Applied Acoustics 187 (2022) 108508

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

The impact of microcellular structures on the sound absorption spectra for automotive exhaust performance mufflers

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ARTICLE INFO

Article history:
Received 10 May 2021
Received in revised form 11 October 2021
Accepted 29 October 2021
Available online xxxx

Keywords:
Sound Absorption
Packed Beds
Microcellular Structures
Modelling and Simulation

ABSTRACT

The role of microcellular structures on the sound absorption spectra of packed structures for automotive exhaust performance mufflers are presented herein, via numerical modelling and simulation. Numerical simulations involving the application of Attenborough's empirical model are demonstrated to be a better predictor for the sound absorption properties for packed beds of near-spherical structures, with reasonable scatter, when compared to experimental data substantiated in contemporary literature. By varying the packing arrangement for packed samples and stacking with differential microcellular structures, improvements in the absorption properties were achieved – thereby highlighting the dependence of propagated pressure waves on the structural configuration, positioning and thickness of soundproofing materials. This approach could assist in the implementation of microcellular structures in reducing unwanted engine noise, reduction in packing weight and improved active product lifetime of miniaturized soundproofing package in automotive exhaust performance mufflers.

The 2030 United Nations sustainable development goals ratified at the 2015 New York summit are grounded in deliverables for improved living conditions, with the promotion of healthy living for the human populace (Goal 3) and making municipalities and human settlements inclusive and safe (Goal 11). While a comfortable environment devoid of excessive/unwanted noise is the aspiration of health experts and policy makers, scientists and engineers are faced with the rather daunting task of developing an ecological healthy living environment for all age groups through utilisation of sustainable and available/affordable materials. One of the sources of unwanted noise is the sound emitted from automotive exhaust performance mufflers [1]. The exhaust system plays a vital role in reducing excessive noise and cutting vibration emanating from car engine systems.

Soundproofing materials are known to provide useful information on sound absorption properties against resonance frequencies, sample position, porosity, porous layer thickness and structural configuration. The presence of pores and cavities characteristic of soundproofing materials, allow sound waves to penetrate through acoustic absorption with minimal reflection [2]. Typical examples of these soundproofing devices are cellular (open-cell foams, polyurethane etc.), fibrous (glass wool fibres, hemps, kevlar, melamine etc.) and granular (asphalt, gravels, soil, concrete, clays etc.) materials. Fig. 1 shows morphological images and experimental and numerically simulated sound absorption spectra for different sound absorbing materials characterised by pore volume fractions ranging between 0.375 and 0.987. These porous materials are representative of packed beds {PB [4]}, bottleneck-shaped porous aluminium foam [BAF [6], sintered fibre metal [SFM [10], glass wool fibre [GWF [12]] and melamine foam [MF [14]] structures. Analogous research work demonstrated in [6,9] showed that Wilson's poroacoustic model [WM] is a better predictor for bottleneck-shaped aluminium foams and polyhedral ceramic foams, with reasonable scatter, when paralleled to experimental measurements in [5,7]. Numerical simulations adopting Johnson-Champoux-Allard [JCA] and Delany-Bazley-Mikki [DBM] models were shown [9] to concur completely with experimental measurements of sound absorption spectra for sintered fibrous metals [SFM] and fibrous materials [GWF and MF] respectively. The utilisation of a similar modelling arrangement in [9] demonstrated that Attenborough's empirical model [AM] provides a better fit to experimental measurements for granular materials as evident in Fig. 1. This could be attributed to the fact that Attenborough's empirical model [15] was originally developed for fibrous structures, rigid sands and soil [15] characterised by lower pore volume fractions between 0.33 (densely packed beds) and 0.48 (for loose packed structures).

