Journal of Physics D:
Applied Physics

ACCEPTED MANUSCRIPT

The 2024 Acoustic Metamaterials Roadmap

To cite this article before publication: Gregory James Chaplain *et al* 2025 *J. Phys. D: Appl. Phys.* in press https://doi.org/10.1088/1361-6463/add306

The 2024 Acoustic Metamaterials Roadmap

G. J. Chaplain[1]*, F. Langfeldt[2], V. Romero-García[3], N. Jiménez[4], Y. Meng[5], J.P. Groby[5], V. Pagneux[5], D. B. Moore[1], A. P. Hibbins[1], J. R. Sambles[1], T. A. Starkey[1], B. Popa[6], Z. Zhang[7], J. Christensen[8]. X. Wen[9], J. Li[9], R. Fleury[10], S. P. Wallen[11,12], M. R. Haberman[11,12], C. Galluscio[13], S. Damani[13], W. N. Alexander[13], W. J. Devenport[13], M. I. Hussein[14], G. Memoli[15], G. Fusaro[16], D. D'Orazio[16], L. Barbaresi[16], M. Garai[16], L. Chisari[15,17], P. Mittal[18], Z. Qi[19], S. Subramanian[18], S. Brûlé[20], S. Enoch[21], S. Guenneau[22], R. Stoakes[23], C. McLean[24], A. Gardiner[25]

[1] Centre for Metamaterial Research and Innovation, The University of Exeter
[2] Institute of Sound & Vibration Research, University of Southampton
[3] Instituto Universitario de Matemática Pura y Aplicada (IUMPA), Universitat Politècnica de Valencia (UPV), València, Spain
[4] Instituto de Instrumentación para Imagen Molecular (I3M), Consejo Superior de Investigaciones Científicas
(CSIC), Universitat Politècnica de València, València, Spain
[5] Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR 6613 CNRS, Le Mans, France
[6] University of Michigan, Mechanical Engineering, Ann Arbor,MI, USA
[7] Nanjing University, China
[8] IMDEA Materials, Spain
[9] The Hong Kong University of Science and Technology
[10] Laboratory of Wave Engineering, EPFL, 1015 Lausanne, Switzerland
[11] Applied Research Laboratories, The University of Texas at Austin, Austin, TX, USA
[12] Walker Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA
[13] Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech, United States of America
[14] University of Colorado Boulder, USA
[15] University of Sussex, UK
[16] University of Bologna, Italy
[17] Metasonixx Ltd, UK
[18] Department of Computer Science, University College London, London, UK
[19] School of Mechatronic and Automation Engineering, Shanghai University, Shanghai, China
[20] Menard, Orsay, France
[21] CNRS, Aix-Marseille Université, Centrale Marseille, Institut Fresnel, Marseille, France
[22] The Blackett Laboratory & UMI 2004 Abraham de Moivre, Imperial College, London, UK
[23] University of Strathclyde, UK
[24] Edinburgh Napier University, UK
[25] University of Glasgow, UK

* Guest editor of the Roadmap - Author to whom any correspondence should be addressed:

g.j.chaplain@exeter.ac.uk

Abstract

Today, acoustic metamaterials form a core area of metamaterial research. They offer bespoke wave control, achievable through their rationally designed structure and are at the forefront of metamaterial applications and commercialisation. They find purpose across science and defence sectors in wave filtering, sensing, communications, energy harvesting, thermal emission control, and aeroacoustics, to name but a few. They enjoy success in metropolitan environments with designer audio and noise mitigation falling within their remit; acoustic metamaterial technologies are already penetrating the market across audio and healthcare sectors.

The landscape of acoustic metamaterial research is continually expanding, now incorporating several wave regimes under a broader definition that we adopt here. The diversity of acoustic metamaterial research displays how they exist not only to translate electromagnetic phenomena, but also to provide a unique platform for exploring all metamaterial physics, and for solving key societal challenges.

The aim of this Roadmap is to present a summary of the state of acoustic metamaterial research and innovation in 2024, with opinions on the challenges and future opportunities from a group of renown experts, covering key interdisciplinary areas from fundamental acoustics to device implementation.

Contents

1. Introduction

G. J. Chaplain

Centre for Metamaterial Research and Innovation, University of Exeter, UK

Acoustic metamaterials (AMMs) grant unprecedented control over acoustic wave fields. By eliciting designer wave interactions, these materials have the potential to unlock new science and technology for a range of transformative applications for example in audio, healthcare, and noise mitigation, some of which shall be showcased in this roadmap. Alongside this, AMMs provide an ideal platform for exploring metamaterial phenomena and enable translational research between wave-regimes by allowing underlying theory to be tested by accessible experimental verification. The advent of AMMs has reignited a concerted research effort into acoustics in both academic and industrial communities, with their importance exemplified by special interest groups within two national networks, the UK Metamaterials Network (UKMMN) and the UK Acoustics Network (UKAN). Both networks strive to bring together experts from academia, industry, and governmental agencies and have promoted acoustics, and AMMs, both nationally and internationally. The future success of AMMs for societal benefit relies on translation from academic settings via collaboration with industrial partners to address current and future challenges in the commercial space.

This roadmap aims to facilitate a bridge between the dichotomy of academic research and industrial applications, from fundamental science to device implementation. It details snapshots of the current status of several sub-themes in AMMs and the corresponding current and future challenges, and the advances required to meet those challenges. It forms part of a series of roadmaps providing a comprehensive review of the state-of-the-art in metamaterials science in 2024, over two decades since the phrase was coined, and demonstrates the breadth of acoustic metamaterial research globally.

Here we aim to cover as broadly as possible the depth of scientific research that could be considered under the umbrella of acoustics, avoiding the limitations of a semantical definition of AMMs (a coherent, global definition of metamaterials in general is an aim of the UKMM). To this end we focus on rationally designed structures that specifically manipulate either acoustic pressure waves or flow in a fluid, or elastic waves in a solid, displaying phenomena that is not possible without the additional structure; the exquisite control achieved should not rely on inherent material properties. As such, in addition to conventional AMMs (that manipulate airborne sound, for example), seismic metamaterials for the manipulation of elastic vibrations feature here, as do phononic crystals, and even nanophononic metamaterials. This inclusive choice was motivated through observation of how perceptions of the definition and applications of AMMs has changed year-on-year at various UKAN and UKMMN events in both academia and industry.

Here we include topics from leading experts in acoustic metamaterial research, that are grouped together according to the themes of 1) canonical subwavelength AMMs for dispersion engineering, absorption, diffusion, and holography; 2) programmable AMMs including topological, time-varying, active, and non-reciprocal AMMs; 3) AMMs for flow, particularly with applications to turbulence; 4) AMMs for noise and ventilation, including advanced sound systems; 5) ‘extended’ AMMs, that includes seismic and nanophononic AMMs; and finally 6) manufacturing, metrology, and scale-up of AMMs.

Canonical Subwavelength AMMs

2. Breaking the mass-law using thin and lightweight acoustic metamaterial plates

Felix Langfeldt
Institute of Sound & Vibration Research, University of Southampton, UK

Status

Reducing low-frequency noise with thin and lightweight structures is a huge challenge in acoustics. At low frequencies, the sound transmission through a homogeneous wall is governed by the mass-law, which states that the sound transmission loss TL increases by 6 dB per frequency doubling or mass doubling. Thus, to significantly improve the STL of a mass-law governed structure at a given frequency, a large increase of its mass is required, which is often prohibitive in noise control applications. With the advent of acoustic metamaterials in the year 2000, many new ways of controlling sound – and, consequently, noise – emerged and "breaking the mass-law" became a major goal in the design of noise control treatments using acoustic metamaterials.

In 2008, Yang et al. [1] proposed a membrane-type acoustic metamaterial (MAM), consisting of a pre-stressed membrane and rigid masses attached to the membrane. Despite being only several millimetres thin and weighing less than 1 kg/m², their MAM was able to break the mass-law by more than 20 dB. This breakthrough paper sparked a lot of follow-up research aiming at overcoming the mass-law using MAM and other thin plate-like acoustic metamaterial designs. One example, closely related to MAM, are plate-type acoustic metamaterials (PAM). PAM have a very similar structure as MAM, however instead of a membrane the added masses are attached to a baseplate without pre-stress [2]. This has several advantages, as the pre-stress of a membrane needs to be sustained by a possibly heavy grid structure and can change, e.g. due to temperature or ageing effects. Figure 1 shows an example of a PAM design and its sound transmission loss. It can be clearly seen how the metamaterial's transmission loss exceeds the mass-law around the so-called anti-resonance frequency of the PAM. Other noteworthy examples for acoustic metamaterial plate designs are cellular metamaterial panels [3] and vibro-acoustic metamaterials, consisting of plates with periodically distributed mechanical resonators [4].

Apart from a few commercialisations which are not publicly available due to trade secrets, these acoustic metamaterials-based noise reduction technologies have not yet made it into widespread practical applications, for the reasons outlined below. However, since noise has a strong negative impact on the health and wellbeing of humans, a lot can be gained by further advancing this field towards more practical solutions.

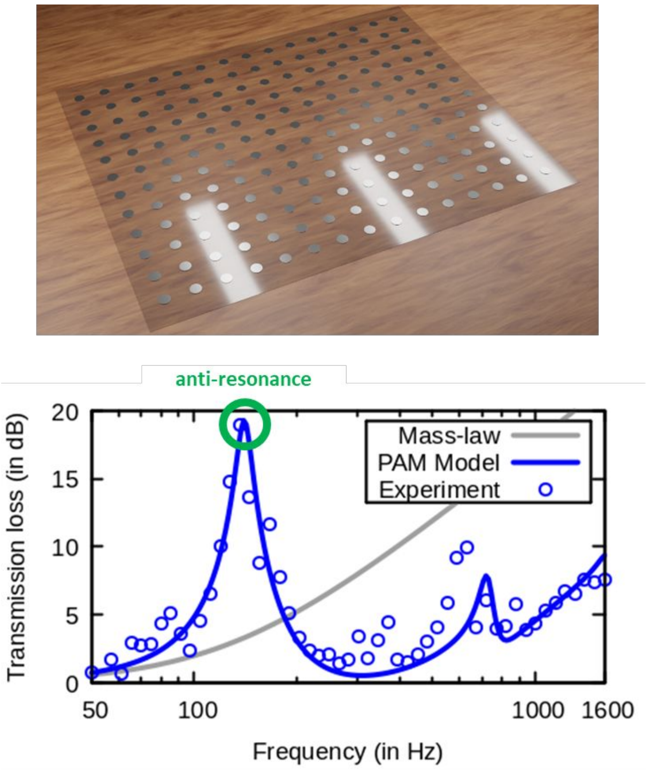


Figure 1. Top: Example of a plate-type acoustic metamaterial (PAM), consisting of circular masses periodically attached to a thin, flexible baseplate. Bottom: Sound transmission loss of the PAM compared to the mass-law (1 kg/m²).

Current and Future Challenges

One key challenge for acoustic metamaterial plates is the narrow bandwidth. An example for this can be seen in the PAM transmission loss plot shown in Figure 1. The narrow bandwidth limits the practical relevance of metamaterial plates to very few applications which involve tonal noise at fixed frequencies (e.g. transformer noise). The impact of noise control measures containing acoustic metamaterial plates would be much bigger, if they could be designed to control low-frequency noise over much wider frequency ranges. It has been demonstrated that his can be achieved by stacking multiple layers of metamaterial plates tuned to different frequencies [5]. This, however, increases the overall thickness of such panels. An alternative approach is to use a single metamaterial plate containing differently tuned unit cells. It has been demonstrated theoretically that this can achieve equal bandwidth enhancements as stacking multiple layers [6], but an experimental demonstration of a single-layer metamaterial plate with a large noise insulation bandwidth is still outstanding.

Apart from the narrow bandwidth, lightweight acoustic metamaterial plates also typically exhibit a strong reduction of noise insulation performance at higher frequencies. This can also be seen in the transmission loss plot shown in Figure 1. Consequently, even though low-frequency noise can be reduced well using an acoustic metamaterial plate, this comes at a cost of high-frequency noise being augmented, compared to a homogenous wall with the same mass. Thus, there is a need for improved acoustic metamaterial plate designs with better high-frequency performance, for example by combining metamaterials with porous absorbers.

Another major challenge is the manufacturing of acoustic metamaterial plates. Especially for thin and lightweight designs consisting of thousands of unit cells per square meter, conventional manufacturing methods (e.g. milling) as well as more recent methods like additive manufacturing are too time consuming and too costly to make acoustic metamaterial plates a commercially viable low-frequency noise control solution. Thermoforming has been explored as a cost-effective process to manufacture large and lightweight acoustic metamaterial panels [7], which, however, still required the use of milling and application of added material to achieve the desired behaviour. Related to this manufacturing challenge is also the difficulty in predicting the sound insulation performance of acoustic metamaterial plates when scaled up to practically relevant sizes and when exposed to realistic boundary conditions. In the design phase of acoustic metamaterial plates, unit cells with periodic boundary conditions and plane incident acoustic waves are usually considered for computational efficiency. Real metamaterial structures, however, will always be finite and can be subject to different boundary conditions (e.g. clamped or elastic boundaries) and acoustic excitations (e.g. diffuse sound fields) that can lead to different acoustic behaviour.

Advances in Science and Technology to Meet Challenges

Based on the challenges outlined above, science and technology need to advance towards improving the bandwidth and high-frequency performance of current acoustic metamaterial plate concepts, without losing their thin and lightweight properties. A promising route to achieve this is by combining different noise reduction mechanisms, possibly derived from other acoustic metamaterial solutions, into a single acoustic metamaterial plate design. A recent example for such a multi-functional or multi-modal metamaterial plate combines a PAM design with Helmholtz resonators to achieve an increase in bandwidth without increasing the mass of the PAM [8]. Optimization methods and generative artificial intelligence could be synergized to create new unit cell designs for acoustic metamaterial plates that exhibit an improved bandwidth as compared to current designs. This could be particularly fruitful for acoustic metamaterial plate designs for which no straightforward relationship between the unit cell design and the resulting anti-resonance frequencies exists.

There is also a need for more fundamental research about the physical limitations of acoustic metamaterial plates. It is still not clear what is possible to achieve with thin and lightweight acoustic metamaterial plates – and what is not possible. Open research questions that need to be addressed are, for example: Is there a fundamental limit for how much the mass-law can be exceed using acoustic metamaterial plates? Or, can the high-frequency noise insulation reduction, that is typical for lightweight acoustic metamaterial plates, be avoided with newly developed designs?

For meeting the manufacturing challenge, appropriate and cost-effective manufacturing processes need to be identified, ideally in close collaboration with the relevant industry. Thin and flexible acoustic metamaterial plate designs could possibly be manufactured in large quantities on rolls, using roll-to-roll processes. For metamaterials consisting of many small resonators, pick-and-place processes, known from electronic circuit board manufacturing, could be a viable solution. Taking this further, common manufacturing methods in electronics could also be a way forward to realizing active acoustic metamaterial plates, which use sensors, actuators, and control circuits to enhance the bandwidth and re-configure anti-resonances of metamaterial plates [9].

Overall, the full noise reduction potential of thin and lightweight metamaterial plates will be transformed into practically relevant solutions more quickly by promoting and facilitating collaborations between researchers, industry, and policy makers, e.g. through knowledge sharing platforms or funding streams targeted at technology maturity enhancement of emergent noise control technologies.

Concluding Remarks

The advent of acoustic metamaterials opened up new ways of breaking the mass law, promising to transform the way how noise problems will be tackled in the future. Many different thin and lightweight acoustic metamaterial plates with exceptional low-frequency noise insulation have since been proposed. As outlined in this contribution, the main challenges needed to be addressed before acoustic metamaterial plates can become a widespread noise control solution are the bandwidth, the high-frequency behaviour, and the manufacturability at larger scale. With these challenges being overcome in future research, acoustic metamaterial plates, due to their light weight and low thickness profile, will have a versatile application portfolio to reduce noise and improve the health and wellbeing of many humans being plagued by noise.

References

[1] Z. Yang, J. Mei, M. Yang, N. H. Chan, and P. Sheng, 'Membrane-type acoustic metamaterial with negative dynamic mass', *Phys. Rev. Lett.*, vol. 101, no. 20, p. 204301, 2008, doi: 10.1103/PhysRevLett.101.204301.

[2] F. Ma, C. Wang, C. Liu, and J. H. Wu, 'Structural designs, principles, and applications of thin-walled membrane and plate-type acoustic/elastic metamaterials', *J. Appl. Phys.*, vol. 129, no. 23, p. 231103, Jun. 2021, doi: 10.1063/5.0042132.

[3] S. Varanasi, J. S. Bolton, and T. Siegmund, 'Experiments on the low frequency barrier characteristics of cellular metamaterial panels in a diffuse sound field', *J. Acoust. Soc. Am.*, vol. 141, no. 1, pp. 602–610, Jan. 2017, doi: 10.1121/1.4974257.

[4] C. Claeys, E. Deckers, B. Pluymers, and W. Desmet, 'A lightweight vibro-acoustic metamaterial demonstrator: Numerical and experimental investigation', *Mech. Syst. Signal Process.*, vol. 70–71, pp. 853–880, Mar. 2016, doi: 10.1016/j.ymssp.2015.08.029.

[5] J. Mei, G. Ma, M. Yang, Z. Yang, W. Wen, and P. Sheng, 'Dark acoustic metamaterials as super absorbers for low-frequency sound', *Nat. Commun.*, vol. 3, p. 756, 2012, doi: 10.1038/ncomms1758.

[6] F. Langfeldt and W. Gleine, 'Optimizing the bandwidth of plate-type acoustic metamaterials', *J. Acoust. Soc. Am.*, vol. 148, no. 3, pp. 1304–1314, Sep. 2020, doi: 10.1121/10.0001925.

[7] N. G. R. de Melo Filho, C. Claeys, E. Deckers, and W. Desmet, 'Realisation of a thermoformed vibro-acoustic metamaterial for increased STL in acoustic resonance driven environments', *Appl. Acoust.*, vol. 156, pp. 78–82, Dec. 2019, doi: 10.1016/j.apacoust.2019.07.007.

[8] F. Langfeldt, A. J. Khatokar, and W. Gleine, 'Plate-type acoustic metamaterials with integrated Helmholtz resonators', *Appl. Acoust.*, vol. 199, p. 109019, Oct. 2022, doi: 10.1016/j.apacoust.2022.109019.

[9] B.-I. Popa and S. A. Cummer, 'Non-reciprocal and highly nonlinear active acoustic metamaterials', *Nat. Commun.*, vol. 5, p. 3398, 2014, doi: 10.1038/ncomms4398.

3. Metamaterial Absorbers, diffusers, holograms, and waveguides – Deep subwavelength and broadband perfect absorption by acoustic metamaterials

V. Romero-García, Instituto Universitario de Matemática Pura y Aplicada (IUMPA), Universitat Politècnica de Valencia (UPV), València, Spain
N. Jiménez, Instituto de Instrumentación para Imagen Molecular (I3M), Consejo Superior de Investigaciones Científicas (CSIC), Universitat Politècnica de València, València, Spain
Y. Meng, Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR 6613 CNRS, Le Mans, France
J. Boulvert, Sil&Add, Le Mans, France
J.-P. Groby, Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR 6613 CNRS, Le Mans, France
V. Pagneux. Laboratoire d'Acoustique de l'Université du Mans (LAUM), UMR 6613 CNRS, Le Mans, France

Status

Acoustic metamaterials consisting of locally resonant building blocks [1] have represented a significant evolution for the material design strategies to engineer acoustic treatments with controlled and tailor-made acoustic wave propagation properties. The Physics of the locally resonant building blocks imposes the frequency-dependent behaviour of the macroscopic effective dynamic properties, in some cases with extraordinary values [2] [3]. It allows for several applications in wave filtering, sensing, communications, energy harvesting, and thermal emission control among others. Perhaps the most known feature of these acoustic metamaterials is their subwavelength behaviour, i.e., their ability to control waves, whose wavelength is much greater than the characteristic size of the metamaterial. The proper design of the locally resonant building blocks considering both the resonance frequency and balance between the viscothermal and/or viscoelastic losses with the energy leakage, as well as the interaction between the resonant building blocks, paved the road to design deep-subwavelength and broadband perfect absorbers [4] [5]. This is a scientific and technological challenge that requires to solve a twofold complex problem: reducing the dimensions of the structure while increasing the number of resonances at low frequencies with the good conditions to impedance match the system with the background medium. Both the universality and the possibility of perfect absorption makes it a fascinating topic not only for fundamental research but also to develop different applications as it is at the heart of its technological relevance in the broad field of wave physics. Moreover, low frequency sound and vibrations represent one of the major societal problems imposing both health issues and annoyance to most of the population around the world and impacting several industrial sectors as aeronautics or civil engineering among others. Recent results have shown realistic samples based on acoustic metamaterial solutions for the perfect absorption in the reflection [6] [7] and transmission [8] [9] problems. However, further advances are needed to improve the broadband behaviour always accounting for the imposed constraints by the causality principle [10].

Current and Future Challenges

The current main challenge is the design of subwavelength broadband prefect acoustic absorbers in realistic conditions. To do that theoretical modelling is used to obtain the scattering matrix, S, relating the outgoing to the incoming complex amplitudes of the scattered and incident waves. Energy conservation and time reversal symmetry imply both the unitarity of the scattering matrix, i.e., $S^{\dagger}S = I$, and the condition, $S^{*}S = I$, respectively. In the lossless case, these two conditions imply equality of the modulus of the reflection coefficients from both sides and the reciprocity condition implies equality of the transmission coefficients from both sides in addition of the energy conservation. Therefore, the scattering matrix of a lossless time-reversible system has always the same form regardless of the physical nature of the involved wave fields and the complexity of the analysed structure. On the one hand, in the case of a reflection problem (i.e. the incident wave is only reflected and not transmitted) the eigenvalues of the scattering matrix collapse to the reflection coefficient. Then, in the presence of losses, the impedance matching conditions or critical coupling conditions implying the perfect absorption can always theoretically be obtained [6]. On the other hand, in ventilated problems (i.e., a transmission problem considering both reflection and transmission coefficients) perfect absorption occurs when the two eigenvalues of the scattering matrix are zero at the same frequency. This condition can only be fulfilled in some cases:

1) In non-mirror symmetric systems unidirectional perfect absorption can be reached.
2) In mirror symmetric systems:
   a) Point resonators: Only one type of resonance can be excited, therefore only one of the two sub-problems (symmetric or antisymmetric) can be impedance matched and thus the maximum absorption is 50% [5].
   b) Degenerate resonators: Symmetric and antisymmetric resonances can be both excited and impedance matched. In this way, the two sub-problems can be critically coupled, and perfect absorption can be obtained from both sides of the system [8].

Fulfilling the conditions to obtain perfect absorbers in purely reflection (see Fig. 1(a-c)) and transmission (see Figs. 1(d,e) and 2) problems represents one of the current challenges in the acoustic metamaterial community.

The broadband character is usually obtained by properly coupling several resonators at close frequencies in the range of interest [5], [9] as well as by using other absorption phenomena provided by porous materials or perforated plates. The challenge appears when wide treatments allowing ventilation are needed. In this case, the quality factor of the resonators is high and then their effects are narrow in frequency. In addition, evanescent coupling has been revealed unavoidable for the proper design of the absorbers [5].

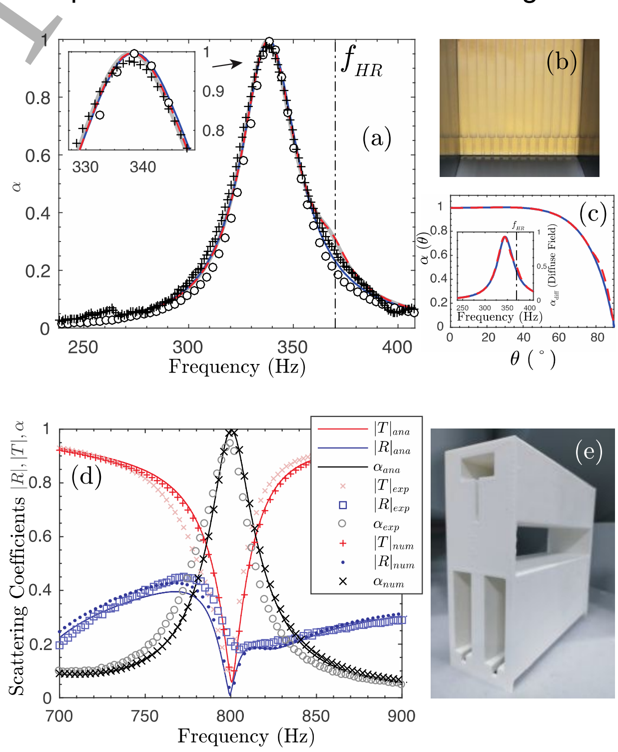


Figure 1. Single frequency perfect absorber for the reflection (a-c)

Previous discussion and the current advances in the topic of acoustic absorption are focused on the linear and reciprocal regime. However, new venues can be envisaged by exploiting the nonlinear and the non-reciprocal sides of the acoustic absorption. On the one hand, concerning the non-linear regime, high level noise is present in aerospace or industrial applications. Therefore, the design of nonlinear broadband perfect absorbers represents a future challenge in the topic of acoustic absorption. On the other hand, non-reciprocal acoustic devices, often found in engines and ventilation systems with background flows, pose another scientific challenge to the topic of acoustic absorption by breaking the symmetry of sound transmission between two points in space. The limitations of the linear and reciprocal problems can be overpassed by acoustic circulators or thermoacoustic systems. In such systems, if their properties are properly designed wave propagation occurs in one direction and it is completely blocked in the reverse direction, violating one of the most basic principles of acoustics and providing an ideal situation to design perfect absorbers.

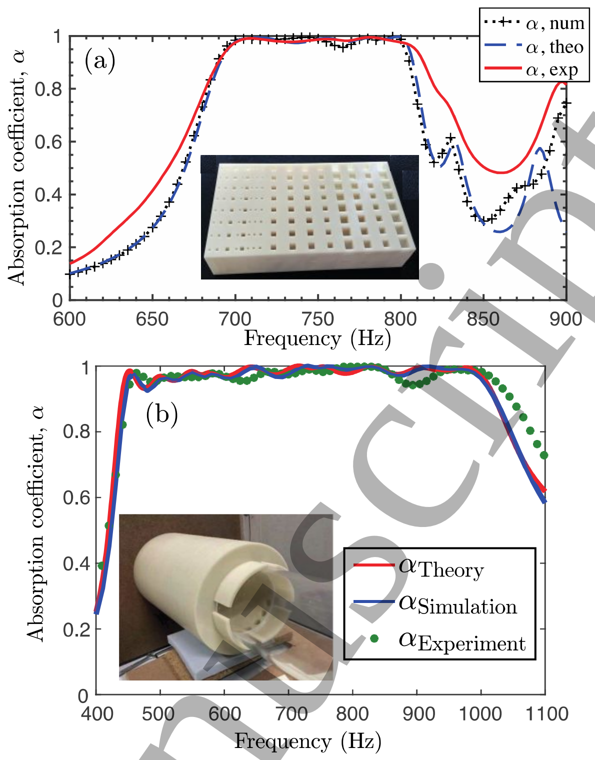


Figure 2. Broadband perfect absorbers in the transmission

Advances in Science and Technology to Meet Challenges

The precise manufacturing of acoustic metamaterials is fundamental to their demanded performance. In this sense, the advances in manufacturing techniques, such as additive manufacturing and nanofabrication, will enable precise control over the geometry and composition of metamaterial structures. This level of control will allow researchers to design and produce materials with tailored acoustic properties in a precise way.

Ensuring that metamaterials are not only effective in laboratory settings but also practical for real-world applications is crucial. On the one hand, as the problem is closer to reality, the complexity of the theoretical model increases. Therefore, advances in computational tools and simulations will play a crucial role in designing and optimizing metamaterials for specific acoustic absorption requirements. Advances in numerical modeling techniques will allow researchers to explore a vast design space efficiently. On the other hand, scalable production methods and assessing the long-term durability and stability of metamaterials in various environments are crucial considerations not only for metamaterials designed for acoustic absorption but also for any material or technology.

