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Characteristics of acoustic metamaterials

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Abstract

The term "metamaterials" refers to artificial constructs whose characteristics are determined by the collective manifestations of local units. When such constructs are designed for acoustic wave manipulation, they are referred to as acoustic metamaterials. Acoustic metamaterials allow controlled wave propagation that is often inconceivable through chemically developed bulk materials. This means that the wave propagation in acoustic metamaterials goes beyond the mass-density characteristics of the material resulting in targeted acoustic outcomes. The unique characteristics of acoustic metamaterials have opened a new direction in the development of effective solutions for a range of applications, including but not limited to low-frequency sound insulation, acoustic cloaking, sound focusing, biomedical acoustics, and passive destructive interference. The overall characteristic of an acoustic metamaterial depends on the type of sound manipulation being targeted. This paper introduces the characteristics associated with some of the most promising acoustic metamaterials from passive to active. An effort is placed to highlighting both the underlying principles and the physical prototypes that were evaluated.

Keywords: Acoustic metamaterials; sound insulation; absorption; transmission; material design; additive manufacturing.

1. Introduction

Acoustic metamaterials have proved to be of great interest due to their superior wave-control characteristics that can be exploited for applications in challenging acoustic environments [1,2]. An acoustic wave is longitudinal and the associated parameters are pressure (P) and particle velocity (u). The analogy between acoustic and transverse magnetic field under a two-dimensional (2D) under harmonic excitation is shown in Table 1. This shows the equivalence in relevant parameters that is necessary for the creation of meta-acoustic characteristics. Similar approaches hold when evaluating synergies between optical and acoustic constructs of metamaterial as well.

Table 1. The analogy between parametric variables associated with acoustic and electromagnetic material characterisation. Adapted from Zhang [3].

Acoustic	**Electromagnetism**	**Analogy**
$\frac{\partial P}{\partial x} = -i\omega \quad u$	$\frac{\partial E_z}{\partial x} = -i\omega\mu_y H_y$	
$\frac{\partial P}{\partial y} = -i\omega \;\; {}_y u_y$	$\frac{\partial E_z}{\partial y} = i\omega\mu \;\; H$	-
$\frac{\partial u}{\partial x} + \frac{\partial u_y}{\partial y} = -i\omega\beta P$	$\frac{\partial H_y}{\partial x} - \frac{\partial H}{\partial y} = -i\omega\varepsilon_z E_z$	
Acoustic pressure P	*Electric field* E_z	$-E_z \leftrightarrow P$
Particle velocity $u \;\; , u_y$	*Magnetic field* $H \;\; , H_y$	$H_y \leftrightarrow -u \;\; , H \;\; \leftrightarrow u_y$
Dynamic density $\qquad {}_y$	*Permeability* $\mu \;\; , \mu_y$	$\leftrightarrow \mu_y , \;\; {}_y \leftrightarrow \mu$
Dynamic compressibility β	*Permittivity* ε_z	$\varepsilon_z \leftrightarrow \beta$

The mechanical characteristics of macroscopic materials are largely dictated by the atomic and molecular arrangements that form them [4–8]. Similarly, the resulting wave characteristics can be considered as the average of fluctuating local fields [9]. However, when it comes to metamaterials the concept of atomic arrangement is superseded by artificially constructed sub-scale repeating structures comparable to that of the wave dimensions. This allows precise control of the wave characteristics in an acoustic metamaterial as the repeating unit cells can be controlled for a targeted outcome that is less influenced by the chemical composition of the material [10–12]. The repeating (not necessarily periodic) unit cells of such structures can be conceived in dimensions depending upon the acoustic application and outcome.

Although this can differ, generally subwavelength local resonant units of an acoustic metamaterial can be considered microscopically as creating a global material response. In this regard, the local units can also be considered oscillators having a resonant frequency, as such acoustic metamaterials are dynamic mediums although the unit cells themselves do not change [13,14]. Although phononic crystals [15] shows negative elastic parameters [16], the validity of the effective medium approximation can be characterised via single-mode approximation.

