bit and the material was such that the hole channel melted locally, thus occluding the internal porous structure of the filament, in fact obtaining the same absorption behavior as the specimen printed with unfoamed filament (blue curve). The second methodology consists of cold drilling using a drill bit and a hand vise to exert compression force. The effect of this second methodology is reported by the green curve. There is a copious shift present due to possible delaminating of the various layers of the specimen and imperfect flatness of the channels. Also from this curve, it is possible to see the presence of a new, higher bell, attributable to the behavior of the foams. Third and last methodology examined consists in directly printing the specimen with the hole locations. First fundamental difference from the previous methodologies lies in the definition of the channel of the hole. The mold in fact overlaps many circles thus obtaining the outer channel of the hole. This overlap is not always perfect and this kind of internal losses in the specimen, thus altering the path that the wave can follow. The result of this condition is the curve in orange. Further tests are in progress to obtain a drilling method that allows full use of the porous structure inside the filament.

Conclusion

Metamaterials are the subject of interest in the world's leading research centers, and the spread of 3D printing has facilitated the creation of prototypes characterized by geometries that cannot be obtained by classical mechanical machining processes. The aim of this work was to create a metamaterial capable of encapsulating all the advantages of the various sound absorption systems. Numerical and experimental analysis were conducted on one of the simplest configurations that could be realized. The results shows that the main difficult aspect is the realization of the holes. Those holes are the inlet for the acoustics wave to the porous foam of the inner part of the filament. If the channel of the hole is melted the only advantage of this technology is the lightness of the sample respect of an unfoamed one. Further analysis would be conducted to determine the best way of perforation and to implement new geometry with an consistent airgap inside the sample.

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