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https://doi.org/10.1016/j.apacoust.2021.108508
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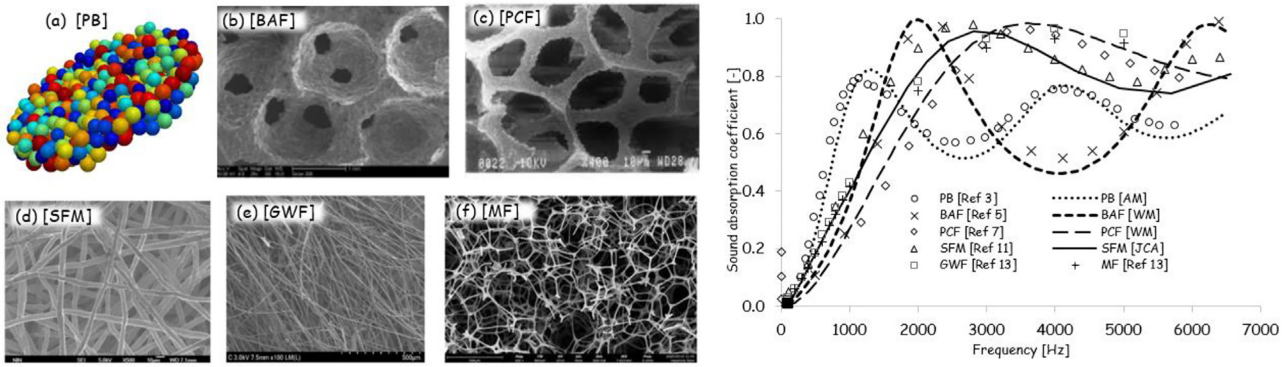

Fig. 1. Experimental and numerically simulated plots of the dimensionless normal incidence sound absorption coefficient against frequency [Hz] for (a) 40 mm-thick packed spheres [PB] [3–4] (b) 20 mm-thick bottleneck-shaped aluminium foam [BAF] [5–6], (c) 16.5 mm-thick polyhedral-shaped ceramic foam[PCF] [7–9], (d) 23.31 mm-thick sintered fibre metal [SFM] [9–11], (e) 25 mm-thick glass wool fibre [GWF] [12–13] and (f) 25.5 mm-thick melamine foam [MF] [13–14] materials.

Automotive exhaust performance mufflers are designed to contain packed beds of structures for catalytic conversion of exhaust gases and reverberation cutback control. Noticeably, Fig. 1 shows the downside of packed structures in exhaust mufflers, to insufficiently absorb sounds at intermediate frequencies even for a given longer porous layer thickness. The smaller volume fraction exhibited by this structure results in a significant amount of reflected sound waves at wavelengths that are too large to be attenuated and must be compensated for by using an absolute thickness of material [1] – thereby increasing the weight and cost of the exhaust performance muffler. Fig. 1 shows that fibrous materials like glass wool fibre and melamine foam provide the largest broadband sound absorption spectra applicability but their inability to withstand high temperature and high pressure applications make them unsuitable for cutting down excessive engine noise in automotive mufflers [16]. Cellular materials made up of metals and ceramics are known to withstand high temperature and pressure. Their unique and combined characteristics of high pore volume, high young modulus, high surface area [4–7] and prolonged useful lifetimes for money makes them natural candidates where mechanical impact and load bearing applicability are imperative. This work, therefore, seeks to investigate the numerical applicability of the impact of microcellular structures and packed spheres on the sound absorption spectra for exhaust performance mufflers.

The numerical prearrangement for this work was carried out in the Acoustic Module of COMSOL Multiphysics 5.2^{TM} – using the procedure substantiated in [4,6,9] but extended in this work, to consolidate modelling of differential stacked samples of porous materials. In brief, a two-dimensional (2D) geometry was created to be a representation of 4-microphone impedance tube, as shown in Fig. 2a. The Helmholtz linear acoustic model was solved on all the various domains (source, background and porous layer) while poroacoustic models were resolved only for the porous layer domain. The inlet and outlet segments of the geometry were conditioned (boundary conditions) to an incidence plane wave pressure field of 1.0 Pa and sound hard boundary wall respectively, while the lateral sides were conditioned to Floquent periodicity. The imposition of the sound hard boundary wall on the outer section is an indication that the presence of back cavity (air-gaps) were neglected during the simulation. Mesh dependence analysis was performed to obtain any likely trade-off between mesh count, convergence time and accuracy. This was achieved by keeping the resolution of narrow regions, curvature factor and growth rate to 1.0, 0.3 and 1.3, respectively while varying the maximum edge cell length to wavelengths ranging between $c_0/100f_{max}$ and c_0/f_{max} (c_0 and f_{max}) are speed of sound in air and the maximum frequency recorded for the system). Furthermore, a minimum edge length equivalent of the minimal wavelength divided by 2,000 ($c_0/2000f_{max}$) was considered which yielded cell densities between 10,000 and 35,000 cells. In terms of accuracy and convergence time, a calculated maximum edge length of $c_0/50f_{max}$ was used giving a negligible difference (less than 0.06%) between available experimental measurements and numerically simulated data taking less than a minute or two to resolve for each solution. The resolution of the poroacoustic acoustic models requires the preknowledge of the pore-structure related parameters and porous layer thickness of the materials – as the input parameters. The input parameters for all the microcellular structures and 0.68 mm particle size packed spheres presented in Fig. 1 were all obtained from existing literature. Using the modelling approach described in [17], virtually-generated packed spherical structures were created for packings characterised by particle diameter