Concluding Remarks

The quest for subwavelength broadband perfect absorbers, addressing societal challenges in noise pollution, needs overcoming intricate theoretical and practical problems. Achieving perfect absorption requires innovative coupling strategies. The exploration of nonlinear and non-reciprocal dimensions can open new avenues, promising breakthroughs in addressing high-level noise and breaking symmetry in sound transmission. As technology advances, precision in manufacturing, scalability and industrial 3D printing, practical applicability, and long-term stability assessments become pivotal for the potential of acoustic metamaterials in real-world scenarios.

Acknowledgements
V.R.-G. and N.J. acknowledge support from project CIAICO/2022/052 of the “Programa para la promoción de la investigación científica, el desarrollo tecnológico y la innovación en la Comunitat Valenciana”. This publication is part of the R&D&I Project/Grant No. PID2020-112759GB-I00 funded by MCIN/AEI/10.13039/501100011033/. N.J. acknowledge financial support from Ministerio de Ciencia, Innovación y Universidades, through grants CNS2023-145707 and RYC2021-034920-I, and Agencia Estatal de Investigación grant PID2022-142719OB-C21. V.P. and J.-P.G. are supported by the EU H2020 ERC StG “NASA” Grant Agreement No. 101077954.

References

[1] P. A. Deymier, Acoustic Metamaterials and Phononic Crystals, Springer, 2013.

[2] Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan and P. Sheng, "Locally resonant sonic materials," *Science,* vol. 289, p. 1734, 2006.

[3] N. Fang, D. Xi, J. Xu, M. Ambati, W. Srituravanich, C. Sun and X. Zhang, "Ultrasonic metamaterials with negative modulus," *Nature Materials,* vol. 5, no. 6, pp. 452--456, 2006.

[4] S. Huang, Z. Zhou, D. Li, T. Liu, X. Wang, J. Zhu and Y. Li, "Compact broadband acoustic sink with coherently coupled weak resonances," *Science Bulletin,* vol. 65, no. 5, pp. 373-379, 2020.

[5] J. Boulvert, G. Gabard, V. Romero-García and J.-P. Groby, "Compact resonant systems for perfect and broadband sound absorption in wide waveguides in transmission problems," *Scientific Reports,* vol. 12, no. 10013, 2022.

[6] N. Jiménez, W. Huang, V. Romero-García, V. Pagneux and J. Groby, "Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption.," *Applied Physics Letters,* vol. 109, no. 12, p. 121902, 2016.

[7] Y. Aurégan, "Ultra-thin low frequency perfect sound absorber with high ratio of active area," *Appl. Phys. Lett.,* vol. 113, no. 201904, 2018.

[8] V. Romero-García, N. Jiménez, J.-P. Groby, A. Merkel, V. Tournat, G. Theocharis, O. Richoux and a. V. Pagneux, "Perfect Absorption in Mirror-Symmetric Acoustic Metascreens," *Phys. Rev. Applied,* vol. 14, no. 054055, 2020.

[9] Y. Meng, V. Romero-García, G. Gabard, J.-P. Groby, C. Bricault and S. Goudé, "Subwavelength Broadband Perfect Absorption for Unidimensional Open-Duct Problems," *Adv.Mater. Technol.,* vol. 8, no. 2201909, 2023.

[10] M. Yang, S. Chen, C. Fu and P. Sheng, "Optimal sound-absorbing structures," *Mater. Horiz.,* vol. 4, no. 4, pp. 673-680, 2017.

4. Acoustic Surface Waves: Controlling Sound with Structured Surfaces

Daniel B. Moore, Alastair P. Hibbins, J. Roy Sambles and Timothy A. Starkey, University of Exeter, UK

Status

Since the advent of metamaterials, there has been a notable resurgence in the study of acoustic materials, with a particular emphasis on the exploration of acoustic 'metamaterials' or 'metasurfaces' designed for controlling sound in both air and underwater [1]. Drawing inspiration from analogous studies in the electromagnetic domain, these designer materials exhibit material properties that have acoustic responses governed by the interaction of sub-wavelength, often periodic, resonant elements. By using these metamaterial properties, new intellectual ideas and research methodology have been developed to overcome long-established challenges in the field of acoustics but has also enabled fundamentally new science for the advanced control of sound.

Acoustic metamaterials typically rely on local interactions between resonant elements. In some materials this interaction is mediated by 'Acoustic Surface Waves' (ASWs), sometimes referred to 'Spoof Surface Acoustic Waves' or 'leaky guided modes'. These waves exist trapped at a metamaterial-fluid interface and are mediated by the diffractive-coupling of local resonators by the bounding fluid. They propagate at sub-sonic speed along the surface, and decay exponentially normal to it [2], in a manner analogous to the dispersion of Spoof Surface Plasmon Polaritons (SSPPs) on a structured metallic substrate. These contrast with Surface Acoustic Waves (SAWs), such as Rayleigh waves which exist at the surface of an elastic, and do not require an adjacent fluid.

An acoustically rigid surface adorned by a periodic tiling of unit-cells that contain a resonator is a simple example of a surface that may support ASWs. Typically, the unit-cell will be comprised of a single resonant element, such as a Helmholtz or membrane resonators [3,4], or multiple-coupled resonators. When unit-cells decorate a rigid surface to form a 1D strip or 2D surface, the supported ASWs can be steered along arbitrary paths and corners (see Fig. 1 for an example) [5,6].

In airborne acoustics, it has been shown that ASWs are important for medicating near-field interactions that occur in metamaterials that exhibit Enhanced Acoustic Transmission (EAT) or subwavelength imaging, collimation and focusing. Since the ASWs propagate wholly within the bounding fluid, these waves have demonstrated at sensitive response to chemical composition or temperature dependence of the air through which the wave propagates [7,8].

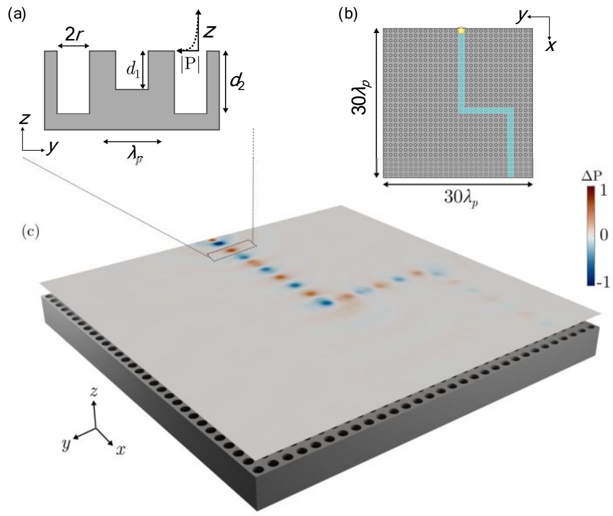


Figure 1. Example of steering sound on an arbitrary path using resonant cavities. Schematics showing (a) reduced resonator depth and supported surface mode evanescently decaying in z, and (b) path through the sample indicated by blue line. (c) Simulated pressure field above the surface.

Current and Future Challenges

To utilise ASWs for applications in fundamental physics or in acoustic engineering applications, their propagation behaviour often requires careful control by engineering their dispersion relation, constrained by some physical requirements. Space, scale, and weight are common considerations which drive the desire for compact devices; this results in, often competing, requirements on the operating frequency, frequency bandwidth, and degree of attenuation of an ASW. Here we present some of the associated challenges:

1. Dispersion engineering: controlling wave propagation, velocity, and direction, has given rise to control via rational design using principles such as unit-cell structure factor (for example unit-cells in Fig. 2) to enable the ready control of band gaps, negative dispersion, band pinching and other such phenomena resulting from the degrees of freedom and their connectivity within and between neighbouring unit-cells. The development of novel control strategies remains an active research area with analogues from solid-state physics frequently demonstrating novel wave transport.

2. Physical requirements: the miniaturisation of ASW device-form-factor is a challenge, because simple volumetric resonators require increasing internal dimensions to produce a resonance of decreasing frequency. One route to overcome this may be combining volumetric resonators into coupled resonator systems, for example with membranes, which could be used to tune operating frequencies. A further challenge in reducing the dimensions of a sample is the increased effects of isothermal boundary layers introducing loss channels. At reduced scales, these boundary layers occupy a larger percentage of the geometry, leading to increased losses which limit the potential miniaturisation of devices, except for absorbers.

3. Fabrication and manufacturing: additive manufacturing methods are ideally suited for fabricating metasurface geometries. However, access to a palette of soft materials (plastics) with well characterised material properties subject to print parameters is needed to enable easier exploration of acoustic-elastic coupled acoustic modes. In addition, a smooth surface finish is required so as not to contribute additional scattering effects or small loss channels.

4. Dynamic tuneability: the dispersion properties of metasurface samples supporting ASWs are typically fixed at fabrication, with (small) dynamic changes possible by changing the fluid properties, e.g., temperature. Future devices that utilise active or time-varying materials or elements may be employed for dynamically-actuated and multifunctional acoustic metasurfaces.

Advances in Science and Technology to Meet Challenges

Advances in the metamaterial field continue to address many of the challenges outlined above. The engineering of surface mode dispersion advances by using ideas developed in electromagnetism or condensed matter physics [8], as well as from fundamentally new concepts for acoustic materials. Synergy between new wave control strategies and, for example, additive manufacturing present opportunities in future science and engineering in this space. 3D printing as an approach to fabricating devices has become increasingly viable through optimisation of the printing procedure, which has led to more complex structures being fabricated, such as embedded waveguides for designer-symmetry waveguides [9] or for mixed-range acoustic interactions [10]. The latter is an example of taking ideas from solid-state-physics whereby unit-cells can be carefully connected to distant cells, to produce an interaction that goes beyond the nearest neighbour, that gives rise to dispersion relations mimicking those of Rotons in liquid Helium, with the analogue exhibiting negative dispersion of ASWs for a fixed frequency range while appearing externally as a simple 1D array of cavities [10].

Future technologies for ASW control may arise with a move toward active and time-varying materials. Dynamic actuation of materials, potentially via acoustic-elastic coupling, would enable real time control of wave propagation. Candidates for active and tuneable elements could be addressable membranes or elastic structures-loaded with magnetic elements, or mechanical shunts. Control of gain and loss in surface wave systems could be used to reconfigure and switch metasurface modalities or amplify or absorb waves readily.

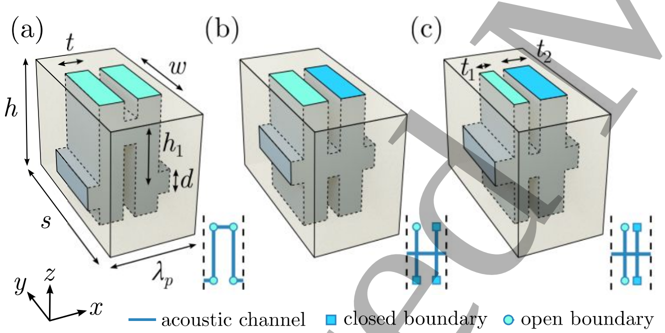


Figure 2. Example unit-cell geometries for utilising Frieze symmetry operations to control bandgaps or band pinching (Figure reproduced from Ref. [10]).

Concluding Remarks

Over the past decade, acoustic metasurfaces have been studied as a route to control sound propagation on a surface. ASWs can be used to passively transport sound along arbitrary paths, attenuate, or slow sound for fixed frequency regions for a range of applications. The development of wave control strategies has seen the evolution from structured arrays of simple resonant cavities towards systems utilising coupled-resonators, cavity-punctured waveguides, crystal symmetries, and beyond-nearest-neighbour couplings.

Future developments in this area will likely involve increased complexity in the design of devices through structure factor, aided through additive manufacturing, or additional functionality added to devices utilising actively controlled time-varying elements. Integrating these elements could lead to the development of tuneable sensors and noise control devices, as well as reconfigurable surfaces for passive beam steering operating at a frequency range below that of the devices' physical size.

Acknowledgements
The authors wish to acknowledge financial support from the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, via the EPSRC Centre for Doctoral Training in Metamaterials (Grant No. EP/ L015331/1). D.B.M., A.P.H., and T.A.S. acknowledge the financial support of Defence Science and Technology Laboratory (Grants No. DSTLXR1000154754 and No. AGR 0117701).

References
[1] Assouar B., Liang B., Wu Y., Li Y., Cheng J. C. and Jing Y. 2018 *Nat. Rev. Mater.* **3** 460–472
[2] Kelders L., Allard J. F. and Lauriks W. 1998 *J. Acoust. Soc. Am.* **103** 2730–2733
[3] Lemoult F., Kaina N., Fink M. and Lerosey G. 2016 *Crystals* **6** 82
[4] Chen X., Liu P., Hou Z. and Pei Y. 2017 *Appl. Phys. Lett.* **110**
[5] Starkey T. A., Ward, G. P. 2024 Acoustic Surface Waves on Metasurfaces in Acoustic Metamaterials: Absorption, Clocking, Imaging, Time-Modulated Media, and Topological Crystals ed Craster R., Guenneau S. (Springer) chap 14, pp 373-400 2nd ed ISBN 9783031600159
[6] Li H. X., Liu J. J., Chen Z. X., Wu K., Liang B., Yang J., Cheng J. C. and Christensen J. 2023 *Nat. Commun.* **14** 7633
[7] Cselyuszka N., Jankovic ́N., Alu A. and Bengin V. 2022 Acoustic Spoof Surface Waves Control in Corrugated Surfaces and Their Applications *Metamaterials: Technology and Applications* ed Choudhury P K (CRC Press, Taylor and Francis Group) chap 11, pp 289–312 1st ed ISBN 9788490225370
[8] Torrent D. and Sánchez-Dehesa J. 2012 *Phys. Rev. Lett.* **108** 174301
[9] Moore D. B., Starkey T. A. and Chaplain G. J. 2024 *J. Acoust. Soc. Am.* **155** 568–574
[10] Moore D. B., Sambles J. R., Hibbins A. P., Starkey T. A. and Chaplain G. J. 2023 *Phys. Rev. B* **107** 144110

5. Wavefront shaping using holograms and metamaterials

Noé Jiménez, Instituto de Instrumentación para Imagen Molecular (I3M), Consejo Superior de Investigaciones Científicas (CSIC), Universitat Politècnica de València, València, Spain
V. Romero-García, Instituto Universitario de Matemática Pura y Aplicada (IUMPA), Universitat Politècnica de Valencia (UPV), València, Spain

Status

Optical holograms can modulate light wavefronts to generate visible images. In the same way, acoustic images can also be synthesized by holograms, shaping the areas where mechanical waves present a high amplitude, and areas where the media is at rest. These acoustic holograms can be rendered as complex lenses that encode the wavefront information, capable of synthesizing a given acoustic field in transmission or reflection mode [1]. These lenses can generate complex fields with a sharp spatial distribution and have found practical application in several industrial and biomedical applications.

In industry, acoustic holograms can be applied to control acoustic scattering, for example, for room acoustics applications. Efficient sound diffusers can be obtained by encoding an holographic vortex in a metasurface [2]. In addition, the thickness of these sound diffusers can be reduced using subwavelength resonant building blocks, i.e., narrowband diffusion using single Helmholtz resonators [3] or broadband diffusion using more complex metamaterials, as those based on slow sound [4]. When using sound waves in air holographic devices can be easily manufactured using 3D printing because the solid frame is nearly incompressible and motionless as compared with the air. In this way, many demonstrators of acoustic holograms have been proposed for sound waves in air [5]. However, when using ultrasound waves in water, the classical topologies to design and fabricate acoustic resonators are no longer valid due to the low acoustic impedance contrast between the fluid and the solid frames.

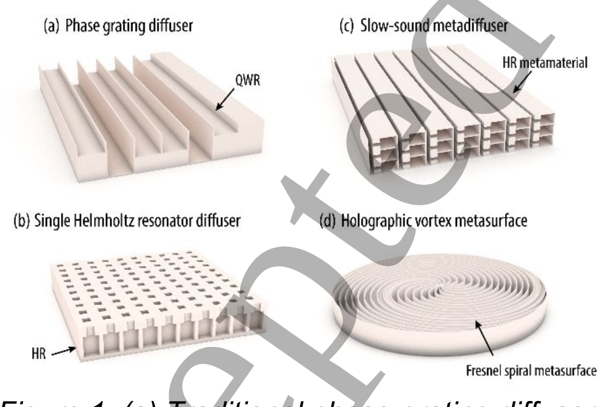


Figure 1. (a) Traditional phase-grating diffuser, where each resonating element is a quarter-wavelength resonator (QWR) built by a well in the panel. (b) Equivalent phase grating diffuser using Helmholtz resonators (HR) to control the reflected field. The HR allows for thinner panels. (c) Slow-sound metadiffuser using a Helmholtz metamaterial to tune the propagation in each slit and producing thinner panels. By tuning the geometrical parameters, broadband diffusion can be obtained. (d) Holographic control of the scattering by rendering a defocused acoustic vortex to produce large sound diffusion and avoiding specular reflections.

Biomedical applications include the use of holograms to modulate ultrasound beams for therapy and particle trapping, as well as ultrasound field modulation for imaging. For example, the aberrations introduced by the skull bones during transcranial propagation can be compensated, generating a sharp and single focal spot, or producing acoustic images that match the shape of therapeutic targets inside the brain [6].

It is worth nothing here that phase arrays can also produce therapeutic beams by electronically tuning the driving signals of a piezoelectric transducer. Indeed, this is currently approved technology in clinics and is used to treat a wide range of diseases. However, these devices need a large surface to generate a therapeutic beam, and, in addition, the power electronics present a poor scalability. Typically, the operating central frequency is in the MHz regime, leading to a wavelength of a millimeter, or even smaller. This results in a limited number of individual transducers, and the size of each active element is larger than a wavelength. These large elements can generate sharp focal spots when arranged in a bowl-shaped transducer, and the focus can be electronically steered in the axial or lateral direction. However, due to the large separation and the high directivity of the individual elements, the emergence of undesired secondary grating lobes limits the electronic steering range to some millimeters. On the other hand, the pixel density of a 3D-printed acoustic hologram is usually large, typically subwavelength in the lateral direction. Therefore, their capability for wavefront modulation goes beyond traditional phased arrays.

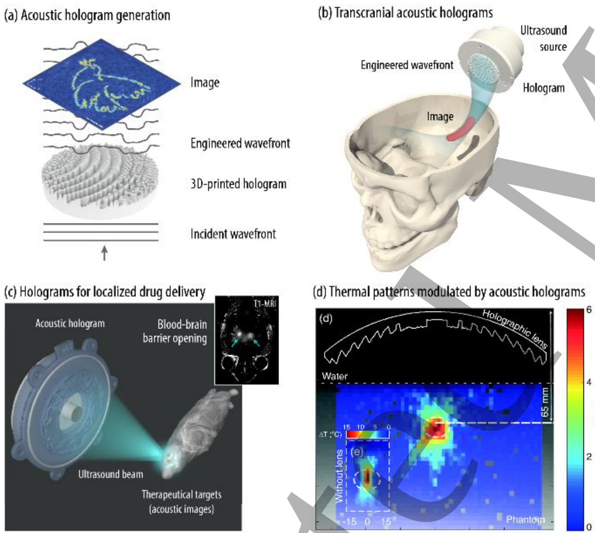


Figure 2. (a) Acoustic image rendering using a 3D-printed hologram. (b) Transcranial application of acoustic holograms, where the wavefront simultaneously encodes the compensation of the skull aberrations and, in addition, the retrieved acoustic image matches a therapeutic target inside of the brain. (c) First in-vivo demonstration of holograms, where 3D-printed lenses were used to open the blood-brain barrier in two bilateral spots inside the brain of a small animal. A drug (contrast agent, gadolinium) was delivered in a local and noninvasive way, as seen in the MRI. (d) Thermal patterns for ultrasound hyperthermia are spatially modulated by acoustic holograms. In this case, the hologram was used to produce an acoustic image matching the shape of a target and the ultrasound produced a temperature rise at this area, as seen by the image of MRI thermometry.

Results from in vivo experiments in mice show that by employing holograms, drugs can be delivered to the central nervous system in a noninvasive and highly localized way [7]. While this can also be achieved using a single element focused transducer, this latter conventional strategy results in an elongated focal spot, typically covering the whole brain of small animals. However, holograms can also encode the multiple reflections and reverberation occurring inside the cranial cavity, increasing the angular spectrum of the wavefront at the focal spot. Time-reversed wavefronts synthesized by holograms in complex environments result in sharp focal spots close to the diffraction limit [7]. In this way, holograms can produce acoustic images that are free of aberrations and sharper than traditional focused ultrasound systems.

Other biomedical applications of acoustic holograms include hyperthermia treatments, where a high intensity beam is used to raise the temperature of the tissue. Using holograms, the local temperature rise inside the tissue can be spatially modulated [8], and the thermal pattern can match a target, e.g., the shape of a tumor. It is worth noting here that holograms can produce uniform acoustic fields over the target but, in general, a uniform field does not produce a uniform thermal pattern. When the acoustic energy is transferred from the beam to the medium on a large temporal scale, heat transport mechanisms blur the contours of the thermal pattern. However, holograms can also be tuned to produce uneven acoustic patterns but optimized to produce a uniform temperature distribution at some point in time, or to deliver a uniform thermal dose across the therapeutic target at the end of the treatment.

On the other hand, since holograms can encode complex wavefronts, they can be used for exotic beam generation, such as vortex beams [9]. In this case, holograms can simultaneously encode wave dislocations, focusing and steering, and the whole wavefront information to compensate for aberrating media such as skull bones or other nonhomogeneous tissue layers. Complex wavefronts can be tuned for particle trapping and wave-matter interaction applications, e.g., for single-shot and rapid 3D printing [10].

Finally, artificial structures can be used for acoustic imaging. Beyond trivially focusing lenses, spatially complex media coupled to a large-aperture single detector have been proposed for 3D ultrasound imaging by using compressive sensing strategies [11]. These devices increase signal complexity and produce unique signals for echoes arriving from different locations. In this way, there is no need for thousand-element arrays and multichannel electronics to obtain 3D images in industrial or biomedical applications.

Current and Future Challenges

Holograms have demonstrated their high performance in matching acoustic wavefronts and synthesizing arbitrary fields. However, while current strategies to fabricate holograms are mostly limited to phase plates, the magnitude of the field is necessary to fully synthesize complex fields and is often not considered by the topology of the holographic lens. For example, phase plates or simple longitudinal elastic resonators can only modify the phase of the wave. Although there are some proposals for phase and magnitude modulation, their application is not yet practical in relevant scenarios.

Another practical limitation of current implementations is reconfigurability: when a hologram is 3D printed, the image cannot be changed. Switching between predefined shapes using diffractive acoustic gratings has also been proposed [12]. However, for practical purposes, full hologram reconfigurability is desired. On the other hand, most holographic techniques are limited to a simple transverse or sagittal plane. Full volumetric holograms are difficult to achieve because of the limited angular spectrum of narrow-band holograms.

A major challenge is the hologram design process, which in complex and realistic scenarios, such as biomedical applications, require full-wave simulations that are slow and computationally expensive. Furthermore, in the case of transcranial ultrasound, the input to these simulations is x-ray tomographic data, which make use of ionizing radiation.

Finally, the practical application of many holographic techniques relies on 3D printing. However, the available 3D printing materials with high acoustic contrast and small absorption are limited. In addition, some patient-specific or application-specific lenses may generate a large amount of waste and incur environmental costs due to fabrication, transportation, deployment, and disposal. For industrial applications, scalability of large acoustic metasurfaces is limited by the current manufacturing processes.

Advances in Science and Technology to Meet Challenges

Holograms have found practical applications to correct the aberrations of the skull for transcranial ultrasound therapies. However, the need for x-ray tomographic data negatively impacts on the clinical adoption of this modality. Currently, machine learning techniques have the potential to solve this issue by using non-ionizing MRI data. Note that, while MRI equipment is in fact expensive, this neuroimaging technique is actually needed for diagnosis and treatment planning. Another low-hanging fruit is applying machine learning techniques for fast simulation or prediction of the acoustic field generated by the holograms, and apply these efficient algorithms for the lens design itself. While current hologram topologies are approximately only-phase lenses for pressure waves, the elastodynamics of these metasurfaces is far more complex and its full modelling results in numerical calculation of high computational cost. Then, standard optimization methods cannot be usually applied to design the best hologram to focus ultrasound on specific targets. In these situations, artificial intelligence tools can help to reduce computational burden for metasurface design.

Early holographic lenses were designed using basic refractive principles, and their performance was not optimal because these models neglected important physical features. Handling water-coupled ultrasonic waves in structured materials involves considering all of the material's elasticity and viscoelastic behavior. In addition, in some key applications, high intensity ultrasound is used, and nonlinear phenomena arise. Most of the advances, concepts and “wave tricks” investigated during the last decades in wave physics in complex media, including artificially structured media and metamaterials, are waiting to be applied in this field.

The emergence of new 3D printing techniques may improve the current manufacturing process, where metasurfaces and holograms can be manufactured in situ, ready for use, and composed of reusable or recyclable materials. In addition, the current state of the art on active and reconfigurable elastic and acoustic metamaterials may replace personalized and patient specific 3D-printed holograms. These approaches can lead to environmentally friendly devices and commercially feasible applications.

Concluding Remarks

Acoustic holograms may have a profound impact on industrial and biomedical ultrasound devices and, in particular, are introducing a paradigm shift in ultrasound imaging and therapy. The use of a 3d-printed lens instead of a phased-array would result in therapeutic devices costing orders of magnitude less. In addition, by encoding time-reversed wavefronts in subwavelength pixels instead of introducing a simple temporal shift in large radiating elements, holograms in complex environments can enhance the angular spectrum of the acoustic images, resulting in sharper focal spots close to the diffraction limit. While most applications have been developed for biomedical ultrasound imaging and therapy, holograms are waiting to be applied in other selected applications in underwater, industrial, or civil engineering techniques.

Acknowledgements
V.R.-G. and N.J. acknowledge support from project CIAICO/2022/052 of the “Programa para la promoción de la investigación científica, el desarrollo tecnológico y la innovación en la Comunitat Valenciana”. N.J. acknowledge financial support from Ministerio de Ciencia,

Innovación y Universidades, through grants CNS2023-145707 and RYC2021-034920-I, and Agencia Estatal de Investigación through grants PID2022-142719OB-C21 and PID2020-112759GB-I00 funded by MCIN/AEI/10.13039/501100011033.

References

[1] K. Melde, A. G. Mark, T. Qiu, and P. Fischer, "Holograms for acoustics," *Nature*, vol. 537, no. 7621, p. 518, 2016.

[2] N. Jiménez, J. P. Groby, and V. Romero-García, "Spiral sound-diffusing metasurfaces based on holographic vortices," *Sci. Rep.*, vol. 11, no. 1, 2021, doi: 10.1038/s41598-021-89487-8.

[3] Y. Zhu, X. Fan, B. Liang, J. Cheng, and Y. Jing, "Ultrathin acoustic metasurface-based schroeder diffuser," *Phys. Rev. X*, vol. 7, no. 2, p. 21034, 2017, doi: 10.1103/PhysRevX.7.021034.

[4] N. Jiménez, T. J. Cox, V. Romero-García, and J.-P. Groby, "Metadiffusers: Deep-subwavelength sound diffusers," *Sci. Rep.*, vol. 7, no. 1, p. 5389, Dec. 2017, doi: 10.1038/s41598-017-05710-5.

[5] Y. Xie *et al.*, "Acoustic holographic rendering with two-dimensional metamaterial-based passive phased array," *Sci. Rep.*, vol. 6, p. 35437, 2016.

[6] S. Jiménez-Gambín, N. Jiménez, J. M. Benlloch, and F. Camarena, "Holograms to Focus Arbitrary Ultrasonic Fields through the Skull," *Phys. Rev. Appl.*, vol. 12, no. 1, p. 014016, Jul. 2019, doi: 10.1103/PhysRevApplied.12.014016.

[7] S. Jimenez-Gambin, N. Jimenez, A. Pouliopoulos, J. M. Benlloch, E. Konofagou, and F. Camarena, "Acoustic Holograms for Bilateral Blood-Brain Barrier Opening in a Mouse Model," *IEEE Trans. Biomed. Eng.*, vol. 69, no. 4, 2022, doi: 10.1109/TBME.2021.3115553.

[8] D. Andrés, J. Vappou, N. Jiménez, and F. Camarena, "Thermal holographic patterns for ultrasound hyperthermia," *Appl. Phys. Lett.*, vol. 120, no. 8, 2022, doi: 10.1063/5.0081565.

