



HAL
open science

Hierarchical porous metamaterial for sound absorption

Svetlana Kuznetsova, Florian Allein, Samuel Deleplanque, Bertrand Dubus,
Marco Miniaci

► **To cite this version:**

Svetlana Kuznetsova, Florian Allein, Samuel Deleplanque, Bertrand Dubus, Marco Miniaci. Hierarchical porous metamaterial for sound absorption. Inter-Noise 2024, Aug 2024, Nantes, France. pp.9582-9589, 10.3397/IN_2024_4267. hal-04780676

HAL Id: hal-04780676

<https://hal.science/hal-04780676v1>

Submitted on 13 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Hierarchical Porous Metamaterial for Sound Absorption

Svetlana Kuznetsova¹, Florian Allein, Samuel Deleplanque, Bertrand Dubus, Marco Miniaci²
Univ. Lille, CNRS, Centrale Lille, Junia, Univ. Polytechnique Hauts-de-France, UMR 8520 - IEMN -
Institut d'Electronique de Microélectronique et de Nanotechnologie
F-59000 Lille, France

ABSTRACT

Absorption of sound is vital in various technological and everyday life spheres of human activity. Utilizing porous materials is traditional for this purpose. However, their performance is limited in the low frequencies, requiring big amounts of material. Thus, the need of smart engineering of their geometry is evident. Inspired by multi-scale self-similar patterns widespread in Nature, we propose a novel design of a hierarchical multilayered porous absorber. We study two types of designs: a hierarchical periodic and a hierarchical gradient. Their geometrical arrangement is obtained by the optimization algorithms (metaheuristic Greedy Randomized Adaptive Search Procedure). The samples are subject to the incidence of a plane wave. In both cases we come to the conclusion that the introduction of multiple hierarchical levels allows to enhance the absorption compared to the bulk block of porous material of the same full length (as well as to the lower hierarchical levels). We considered the dependence of the absorber performance on the angle of the plane wave incidence, as well as of the values of the static air flow resistivity of material. The absorption coefficient was retrieved using the transfer matrix method and finite element calculations, which exhibit an excellent agreement.

1. INTRODUCTION

Being a challenge in modern acoustics, the low-frequency sound absorption is highly demanded in most of the noise mitigation applications of human activities. As a response to this issue, porous materials have appeared as a sustainable solution allowing high absorption performance and lightweight designs [1, 2]. One of the most frequently utilized models of porous media is the Johnson-Champoux-Allard (JCA) model [3]. It deals with five physical parameters, namely: the static air flow resistivity σ , the open porosity ϕ , the tortuosity α_∞ , the viscous characteristic length Λ and the thermal characteristic length Λ' .

To overcome the limited performance of porous materials at low frequencies [4] specific engineered porous metamaterials have been recently proposed [5]. One of the most common designs is multilayered porous media, whose performance strongly depends on the geometrical arrangement of its constituents. This meta-porous approach, being initiated several decades ago [6–8], became popular again due to the recent advances in acoustic metamaterials [9, 10] and fabrication techniques [11], allowing an efficient and broadband absorption at the low frequencies using moderate amounts of absorbers [5].

¹smkuznetsova1@gmail.com

²marco.miniaci@gmail.com

Proceedings of INTER-NOISE 2024

The concept of hierarchy, inspired by Nature, has recently emerged as a promising platform of metamaterial engineering leading to improvement of functional properties in different areas of research, from electromagnetism to elasticity and acoustics [12–18]. Hierarchical architectures are widespread in Nature and represent self-similar patterns repeated on different length scales, beneficial compared to simpler structural organizations [19].

In this article, we introduce a self-replicating layered porous structure (see Figure 1). Through numerical calculations based on the transfer matrix method, optimization procedure (metaheuristic Greedy Randomized Adaptive Search Procedure), and FEM simulations, we show the enhanced absorption as additional hierarchical levels are added into the porous layers(s). Two types of organization are investigated – a hierarchical periodic (HP) and a hierarchical gradient (HG), and their performances are compared to those of the corresponding blocks of bulk materials of the same full lengths. In both cases the introduction of higher levels of hierarchy increases the absorption, and reduces the amount of porous material. The influence of the angle of a plane wave incidence and the static air flow resistivity are considered. The optimization procedure maximizes the performance of the highest hierarchical level in the frequency range [20, 2000] Hz.