In general, acoustic metamaterials provide increasing opportunities for the development of targeted acoustic performance through the creation of functional materials. Acoustic metamaterials offer unprecedented properties that are often challenging to be realised from natural materials [17,18]. The increased interest in widening the scope of acoustic metamaterials and the design freedom offered by additive manufacturing (3D printing) is likely to enable a new generation of acoustic metamaterials that are smaller and more efficient expanding the acoustic characteristics in the near future.

2. Characteristics in acoustic metamaterials

2.1. Negative (<0) mass and stiffness

The parameters that are of primary importance in the characterisation of acoustic metamaterials are the effective -mass density (ρ) and the -bulk modulus (k). These two parameters can be used to determine the characteristics of acoustic wave propagation in a medium. Both the sonic velocity (c) and the characteristic impedance (Z) of a medium are expressed by these two parameters as shown in Eq. (1) [4,5,13]:

$$c = \sqrt{k/\rho} \tag{1}$$

$$Z = \sqrt{k\rho} \tag{2}$$

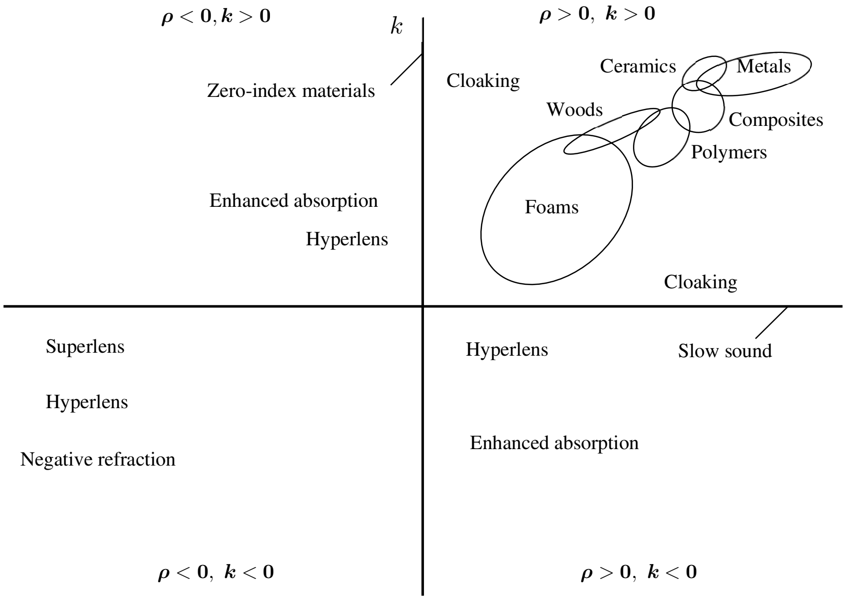


Fig. 1. Influence of mass density (ρ) and bulk modulus (k) on the resulting performance characteristics of acoustic metamaterials [19]. $\rho > 0, k > 0$ characterises conventional materials and metamaterial cloaking devices. The remaining three quadrants are currently used only for characterising metamaterials. Zero-index and slow-sound metamaterials have vanishing ρ and k respectively. Superlenses and hyper lenses are metamaterials that go beyond the diffraction limit characterised by $< 0, k < 0$. Acoustic wave bending is characterised by a negative index of refraction that leads to the propagation and magnification of evanescent waves resulting in going beyond the diffraction effect.

In conventional materials, both ρ and k are higher than zero (+) largely dictated by the chemical composition and microstructure of the material. When resonance inclusions are placed within such a material, the interaction between sound waves and the matter increases drastically [20,21]. These interactions can lead to ρ and k going below zero (-) at selected eigenmodes. The resulting characteristic can give rise to $-\rho$ and k leading to unprecedented or rare acoustic phenomenon such as negative refractive index [1]. Fig. 1 shows that while chemically conceived bulk materials can be characterised by a positive (+) density and bulk modulus placing them in the upper-right quadrant of the ρ k plot. As can be seen the parametric quadrant occupied by acoustic metamaterials goes well beyond the domain of classical materials and even occupy space where either one parameter can be positive or negative giving rise to extremely rare wave phenomena.

