Acoustic performance of an additive manufactured lattice structure

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Abstract. In this paper, a new type of fibreless, bulk, sound absorber is studied. The acoustic material is an additive manufactured lattice structure constituted by a mesh of pins generated by uniform spatial translation of a regular hexagonal prismatic open cell. The material presents remarkable advantages of metal foams: it is “green”, since no deteriorating, air polluting fibres are used; it is thermally and mechanically resistant, thus fire retardant, self-supporting and impact resistant. Compared to fibrous acoustic materials, it has low moisture absorption although the weight is higher. In addition to these properties, this additive manufactured material is provided with regular open cells whose geometry can be precisely controlled according to the desired performance. Moreover, the acoustical behaviour can be well modelled by simulating the air-solid thermo-viscous interaction within one single cell. The high, broad band sound absorption is a major result of the large viscous losses occurring in the flow which oscillates within the small hexagonal apertures. This lattice, referred to as honeycomb skeleton absorber (HAS), is a multifunctional material which can be used in a variety of structural applications where the sound levels must be controlled and/or a certain thermal resistance/insulation is required (for instance car floors).

1. Introduction

The recent developments in AM technologies has been utilized in the field of applied acoustics mainly to produce 3D printed acoustic metamaterials, in a variety of forms and for diverse purposes [1] and, very recently, the Selective Laser Melting has been used to 3D print metal cores for thermo-acoustic applications [2-4].

At the current state, technical solutions for broad band medium-high frequency ranges still rely on the use of traditional porous materials, such as fibrous elements (e.g. glass- or rock-wools), foams (typically of polyurethane) and textiles [5]. In these materials the dissipation of acoustic energy occurs by means of viscous losses within the small air saturated apertures. The main advantage of these solutions is represented by the wide frequency range of sound absorption, although the absorption at low frequencies is poor. Several drawbacks are associated to these materials, especially to the fibrous ones and to the plastic foams, which are also the most widely spread: they are often non-renewable; their performance can deteriorate over time; small particles can separate and pollute the surrounding media; the oil particles/moisture absorption makes these materials unsuitable in applications like turbine liners.
and compressor silencers of supercharged engines. For similar reasons, a recent trend also in HVAC systems has seen gradual reduction in the use of these solutions.

Recently, micro-perforated and micro-grooved panels have been designed to be used in modern HVAC systems, turbine liners and silencers [6,7]. These panels are constituted by one of more thin metal layers provided with sub-millimeter apertures [8-10].

Special mention is deserved by metal foams, because these materials are not affected by major deterioration, they preserve air cleanliness while being thermally and mechanically resistant, thus fire retardant, self-supporting and impact resistant [11-13]. Compared to fibrous materials, these foams have larger weight. However, by providing also lower moisture absorption than fibrous materials, metal foams can be used in several applications where fibrous and plastic absorbers are unsuitable. Traditional metal foams are usually manufactured by means of high-pressure infiltration process, which provides closed cells specimens, resulting in low absorption coefficient. Often, such operations as compressive deformation or hole-drilling are needed to increase the open porosity in order to improve the absorption performance.

In this paper the metal AM technology is used to produce a new type of open-cell lattice structure, referred to as honeycomb skeleton absorber (HSA), where sound absorption can be combined together with mechanical stiffness and thermal resistant properties. The HSA is provided with a mesh of pins generated by uniform spatial translation of a regular hexagonal prismatic unit open cell. As a major advantage, the additive manufacturing process gives the possibility to precisely control the geometry of the unit cell in order to meet the acoustical/mechanical/thermal requirements. Moreover, due to the regular geometry, the performance of the HSA can be modelled accurately. In this paper, the acoustic behavior of several HSA provided with different cell sizes has been studied by means of FEM accounting for thermo-viscous interaction between air and solid structure. The samples have been additive manufactured and tested in an impedance tube.

