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Advances on acoustic metamaterials

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Abstract

Acoustic metamaterials offer a new paradigm for the control and manipulation of sound waves that are often unachievable through conventional materials. The potential this offers to the field of sound absorption, insulation, cloaking, and imaging are remarkable. Acoustic metamaterials also allow material constructs to be tuned both actively and passively for reconfigurable material that offers unprecedented wave manipulation. Challenges remain, in simplifying, identifying scaling techniques and deriving design guidelines for the manufacture of large-scale acoustic metamaterials to transform laboratory prototypes to useful devices. However, research in this area is rapidly evolving with the necessary building blocks that can be additively manufactured or assembled to form metamaterials. In this regard, the paper provides a general introduction into acoustic metamaterials followed by their qualifiers. The focus is placed on summarising the advances that are happening in the field of acoustic metamaterials classified based on potential application. In doing so key design approaches and resulting properties of acoustic metamaterials are discussed in relation to their most recent advancements.

Keywords: Acoustic metamaterials; sound absorption; transmission; imaging; cloaking.

1. Introduction

Research on sound wave propagation in engineered materials offers great promise in achieving highly novel and exotic acoustic characteristics suitable for a range of applications [1–6]. In general, engineering material with elastic modulus and mass density corresponding to the impinging sound wavelength is the process behind phononic crystals and acoustic metamaterials. In doing so rare properties can be unlocked from frequency dependence to band gaps and reduction in sonic velocity [7–10].

While acoustic metamaterial is a broad term, researchers generally refer to metamaterial as engineering material or construct that feature exotic and counterintuitive characteristics at a scale comparable to the wavelength. The concept also extends and covers phononic crystals and similar constructs that also falls within the category. These state-of-the-art, engineered materials featuring targeted bulk and surface properties can be referred to as acoustic metamaterials. Overall, acoustic metamaterials are an emerging field where the properties are a result of the structural and geometrical arrangement as opposed to the material chemist. Acoustic metamaterials offer the potential for applications that can revolutionise the way resonance behaviour is used in the field of acoustics.

Acoustic resonance within a material at a local scale can result in interesting wave properties. The sound wave vector in a homogeneous medium can be represented as $k = |n|\omega/c$, with $n = \ /\kappa$. Accordingly, the mass density and bulk modulus k are the primary parameters that dictate the acoustic behaviour of a material [11]. If is negative (−) and k is positive (+), then the wave vector becomes imaginary resulting the acoustic wave decaying as it propagates. This giving rise to the band gaps of the locally resonant material.

Various efforts can be found in the literature [12–14] where $-k$ acoustic metamaterials are being demonstrated theoretically, numerically and experimentally. It should also be noted that the principle of acoustic metamaterials is not merely of utilising resonance or strictly periodic structures. In a broader sense, submicron waveguides that exhibit acoustic characteristics that are not driven by the chemical combination or natural microstructure can also be referred to as acoustic metamaterials. The field of acoustic metamaterial is evolving rapidly with and novel involve constructs that have both $\mp$ and $\mp k$ resulting in new wave characteristics. The behaviour includes the reversed Doppler effect [15] often seen in double-negative materials, high-resolution imaging, transformation acoustics, invisibility cloaking [16–18].

The last fifteen years have seen the proliferation of research in acoustic metamaterials proving their suitability in many domains. Many constructs have established precise manipulation of acoustic waves in ways previously inconceivable. Accordingly, this paper presents the advances in the field and identifies the technical challenges and possible future directions for acoustic metamaterials. The focus is placed on those emerging fields in acoustic metamaterials that are edging closer to experimental reality rather than sole theoretical concepts. Consequently, numerous acoustic metamaterial concepts are beyond this paper and the field itself is being expanded to elastic metamaterials that control vibrations, waves, and the motion of solid materials [19–21].

2. Advances in acoustic metamaterials

2.1. Phononic crystals

Although it is hard to know the exact beginning regarding the development of acoustic metamaterials, phononic crystals were perhaps the first to show exotic acoustic phenomena. Phononic crystals are a type of metamaterial that allows the realisation of exotic acoustic characteristics because such sound wave propagation is often unattainable in chemically conceived materials. They consist almost entirely of carefully assembled inclusions that behave like scatterers [22–24]. One of the most notable characteristics of phononic crystals was regarding the Bragg bandgap which is closely related to Bragg diffraction [25].