2. METHODS

2.1. Design and description of the meta-porous materials

The construction algorithm of designs under investigation is shown in Figure 1. The stiffer layers (violet for the HP and yellow for the HG) are made of porous melamine, whereas the softer ones (white) are air. The simplest 0^{th} hierarchical level is a bulk block of porous material of length p_0 (top panels of Figure 1), where $p_0 = L_{HP} = 26$ cm in the case of HP, and $p_0 = L_{HG} = 41.3$ cm in the case of HG. In the HP case, the recursive rule adopted to build each next level is to divide the porous domain(s) of the previous level into 3 unit cells (supercells) made of porous and air layers. Thus, the supercell of the last 3^{rd} HL consists of the following combination of porous and air layers $p_3 f_3 p_3 f_3 p_3 f_2 p_3 f_3 p_3 f_3 p_3 f_2 p_3 f_3 p_3 f_3 p_3 f_2 p_3 f_3 p_3 f_3 p_3 f_2 f_1$. The thinnest porous layer thickness has been limited to at least 4 mm for the validity of the JCA model [3]. The other lengths of the porous and fluid layers are determined from an optimization of the last HL.

The difference in HG case is that the three unit cells (supercells) belonging to the same HL have different lengths. The recursive rule to build each next level is to divide the porous domain(s) of the previous HL into 3 porous and air layers keeping the proportions of the previous HL constants, i.e., maintaining the ratio $\frac{p_i}{f_i}$ constant. The last 3^{rd} HL is constructed from the supercells $C = p_3, f_3, \beta p_3, f_3, \beta^2 p_3, f_3$ in the following sequence

$$\begin{aligned} & C, f_2, \beta C, f_2, \beta^2 C, f_2, f_1, \\ & \beta C, \beta f_2, \beta^2 C, \beta f_2, \beta^3 C, \beta f_2, f_1, \\ & \beta^2 C, \beta^2 f_2, \beta^3 C, \beta^2 f_2, \beta^4 C, \beta^2 f_2, f_1. \end{aligned} \tag{1}$$

We optimize the absorption coefficient of the highest HL minimizing the area above the absorption curve $\alpha_3(f)$ in the frequency range [20, 2000] Hz focusing of the global performance rather than the perfect absorption. We utilize the metaheuristic Greedy Randomized Adaptive Search Procedure GRASP [20] which performs a randomized exploration of the greedy algorithm and assigns values to the lengths of the porous (p_3 in the HP and p_3^j in the HG) and fluid (f_i) layers, the number of hierarchical levels m , the number of unit cells (supercells) n , and the evolution coefficient β of growth of the porous layers lengths in HG case. The limits on the parameters $p_i \geq 4$ mm, $f_i \geq 1.8$ mm, $m \leq 3$, $n \leq 3$ were dictated by practical reasons.

The porous layers are made of melamine described by the Johnson-Champoux-Allard (JCA) model [21] with the following parameters: porosity $\phi = 0.98$, tortuosity $\alpha = 1.24$, viscous

(JCA) model [21] with the following parameters. porosity $\psi = 0.98$, tortuosity $\alpha_\infty = 1.54$, viscous characteristic length $\Lambda = 150 \mu\text{m}$, thermal characteristic length $\Lambda' = 560 \mu\text{m}$, and static air flow resistivity $\sigma = 49000 \text{ Pa}\cdot\text{s}/\text{m}^2$ and $\sigma = 10000 \text{ Pa}\cdot\text{s}/\text{m}^2$. These two values of σ have been chosen

