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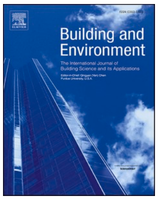

Acoustic metamaterials for sound absorption and insulation in buildings

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ABSTRACT

Despite the emergence of acoustic metamaterials with superior sound absorption and transmission loss, their adoption for building sound insulation has been limited. Sound insulation design in buildings is still informed by the acoustic performance of conventional materials, where the mass law contradicts light weighting when it comes to acoustic design. In any case buildings close to noisy environments such as motorways, railway lines and airports still suffer from significant low frequency noise pollution. Although the limited working bandwidth of acoustic metamaterials is a major issue limiting its application, combining meta-units that interact at various frequencies alongside multi-layer conventional solutions can deliver superior sound insulation in buildings. The review put forwards acoustic metamaterials, specifically emphasising superior sound absorption and transmission/insertion loss as critical properties for effective building sound insulation. The paper reveals a variety of acoustic metamaterials that can be adopted to compliment conventional sound insulation approaches for acoustically efficient building design. The performance of these metamaterials is then explained through their characteristic negative mass density, bulk modulus or repeating or locally resonating microstructure. The review is also extended to air transparent acoustic metamaterials that can be used for sound insulation of building ventilation. Lastly the prospects and challenges regarding the adoption of acoustic metamaterials in building insulation are also discussed. Overall, tuneable, and multifunctional acoustic metamaterials when thoughtfully integrated to building sound insulation can lead to significant acoustic comfort, space-saving and light-weighting.

1. Introduction

The relevant metamaterial acoustic parameters that are of interest when it comes to sound insulation in buildings are the coefficient of sound absorption (α) and the sound transmission loss or the sound reduction index (R) they can offer. Conventional materials offer limited performance when it comes to α and R at low frequency. Although natural fibres and recycled materials are eco-friendly alternatives to traditional building materials, they are also bound by similar physics leading to poor low frequency attenuation [1]. Furthermore, a large variety of both natural and synthetic materials have limitations such as high flammability and moisture absorption. While traditional building materials rely on their unique material architecture, density and porosity to offer improved global acoustic parameters, the performance of metamaterials are largely dictated by their geometric, structural or stiffness architecture allowing them to be conceived into a variety of suitable bulk materials [2].

The use of acoustic metamaterials for building insulation has gained significant attention due to their exceptional wave-control properties in challenging acoustic environments [3,4]. Metamaterials are artificially engineered materials that offer unique properties that are not typically found in bulk materials, making the field of metamaterial research interdisciplinary, involving fields such as electromagnetics, optics, solid-state physics, and acoustics. Acoustic metamaterials are constructed with periodic or non-periodic elements, resulting in targeted or exotic acoustic performance [5–10]. The physical acoustic phenomenon informing acoustic metamaterials are varied depending on the type of acoustic metamaterials and can be found in previous literature [5,11–13].

Metamaterials that can offer targeted sound absorption and sound

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reduction index offer exciting avenues for designing building components with targeted acoustic performance that may be difficult to achieve with natural materials [14,15]. The increasing fascination with broadening the range of acoustic metamaterials, combined with the liberty to design using additive manufacturing (3D printing) [16,17], could result in the emergence of new types of acoustic metamaterials. These could revolutionise insulation architecture and lead to the creation of thinner, more efficient, and eco-friendly building insulation in the future. To this extent, the review discusses sound absorption in acoustic metamaterials, covering both sound absorption (α) and sound reduction index (R) which are the two critical parameters from a building acoustics point of view. Acoustic metamaterials have the potential to revolutionise building design by making structures quieter, more comfortable, and energy-efficient [18].

New ideas and constructions for acoustic metamaterials (AMM) are still possible. Metamaterials having non-linear acoustic couplings and those composed of inhomogeneous and anisotropic component units, for instance, are still scarce. The limited working bandwidth of acoustic metamaterials is another major issue, which is still difficult to resolve. The technique might include compressing separate meta-units that interact at various frequencies, but it might also work well to combine metamaterials with conventional acoustic materials. However, without the requirement for laborious lab experiments, the majority of metamaterial applications in building acoustics are essentially case studies based on simulations or measurements carried out on plane wave excitation, often perpendicular plane wave excitation. Compiling simulation solutions from ANSYS and Comsol, the majority of the reports use the finite element technique analysis. Using a membrane-type metamaterial design, Yang et al. [19] completed a number of finite element simulations. The negative mass coefficient at the frequency where a total wave reflection happens was supported by their calculations.

The article explores the concept of acoustic metamaterials and their application in sound insulation for buildings. It presents the benefits of this technology and the challenges that need to be overcome to make it a viable solution for building design. To aid in metamaterial characterisation for building insulation, the basic concepts of sound absorption and sound reduction are also introduced and summarised in Fig. 1. Furthermore, a classification system is presented to determine the suitability of acoustic metamaterials for building insulation using “sound absorption” and “sound reduction index” as key parameters. The article highlights a variety of metamaterial architectures, including cavity-based, membrane-type, gradient-indexed, impedance-matched, scatterer-based, and ventilated acoustic metamaterials, that are deemed suitable for sound insulation. The article concludes by providing a summary of the potential applications of acoustic metamaterials in building insulation. A comprehensive overview of the concept and its relevance in sound insulation for buildings is presented. Furthermore, the technology’s potential for future building design is discussed.

2. Basic aspects of acoustic metamaterials in building design

2.1. Relevance of acoustic metamaterials

Sound insulation in buildings is the method of controlling noise through a range of acoustic techniques as highlighted in Fig. 1. This includes reducing the sound transmission from one space to another and controlling the reverberation characteristics within a space. Sound insulation is a critical consideration during the design and construction of buildings to meet the relevant standards in addition offer the acoustic comfort suitable for its operation. As such appropriate sound insulation in buildings have a significant impact on health and wellbeing, communication, and productivity of its occupants.

As shown in Fig. 1, the research on acoustic metamaterials have not yet matured to influence all areas of sound insulation in buildings. As such their applicability is primarily limited to areas of controlling airborne sound insulation. Acoustic metamaterials are well suited to replace or supplement traditional materials when it comes to sound absorption and sound reduction (soundproofing/sound transmission loss/insertion loss). Consequently, selecting and appropriately applying relevant acoustic metamaterials that offer high sound absorption can offer reverberation control that can significantly improve speech intelligibility and acoustic comfort in buildings.

A range of acoustic metamaterials have demonstrated high sound reduction or sound transmission loss, these metamaterial architectures

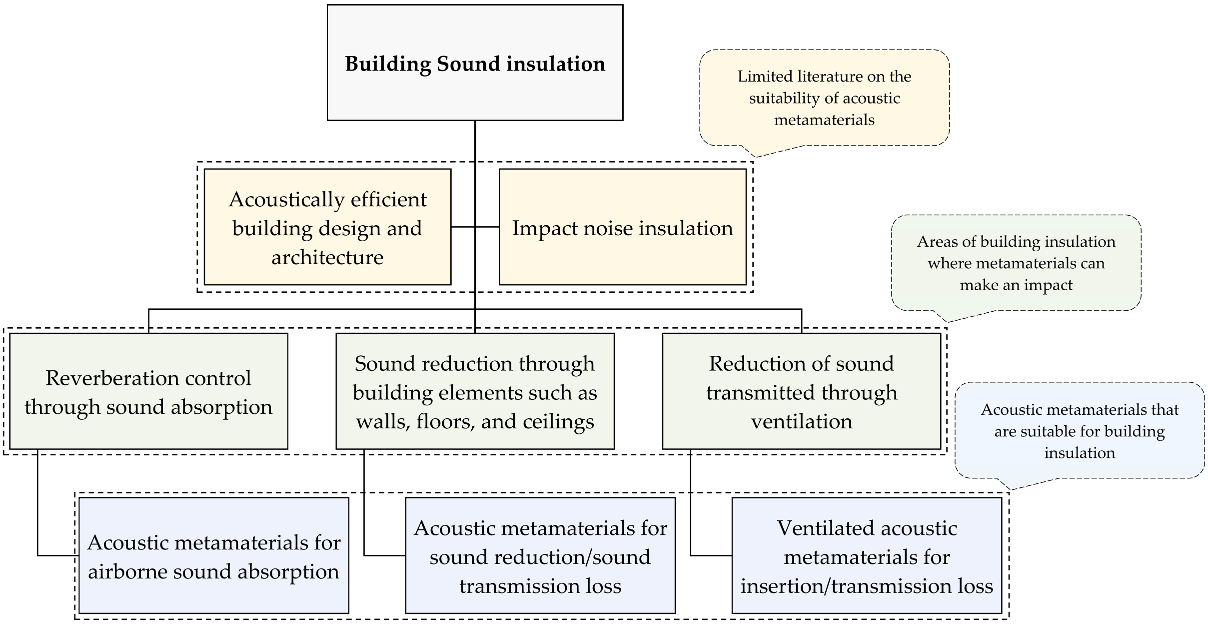


Fig. 1. Sound insulation in buildings showing potential areas where acoustic metamaterials can be applied to enhance performance through enhanced sound absorption, transmission loss or frequency control. These are the areas of focus when reviewing acoustic metamaterials in this paper. It is also highlighted that while areas such as building design and impact noise isolation contributes to the overall sound insulation of buildings metamaterials are yet to demonstrate their suitability for their application.

can work alongside traditional light-weight construction such as single leaf and double leaf walls construction to significantly reduce the sound transmitted from one space to other. Although the high cost of acoustic metamaterials is a limiting factor this is expected to reduce as further cost effective and mass market architectures are conceived. In addition, the area where acoustic metamaterials are expected to make the largest contribution is in the improvement of ventilated spaces such as air vents, ducts, and windows. Ventilated acoustic metamaterials are class of architecture that can significantly increase sound reduction by contributing to the insertion loss while allowing air flow. These materials can drastically improve the sound reduction performance of air vents, ducts, and air transparent windows.

Overall, when it comes to the selection of metamaterials for sound insulation in buildings that focus should be on the sound absorption and sound reduction performance of the metamaterial architecture. When it comes to ventilation design, the insertion loss which is like the transmission loss should be paid attention to. In this regard, the review is focused on identifying suitable acoustic metamaterials that can be used for sound insulation in buildings based on their high sound absorption and sound reduction performance. Before revealing a range of suitable acoustic metamaterials that may offer the potential to be adopted for sound insulation in building insulation, that relevant performance parameters namely sound insulation and sound reduction are briefly introduced. This review is focused on identifying both sound absorbing and sound reducing acoustic metamaterials and their different structures that can be adopted for building sound insulation. Once the literature on acoustic metamaterials for building acoustics matures, it becomes essential to compare the broadband performance of acoustic metamaterials in combination with conventional materials to identify the most suitable combination that offer the best broadband performance.

2.2. Sound absorption

Other than from an anechoic chamber, sound in buildings is composed of both the direct sound from a source and the indirect reflections from adjacent surfaces and objects. As such, controlling the sound reflections from the walls, floors and ceilings are an important consideration when it comes to sound insulation in buildings. The interaction of sound with a building component can result in transmission, absorption, or reflection of sound energy. This phenomenon is determined by the acoustic characteristics of the structure, and surfaces that effectively absorb sound are referred to as good sound absorbers. A visual representation of a building environment with and without sound absorption treatments is depicted in Fig. 2, illustrating the temporal and spatial aspects of sound within a space.

In building design, sound absorption plays an important role in mitigating noise and enhancing acoustic comfort. Although people often use the terms “sound absorption” and “sound insulation” interchangeably, they actually refer to different concepts. Sound absorbing materials are intended to enhance sound quality by minimising echoes and undesirable reverberations in a given space. They do not block sound, but rather reduce reflections. In contrast, sound reducing or soundproofing materials are utilised to decrease the amount of sound that passes through a material from one space to another, thereby serving as a sound barrier. Furthermore, sound absorbing materials are increasingly being used in the design of soundproofing materials [21].