[9] S. Jiménez-Gambín, N. Jiménez, and F. Camarena, "Transcranial Focusing of Ultrasonic Vortices by Acoustic Holograms," *Phys. Rev. Appl.*, vol. 14, no. 5, p. 54070, 2020, doi: 10.1103/PhysRevApplied.14.054070.

[10] K. Melde *et al.*, "Compact holographic sound fields enable rapid one-step assembly of matter in 3D," *Sci. Adv.*, vol. 9, no. 6, Feb. 2023, doi: 10.1126/sciadv.adf6182.

[11] P. Kruizinga *et al.*, "Compressive 3D ultrasound imaging using a single sensor," *Sci. Adv.*, vol. 3, no. 12, Dec. 2017, doi: 10.1126/sciadv.1701423.

[12] A. G. Athanassiadis, L. Schlieder, K. Melde, V. Volchkov, B. Schölkopf, and P. Fischer, "Multiplane Diffractive Acoustic Networks," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 70, no. 5, pp. 441–448, May 2023, doi: 10.1109/TUFFC.2023.3255992.

[13] IEEE Transactions on Biomedical Engineering. Frontcover. 69 (4) pp C1, 2022

Programmable AMMs

6 – Extending the range of realizable acoustic properties with active metamaterials

Bogdan-Ioan Popa,

University of Michigan, Mechanical Engineering, Ann Arbor, MI, USA

Status

Extensive metamaterial research has shown that remarkable advances in strategically important fields such as healthcare, defense, and civil engineering would be possible if only one had access to media having the right material parameters [1, 2]. Transformation acoustics provided the blueprints for unparalleled sound manipulation by leveraging mass density anisotropy and by carefully controlling distributions of bulk modulus and mass density [3]. This novel theory enabled new and exciting applications such as cloaking and produced new methods for noise mitigation and acoustic imaging. Willis media added two more material parameters – the Willis coupling tensors – which provided even more degrees of freedom to control sound with potential applications including efficient diffracting elements for imaging [4] and noise mitigation [5], and non-reciprocal sound transport [6].

These developments ushered in new efforts to realize physical metamaterials with the material parameters prescribed theoretically. Initial work involved passive metamaterials, but it was soon realized that these structures have fundamental limitations in terms of operational bandwidth and accuracy and were never able to realize convincingly the remarkable applications they were supposed to enable [1].

Active metamaterials have been recognized as alternatives that avoid the limitations of passive media. Early efforts focused on metamaterials with dynamically adjustable geometry and thus properties tunable on-demand [2], but their acoustic properties were essentially those of passive structures. Particularly promising has been an active metamaterial architecture in which the unit cells are composed of pairs of sensing and driven transducers [5-11] (Fig. 1). The former sense the local condition of pressure and/or particle velocity, and the latter produces an acoustic response coherent with the sensed quantity. Each pair's (and thus metamaterial's) acoustic behavior is programmed by selecting the right gain between the sensor and the paired driver.

Promising proof of concept experiments demonstrated a wide range of material parameters unavailable in passive media such as some bulk moduli [5, 6], mass density tensors [5, 6] (including the non-symmetric kind for non-Hermitian media [11]), and Willis coupling tensors [8], but they only involved a very small number of cells and carefully selected geometries in which these cells were not interacting with each other. There are significant challenges that need to be overcome to employ them in more realistic settings and finally bring to reality the compelling applications promised by past theoretical work on metamaterials.

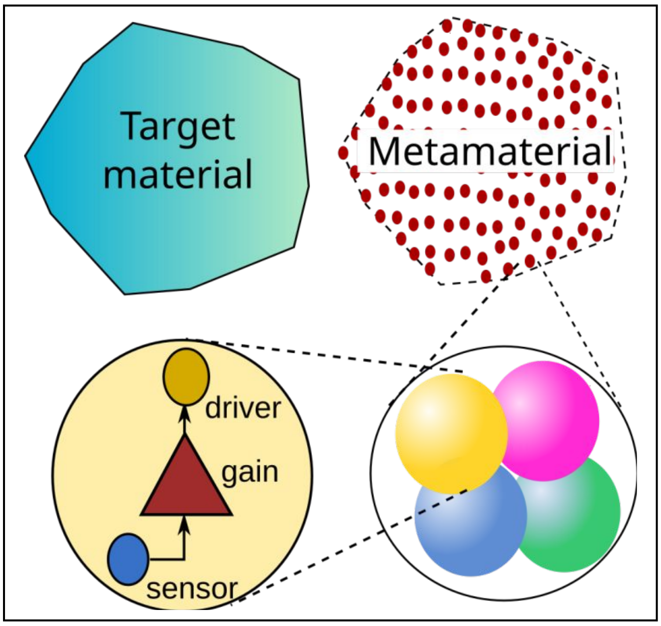


Figure 1. Active metamaterial architecture. An ideal material (top-left) is realized as a collection of unit cells (top-right). Each cell (bottom-right) contains multiple sensor-driver pairs (bottom-left) whose acoustic behavior is programmed through the gain element.

Current and Future Challenges

The active metamaterial architecture shown in Fig. 1 is maximally versatile in that the driven transducers can, in principle, create any causal acoustic response desired, which translate into a very large range of realizable material parameters unachievable with other methods. However, this versatility comes with unique challenges in terms of stability, scalability, accuracy, and bandwidth.

Most of these challenges originate in the numerous feedback loops involving pairs of sensors and drivers. Special care needs to be taken to insure the stability of all these loops. Analysis of these systems' stability has largely been avoided so far. Experimental work has either involved very few cells (often only one or two [7-9]) or has considered carefully selected setups in which the cells are not interacting with each other [5,6], i.e., the sound created by one sensor-driver pair is not captured by the others. In these scenarios, conventional stability analysis tools such as those provided by sound control theory suffice. However, these methods do not scale well as the number of cells increases and in realistic scenarios involving strongly interacting sensor-driver pairs. Future research should consider the latter, more challenging scenarios. New metamaterial design methods need to be devised to take stability and scalability into account.

Moreover, accuracy and repeatability have long been challenging for experimental metamaterials. For the active kind, most proof of concept experimental active cells achieved the desired acoustic properties with large tolerances mainly due to the variability in the transducers themselves and the variability in their mounting frames. New algorithms to tune the gain elements are needed to mitigate the tolerance issue and produce repeatable, highly accurate sensor-driver pairs.

Finally, extending the operational bandwidth of active metamaterials is another challenge. Most acoustic devices such as sonar, ultrasound imaging machines, noise mitigation systems involve broadband sound. Active metamaterials can in principle provide the necessary bandwidth but achieving it is difficult in the general cases in which the sensor-driver pairs are interacting with each other.

Advances in Science and Technology to Meet Challenges

Active metamaterials following the sensor-driver pair architecture may resemble typical sound control systems. Consequently, conventional controls methods have been used in which the gain of each driver-sensor pair is changed adaptively based on the sensed local acoustic conditions [4]. In these approaches there is a need to reduce the convergence time to the optimal gain to preserve bandwidth. Also, new methods are needed to sense the metamaterial acoustic properties in real time. Moreover, these methods are centralized methods in which all gains are set by a central control unit receiving inputs from all sensors. Adding more unit cells to an existing metamaterial potentially changes the gains in all the sensor-driver pairs reducing scalability. Mitigating this issue is work in progress.

Decentralized methods to select the gains are very promising alternatives tried by various groups [6,7,9]. One example is shown in Fig. 2 showcasing a highly efficient reflectionless absorber. In this approach the desired medium is first implemented as an array of subwavelength particles [12]. Their material parameters can be as exotic as those of the desired target medium, but the subwavelength nature of the particles means they can be modeled in terms of monopole and dipole moments, which can be trivially implemented with sensor-driver pairs [10,12].

The technology is very promising because the design process assures stability at the design frequency, naturally considers the complex scattering of impinging sound from the metamaterial cells. It is also scalable because each gain element is set independent on the surrounding cells. Adding more cells to enlarge the metamaterial does not require changing the acoustic properties of the existing metamaterial thus mimicking how natural materials behave. It has potential for large bandwidth since the gain is determined a priori from the desired acoustic properties of the metamaterial and does not require change during operation, a behavior achievable with fast basic electronics.

Although metamaterials designed in this fashion are stable at the design frequency, the causality of the sensor-driver pair means that the desired gain phase cannot be maintained in a large bandwidth. Exploring how causality affects stability, bandwidth, and realizable acoustic properties is still needed.

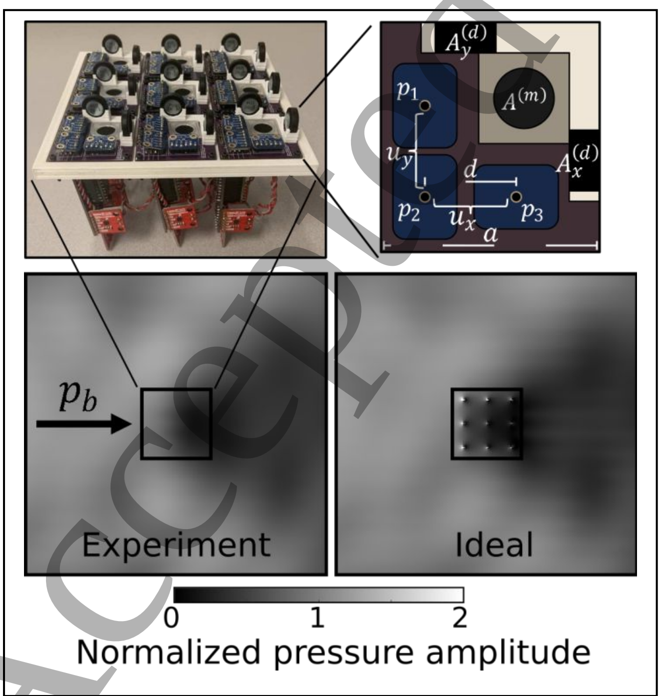


Figure 2. Highly efficient reflectionless absorber realized as an effective medium with relative mass density $e^{j\pi/6}$ and bulk modulus $e^{-j\pi/6}$ (adapted from [10]). The sought metamaterial scattering characteristics are validated by comparison with the ideal behavior.

Concluding Remarks

Transformation acoustics, Willis materials, time modulated media are examples of theoretical work producing blueprints for remarkable advances in noise mitigation and acoustic imaging, sensing, diagnostics, and communications. However, realizing the potential promised by past theoretical developments requires new generations of active metamaterials, which can be made possible only through new challenging scientific developments and difficult experimental work. Since the beginning, the metamaterial community adopted a breadth-first approach in which the low hanging fruits connected to an upcoming technology were collected and the technology was sidelined in favor of another unexplored one. After several decades, the metamaterial field should change strategy and adopt a depth-first approach in which truly difficult challenges are addressed. Doing so is probably the only way to realize the great potential of metamaterial research to advance strategic areas such as defense, health care, and civil engineering.

Acknowledgements
This work was supported by the National Science Foundation under Grant No. CMMI-1942901.

References

[1] S. A. Cummer, J. Christensen, and A. Alu, "Controlling sound with acoustic metamaterials," *Nature Reviews Materials*, vol. 1, art. 16001, Feb. 2016. doi:10.1038/natrevmats.2016.1.
[2] F. Ma, C. Wang, C. Liu, J. H. Wu, "Structural designs, principles, and applications of thin-walled membrane and plate-type acoustic/elastic metamaterials", *Journal of Applied Physics*, vol. 129, art. 231103, Jun. 2021. doi: 10.1063/5.0042132.
[3] A. N. Norris, "Acoustic cloaking theory," *Proceedings of the Royal Society A*, vol. 464, pp. 2411-2434, Apr. 2008. doi:10.1098/rspa.2008.0076.
[4] J. Li, C. Shen, A. Díaz-Rubio, S. A. Tretyakov, and S. A. Cummer, "Systematic design and experimental demonstration of bianisotropic metasurfaces for scattering-free manipulation of acoustic wavefronts," *Nature Communications*, vol. 9, art1342, Apr. 2018. doi:10.1038/s41467-018-03778-9.
[5] B.-I. Popa, Y. Zhai, and H.S. Kwon, "Broadband sound barriers with bianisotropic metasurfaces," *Nature Communications*, vol. 9, art. 5299, Dec. 2018. doi:10.1038/s41467-018-07809-3.
[6] Y. Chen, X. Li, H. Nassar, G. Hu, and G. Huang, "A programmable metasurface for real time control of broadband elastic rays," *Smart Materials and Structures*, vol. 27, art. 115011, Oct. 2018, doi:10.1088/1361-665X/aae27b.
[7] A. Baz, "Active nonreciprocal acoustic metamaterials using a switching controller," *Journal of the Acoustical Society of America*, vol. 143, pp. 1376-1384, Mar. 2018. doi:10.1121/1.5026510.
[8] B.-I. Popa, L. Zigoneanu, and S. A. Cummer, "Tunable active acoustic metamaterials," *Physical Review B*, vol. 88, art. 024303, Jul. 2013. doi:10.1103/PhysRevB.88.024303.
[9] C. Cho, X. Wen, N. Park, and J. Li, "Digitally virtualized atoms for acoustic metamaterials," *Nature Communications*, vol. 11, art. 251, Jan. 2020. doi:10.1038/s41467-019-14124-y.
[10] D. Kovacevich and B.-I. Popa, "Active acoustic metamaterials with on-demand bulk modulus and full mass density tensor," *Smart Materials and Structures*, vol. 33, art. 105012, Sep. 2024. doi: 10.1088/1361-665X/ad7550.

[11] Q. Wu, X. Xu, H. Qian, S. Wang, R. Zhu, Z. Yan, H. Ma, Y. Chen, and G. Huang, "Active metamaterials for realizing odd mass density", *Proceedings of the National Academy of Science*, vol. 120, art. E2209829120, Mar. 2023. doi: 10.1073/pnas.220982912.
[12] D. Kovacevich and B.-I. Popa, "Transformation acoustics with bulk media composed of polarized sources," *Physical Review B*, vol. 104, art. 134304, Oct. 2021. doi:10.1103/PhysRevB.104.134304.

7. Topological Sonic Metamaterials

Zhiwang Zhang, Nanjing University, China
Johan Christensen, IMDEA Materials, Spain

Status

Attributing properties pertaining to symmetry in metamaterials constitutes the latest frontier of activities in this arena. These topological metamaterials have become very interesting, because the prospect of guiding waves can now be fully associated with the notion of nontrivial and obstacle-resilient characteristics. In other words, the unique feature of topological metamaterials is that their surface states are topologically protected, which means that certain characteristics of these states are guaranteed to remain the same despite small changes or defects in the material. What started as a mere exercise to unveil acoustic analogies of unique electronic surface conducting topological properties, evolved into well-established lines of research. These include acoustic valley and spin Hall systems, Chern insulators, topological semimetals, higher-order topological phases, and non-Hermitian topology, only to scratch the surface (see Fig. 1) [1-6].

Time-reversal invariant valley and pseudospin degrees of freedom (DOFs) in sonic lattices, which describe the degenerate energy extrema of the band structure and the wave functions in two inequivalent sites of a honeycomb lattice respectively, are experimentally not hard to attain. To begin, in two dimensions, Dirac cones (two conical frequency bands that meet at a single point) emerge at the high symmetry points of the Brillouin zone. To break these degeneracies and introduce a valley DOF, the rotation of the involved scatterers induces a reduction in the lattice symmetry, which facilitates the generation of valley states with opposite chiralities, an attribute harnessed for valley-contrasting sound steering and beam splitting applications. Higher levels of Dirac cones degeneracies are used to unlock pseudospin Hall acoustics through the band or zone folding approach. This effect enables sound with opposite pseudospins to move in opposite directions along the edges without scattering. In contrast, constructing an acoustic Chern insulator demands substantial effort due to the essential need for precision in engineering time-reversal symmetry breaking through moving fluids. Along these lines, the realization of such a topological insulator with gapless chiral edge states was only recently achieved using an artificial honeycomb lattice with rotating metafluid units.

Instead of engineering a gapped Dirac spectrum, topological semimetals feature band touching in momentum space, comprising point, line, or surface degeneracies. The most prominent example are Weyl semimetals that are three dimensional nontrivial phases of matter. An acoustic version requires multiple stacked acoustic graphene layers that are connected through a chiral interlayer coupling, which enables a Fermi-arc surface dispersion analogy. Higher-order topological phase go beyond the bulk-boundary correspondence, as engineered edge states themselves, can be gapped to give birth to lower dimensional nontrivial hinge or corner states. In the form of a topological hierarchy, through dimerization, Kekulé distortions, and mirror symmetry breaking, various topological states at decreasing dimensionality can be targeted [7].

Interestingly, most of what have been mentioned above can be significantly expanded upon by adding a complex channel. Non-Hermitian topology is fascinating, because added wave attenuation or amplification, again, not only challenges the conventional bulk-boundary correspondence, moreover, it gives rise to an array of unusual topological acoustic possibilities [8]. E.g., the non-Hermitian effect makes bulk states localize, breaks the chiral symmetry in topological sonic whispering gallery lattices [9], and enables lossy or amplifying valley-contrasting wave physics. The exact loss and gain textures in second-order topological insulators enables exceptional points across which complex corner state confinements undergo spatial transitions. On a more application-oriented side, modulating loss in topological acoustic waveguide-chains will generate directional dependent sound absorption. Future challenges and phenomena interesting for real world applications will be addressed in the ensuing section.

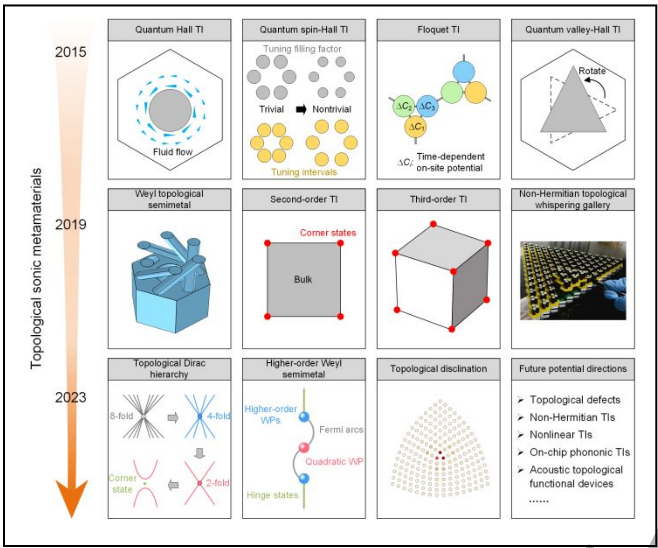


Figure 1. Timeline of topological sonic metamaterials during the last decade. Topological insulator and Weyl point are abbreviated as TI and WP, respectively.

Current and Future Challenges

Topological sonic metamaterials elegantly bridge condensed matter physics with classical acoustics thanks to the advanced fabrication technologies and precise measuring methods. Although versatile sonic topological phenomena have been demonstrated as reviewed in the previous section, we expect this research trend to persist for some years and several challenges are still waiting to be conquered. In the following, we discuss promising potential directions for future explorations in this field.

One intriguing avenue is the exploration of topological defects [10], which originate from a broken continuous symmetry in ideal lattices. For instance, square, pentagonal, heptagonal, etc. defects in fullerene structures with highly confined topological states were only theoretically studied and hard to be directly probed. For this, topological sonic metamaterials provide an opportunity to engineer such kind of topological defects, which may give rise to deeper understanding of emergent phenomena of nanoscale structures. Moreover, attributing non-Hermitian features with topological characteristics, introduces exciting possibilities for sound wave manipulations. Gain/loss textures and non-reciprocal coupling play pivotal roles in topological non-Hermitian metamaterials featuring the skin effect, amplified/attenuated topological boundary states, non-Hermitian higher-order topological insulators, or non-Abelian band braiding. Unlike the ubiquitous laser, an acoustic laser is hard to come by. However, taking advantage of the thermoacoustic coupling, researchers recently electrically loaded carbon nanotube films with an AC current as a means for active sound generation in a topological lattice. This approach not only creates a non-Hermitian component, but may indeed enabled new technological avenues beyond the already far-reaching scientific implications. Further, non-reciprocity is usually broken by introducing active control, but a question remains whether passive structural modulations using metamaterials in the form of engineered degrees of freedom could do the job. These possibilities will broaden abilities for topological sonic metamaterials with eased non-Hermitian and non-reciprocal features. In addition, considerable efforts have been made to in studying nonlinear topological physics, yet this avenue remains rather unexplored and timely to observe nonlinearity-induced topological phase transitions using sound.

Finally, topological sonic metamaterials are slowly maturing towards potential functional devices. Consequently, there is a growing emphasis on engineering emerging acoustic devices, including scattering-free waveguides, filters, sensors, directional antennas, (de)multiplexers, logic gates, tweezers and analog signal processing [11-16], all featuring the hallmarks of topological insulators, showcasing robust surface, edge, corner, hinge, and defect states. Beyond this, recent progress in integrated micro-mechanical components for logics and filtering applications indicates a continued interest in the development of on-chip phononic topological systems, which are promising candidates for exploring nonlinear, non-Hermitian, etc. vibrations at MHz frequencies. Approaching these frequencies and beyond, require facing challenges in terms of both fabrication and measurement techniques at scales approaching nanometers [17].

Concluding Remarks

Based on this brief survey, it can be confidently concluded that both topological acoustics and its mechanical counterpart hold great promise for ongoing basic and application-oriented research.

Acknowledgements

Z.Z. acknowledges support from the National Key R&D Program of China (2022YFA1404501), NSFC (12474439) and the Natural Science Foundation of Jiangsu Province (BK20240061). J.C. acknowledges support from the Spanish Ministry of Science and Innovation through a Consolidación Investigadora grant (CNS2022-135706).

References

[1] X. Zhang, M. Xiao, Y. Cheng, M.-H. Lu and J. Christensen, “Topological sound”, *Commun. Phys.*, vol. 1, no. 97, December 2018.
[2] G. Ma, M. Xiao and C. T. Chan, “Topological phases in acoustic and mechanical systems”, *Nat. Rev. Phys.*, vol. 1, pp. 281–294, March 2019.
[3] H. Xue, Y. Yang and B. Zhang, “Topological acoustics”, *Nat. Rev. Mater.*, vol. 7, pp. 974–990, August 2022.
[4] X. Ni, S. Yves, A. Krasnok and A. Alù, “Topological metamaterials”, *Chem. Rev.*, vol. 123, no. 12, pp. 7585-7654, May 2023.
[5] X. Zhang, F. Zangeneh-Nejad, Z.-G. Chen, M.-H. Lu and J. Christensen, “A second wave of topological phenomena in photonics and acoustics”, *Nature*, vol. 618, pp. 687-697, June 2023.
[6] W. Zhu, W. Deng, Y. Liu, J. Lu, H.-X. Wang, Z.-K. Lin, X. Huang, J.-H. Jiang and Z. Liu, “Topological phononic metamaterials”, *Rep. Prog. Phys.*, vol. 86, no. 106501, September 2023.
[7] L. Zheng and J. Christensen, “Dirac hierarchy in acoustic topological insulators”, *Phys. Rev. Lett.*, vol. 127, no. 156401, October 2021.
[8] J. Lu, W. Deng, X. Huang, M. Ke and Z. Liu, “Non-Hermitian topological phononic metamaterials”, *Adv. Mater.*, no. 2307998, December 2023.
[9] B. Hu, Z. Zhang, H. Zhang, L. Zheng, W. Xiong, Z. Yue, X. Wang, J. Xu, Y. Cheng, X. Liu and J. Christensen, “Non-Hermitian topological whispering gallery”, *Nature*, vol. 597, pp. 655-659, September 2021.

[10] Z.-K. Lin, Q. Wang, Y. Liu, H. Xue, Y. Chong and J.-H. Jiang, “Topological phenomena at defects in acoustic, photonic and solid-state lattices”, *Nat. Rev. Phys.*, vol. 5, pp. 483–495, July 2023.
[11] H. He, C. Qiu, L. Ye, X. Cai, X. Fan, M. Ke, F. Zhang and Z. Liu, “Topological negative refraction of surface acoustic waves in a Weyl phononic crystal”, *Nature*, vol. 560, pp. 61-64, August 2018.
[12] M. Yan, J. Lu, F. Li, W. Deng, X. Huang, J. Ma, and Z. Liu, “On-chip valley topological materials for elastic wave manipulation”, *Nat. Mater.*, vol. 17, pp. 993-998, October 2018.
[13] Z. Zhang, Y. Tian, Y. Wang, S. Gao, Y. Cheng, X. Liu and J. Christensen, “Directional acoustic antennas based on valley-Hall topological insulators”, *Adv. Mater.*, vol. 30, no. 1803229, September 2018.
[14] F. Zangeneh-Nejad and R. Fleury, “Topological analog signal processing”, *Nat. Commun.*, vol. 10, no. 2058, May 2019.
[15] Z. Zhang, P. Gao, W. Liu, Z. Yue, Y. Cheng, X. Liu and J. Christensen, “Structured sonic tube with carbon nanotube-like topological edge states”, *Nat. Commun.*, vol. 13, no. 5096, August 2022.
[16] D. Liao, J. Zhang, S. Wang, Z. Zhang, A. Cortijo, M. A. H. Vozmediano, F. Guinea, Y. Cheng, X. Liu and J. Christensen, “Visualizing the topological pentagon states of a giant C_{540} metamaterial”, *Nat. Commun.*, vol. 15, no. 9644, November 2024.
[17] A. Rodriguez, K. Papatryfonos, E. R. Cardozo de Oliveira and N. D. Lanzillotti-Kimura, “Topological nanophononic interface states using high-order bandgaps in the one-dimensional Su-Schrieffer-Heeger model”, *Phys. Rev. B*, vol. 108, no. 205301, November 2023.

8. Programmable metamaterials to realize non-Hermitian and time-varying properties

Xinhua Wen, Jensen Li,

The Hong Kong University of Science and Technology

Status

While metamaterials initially emerged for electromagnetic waves, acoustic metamaterials have played a pivotal role, not only in translating phenomena from the electromagnetic to the acoustic domain but also in providing a unique platform to implement various acoustic constitutive relations. Currently, gain-loss contrast and temporal modulation are being incorporated as new dimensions of metamaterials to explore more counter-intuitive phenomena. Gain-loss ~~contrast~~ enables the emergence of the so-called non-Hermitian exceptional point, capturing degeneracy for both eigenvalues and eigenvectors of a response matrix function, such as the effective Hamiltonian or the scattering matrix of the system. These exceptional points can then be leveraged for achieving ultrasensitive sensing, absorption, and other tunable properties [1]. Temporal modulation or variation of the constitutive parameters allows for a range of exotic phenomena, such as parametric amplification and band-gap formation in the reciprocal space [2].

To implement these new dimensions of constitutive parameters, various approaches have been employed, including the addition of absorption sponge or holey structures, external mechanical driving, feedback electronics, to resonating metamaterial structures like Helmholtz resonators. These methods aim to introduce additional loss, time-varying resonating parameters, and adjust the tunable size of the response, respectively [3-5]. Moving forward, these techniques hold the potential to enable comprehensive control over all elements of the constitutive parameters. In the case of sound waves, the constitutive matrix is represented as a 2×2 matrix, with compressibility ($\boldsymbol{\beta}$) and density ($\boldsymbol{\rho}$) as the diagonal elements and two Willis coupling (labelled $\boldsymbol{\gamma}$, $\boldsymbol{\gamma}'$) as the off-diagonal elements. We seek flexible approaches to introduce imaginary parts to the diagonal elements as non-Hermitian parameters, assign non-zero and independent values to the off-diagonal elements, and allow for temporal variation in these parameters. A full control over the constitutive matrix can lead to the development of a versatile acoustic metamaterial blueprint capable of realizing both fundamental physics and practical applications.

Current and Future Challenges

One of the current challenges in achieving active acoustic metamaterials is establishing feasible and precisely controlled methods for introducing material gain parameters. Without such parameters, acoustic metamaterials remain passive in nature. While passive metamaterials, potentially incorporating absorptive elements [5], can still exhibit non-Hermitian exceptional points, they lack the ability to govern wave or signal amplification. Additionally, research indicates that the size of the Willis coupling must be constrained by the passivity of the system [3]. Incorporating gain through electronic feedback [4] presents a viable solution, but caution must be exercised to ensure the stability of these metamaterials, adhering to the bounded-input-bounded-output criterion. Concerning the response function of the metamaterial in the complex frequency plane, it is imperative that all system poles reside below the real frequency axis to maintain stability. Is it feasible to develop a tunable implementation allowing for adjustment of the location of system poles on-site? This capability is particularly crucial when employing electronic feedback, as the response functions of certain components may only become apparent after the metamaterial is assembled.