Proceedings of INTER-NOISE 2024

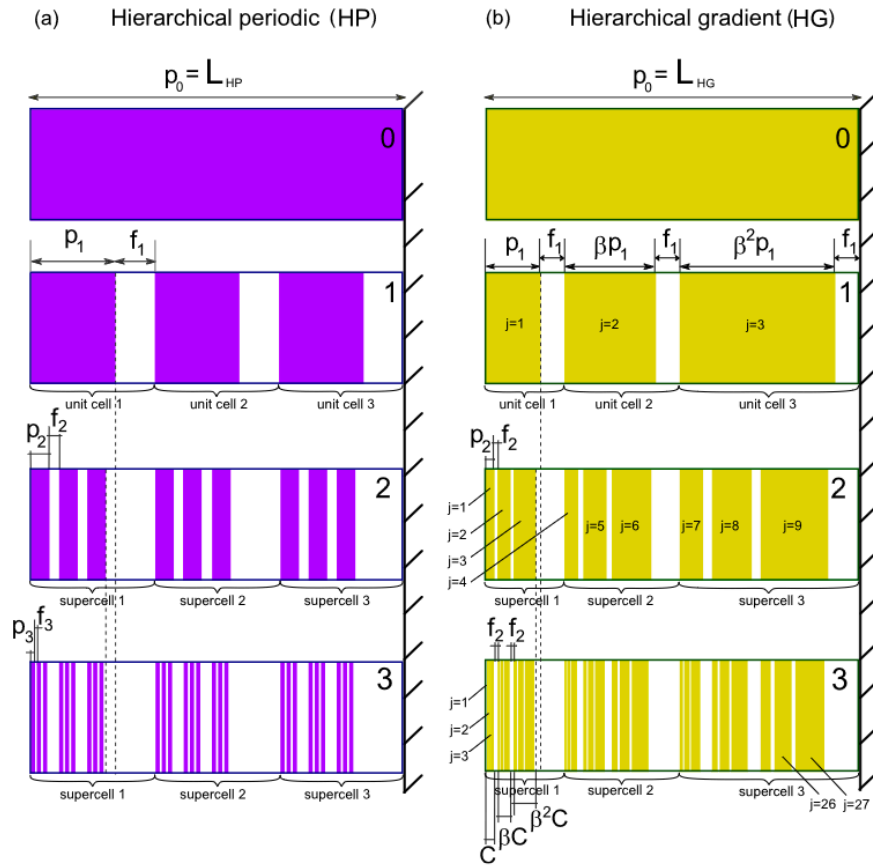


Figure 1: Geometry of the HP and HG cases.

as belonging to the range of most common values.

2.2. Absorption coefficient

We consider a harmonic plane wave incident from the left on the rigidly backed multilayered hierarchical structures and adopt the transfer matrix formalism. The transfer matrix of each layer is

$$T_i = \begin{pmatrix} \cos k_{ix} l_i & \frac{iZ_i}{\cos \theta} \sin k_{ix} l_i \\ \frac{i \cos \theta}{Z_i} \sin k_{ix} l_i & \cos k_{ix} l_i \end{pmatrix}, \quad (2)$$

where l_i is the length of the corresponding layer, $k_{ix} = k_{px}(k_{0x})$ is the component of the wavenumber normal to the layers, $Z_i = Z_p(Z_0)$ is the impedance, θ is the angle of incidence. The subscripts p and 0 refer to porous or air layer, respectively. The total transfer matrix $T^{(n)}$ of the n^{th} HL is a consecutive product of all the layers

$$T^{(n)} = \prod_i T_i. \quad (3)$$

The absorption coefficient is obtained as follows

$$\alpha_n = 1 - \left| \frac{T_{11}^{(n)} \cos \theta - Z_0 T_{21}^{(n)}}{2} \right|^2. \quad (4)$$

3. RESULTS AND DISCUSSION

The following geometrical parameters were obtained by the optimization procedure: $L_{HP} = 26$ cm, $p_3 = 4$ mm, $f_3 = 2$ mm, $f_2 = 6$ mm, $f_1 = 14.7$ mm for the HP case and $L_{HG} = 41.3$, cm $p_3 = 4$ mm, $f_3 = 1.8$ mm, $f_2 = 8.4$ mm, $f_1 = 39.4$ mm and $\beta = 1.1085$ for the HG case. The sizes are rounded to 0.1 mm. This allowed to reduce the porous volume by 48.5% for in the HP case and by 64% in the HG case for the 3rd HLs.