When it comes to building acoustics, porous and resonant absorbers are generally used. The performances of these are mostly evaluated using the sound absorption coefficient (α) that varies from 0 to 1, representing no and complete absorption, respectively. Fig. 3 shows the sound absorption of some materials, including porous, resonant and metamaterials architectures. The most common type of porous absorbent is mineral wool, such as fiberglass has a representation performance as shown. Materials with pores for sound absorption allow sound waves to enter through channels, cracks, or cavities. Both heat and viscous loss, which are brought on by the materials’ viscous airflow and the friction against pore walls, contribute to the dissipation of sound energy. The limitation with porous materials is generally their ineffectiveness if the thickness is low in comparison to the wavelength. In addition, fabricating porous materials with a high sound absorption coefficient over the whole frequency range while maintaining the materials’ minimal thickness and light weight continues to be an enormous challenge. Flame resistivity and moisture resistance need to be considered to ensure the durability and stability of the porous sound absorption materials. In comparison, resonance and metamaterial-based architectures offers high peak sound absorption at targeted frequencies as shown in Fig. 3. This ability of acoustic metamaterial architectures can be adopted to offer superior sound absorption at frequencies that are challenging for traditional metamaterials. Exposed materials with high α in buildings targeted at controlling reverberations are examples of sound absorption treatments. Insulated building walls, floors and windows

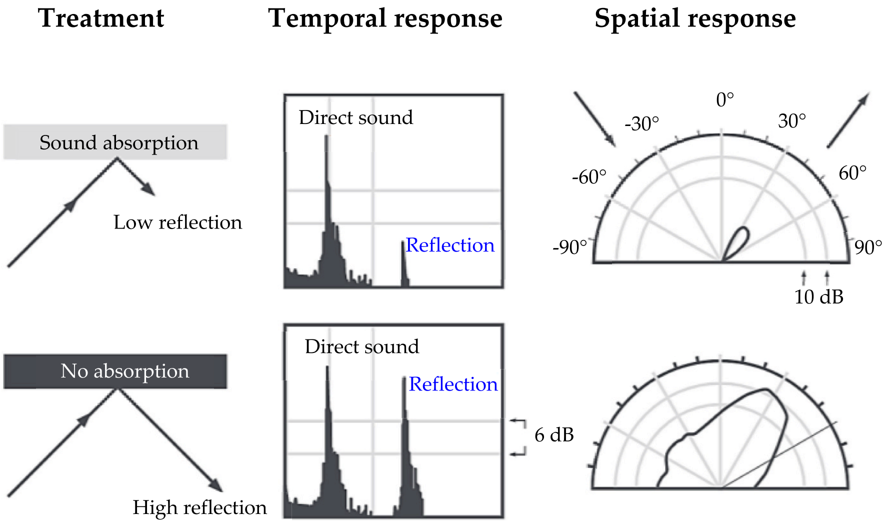


Fig. 2. The temporal and spatial response of using sound absorbing treatments compared with a case where no sound absorbing acoustic insulation is used in a room. Adapted from Cox and D’Antonio [20].

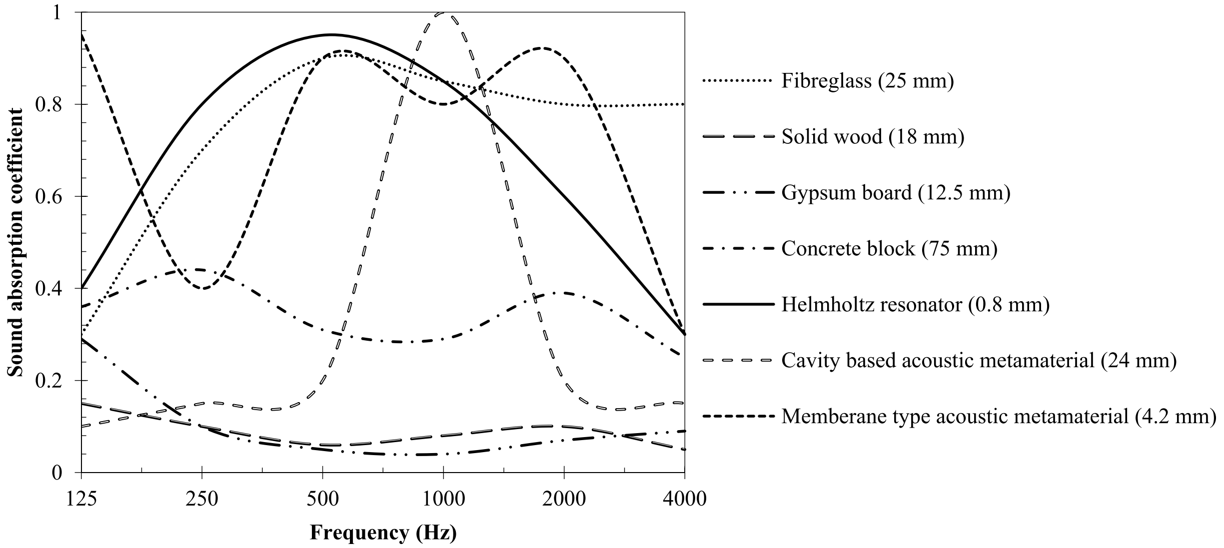


Fig. 3. Frequency dependent sound absorption coefficients of porous and resonant building materials compared with cavity with resonant and metamaterial type absorbers. Informed by data from literature [20,22–25].

with high sound reduction index are example of sound proofing structures. The sound absorbing and sound reducing treatments collectively represent noise mitigation strategies employed in a building and as such forms part of the building sound insulation strategy.

Theoretically, the ability of a structure or material to absorb sound is dependent on its acoustic impedance; the optimal sound absorption effect is only possible when the impedance of the material is equal to that of the sound propagation medium. Acoustic metamaterials use comparable negative characteristics and bandgaps to accomplish high sound absorption, with examples including Helmholtz cavities, membrane types, space coiling, gradient index, and adjustable acoustic metamaterials. Through careful design considerations, a Helmholtz resonator AMM can offer negative equivalent elastic modulus (EEM). The membrane-type AMM is made up of a small mass connected at the centre of the relatively hard plastic grid, which holds an elastic thin membrane that is slightly stretched. One relatively new AMM with intricate operating principles is the spatially coiled AMM that feature a Helmholtz cavity within the space-curved offering both local and global resonance as a result of the space coiling architecture itself [26].

Despite the significant improvements that AMMs offer, the improvements in acoustic properties are often limited to narrow band frequencies due to its dependence on resonant frequencies. Gradient-index structures for AMMs are suggested to overcome that barrier where lattice spacing, orientation angle, thickness, radii or elastic characteristics of the inclusions, and other characteristic variables may all be modulated to improve sound absorption [5]. By adjusting its features, tunable AMMs, which typically have a particular structure can offer targeted performance suitable for challenging building acoustic scenarios.

2.3. *Soundproofing or sound reduction*

Sound proofing is the reduction of sound transmitted across a solid or ventilated partition. This is different to sound absorption and is measured as the sound in decibels (dB) being reduced without being transmitted from one side of a partition to other. Sound proofing is often characterized by sound transmission loss (STL) or sound reduction index (R) in the case of partitions and insertion loss (IL) in the case of

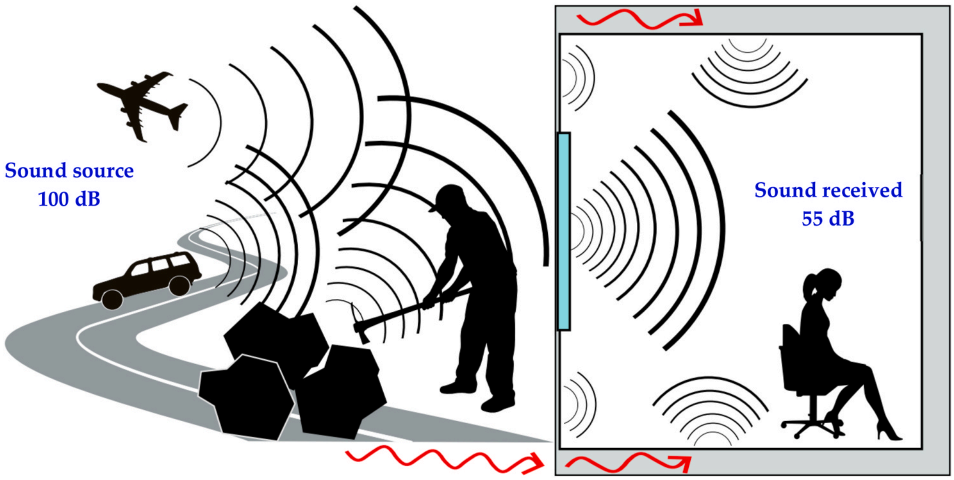


Fig. 4. The illustration shows the sound reduction index (UK) or sound transmission loss (USA) for various sound sources and transmission paths between an outdoor environment and a room. The window offers the least acoustic resistance, indicating the lowest sound transmission loss. The sound pressure level reduction in dB from the source to the receiver is influenced by the sound transmission loss of all elements in the sound path. Effective soundproofing is achieved through higher sound transmission loss. The illustration is based on data from Steiger [27], with adaptations.

ventilated or air transparent barriers. STL and R are terminology employed to denote the indicator that represents the distinction in sound intensity between the two sides of a component or partition, as shown in Fig. 4. Conversely, IL is defined as the decrease in the sound level caused by the placement of an attenuator in the sound path.

In this regard, one can think of the simplest sound proofing material as a thin partition placed in the path of sound transmission. The acoustic energy approaches the surface as a pressure wave, and a portion of it goes through the barrier while the remainder reflects. Some of the sound that goes through may be partly absorbed and turned into heat. Typically, the efficiency of the soundproofing material is determined by the ratio of the incoming energy to the outgoing energy, which is expressed as the sound transmission loss (STL) or the sound reduction index (SRI) in decibels [28].

Within the context of sound proofing, the indoor acoustic performance of an office or home should be is typically 45 dB. This means that if the sound level in outside the receiving room is around 100 dB, the sound level in the adjacent or the receiving room must be ≈ 55 dB. Sound proofing therefore describes the acoustic pressure lost across the partitioning element. Different to sound absorption, sound proofing approaches looks at improving the STL considering the stiffness, material, mass, and isolation of the portioning element. For a traditional soundproofing panel, a higher mass corresponds to a higher vibro-acoustic resistance especially at higher frequencies commonly referred to as the mass law.

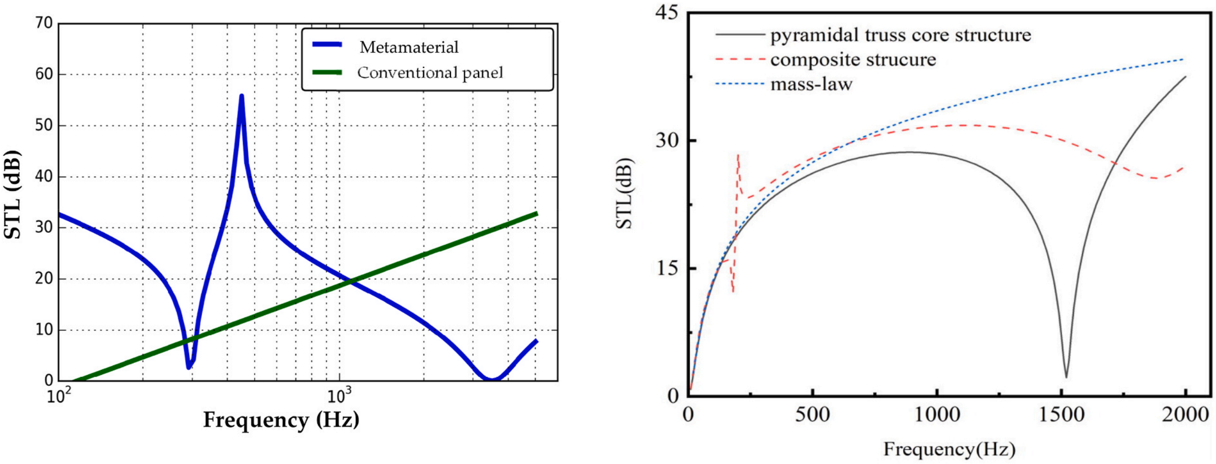
In comparison, acoustic metamaterials can offer significantly different performance superseding many of the stiffness and mass limitations associated with traditional soundproofing materials, an example of which is shown in Fig. 5a. For building insulation, there are many situations that require soundproofing at a targeted frequency range. The sound reduction techniques conventionally utilised involve incorporating large acoustic panels or decoupled structures. However, in weight-critical applications, achieving sufficient damping of low-frequency sound waves requires significant mass, rendering this approach infeasible. This review explores the effectiveness of acoustic metamaterials as narrow-band, low-frequency acoustic barriers and provides an overview of their identification and performance.

The dominant reflection resulting from the out-of-phase resonance between the various resonant frequencies of the resonant unit is the main mechanism responsible for sound insulation through AMMs. Thin-walled membrane- and plate-type structures are anticipated to become the standard option for low-frequency vibration and noise reduction in practical engineering due to their benefits, which include decreased thickness and low surface density. In thin plate-type AMMs, the holes or pillars are often placed on a continuous plate with changeable thickness and holes or pillars of different sizes and shapes [32]. In contrast to the plate-type AMM, the membrane-type AMM always uses a frame to divide individual cells while one or more masses are organised on the membrane. Initial stress must be given to the membrane to sustain the propagation of vibrations, as the membrane's stiffness is insufficient to resist its own gravity.