On the other hand, there remains nontrivial in implementing time-varying properties across all four constitutive matrix elements. Ideally, such time-varying properties should offer flexibility for on-site adjustments as well. Moreover, many intriguing wave phenomena, such as the band gap in reciprocal space [2] necessitate rapid modulation of the constitutive parameters. While achieving this can pose challenges in the electromagnetic domain, the acoustic domain presents a promising avenue, given its extensive history of using digital signal processors for speech signal processing. Leveraging similar techniques could facilitate the transformation of scattering responses and the introduction of time-varying capabilities of metamaterials. Consequently, these methods may unlock opportunities to control non-reciprocal propagation, amplification, and frequency conversion [6,7]. It is also worth to note that when desiring a specific constitutive parameter to vary over time, such as with a step function, the response may not be immediate, but with a response time. Will a frequency non-dispersive model of the constitutive parameters, represented simply as β(t) for the case of compressibility, always be adequate in a real experiment?

Advances in Science and Technology to Meet Challenge

In response to these challenges, programmable metamaterials with feed-back digital control offers a valuable platform for achieving controllable non-Hermitian and time-varying constitutive parameters. Figure 1 depicts such a platform for 1D wave propagation using digital approach. Within a waveguide, there exists an array of meta-atoms, each comprising two microphones interconnected to two speakers through a microcontroller. The local fields are detected (from microphones) and are time-convoluted with four kernels (Y_{ij}) by a program in the microcontroller, outputting the results to the speakers [8]. It defines an arbitrary scattering response in either monopolar or dipolar channels, thereby giving rise to a 2×2 constitutive matrix designed at a specific frequency. In this manner, we can flexibly mimic any physical metamaterial resonating response.

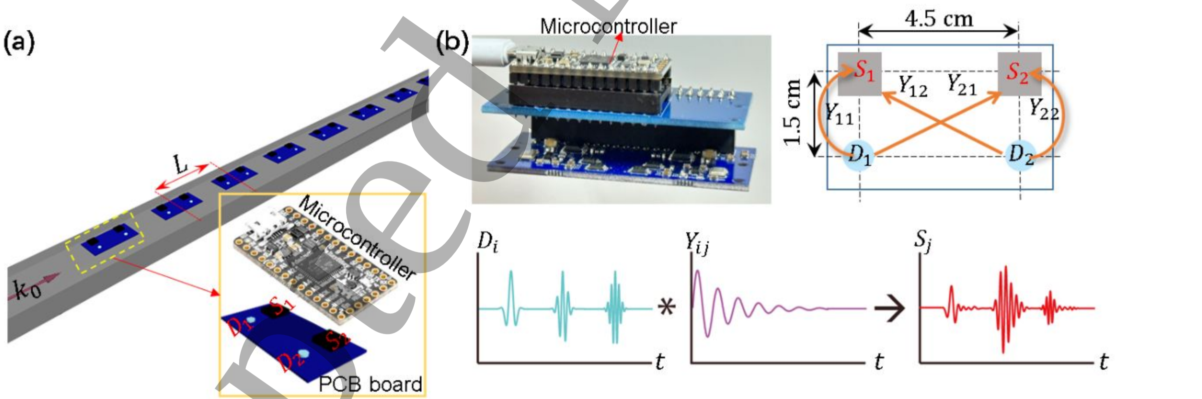


Figure 1 Programmable approach towards full control of acoustic constative matrix for 1D propagation. (a) The virtualized meta-atoms in mimicking physical resonating structures, comprising speakers and microphones interconnected to a microcontroller at each meta-atom. (b) Four convolutional kernels (Y_{ij}) in connecting two microphones (D_1, D_2) and two speakers (S_1, S_2) to generate monopolar and dipolar atomic response, resulting a programmable 2×2 constitutive matrix of the metamaterial $\{\{\beta,\gamma\},\{\gamma',\rho\}\}$.

Figure 2(a) illustrates the scenario where the time-convolution kernel Y_{11}/Y_{22} consists of a sinusoidal function (with decay linewidth) of only one resonating frequency, implementing either a Lorentzian response in β/ρ, which can be made passive (positive imaginary part) or active (negative imaginary part) around resonating frequency. In addition, the metamaterial can also implement Willis coupling using Y_{12}/Y_{21}, surpassing the passivity bound [9], as depicted in Fig. 2(b). Given the ability to independently control all parameters, including β, ρ, and Willis coupling, programmable metamaterials can be readily used to achieve unusual scattering properties, such as invisible sensing [10], coherent perfect absorption [11]. For time-varying properties, we can begin with a defined Lorentzian response in β and modulate it on and off with a duty cycle of η. The resultant effective $\boldsymbol{\beta}$ (real part) are shown for three different cases of η in Fig. 2(c), with a high modulation frequency [12]. The programmable metamaterial, offering flexible control over temporal modulation parameters, provides a versatile platform for advanced dispersion engineering beyond the conventional approaches [2,13]. The initial attempts at controlling individual constitutive matrix elements lead to further control over the entire constitutive matrix, such as achieving larger bandwidth by incorporating more resonances, or advancing the 1D propagation control to higher dimensions, which allows for studying non-Hermitian topology [14]. Further investigations into the effect of power saturation and effective nonlinearity are possible when raising the power of the incident wave.

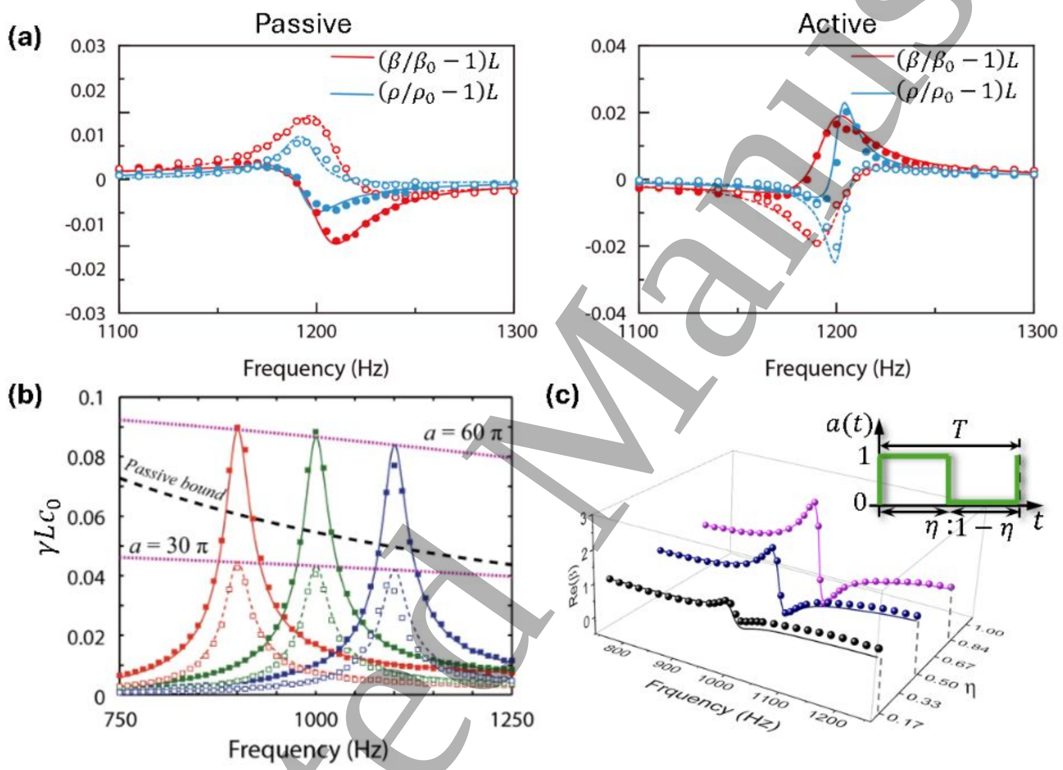


Figure 2 Programmable constitutive parameters. (a) passive and active Lorentzian resonance on β and ρ with solid/hollow symbols showing real and imaginary parts [9] (b) Willis coupling γ beyond passivity bound (dashed line) with stable response for 3 different target resonating frequencies [10] (c) Temporal effective compressibility by switching on and off of a frequency dispersion response with temporal duty cycle $\eta = 0.17, 0.5, 0.84$ [11]

Concluding Remarks

Using programmable acoustic metamaterials, the material response can be precisely defined, enabling the construction of arbitrary constitutive matrices for acoustic waves, encompassing compressibility, density, and Willis coupling parameters. These parameters can span both the active and time-varying regimes. In the future, this flexible control over the entire constitutive matrix may facilitate applications in non-reciprocal propagation, communications, and sensing. Moreover, we can explore fundamental concepts, including those in non-Hermitian topology, utilizing the programmable platform, while the necessity of the promotion to higher spatial dimensions and nonlinearity awaits further exploration. Particularly, the programmable platform offers the capability to precisely control non-Hermiticity in the time domain, promising advancements in the exploration of temporal PT symmetry for extreme energy manipulation.

References

[1] Huang L et.al., 2023 Acoustic resonances in non-Hermitian open systems *Nature Rev. Phys*. **6** 11-27
[2] Trainiti, G., Xia, Y., Marconi, J., Cazzulani, G., Erturk, A., & Ruzzene, M. 2019 Time-periodic stiffness modulation in elastic metamaterials for selective wave filtering: Theory and experiment. *Phys. Rev. Lett.*, **122** 124301
[3] Popa, B. I., & Cummer, S. A. 2014 Non-reciprocal and highly nonlinear active acoustic metamaterials. *Nat. Commun.* **5** 3398.
[4] Liu, T., Zhu, X., Chen, F., Liang, S., & Zhu, J. 2018 Unidirectional wave vector manipulation in two-dimensional space with an all passive acoustic parity-time-symmetric metamaterials crystal. *Phys. Rev. Lett.* **120** 124502.
[5] Shen, C., Zhu, X., Li, J., & Cummer, S. A. 2019 Nonreciprocal acoustic transmission in space-time modulated coupled resonators. *Phys. Rev. B*, **100** 054302.
[6] Wen, X., Yip, H. K., Cho, C., Li, J., & Park, N. 2023 Acoustic Amplifying Diode Using Nonreciprocal Willis Coupling. *Phys. Rev. Lett.* **130** 176101.
[7] Wen, X., Zhu, X., Fan, A., Tam, W. Y., Zhu, J., Wu, H. W., Lemoult, F., Fink, M. & Li, J. 2022 Unidirectional amplification with acoustic non-Hermitian space-time varying metamaterial. *Commun. Phys.* **5** 18.
[8] Cho, C., Wen, X., Park, N., & Li, J. 2020 Digitally virtualized atoms for acoustic metamaterials. *Nat. Commun.* **11** 251.
[9] Cho, C., Wen, X., Park, N., & Li, J. 2021 Acoustic Willis meta-atom beyond the bounds of passivity and reciprocity. *Commun. Phys*., **4** 82.
[10] Fleury, R., Sounas, D., & Alu, A. 2015 An invisible acoustic sensor based on parity-time symmetry. *Nat. Commun.* **6**, 5905.
[11] Gu, Z., Liu, T., Gao, H., Liang, S., An, S., & Zhu, J. 2021 Acoustic coherent perfect absorber and laser modes via the non-Hermitian dopant in the zero index metamaterials. *J. Appl. Phys.* **129**, 234901.
[12] Wen, X., Zhu, X., Wu, H. W., & Li, J. 2021 Realizing spatiotemporal effective media for acoustic metamaterials. *Phys. Rev. B*, **104** L060304.
[13] Solís, D. M., Kastner, R., & Engheta, N. 2021 Time-varying materials in the presence of dispersion: plane-wave propagation in a Lorentzian medium with temporal discontinuity. *Photonics Res.* **9**, 1842.
[14] Cheng, W., & Hu, G. 2022 Acoustic skin effect with non-reciprocal Willis materials. *Appl. Phys. Lett.* **121** 041701.

9. Nonreciprocal and nonlinear acoustic metamaterials

Romain Fleury[1], Samuel P. Wallen[2,3], Michael R. Haberman[2,3]

1. Laboratory of Wave Engineering, EPFL, 1015 Lausanne, Switzerland

2. Applied Research Laboratories, The University of Texas at Austin, Austin, TX, USA

3. Walker Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA

Status

The propagation of pressure fluctuations in conventional acoustic media typically obeys the general principle of reciprocity, which refers to the symmetry of sound transmission between two points A and B; namely, $T_{AB} = T_{BA}$, where T_{IJ} represents the transmission coefficient between field points *I* and *J*. Reciprocity is rooted in a principle called microscopic reversibility, initially described by Casimir and Onsager, which holds in general linear time-invariant media [1]. Breaking this property in metamaterials allows for unidirectional transfer of acoustic energy, which may open fascinating new opportunities in noise control, energy harvesting, imaging technologies, and sensors. The centre of Fig. 1a represents such a non-reciprocal situation where $T_{AB} \gg T_{BA}$, a property that is not possible to achieve even if the properties of the medium are strongly inhomogeneous, asymmetric, or absorptive. Instead, one must carefully break spatial and temporal symmetries through the introduction of momentum bias, time-dependence, or nonlinearity to achieve nonreciprocal propagation [1, 2]. Figure 1a represents various means by which reciprocity has been broken in engineered media.

Nonlinearity in acoustic and elastic media has a long and rich history in physical acoustics in addition to its use in enabling strongly nonreciprocal propagation [3]. Acoustic propagation beyond the weak signal regime is generally nonlinear; describing sound propagation as a linear process is always an idealisation of the actual continuum dynamics involved, which break down quickly at high excitation levels. Therefore, nonlinear acoustics has traditionally been an important subfield in acoustics, with numerous practical applications including drug delivery, therapeutic ultrasound, harmonic imaging, damage detection, and devices such as the parametric array [3]. The field has, however, been rejuvenated by the advent of metamaterials and architected media, in which the geometry and material distribution have been designed to enable nonreciprocal wave phenomena, generate solitons, elicit on-demand domain reconfigurability, mitigate impacts, and tailor waveforms [4, 5]. Some relevant nonlinear phenomena are highlighted in Fig. 1b. Extensive reviews of historical and current research in this area can be found in several detailed reviews of nonlinear metamaterials and additional applications [4, 5].

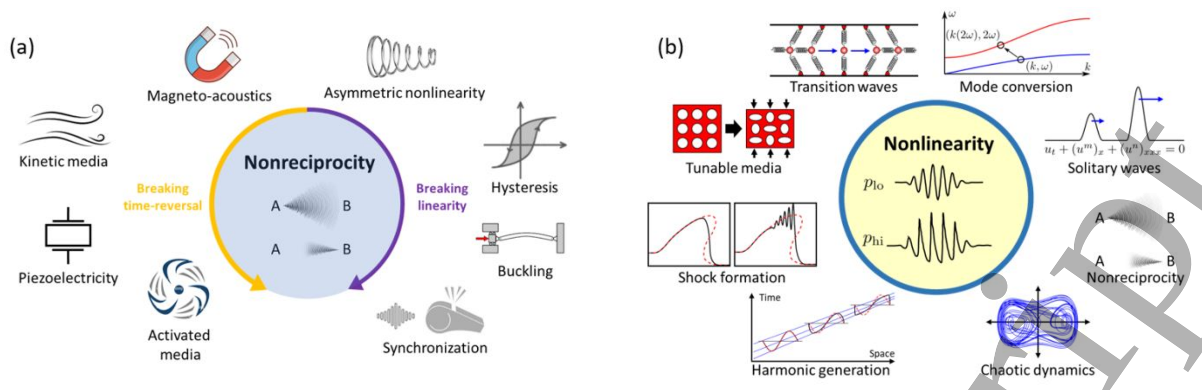


Figure 1. (a) Nonreciprocal propagation is indicated by differences in magnitude and phase of a transmitted signal between points *A* and *B* source and receiver are exchanged. Physical mechanisms that lead to nonreciprocal acoustic wave propagation. The left part of the figure focuses on schemes that leverage a breaking of time-reversal and time-invariance, whereas the right part highlights the important role of nonlinearities. (b) Nonlinearity in metamaterial systems is achieved by designing subwavelength nonlinear deformation in architected media and/or exploiting locally resonant structures created from constituents with material nonlinearity. The figure indicates different nonlinear phenomena demonstrated with nonlinear acoustic and elastic metamaterials.

Current and Future Challenges

Prior research has shown that nonreciprocal wave propagation in metamaterials is possible by exploiting several different mechanisms. Without breaking linearity or time-invariance, one needs to bias the medium with a time-odd external quantity. Examples include magnetostrictive effects to polarize the medium to exploit magneto-acoustic coupling. Unfortunately, time-invariant coupled-domain effects in conventional materials are often weak or restricted to exotic solid-state crystals. Nonreciprocal behaviour in linear kinetic media, which employ fluid flow or rotation, is a better option particularly in fluids [2]. Breaking time invariance by varying electrical boundary conditions of piezoelectric materials or magnetic actuators can introduce nonreciprocal wave propagation while maintaining linearity, although it alters the frequency content of the signals [1, 6, 7]. All these effects, however, are usually weak and are therefore only appreciable over large propagation distances or when combined with resonances, which make them bandwidth-limited and prone to losses. The use of nonlinearity, on the other hand, is a rich yet largely uncharted opportunity to overcome these drawbacks. Combining nonlinearity with geometrical asymmetries allows the creation of systems having a direction-dependent response, thereby strongly breaking reciprocity [1, 8, 9]. In addition, synchronization between waves and limit cycles, such as those generated by aeroacoustic instabilities or parametric amplification, is an active area of investigation as a promising means to extract energy from an external bias to compensate losses and enhance the bandwidth of nonreciprocal behaviour [10].

Research in nonlinear acoustic and elastic metamaterials has an established history of leveraging subwavelength geometric features to achieve effective material nonlinearity that is significantly stronger than most naturally-occurring materials. For example, buckling instabilities can change the effective modulus and even reconfigure the medium depending on the local field amplitude [4, 5]. Essential nonlinearity (i.e., vanishing linear restoring force at small amplitudes) has been achieved, e.g., using contact mechanics [11] and elastic strings with no static pre-tension [12]. Recently, large local rotation has been leveraged to achieve strong hybridization between translational and rotational motion [13] and unit cells with chaotic dynamics enabled by magnetic interactions to create ultra-low frequency and ultra-broad bandgaps [14]. Despite the plethora of rich nonlinear dynamics that has been demonstrated in prior works, some notable challenges remain. For example, theoretical prediction of nonlinear dynamics typically relies on low-order systems of differential equations capturing essential features of a system, which are especially difficult to obtain for intricate lattice geometries in two and three dimensions. Additionally, due to the need for recoverable deformation, works involving large local strains have generally been restricted to hyperelastic polymers, which have low stiffness and may exhibit significant relaxation. Furthermore, few works on nonlinear acoustic metamaterials have thoroughly treated irreversible effects, such as viscous relaxation, plasticity, and friction.

Advances in Science and Technology to Meet Challenges

Despite these promising behaviours and applications, significant challenges remain in the creation of nonreciprocal and nonlinear metamaterials. Prominent examples include the fabrication of large amounts of material containing small-scale structure, multi-material fabrication (particularly stiff and compliant materials bonded together), and transduction materials. Transduction materials, such as piezoelectric or opto-mechanically coupled materials, are the most likely candidates to realize activated materials to achieve spatiotemporal modulation, non-trivial topological materials, and non-Hermitian materials. Similarly, the creation of materials whose properties can change when subjected to external stimuli are of significant interest to tailor nonreciprocal and nonlinear wave propagation and only limited progress has been made in the realization of these materials. The creation of nonlinear media is hampered by the need to undergo large, recoverable deformations. When damage such as plastic deformation is unavoidable, models must be developed to account for changes in the subsequent linear and nonlinear dynamic behaviour, e.g., by incorporating loading history via internal variables. To address these challenges, metamaterial researchers must interact with the advanced manufacturing community, particularly those creating new additive manufacturing processes, to fabricate transduction materials with customizable properties and geometry, as well as materials that can undergo large, recoverable deformations without significant degradation to their performance. In addition, researchers should extend existing continuum and discrete-element material models to consider history-dependent effects, such as elasto-plasticity, in order to assess the influence of damage on nonlinear wave propagation and the efficacy of nonlinear materials for achieving their intended performance. Data-driven methods, such as machine learning-enhanced topology design and physics-informed neural networks, comprise an active area of investigation with ever-increasing relevance to engineered acoustic materials and may play an integral role in achieving these objectives.

Concluding Remarks

Nonreciprocal propagation in acoustic media has been studied extensively for over a decade. We anticipate that future research will make use of knowledge gained to create new technology enabled by nonreciprocal wave transport, such as devices capable of simultaneous transmit and receive operations or sensing acoustic signals without being detected. Creating nonlinear materials for the purpose of breaking reciprocity or other applications, such as frequency conversion, tunability, and reconfiguration, is a very active and promising field of research. We expect that many new physical phenomena and functionalities will be discovered at the intersection between the fields of architected media, nonlinear systems, and nonreciprocal wave propagation.

Acknowledgements

M.R.H. and S.P.W. acknowledge funding from The Office of Naval Research Award N00014-23-1-2660 and US DOE Kansas City National Security Campus Award DE-NA0002839. R.F. acknowledges funding from the Eccellenza award 181232 of the Swiss National Science Foundation.

References

[1] H. Nassar, B. Yousefzadeh, R. Fleury, M. Ruzzene, A. Alù, C. Daraio, A. Norris, G. Huang and M. Haberman, “Nonreciprocity in acoustic and elastic materials,” Nature Reviews Materials, vol. 5, pp. 667-685, 2020.

[2] R. Fleury, D. Sounas, C. Sieck, M. Haberman and A. Alù, “Sound isolation and giant linear nonreciprocity in a compact acoustic circulator,” Science, vol. 343, no. 6170, pp. 516-519, 2014.

[3] M. Hamilton and D. Blackstock, Nonlinear Acoustics, Melville, NY: Acoustical Society of America, 2008.

[4] D. Kochmann and K. Bertoldi, “Exploiting Microstructural Instabilities in Solids and Structures: From Metamaterials to Structural Transitions,” Applied Mechanics Reviews, vol. 050801, p. 69, 2017.

[5] G. Patel, Matlack and K.H., “Review of exploiting nonlinearity in phononic materials to enable nonlinear wave responses,” Acta Mechanica, vol. 233, no. 1, pp. 1-46, 2023.

[6] G. Trainiti and M. Ruzzene, “Non-reciprocal elastic wave propagation in spatiotemporal periodic structures,” New Journal of Physics, vol. 18, no. 8, p. 083047, 2016.

[7] Y. Chen, X. Li, H. Nassar, A. Norris, C. Daraio and G. Huang, “Nonreciprocal wave propagation in a continuum-based metamaterial with space-time modulated resonators,” Physical Review Applied, vol. 11, no. 6, p. 064052, 2019.

[8] A. Blanchard, T. Sapsis and A. Vakakis, “Non-reciprocity in nonlinear elastodynamics,” The Journal of Sound and Vibration, vol. 412, pp. 326--335, 2019.

[9] C. Coulais, D. Sounas and A. Alù, “Static non-reciprocity in mechanical metamaterials,” Nature, vol. 542, no. 7642, pp. 461-464, 2017.

[10] T. Pedergnana, A. Faure-Beaulieu, R. Fleury and N. Noiray, “Synchronization-based lossless non-reciprocal scattering,” arXiv, p. 2403.06161, 2024.

[11] C. Chong and P. G. Kevrekidis, Coherent structures in granular crystals: From experiment and modelling to computation and mathematical analysis, Springer, 2018.

[12] D. M. McFarland, L. A. Bergman and A. F. Vakakis, “Experimental study of non-linear energy pumping occurring at a single fast frequency,” International Journal of Non-Linear Mechanics, vol. 40, no. 6, pp. 891-899, 2005.

[13] B. Deng, J. R. Raney, K. Bertoldi and V. Tournat, “Nonlinear waves in flexible mechanical metamaterials,” Journal of Applied Physics, vol. 130, no. 4, 2021.

[14] X. Fang, J. Wen, B. Bonello, J. Yin and D. Yu, “Ultra-low and ultra-broad-band nonlinear acoustic metamaterials,” Nature Communications, vol. 8, no. 1288, 2017.

AMMs for flow

10. Metasurfaces for applications in low Mach number turbulent flow

Timothy A. Starkey*, Charles Galluscio†, Shishir Damani†, William N. Alexander†, and William J. Devenport†

*Centre for Metamaterial Research and Innovation, University of Exeter, United Kingdom

†Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech, United States of America

Status

Metamaterials offer a route to engineer new materials with advanced functionality for a range of applications. Recent work has looked to leverage metamaterial concepts to find opportunities at the apex between the fields of acoustics metamaterials and aeroacoustics in low Mach number turbulent flow.

In each field structured surfaces have been designed for specific modalities; in the field of acoustic metamaterials, or more specifically metasurfaces, typically a surface is structured using a periodic lattice of resonant elements to exhibit some effective properties or functionality achieved by tuning the local acoustic fields at the surface for control airborne sound [1]. From the metamaterial perspective, often structures seek to control acoustic waves using subwavelength elements. The physics is usually explored and described by the dispersion relation, which essentially describes the relationship between the frequency of a wave, and its wavenumber; providing information about the direction, phase, and group velocity of the propagating mode.

In the field of aeroacoustics of turbulent flows, structured fetches that sit above a rigid boundary, have been utilised to both control the acoustic radiation and aerodynamic efficiency. From the flow perspective, when a turbulent flow moves past a rigid wall, there are structures within the boundary layer, that are transported downstream, i.e. along the flow direction, with pressure fluctuations that present a well-defined pressure spectrum at the wall [2], with its own dispersion relation. Various surface topologies have been developed to mitigate the effects of these surfaces on the flow using surface treatments, including ordered roughness fetches, bioinspired canopy structures, and porous surfaces [3].

The proposition here is the following: in both fields surface structures are used to influence the local behaviour of some field (pressure, velocity, displacement etc), and therefore can this commonality be harnessed for useful applications? Our recent work brings these fields together by demonstrating experimentally that acoustic modes on periodic-structured surfaces can be driven by pressure fluctuations from a turbulent source [4]. The follow-on question is how else might this be leveraged, particularly for aviation or maritime applications.

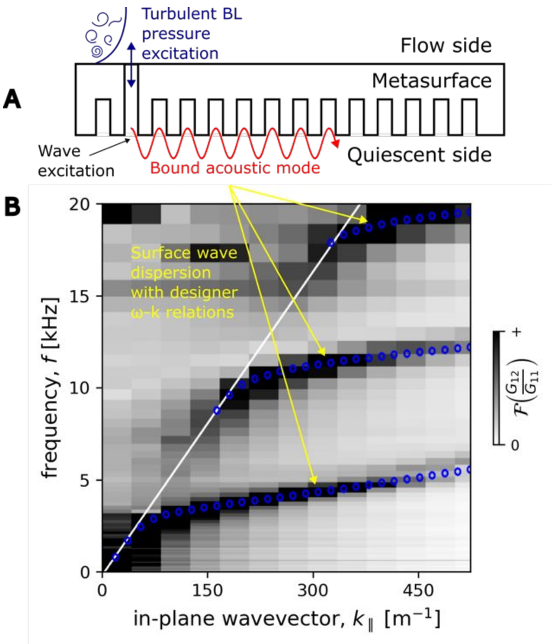


Figure 1. Example of a flow-driven metasurface; (a) schematic of metasurface interfaced with turbulent flow, and (b) the measured dispersion relation.

Current and Future Challenges

Turbulent flows present ongoing difficulties within aeroacoustic and hydroacoustic communities. The following scenarios highlight potential applications of metamaterials:

1. *Flow Noise Generation*: Turbulence in fluid flow results in fluctuating pressure fields, causing noise production. Utilizing targeted metamaterials, such as at a trailing edge, could filter or average turbulent structures, thereby reducing radiated noise or specific spectral tones.

2. *Sensor Dynamic Range and Sensitivity*: Acoustic sensors near turbulent noise sources often suffer from poor signal-to-noise ratios. Tailoring the acoustic environment to enhance sensor performance in challenging conditions is a potential solution.

3. *Energy Harvesting/Attenuation*: Managing energy within a flow through metamaterial interfaces offers an efficient way to convert and dissipate energy associated with flow-induced noise without compromising aerodynamics or hydrodynamics.