3.1. Normal incidence

In Figure 2 we plot the absorption coefficient α as a function of frequency f for the HP (a,b) and for HG (c,d) cases. The HLs are marked by the corresponding curves and the calculations are performed for two different values of σ , 49000 Pa.s/m² (left panel) and 10000 Pa.s/m² (right panel), respectively. The results obtained by the transfer matrix method are reported as continuous lines while the FEM-simulation results obtained by Comsol Multiphysics are shown as markers and are in a perfect agreement with the TMM results.

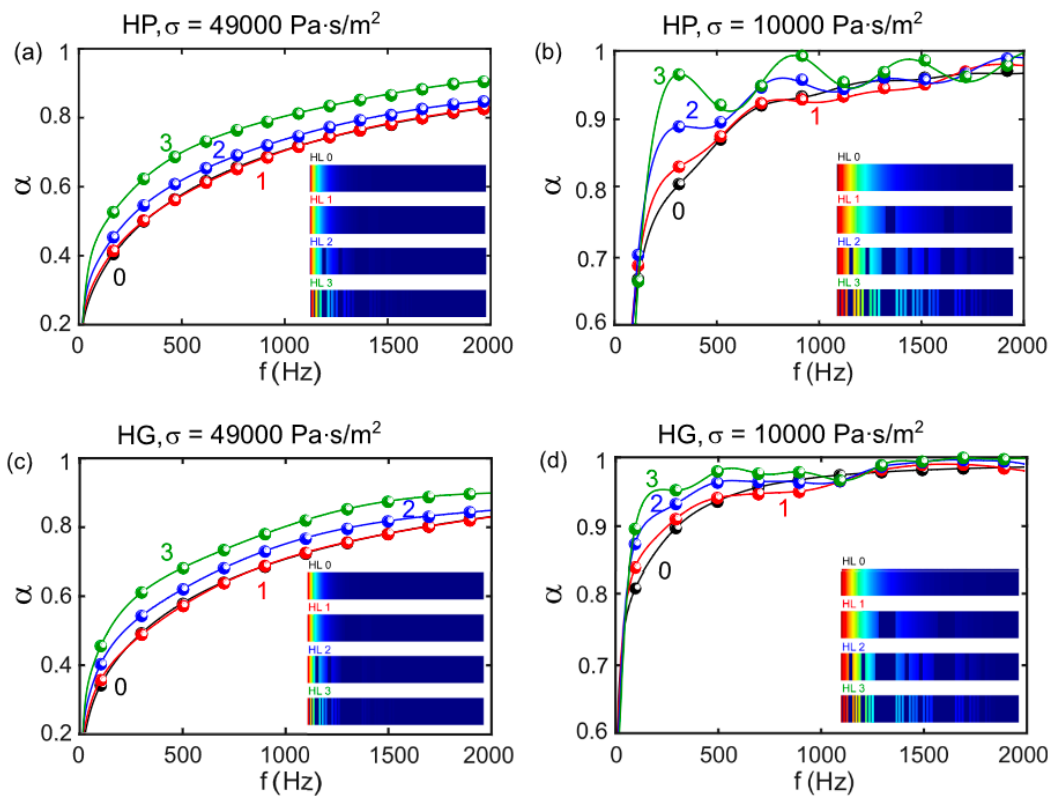


Figure 2: (a), (b) The absorption coefficient α for different hierarchical levels of HP case, (c), (d) the same for the HG case. The dissipated intensities at $f = 900$ Hz for HP and $f = 600$ Hz for HG are shown on the insets.

Introduction of hierarchy results in a considerable enhancement of the absorption properties of the structure, for both values of σ and both designs. The largest enhancement (39%) is reached for a HP case at $f = 75$ Hz and an increase between 20% and 25% is observed when $f \geq 200$ Hz. Similarly, for the smaller values of σ the introduction of hierarchy still remains beneficial, especially at the low frequencies. In the HP case for small σ , the absorption coefficient exhibits

especially at the low frequencies. In the HP case for example, the absorption coefficient exhibits oscillations reaching a maximum enhancement of 20% at $f = 330$ Hz (corresponding to the $\lambda/4$ resonance). For HG case, the results are similar, though the increase of α at $f = 200$ Hz ($\lambda/4$

Proceedings of INTER-NOISE 2024

resonance) is slightly lower.