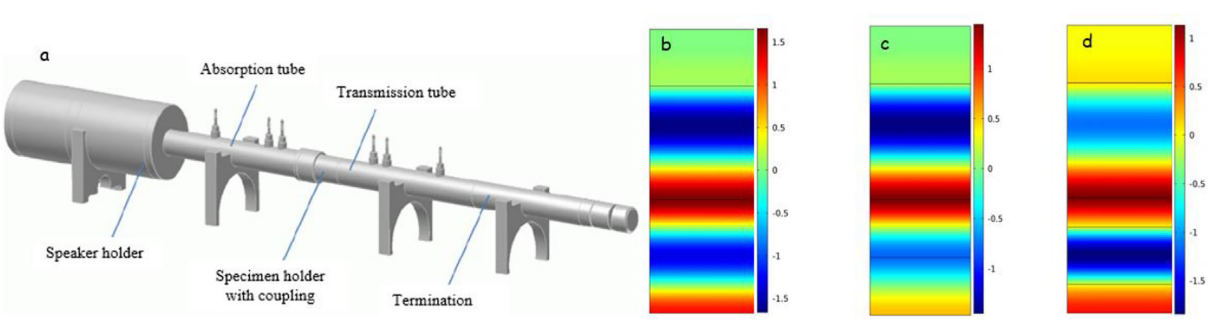

Fig. 2. Right of a 4-microphone, AFD 1200-AcoustiTube® - measuring setup with sample holding section [9] is the 2D simulated plots of the total acoustic pressure [Pa] for (b) a 40 mm PB3, (c) SFM [20 mm] + PB3 [20 mm] and (d) SFM [10 mm] + PB3 [20 mm] + SFM [10 mm].

ranging between 0.5 and 2.0 mm at 37.5% volume fraction for each packed bed. Advance imaging techniques (involving rendering, thresholding, watershed segmentation, Bolean inversion, etc.) and computational fluid dynamics modelling and simulation of the unit pressure drops were carried out on a workable representative volume of the porous structures (whose size is 3x greater than their average particle size) to obtain pore-structure related parameters of the porous materials. These parameters are Darcian permeability, porosity, dynamic tortuosity, viscous characteristic length and thermal characteristic length. Similarly, sound absorption properties: quarter-wavelength layer peak in sound absorption (Ap, sound absorption average (SAA) and noise reduction coefficient (NRC) were obtained to describe a quantitative assessment of the sound absorption spectra. This approach was done for both 40 mm-thick single and stacked samples of porous materials as shown by the 2D simulated total acoustic pressure [Pa] plots represented by Fig. 2 (b –d).