4. *Aero- and Hydro-acoustic Coupling*: Understanding the intricate interactions between aerodynamics and acoustics at the boundary layer is a long- standing research area. Employing tailored metamaterial surfaces to alter flow conditions and influence noise production, and vice versa, could be a route to comprehend coupling mechanisms in terms of surface impedance.

In addition to these challenges, technological advancements could drive the development of multifunctional surfaces. An example is autonomous vehicles, where future unmanned underwater vehicles must be lightweight, energy-efficient, and compact. These constraints prompt modifications in on-board sonar systems to reduce sensors and processing while maintaining acceptable performance levels. Flow-coupled acoustic metasurfaces may offer more passive solutions compared to traditional, highly intensive beamforming. Figure 2 shows a conceptual example for a passive beamforming readout.

Advances in Science and Technology to Meet Challenges

Motivated by these challenges, studies have examined how metasurfaces can be coupled with a turbulent boundary layer. Damani *et al.*, reports the flow-driven generation of trapped acoustic surface waves [4] excited by coupling pressure fluctuations at the interface between a flow environment and an acoustic metamaterial [5]. Figure 1 depicts a schematic of the experiment and measured data; which shows sub-sonic modes of the metasurface have been excited and detected. A key observation is that the resonator-based flow metasurface filters out fluctuations on scales less than the interface size, and thus the excitation can be tailored to larger turbulence scales, suggesting possible applications in aeroacoustic noise control.

A subsequent study examines the nature of flow coupling to a resonant cavity. It was shown that a Kevlar-covered acoustic resonator can behave as a surface-averaging pressure sensor, i.e. spatially averaging pressure fluctuation in the flow, with minimal impact to the flow field [6]. This finding inspired new embedded sensors that measure the sub- convective wavenumber-frequency pressure spectrum in boundary layer flows [7], and could improve wall pressure measurements for use in wall pressure models used as forcing functions for structural analysis.

Building on this, research has progressed toward designing flow driven metasurfaces for sensing acoustic sources beyond the boundary layer. Figure 2 depicts the challenge being addressed. The approach couples a meander-like metasurface [8] to the flow environment above via multiple coupling channels. The metasurface can both be excited by acoustic fields incident in the far-field and be driven by the turbulent flow; this sensing principle relies on incident acoustic radiation producing coherent excitation to the metasurface, while excitation of flow induced near-field pressure fluctuations, contributing incoherent signals that average to zero. The multiple through holes can be used to constructively couple acoustic surface waves [9] propagating from individual through cavities to excite a metasurface that encodes a unique relationship between the source location and the excited acoustic surface waves [10]. This study may be exploited to reduce the weight, power consumption, and processing required of conventional beamforming arrays in flow. This type of sensor scheme is now being tested in more channelling flow and signal-to-noise conditions [11].

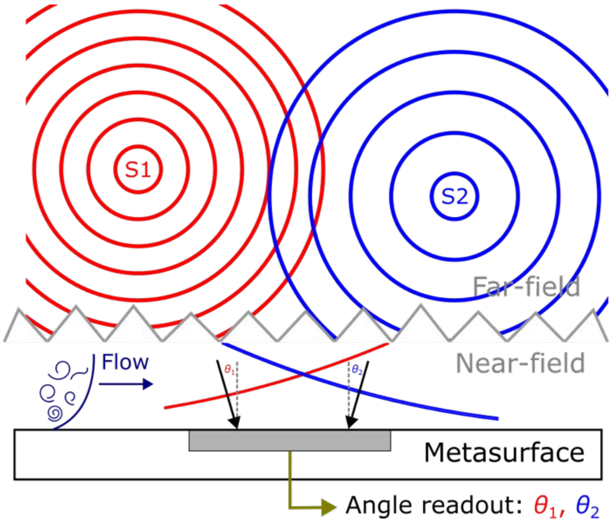


Figure 2. One example application of flow-coupled metasurfaces: detection of multiple sources beyond the boundary layers

Concluding Remarks

Research into turbulence-driven metamaterials is in its infancy. We have presented work demonstrating that a turbulent flow can be used to excite acoustic surface modes, and that this result can be exploited to create sensors based on upon resonant cavities or metasurface arrays for application in a low Mach number turbulent flow.

The studies described above are an illustration of low technology readiness level research in this flow- driven metamaterial research space that may advance ideas in already mature technologies to meet current and future challenges. The studies presented in this area on the interaction of subsonic flow ($M < 0.3$) and metasurfaces in air with a range of Reynolds numbers. We believe that there are opportunities to develop flow-driven metasurfaces for a range of applications in aero- and hydro-acoustics beyond the few concepts described.

Acknowledgements

The authors wish to acknowledge financial support of Defence Science and Technology Laboratory (Dstl) and the Office of Naval Research (ONR).

References

[1] B. Assouar, B. Liang, Y. Wu, Y. Li, J.-C. Cheng, and Y. Jing, “Acoustic metasurfaces,” *Nat. Rev. Mater.*, vol. 3, no. 12, pp. 460–472, 2018, doi: 10.1038/s41578-018-0061-4.

[2] S. Glegg and W. Devenport *Aeroacoustics of Low Mach Number Flows*, 2nd ed., Elsevier Inc., 2023.

[3] M. R. Raupach, R. A. Antonia, and S. Rajagopalan, “Rough-Wall Turbulent Boundary Layers,” Appl. Mech. Rev., vol. 44, no. 1, pp. 1–25, 1991, doi: 10.1115/1.3119492.

[4] T.A Starkey and G.P. Ward, 2024 Acoustic Surface Waves on Metasurfaces in Acoustic Metamaterials: Absorption, Clocking, Imaging, Time-Modulated Media, and Topological

Crystals ed Craster R., Guenneau S. (Springer) chap 14, pp 373-400 2nd ed ISBN 9783031600159

[5] S. Damani et al., "Excitation of Airborne Acoustic Surface Modes Driven by a Turbulent Flow," AIAA J., vol. 59, no. 12, pp. 5011–5019, 2021, doi: 10.2514/1.J060662.

[6] S. Damani et al., "Resonator-based Pressure Sensor for Wall Pressure," in 28th AIAA/CEAS Aeroacoustics 2022 Conference, American Institute of Aeronautics and Astronautics, 2022, doi:10.2514/6.2022-2956.

[7] H. Butt et al., "Pressure Gradient Effects on Low-Wavenumber Wall-Pressure Fluctuations in Turbulent Boundary Layer Flows," in 28th AIAA/CEAS Aeroacoustics 2022 Conference, American Institute of Aeronautics and Astronautics, 2022, doi:10.2514/6.2022-2803.

[8] J. G. Beadle, I. R. Hooper, J. R. Sambles, and A. P. Hibbins, "Broadband, slow sound on a glide-symmetric meander-channel surface," *J Acoust. Soc. Am.*, vol. 145, no. 5, pp. 3190–3194, 2019, doi: 10.1121/1.5109549.

[9] J. Lu, C. Qiu, M. Ke, and Z. Liu, "Directional excitation of the designer surface acoustic waves," Appl. Phys. Lett., vol. 106, no. 20, 2015, doi: 10.1063/1.4921397.

[10] E. Braaten et al., "Directionally Sensitive Sensor Based on Acoustic Metamaterials," in AIAA AVIATION 2023 Forum, American Institute of Aeronautics and Astronautics, 2023, doi:10.2514/6.2023-3828.

[11] C Galluscio, et al., "Wind Tunnel Testing of the Directionally Sensitive Meander Metasurface Array", 30th AIAA/CEAS Aeroacoustics Conference, AIAA 2024-3025, 2024, doi:10.2514/6.2024-3025

11. Phononic subsurfaces: Crystals and metamaterials for flow control

Mahmoud I. Hussein, University of Colorado Boulder, USA

Status

The advent of phononic crystals [1] and acoustic/elastic metamaterials [2] has ushered a new era in the fields of vibrations and acoustics as it allowed for dynamical properties to be analysed and designed intrinsically at the material (i.e., unit-cell) level, as opposed to only the finite structural level as done traditionally. Moreover, the interplay between these two levels in itself has expanded the design space even further allowing resonances associated with structural truncation to emerge with characteristics influenced not only by the nature of the truncation and the boundary conditions but by the material unit-cell dispersion properties as well [3]. In 2015, flow control emerged as a new application that utilizes the properties of phononic materials and structures [4]. Referred to as a *phononic subsurface* (PSub), a finite-sized phononic structure is placed underneath an elastic surface exposed to a flow such as the surface of an aircraft wing, for example. With this concept, undesirable instabilities/fluctuations in a laminar or transitional boundary-layer flow could be passively and precisely controlled rather than be left to grow and ultimately trigger transition to turbulence [4-9]. The underlying mechanism of a PSub is destructive interference of elastic waves that ultimately leads to destructive interference of the interfacing flow fluctuation waves, causing them to acquire less kinetic energy from the underlying mean flow and decay within the vicinity of the control region (see Fig. 1) [6]. The opposite effect of flow destabilization may be induced as well, creating constructive interferences to delay flow separation rather than transition [4,6,8]. While still at its infancy, the field of phononic subsurfaces is experiencing rapid expansion as evidenced by the growing number of research groups exploring it and the recent award of two Department of Defence Multidisciplinary University Research Initiative (MURI) grants on the topic—in 2023 and 2024 considering the subsonic [10] and hypersonic [11] regimes, respectively [10]. Considering the elevated levels of skin-friction drag associated with early laminar-to-turbulence, and its negative impact on fuel efficiency, a successful deployment of PSubs in future aircrafts promises to bring about enormous economical and environmental benefits. In fact, such benefit would potentially also extend to land and sea vehicles, wind turbines, long-range pipelines, among other applications, bringing further benefits to society.

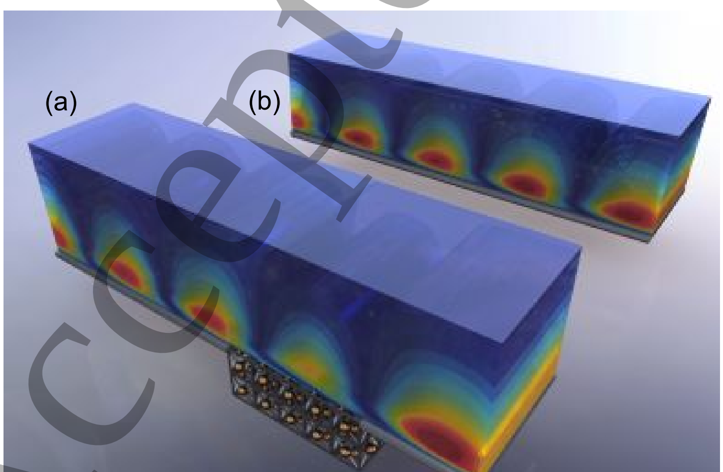


Figure 1. Demonstration of passive local flow stabilization by a PSub. Color contours represent the streamwise-component of a flow fluctuation velocity field in a channel when (a) a PnC-based PSub is installed versus (b) an all-rigid-wall surface. Yellow color represents low-fluctuation intensity, red color represents high-fluctuation intensity. The reduced color intensity adjacent to the location of the PSub indicates stabilization. Adapted from [4]

Current and Future Challenges

The research published on PSubs to date has established a new research discipline that promises to ignite the imagination of both the phononics and flow control communities well into the future [5-9]. Yet, numerous research issues and challenges remain ahead, from both the phononics and fluids dynamics perspectives. From the phononics side, when the general concept of PSubs was first introduced, there was an indication that any type of phononic structure may be used as long as certain design criteria are followed [4]. As a first demonstration, a finite phononic crystal [1] was utilized to form the PSub. While this has provided a valid proof-of-concept, it required a structure that is too long in length (on the order of 2 meters) to be viable for practical application considering the relatively low frequencies of instabilities in a flow (Hz-KHz). In Ref. [5], this limitation was addressed by employing a coiled phononic crystal structure, which reduced the total length significantly, although at the expense of requiring additional space in the lateral directions. A finite locally resonant elastic metamaterial was then demonstrated as a PSub in Refs. [6] and [8], where again the length issue was addressed, this time because metamaterials may be designed to operate in the subwavelength regime [2]. However, metamaterials on their part suffer from the disadvantage of operation at typically very narrow frequency bands. A key future goal, therefore, for research and development is to create PSub architectures that are capable of controlling flow fluctuations over a broad frequency range—this is critical because of the wide range of frequencies typically encountered in both air and water boundary-layer problems as well as the inherent uncertainty in predicting the specific frequencies under various flow conditions. Another important challenge is the ability to induce flow stabilization over a long spatial domain, as opposed to only a local region where a single PSub is installed as done in Refs. [4-6]. Utilization of multiple PSubs where each engenders local effects, but collectively extends the region of influence was proposed in Refs. [7,8]; however, as shown in Ref. [8] this approach brings rise to a trade-off between the strength of flow stabilization and the total length of region covered. The concept of a multi-input multi-output (MIMO) PSub was proposed as an alternative solution to achieving nonlocal, downstream flow control (see Fig. 2) [9]. This approach while was shown to effectively delay laminar-to-turbulent transition has some limitations such as restriction to a certain direction of propagation for the flow instability. The overall compliance of the PSub is another critical consideration. A PSub must be delicately designed to be compliance enough to enable sufficient interaction with the flow, yet sufficiently stiff to main structural shape and integrity. On the fluids side, research on effective utilization of PSubs for more advanced flow conditions, such as bypass transition, fully turbulent flows, unsteady flows, and high-speed flows (supersonic and hypersonic), among others, will play a key role in improving the effectiveness of PSubs and expanding the reach of the technology over a broader range of applications.

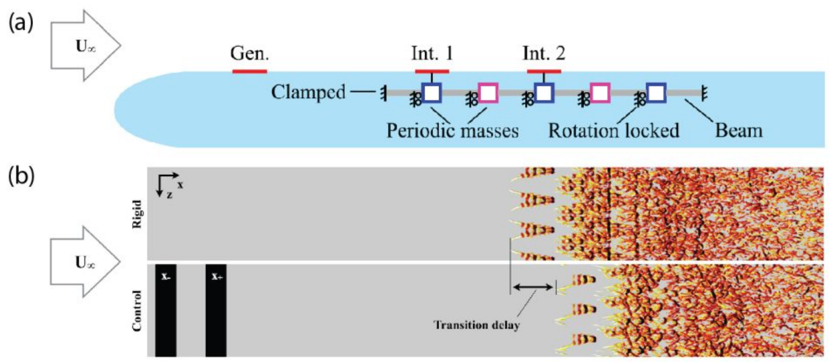


Figure 2. Demonstration of passive downstream flow stabilization by a MIMO PSub. (a) Schematic of PSub architecture. (b) Three-dimensional flow structure of case without MIMO PSub (top) and case with MIMO PSub (bottom). [9]

Advances in Science and Technology to Meet Challenges

Future research will target PSub employment that would allow for broad frequency and wavelength control, as well as an ability to effectively and efficiency influence multi-directional fluctuations in regions downstream to where the PSub(s) are installed. In addition, the elastic-fluid coupling will require optimization to ensure effective transfer of phase information between the solid and flow media, especially under realistic operational conditions. With all these challenges met, what will remain is further improvement of the strength of the PSub flow control effect, as well as its reliability under real-world flight or marine conditions. Recent and ongoing innovations in phononics research will be required to produce unit-cell and finite-structure configurations that meet these target performance metrics. Reduction of weight and manufacturing costs will naturally also be a factor for eventual success of this emerging technology. Recent advances in additive manufacturing and the growing transition to composite materials within both the aeronautical and marine vehicle industries offer a positive outlook.

Concluding Remarks

The concept of PSubs brings the field of elastic metamaterials and phononic materials in general to the heart of fluid dynamics, a major field in applied physics and engineering, with a promise to impact a vast array of applications ranging from aviation and ships, to water and oil/gas transport, to advanced industrial machinery. Given that it is a concept that is based on rigorous tuning of amplitude and phase, over target frequencies and wavelengths, it promises transformative performance improvements in these numerous industrial domains. Should PSubs reach its full potential, the economic and environmental benefits worldwide could potentially be measured in the billions of dollars. Similar to championed technologies that have impacted society over the last few decades, such as the transistor, the laser, the solar cell, and the Global Positioning System, PSubs will only reach its maximum potential with the collective effort of multidisciplinary research communities and the support of government agencies and industrial ventures.

Acknowledgements

The author acknowledges funding for research on phononic subsurfaces from the National Science Foundation, Air Force Office of Scientific Research, and Office of Naval Research. The author is grateful to his late colleague, Professor Sedat Biringen (1945–2020), for the research collaboration that led to the discovery of PSubs in 2015. The author also acknowledges former and current doctoral students A. Kucala, O.R. Bilal, A. Hsieh, A. Kianfar, and A. Harris, as well as collaborators A. Juhl and her team and D. Roca, for their contributions.

References

[1] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, "Acoustic band structure of periodic elastic composites," *Physical Review Letters*, vol. 71, no. 13, pp. 2022–2025, 1993.

[2] Z. Y. Liu, X. X. Zhang, Y. W. Mao, Y. Y. Zhu, Z. Y. Yang, C. T. Chan, and P. Sheng, "Locally resonant sonic materials," *Science*, vol. 289, no. 5485, pp. 1734–1736, 2000.

[3] M. Rosa, B. L. Davis, L. Liu, M. Ruzzene, and M. I. Hussein, "Material vs. structure: Topological origins of band-gap truncation resonances in periodic structures," *Physical Review Materials*, vol. 7, p. 124201, 2023.

[4] M. I. Hussein, S. Biringen, O. R. Bilal, and A. Kucala, "Flow stabilization by subsurface phonons," *Proceedings of the Royal Society A*, vol. 471, p. 20140928, 2015.

[5] C. J. Barnes, C. L. Willey, K. Rosenberg, A. Medina, A. T. and Juhl, "Initial computational investigation toward passive transition delay using a phononic subsurface," in AIAA Scitech 2021 Forum, AIAA 2021-1454, 2021.

[6] A. Kianfar and M. I. Hussein, "Phononic-subsurface flow stabilization by subwavelength locally resonant metamaterials," *New Journal of Physics*, vol. 25, p. 053021, 2023.

[7] T. Michelis, A. Putranto, and M. Kotsonis, "Attenuation of Tollmien–Schlichting waves using resonating surface-embedded phononic crystals," *Physics of Fluids*, vol. 35, p. 044101, 2023.

[8] A. Kianfar and M. I. Hussein, "Local flow control by phononic subsurfaces over extended spatial domains," *Journal of Applied Physics*, vol. 134, p. 094701, 2023.

[9] C. L. Willey, C. J. Barnes, V. W. Chen, K. Rosenberg, A. Medina, A. T. Juhl, "Multi-input multi-output phononic subsurfaces for passive boundary layer transition delay," *Journal of Fluids and Structures* vol. 121, p. 103936, 2023.

[10] https://www.defense.gov/News/Releases/Release/Article/3336228/fiscal-year-2023-research-funding-awards/

[11] https://www.defense.gov/News/Releases/Release/Article/3700836/department-of-defense-announces-fiscal-year-2024-university-research-funding-aw/

AMMS for noise and ventilation

12. Acoustic metamaterials for noise and ventilation

Gianluca Memoli,

University of Sussex, UK

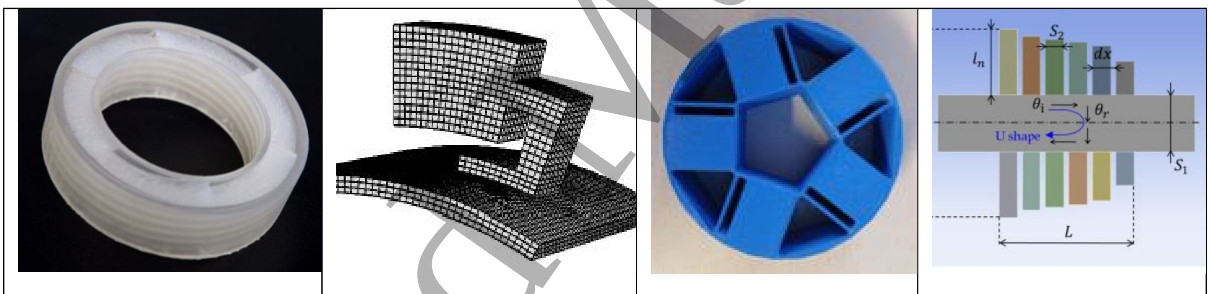
Status

Since 2014, when the first acoustic metasurface came out, the first answer to the question "what is the main application you expect from acoustic metamaterials?", whether in academia or with the general public, is always "noise management" [1]. It is therefore not surprising that the companies explicitly commercialising acoustic metamaterials[1] focus on managing unwanted sound or vibrations. Multiple solutions have been described: initially narrow band, but recently over multiple octaves [2].

A key opportunity for acoustic metamaterials (in this space) is to offer innovative solutions to the problem of managing noise and ventilation simultaneously: a well-known challenge to practitioners still in 2020 [3]. The importance of this challenge is only due to increase, in an overheating world trying to reduce carbon emissions[2]. Moreover, solutions that offer more ventilation and less noise are required by the increased acoustic sensitivity registered worldwide post-pandemic.

Mass-based solutions are not effective, because intrinsically against airflow. Therefore, traditional approaches – trickle vents, acoustic windows, louvres, silencers – rely on the physical mechanism of *absorption*. In our space-hungry world, however, these devices still need a lot of (relative) space, with denser materials being more effective and dimensions on the scale of the largest wavelength of operation[3]. Moreover, most absorptive materials require complex disposal procedures at life end.

Metamaterial-based solutions, instead, promise less space and lower densities. The base material is less important than the geometry, and this makes metamaterials open to greener manufacturing. Crucially, some geometries allow airflow (see [4] and references therein). To highlight what research is still needed, this part of the roadmap focuses on the development of metamaterial silencers to highlight (some in Figure 1).



(a) Boston University, 2019	(b) KU Leuven, 2019	(c) University of Sussex, 2022	(d) Dong-eui University, 2023

Figure 1. Examples of metamaterial approaches to silence noise in a pipe with forced ventilation: (a) using Fano resonances [5]; (b) using Helmholtz-**like** resonators [6]; (c) using phase delays along the direction of the flow [7] and (d) using quarter-wave resonators perpendicular to the flow, in a rainbow configuration [8]. Images **reproduced** with permission from the corresponding authors.

Current and Future Challenges

[1] At the time of writing, and to the author's best knowledge, these were (in alphabetical order) AMG (HK), KEF (UK), Metacoustic (F), MetaPax Akustik (TR), Metasonixx (UK), Phononic Vibes (I), Sonobex (UK), Sound maTERia (I).
[2] A widespread use of heat pumps, for instance, would create a significant source of noise in high population density areas.
[3] The fundamental frequencies for speech (90-255 Hz) correspond to wavelengths of 1.3-3.8 m.

Nature of the noise. The typical noise from forced ventilation has two components: one due to the airflow (broadband, typically peaked at 1000-2000 Hz) and one due to the pump/fan (tonal, typically below 250 Hz). Traditional absorbers are extremely cost-effective above 2000 Hz, thus metamaterials focused on lower frequencies. So far, however, solutions were either focused on the tonal part [5, 6] or on the range 1000-2000 Hz [8], where reductions of at least 20 dB were observed. These studies proved that a specific metamaterial-based solution is available for each pipe/pump system. Existing forced ventilation systems, however, come in all shapes and pipe diameters: not only we need solutions that approach simultaneously both components of this type of noise, but they need to be tunable to allow retrofitting. For people-focused applications, solutions should improve perception and not just merely reduce emissions in dB (see ISO 12913).

Metrology. Metamaterials are far from being homogeneous and uniform, while these are two key assumptions of standard measurement methods like ISO 10534 (i.e. the one using impedance tubes). Measurement methods should be revised and uniformed, to allow effective comparisons.

Fluid dynamics. Not all the designs from Figure 1 were tested for pressure losses, while this should be part of every work in this area. When pressure drop was measured, a variation of ISO 7235 was used (i.e. the one used for duct terminations). Once again, this standard only considers the average air speed, while comparing solutions that are not necessarily homogeneous would require a full measurement of the velocity profile in the pipe (or at the exit of it). This becomes crucial e.g. to assess whether dust (and bacteria) would accumulate when devices are used in real applications.

Physical mechanism. Even if designed with an innovative metamaterial approach, the solutions [5, 6, 8] are based on resonators. These are instruments that acousticians have used for many years: extremely effective, but (potentially) prone to change with temperature. Even the speed of sound used in simulations changes with temperature, but this effect is not investigated (or mentioned). Practical applications need an assessment in this sense.

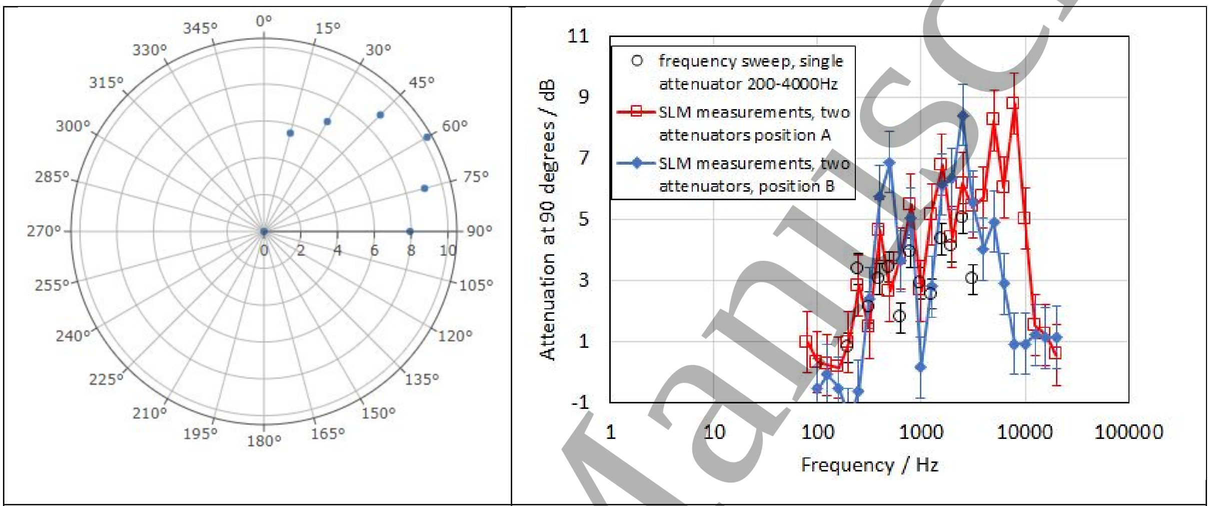
Scaling-up dimensions. While some of the solutions in Figure 1 are already 3D, most of the modelling is still made using 1D or 2D. Not only moving to 3D introduces new solutions and new eigenvalues that may change how the (acoustic) energy is managed by a given geometry, but most real-world problems are three-dimensional without doubt. Care needs to be taken in extending the results of 1D modelling.

Advances in Science and Technology to Meet Challenges

This type of applications may require a step beyond the physical mechanisms used by acousticians for centuries. It requires solutions that are tunable (to different set-ups), fully characterised (also in terms of their directionality, thermal dependence and fluid dynamics) and ideally designed in collaboration with experts of fluid dynamics.

Multi-disciplinarity. Solution [7] wants to be a first step in this direction. It way of functioning has been inspired by optics, and in particular by the interaction between two interferential filters or polarisers. Used as a single attenuator, the device in Figure 1c has a broadband attenuation of 4 dB (over 4 octaves) with a thickness of 25mm (see Figure 2a). For comparison, the designs from [5] and [6] achieve at least 40 dB reduction (over a single frequency, which was 460 Hz in their tests with a thickness of 52 mm) while the solution proposed in [8] reaches at least 20 dB, with peaks as high as 40 dB (over ½ octave). The current design, however, increases the speed at the centre of the pipe (thus causing a + 3 dB to the noise in front of it) while reducing noise emissions elsewhere (i.e. already at angles greater that 10° from the axis). Its characterisation thus requires a full velocity (and attenuation) angular profile, similar to the one of a loudspeaker (see Figure 2a). Furthermore, when two attenuators are used, the device in [7] generates also an additional peak, whose position in the spectrum can be moved by changing the relative position of the devices. Figure 2b show the case of two attenuators with a different rotational symmetry (C_5 and C_6), aligned in 2 different positions.