The onsets on Figure 2 show the dissipated acoustic intensity normalized to its value at the left edge of the structure. Introduction of air layers allows the pressure field to propagate further inside the structure, exposing the propagating wave to multiple reflections while traversing the porous layers resulting in the increased dissipation. In the case of smaller value of σ , hierarchy increases the absorption related to the first quarter-wavelength resonance and to the higher order resonances. For the larger values of σ the field decreases more rapidly inside the structure without any noticeable geometrical resonances.

3.2. Oblique incidence

In Figure 3 we report the absorption coefficient α at 500 Hz as a function of $\theta \in [0, 90]^\circ$ for the three hierarchical levels and the bulk block of porous material with $\sigma = 10000$ Pa.s/m². The introduction of hierarchy is advantageous for the absorption for most of the angles of incidence. For large angles, the absorption curves converge and drop to 0 when $\theta = 90^\circ$. The largest enhancement of absorption is observed at normal incidence ($\theta = 0^\circ$), for both HP and HG designs. It is worth reminding here that the geometry was only optimized for $\theta = 0^\circ$, nevertheless it remains advantageous in a wide range of angles. The normalized total acoustic pressure fields

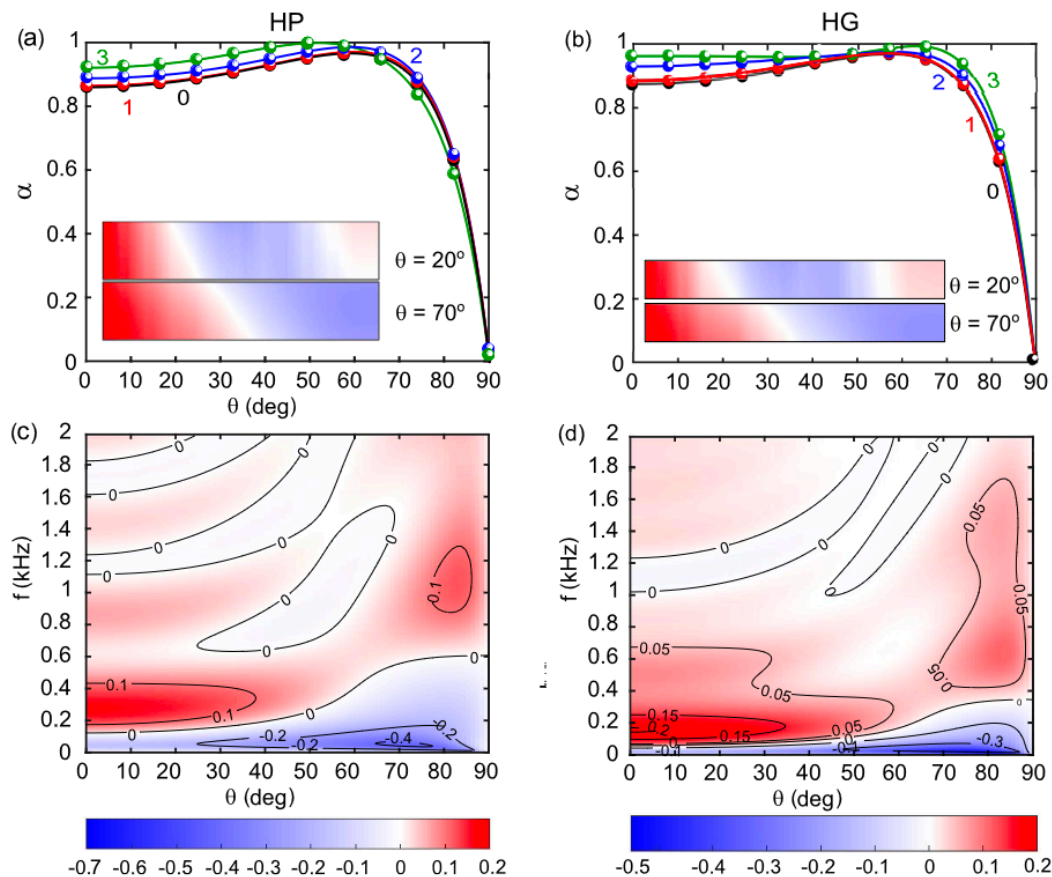


Figure 3: The absorption coefficient α for different hierarchical levels of (a) HP case and (b) HG case, (c), (d) the maps of the difference $\alpha_3 - \alpha_0$ for HP and HG designs as a function of frequency and the angle of incidence.