Poroelastic materials provide advantages over traditional standard materials by being lighter, thinner, and possessing higher broadband absorption capacities at lower frequencies. Poro-elastic materials like fibreglass and foam with recurrent layers of micro-perforated sheets imbedded are part of this new class of materials [33]. An array of mass-spring-damper systems is created using poroelastic material with a periodic arrangement of embedded masses in poroelastic acoustic heterogeneous (HG) metamaterials. In order to comprehend the consequences of changing the microperforated panel position and distribution in poroelastic material, as well as the density, size, shape, and placement of the embedded masses, design studies are conducted. The construction of a large-scale metamaterial panel with periodic tunable resonant cell arrays addressed the conventional issue of filtering low-frequency noise. The adjustable metamaterial panels, according to numerical simulations, display several local resonance processes that lead to improvements in sound transmission loss (STL) over conventional mass law in low-frequency zones.

2.4. Passive and active controlled sound absorption and sound reduction

The overall sound absorption and reduction value for building insulation application will be found between the application requirement, insulation capability and economic viability. Whilst it is possible to achieve control of noise pollution using passive, active or hybrid means, the additional energy requirement and heightened complexity of active measures must be represented. The necessity to externally energise active technologies differentiate these from passive techniques and present economic challenges. Interestingly, the opportunity to utilise active means of absorption and reduction becomes more practical at low



(a)

(b)

Fig. 5. (a) Illustration of sound transmission loss performance of a conventional panel obeying mass law compared to the performance of a membrane type metamaterial, compiled from data informed by Naify et al. [29] and Bill Edwards [30]. The higher the sound transmission loss curve the superior the soundproofing. In this regard, the metamaterial offers higher sound proofing going beyond the conventional mass law of a traditional soundproofing material demonstrating significant potential for its use at targeted frequencies. (b) Illustration of sound transmission loss performance of a composite structure compared to the sandwich panel with pyramidal truss core in the same mass in normal incident sound wave, obtained from Wang et al. [31]. Combining the membrane metamaterial with the sandwich panel with pyramidal truss core resulted improved low frequency in the STL and the dip near 1500 Hz is eliminated.

frequencies whilst passive mediums demonstrate good performance at medium to high frequency ranges [34–36]. Moreover, low frequency noise is increasingly ever-present throughout domiciliary and urban environments with polluters not limited to heating and ventilation systems, boilers, and fans and pumps in appliances. The health burden of environmental noise is recognised globally with considerable adverse effects of prolonged night-noise exposure, as such interventions achieving pollution below 45 dB, 44 dB and 40 dB are recommended for road traffic, railway and aircraft noise respectively [37]. It is considered that each active, passive and hybrid forms of sound absorption and sound reduction have relevant positioning throughout the spectrum of application.

3. Acoustic metamaterial features for building applications

3.1. *Concepts of negative mass density and bulk modulus*

To comprehend the creation of an acoustic metamaterial, it is crucial to understand the basic analogies used in describing acoustic responses. Two important concepts in acoustic metamaterials are negative mass density ($-\rho$) and bulk modulus (k). Mass density is a measure of how much mass is contained in a given volume of a substance typically represented by ρ. In conventional materials, mass density is always positive, meaning there is a certain amount of mass within a given volume. Negative mass density evolved as a hypothetical concept that suggests the mass within a certain region is effectively negative. Transforming, this to the theory of vibrations and metamaterials, negative mass density can be created using a dynamic microstructure as illustrated in Fig. 7b. Negative mass density is a property of materials that have a mass density that is less than zero. This counterintuitive property allows objects with $-\rho$ to move in the opposite direction of an applied force. While negative mass density does not exist in naturally occurring materials, it can be engineered using acoustic metamaterials [38,39]. Further detailed explanation of negative mass density from an acoustic metamaterial point of view can be found in previous literature [40].

Bulk modulus, on the other hand, measures a material's resistance to compression. The bulk modulus is a measure of a material's resistance to changes in volume under an applied external pressure. It is a property that characterises the compressibility of a substance. Mathematically, the bulk modulus is defined as the ratio of the change in pressure to the fractional change in volume. Materials with a high bulk modulus are less compressible, meaning they resist changes in volume more effectively. Liquids and solids typically have non-negative bulk moduli, while gases can have negative bulk moduli under certain conditions. It is a key parameter in acoustic metamaterials because it can be used to control the speed and direction of sound waves. By adjusting the bulk modulus of a material, it is possible to manipulate the propagation of sound waves. Together, $-\rho$ and k can be used to create materials with unique acoustic properties as summarised in Fig. 6. For example, an acoustic metamaterial with negative mass density and a high bulk modulus could be designed to absorb sound waves in a specific frequency range. Conversely, an acoustic metamaterial with negative mass density and a low bulk modulus could be used to amplify sound waves, which could have applications in ultrasound imaging and sonar technology. Nevertheless, it is important to note that while the concepts of negative mass density and bulk modulus are essential to the design of acoustic metamaterials, they are not the only factors to consider. Other properties, such as the material's density, stiffness, and damping, also play a critical role in the overall behaviour of the metamaterial.

3.2. *Dynamic microstructure*

Dynamic microstructure is a critical concept within the context of acoustic metamaterials, as it enables materials to change their structure in response to external stimuli, such as sound waves, [41–43]. The unique microstructure of acoustic metamaterials is engineered to control the propagation of sound waves. For instance, periodic variations in the density or stiffness of the material can create band gaps that prevent sound waves from propagating through the material. By adjusting the size and spacing of the periodic structure, the location and width of these band gaps can be controlled.

The response of the dynamic microstructure can become noticeable at specific frequencies, causing it to be out of sync with the incoming sound waves. This results in the overall performance of the acoustic metamaterial being determined by the inclusions that possess negative effective material characteristics. This frequency-dependent reaction differs from the usual macroscopic response of the material [44–46].

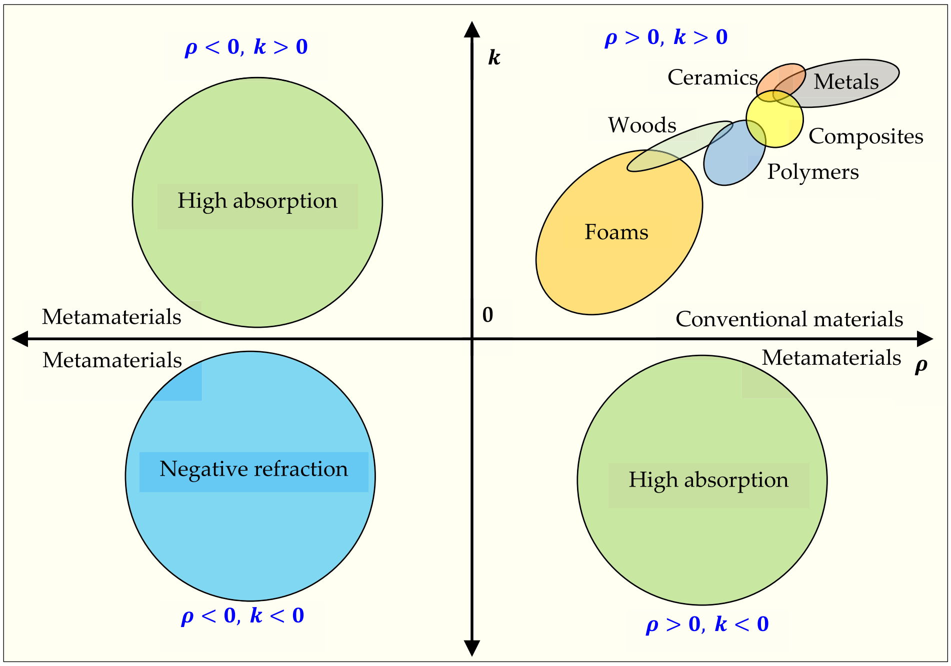


Fig. 6. Effect of negative mass density ($-\rho$) and bulk modulus (k) on the acoustic characteristics of materials [41].

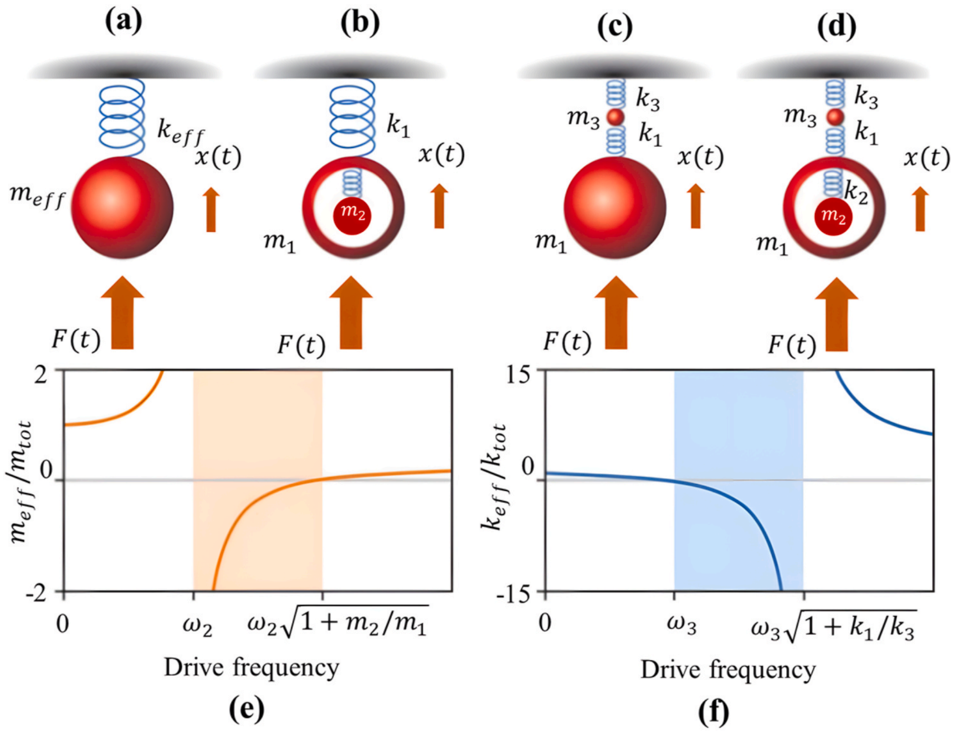


Fig. 7. Spring mass system that showing the evolution of dynamic microstructure as hidden degrees of freedom (DoF) in an acoustic metamaterial [41] where (a) shows the displacement $\boldsymbol{x}(\boldsymbol{t})$ in response to force $\boldsymbol{F}(\boldsymbol{t})$ informed by masses $(\boldsymbol{m_i})$ and stiffness $(\boldsymbol{k_i})$. Depending on the specific arrangement of the masses, negative mass (panel (b)), negative spring stiffness (panel (c)), and negative mass and stiffness (panel (d)) can be achieved, assuming that $\boldsymbol{m_3}$ is lighter than $\boldsymbol{m_1}$ and $\boldsymbol{m_2}$. Panels (e, f) show the normalized effective mass and spring stiffness as a function of the drive frequency, where the resonance frequencies $\boldsymbol{\omega_2}$ and $\boldsymbol{\omega_3}$ are, respectively, $\sqrt{\boldsymbol{k_2}/\boldsymbol{m_2}}$ and $\sqrt{\boldsymbol{k_3}/\boldsymbol{m_3}}$. In panel (e) and (f), the highlighted section refers to the negative dynamic mass region and the negative-stiffness region in panels (b) and (c), respectively. The normalizations are determined by the quasistatic mass $\boldsymbol{m_{tot}} = \boldsymbol{m_1} + \boldsymbol{m_2}$ and the quasistatic spring constant $\boldsymbol{k_{tot}} = (\boldsymbol{1}/\boldsymbol{k_1} + \boldsymbol{1}/\boldsymbol{k_3})^{-\boldsymbol{1}}$.

Hence, Fig. 7 accurately portrays the system's dynamic response by presenting the concept of extra degrees of freedom. The arrangements of inclusions in the microstructure give rise to these additional degrees of freedom, which, in turn, produce the acoustic responses illustrated in Fig. 6.