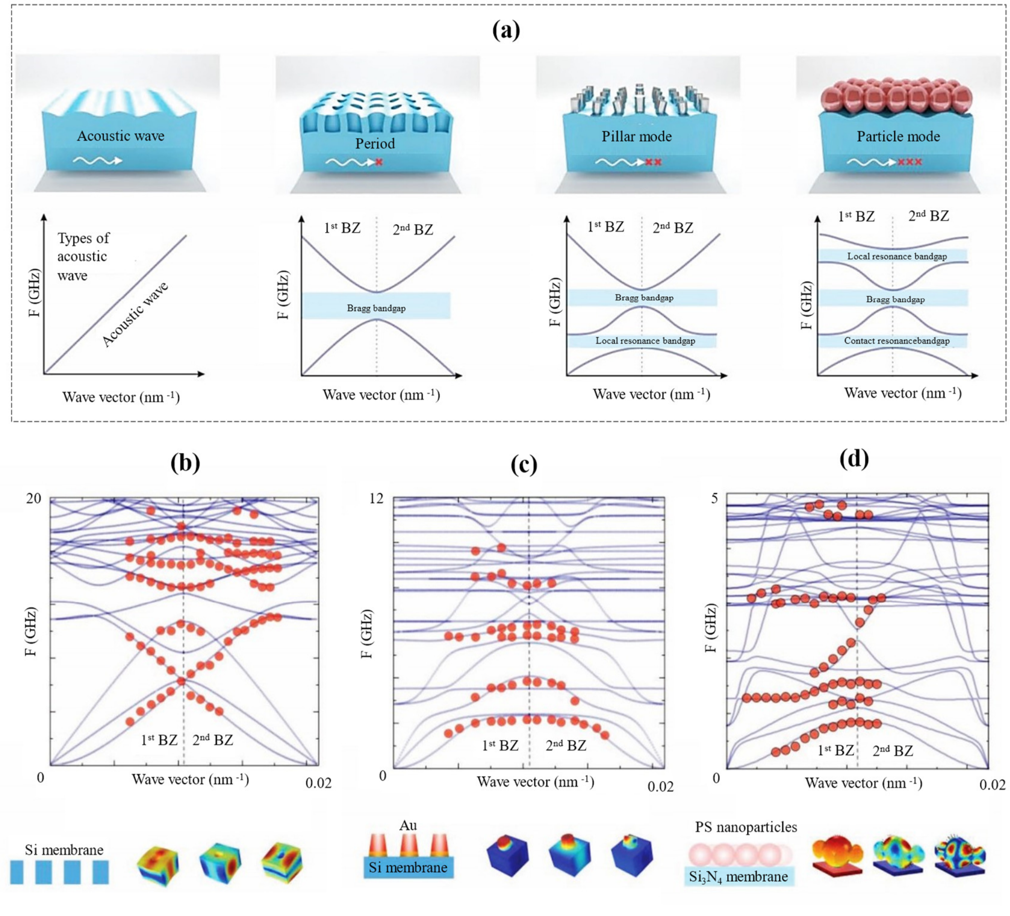


Fig. 1. Representative examples regarding different types of phononic crystals adapted from [26] showing (a) types of phononic crystals and the associated frequency and wave vector relationships. (b), (c), and (d) shows and an indication of the phonon dispersion from experimental, theoretical, and numerical models as available [27].

This means that the sound wavelength (λ) and lattice periodicity (a) becomes comparably close establishing $\lambda \approx a$. When another condition is also satisfied when the global thickness (t) of the crystals satisfies multiple (often 4 or 5) at $t >> a$, the crystal shows hybridisation band gaps at $\lambda >> a$ leading to exotic phenomenon such as negative mass density ($-\ $) and elastic modulus ($-k$). When such characteristics are being demonstrated, the phononic crystals satisfies the criteria of acoustic metamaterials [28,29]. The subsequent research efforts carefully studying the characteristics of such architecture has led to the proliferation of acoustic metamaterials that exhibit a range of novel functionalities [30–34].

Two-dimensional phononic crystals are often in the hypersonic range with element sizes at submicron and nanometre-scale [26]. Numerous approaches to the fabrication of phononic crystals are available in the literature. A quick survey revealed that the most popular approach was to use electron-beam lithography (EBL) [27,35–37] followed by focused ion beam milling [38,39]. Nevertheless, studies have also demonstrated the use of block-copolymer [40] and colloidal crystal [41] self-assembly techniques to obtain precise feature size.