$\frac{\Re(p)}{\max \Re(p)}$ for the 3rd HL at different angles of incidence ($\theta = 20^\circ$ and $\theta = 70^\circ$) are also reported as insets in Figures 3a and 3b.

Proceedings of INTER-NOISE 2024

Considering the broadband response, Figures 3c and 3d report the maps of $\alpha_3 - \alpha_0$ in the (f, θ) plane for $\sigma = 10000 \text{ Pa}\cdot\text{s}/\text{m}^2$ and for HP and HG cases, respectively.

3.3. Influence of the static air flow resistivity

The behaviour of $\alpha_3 - \alpha_0$ is reported in Figures 4a and 4b as a function of frequency f and of the static air flow resistivity σ for the normal incidence. The enhancement of absorption increases with the increase of σ (except a narrow low frequency region).

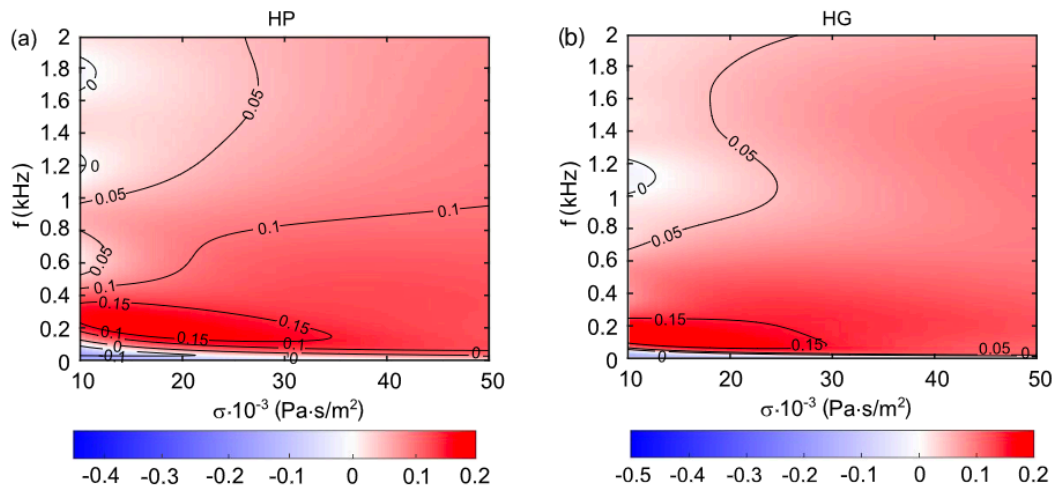


Figure 4: Maps of the difference $\alpha_3 - \alpha_0$ for HP and HG designs as a function of frequency and resistivity.

4. CONCLUSIONS

We have investigated numerically the absorption coefficient of hierarchical meta-porous structure composed of alternating melamine and air layers. Two types of design were proposed: a hierarchical periodic and a hierarchical gradient ones. Both structures exhibit beneficial absorbing properties in the [20, 2000] Hz frequency range compared to a block of porous material of the same length. A maximum enhancement of 39% was observed in the HP organization. Proposed designs also introduce porous volume reduction of 48.5% in the HP case and 64% in the HG case for the 3rd HL.

Designs optimized for a single value of static air flow resistivity (σ) and for normal wave incidence ($\theta = 0$) only, remarkably remain advantageous in a wide range of angles of incidence and static air flow resistivities. The proposed structures are promising for improving the low-frequency performance of porous absorbers.

ACKNOWLEDGEMENTS

S.K., B.D. and M.M. acknowledge the EU, H2020 FET Open « BOHEME: Bio-Inspired Hierarchical Metamaterials » (grant number 863179).