The spring-mass system shown in Fig. 7a acts as a single effective system, where the mass is displaced by a distance $x(t)$ under a time-dependent force $F(t)$, although it is shown as a component system. By rearranging classical Hooke's relationship, it is possible to obtain the effective mass and spring constant of the system as $m_{eff} = F(t)/\ \ddot{x}(t)$ and $k_{eff} = F(t)/x(t)$, where the double dots denote the second derivative with respect to time [40,41,43,47]. The arrangement and relative magnitudes of these masses and stiffness coefficients play a crucial role in determining the overall dynamic response of the system. Fig. 7b–d shows different scenarios based on the specific arrangement of masses. When Fig. 7b shows a configuration where negative mass can be achieved, Fig. 7c shows a case of negative spring stiffness. A combination of both negative mass and negative stiffness, assuming that m_3 is lighter than m_1 and m_2 is shown in Fig. 7d. These configurations demonstrate the potential for creating acoustic metamaterials with unconventional properties, such as negative mass and stiffness, through careful manipulation of the components of the system.

Fig. 7e and f presents the normalized effective mass and spring stiffness as functions of the drive frequency. Here, the highlighted sections correspond to the negative dynamic mass region and the negative-stiffness region corresponding to Fig. 7b and c. The normalisations are based on the quasistatic mass and the quasistatic spring constant acting as a reference to demonstrate the behaviour of the system under different frequency conditions. This detailed representation provides a valuable visual guide for understanding the intricate interplay of masses and stiffness in a dynamic microstructure, enabling the creation of acoustic metamaterials with tailored properties. The figure highlights the potential for achieving negative mass and stiffness, paving the way for innovative applications in sound control and wave manipulation within the field of acoustic metamaterials.

Dynamic microstructure can also be used to create materials that selectively respond to sound waves in specific frequency ranges. A material with a microstructure that changes in response to a particular frequency of sound waves can be designed to selectively absorb or reflect those waves. By engineering the microstructure of materials, it is possible to create unique acoustic properties that have applications in diverse fields. While there is still much to learn about acoustic metamaterials, dynamic microstructure holds great promise for advancing the field of acoustics research and technology [48–50].

4. Acoustic metamaterials for sound absorption

4.1. Helmholtz type architecture

In recent times, there has been an upsurge in acoustic metamaterial research aimed at sound absorption and noise reduction [51]. The use of solid scatterers within a fluid matrix is the most common sound absorption approach, which builds upon bandgap research as described in the previous section. However, this technique only results in improved α influenced by metamaterial at narrow or isolated frequency bands. To expand the scope of acoustic metamaterial research, attempts have been made to utilise thermal and viscous damping for noise reduction. This was accomplished by using sonic crystals in a layered format and analysing thermo-viscous losses [52].

To improve the acoustic absorption properties of acoustic metamaterials, solid scatterers were combined with traditional sound-absorbing constructs. For example, Slagle and Fuller [55] employed mass concentrators within a porous architecture, leading to exceptional α at low frequencies. Other studies have employed three-dimensional rigid inclusions within porous layers, hybrid acoustic metamaterials involving microperforated architecture, crystal filling fractions, acoustic coatings in combination with resonance-based metamaterials or sonic crystals [56–59]. Although the principles governing the acoustic behaviour of microperforated panels (MPPs) are well established [60,61], achieving high α calls for microscopic perforations, requiring expensive fabrication techniques. Additive manufacturing (AM) techniques such as Selective Laser Melting (SLM) [62,63] provides a sustainable alternative approach to create complex perforations and waveguides [64,65]. Despite this, research on the acoustic performance of AM metal MPPs that offer high sound absorption are scarce.

Acoustic metamaterials have been developed in recent years by merging microperforated panels with acoustic meta-architecture [66–69]. Fig. 8 demonstrates various notable examples where the benefits of frequency-based resonators were combined with micro perforations to significantly enhance α. As demonstrated in the corresponding acoustic performance versus frequency curves, all configurations could achieve peak performance within a particular frequency band as a function of resonance. Another noteworthy example is a recent study [70] that utilised a thin metamaterial construct consisting of a solid-fluid architecture, leading to complete sound absorption. The design comprised micro perforations and a subwavelength channel of air, where the improvement in α can be attributed to the thermo-viscous losses that occur during fluid-structure interaction. Table 1 summarises some remarkable architectures with the potential to be utilised in constructing sound absorption mechanisms.

Table 1
Acoustic metamaterials that offer high frequency dependent sound absorption suitable for application in building acoustics [5].

Material	Size (mm)	Frequency (Hz)	Ref.
Honeycomb corrugated core combined with resonance cavities	60	2000	[53]
Waveguide that combines tubes and MPP metamaterials	54	800–1000	[71]
Acoustic metamaterial combining Helmholtz apertures	50	130–170	[72]
Helmholtz resonators featuring microperforated panels	62	450–1360	[73]
Resonance cavities featuring aerogels	42	600	[74]
Metamaterials featuring coplanar waveguides	17	600	[75]
Coiled waveguides that feature geometrical features	24	146–168	[76]

4.2. Membrane type architecture

Different membrane type acoustic metamaterials that can be used to create complete sound absorption ($\alpha = 1$) have been demonstrated in literature. One such architecture featuring a membrane platelet in a sealed gas as shown in Fig. 9 was experimented by Ma et al. [77]. The architecture resulted in achieving 100 % narrow band sound absorption between 150 and 160 Hz showing its suitability for targeted sound absorption. The acoustic metamaterial of this type utilizes the occurrence of resonance frequencies to improve sound absorption. This results in the conversion of acoustic energy into elastic energy through the flapping movement of the platelets, which is then dissipated with high efficiency. The resonance frequencies, where maximum absorption happens, can be altered by adjusting either the weight of the platelet or the distance between two platelets. By increasing the weight of the platelets, the lower frequencies for absorption can be decreased, whereas by increasing the distance between the platelets, the higher frequencies for absorption can be reduced [19].

Membrane based acoustic metamaterial have also been shown to be suitable for multi frequency acoustic absorption in a single architecture. The deep sub-wavelength acoustic metamaterial (Fig. 10a) developed by Mei et al. [25] have shown significant absorption between a frequency range of 100–1000 Hz as shown in Fig. 10b. The design featured thin elastic membranes carrying rigid plates that could absorb 86 % of the acoustic waves at ~170Hz, with two layers absorbing 99 % at the lowest frequency resonant mode as well as at higher frequency modes. Other notable membrane based acoustic metamaterial design includes the ones developed by featuring Auregan et al. [78]. This work fabricated an acoustic metamaterial with low thickness membrane attached to a mass block which also showed near perfect sound absorption at particular frequencies. Similarly, a broadband membrane based acoustic metamaterials consisting of a porous material demonstrating near perfect acoustic insulation [79]. Using similar principles, a multi-channel resonator metamaterial featuring a silica gel membrane was developed by Xu et al. [80] demonstrating acoustic absorption between 80 and 100 % at a frequency range of 400–650 Hz. In addition to the membrane type architectures discussed asymmetric structures could be coupled with membrane-based metamaterials to enhance sound absorption for a wide range of frequencies. Another approach is to use membrane-type acoustic metamaterials backed by air cavity to widen the frequency

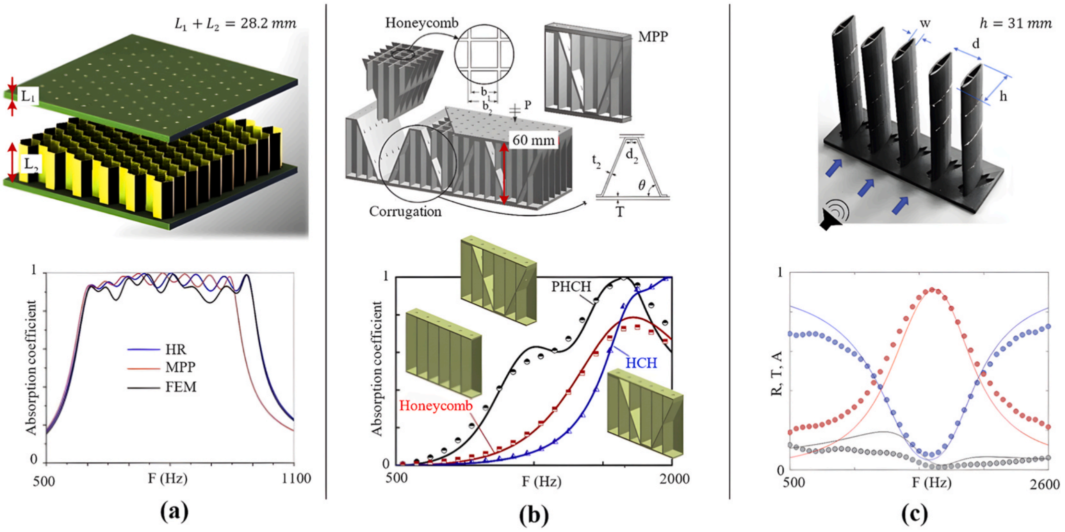


Fig. 8. Examples of sound-absorbing metamaterials and the resulting sound absorption showing (a) microperforated layer featuring a honeycomb cavity (b) microperforated panel featuring a customised back cavity and (c) 3D printed sound-absorbing cavity architecture. Data compiled from sources [5,24,53,54].

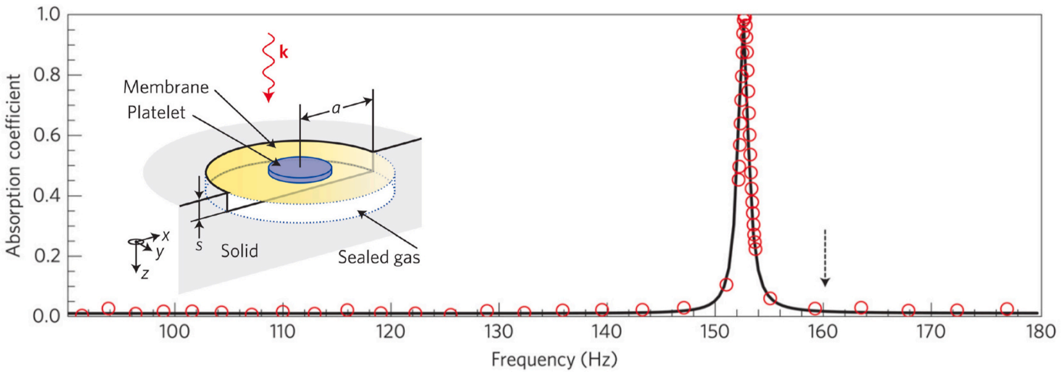
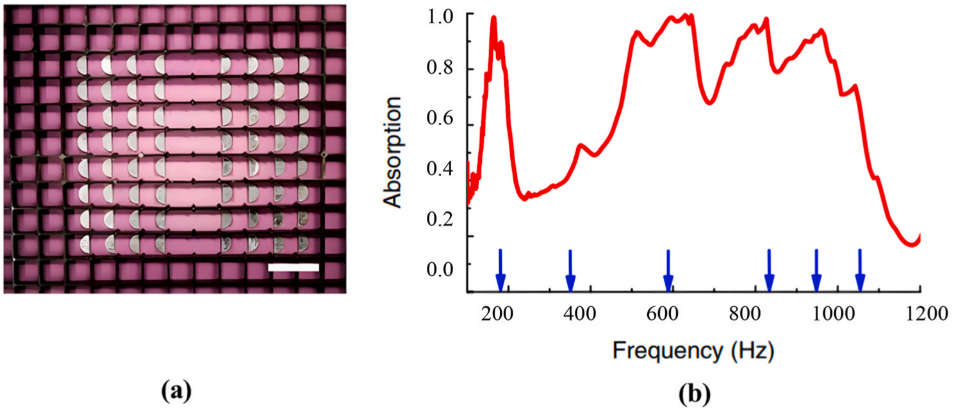


Fig. 9. Complete acoustic absorption at targeted frequency of an ultra-thin membrane type acoustic metamaterial demonstrated by Ma et al. [77].