Studies on phononic crystal metamaterials were initially related to the creation of the band structure. However, soon it was revealed that a complete bandgap called for complex topological architecture that combines a range of dimensional features builds into a period arrangement. Studies by Economou and Sigalas [42] along with Kushwaha and Halevi [43] showed that phononic crystal band structures can be customised through the use of filling ratio featuring materials with varying elastic constants. For example, components with varying mass density in a matrix can result in a full band gap contrasting sonic velocities. For 3D phononic crystals, FCC lattices were favourable for full band gap in comparison to BCC architecture. Overall, phononic crystals to date exhibit huge potential for a range of applications from acoustic insulation, wave slowing, filtering, novel waveguides, collimation [44], beaming, shock proofing, and acoustic imaging. They have also been investigated for acoustic cloaking and transformation acoustics.

2.2. Sound absorbing metamaterials-based cavity architecture

Recent years have seen the proliferation of acoustic metamaterials research targeted for noise pollution and general-purpose sound absorption [45]. The attempts in this regard largely fall based on the interaction of the incoming sound wave with a solid, fluid, or solid-fluid composite [46]. Solid-fluid interaction-based acoustic metamaterials often featured solid scatterers arranged within a fluid matrix. The technique was closely following the research on bandgap as discussed in the section above, for these devices' metamaterial influenced acoustic absorption was only seen at narrow frequency bands, often even at isolated frequencies.

When research on acoustic metamaterials broadened, attempts to utilise thermal and viscous damping for noise reduction was attempted by several metamaterials. The approach was to use sonic crystals in a layered format and to evaluate the thermo-viscous losses [47]. Consequently, attempts to improve the acoustic absorption characteristics of acoustic metamaterials saw the use of solid scatters in combination with traditional sound-absorbing constructs. Studies by Slagle and Fuller [48] used mass concentrators within a porous architecture which showed superior acoustic absorption (α) at low frequencies. Subsequent studies [49] used three-dimensional rigid inclusions into the porous layers and also showed improvements in α. Other notable studies include hybrids acoustic metamaterials involving microperforated architecture, crystal filling fraction, acoustic coating in combination with resonance-based metamaterials or sonic crystals [50–53].

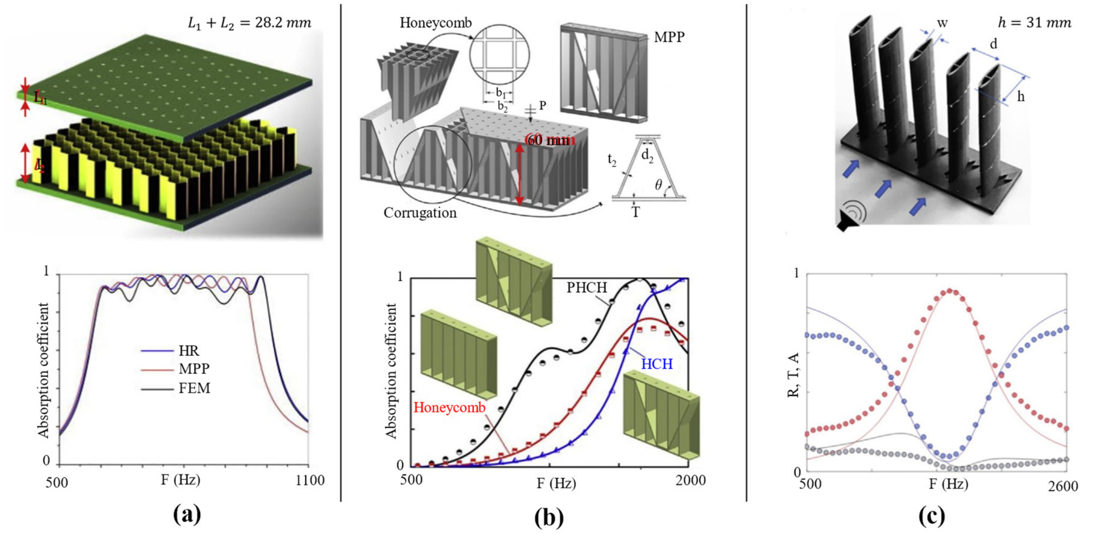


Fig. 2. Selection of sound-absorbing metamaterials adapted from [46], where (a) shows the representative example of a metamaterial architecture that brings together microperforated architecture with a honeycomb back cavity [54]. (b) a hybrid sound absorber using a microperforated panel on top of a honeycomb lattice [55]. (c) shows an additively manufactured sound absorbing ventilation [56].