This work has been inspired by the contribution provided by Fotsing et al [14] and Deshmukh et al [15] where the AM has been first utilized for designing acoustic absorbers.

2. Theory

The propagation of sound waves in porous materials and, generally, in geometries with small dimensions, is primarily affected by viscous and thermal losses. In fact, nearby the solid walls, viscous and thermal boundary layers emerge, due to the viscosity and the thermal conductivity of the oscillating fluid medium. A measure of the length scale for the oscillatory thermal and viscous diffusion is give by the thickness of the viscous boundary layer, \( \delta_v = \sqrt{2\mu/\omega} \), and the thickness of the viscous thermal layer, \( \delta_k = \sqrt{2k/\omega} \). Here \( \mu \) is the dynamic viscosity of the fluid, \( k \) is the thermal conductivity and \( \omega \) is the angular frequency (linked to the frequency \( f \) by means of \( \omega = 2\pi f \)). The two layers are linked by the dimensionless Prandtl number, \( Pr = v/k = (\delta_v/\delta_k)^2 \) (it is ~0.7 for air at 20°C). At longer distances or higher frequencies, the fluid responds adiabatically, and with no major viscous losses, to the acoustic perturbation, whilst in the very proximity of the walls the response is isothermal and lossy. Within small (e.g. submillimeter sized) apertures and audible/low frequencies, the boundary layers cover large part of the volumes. This condition represents the principal mechanism on which porous absorbers work.

In order to model the propagation of acoustic waves in porous media it is, therefore, necessary to include thermal conduction effects and viscous losses explicitly in the governing equations. In this sense, a suitable set of equations is represented by the linearized Navier-Stokes equations in quiescent background conditions which account for mass continuity, momentum, and energy balance. In absence of thermal gradient, these equations simplify as follow:

\[
\begin{align*}
    i\omega \rho_m u_1 &= -\frac{dp_1}{dx} + \mu \nabla^2 u_1, \\
    \quad i\omega \rho_m c_p T_1 &= \kappa \nabla^2 T_1 + i\omega p_1
\end{align*}
\]  

(1)
In Eqs. 1 the subscript 1 indicates a complex term, i.e. the oscillating part of a certain physical quantity, the subscript \(m\) indicates the mean value, \(u\) is the particle velocity, \(p\) is the pressure, \(\rho\) is the density and \(T\) is the temperature (thus, for instance, \(p = p_m + Re[p_1 e^{i\omega t}]\)).

3. Additive manufactured HSE
The honeycomb skeleton shape of acoustic material has been chosen to provide quasi-circular geometries within the sound absorptive cross sections. In fact, although the circularly shaped apertures are well known to be the most effective for the energy dissipation process, the hexagonal shape of the apertures allows minimizing the solid region between adjacent apertures in order to keep the porosity of the material as high as possible.
Several cylindrical samples, provided with 27mm diameter and 50mm height, have been manufactured by means of Selective Laser Melting (SLM). Magnified images of a HSE sample are reported in Fig.1.

![Magnified images of a HSE sample](image)

Figure 1. 15x-magnified images of the cells within the HSE. a) front view, b) side view.

The fabrication of the parts is based on solid CAD 3D models (see Figure 2a). has it been performed using SLM280 HL from SLM Solutions, which uses stainless steel AISI 316L powder as feedstock. The AM process is thoroughly described in reference [2].

4. Modelling and experiments
The Eq.s 2 and 3 can be modelled for complex geometries by means of finite element method. For the regularly shaped unit cell in Fig.2a, only the fluid inside of it is modelled by means of FEM. The symmetry of the geometry can be used to limit the discretized domain and an isothermal condition is applied on the surfaces where the solid walls are located. This is shown in Fig.2b.