(a)

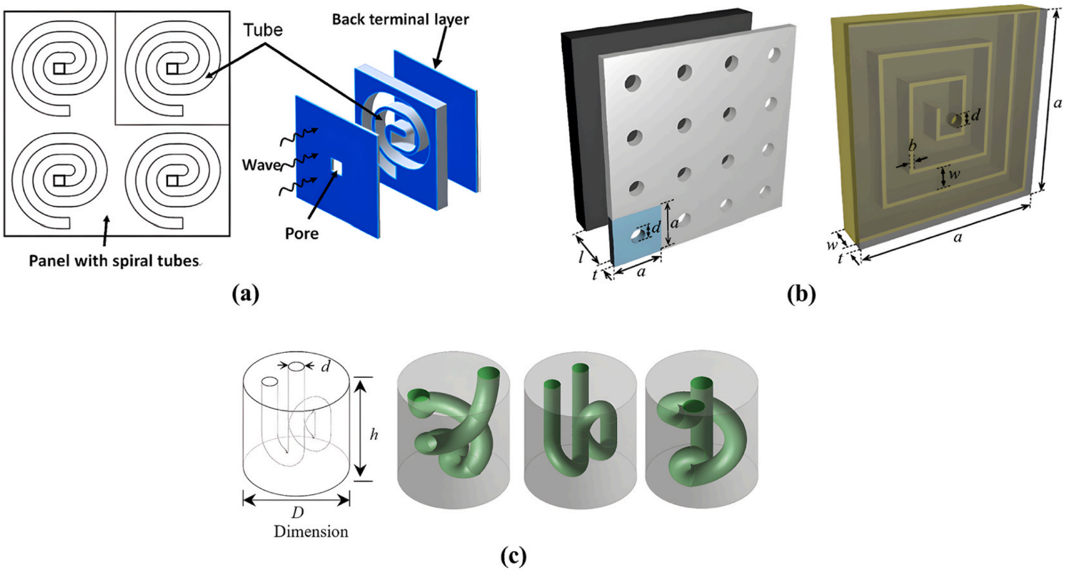
(b)

Fig. 10. Membrane type acoustic metamaterial where (a) shows the metamaterial prototype developed by Mei et al. [25] and (b) the corresponding sound absorption characteristics.

band for building and architectural applications.

4.3. *Space coiling acoustic metamaterials*

Although membrane based acoustic metamaterials can achieve near perfect absorption, their large-scale fabrication to be used in building acoustics is challenging. However, this can be overcome by using space coiling acoustic metamaterials which can also achieve near perfect sound absorption. As such the primary advantage of space coiling acoustic metamaterial over membrane based is their ease of scalability



(a)

(b)

(c)

Fig. 11. Space coiling acoustic metamaterials where (a) shows repeating 3D unit cells of spiral tubes developed by Cai et al. [75] (b) hybrid architecture showing traditional perforated plate on top of a space coiling architecture developed by Li and Assouar [84] and (c) a range of space coiling architecture with near perfect sound absorption coefficient developed by Arjunan [64].

making them suitable for building acoustics [81,82].

Fig. 11 shows examples of space coiling metamaterials that are suitable from a building acoustics point of view. For these metamaterials, the length, size, and volume of space coiling can be manipulated to achieve near perfect absorption at a range of audible frequencies. For instance, the space coiling architecture in Fig. 11a developed by Cai et al. [75] is capable almost 100 % acoustic absorption at low frequencies where the impedance of overall structure matches with the incoming sound wave. When sound wave enters a space coiling architecture, some portion of it is absorbed through resonance, viscous friction and heat transfer, similar to what happens in a porous material [83]. The remaining acoustic pressure slows down as a result of the coiling space inside the air cavity [51]. Fig. 11b represents a coupled space coiling acoustic metamaterial which feature a perforated panel on top of the labyrinthine air cavity. This architecture was proposed by proposed by Li and Assouar [84] demonstrating near perfect α at targeted frequencies.

Experimental studies conducted by Arjunan [64,65] demonstrated the use of additively manufactured space coiling architecture to create destructive interference through a complex inclusions as shown in Fig. 11c. The principle here is to use space coiling to create destructive interference to cancel the incoming acoustic wave at selected frequencies. For the designs proposed by Arjunan, the change in phase angle to cancel the incoming wave is informed by the frequency which subsequently dictate the length of the space coiling cavity. As such this model allows multiple length of space coils to be created in a single metamaterial leading to sound absorption peaks at multiple frequencies. Overall, space coiling metamaterial architecture offers a great opportunity in achieving near perfect air borne sound absorption that can be seamlessly integrated to building architecture. Moreover, the twisted perforations in these structures have become a significant approach for decelerating sound waves, leading to the creation of acoustic mediums with significant refractive indices. This property is difficult to attain in airborne acoustics because the speed of sound in air is lower than in any solid material.

4.4. *Gradient index acoustic metamaterials*

Despite the high sound absorption of acoustic metamaterials, they exhibit a narrow frequency band when it comes to peak performance. To alleviate this problem gradient index acoustic metamaterials are developed which offer high sound absorption coefficient across a broad frequency band. Gradient index acoustic metamaterials are conceived by changing the characteristic factors of a metamaterial such as the cavity dimensions, elastic properties, the lattice spacing, orientation and/or thickness.

Comparing the sound absorption coefficient offered by various metamaterials, the gradient-index architecture is most favourable where a high α is required for a broad range of frequencies. Some examples of gradient index metamaterials are shown in Fig. 12 which clearly shows how a gradient architecture is used for sound absorption. Fig. 12a shows the case of an acoustic metamaterial featuring graded porosity that is 3D printed and experimentally validated. It was shows that these gradient porous architectures demonstrate excellent α due to their continuously graded structure.

According to Zhang et al. [85], the continuously varying arrangement and intricate path for sound propagation facilitated by the grading aid in dissipating more energy. This leads to excellent performance in sound absorption. Fig. 12b shows how Climente et al. [86] used pillars of graded diameter as they move away from the centre to create broadband sound absorption. The shell's gradient structures were tailored to match the acoustic impedance of both the air and the metamaterial. This resulted in the creation of broadband sound absorption performance as intended.

Xu et al. investigated the possible use of perfect magnetic conductors (PMCs) and epsilon-negative (ENG) metamaterials (MMs) in one-way terahertz waveguide [87]. The PEC-medium-semiconductor-PMC (EMSM), PMC-medium-semiconductor-PEC (MMSE), and

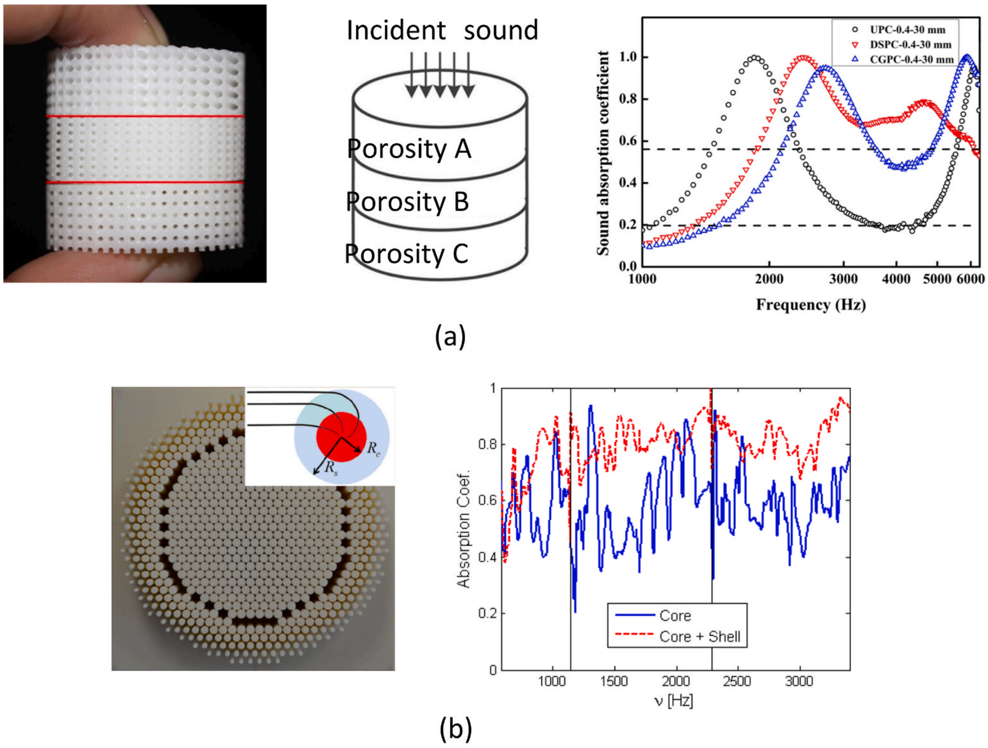


Fig. 12. Examples of Gradient index metamaterials where (a) shows an axially graded architecture additively manufactured by Zhang et al. [85], the corresponding porosity grading and the resulting broadband sound absorption and (b) shows the radially graded architecture developed by Climente et al. [86] showing both the prototype used for experimental testing and the resulting absorption coefficient.

PMC-medium-semiconductor-PMC (MMSM) waveguides are the three PMC-based structures in which they further investigated the broadband TRT. Broadband TRT was therefore discovered in both the gradient-index MMSE structure made up of ENG MMs and the gradient-index MMSM structure made up of epsilon-near-zero (ENZ) MMs. Clear broadband TRT without back reflection is observed in the terahertz range in the full-wave simulations.

According to Li et al., gradient metamaterials can cause the rainbow trapping effect, which is the progressive slowing down of mechanical waves to a stop, which traps them and causes them to become spatially and spectrally separated as they propagate [88]. It is also shown that the seismic Rayleigh waves may be regulated by the use of gradient metamaterials. The usage of planar gradient metamaterials for surface plasmon polaritons support, wave bending and focusing in free space, and trapped rainbow realisation was explored by Xu et al. [89] With the application of gradient index metamaterials (GIMs) in waveguide systems, novel physics and broadband functions are achieved without polarisation constraints.

Other notable architecture include the acoustic rainbow trapping acoustic metamaterials developed by Jie et al. [90], Alshaqaq et al. [91] and Xu et al. [92]. These studies demonstrated a metamaterial that is capable of trapping broadband acoustic waves and spatially separates different frequency components by designed gradient subwavelength structures. It was shown that the trapping positions can be conceived as the interplay between the acoustic resonance inside individual apertures and the mutual coupling among them. With the enhanced wave-structure interactions and the tailored frequency responses, such metamaterial allows precise spatial-spectral control of acoustic waves and opens new venue for high performance acoustic applications. As can be seen, gradient-index metamaterials can be used to widen the frequency band of acoustic insulation making them particular suitable for architectural application. However, to meaningfully enhance the acoustic ambience require conceiving gradient index metamaterials that offer impedance matching adding to the energy loss through sound propagation.

4.5. *Tunable acoustic metamaterials*

When it comes to building acoustics, the frequency distribution of the sound source keeps fluctuating depending upon the noise. Similar to traditional materials, the frequency band for peak performance for passive acoustic metamaterials are determined during their fabrication and assembly. As such passive metamaterial architectures cannot operate at their peak performance when reacting to a changing noise source. This is where active metamaterial architectures come into play by offering dynamic control on their acoustic parameters enabling them to offer peak performance under multiple frequency bands.

The dynamic control is often enabled through external stimuli such as piezoelectricity, mechanical pressure and temperature control. According to Gao et al. [93] investigated the configurability of active acoustic metamaterials to make them suitable for noise control application. Similar to other metamaterial architectures discussed so far, active metamaterials in literature were found for both airborne sound absorption and sound insulation. Theoretically, piezoelectric transducers might be used to model an actively adjustable acoustic metamaterial, as demonstrated by Akl and Baz [94]. A precise model of a water-filled cell surrounded by bimorphs was created using the finite element method. Nonetheless, significant challenges still exist concerning the structural design and cost effective manufacturing.

A number of passive sound absorbing architectures uses back cavity as a means of enhancing their acoustic response for low frequency absorption. Building on this principle, Zhao et al. [95] demonstrated an active sound absorbing metamaterial architecture through controlling the depth of back cavity using magnetic negative stiffness as shown in Fig. 13a. It was showed that through active control a small cavity with negative stiffness can mimic the acoustic impedance of a large cavity resulting in peak acoustic absorption at low frequencies.