Manufacturing. It can be argued that the progresses of acoustic metamaterials and advanced manufacturing have gone in parallel, but only a few years ago the cost of 3D-printing was too high for mass-production: any business proposition would have been a high-value, niche one. Over the years, however, research designs have become simpler and additive manufacturing continues to improve. The challenge of mass-producing metamaterial solutions is still far from being solved, though.



(a) (b)

Figure 2. Attenuation of the device in Figure 1c, with positive values corresponding to a reduction in amplitude, in a configuration with one and two attenuators: (a) single attenuator at 1000 Hz, as a function of the angle (values relative to the one at $0°$) and (b) single and double attenuator as a function of frequency, as measured at $90°$ from the axis of the pipe with airflow. The measurement set-up was similar to the one described elsewhere [9]. The maximum pressure drop measured during these tests was 20 Pa at 1 m/s.

Concluding Remarks

The first metasurface dates back to 2014: seven years after the pioneering work in optics that introduced the concept of "metamaterial". Since then, the term "acoustic metamaterial" has migrated from being perceived as science fiction to applications, with companies starting to work with the different research groups worldwide. There is amazing science to be made at the frontier between optics and acoustics but, in the short term, helping society with the simultaneous management of noise and ventilation may be the most significant contribution of the field to everyday life, and in particular to non-zero targets. To get there, scientists need to move out of their laboratories and reach out to other disciplines, adding metrological and manufacturing considerations to their amazing metamaterial designs.

Acknowledgements

This work would have not been possible without the UKRI grant “EP/S001832/1, AURORA: Controlling sound like we do with light”, that lasted between 2018 and 2021. Thanks are due also to the University of Sussex and to Metasonixx Ltd for their contributions to fund this research afterwards.

References

[1] G. Memoli, L. Bonoldi and L. Chisari, "Shaping sound with Acoustic Metamaterials," *Acoustic Bulletin,* pp. 52-58, November/December 2020.

[2] G. Memoli, L. Chisari, L. Bonoldi and A. El Ouahabi, "Bringing acoustic metamaterials to hospitals," *IOA Acoustic Bulletin,* pp. 42-56, November-December 2021.

[3] Acoustics and Noise Consultants Association, "Acoustics, Ventilation and Overheating Guide," 30 1 2020. [Online]. Available: https://www.association-of-noise-consultants.co.uk/avo-guide/.

[4] L. Y. Leng Ang, F. Cui, K.-M. Lim and H. Pueh Lee, "A Systematic Review of Emerging Ventilated Acoustic Metamaterials for Noise Control," *Sustainability,* vol. 15, no. 5, p. 4113, 2023.

[5] R. Ghaffarivardavagh, J. Nikolajczyk, S. Anderson and X. Zhang, "Ultra-open acoustic metamaterial silencer based on Fano-like interference," *PHYSICAL REVIEW B,* vol. 99, p. 024302, 2019.

[6] A. Nateghi, L. Sangiuliano, C. Claeys and E. P. B. D. W. Deckers, "Design and experimental validation of a metamaterial solution for improved noise and vibration behavior of pipes," *Journal of Sound and Vibration,* vol. 455, pp. 96-117, 2019.

[7] G. Memoli, A. A. El Ouahabi, L. Bonoldi and L. Chisari, "ACOUSTIC METAMATERIALS". Patent WO2024003559A1, 29 06 2022.

[8] H. Kim, K. Yoonjung and S. Lee, "Acoustic Metamaterial Design by Phase Delay Derivation Using Transfer Matrix," *Symmetry,* vol. 15, p. 689, 2023.

[9] A. A. El Ouahabi and G. Memoli, "A transfer matrix method for calculating the transmission and reflection coefficient of labyrinthine metamaterials," *Journal of the Acoustical Society of America,* vol. 151, p. 1022–1032, 2022.

13. Advancement in metamaterial tuning for sound-proof and ventilated window

Gioia Fusaro, Dario D'Orazio, Luca Barbaresi, Massimo Garai
University of Bologna - Italy

Status

Strategies to control façade sound insulation and ventilation have been developed with completely separate approaches in buildings [1]. Traditional windows, for example, allow visual connection with the outside, natural ventilation, and, when closed, partial sound insulation. However, traditional systems limit the user to choosing one function at the expense of the other, mining indoor environmental quality (IEQ) [2]. So far, researchers have used different methodologies to overcome both problems using, for example, mechanical ventilation [3] and active or passive noise control systems [4], [5]. The latter has the advantages of consuming low amounts of energy and can be implemented directly inside the window leading to improved durability, such as with microperforated panels (MPPs) [4] or Acoustic Metamaterials (AMMs) [6]. Metamaterials for noise and ventilation control are typically duct-like structures with resonant systems embedded (e.g., metasurfaces, metamaterial cages, and labyrinthine structures) [7] and originated for mechanical applications (sound-proofing of endothermic engines) [8]. Three of the current challenges about metamaterials for ventilated and sound-proof windows are: i) a consistent multiphysical analysis from both numerical and experimental points of view [8], ii) ergonomic design of acoustic metawindows (meaning AMMs-based windows, AMW) for natural ventilation and noise attenuation [7], and iii) the lack of consistent standard regulations concerning noise façade insulation for open windows [9].

Table 1. Stages of the multi-disciplinary approach used in the AMW for ventilation and noise attenuation.

METHOD	VALIDATION FIELD	AIMS	STANDARDS
1. Analytical	Acoustics	Studying metamaterial principle for noise and ventilation requirements	EN 13779, UK *Approved Document F Volume 1, 2021* and DS 447:2021, *Ventilation for buildings - Mechanical, natural and hybrid ventilation systems* on ventilation requirements
2. Numerical	Acoustics and Fluid Dynamics	Parametric optimisation on specific acoustic/ventilation requirements	The numerical setup should consider the experimental standards
3. Experimental	Acoustics and Fluid Dynamics	Assessment of the numerically optimised final design	ISO 717 and ISO 10140-1,2,4,5 and ISO 16283-3 on facade noise insulation, and ISO 9972, EN 13779, UK *ADO-F Vol. 1, 2021* and DS 447:2021, on ventilation requirements
4. Ergonimics/ Human perception	Psychoacoustics and Soundscape	Evaluation of the final design's impact on human perception and ergonomic function	ISO 532-1-3 on Loudness, and ISO ISO 12913-1,2 on Soundscape

Current and Future Challenges

The latest metamaterials research concerning aero-acoustic interaction shows that there is still a lack of studies and methodologies about such a realistic multiphysical model (numerical or experimental) [8]. The literature review conducted by Fusaro et al. highlights particular attention on fluid dynamics turbulence generation, propagation and contamination on the acoustic field [8]. The most used parameters in the studies published are Transmission Loss (TL), absorption coefficient (α), Mach number (Ma), Acoustic Transmission (T), and Flow Veocity (v) [8]. Most analyses involving such parameters are conducted as parallel mono-physics, and only a few studies combine multi-physical models (16% present TL+Ma, α+Ma, or TL+v). On the other side, focusing on windows applications, the latest research developments have shown a good - yet not final -improvement in the ergonomic design of AMMs-based implementation within industrial design [9], [10]. So far, The AMMs assessment methods are limited in the field of physical and psychophysical analysis (see Table 1). Finally, European regulations have drawn precise directions for assessing façade insulation properties to characterise windows and ensure a healthy indoor environment [9]. However, most of these regulations (excluding the UK and the Danish ones in Table 1) concern closed partitions, limiting the application when open systems for noise insulation are involved [9]. For this reason, standard experimental methods should be combined to assess an example of AMW.

Advances in Science and Technology to Meet Challenges

FEM softwares (such as COMSOL Multiphysics) allows to simulate the aeroacoustics interaction using a combined mesh method and the linearised Navier-Stokes equations including: resolution of both thermal and viscous boundary layers, attenuation due to the turbulence with the coupling of the turbulent viscosity, analyses through reactive terms of the interaction of entropy, shear and acoustic compressibility waves, and Fluid-Structure Interaction (FSI) with flow gradient [8]. Regarding the ergonomic study to implement AMWs, an effective method is demonstrated to be the following [2], [10]: i) define the multiphysical requirements (due to the application) and develop few basic AMMs principles to be used to achieve such requirements (analytical and numerical analysis), ii) embed ergonomic design approach in the defined AMMs principles to draw a final prototype (through literature review research or focus group studies), and iii) test the final prototype with both physical and psychophysical methods (FEM, experimental measurements, psychoacoustic analysis and soundscape questionnaires). Following this method, the AMW will be as comprehensive as possible (see Figure 1). Finally, to adapt available national or international standards (e.g. ISO 10140 series, ISO 16283-3) for assessing AMMs-based partitions for noise attenuation and ventilation, a recent study by Fusaro et al. showed encouraging results [9]. This study considers a combined numerical and experimental study to determine the noise sound insulation index (SI), the sound level difference ($D_{n,e}$) and the ventilation potential (blower door test method, ISO 9972) of the AMW. The results discussed in the work of Fusaro et al. show the potential applicability of standard regulation methods for such prototype.

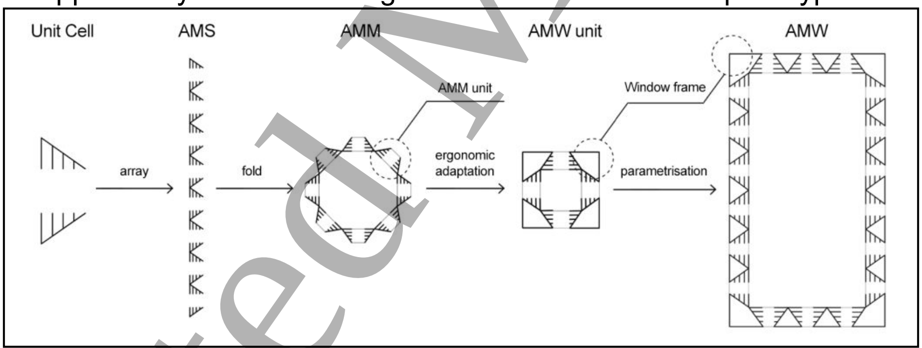


Figure 1. Schematic of the development of a metamaterial-based window for ventilation and noise attenuation by Fusaro

Concluding Remarks

This research aimed to develop an ergonomic AMW and test it through several approaches (based on physics, psychophysics, ergonomics, and standard regulations). The final metamaterial-based design includes a ¾ wavelength resonator elements (ergonomically embeddable within the window frame and easily manufacturable by extrusion). The AMW consists of a cubic main structure measuring 1.2 x 0.8 x 0.2 m, which incorporates an Acoustic Metamaterial (AMM) system within the window frame area, as depicted in Figure 1. Each unit cell contains eight resonance cavities. By adjusting the internal structure, local resonances create a stopband effect. Structurally, the unit cell resembles a waveguide with periodic scatterers that allow lateral flow exit. Inspired by the acoustic black hole effect, the theoretical wave propagation in this design results in an acoustic stopband due to the resonant tubular array [9]. More details on simulation results and theoretical discussions are available in a prior

publication [11], [12]. To enable practical use in buildings, the design must shift towards a more ergonomic and traditional form. Parameters like specific impedance ($Z_{1,2}$) and refractive index ($n_{1,2}$), associated with different geometrical areas of the AMW unit, were analyzed. Variations in refractive indices across these areas create an out-of-phase effect for sound waves travelling through the AMM unit cell, a phenomenon confirmed regardless of the angle of incidence for any refractive index. This principle supports the AMW's ability to function as an omnidirectional sound barrier, as validated by preliminary numerical analyses that confirm its effectiveness against waves from all directions. The prototype was created by laser-cutting a 0.01 m thick plexiglass layer (for the indoor and outdoor panels) and 3D printing the AMM unit cells using fused deposition modelling (FDM) and polylactic acid (PLA) filament.
The final AMW results performing better than an equivalent window (with the same opening ratio) with a $D_{n,e}$ that goes from 30 to 40 dB (frequency range of 100-5000 Hz) with a fully open window (flow rate per person satisfies the EN 13779 standards). Such findings advocate for adopting these advanced AMWs over traditional ones, offering effective ventilation and noise reduction benefits and could help develop more inclusive regulations also considering open sound insulating devices as vertical partitions for the built environment.

Acknowledgements
This work started through the ARAP Programme fundings (University of Sheffield and A*STAR Institute) and has been further developed in the last 3 years in the frame of the projects PRIN 2017 and PRIN 2022, funded by the Italian Ministry of University, Grants No. 2017T8SBH9 and 2022RA785R.

References

[1] J. Harvie-Clark, A. Chilton, N. Conlan, and D. Trew, “Assessing noise with provisions for ventilation and overheating in dwellings,” *J. Build. Serv. Eng. Res. Technol.*, vol. 40, no. 3, pp. 263–273, 2019, doi: 10.1177/0143624418824232.
[2] G. Fusaro and J. Kang, “Participatory approach to draw ergonomic criteria for window design,” *Int. J. Ind. Ergon.*, vol. 82, pp. 1–12, 2021, doi: 10.1016/j.ergon.2021.103098.
[3] L. Du, S. K. Lau, S. E. Lee, and M. K. Danzer, “Experimental study on noise reduction and ventilation performances of sound-proofed ventilation window,” *Build. Environ.*, vol. 181, no. May, p. 107105, 2020, doi: 10.1016/j.buildenv.2020.107105.
[4] J. Kang and M. W. Brocklesby, “Feasibility of applying micro-perforated absorbers in acoustic window systems,” *Appl. Acoust.*, vol. 66, no. 6, pp. 669–689, 2005, doi: 10.1016/J.APACOUST.2004.06.011.
[5] B. Lam, C. Shi, D. Shi, and W. S. Gan, “Active control of sound through full-sized open windows,” *Build. Environ.*, vol. 141, no. May, pp. 16–27, 2018, doi: https://doi.org/10.1016/j.buildenv.2018.05.042.
[6] N. Jiménez, V. Romero-García, V. Pagneux, and J. P. Groby, “Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems,” *Sci. Rep.*, vol. 7, no. 1, pp. 1–12, 2017, doi: 10.1038/s41598-017-13706-4.
[7] S. Kumar, T. B. Xiang, and H. P. Lee, “Ventilated acoustic metamaterial window panels for simultaneous noise shielding and air circulation,” *Appl. Acoust.*, vol. 159, p. 107088, 2020, doi: 10.1016/j.apacoust.2019.107088.
[8] G. Fusaro, S. D’Auria, and D. D’Orazio, “Multiphysical numerical analysis for acoustic metamaterials in ventilated ducts,” in *Internoise 2023*, 2023, pp. 7–8. doi: https://doi.org/10.3397/IN_2023_0699.
[9] G. Fusaro, L. Barbaresi, P. Guidorzi, and M. Garai, “Investigation of the sound insulation and natural ventilation performance of a metamaterial-based open window,” *Build. Environ.*, vol. 266, no. June, p. 112140, 2024, doi: 10.1016/j.buildenv.2024.112140.

[10] G. Fusaro, J. Kang, F. Asdrubali, and W.-S. Chang, “Assessment of Acoustic Metawindow unit through psychoacoustic analysis and human perception,” *Appl. Acoust.*, vol. 196, p. 108885, 2022, doi: https://doi.org/10.1016/j.apacoust.2022.108885.

[11] G. Fusaro, X. Yu, J. Kang, and F. Cui, “Development of metacage for noise control and natural ventilation in a window system,” *Appl. Acoust.*, vol. 170, p. 107510, 2020, doi: 10.1016/j.apacoust.2020.107510.

[12] G. Fusaro, X. Yu, Z. Lu, F. Cui, and J. Kang, “A Metawindow with optimised acoustic and ventilation performance,” *Appl. Sci.*, vol. 11, no. 7, pp. 1–16, 2021, doi: 10.3390/app11073168.

14. Advancing Sound Systems through Acoustic Metamaterials

Letizia Chisari,

University of Sussex (UK) + Metasonixx Ltd

Status

With roots in manipulating sound waves as we do with light [1], the application of acoustic metamaterials in professional and immersive audio has grown in importance due to its potential to revolutionize audio technologies. The continued relevance lies in the pursuit of advanced capabilities for audio reproduction quality, spatial soundscapes delivery, and unprecedented control over acoustic environments response.

Acoustic metamaterials have demonstrated the ability to encode a desired sound filter by engineering their geometrical characteristics. Metasurfaces having sub-wavelength dimensions have been successfully integrated in a listening environment for shaping room acoustics, by tuning acoustic metamaterial panels response as desired [2]. Metamaterial panels have also provided tailored absorption and diffusion, even when seeking a non-intrusive solution for low frequencies treatment, as predicted by [3].

System of metamaterial lenses capable of overcoming the diffraction limit have also been coupled with a sound system, enhancing efficient control on its emitted wavefront [4].

Figure 1 shows a metamaterial Keplerian telescope, whose objective consists of two converging lenses positioned at a variable distance, used to deliver sound following a listener moving in the horizontal plane [5]. Metamaterial-based solutions have also proved to reduce the unwanted sound emissions in loudspeaker systems [6], resulting in a lighter and more compact system as a first benefit. Therefore, the ability of metasurfaces to manipulate sound propagation could ensure the optimal delivery of audio in various professional settings. For example, the integration of acoustic lenses in studio monitors might improve precision and accuracy of the emitted signal, focusing sound around the listener position and limiting the contribution of the room response.

Moreover, further advances could become instrumental in creating immersive audio experiences in VR and AR environments. Acoustic metamaterials can indeed enable the simulation of realistic three-dimensional soundscapes when combined with audio systems, enhancing their overall immersiveness. Their ability to control sound reflections can also enhances the listener's sense of space.

Therefore, acoustic metamaterials are allowing for the design of new perspectives in the audio sector, which is becoming increasingly tuned to the sound preferences of the listener.

The transformative impact of acoustic metamaterials on audio technologies is set to redefine industry standards, offering enhanced auditory experiences and novel applications.

Figure 1. (a) Photograph of acoustic telescope with auto-zoom lens, designed to deliver sound to a target listener. (b) A potential application, connecting acoustically with a single person in a crowd [1].

Current and Future Challenges

Once a passive acoustic metasurface is designed, that is what you have to shape sound delivery. Recent breakthroughs involve the development of dynamic metamaterials, allowing adaptive control of acoustic properties. This innovation promises even greater versatility in the audio application area. Recent findings allow for tunable active metamaterials, enabling real-time adjustments to suit specific acoustic requirements [7]. Continued advancements will have profound implications for concert halls, recording studios, and auditoriums as well as contributing to the development of high-performance sound reinforcement systems. However, issues arise due to the need for a real-time response from such devices, which may have to rapidly vary their internal geometry (i.e., their response) while ensuring high-quality sound, even when changing the listening environment conditions. The challenge is to design a system that is both mechanically efficient and acoustically effective, over a sufficiently wide range of frequencies and signal amplitudes.

The demand for miniaturization became crucial also in acoustics, greatly influenced by developments in its neighbouring field like optics. To facilitate integration with consumer electronics and smart sound systems, it is imperative that acoustic metamaterials become increasingly lightweight and compact. Therefore, there is a high demand for the development of nanostructured metamaterials. However, complexity arises when low frequencies are involved. Nevertheless, such advancements could open up new possibilities for miniaturized devices with exceptional acoustic performance.

To address the imperative of minimizing our environmental impact, a future objective will undoubtedly involve meeting the biodegradability requirements of the materials they composing acoustic metasurfaces. In conclusion, there is a rising demand for the advancement of curved and flexible acoustic metamaterials. Depending on the specific application context, it becomes imperative to enhance their properties, such as resilience or auxetic behaviour.

Advances in Science and Technology to Meet Challenges

To address current challenges, advancements in the materials science, design methods, and fabrication techniques for acoustic metamaterials in audio systems are becoming crucial. Innovations in metamaterial design, incorporating dynamic elements and adaptive features, are contributing to approach the requirements of real-world applications. Interdisciplinary collaborations between acousticians, material scientists, and engineers are demonstrating to be pivotal for developing commercially viable solutions to match the listener desired sound experience.

Physics and human expertise have always guided the design of acoustic metamaterials. Historically, to achieve the desired goals, some parameters are fixed while others are iteratively modified through computationally intensive numerical simulations. Over the years, the complexity of the internal geometry of these engineered materials has increased [8], together with the demand for controlling multiple parameters simultaneously. More recently, the new strategy of inverse design optimisation using gradient-based, gradient-free methods [9] and evolutionary algorithms, has started to gain traction. Rather than starting from physical principles describing the behaviour of the metamaterial, these methods aim to achieve the desired acoustic functionalities through optimisation within a search space often defined by the metamaterial parameters. Inverse design methods also allow the user to specify multiple objectives in the optimisation of the metamaterial design such as, the sound system response and the spatial response of the listening environment.

Integrating machine learning and optimisation algorithms to retrieve metamaterial designs represents a promising avenue for addressing complex challenges in the acoustic metasurfaces coupling with modern sound systems. Taking inspiration from digitally controlled loudspeakers, metasurfaces are realizing sound zone filters [10], shaping the wavefront to follow a desired pressure distribution in a target listening area.

The emission correction methods in optics, are aiding to accurately retrieve the design of an acoustic metasurface, by targeting a desired wavefront shape in a listening area.

To reduce the spherical aberration of a metasurface superlens coupled with a simplified sound system, a corrective metasurface design is retrieved by hill descending. In Figure 2 the pressure distribution comparison obtained with and without the corrective device, retrieved using two different objective functions is showed, together with the sound pressure level difference of the two.

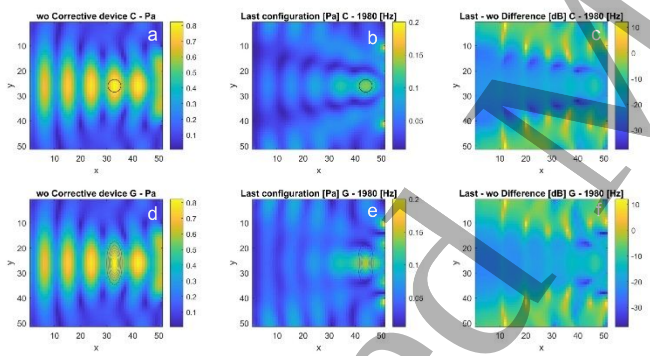


Figure 2. (a, b, d, e) Two objective functions, pressure distribution comparison: (a, d) without corrective device, (b, e) with last combination of metamaterials found by the algorithm; (c, f) SPL difference between the last and without corrective device [9].

Concluding Remarks

The integration of acoustic metamaterials in audio systems promises to redefine the way we perceive and interact with sound. Acoustic metasurfaces, when integrated with sound systems, provide VR users with greater control over the desired sound, offering the freedom to move more freely within the listening space without the need for headphones. Incorporated within sound systems and the listening environment, acoustic metasurfaces contribute positively to enhancing control over the sound experienced by the listener.

In the future, systems similar to the one shown in Figure 1, promise to become valid allies for the digitally controlled wavefront shape loudspeakers typically used to control the response of a sound system. The increasing research on the optimal design methods for metamaterials, also drawing inspiration form design methods used for both digital filters and optical lenses, will increasingly allow a desirable coupling of metasurfaces with audio system.

References

[1] G. Memoli, T. J. Graham, J. T. Kybett, and A. Pouryazdan, *From light to sound: prisms and auto-zoom lenses*, in ACM SIGGRAPH 2019 Talks, Association for Computing Machinery, New York, NY, USA, Article 36, 1–2, https://doi.org/10.1145/3306307.3328206

[2] G. Ma, X. Fan, P. Sheng and M. Fink, "Shaping reverberating sound fields with an actively tunable metasurface", Proc. of the National Academy of Sciences, Vol. 115, Iss. 26, 2018.

[3] T. J. Cox and P. D'Antonio*, Acoustic absorbers and diffusers: Theory, Design and Application,* 3rd ed., Taylor & Francis Ltd, 2020.

[4] L. Chisari, E. Ricciardi and G. Memoli, "Numerical and Experimental Analysis of a Metamaterial-based Acoustic Superlens", presented at the 152nd Audio Eng. Soc. Convention, 2022.

[5] C. Rajguru, D. Blaszczak, A. PourYazdan, T. J. Graham and G. Memoli, *AUDIOZOOM: Location Based Sound Delivery system*, in SIGGRAPH Asia 2019 Posters, Association for Computing Machinery, New York, NY, USA, Article 35, 1–2. https://doi.org/10.1145/3355056.3364596

[6] S. Degraeve and J. Oclee-Brown, "Metamaterial Absorber for Loudspeaker Enclosures", presented at the 148th Audio Eng. Soc. Convention, 2020.

[7] B. I. Popa, D. Shinde, A. Konneker, and S. A. Cummer, "Active acoustic metamaterials reconfigurable in real time", PHYSICAL REVIEW B 91, 220303(R) (2015), https://doi.org/10.1103/PhysRevB.91.220303

[8] Muhammad, J. Kennedy, C.W. Lim: "Machine learning and deep learning in phononic crystals and metamaterials A review", Materials Today Comm., Vol. 33, 2022, https://doi.org/10.1016/j.mtcomm.2022.104606

[9] L. Chisari, A. Philippides and G. Memoli, OPTIMISING METASURFACE RETRIEVAL BY HILL DESCENDING, Forum Acusticum 2023.

[10] R. Alessandri, "A Deep Learning-based method for Multi-Zone Sound Field Synthesis", (2023)

15. ENAM: Enhanced energy Noise-reduced wind farms with Acoustic Metamaterials

Prateek Mittal[1*], Zhu Qi[2*], Sriram Subramanian[1]

[1]Department of Computer Science, University College London, London, UK

[2]School of Mechatronic and Automation Engineering, Shanghai University, Shanghai, China

Status

The worldwide interest in renewable energy, especially wind energy, has skyrocketed due to its immense potential for generating electricity, reducing our reliance on depleting fossil fuels, and promoting net zero carbon emissions [1]. However, wind turbines (WTs), the governing mechanism of wind energy, suffer from excessive noise, which constricts their constructions in urban-suburban areas, alongside the regulated operation in rural areas with compromised energy yield, posing significant challenges to pursuing net zero. Specifically, noise annoyance contributes to adverse human health, fears of deprecating nearby property values, and hinders the development of new and existing projects, thus limiting the acceptance of wind farms among local communities [2]. Nevertheless, this dire situation is mainly dealt with by incentivising nearby residents with the likelihood of gaining their acceptance [3].

A crucial aspect is to develop an innovative solution to increase the trust and support of the community towards sustainable power generation by enhancing the attractiveness of wind farms without depending on additional incentives. Using recent advances in Acoustic Metamaterials (AMMs) [4], one innovative solution is integrating wind farms with visually appealing sculptures or green spaces within and surrounding areas. These structures (which can be trees, bushes, or any human-made sculptures) acting as phase and amplitude-modulating metamaterials would not only reduce noise levels but also address residents' aesthetic and landscaping preferences and promote their comfort and well-being, all while being sustainable and adhering to the relevant government regulations and policies.

Current and Future Challenges

Various low-noise strategies have been devised and adopted in practice to mitigate the adverse noise impacts inside wind farms [5]. However, these measures necessitate significant amendments to existing systems that often entail high costs or failure to reach the desired level of noise reduction. Techniques like operating WTs at reduced power output or strategic distancing of WTs from residents typically result in compromised energy throughput or land wastage (~300m) that could be otherwise used for practical purposes. Despite these challenges, the wind community continues to strive towards minimising noise levels with no compromise in the effectiveness of the existing processes to exploit wind energy to its full capacity.

With new wind farm development, it is challenging to develop comprehensive solutions with recommended policies to increase the likeliness of wind farms as low environmental impact, enhanced energy, and human-friendly operation. Traditional noise barriers are often ineffective, expensive, and aesthetically unappealing, whereas the challenge persists in designing them as aesthetically pleasing, resembling natural structures such as trees or mini gardens or visually pleasing figurines, to enhance the public perception satisfying landscape principles and visual impact and promote community engagement towards wind farms. Most noise control solutions are implemented with constant wind flow (wind speed and direction); however, analysing erratic wind flow patterns with emerging machine learning can provide more robust and realistic solutions complying with noise standards. Furthermore, the increasing penetration of wind energy and the placement of more WTs can amplify the probability of WT and bird or bat collision deaths and can also induce a complex predicament of WT blade wastage problems, which may present a formidable challenge for futuristic wind farms.