The theoretical principles that describe the acoustic properties of microperforated panels (MPPs) are well known [57,58]. Nevertheless, a broadband MPP with high α require microscopic perforations requiring the use of expensive machining techniques. The rise in AM techniques such as Selective Laser Melting (SLM) [59,60] allows the creation of complex perforations and waveguides [61,62]. However, studies on the acoustic performance of AM metal MPPs that feature high α and STL are scarce. In any case, no study has reported the acoustic performance of non-circular perforations except for slits. Accordingly, this study explores the potential of developing an AM Ti6Al4V non-circular MPP system that may have a potential impact on both α and STL.

Recently, metamaterial-based MPPs have been developed by bringing together MPP panels with acoustic meta-architecture [63–66]. Some notable cases are shown in Fig. 2 where the advantage of frequency-based resonators was combined with MPPs which was able to significantly enhance low-frequency sound absorption. Overall, as shown in the associated acoustic performance vs frequency curves, all constructs were able to demonstrate peak performance at a certain frequency band as a function of resonance. Other notable works include a recent study [67]where a thin metamaterial construct comprising of solid-fluid architecture demonstrated complete absorption (α) inducing airborne resonance. The structure was a combination of MPP and a deeply subwavelength channel of air where the α enhancement can be attributed to the thermo-viscous losses happening during fluid-structure interaction.

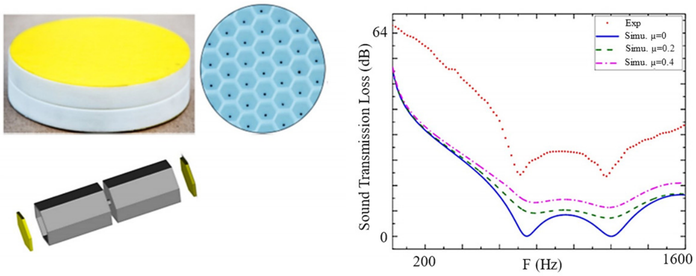
Table 1. Acoustic metamaterials architecture featuring other elements developed for sound absorption [46].

Architecture	**~Size (mm)**	**Frequency range**	**Ref.**
Hybrid architecture combining a honeycomb corrugated core and resonance cavities	60	$< 2\ kHz$	[55]
A waveguide type architecture combining tubes and multi-layered MPP metamaterial	54	$0.8 - 1\ kHz$	[68]
Acoustic metamaterial combining Helmholtz architecture with geometrical apertures	50	$0.13 - 0.17\ kHz$	[69]
Helmholtz resonator with inserted perforated composite	62	$0.45 - 1.36\ kHz$	[70]
Resonance cavities and back walls using aerogels	42	~$0.6\ kHz$	[71]
Acoustic metamaterials based on curved coplanar waveguides	17	~$0.6\ kHz$	[72]
Coiled waveguides featuring geometrical features	$20 - 24$	$0.146 - 0.168\ kHz$	[73]

2.3. Sound barrier metamaterials for airborne sound

Although in their infancy, acoustic metamaterials are being developed for sound insulation targeted for both temporary and permanent installations [74,75]. If successful, this will allow for sustainable buildings close to noisy environments such as airports, railways, and highways [75,76]. Acoustic metamaterials featuring resonant membrane were one of the earlier constructs that showed high efficiency towards isolating low-frequency sound [77–79]. One of the most popular designs [80] in this regard is shown in Fig. 3a featuring a rigid honeycomb and a flexible outer layer which was referred to as a meta-structure resulting in a sound reduction index (R) of 45 dB below 0.5 kHz as shown in Fig. 3b.