REFERENCES

1. ET Paris. On the reflexion of sound from a porous surface. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 115(771):407–

2. Peter Göransson. Acoustic and vibrational damping in porous solids. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 364(1838):89–108, 2006.
3. Noé Jiménez, Olga Umnova, and Jean-Philippe Groby. Acoustic waves in periodic structures, metamaterials, and porous media. *Ch. the Transfer Matrix Method in Acoustics*, Springer International Publishing, Cham, pages 103–164, 2021.
4. Leitao Cao, Qiuxia Fu, Yang Si, Bin Ding, and Jianyong Yu. Porous materials for sound absorption. *Composites Communications*, 10:25–35, 2018.
5. Nansha Gao, Zhicheng Zhang, Jie Deng, Xinyu Guo, Baozhu Cheng, and Hong Hou. Acoustic metamaterials for noise reduction: a review. *Advanced Materials Technologies*, 7(6):2100698, 2022.
6. IP Dunn and WA Davern. Calculation of acoustic impedance of multi-layer absorbers. *Applied acoustics*, 19(5):321–334, 1986.
7. Walter Lauriks, P Mees, and Jean François Allard. The acoustic transmission through layered systems. *Journal of sound and vibration*, 155(1):125–132, 1992.
8. B Brouard, Denis Lafarge, and J-F Allard. A general method of modelling sound propagation in layered media. *Journal of Sound and Vibration*, 183(1):129–142, 1995.
9. Richard V Craster and Sébastien Guenneau. *Acoustic metamaterials: Negative refraction, imaging, lensing and cloaking*, volume 166. Springer Science & Business Media, 2012.
10. Vicente Romero-Garcia and Anne-Christine Hladky-Hennion. *Fundamentals and applications of acoustic metamaterials: from seismic to radio frequency*. John Wiley & Sons, 2019.
11. Shahrzad Ghaffari Mosanenzadeh, Hani E Naguib, Chul B Park, and Nouredine Atalla. Design and development of novel bio-based functionally graded foams for enhanced acoustic capabilities. *Journal of materials science*, 50:1248–1256, 2015.
12. Gang Yong Song, Qiang Cheng, Bei Huang, Hui Yuan Dong, and Tie Jun Cui. Broadband fractal acoustic metamaterials for low-frequency sound attenuation. *Applied Physics Letters*, 109(13):131901, 2016.
13. Davood Mousanezhad, Sahab Babaee, Hamid Ebrahimi, Ranajay Ghosh, Abdelmagid Salem Hamouda, Katia Bertoldi, and Ashkan Vaziri. Hierarchical honeycomb auxetic metamaterials. *Scientific reports*, 5(1):1–8, 2015.
14. Marco Miniaci, Anastasiia Krushynska, Antonio S Gliozzi, Nesrine Kherraz, Federico Bosia, and Nicola M Pugno. Design and fabrication of bioinspired hierarchical dissipative elastic metamaterials. *Physical Review Applied*, 10(2):024012, 2018.
15. Vinícius F Dal Poggetto. Bioinspired acoustic metamaterials: From natural designs to optimized structures. *Frontiers in Materials*, 10:1176457, 2023.
16. Thomas R Neil, Zhiyuan Shen, Daniel Robert, Bruce W Drinkwater, and Marc W Holderied. Moth wings as sound absorber metasurface. *Proceedings of the Royal Society A*, 478(2262):20220046, 2022.
17. Yao-Ting Wang, Zhiyuan Shen, Thomas R Neil, Marc W Holderied, Elizabeth A Skelton, and Richard V Craster. Models for resonant acoustic metasurfaces with application to moth wing ultrasound absorption. *Philosophical Transactions of the Royal Society A*, 380(2237):20220005, 2022.
18. Bryn Davies and Laura Herren. Robustness of subwavelength devices: a case study of cochlea-inspired rainbow sensors. *Proceedings of the Royal Society A*, 478(2262):20210765, 2022.

19. Roderic Lakes. Materials with structural hierarchy. *Nature*, 361(6412):511–515, 1993.

Proceedings of INTER-NOISE 2024

20. Thomas A Feo and Mauricio GC Resende. Greedy randomized adaptive search procedures. *Journal of global optimization*, 6:109–133, 1995.
21. Jean Allard and Noureddine Atalla. *Propagation of sound in porous media: modelling sound absorbing materials*. John Wiley & Sons, 2009.