A variation of this architecture leading to an active metamaterial that has offer broadband sound absorption at low frequencies was developed by Li et al. [96]. The active metamaterial architecture featured a flexible panel with a magnetic mass as shown in Fig. 13b. The findings of this design revealed that the sound absorption frequency can be reduced by actively controlling the magnetic field. Furthermore, the metamaterial's bandwidth was observed to widen with a rise in the magnetic field. This

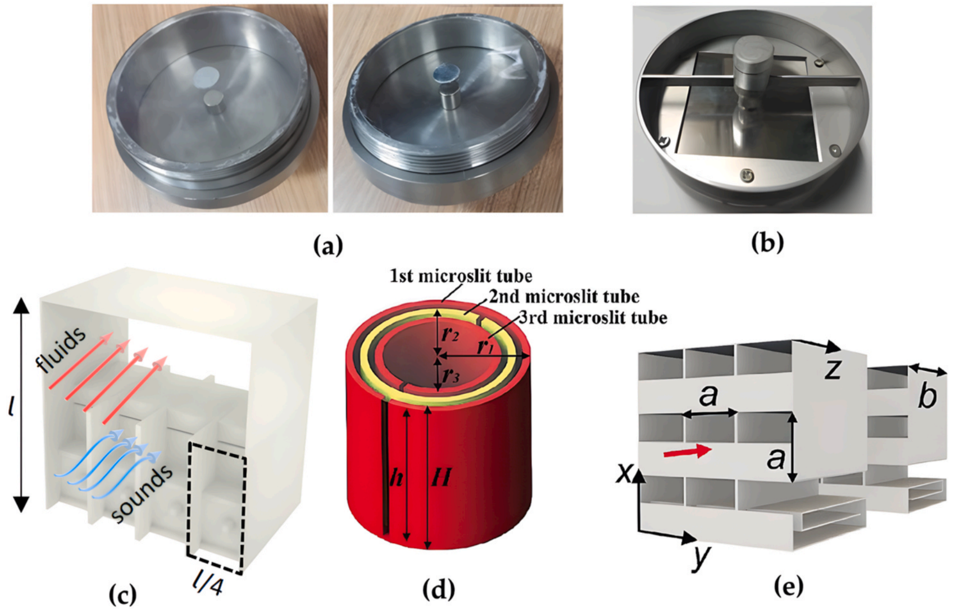


Fig. 13. Examples of active sound absorption metamaterial architectures where (a) shows a membrane based acoustic metamaterial actively controlled using a magnetic negative stiffness developed by Zhao et al. [95], (b) active acoustic metamaterial developed by Li et al. [96] featuring a magnetic mass, (c) ventilated acoustic metamaterials developed by Xiang et al. [97] that allows for active tuning, (d) architecture by Xu et al. [98] featuring tube type and (e) labyrinth-type acoustic metamaterial proposed by Du et al. [99].

is due to its inverse relationship with the frequency of peak acoustic absorption.

Different from using magnetic control, Xiang et al. [97] propose a ventilated sound absorber as shown in Fig. 13c that can be tuned for targeted acoustic absorption. The active control for this metamaterial architecture was achieved through a slider mechanism leading to high sound absorption while allowing ventilation. This type of metamaterial architecture has significant potential to be used in building acoustic where a frequency varying noise source is situated.

Other notable active metamaterials for sound absorption suitable for building acoustics are the ones developed by Xu et al. [98] and Du et al. [99] featuring a tube and labyrinth (Fig. 13e) type architecture respectively. This was a low-frequency sound absorber conceived using multi-layered slotted tubes with a thickness below the wavelength scale where frequency for peak α can be adjusted by rotating the tubes. On the other hand, the active metamaterial with a labyrinth-like structure, depicted in Fig. 13d, can be fine-tuned by modifying the opening ratio. Compared to the growth in passive acoustic metamaterials suitable for sound absorption, the number of architectures featuring active control for α is limited. This is primarily due to the high cost in the fabrication of highly complex architectures with added mechanisms for active control. Nevertheless, the area of active acoustic metamaterials suitable for high sound absorption is a growing field and commercial architectures suitable for building acoustics will become widespread in the near future [93].

5. Acoustic metamaterials for sound insulation

5.1. *Poroelastic metamaterials*

Although still in their early stages, acoustic metamaterials are being developed for sound insulation in both temporary and permanent installations [39,100]. If successful, this could pave the way for the construction of sustainable buildings in noisy environments like airports, railways, and highways [39,101]. One of the earlier designs for acoustic metamaterials that exhibited high efficiency in isolating low-frequency sound involved resonant membranes [19,102,103]. One such architecture [104] featuring a rigid honeycomb and a flexible outer layer, known as a meta-structure (Fig. 14a), which resulted in a sound reduction index (R) of 45 dB below 0.5 kHz is shown in Fig. 14b.

The architecture has been modified in various ways [105–107] to achieve superior performance at specific frequency ranges. There are two primary methods used for constructing sound barriers: one involves thin walls with resonators featuring positive lumped coupling, and the other is a bi-layer architecture that utilizes Willis coupling, which has proven to be effective in sound barrier applications. Another methodology involves planar meta-structures with linked cavities through an orifice, which was selected to improve the sound reduction index. The findings indicate that the coupling effect between enclosed cavities linked through an orifice can influence sound behaviour. Thus, the orifice's radius can be adjusted to achieve frequency-dependent performance. This design has significant potential as a noise barrier [38,108] and can address concerns related to membrane metamaterials. These examples demonstrate how acoustic metamaterials can be used to create scalable sound barriers that are suitable for mass production.

5.2. *Tunable acoustic metamaterials*

Looking at tunable acoustic metamaterials suitable for sound reduction, most of the approaches seem to be combine piezo with acoustic metamaterials [109–112]. A theoretical examination of an acoustic metamaterials consisting of piezoelectric boundaries was carried out [113]. The application of shunted piezo for acoustic metamaterial research was also shown [114–116], in which a piezoelectric patch can modify the resonant frequency. These demonstrations led to the development of customisable concepts that incorporated piezoelectric domains, such as the one in Fig. 15. The design is constructed using a series of identical elements made by placing piezoelectric layers on parallel planes of a disk, as illustrated in Fig. 15b. This method allows the stiffness along the path of acoustic propagation to be adjusted for specific sound transmission goals.

In addition to piezoelectric control, metamaterial architectures featuring mechanical control have also been experimented in literature [4]. Here targeted resonance is used to control the transmission by varying the cavity volume through the use of a plunger. While this method is theoretically efficient and has potential for use in reducing sound transmission through ducts, there are mechanical limitations to its control. Active control may be a possibility, but mechanical adjustment is primarily passive in nature. Once the adjustment has been made, it is not possible to make any modifications based on the response.

An alternative method involves utilizing the buckling phenomenon to manage acoustic transmission [120]. The technique entails using a structural matrix with an elastic membrane that encloses a plate-like structure, as depicted in Fig. 16. The beams are arranged in such a way as to provide enough room for buckling under compression, causing a change in the structure's resonant frequency and resulting in varying acoustic transmittance levels across the structure. While these structures offer significant potential, implementing active strain-induced acoustic control is difficult.

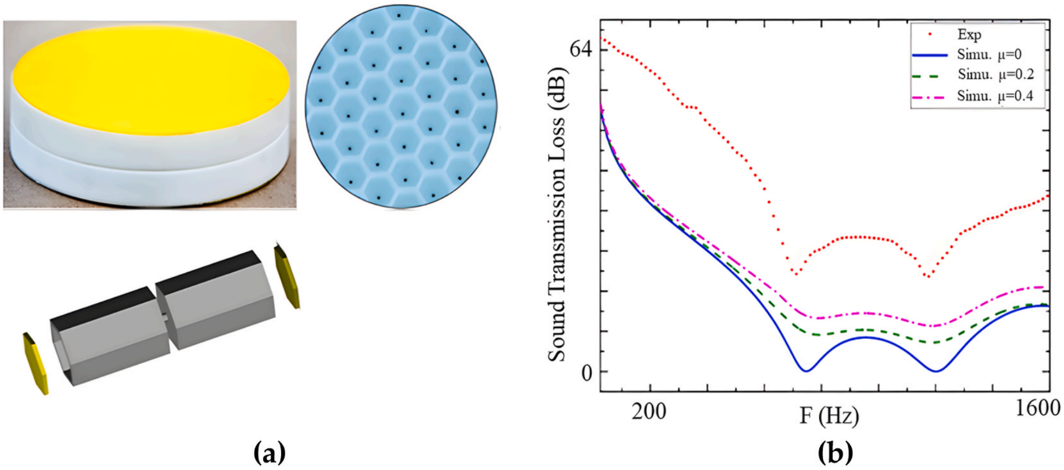


Fig. 14. Metamaterial sound isolator showing (a) the overall architecture and the different elements and (b) the resulting improvement in low-frequency transmission loss. Adapted from Refs. [51,104].

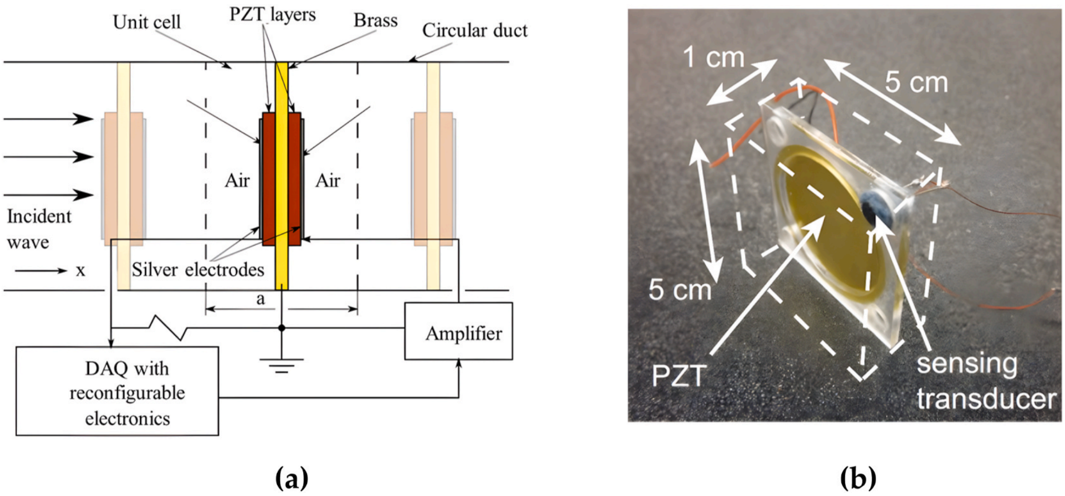


Fig. 15. Piezoelectrically customisable acoustic metamaterial [117] showing (a) the assembly layers [118] and (b) the fabricated metamaterial [119].

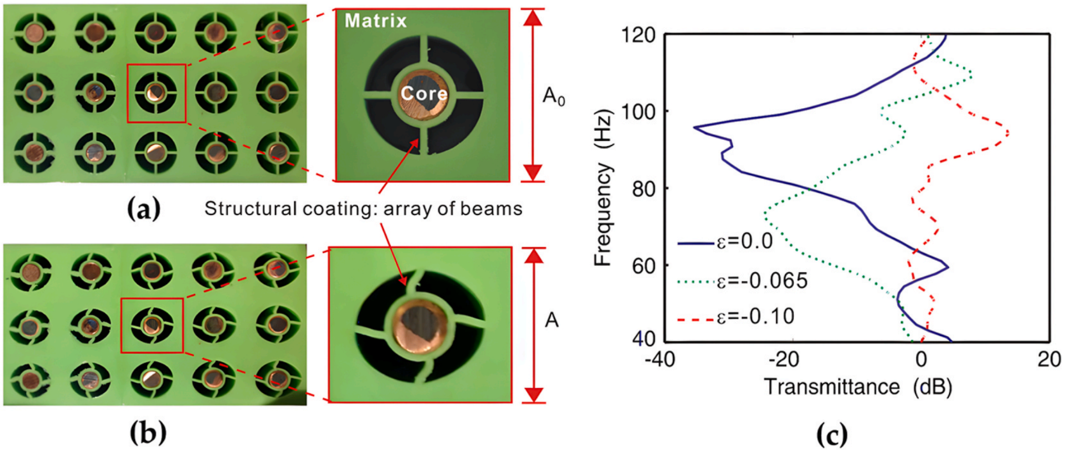


Fig. 16. Acoustic metamaterials where the sound frequency can be controlled using buckling [120] showing (a) the architecture before buckling is introduced (b) the architecture post-buckling and (c) the variation in the frequency of the sound decibels transmitted.

5.3. Membrane type passive acoustic metamaterials

Another class of acoustic metamaterial suitable to be adopted for airborne sound insulation are the ones that feature a membrane type architecture [19,93]. These classes of metamaterials offer characteristics that are particularly suitable for lightweight building structures where a compact installation is demanded for targeted noise reduction. As such the membrane type acoustic metamaterials are often developed using ultra-thin membranes that are kept in tension through the help of strategically placed lumped masses. The oscillation of these plane strain membranes results in narrow frequency bands at low frequencies (50–1000 Hz) significantly reducing the sound that is being transmitted [121]. As such these metamaterials are particularly useful in improving sound insulation in low frequency where traditional acoustic materials often underperform. Furthermore, when it comes to membrane type acoustic metamaterials, the frequency bands required for noise reduction can be tuned during their fabrication by choosing suitable membrane tension along with the magnitude and positioning of the lumped masses [102,122–125].

Locally resonant membrane type acoustic materials were shown to reduce transmission of acoustic waves 5 times in comparison to the forecasts of the acoustic mass law, particularly at frequencies of maximum TL. These characteristics make them an attractive option for constructing lightweight buildings, with minimal additional mass [126]. Studies conducted by Sui et al. [127] have refined the membrane-type acoustic metamaterials using a honeycomb architecture as shown in Fig. 17a to attain excellent transmission loss for low frequencies (Fig. 17b).