Both the numerical model and the experimental approaches are based on transfer-matrix. Named \(S_i\) and \(S_o\) the surfaces which limit the domain modelled, the acoustic pressure and particle velocity at these surfaced are by means of the transfer matrix \(T\) so that:

\[
\begin{bmatrix}
p_1 \\
u_1
\end{bmatrix}_{S_i} = \begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix} \begin{bmatrix}
p_1 \\
u_1
\end{bmatrix}_{S_o}
\]

As demonstrated in [16], the wavenumber of the fluid within the acoustic material, \(k_p\), and its characteristic impedance \(Z = \rho_p c_p\) can be obtained as:

\[
k_p = \frac{i}{d} \cos^{-1} T_{11} \quad \text{and} \quad Z = \sqrt{\frac{T_{12}}{T_{21}}} \]

By utilizing the definition of transfer matrix and its matrical properties, it is possible to show that, if a rigid wall \((u=0)\) condition is imposed at the surface \(S_o\) and an acoustic pressure is imposed at \(S_i\), the terms \(T_{11}, T_{12}\) and \(T_{21}\) reduce to:
\[ T_{11} = \frac{p_{1|S_i}}{p_{1|S_d}}, \quad T_{12} = \frac{(p_{1|S_i})^2 - (p_{1|S_o})^2}{p_{1|S_o}u_{1|S_i}}, \quad T_{21} = \frac{(u_{1|S_i})}{p_{1|S_o}} \] (4)

As a consequence, \( k_p \) and \( Z \) can be obtained by using Eq.3. When FEM is utilized, the averaged values of pressure and particle velocity at \( S_i \) and \( S_o \) can be directly computed. In case of experiments, those values are carried out by using a 3-microphone impedance tube [16]. The surface impedance \( Z_s \), the reflection coefficient \( R_x \) and, finally, the absorption coefficient \( \alpha \) of the acoustic element of length \( L \) can be computed as follows:

\[ Z_s = -1iZ\cot(k_pL) \quad R_x = \frac{Z_s - \rho c}{Z_s + \rho c} \quad \alpha = 1 - |R_x|^2 \] (5)

Figure 2. HSA modelling. a) CAD, b) axis-symmetry of the cell, c) side view of modelled cell.

5. Results

The results are expressed, in Figure 3a, in terms of absorption coefficient as a function of the sound frequency for three different geometries (S01, S02, S03). The figure also includes the geometrical data of the samples, which have different values of the radius \( R \) of the circle inscribed in the hexagon and of the height \( t \) of the unit cell (see Figure 2a). For all samples, the diameter of the struts of the constitutive mesh is 0.18mm, which is considered to be the minimum value for an acceptable printing process. Only the sample S01 has been additive manufactured and tested in impedance tube. However, this is enough to validate the FEM approach, thus to provide reliability to the simulation of the other geometries. The graphs of the absorption coefficient show that the best performance, with total sound absorption at certain frequencies, is reached for \( R=0.5\text{mm} \), and \( t=0.25\div0.5\text{mm} \).

Figure 3. Performance of HSA: a. Absorption coefficient, b. Total thermo-viscous power dissipation density (W/m³)
The Figure 3b confirms that major thermo-viscous losses take place in proximity of the struts, i.e. within the previously mentioned viscous and thermal boundary layers. It must be pointed out that 3D printing geometries provided with very small apertures might be critical because of possible clogging due to the powder bed used in the process. As a consequence, the actual porosity might appear to be fairly different from the desired one and modelling of sound propagation within the geometry provided by the CAD drawing might be misleading.

6. Conclusions

The acoustic performance of the additive manufactured HSA open cell metal lattice structure has been studied. The HSA provides good sound absorption and its multifunctional potentialities will be explored in future investigations by testing mechanical strength and thermal resistance/insulation. Differently from metal foams, the HSA is provided with a regular inner geometry and open cells, which result in good sound absorption. Several configurations of HSA have been studied, their acoustic behavior has been modelled by means of FEM and the results, in terms of absorption coefficient, have been confirmed experimentally. The absorption coefficient reaches unitary values for the samples with smallest geometries, but the printing process in this case still requires further optimization.

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