Variations in this architecture were studied by Ma *et al.* [81,82] and Ang *et al.* [83] resulting in superior performance at predetermined frequency ranges. Ma *et al.* used two approaches; the first case was to use thin walls with positive lumped coupling resonators. A bi-layer architecture with Willis coupling was another approach that also showed to be suitable for sound barrier applications. For Ang *et al.*, planar meta-structures with cavities linked through an orifice were the chosen architecture for improving the sound reduction index. The results demonstrated that the sound behaviour can be influenced by the coupling effect happening between the enclosed cavities connected through an orifice. This meant that the radius of the orifice can be modified for targeted frequency-dependent performance. This offered significant potential for this design to act as noise barriers [84,85] solving the general concerns associated with membrane metamaterials. These are few examples of how acoustic metamaterials are being used to conceive sound barriers which are also suitable to be scaled up and mass-produced for functional sound insulation.



(a)

(b)

Fig. 3. A meta-structure sound barrier showing (a) the multi-element design and (b) the resulting enhancement in low-frequency sound transmission loss as adapted from [45,80].

2.4. Acoustic metamaterial lens

Exotic characteristics of acoustic metamaterials offer significant potential to be used for diffraction-less acoustic imaging [86]. The potential for metamaterial was first explored for the field of optics where possibilities were identified for high-resolution imaging that go beyond the normal diffraction limit [87]. Studies conducted by Zhang and Liu [88] along with Yang *et al.* [89] were critical in demonstrating the use of acoustic metamaterials in manipulating fundamental properties such as negative refractive index. As a result, acoustic metamaterials offer desirable properties for ultrasonic imaging suitable for applications in biomedical diagnostics and regular non-destructive testing. While ultrasonic imaging as technology is well established, it is improving the resolution where acoustic metamaterials feature the distinctive advantage.

Due to this reason, acoustic metamaterial featuring parallel surfaces that allow for a negative refractive index is of interest to ultrasonic imaging due to their capacity to act as wave lenses as shown in Fig. 4. Acoustic metamaterial lenses offer superior resolution in comparison to their conventional counterparts due to the existence of a sub-wavelength evanescent field [92]. The advantage of using metamaterials is that the imaging resolution can be improved at the same inspection frequency. At the same time, low frequencies can be used for increasing the wave penetration depth [87].

In classical imaging techniques, performance is significantly affected due to the inherent diffraction limit resulting from the loss of subwavelength information featured within the evanescent waves. The wave loss occurs exponentially as it travels away from the target while carrying large lateral wave vectors as shown in Eqn. (1):

$$k \; = k_{\perp} + k_{\parallel} = \left(\frac{2\pi}{\lambda}\right) \tag{1}$$

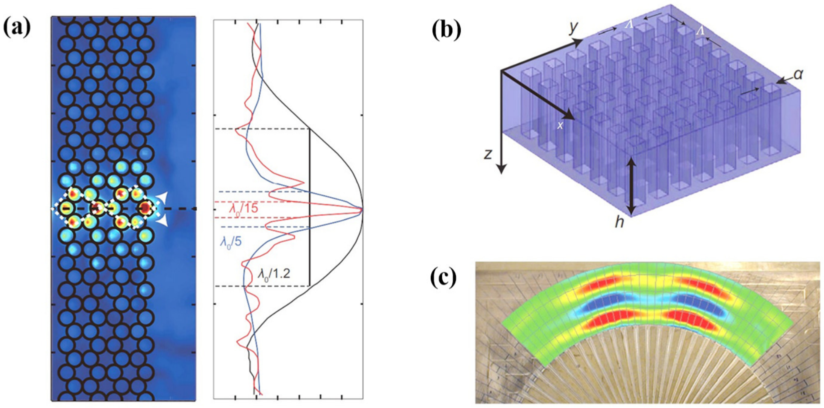
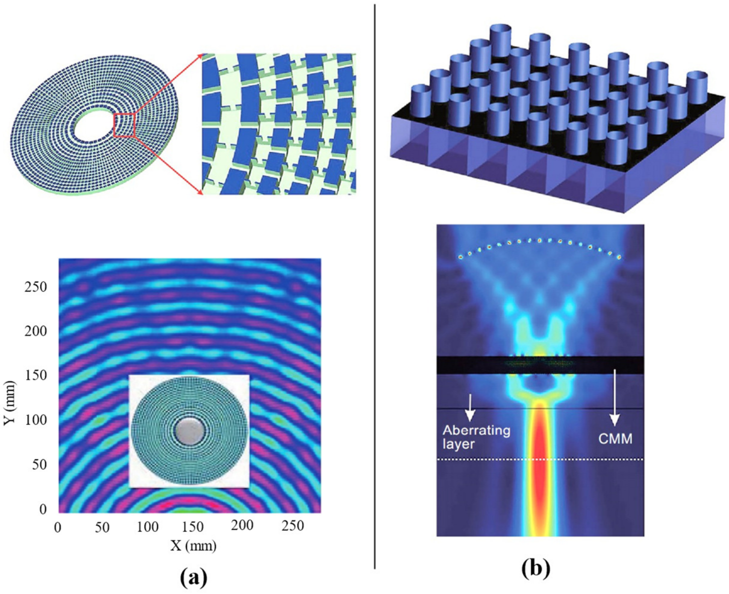