In addition to the above architecture, a range of other membrane type metamaterials have been conceived and studied by researchers over the years to explore their potential application to real life acoustic challenges. One of the earliest works with respect to membrane type acoustic metamaterials featured a stretched membrane with different masses attached resulting in different vibrational modes leading to unique transmission behaviours [19]. In general, this type of metamaterial architecture often shows two peaks and one dip in the sound transmission curve [19]. While the eigen mode frequencies of the membrane-mass system is responsible for the dip, anti-resonance in opposite phase caused the peak. At the two eigenmode frequencies, the average displacements on the membrane were relatively large, resulting in high acoustic transmission. The vibrational displacement is minimum at the dip frequency causing extremely low sound transmission that goes beyond the mass law for sound transmission loss. The mass attached to the membrane can also be further manipulated for targeted sound insulation or transmission performance.

In addition, a restricted membrane-style acoustic metamaterial was designed by Wang and colleagues [128], as depicted in Fig. 17c. The size of the restricted struts can be adjusted to alter the sound insulation,

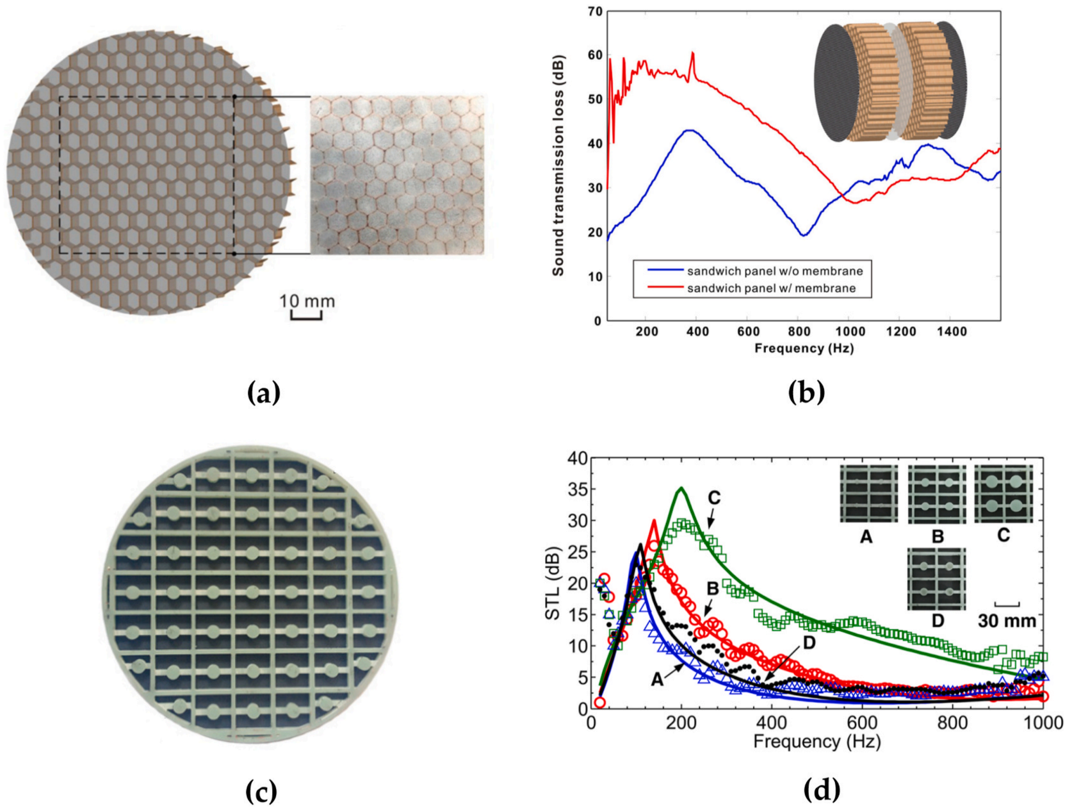


Fig. 17. Metamaterial featuring a membrane type architecture for sound reduction showing (a) the honeycomb architecture developed by Sui et al. [127], (b) the resulting sound transmission loss when combined with a sandwich panel, (c) membrane-constrained acoustic metamaterials for low frequency sound insulation developed by Wang et al. [128] and (d) the resulting STL when altering the diameter of the constrained struts.

resulting in varying peak sound transmission loss, as shown in Fig. 17d. This leads to notably elevated sound insulation levels. These architectures are well suited for light weight and thin-walled building partitions notorious for poor low frequency sound reduction index. They can also be used for industrial building walls where low frequency sound attenuation if of significant importance.

Variations of the membrane type metamaterial architecture suitable to be adopted for sound insulation of buildings includes a perforated architecture demonstrated by Langfeldt et al. [101]. This architecture featured a ring mass attached to a perforated membrane facilitating airflow through the membrane. The experimental results revealed this architecture to offer a wide sound insulation bandwidth along the lower frequencies. Other notable architecture includes a thin membrane metamaterial featuring a simple spring mass architecture arranged linearly resulting in targeted acoustic performance [129]. According to Park et al. [129] the ultrathin and ultralight metamaterials architecture is suitable for low frequency sound insulation making them suitable for buildings close to motorways and railway lines.

5.4. Plate like acoustic metamaterials

Amongst the different types of acoustic metamaterials, the plate like architecture is of particular interest when it comes to its application in building acoustics. These metamaterials can particularly be effective for low-frequency sound insulation in buildings if incorporated appropriately to building walls. According to Langfeldt and Gleine [130] plate like acoustic metamaterials are characterized by thin two-dimensional architecture reactive to low frequencies with negative density offering significantly enhanced R in comparison to the mass law. As such plate acoustic metamaterials are promising noise control applications where mass and installation space are constrained.

Comparing the performance of plate like metamaterials to membrane type architecture, the latter is affected by the tension in the membrane which changes over repeated use limiting their applications in areas that require long term installation. In this regard, metamaterials featuring the plate type architecture may offer a higher likelihood for noise-reduction in buildings. A light weight ultrathin plate type acoustic metamaterial architecture consisting of nylon plate and elastic ethylene-vinyl acetate copolymer was designed by Ma et al. [105]. The data revealed the plate type architecture to offer improved sound reduction along the low frequencies. According to Varanasi et al. [131], the plate-type metamaterials were found to possess a superior sound reduction index, as evidenced by a periodic array of unit cells comprising plates that are held within a grid-like framework, as shown in Fig. 18a. This design is slender and devoid of weighty resonating or restrictive elements that restrict its application. This plate-type metamaterial structure is also ideally suited for noise control applications where the goal is to minimize treatment mass while achieving a specified R value.

When it comes to developing metamaterials for sound insulation in buildings, the scalability of the architecture is an important consideration. For membrane-type metamaterials, cost of precision fabrication and controlling the stiffness uniformity of the membrane are still challenging problems. Focusing on solving these issues, Ang et al. [132] developed a plate-type acoustic metamaterials featuring strategically placed resonators as shown in Fig. 18b. A similar architecture featuring different type of resonators featuring 32 × 32 unit cells as shown in Fig. 18c was proposed by Lin et al. [133]. Assessing the performance, both metamaterials showed significant transmission loss for a broadband frequency spectrum. It was also found that sound reduction performance of these two architectures were not dependent on the panel orientation making them particularly suitable for building installation. Combining the efficiencies of a double-leaf architecture, Gazzola et al. [134] developed a plate type sandwich metamaterial unit cell with

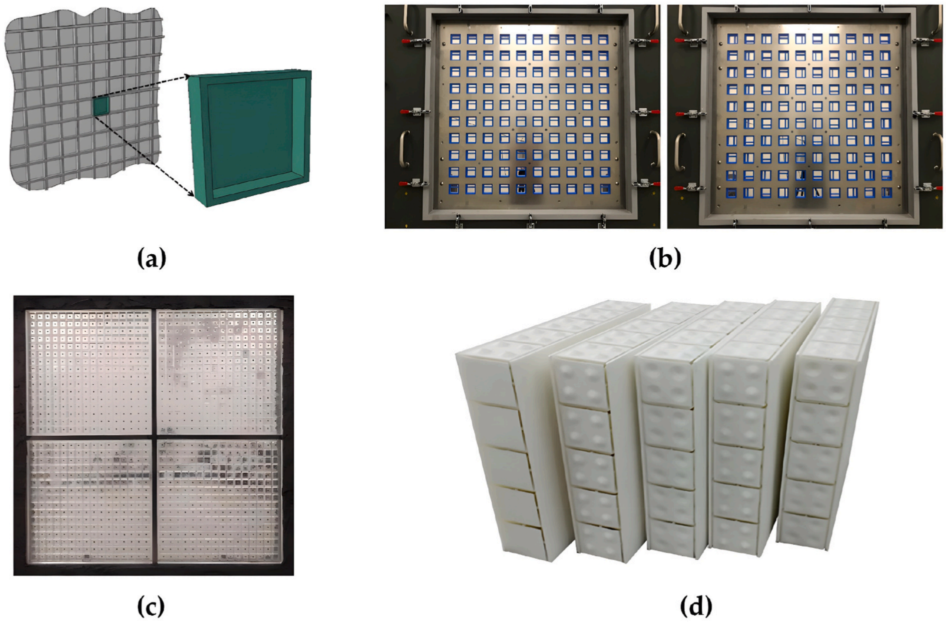


Fig. 18. Plate type acoustic metamaterials for sound reduction showing (a) the cellular architecture developed by Varanasi et al. [131], (b) plate type modular acoustic metamaterials for large scale implementation developed by Ang et al. [132], (c) plate-type sandwich acoustic metamaterial suitable for sound insulation conceived by Lin et al. [133] and (d) multi-layer metamaterial featuring a plate architecture offering high R/STL values developed by Gazzola et al. [134].

integrated faceplates as shown in Fig. 18d. The panel was additively manufactured in Nylon using the selective laser melting process and found that the panel created broadband acoustic insulation suitable for application to building walls. Overall, the plate type metamaterial architectures shown in Fig. 18 address the manufacturing, customizability and scalability issues making them suitable for wider adoption to building sound insulation.

6. Ventilated acoustic metamaterials

When it comes to building acoustics, sound reduction through natural ventilation and windows are significantly challenging. While increasing the area of external openings results in a higher air flow, noise reduction capability is inversely affected. Solving this problem require hybrid ventilation system that feature sound reduction strategies without obstructing air flow [135]. Despite introducing several types of

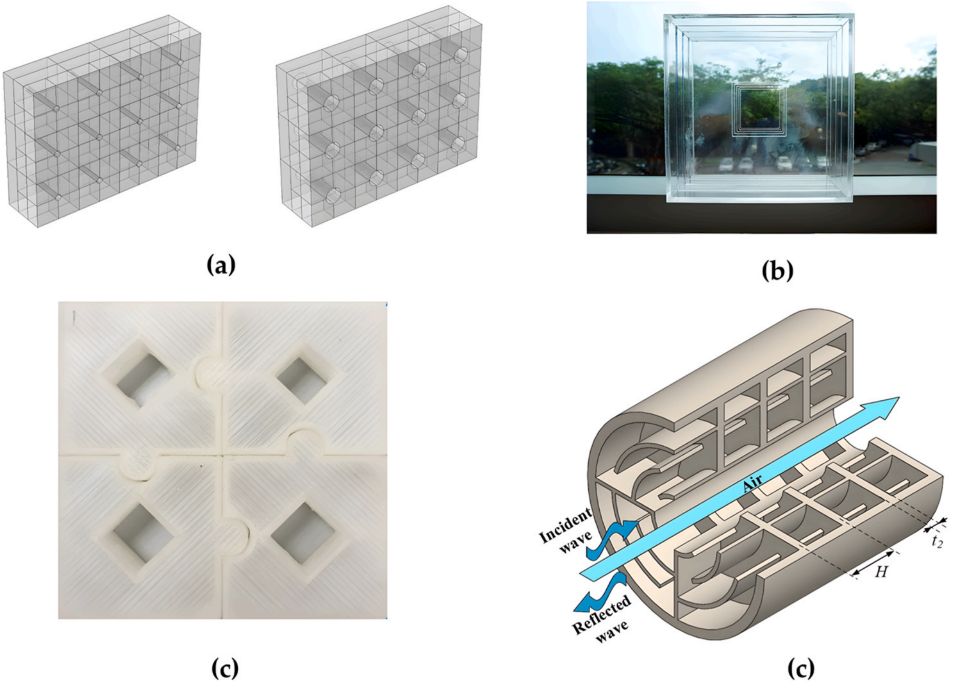


Fig. 19. Ventilated acoustic metamaterial architecture for sound reduction showing (a) the air transparent sound proof window architecture developed by Kim and Lee [136], (b) acoustic metamaterials with ventilation function implemented on a building window demonstrated by Yu et al. [137], (c) ventilated acoustic metamaterial window panels that provide both sound isolation and air circulation developed by Kumar et al. [138] and ventilated metamaterials for broad-spectrum sound insulation with adjustable transmission at low frequencies created by Xiao et al. [139].

acoustic metamaterials so far, none of them are suitable for when ventilation or permitting air flow through are a requirement. However, several metamaterial architectures are being proposed that can offer acoustic insulation without affecting ventilation.