Advances in Science and Technology to Meet Challenges

AMMs have emerged as the potential tool for manipulating and controlling noise with unprecedented capabilities that are impossible to gain through conventional materials, making them a suitable candidate for noise control [8], [9]. However, traditional full-walled solid structure AMM designs limit their acceptance to outdoor environments, especially when dealing with low-frequency sound (~ 100 - 6000 Hz), where the placement of AMM as large walls can disturb nearby residents. Thus, there is a need for innovative and sustainable noise control solutions that not only reduce noise levels but also blend into the surroundings and be well-accepted by society. Our recent analysis demonstrated the novel optimal design of AMMs as aesthetic ‘holey’ segmented structures, where metamaterial unit cells are arranged in subgroups with bare minimum coverage, yielding a similar wind farm noise reduction as full-walled structures [10]. This will give researchers an edge in designing aesthetically pleasing AMM structures resembling natural figurines (with bare minimum metamaterial unit cells) that will facilitate the placement of these noise-manipulating structures inside wind farms or in the neighbourhood of nearby settlements, addressing their landscape and visual requirements. Furthermore, the strategic placement of these aesthetic AMMs in and around wind farms can have a massive potential for noise manipulation without disrupting the operating performance or sacrificing the energy throughput, facilitating early approval from the local authorities. Additionally, the placement of these innovative noise-reducing aesthetic sculptures enables wind farmers to leverage the unused noise-restricted areas for practical purposes, such as building new residential developments or positioning additional WTs within existing wind farms in compliance with noise standards and regulations, as visualised in **Figure 1**. Being material agnostic, building AMMs with recycled WT blades can be a latent opportunity for wind farmers to reduce the WT blade wastage problem. Furthermore, the ability of AMMs to manipulate and control sound fields can be exploited further to redirect bats and birds away from WTs, thus envisioning wildlife conservation by mitigating wind turbine collisions or turbine-induced death rates.

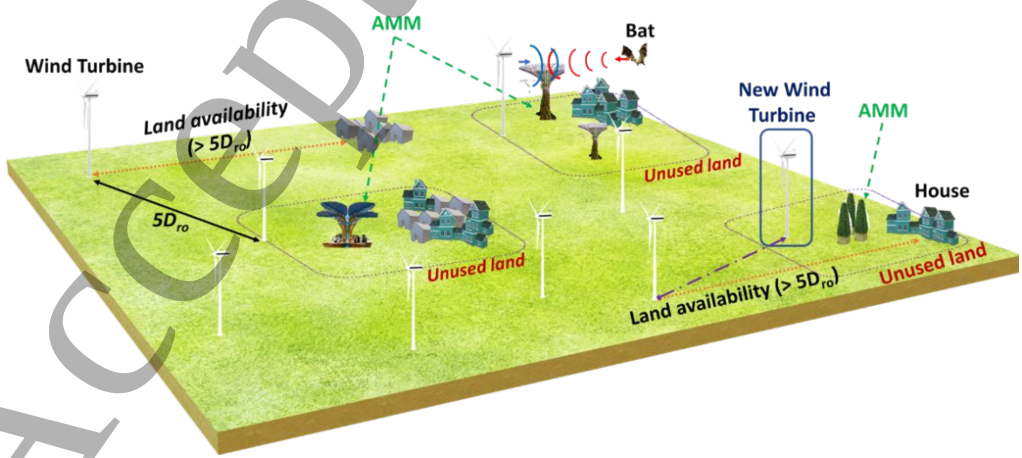


Figure 1: Illustration of the prospective usage of AMMs as noise-cancelling innovative sculptures to preserve human health and wildlife while retaining the aestheticism of wind farms. (*Here, we have envisioned AMMs as aesthetic solar trees and palm tree structures; 'House' are the sound receptors; 5D_{ro} is the sufficient inter-turbine distance to avoid wake-induced power loss; and 'unused land' is the noise-restricted area for WTs to prevent adverse impacts on human health*).

Concluding Remarks

The persistent noise issue from wind farms negatively impacts the nearby human health and surroundings, limiting its acceptance by local communities. Existing solutions predominantly compromise wind farm efficiency, increase unused land area, limiting the full utilisation of wind energy. Acoustic metamaterials, with their advanced noise-manipulation capabilities, material versatility, and sub-wavelength unit-cell patterned design, offer a promising path forward in dealing with the challenging wind farm noise while complying with landscape and visual impact policies. This opens up a new opportunity for wind farmers to build enhanced energy throughput and noise-less, human, and wildlife-friendly onshore wind farms in urban and suburban locations, meeting climate control targets.

Acknowledgements

The authors gratefully acknowledge the funding support by EU-H2020 through their ERC Advance Grant (number 787413) and the Royal Academy of Engineering (CIET 18/19). The authors would also like to thank Prof. Gianluca Memoli for the insightful and useful discussions on acoustic metamaterials.

References

[1] K. F. Sotiropoulou, A. P. Vavatsikos, and P. N. Botsaris, "A hybrid AHP-PROMETHEE II onshore wind farms multicriteria suitability analysis using kNN and SVM regression models in northeastern Greece," *Renew Energy*, vol. 221, p. 119795, Feb. 2024, doi: 10.1016/J.RENENE.2023.119795.

[2] J. M. Ellenbogen, C. B. Kellam, and M. Hankard, "Noise-induced sleep disruption from wind turbines: scientific updates and acoustical standards," *Sleep*, Nov. 2023, doi: 10.1093/SLEEP/ZSAD286.

[3] "Local areas supported to progress onshore windfarms - GOV.UK." Accessed: Jan. 15, 2024. [Online]. Available: https://www.gov.uk/government/news/local-areas-supported-to-progress-onshore-windfarms

[4] C. Choi, S. Bansal, J. Hardwick, N. Münzenrieder, M. K. Tiwari, and S. Subramanian, "A magnetically actuated dynamic labyrinthine transmissive ultrasonic metamaterial," *Communications Materials 2024 5:1*, vol. 5, no. 1, pp. 1–12, Jan. 2024, doi: 10.1038/s43246-023-00438-4.

[5] C. Hansen and K. Hansen, "Recent Advances in Wind Turbine Noise Research," *Acoustics*, vol. 2, no. 1. MDPI, pp. 177–206, Mar. 01, 2020. doi: 10.3390/acoustics2010013.

[6] Z. Jia, X. Yang, A. Chen, D. Yang, M. Zhang, and L. Wei, "Localized Eco-Climatic Impacts of Onshore Wind Farms: A Review," *https://doi.org/10.5814/j.issn.1674-764x.2024.01.013*, vol. 15, no. 1, pp. 151–160, Jan. 2024, doi: 10.5814/J.ISSN.1674-764X.2024.01.013.

[7] P. Liu and C. Y. Barlow, "Wind turbine blade waste in 2050," *Waste Management*, vol. 62, pp. 229–240, Apr. 2017, doi: 10.1016/J.WASMAN.2017.02.007.

[8] G. Memoli, M. Caleap, M. Asakawa, D. R. Sahoo, B. W. Drinkwater, and S. Subramanian, “Metamaterial bricks and quantization of meta-surfaces,” *Nat Commun*, vol. 8, pp. 1–8, 2017, doi: 10.1038/ncomms14608.

[9] C. Choi, S. Bansal, N. Münzenrieder, and S. Subramanian, “Fabricating and Assembling Acoustic Metamaterials and Phononic Crystals,” *Adv Eng Mater*, vol. 23, no. 2, Feb. 2021, doi: 10.1002/ADEM.202000988.

[10] P. Mittal, C. Giorgos, and S. Subramanian, “Energy Enhancement Through Noise Minimization Using Acoustic Metamaterials in a Wind Farm”, doi: 10.2139/SSRN.4597739.

Extended AMMs

16. Seismic Metamaterials and their development

Brûlé S., Menard, Orsay, France
Enoch S., CNRS, Aix-Marseille Université, Centrale Marseille, Institut Fresnel, Marseille, France
Guenneau S., The Blackett Laboratory & UMI 2004 Abraham de Moivre, Imperial College, London, United Kingdom

Status

Studies on real structured soils (figure 1), including seismic metamaterials, have unveiled the existence of complex wave phenomena within and around the structured zone [1,2]. The aim is to assess areas where seismic or vibratory energy is concentrated, and to decide whether it would be worthwhile to exploit them by judiciously placing piezoelectric energy sensors [3]. It is interesting to note what can be done with vibration sensors implanted in civil engineering structures, and to show the potential interest of seismic metamaterials in this context. The modification of the surface signal by both structured soil and surface resonators meets the challenges of Civil Engineering through the effects of soil-structure interaction. Seismic metamaterials can therefore not only be considered for building protection, lensing and minimizing the effects of potentially deleterious Rayleigh waves [1,2], but also have potential applications in energy harvesting using ambient seismic noise [3,4]. We do not claim collecting energy from devastating earthquake can become a reality, but we stress that small ground vibrations due to ambient seismic noise and human activities can be harvested through artificial defects in, or spatial graduation of, large scale periodic structures.

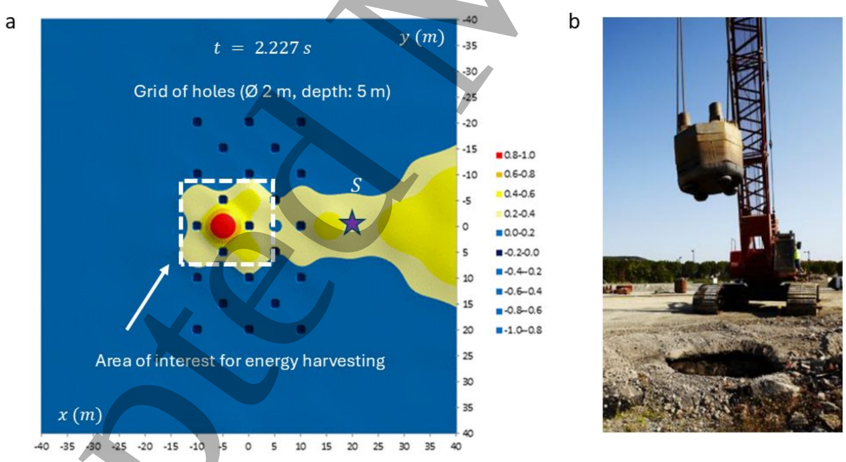


Figure 1. (a) Example of a staggered hole pattern (20 – 40 m) in a soil near the French city of Lyon. The impact source (S) is located at 10 m from the long side [2]. The energy scale is arbitrary and normalized. The figure shows energy concentrations at locations of interest for positioning vibration sensors [2,3] after a time lapse of 2.227s following an impact. (b) Impact source compaction equipment with a 17t punch mass (courtesy of Menard).

Current and Future Challenges

The principles of periodic media cannot be easily transposed to terrestrial materials without a rigorous definition of the conditions of validity. Notably, these conditions are the strain range of the soil making possible the justification of an elastic behaviour and a thick and

homogeneous sedimentary site to limit the reflection effects of the underlying geological layers of contrasted impedance [4].
Measurements must be interpreted in light of the physical phenomena expected in periodic media (the seismic mirror [1] and lens [2] implemented and tested by the Menard company near the French cities of Grenoble and Lyon in 2012 are explored both as scaled up versions of phononic crystals and metamaterials. However, in the case of these large-scale experiments, the focus was mostly on the control of ground acceleration around 1 to 2 Hz, since 5 to 10 storey buildings have a fundamental frequency in the same frequency range. It was observed that the horizontal to vertical ratio can be dramatically reduced or enhanced in specific areas, around, and within, the seismic lens, thereby allowing either for earthquake protection, or other functionalities such as energy rerouting and localisation). Diffraction, including Bragg reflection [1] and the double image of the source due to the negative refraction of a flat lens [2] are particularly noteworthy (figure 1 shows the formation of a first image of the source within a staggered hole pattern which effectively behaves like a Pendry-Veselago lens). However, it should be remembered that a metamaterial is defined as an artificial composite material made from the assembly of smaller resonators, whose wavelength at resonance is much greater than their physical dimension. Then, to obtain local resonances, holes in the ground such as Helmholtz resonators or rigid inclusions can be considered [5,6]. The modification of the signal by a structured soil and surface resonators meets the demands of civil engineering and the soil-structure interaction practiced in earthquake engineering (figure 2b). Research topics converge on seismology and the effects of secondary sources generated by surface buildings.

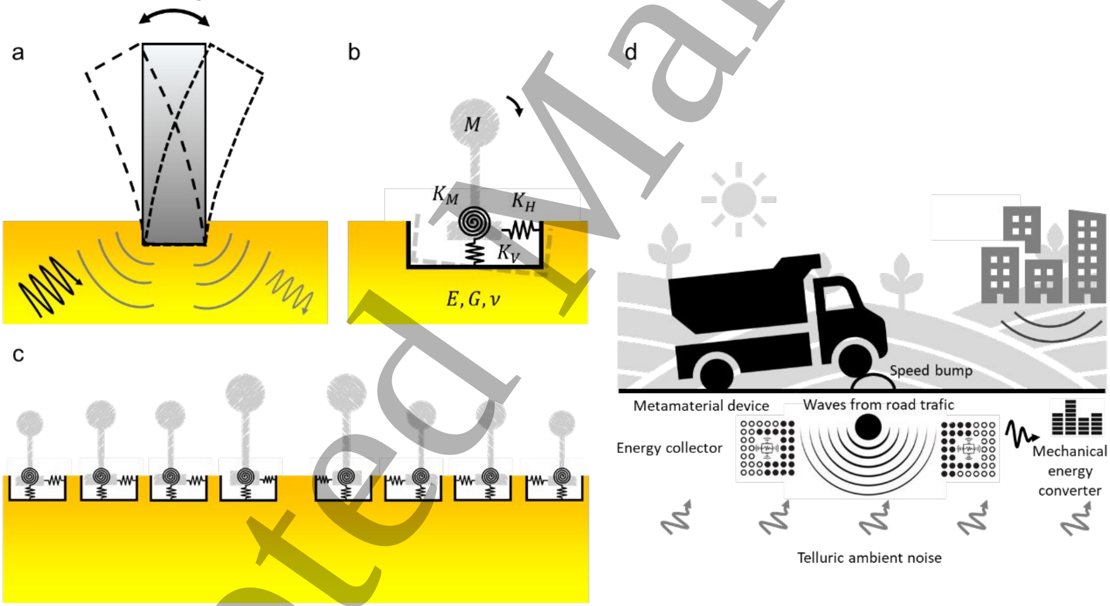


Figure 2. (a) The building vibrates as a result of seismic waves, and then, through inertial effects, becomes a secondary source of vibration itself. (b) Soil-foundation interface is modelled here in the case of three degree of freedom with analogic Maxwell models (K_H, K_V, respectively horizontal and vertical stiffnesses, K_M is the rotational stiffness of the model). (c) Concept of Metacity cloak based upon transformation urbanism using a conformal mapping [3] with, in addition, soil-structure interaction. (d) Principle of ambient seismic noise collection [19]. Energy comes from several mechanical sources: telluric ambient noise (imperceptible micro-earthquakes) and human activity on the surface (e.g. the use of speed bumps to create impact and diffuse mechanical waves). The device can be composed of a soil-metamaterial that enhances energy and a judiciously placed converter that transforms mechanical waves into electrical energy.

conformal mapping

Advances in Science and Technology to Meet Challenges

Metacity was a concept first put forward in the late 1980s based on experimental observations of soil response and its devastating effects [7]. It has been known since the 1950s that the natural frequencies of any man-made structure are influenced by soil-structure interaction, particularly on soft soils, and that the presence of structures on the surface of a homogeneous half-space can significantly modify ground motion, as buildings can act as secondary sources (figure 2a). This is a paradigm shift with the usual earthquake engineering design process, that studies each building as if it were in a space with no other constructions around it. Assuming that the wave field is influenced by all the surrounding buildings makes a seismic cloak possible at the scale of the city (figure 2c). Its design is based on a spatially graded structured soil with effective properties deduced from some conformal mapping [3]. Such effective properties are achieved in practice with buildings of varying heights described by analogic Maxwell models as shown in figure 2. It is also possible to detour surface Rayleigh waves around a building with concrete columns buried in the soil [8]. On the other hand, one can attenuate vibrations of a building with auxetic concrete foundations [9], and of fluid-filled storage tanks with metamaterial foundations consisting of a mixture of rubber and concrete [10]. These concepts of anti-vibration systems via low frequency stop bands would also be applicable to lateral vibrations of bridges induced by pedestrians [11], as an alternative to phononic stop band systems implemented notably beneath the London Millenium bridge [12]. Because of studies carried out on the interaction of cities with the seismic signal [7], some researchers have studied the influence of the trees of a forest on the surface waves [13] and wind turbines as a metamaterial-like urban layer [14]. The concept here is to position sensors in areas where vibratory motion is amplified by surface resonators [3]. Seismic metamaterials come into play by virtue of their ability to concentrate the mechanical energies of seismic waves and seismic ambient noise. It should be noted that seismic metamaterials were first studied in the case of earthquakes [1]. City vibrations are also of interest to researchers, who are using the fibre optics (D.A.S. – Distributed Acoustic Sensing) already installed in cities as a gigantic network of seismic sensors [15-16]. Distributed Acoustic Sensing is a technology that enables continuous, real-time measurements along the entire length of a fibre optic cable. For example, each building can be modelled as an oscillator with soil-foundation interface conditions.

In urban areas and for the frequency range of interest for civil engineering structures (0.1 Hz to 30 Hz), the orders of magnitude for particle velocities at ground level are 10^{-6} to 10^{-5} m/s. For accelerations, values are of the order of 10^{-5} to 10^{-3} m/s^2. The rapid development of sensor sensitivity, miniaturization, falling costs and energy storage capacities will make it possible to exploit seismic ambient noise exacerbated by structured materials (in the ground or in buildings).

An example of potential application

One example of this approach is the use of speed bumps for car and truck traffic. Interestingly the vibratory regime is also constantly maintained by natural telluric activity, with all the micro-earthquakes being imperceptible to man, as well as by human activity on the surface. The advantage of structured soils, including metamaterials, is that they create a concentration of mechanical energy with the possibility to place a sensor in the best place to transform mechanical energy into electricity [17-19]. Anyone living in a building with a truck lane nearby can feel the vibrations produced (figure 2d). The twofold challenge of mitigating ground vibration and simultaneously harvesting the associated mechanical energy requires damping seismic waves in some areas and enhancing them in others through localization mechanisms (e.g. creating defect in otherwise periodic structures). It is therefore of foremost importance to further investigate interplay between seismic wave dispersion and dissipation in periodic, graded, quasiperiodic metamaterials [20-24]. Theoretical, numerical and experimental crossed analysis of site-city interactions as proposed in [25] is a promising route towards the design of seismic metamaterials with applications ranging from earthquake protection and reduction of seismic ambient noise caused by human activities to seismic energy harvesting in urban areas.

Concluding Remarks

The development of building construction is steadily moving towards smart buildings and cities. All free energies will be exploited: solar, geothermal, wind energy, seismic ambient noise, etc. A decisive turning point in the evolution of seismic metamaterials is their ability to create energy channels - rather chaotic as there is a certain level of unpredictability in current models (notably due to soil's inherent anisotropy, heterogeneity, absorption and various sources of non-linearities), but potentially profitable for installing sensing devices.

References

[1] S. Brûlé, E.H. Javelaud, S. Enoch, S. Guenneau, "Experiments on Seismic Metamaterials: Molding Surface Waves," Phys. Rev. Lett., vol. 112, 133901, 2014.

[2] S. Brûlé, E.H. Javelaud, S. Enoch, S. Guenneau, "Flat lens effect on seismic waves propagation in the subsoil," Sci. Rep., vol. 7, 18066, 2017.

[3] S. Brûlé, S. Guenneau, "Past, present and future of seismic metamaterials: experiments on soil dynamics, cloaking, large scale analogue computer and space–time modulations," C. R. Phys., vol. 21, no 7-8, pp. 767-785, 2020.

[4] S. Brûlé, S. Enoch, S. Guenneau, "The importance of full-scale experiments for the study of seismic metamaterials," in Encyclopedia of Condensed Matter Physics (Second Edition), Tapash Chakraborty, Eds. Academic Press, pp. 519-528, 2024.

[5] M. Miniaci, A. Krushynska, F. Bosia, N.M. Pugno, "Large scale mechanical metamaterials as seismic shields," New Journal of Physics, vol. 18, no 8, 083041, 2016.

[6] Y. Achaoui Y., T. Antonakakis, S. Brûlé, R.V. Craster, S. Enoch, S. Guenneau, "Clamped seismic metamaterials: Ultra-Low Broad Frequency stopbands," New J. Phys., vol. 19, 063022, 2017.

[7] P-Y. Bard, M. Campillo, F.J. Chávez-Garcia, F.J. Sánchez-Sesma, "The Mexico earthquake of September 19, 1985 - A theoretical investigation of large-and small-scale amplification effects in the Mexico City Valley, Earthquake Spectra," vol. 4, no 3, pp. 609–633, 1988.

[8] A. Diatta, Y. Achaoui, S. Brûlé, S. Enoch, S. Guenneau, "Control of Rayleigh-like waves in thick plate Willis metamaterials," AIP Adv., vol. 6, issue 2, Dec., 121707, 2016.

[9] B. Ungureanu, Y. Achaoui, S. Enoch, S. Brûlé, S. Guenneau, "Auxetic-like metamaterials as novel earthquake protections," EPJ Appl. Metamat, vol. 2, no. 17, pp. 1-8, 2015.

[10] V. La Salandra, M. Wenzel, O.S. Bursi, G. Carta, A.B. Movchan, "Conception of a 3D metamaterial-based foundation for static and seismic protection of fuel storage tanks," Frontiers in Materials vol. 4, 30, 2017.

[11] J.H.G. McDonald, "Lateral Excitation of Bridges by Balancing Pedestrians," Proc. R. Soc. A 465, pp. 1055-1073, 2009.

[12] M. Brun, A.B. Movchan, I.S. Jones, "Phononic band gap systems in structural mechanics: finite slender elastic structures and infinite periodic waveguides," Journal of Vibration and Acoustics vol. 135, no. 4, 041013, 2013.

[13] P. Roux, D. Bindi, T. Boxberger, A. Colombi, F. Cotton, I. Douste-Bacque, S. Garambois, P. Gueguen, G. Hillers, D. Hollis, T. Lecocq, I. Pondaven, "Toward seismic metamaterials: the METAFORET project," Seismological Research Letters, vol. 89, no 2A, pp. 582-593, 2018.

[14] M. Pilz, P. Roux, S.A. Mohammed, R.F. Garcia, R. Steinmann, C. Aubert, F. Bernauer, P. Guéguen, M. Ohrnberger, F. Cotton, "Wind turbines as a metamaterial-like urban layer: an experimental investigation using a dense seismic array and complementary sensing technologies," Front. Earth Sci. Vol. 12, 1352027, 2024.

[15] J. Rodet, S. Brûlé, Ph. Gueguen, B. Tauzin, O. Coutant, V. Lanticq, R. Rollet, J. Granger, O. Depret, “Fibres optiques, sismologie et géotechnique pour ville intelligente : le projet DASARA à Lyon,” In Proc. 11ème JNGG 2022, 28-30 juin 2022, Lyon, France, pp. 917-925, 2022.
[16] J. Rodet, B. Tauzin, M. Amin Panah, P. Guéguen, D. Nziengui Ba, O. Coutant, S. Brûlé, “Urban dark fiber distributed acoustic sensing for bridge monitoring,” Structural Health Monitoring, 2024;0(0), 2024.
[17] A. Pirisi, F. Grimaccia, M. Mussetta, R.E. Zich, “Novel Speed Bumps Design and Optimization for Vehicles’ Energy Recovery in Smart Cities,” Energies, vol. 5, pp. 4624-4642, 2012.
[18] G.J. Chaplain, J.M. De Ponti, G. Aguzzi, A. Colombi, R.V. Craster, “Topological Rainbow Trapping for Elastic Energy Harvesting in Graded Su-Schrieffer-Heeger Systems,” Phys. Rev. Applied vol. 14, 054035, 2020.
[19] S. Brûlé, S. Enoch, S. Guenneau, “State of the art on the recovery of mechanical energy in the city. The role of seismic metamaterials,” in Proceedings of the XVIII ECSMGE 2024 in Lisbon, N. Guerra, M. Matos Fernandes, C. Ferreira, A. Gomes Correia, A. Pinto, P. Sêco e Pinto (eds.), CRC, pp. 3483-3486, 2024.
[20] M.I. Hussein, M.J. Frazier, “Metadamping: An emergent phenomenon in dissipative metamaterials,” Journal of Sound and Vibration, vol. 332, pp. 4767-4774, 2013.
[21] V.K. Dertimanis, I.A. Antoniadis, E.N. Chatzi, “Feasibility analysis on the attenuation of strong ground motions using finite periodic lattices of mass-in-mass barriers,” Journal of Engineering Mechanics, vol; 142, nº 9, 04016060, 2016.
[22] Y. Achaoui, B. Ungureanu, S. Enoch, S. Brûlé, S. Guenneau, “Seismic waves damping with arrays of inertial resonators,” Extreme Mechanics Letters, vol. 8, pp. 30-37, 2016.
[23] Z. Cheng, Z. Shi, A. Palermo, H. Xiang, W. Guo, A. Marzani, “Seismic vibrations attenuation via damped layered periodic foundations,” Engineering Structures, vol. 211, 110427, 2020.
[24] S. Brûlé, S. Enoch, S. Guenneau, “Emergence of seismic metamaterials: Current state and future perspectives,” Physics Letters A, vol. 384, no 1, 126034, 2020.
[25] L. Schwan, C. Boutin, L.A. Padrón, M. Dietz, P-Y. Bard, C. Taylor, “Site-city interaction: theoretical, numerical and experimental crossed-analysis,” Geophysical Journal International, vol. 205, no 2, pp. 1006-1031, 2016.

Nanophononic metamaterials: Thermal conductivity reduction by atomic-scale local resonances

Mahmoud I. Hussein,
University of Colorado Boulder, USA

Status

Phononics is an emerging field that seeks to elucidate the nature of intrinsic vibrational motion in artificially structured materials, and uses this knowledge to bring rise to unique and often superior forms of physical behaviour compared to conventional materials. The field bridges multiple disciplines across materials physics and engineering, and spans multiple scales reaching the atomic scale where a rigorous definition of phonons originates–quanta of lattice vibrations. In this section, the concept of a metamaterial is taken to the nanoscale realm where the notion of a *nanophononic material* (NPM) resides [1]. An NMP is a nanostructured crystalline material that comprises two components: (1) a host medium where thermal transport takes place and (2) intrinsic substructures that serve as nanoresonators. A common configuration of an NPM, for example, is a freestanding membrane (thin film) with a periodic array of nanoscale pillars extruding from one or both free surfaces. The base membrane and nanopillars could be made out of a semiconductor, such as silicon. Heat is partially transported along the base membrane segment of this configuration in the form of vibrational wave propagation, referred to as *phonons*. The atoms making up the miniscule pillars on their part generate stationary vibrational waves, referred to as *vibrons*. These two types of waves linearly couple to from an avoided crossing in the nanopillared membrane's phonon band structure [2]; see Fig. 1. This coupling process causes a hybridization between the two corresponding mode types, the traveling modes and the standing modes. This in turn causes reductions in the base membrane phonon group velocities, as well as enables the generation of new modes localized spatially in the nanopillar portion(s); it also reduces, albeit moderately, the phonon lifetimes at and around the phonon-vibron coupling regions in the phonon band structure. These effects together cause a drop in the in-plane lattice thermal conductivity of the hosting membrane [3]. It's noteworthy that an NPM does not necessarily need to be periodic, although periodicity is convenient for analysis and design. While electromagnetic [4] and acoustic [5] metamaterials are championed because of their unique resonant properties in the subwavelength regime (i.e., where the microscopic architectural features are much smaller than the travelling wavelength), the intrinsic resonances in an NPM produce desirable effects across the entire spectrum, including the superwavelength regime. Another key difference is that phonon motion in an NPM is dominated by anharmonic (nonlinear) effects due to the nature of interatomic interactions. It is therefore necessary to ensure that the nanoresonator features are smaller than the mean free path of most of the phonon modes at the temperature of interest [6]. Since their discovery in 2014, NPMs have attracted numerous research exploring a wide range of base materials and geometric configurations, such as nanowires with nanoresonating walls [7], graphene ribbons with nanoresonating flaps [8], carbon nanotubes [9] and graphene sheets [10] with nanoresonating bucky balls, among others [6]. Recently, a project partially funded by the Advanced Research Projects Agency-Energy (ARPA-E) produced the first experimental validation of NPMs demonstrating not only reduction in the thermal conductivity but also a decoupling between the thermal and electrical properties—a much desired outcome for thermoelectric energy conversion [11]. A significant advance in the efficiency of a thermoelectric device based on materials with favorable cost, fabrication, and device integration attributes—all possible with NPMs—has the potential to spark a revolution in solid-state energy conversion across numerous industries. Promising applications include recovery of waste heat in power plants, computer microprocessors, vehicle engines; improvement of solar cell efficiency; development of efficient solid-state (e.g., fluid- and compressor-free) air conditioning and refrigeration.