Fig. 4. Acoustic metamaterials based negative index lens, adapted from [11]. (a) shows the negative index architecture composed of a repeating array of resonator elements [16]. (b) Subwavelength inclusion that is necessary for relevant resonant modes [90] and (c) the metamaterial hyper-lens featuring air and brass periodic architecture, and the transforming evanescent to propagation waves at far-field [91].

If the lateral wave vector $k_{\parallel}$ exceeds $2\pi/\ \lambda$, where λ is the wavelength, the wave vector $k_{\perp}$ in the longitudinal direction must be imaginary. As a result, the wave decays exponentially away from the source. The scattering of the acoustic wave is generally composed of both propagating and evanescent waves. To overcome the limits associated with diffraction, the evanescent waves are required to be transmitted and collected before they become too weak to be detected. Consequently, two methods are being explored, a case of evanescent wave amplification that is subsequently captured at the near field or the addition of extra wave vectors in the adjacent medium to sustain the evanescent waves, or converting them into propagating waves [11,93,94]. The diffraction-less acoustic metamaterial-based imaging is also suitable for high-efficiency sonar. There are numerous studies [95,96] in this regard demonstrating the use of locally resonant 2D geometrically specific voids in an elastic medium in combination with thin stiff bars to generate a negative refraction effect at low frequency [97]. The acoustic metamaterial based magnification of a far-field image using sound wave was demonstrated by Ao and Chan [98] showcasing potential application for systems that obey the scalar wave equation.

2.5. Acoustic invisibility cloaking

Acoustic cloaking or invisibility (non-optic) is one of the most exotic phenomena that can be achieved by specifically designed acoustic metamaterials. Here cloaking is referring to a case where a target is undetected by sound waves, meaning the target object is neither reflecting nor absorbing sound giving an illusion of acoustic invisibility. Acoustic metamaterials achieve this by carefully redirecting the wave from the source around the target to an unaltered course [99–101]. The physics behind the concept is usually referred to as wave transformation using a metamaterial architecture to transform the wave to the coordinates. Transformation acoustics can be explained using the time-harmonic acoustic wave equation [102].



(a) **(b)**

Fig. 5. Acoustic metamaterial-based cloaking architecture and representative examples of resulting performance adapted from [105,106]. (a) shows a two-dimensional architecture suitable for underwater ultrasound cloaking [106] and (b) a metamaterial architecture that can cancel aberrating layers for biomedical imaging application [105].

As shown in Fig. 5a, acoustic metamaterial cloaking was initially explored for underwater acoustics using constructs featuring specifically arranged cavities in a ring format. The design of each inclusion was parametrically conceived based on the acoustic frequency and the targeted characteristics being explored. The ring format enabled an object to be placed at the centre which was then acoustically cloaked as can be seen from the unaffected wave pattern. Although there are numerous other constructs focused on achieving various cloaking effects. One notable strategy that gained popularity was the so-called carpet approach that was specifically targeted for airborne acoustics [103,104]. This approach was successful in acoustically concealing objects in three dimensions. A different application that explored cloaking through exploiting the negative index was the termination of aberrating intermediate layers between source and target to allow deep ultrasound transmission for medical imaging as shown in Fig. 5b [105].

2.6. Acoustic interference cavities

The rise in additive manufacturing [107] allows having precise control of geometry at the sub-micron level which can be exploited for the development of acoustic metamaterials exploiting the principles of interference [75,108]. Acoustic interference occurs when two waves superimpose to form a resultant wave that is of higher (constructive interference) or lower amplitude (destructive interference) as shown in Fig. 6. The principle itself is well known and is generally employed in an active form in the case of active noise cancellation. However, acoustic metamaterial makes it possible to conceive destructive interference passively by precisely placed geometrical cavities which offer significant promises for a range of sound attenuating products. Several attempts in this regard are visible from literature demonstrating varying degrees of acoustic performances [109–112].