One of earliest architecture that showed the potential of ventilated acoustic metamaterials in building acoustics is the ventilated acoustic resonator window proposed by Kim and Lee [136] as shown in Fig. 19a. The acoustic performance of the architecture showed a reduction of up to 35 dB in acoustic pressure levels at 400–5000 Hz frequency across the 20 mm window. The potential for using ventilated metamaterial that can offer significant acoustic insulation was demonstrated by Yu et al. [137]. The proposed architecture was implemented on a building window as shown in Fig. 19b and was shown to offer significant acoustic insulation from 0.6 to 1.6 kHz.

Kumar et al. [138] created a ventilated metamaterial, which is suitable for decreasing sound transmission, as shown in Fig. 19c. The design achieved a R values of 18 dBs, while almost half (45 %) of the metamaterial remained open to ventilation. Xiao and team [139] employed the space-coiling approach to introduce a space-saving metamaterial that involves labyrinth resonators surrounding a central ventilation channel, demonstrated in Fig. 19d. This structure presents a possible avenue for sound insulation that permits building ventilation while offering R values of up to 30 dBs at 660–1200 Hz. Other notable ventilated metamaterial includes the ones developed Jung et al. [140] and Ghaffarivardavagh et al. [141] reporting ventilated acoustic metamaterial featuring holes to offer broadband sound insulation. Overall, the implementing ventilated acoustic metamaterials is a promising route in achieving high sound reduction indices without sacrificing air flow.

There have been several examples of ventilated metamaterial absorbers in the literature [54,71,142]. Still, few of them are able to accomplish high-efficiency sound absorption (>90 %) and ventilation (>60 % wind velocity ratio) at the same time, therefore their performances in terms of absorption and/or ventilation are lacking [143–145]. In order to accomplish high-performance ventilation (>80 % wind velocity ratio) and acoustic absorption (>95 %) at the same time, Xiang et al. developed and experimentally proved the use of an ultra-open ventilated metamaterial absorber (UVMA) [146]. Experimental measurement and numerical computations are used to illustrate the absorption of the UVMA unit, which consists of weakly coupled split-tube resonators. Sun et al. conducted research on broadband acoustic ventilation barriers and created a planar-profile, subwavelength-thick (about $\lambda/8$) acoustic ventilation barrier that blocks sound across a wide frequency range [147]. Two encircling helical routes with different pitches and a metasurface with a centre hollow orifice were part of the design. They stated that their design has promise for applications requiring both air permeability and soundproofing, such as noise reduction and natural ventilation in green buildings.

In light of the unsustainable temperature increase brought on by climate change, buildings' mechanical ventilation systems have undergone efficient improvement in recent years. The noise produced by the refrigerator fan's revolving blades is one of the main issues if every residential building has a mechanical ventilation system. In order to achieve sound attenuation, Trematerra et al. investigated the use of metamaterials to produce attenuation filters that would be placed inside the mechanical ventilation systems' casings [148]. Various configurations of a three-dimensional spherically shaped reticular structure with respect to the number of layers employed have been analysed. Furthermore, Kumar et al. investigated the use of 3D printed ventilated acoustic metamaterial window panels for noise shielding and air circulation [138]. They stated that the metastructure, which results from the weak coupling of the two identical square perforated holes and a common Helmholtz chamber constituting the absorber, is responsible for the high efficiency peak normal incidence absorption (>96 %) and the peak normal incidence transmission loss of roughly 18 dB.

However, in order to surpass the mass law, careful consideration must be given when choosing acoustic metamaterials for sound isolation considering type of building walls, windows and ventilation being treated. Nevertheless, for practical large-scale implementation of acoustic metamaterials for building acoustics, there is a need for continued development of lightweight load-bearing structures that possess remarkable strength and longevity [93].

7. Prospects and challenges of metamaterials in building insulation

7.1. Low frequency noise mitigation

Sound pollution is a significant global problem where conventional acoustic materials cannot always offer the required acoustic comfort. However, acoustic metamaterial architectures can offer new solutions for noise mitigation especially in light-weight buildings. As discussed so far recent development in acoustic metamaterials have revealed numerous architecture suitable for both sound absorption and sound proofing. Metamaterials are frequently lightweight and compact and have demonstrated exceptional effectiveness in diminishing low-frequency noise, a task that conventional acoustic materials have traditionally struggled with.

7.2. Targeted sound insulation

Despite consistent research, commercial sound insulation products based on acoustic metamaterials are yet to materialise. Nevertheless, it is clear that the research efforts constitute the inevitable steps eventually leading to architectures suitable for lightweight building construction. In this regard, the research informs that the advancements in acoustic metamaterials for the building industry is entering a stage where customizability is the primary target. On the other hand, the control over frequency is expected take metamaterials to an ever-broadening horizon where occupants will be able to customise the frequency spectrum that is required to be insulated.

7.3. Multiple acoustic metamaterials into a single architecture

A significant hindrance to the actual usage of most developed AMMs is their limited frequency band or occasionally single frequency operation. For resonant structures in particular, this is accurate. Many integrated design techniques are available to increase the bandwidth and improve their qualities throughout a wide range of frequencies. Nevertheless, the structure's compactness could be compromised by this strategy. Thus, the employment of active metamaterials as a unique design approach that may, to some extent, ensure both a broad working frequency range and the compactness of the structure. Moreover, it is evident that inherent thermos-viscous losses within AMMs significantly affect their characteristics and operations, particularly for transmissive AMMs where these losses may result in low transmitted acoustic energy and poor transmission coefficients.

For a vast majority of acoustic metamaterials, the local resonance phenomenon informs their high sound absorption or low sound transmission capabilities. However, this leads to a narrow frequency band of peak performance which is a major shortcoming. A potential way to improve the performance frequency range is to assemble multiple metamaterials graded for their resonance bandwidth. Although examples of such assemblies in isolation have been shown by Jiang et al. [56] and Jiménez et al. [149], their installation and assembly from a building acoustics point of view require further research.

7.4. Low-cost manufacturing and scale up are key barriers

One of the challenges in acoustic metamaterials field is how to fabricate them. Although the development of additive manufacturing and its widespread use has spurred scientific advancements, there remain obstacles to the practical application of AMMs. The development of metamaterials and the verification of complex designs have been made possible by advances in 3D printing technology. On the other hand, due of the lack of robustness in fabrication processes, sizes, and material qualities, process optimisation and sustainability for 3D printing technology remain significant challenges. For instance, prestressing pressures that are challenging to modify and sustain over an extended period of time may have an impact on certain features for the majority of membrane-type AMMs. The majority of membrane-type AMMs are now produced manually and necessitate a wide range of materials with various qualities, which unfortunately results in a loss of uniformity. For AMM technology to be used in real applications, therefore, more sophisticated manufacturing techniques must be developed [150].

Before acoustic metamaterials can become common place for sound insulation in buildings, the current challenges regarding large-scale and low cost mass manufacturing have to be addressed. In order to do this AMM designs, have to be conceived giving due consideration to easy scale up and low-cost manufacturing [151]. The accessibility of additive manufacturing techniques also offers a promising route regarding the fabrication of complex geometries which are an integral part of acoustic metamaterials. Nevertheless, additive manufacturing is still a slow and relatively expensive process for mass manufacturing. Furthermore, the capability of additive manufacturing as a technology to work with multiple and eco-friendly materials are still not widespread. Even though additive manufacturing is not yet a mass fabrication technique, the technology is evolving rapidly aimed at closing this gap. As such the adoption of acoustic metamaterial for sound insulation in building will happen in the near future.

7.5. Control of structural borne sound within buildings

Structure-borne sound at mid-to high-frequency may be effectively reduced by conventional noise control methods employed in the building sector; low-frequency structure-borne sound is still difficult to manage with such a lightweight method. Researchers have been able to design new acoustic metamaterial ideas that can reduce low-frequency structure-borne sound due to recent improvements in additive manufacturing technology [152]. In ways that are not achievable with traditional materials, acoustic metamaterials may modify and control sound waves. Sound control at subwavelength scales and acoustic imaging are made possible by metamaterials that have a zero or even negative refractive index for sound. Very anisotropic acoustic metamaterials and transformation acoustics theory work together to precisely regulate how sound fields are deformed. This ability may be utilised, for example, to cloak or conceal things from being detected by sound waves [6]. This has led to the creation of dynamically reconfigurable, loss-compensating, parity-time-symmetric materials for sound manipulation. Active acoustic metamaterials utilise external control to provide effective material features that are not feasible with passive structures. Developing effective methods for creating large-scale metamaterial structures and turning lab research into functional devices are among the ongoing challenges.

Efficient noise evaluation in a setting (traffic, airport, theatre and other public areas) where sound sources change at random is another significant problem. An inaccurate noise evaluation might lead to the installation of poorly designed acoustic meta-structures. The development of acoustic metamaterials for outdoor applications should also take environmental conditions like humidity and temperature into account. The behaviour of sound propagation is influenced by environmental conditions [153,154].

Timber constructions often give less inertial and elastic resistance to impact pressures because they are lighter and less rigid than steel and concrete, and the sound insulation treatments now in use do a poor job of attenuating sound in the 20–120 Hz range. Wave attenuation is now conceivable in acoustic metamaterials due to the success of unattainable qualities including bulk modulus, stiffness, and infinite or negative mass density [155]. But there are still problems to be resolved in terms of structural capacity, imposed extra mass, and the range of attenuated frequency bands. In an effort to better understand sound mitigation applications, Assouar et al. [156] conducted theoretical and numerical assessments of the behaviour of a plate-type acoustic metamaterial in an airborne sound environment. Two configurations were taken into consideration: one based on pillars and the other on springs and mass. They have demonstrated that the examined metamaterial may generate a significant sound transmission loss (STL) in the sonic frequency range, indicating that the system is very appropriate and efficient for applications involving the mitigation of sound and vibration. Furthermore, they proposed that the plate-type metamaterial can be a potential way to get around the coincidence frequency constraint, which results in high sound transmission via plates for sound shielding, by employing carefully selected low-frequency resonators.

8. Conclusions

The research on acoustic metamaterials that can offer high sound absorption and sound proofing characteristics are increasingly being documented. As such, the review has identified a range of acoustic metamaterial architectures that can be adopted to enhance sound insulation in buildings. These metamaterials not only offer highly customisable acoustic properties but also significantly outperform traditional materials in low frequency sound attenuation beyond the mass law. These characteristics make acoustic metamaterials ideal candidates for light-weight buildings and housing projects near airport, railway lines and motorways. Although most acoustic metamaterials can be accommodated when it comes to the design of light weight building structures, the plate like architecture seems to offer the most cost-effective route to enhance sound proofing. This means that the plate-type metamaterial architecture can be incorporated to building walls and floors to increase its Sound Reduction Index (R) while keeping the mass low. To improve room acoustics on the other hand attention should be placed on the selection of acoustic metamaterials that can offer the highest sound absorption coefficient (α) over a wide frequency range. Other than for specialist application, the standard practice in the building industry is to use materials that offer broad band sound absorption for general acoustic comfort. Here the cavity based, space coiling or gradient acoustic metamaterials can be used in combination with traditional materials to achieve improved low frequency sound absorption. This approach is also suitable to improve the sound insulation at targeted range of frequencies that are of particular interest offering significant versatility. Perhaps the most transformative role of acoustic metamaterials in future buildings will be their contribution to improving the acoustic insulation of ventilation, ducts, and windows. The ventilated acoustic metamaterials offer significant promise in this regard and have demonstrated significant sound insulation while facilitating air and light ventilation. Overall, tuneable, and multifunctional acoustic metamaterials when integrated into future buildings with lead to significant space-saving and light-weighting in comparison to traditional insulation design. Notwithstanding the encouraging attention and small-scale models, the exhibition of large-scale productions is still pending in many instances. An additional factor is the high-volume production and expandability that raise uncertainties about their economic feasibility. Lastly, accelerating the uptake of acoustic metamaterials by the building industry require further research demonstrating their sound insulation performance at suitable scales following appropriate acoustic standards.

CRediT authorship contribution statement

Arun Arjunan: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ahmad Baroutaji:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **John Robinson:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Aaron Vance:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Abul Arafat:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

All authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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