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Enhancing the sound absorption performance of porous metals using tomography images

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ABSTRACT

Commercially available porous metals are known to provide useful sound absorption, but it may be possible to modify their structures to improve their acoustical properties. Images from high-resolution X-ray computer tomography have been used to make pore-level characterization of Inconel, Recemat and Porvair foams. Based on these characterisations, flow simulations have been used to deduce parameters that determine the acoustical properties according to the Johnson-Champoux-Allard (JCA) and Delany-Bazley-Miki (DBM) models. While the DBM model enables a good agreement with measured normal incidence absorption coefficients for glass fiber materials, the JCA model enables a better agreement with data for metallic foams. The predicted sound absorption spectra were observed to depend mainly on the permeability of the porous medium being better for structures with the smallest openings and extremely poor for those with larger connectivity. It is shown that dilating the skeletal frame i.e. increasing the width of the 'struts' in a metallic foam should lead to more efficient sound absorption. It is the hope that this approach would lend itself well to use in the design of enhanced soundproofing porous metals.

Acoustic foams are used to minimize reflections and reverberation, in music rooms, studios, and cinemas in a variety of locations. The use of fibrous as sound absorbing material is commercially known. Synthetic fibers like kevlar, polyester, polyurethane, melamine, polyethylene, polypropylene absorb most sound energy striking them and reflect very little [1]. These fibrous materials are made from high-temperature extrusion and industrial processes based on synthetic chemicals (petrochemical source). Their carbon footprint is quite significant, and their manufacturing processes contribute to release of some greenhouse gasses like methane, carbon dioxide, sulfur dioxide [2].

Natural fibrous materials (wool, cotton, asbestos, fur felt, hemp, flax) are generally porous and can absorb sound both at low and high frequencies [3]. They are biodegradable, inexpensive, and environmentally friendly but their low strength, softness, decrease in absorption potential over time [4] and damage to the respiratory system, human skin, eye and mucous membrane during production [5] is of concern and has limited the use of this material. Studies have shown that the broadband characteristics of noise reduction can be achieved through open-celled metallic foam structures [6,7] and have earned significant attention resulting from increased worldwide technological research and development. They are expensive to produce but are environmentally friendly, easily recycled, high durability and resistance, less harmful, can be used to reduce vibrations and longer useful lifetimes.

Commercially available open-celled metallic foam structures (Fig. 1) such as nickel, steel, titanium, copper, and aluminium have low weight, high stiffness, an excellent fire resistance and low moisture absorption. They are generally considered as poor sound absorbers when compared to the performance of hard-backed fibrous materials especially at the region of quarter wavelength layer resonance frequencies ($\leq$2.0 kHz). The performance enhancement of these materials as described in [6–9] can be achieved through hole-drilling or rolling and prearrangement of space fillers adopting replication casting method of foam production [16]. Air gap insertion or presence of back cavity (which predominantly becomes Helmholtz resonance absorption) [10] and increased porous layer thickness are described in [11,12] to enhance the sound absorption performance of porous absorbers. An experimental study on the sound absorption coefficient measurements of Alporas foam structure in [13] pointed out the sound absorption spectra of this porous medium increases with a decrease in the relative density (R.D) of the sample. The relative density was observed to be small ($\sim$0.1) for effective sound absorption and under compression, sample porosity decreases (becoming closed-cells) and a shift in the absorption curve to the frequency minimum (or a reduction in the frequency of the quarter wavelength layer resonance) and

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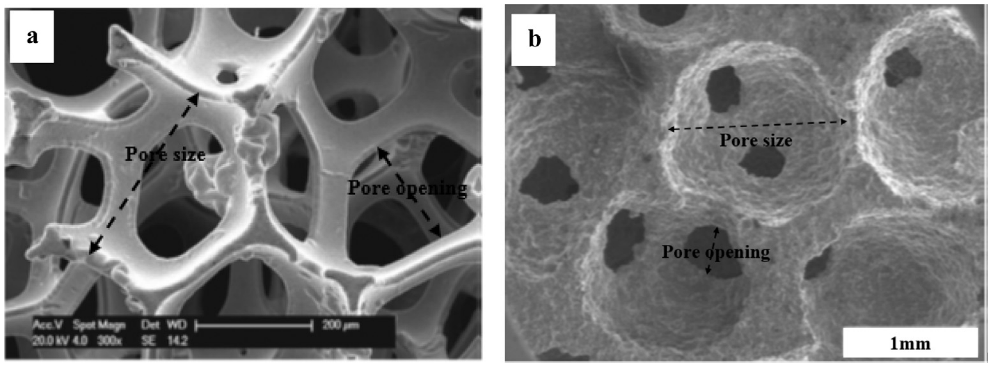

Fig. 1. Scanning electron micrographs (SEM) of (a) pure nickel 450 μm foam [15] and (b) "bottleneck-type" aluminium foam made by replication casting process [7,16] showing the typical pore sizes and openings.

reduced peak of absorption were observed when compared to a non-compressed foam of similar thickness.