Acoustic metamaterials constructs utilising the principles of interference wave superimposition was experimentally investigated by Arjunan [61,62]. All the metamaterial constructs exhibited acoustic interferences causing significant improvements in both sound absorption (α) and sound reduction index (R) making them suitable to be used for absorption or insulation. However, the spike in performance was found at a reduced frequency band requiring further studies for broadband application. A shift in resonance frequency was also observed in comparison to theoretical prediction attributed to the complex geometrical inclusions. Overall, the studies in this regard show that interference-based acoustic metamaterials are highly desirable to be used for frequency-based noise abatement. Nevertheless, further studies in this area are required before the technology matures, and broad design guidelines are generated.

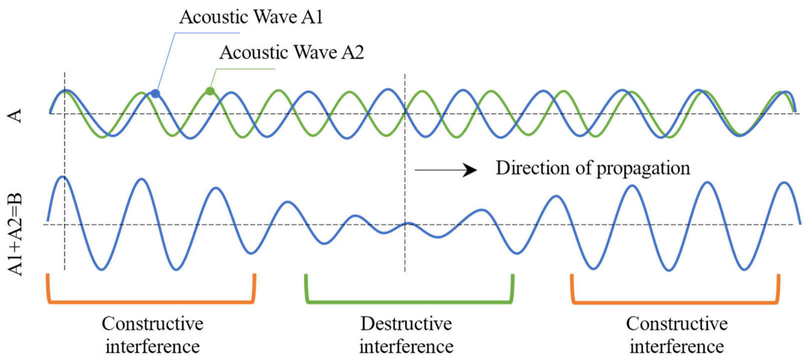


Fig. 6. A simplified case of acoustic interference showing wave superimposition [62].

3. Challenges and future perspective

Although the last decade of research on acoustic metamaterials has significantly enhanced the understanding of their behaviour, significant challenges are remaining to be overcome before the effective realisation of real-world applications [19,113–116]. One of the primary challenges in this regard is the link between acoustic metamaterials and the narrow working bandwidth. In most cases, the principle of resonance and frequency dependence targeted by acoustic metamaterials make them effective at very specific or narrow frequency ranges. For a large number of applications, this problem can be solved by coupling acoustic metamaterial constructs with traditional acoustic architecture in a way that harvests the potential of both within a single structure [117–120]. Another approach can be the integration of multi-band resonances like the way it is conceived in broadband acoustic devices. Lastly, acoustic metamaterials featuring active tuning or source dependent tuning can also be explored to solve narrowband frequency issues.

So far, the physically conceivable acoustic metamaterials are in the range that is predictable using the effective medium theory. The geometrical complexity is also increasingly becoming achievable due to the developments in digital fabrication techniques such as additive manufacturing. However, the limits of what is physically achievable will be largely dependent on the feature size that can be achieved. This can be a deterrent in the fabrication of acoustic metamaterials that is otherwise theoretically possible.

4. Conclusion

The area of acoustic metamaterials has seen significant research interest over the years. As discussed thus far, studies have been exploring the physics of acoustic metamaterials using theoretical, numerical, and experimental techniques. Despite the promising interest and lab-scale prototypes, large scale fabrications are yet to be demonstrated in most cases. Another aspect is the manufacturing and accessibility of highly precise, sub-micron, and nanoscale additive manufacturing seems to be the fabrication of choise for most lab-scale devices leading to questions regarding the commercial viability of highly complex constructs. Although the research contributes significantly to many areas, gradient index acoustic metamaterials seems to offer significant promise as the next generation of sound absorbers. These architectures have demonstrated enhanced acoustic absorption and be designed to target the frequencies of interest. In addition targeting specific applications such as underwater acoustics and frequency-dependent tuneable devices, multifunctional acoustic metamaterials that can be integrated into other application leading to space-saving or light-weighting require further studies. Nevertheless, the field of acoustic metamaterials is expanding with novel characteristics and new applications being proactively unveiled. Overall, the the areas of metamaterial development that is seeing the most advances include elastic wave absorption, tuneable, multifunctional, and submicron scale meta-structures. The areas that require significant further studies to be fully understood include gradient index, underwater, and hybrid acoustic metamaterials.

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