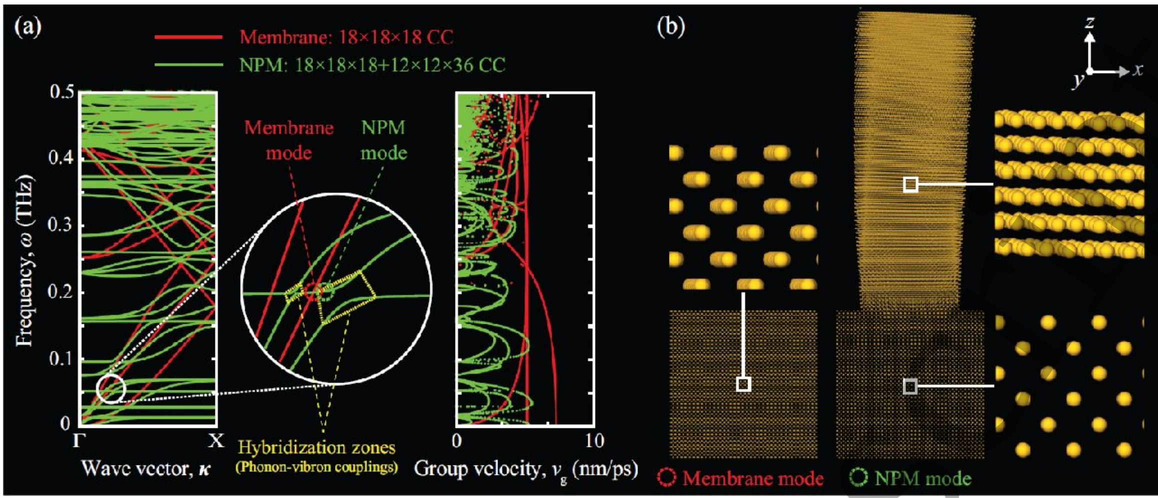


Figure 1. Phonon band structure and mode shapes for a nanophononic metamaterial in the form of an all-silicon nanopillared membrane. (a) Phonon frequency and group velocity dispersion curves of a silicon membrane with (green) or without (red) silicon nanopillars standing on one surface. (b) Membrane atomic displacements for a phonon mode without and the addition of a nanopillar in the unit cell. The uniform membrane mode shape shows significant motion. In contrast, the NPM hybridized mode shape exhibits localized nanopillar motion and almost "thermal silence" in the base membrane portion. In (a), a zoom-in is provided for two hybridization zones including the one illustrated in (b). A magnification factor of 2000 is applied to the atomic displacements in the mode-shape images. [3]

Current and Future Challenges

The research published on NPMs has established a new research area in nanoscale thermal transport that promises rewarding results not only in producing new nanostructured materials with exceptionally low thermal conductivity [3,6-10] and high thermoelectric energy conversion figure of merit [11], but also potentially impacting other domains in condensed matter physics in general where phonons play a critical role in shaping intrinsic properties. However, numerous research issues and challenges remain ahead, particularly on the nanofabrication, quality control, and device integration fronts. A key requirement for an NPM to function is to ensure that the feature sizes at the unit-cell level (for a periodic configuration, for example) are small compared to the mean free paths (MFP) of the phonons. Given that the thermal transport is carried by a large number of phonons, defined across the unit-cell's Brillouin zone and spanning the full spectrum, it is desirable to limit the feature sizes to at least the average phonon MFP at the temperature of interest, which is estimated to be a few hundred nanometers in silicon [12]. This, in turns, places considerable size constraints on the nanofabrication process, whether it is based on a form of epitaxial growth [11] or E-beam lithography techniques [13]. Furthermore, the nanoresonators, e.g., nanopillars on a membrane, must be composed of a single-crystal material with minimal defects to avoid excessive reduction of the phonon MFP, which would prevent the resonances from influencing the phonons traveling in the host material, e.g., the base membrane supporting the nanopillars [6]. Such stringent requirements on material quality imposes constraints on the nanofabrication process, including the need for avoidance of undesired residual stress, diffusion of elements, and rough surfaces [11]. Lastly, an NPM will only be effective when integrated into a device structure with minimal parasitic losses. Given the need for nanoscale features, such fabrication challenges must be addressed in a manner as to keep open a path for upscaling and mass production—in order to meet economic feasibility targets.

Advances in Science and Technology to Meet Challenges

Future research will target further NPM nanofabrication and characterization with a focus on optimizing relative design dimensions to maximize the resonance hybridization effect and realize its maximum impact within an experimental setting. These steps must capitalize on the recent advances

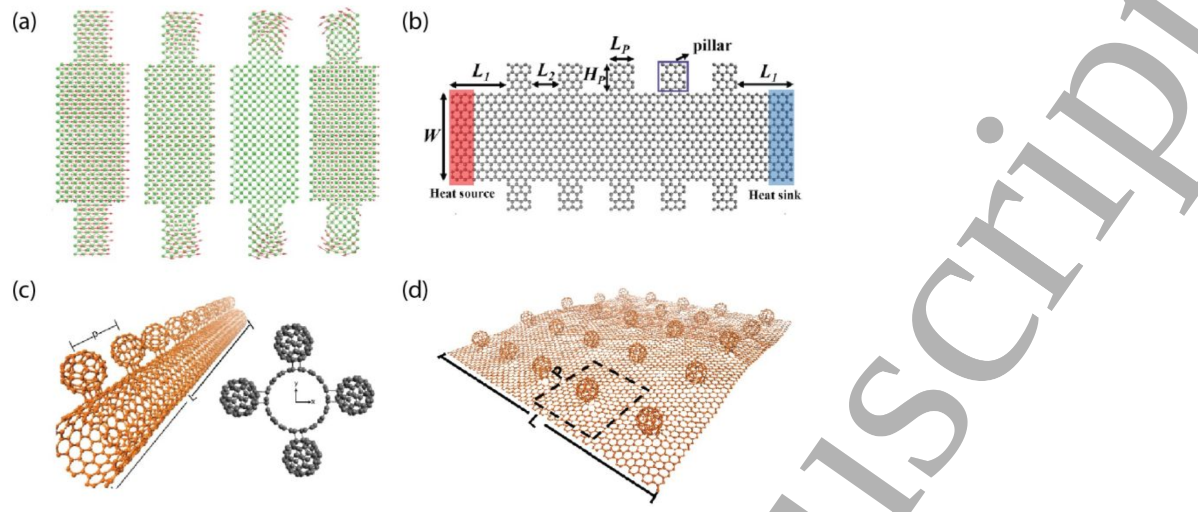


Figure 2. Atomic-scale configurations of various types NPMs investigated in the literature: (a) silicon nanowire with extruding silicon walls serving as nanoresonators [7], (b) graphene sheet with carved out flaps acting as nanoresonators, of passive downstream flow stabilization by a MIMO PSub [8], (c) carbon nanotube with carbon bucky balls as nanoresonators [9]. (d) graphene sheet with carbon bucky balls as nanoresonators [10].

in nanofabrication and characterization technology, particularly lithography and laser spectroscopy techniques, respectively. Parallel advances in high-performance computing and machine learning will enable faster and more accurate prediction of the performance of atomic-scale NPM models, which is needed for efficient realization of the experimental targets. Furthermore, new configurations of NPMs, based on different constituent materials, will emerge to impact a wide range of applications; see, for example, the NPM architectures shown in Fig. 2.

Concluding Remarks

The concept of NPMs bridges the fields of elastic metamaterials with condensed matter physics, with a promise to impact a vast array of applications in materials physics including thermal management, thermoelectricity, quantum devices, and more. Realization of tunable, broad-spectrum phonon resonances intrinsically in a crystalline material is a concept that alters the fundamental properties of the material, at the atomic level, as demonstrated by the changes in the thermal conductivity. Other key material properties may be altered as well by the phonon resonances. Other aspects that will grow in the future is further understanding of phonon resonances from a variety of perspectives, such as their localization properties [14] and their thermodynamics behaviour [15]. As basic research on NPMs develops further, opportunities for industrial applications will present themselves, particularly with the continuing advances in nanodevice technology. Similar to impactful technologies that have transformed society over the last few decades, such as the transistor, the laser, the solar cell, and the Global Positioning System, NPMs will only reach its maximum potential with the collective effort of multidisciplinary research communities and the support of government agencies and industrial ventures.

Acknowledgements

The author acknowledges funding for research on nanophononic metamaterials from the National Science Foundation and the Advanced Research Projects Agency—Energy. The author is grateful to Dr. Kris Bertness and her team at the National Institute of Standards for the long-term research collaboration that has recently led to the first experimental validation of NPMs [11]. The author also acknowledges M. Murnane, M. Lee, I. Smalyukh, Y.C. Lee, H. Branz, and E.S. Toberer and their respective teams for their collaboration on various aspects of the problem. In addition, the author acknowledges his former and current doctoral students and postdoctoral researchers B.L. Davis, H. Honarvar, L. Yang, C.-N. Tsai, and P. Rawte, as well his collaborators A. Beardo, P. Desmarchelier, and K. Termentzidis for their contributions.

References

[1] B. L. Davis and M. I. Hussein, "Nanophononic metamaterial: Thermal conductivity reduction by local resonance," *Physical Review Letters*, vol. 112, p, 055505, 2014.

[2] H. Honarvar and M. I. Hussein, "Spectral energy analysis of locally resonant nanophononic metamaterials by molecular simulations," *Physical Review B*, vol. 93, p. 081412(R), 2016.

[3] H. Honarvar and M. I. Hussein, "Two orders of magnitude thermal conductivity reduction in silicon membranes by resonance hybridizations," *Physical Review B*, vol. 97, p. 195413, 2018.

[4] J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, pp. 2075, 1999.

[5] Z. Y. Liu, X. X. Zhang, Y. W. Mao, Y. Y. Zhu, Z. Y. Yang, C. T. Chan, P. Sheng, "Locally resonant sonic materials," *Science*, vol. 289, pp. 1734, 2000.

[6] M. I. Hussein, C.-N. Tsai, and H. Honarvar, "Thermal conductivity reduction in a nanophononic metamaterial versus a nanophononic crystal: Review and Comparative Analysis," *Advanced Functional Materials*, vol. 30, p. 1906718, 2020.

[7] S. Xiong, K Sääskilahti, Y. A. Kosevich, H. Han, D. Donadio, and S. Volz "Blocking phonon transport by structural resonances in alloy-based nanophononic metamaterials leads to ultralow thermal conductivity," *Physical Review Letters*, vol. 117, p. 025503, 2016.

[8] D. Ma, X. Wan, and N. Yang, "Unexpected thermal conductivity enhancement in pillared graphene nanoribbon with isotopic resonance," *Physical Review B*, vol. 98, p. 245420, 2018.

[9] A. Giri and P. E. Hopkins, "Giant reduction and tunability of the thermal conductivity of carbon nanotubes through low-frequency resonant modes," *Physical Review Letter*, vol. 98, p. 045421, 2018.

[10] A. Giri and P. E. Hopkins, "Resonant phonon modes in fullerene functionalized graphene lead to large tunability of thermal conductivity without impacting the mechanical properties," *Journal of Applied Physics*, vol. 125, p. 205102, 2019.

[11] B. T. Spann, J. C. Weber, M. D. Brubaker, T. E. Harvey, L. Yang, H. Honarvar, C.-N. Tsai, A. C. Treglia, M. Lee, M. I. Hussein, and K. A. Bertness, "Semiconductor thermal and electrical properties decoupled by localized phonon resonances," *Advanced Materials*, vol. 35, p. 2209779, 2023.

[12] K. Esfarjani, G. Chen, H. T. Stokes, "Heat transport in silicon from first-principles calculations," *Physical Review B*, vol. 84, p. 085204, 2011.

[13] J. Lees, B. Durham, C. Reardon, M. Anderson-Taylor, M. Probert, P. Hasnip and S. Thompson, "Nanoscale Si fishbone structures for manipulating heat transport using phononic resonators for thermoelectric applications," *Physica Scripta*, vol. 98, p. 095928, 2023.

[14] A. Beardo, P. Desmarchelier, C.-N., Tsai, P. Rawte, K. Termentzidis, and M.I. Hussein, "Resonant phonons: Localization in structurally ordered crystals," *Physical Review B*, vol. 110, p. 195438, 2024.
[15] A. Beardo, P. Rawte, C.-N. Tsai, and M.I. Hussein, "Entropic signature of resonant thermal transport: Ordered form of heat conduction," *Proceedings of the Royal Society A*, under review; arXiv 2404.15831v3.

Manufacturing, metrology and scale-up

Section 18 - Manufacturing, Metrology, and Scale-up

Stoakes, Rachel (University of Strathclyde). McLean, Conor (Edinburgh Napier University). Gardiner, Alicia (University of Glasgow).

Status

Despite rapid development in recent years, both in modelling and fabrication, and the realisation of practical applications, Acoustic Metamaterials (AMMs) remain underutilised by industry. Particularly attractive uses for AMMs are for noise control at frequencies in the audible range (16Hz – 20kHz) and absorption for medical devices at ultrasonic frequencies (≥ 20kHz). Here, a discussion on applications relevant to these use cases is provided below.

The prevalence of building acoustics design and environmental noise applications demonstrates a strong need for new acoustic absorbing materials. Environmental noise, typically widespread in its coverage, is routinely associated with poor health and is linked closely with psychological symptoms and the use of psychotropic medications [1]. To address increasing demand for low-cost, high-density housing, metamaterials may offer extraordinary noise attenuation solutions for separating panel designs with enhanced sound absorption [2], for example – see ***Figure 1A***. Considerable work is being done in the aeronautics industry to reduce excessive noise levels from aircraft. Current approaches involve using wall lining absorbers that exploited quarter wavelength absorption – metamaterials offer a sub-wavelength, enhanced noise reduction though Fabry-Perot resonance [3].

Metamaterial design for ultrasonic frequencies would be especially useful for use in medical ultrasound applications such as imaging or therapy, which are rapidly growing fields in ultrasonics. While there have been many studies focused on the theory behind AMMs, designs for the ultrasonic regime approaching the Megahertz range are largely still not reported in the literature [4], mainly due to the difficulty in manipulating extremely small wavelengths. ***Figure 1B*** shows an example of AMMs applied in medical ultrasonics. Additionally, the experimental realization of theoretical high frequency models has still been slow to progress, in part attributed to the small, complex features required.

Fabrication approaches like additive manufacturing have already been applied to realise early AMM prototypes, with a variety of extraordinary properties demonstrated. Additive manufacturing has been identified as a potential solution to fabricate the small features required for high-frequency ultrasonic metamaterials [5]. While manufacturing methods that utilize a single-step approach can create periodic structural elements with high validity, a multi-step fabrication approach is the preferred choice to obtain elaborate features in the micro and even nanoscale [6].

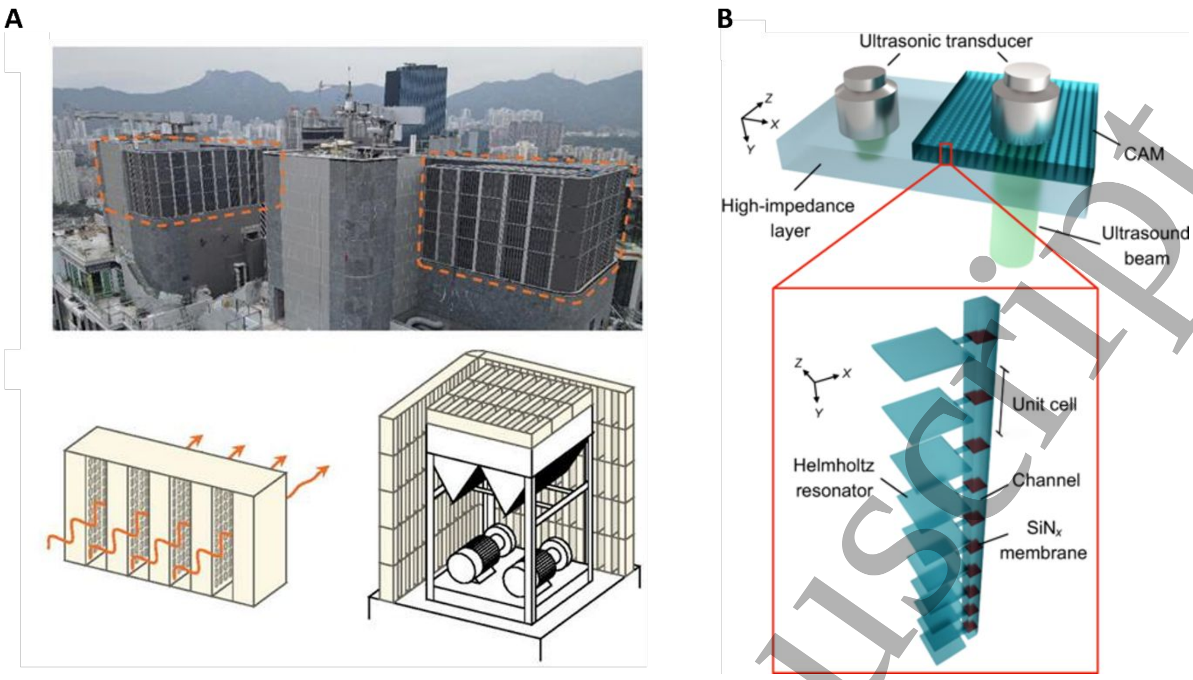


Figure 1A: A structured metamaterial panel for noise absorption. This ventilated silencer is made of an array of several acoustic metamaterial panels and combine to form a 3D enclosure. The dimensions are customized to target the noise spectrum of specific devices (Pumps and chillers in this example). [Reproduced from [2], under Creative Commons CC-BY License]. ***Figure 1B:*** Metamaterial design for a matching layer in an ultrasonic transducer. This design bridges the impedance mismatch between the transducer and material of interest, resulting in extraordinary acoustic transmission. [Reproduced with permission from [10]. © [2021] American Physical Society].

Current and Future Challenges

While additive manufacturing shows promise, techniques are not yet progressed enough for the high throughput scenarios required in commercial use. Different AMM applications have extremely varied requirements, and hence face different challenges in their widespread deployment. For these complex structures, cost is arguably the main apprehension when looking at large scale industrial deployment [3].

Challenges associated with applying ultrasonic metamaterials include the resolution needed to manufacture subwavelength structures that are, in most cases, fundamental components of metamaterials [7]. To implement theoretical designs into industrial applications, versatility is important in device design. Examples of increasing versatility include, broadening working bandwidths and increasing absorption properties with reduced thicknesses [7]. This issue could be addressed through Active AMMs - metamaterials that can be altered through an external stimulus - to create tuneable broadband absorbers/attenuators.

Manufacturing AMM devices is difficult due to their unique structures and surpass the current capabilities of pre-existing fabrication techniques [8], see ***Figure 2*** for further detail. The three broad types of 3D printing are: Vat Polyermization; Powder Bed Fusion; and Extrusion/Deposition. These span a wide range of resolutions (see ***Figure 2***). Despite the significant promise of Vat Polymerisation techniques, a major disadvantage is its failure to incorporate multi-material capabilities [6]. Active AMMs have a variety of frequency modulation methods, however all require specialist materials typically incompatible with additive manufacturing techniques. The use of support structures in additively manufactured parts have increased design flexibility. However, the addition and removal of supports introduces some challenges, namely the overuse of time, energy, and increased cost from additional materials [5].

An additional challenge in AMM manufacturing is the tolerance difference between the original and final part dimensions. Dimensional metrology is crucial for metamaterial development, due to the nature of metamaterials' function being solely reliant on their geometric structure. Options for measuring and assessing the quality of metamaterial fabrication are visual inspection, callipers/rulers, CT scanning and Non-Destructive Testing (NDT) methods such as using pitch-catch transducers. Despite these examples, there is still no standardised method for measuring AMM fabrication conditions, which consequently is hindering the manufacturing quality in preparation for industrial scale-up [9].

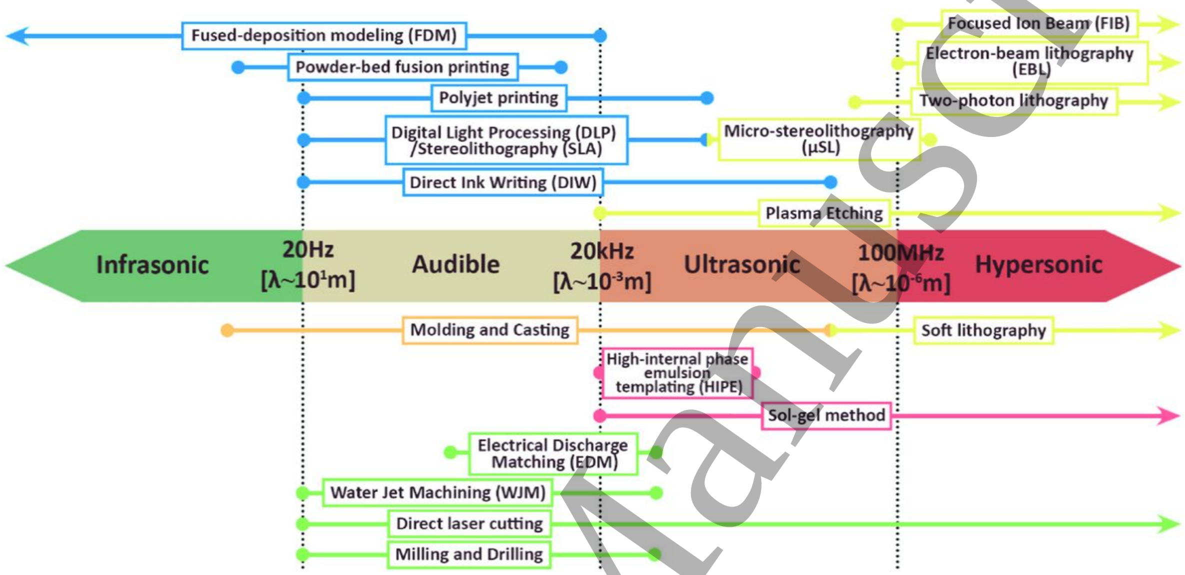


Figure 2: "Phononic spectrum showing the fabrication methods for various operating frequency ranges for AMMs and PCs. The colour schemes for the lines and boxes denote the type of fabrication method. Blue refers to "3D printing," green refers to "machining," yellow refers to "microfabrication," orange refers to "molding and casting," and coral pink refers to "microfluidics and wet-chemical techniques." λ refers to the order of the wavelength of the listed frequency." [Reproduced from [6] under the Creative Commons CC-BY Licence]

Advances in Science and Technology to Meet Challenges

A key topic of interest for metamaterial research progress is additive manufacturing, and in turn, the ability to assess fabrication quality. The quality requirements vary substantially depending on application area. For building acoustics, there is a need for AMMs with large dimensions and high detail that can be scaled up. In the medical field, sub-micron resolutions are relevant for high frequency devices, therefore manufacturing precision is extremely important. Despite different requirements, multi-material printing is a promising development that would enable further advancements for both applications alike.

To progress additive manufacturing methods, minimum feature size, material options and scale-up potential are of interest. Vat polymerisation methods show promise in terms of minimum feature size, with dimensions approaching the nanoscale. Digital light processing enables many parts to be printed simultaneously with no additional time and could be honed to produce detailed parts on an industrial scale [8]. Extrusion/deposition techniques show the most potential for multi-material printing and material options. For example, direct ink writing can utilise a large selection of materials and can print dimensions as small as 100 μm, but insufficient time has been devoted to these microfabrication approaches to uncover their full potential for the fabrication of high-frequency acoustic devices [6]. Similarly, micro-stereolithography has been identified as promising to create AMMs that are functional up to 2 MHz [4]. Additionally, the design of support structures of additively manufactured parts needs to be better developed. Studies have been carried out to investigate the introduction of support structures that can be dissolved for ease in post processing [5].

Alongside manufacturing progress, there also needs to be a standardized method of measuring part dimensions. Regarding metrology, uptake and development of methods considered unconventional is required before the quality of metamaterial parts can be assessed on an industrial scale. A study using x-ray CT technology to assess lattice structure dimensions suggest a blend of techniques could alleviate issues associated with unit-cell structure measurement [9]. Without this focus on metrology, there would be no way to ensure uniform, high-quality AMM devices, which is vital for industrial use.

Concluding Remarks

This work identifies the key applications relevant to AMMs, and the respective issues associated with manufacturing and measuring these devices. Two key applications, noise attenuation and medical imaging, have widely different requirements, and therefore, separate recommendations for progress in each field.

Acoustic attenuation applications require both high detail and in-bulk production. Digital Light Processing and Extrusion Techniques offer robust resolutions while allowing production scale-up with minimal time penalties. For metrology, standard methods like callipers, visual inspection, and NDT may be sufficient – dependant on design complexity. Ultrasonic applications require precise fabrication at sub-micron resolution, as such, micro-stereolithography is a method of interest. Alongside this, hybrid CT-scanning techniques show promise for assessing part quality in high resolution. For adjustable AMMs, extrusion deposition methods show the best multi-material capabilities with limited resolution. In general, significant further innovation in additive manufacturing is required before the production of AMMs is observed at greater scale in industry, and their notable benefits utilised.

Acknowledgements

Rachel Stoakes and Alicia Gardiner are funded by the Engineering and Physical Sciences Research Council (EPSRC). Proofreading Contributions by Dr Andrew Feeney (University of Glasgow).

References

[1] S. Stansfeld, M. Haines, and B. Brown, "Noise and health in the urban environment," *Reviews on Environmental Health*, vol. 15, no. 1–2, 2000. doi:10.1515/reveh.2000.15.1-2.43

[2] M. Yang and P. Sheng, "Acoustic metamaterial absorbers: The path to commercialization," *Applied Physics Letters*, vol. 122, no. 26, 2023. doi:10.1063/5.0147941

[3] G. Palma, H. Mao, L. Burghignoli, P. Göransson, and U. Iemma, "Acoustic metamaterials in Aeronautics," *Applied Sciences*, vol. 8, no. 6, p. 971, 2018. doi:10.3390/app8060971

[4] M. Askari et al., "Additive Manufacturing of Metamaterials: A Review," *Additive Manufacturing*, vol. 36, p. 101562, 2020. doi:10.1016/j.addma.2020.101562

[5] X. Wu, Y. Su, and J. Shi, "Perspective of additive manufacturing for metamaterials development," *Smart Materials and Structures*, vol. 28, no. 9, p. 093001, 2019. doi:10.1088/1361-665x/ab2eb6

[6] C. Choi, S. Bansal, N. Münzenrieder, and S. Subramanian, "Fabricating and assembling acoustic metamaterials and Phononic Crystals," *Advanced Engineering Materials*, vol. 23, no. 2, 2020. doi:10.1002/adem.202000988

[7] X. Zhang, Z. Qu, and H. Wang, “Engineering acoustic metamaterials for sound absorption: From uniform to gradient structures,” *iScience*, vol. 23, no. 5, p. 101110, 2020. doi:10.1016/j.isci.2020.101110

[8] A. Gardiner et al., “Additive manufacture of small-scale metamaterial structures for acoustic and ultrasonic applications,” *Micromachines*, vol. 12, no. 6, p. 634, 2021. doi:10.3390/mi12060634

[9] P. Sperling, A. du Plessis, and G. Schwaderer, “Challenges and approaches for metrology of additive manufactured lattice structures by industrial X-ray computed tomography,” *Advanced Materials Research*, vol. 1161, pp. 131–136, 2021. doi:10.4028/www.scientific.net/amr.1161.131

[10] J. Wang, F. Allein, N. Boechler, J. Friend, and O. Vazquez-Mena, “Design and fabrication of negative-refractive-index metamaterial unit cells for near-megahertz enhanced acoustic transmission in biomedical ultrasound applications,” *Physical Review Applied*, vol. 15, no. 2, 2021. doi:10.1103/physrevapplied.15.024025