A previous study reported in [16], showed that the predicted sound absorption coefficient spectra of low-density "bottleneck-type" porous structures (Fig. 1b) look better for structures with mean opening to pore size ratio ranging between 0.1 and 0.3 and permeability in the order of 10^{-10} m^2. Though, the performance of these structures were observably poor, typically, beyond the quarter wavelength layer resonance frequencies due to their low porosity, stiffness (deformation resistance) and surface area being significantly difference from those for highly porous fibrous materials. Also, the compression technique described in [13] has been successfully adopted by many researchers in this field to make useful high-density porous metals. To minimize the number of design iteration, operational cost and time, we look to explore the contribution of pore-structure related parameters of high-density porous metallic foams working from tomography images of "real" structures to describe the acoustic response of the materials and to provide some optimal values of structural information needed to design self-supporting sound absorption porous metals.

Structural characterisation of the porous structures was carried out using pore-level approach by taking a high-resolution (15 μm voxel dimension in x, y and z coordinates) X-ray computerized tomography (CT) images of the porous metallic structures. These high-density porous metals are Inconel 450 μm, Inconel 1200 μm, Recemat RCM-NCX 1116, Recemat RCM-NCX1723 and Porvair 7PPI foams. The ScanIP module of Simpleware™ (3D image processing software) was used for processing of the 2D CT images into the 3D volume. To minimize noise effect within masked structure, smart mask filtering process (with 20 iterations) was preferred over recursive Gaussian due to the important preservation of pore geometry, in particular, the pore openings of the porous materials. Unlike recursive Gaussian filtering, the ScanIP in-built smart mask filter is a smoothing algorithm that helps preserve volume and geometry of the structures [14]. The geometry preservation means that the "connecting struts" are not reduced or separated by the filtering process and volume preservation means that the important openings, cell (pore) sizes and volume of the segmented mask are not affected by the filtering process. Structural characterization was done on a representative volume that is 8–10 times the pore sizes taken from the center of the 3D structure with porosity differing by ±2 percent. Pore sizes were obtained through a watershed segmentation (disconnecting pores) of the RVE fluid domain whilst the openings were achieved by running a centreline through the pores and connectivity of the 3D RVE CT structure. Fig. 2 (top, left–right) presents the two-dimensional image of the high-resolution CT structure, three-dimensional reconstructed volume, three-dimensional representative volume element (RVE) and an expanded view of the Inconel 450 μm foam sample. Images of the disconnected pores of the RVE microstructure are presented in Fig. 2 (mid-section) while the bottom section of the Figure represents images of the meshed structures, CFD computed velocity and pressure plots.

Up to eight parameters are used to describe the acoustical properties of porous materials [17,25] but only five parameters of the Johnson-Champoux-Allard model are determined in this work. These parameters are open porosity ($\varnothing$), airflow resistivity (σ), high-frequency tortuosity (τ), viscous characteristic length ($\bigwedge$), and thermal characteristic length ($\barwedge$). The Porosities of the materials were directly measured in ScanIP as the ratio of the RVE fluid volume to the total volume of the skeletal and fluid domains. The high-frequency tortuosity of the materials was also measured in ScanIP as the ratio of the shortest route to the sample thickness, obtained from the centre lines of RVE structural phase of the porous materials. The airflow resistivity of the materials was determined as the ratio of the dynamic viscosity of air to the permeability of the porous medium. Flow permeability of the materials were accounted for by computational fluid dynamics (CFD) modelling of the pressure drops developed across the meshed fluid domain of the porous structures in the Darcy regime using the well-known low velocity Stokes equation. Velocity inlet, zero pressure outlet, zero-velocity at the walls and symmetrical boundary conditions on the opposite side faces were imposed on the meshed matrix in the fluid module of Comsol Multiphysics 5.2™.

The choice of mesh and optimum meshing parameters were obtained through a workable mesh scale dependent study conducted using a high-density hexahedral quadratic tetrahedral meshes (HQTM) in the order of 30–40 Mcells as the basis for computation using the +FLOW solver of Simpleware™. An optimised linear tetrahedral meshes (LTM) with mesh density in the ranges of 2.0–2.5Mcells was obtained to capture the gradient of velocity within the openings of the porous materials. By plotting the CFD computed pressure drop per unit length (∇p) against superficial fluid inlet velocity and a fit into Eq. (1), the permeability of the porous structures was attained. For all the five foam structures, tolerable 4 percent less in permeability values of the HQTM based meshed structures were observed for the LTM based mesh structures. The viscous characteristic length ($\bigwedge$) was determined to be twice the ratio of weighted by the velocity in the RVE volume and that of the RVE surface whilst the thermal characteristic length ($\barwedge$) was determined to be twice the ratio of the wet pore RVE volume to the interconnected pore RVE surface as reported in [15].

$$v_s = -\frac{k_o}{\mu} * \nabla p \tag{1}$$