With a pore shape factor ratio of 1.0, Attenborough's empirical model proves to be a better predictor of sound absorption spectra when characterised for near-spherical packed structures. Fig. 1 shows this behaviour with numerically predicted values completely coinciding experimental data (substantiated in [3] on sound absorption spectrum for packed beds (0.68 mm mean particle size) for frequencies between 200 and 6000 Hz. Fig. 3a presents the sound absorption spectra for 40 mm-thick packed near-spherical spheres characterised by a mean particle size ranging between 0.5 and 2.0 mm and constant pore volume fraction of 0.375. Optimum sound absorption properties and a shift in absorption spectra to a frequency minima were obtained for structures characterised by 1.0 mm mean particle size. This could be attributed to a moderate permeability ($8.08 \times 10^{-10} m^2$) and viscous characteristic length (130 μm) exhibited by this packing arrangement. Values far below this were observed to yield poorer sound absorption which can be attributed to densely packed structures characterised by excessive surface area significantly restricting the penetration of sound into the inlet surface of the porous layer. Similarly, values far above the computed permeability and viscous characteristic length data also yielded poorer absorption – as the materials lack the needed restrictive ligaments and walls to absorb propagated pressure waves.

Fig. 3b compares the normal incidence sound absorption spectra developed across 40 mm-thick packed beds (1.0 mm particle size) and several microcellular structures presented in Fig. 1. These microcellular structures are bottleneck-shaped aluminium foam [BAF], sintered fibre metal [SFM], glass wool fibre [GWF], tetrakaidecahedron-shaped Inconel 450 μm [INC 450 μm] and highly porous porvair metallic foam [POR]. Evidently, wider broadband absorption spectra were observed for 40 mm-thick BAF and SFM porous materials (Fig. 3) and would therefore make them more suitable candidates as soundproofing materials for high temperature automotive muffler applications. The packed bed structures appear positive at quarter wavelength layer frequencies (below 2000 Hz) but the incline in absorption obtained beyond this quarter wavelength layer frequency indicates that greater amounts of sound waves are reflected backward during the propagation of pressure waves across the interstices of the low pore volume packed structures (0.375). Fig. 4 shows that a convalescence in this dip in absorption characterised by packed structures can be achieved by placing either PCF (Fig. 4a) or SFM (Fig. 4b) microcellular structures at the rear end of the packed beds or sandwiched between the microcellular structures. Moreso, further improvement in the sound absorption properties were achieved by placing the selected microcellular materials at the front of the packed beds (i.e. PCF/PB3 and SFM/PB3). This resulted in a change of resonance peak in absorption (Ap) close to unity, widening the absorption band with a shift in the absorption spectra to the frequency minima. Fig. 4 also presents the calculated values for the sound absorption properties (SAA, NRC and Ap) for each plot – an indication of the improvement made on the acoustical behaviour of the original packed structures demonstrated in [3], using selected microcellular structures. This approach helps absorb significant amounts of pressure waves thereby reducing excessive noise from a point source. The improvement in the sound absorption spectra and properties of the integrated structures could be attributed to the high pore volume and surface area [19] exhibited by the microcellular structures. The interconnection of pores within microcellular structures enable an establishing of extra cavities from precursive to succeeding cells within the matrices resulting in increased penetration of sound waves with minimal reflection [2] over different range of resonant frequencies. Numerical simulations in [18] demonstrated that improved sound absorption properties are obtained for microcellular structures characterised by higher pore densities (i.e. smaller pores in a linear each, typically between 0.5 and 1.0 mm) when compared to cellular materials characterised by lower pore densities (flow permeability $> 10^{-09}$). Both the polyhedral ceramic foam (PCF) [7] and glass wool fibre (GWF) [13] materials were characterised by higher pore volume (87.9 and 90.9% respectively) and flow permeability in the range between 10^{-10} and $10^{-09} m^2$, respectively. Microcellular materials exhibiting this range of flow permeability have been described in [6,18] to be an excellent sound absorption performer and increasing their sample thickness simply extends the available pore-nonuniformity (dynamic tortuosity) and cavities contributing to the overall improvement in sound absorption properties of the microstructure. It is noteworthy to identify that a total 40 mm-thick porous layer thickness was maintained for each modelling study. For example, in Fig. 4a, the 40 mm thickness length was used for a single sample and divided for several stacked samples of materials as follows:

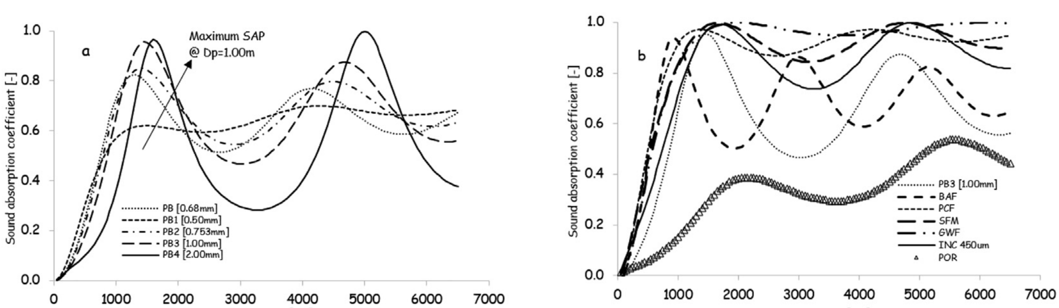

Fig. 3. Numerically simulated sound absorption spectra against frequency [Hz] for (a) packed beds at 37.5% void fractions but varying particle size and (b) 1 mm particle-sized packed beds [Pb3] and several microcellular structures (bottleneck aluminium foam [BAF], polyhedral ceramic foam [PCF], sintered fibre metal [SFM], glass wool fibre [GWF], Inconel 450 μm [INC 450 μm] and porvair [POR] metallic foams.

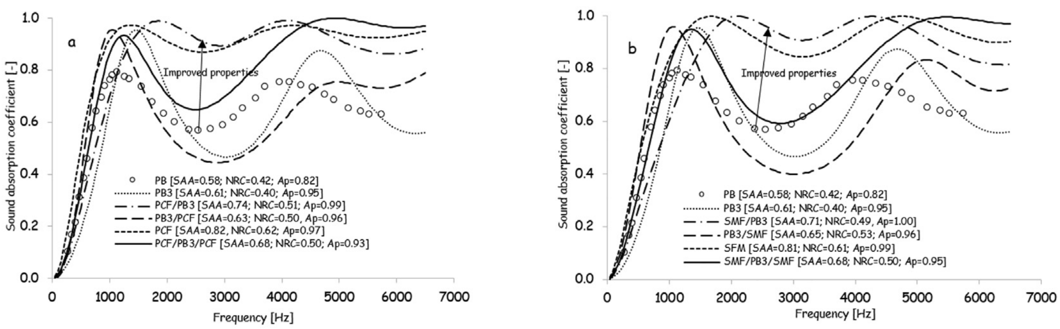

Fig. 4. Numerically simulated sound absorption spectra indicating the impact of (a) polyhedral ceramic foam [PCF] on packed beds and (b) sintered fibre metal [SFM] on packed beds of spheres at 40 mm hard-backed porous layer length.

PB[40 mm], PB3[40 mm], PCF[20 mm]/PB3[20 mm], PB3[20 mm]/PCF[20 mm], PCF[40 mm] and PCF[10 mm]/PB3[20 mm]/PCF[10 mm]. This was also repeated in a similar manner for the study on the acoustical behaviour imposed by the sintered fibre metallic material on packed beds, represented by Fig. 4b.

In conclusion, this study highlights the importance of microcellular structures in reducing unwanted noise and vibration emitted from automotive engine systems. The numerical simulations used herein confirm the reliability of Wilson (WM), Attenborough (AM) and Johnson-Champoux-Allard (JCA) empirical models to accurately predict the characteristic sound absorption spectra for bottleneck-shaped, near-spherical packed beds and structures characterised by non-uniform sections and possible constriction, respectively. By keeping the void fraction constant, optimum applicability of the packed structures for lower frequency sound absorption were obtained for 1.0 mm mean particle size packed spheres. While the packed beds may be suitable for catalytic oxidation and reduction of unwanted gasses emitted from modern automotive engine systems, improved ceramic or metallic porous structures could serve as a potential barrier, which significantly reduces engine noise and vibration thereby improving the active product lifetime of the packed structures with a reduction in the overall weight of exhaust performance mufflers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Dr. AJ would like to thank the University of Nottingham, Nottingham, United Kingdom, Simpleware-Synopsys^{TM} Ltd California, United States of America, Bowers and Wilkins Group, West Sussex, United Kingdom for the provision of technical support, needed space and license toward the successful completion of this work.

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