2.2. Dynamic microstructure

Due to the artificially constructed nature of the fundamental units in a metamaterial, the microstructure can be referred to as dynamic due to added degrees of freedom (DoF). These DoFs are created through the careful arrangement of the fundamental elements that constitute the dynamic microstructure. Depending on the characteristics of the acoustic metamaterial, these fundamental units can be resonant inclusions, Helmholtz architecture, scatterer geometries, elastic membranes, and complex mass or stiffness arrangements.

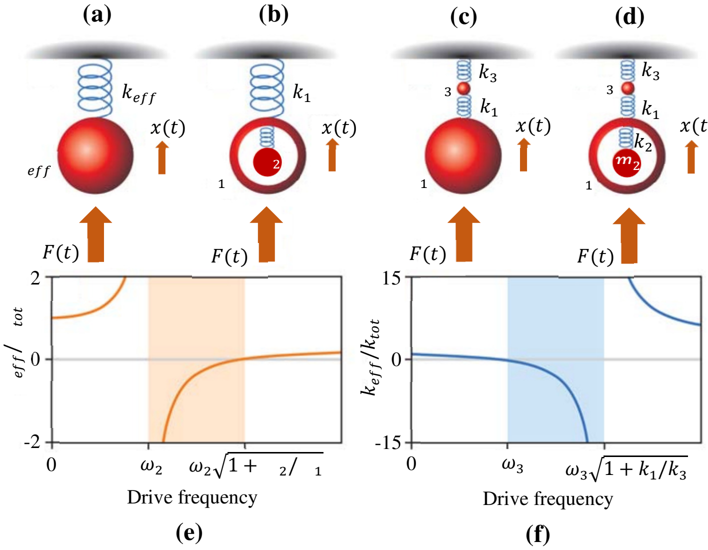


Fig. 2. Spring mass system showing hidden DoF in an acoustic metamaterial as adapted from Haberman and Guild [19]. (a) shows the arrangements of masses ($_i$) and spring constants (k_i) that describe displacement $x(t)$ in response to a driving force $F(t)$. Assuming $_3$ is lighter than $_1$ and $_2$ then specific arrangements allow (b) negative mass, (c) negative spring stiffness, and (d) negative mass and stiffness. (e, f) shows normalized effective mass and spring stiffness as a function of the drive frequency. The resonance frequencies ω_2 and ω_3 are, respectively, $\sqrt{k_2/ \;\; _2}$ and $\sqrt{k_3/ \;\; _3}$. In graph (e) and (f) the highlighted section is referring to the negative dynamic mass region and negative-stiffness region in (b) and (c) respectively. The normalizations are determined by the quasistatic mass $_{tot} = \;\; _1 +$ $_2$ and the quasistatic spring constant $k_{tot} = (1/k_1 + 1/k_3)^{-1}$.

Even though these fundamental units have peculiar physics associated with them, the type and arrangement dictate the global performance making them comparable to microstructure in the traditional sense. Although the contribution from a single unit is insufficient to influence the global acoustic response, the cumulative effect of multiple units leads to a substantial effect. As such, carefully conceived units cause an exotic acoustic response which allows further tuning by tweaking the so call microstructure arrangement [22–24].

At certain frequencies, the response of the dynamic microstructure becomes significant and out of phase with the incident sound wave. In such a case, it can be considered that the global performance of the acoustic metamaterial is dictated by the inclusions whose effective material properties are negative. The resulting characteristics of the acoustic metamaterial are often frequency-dependent and different from that of the otherwise macroscopic response of the material [25–27]. As such the notion of additional DoFs as shown in Fig. 2 is an adequate representation of the dynamic response of the system. Such theoretical constructs show how the microstructural arrangements of inclusions result in additional DoFs that subsequently results in acoustic responses shown in Fig. 1. Although shown as a component system, the spring-mass system shown in Fig. 2a acts as a single effective system where the mass is displaced by a distance $x(t)$ under a time-dependent force $F(t)$. By rearranging classical Hooke's relationship, it is possible to obtain the effective mass and spring constant of the system as $_{eff} = F(t)/\ddot{x}(t)$ and $k_{eff} = F(t)/\ddot{x}(t)$ [28–30].

2.3. Transformation acoustics

Another characteristic of acoustic metamaterials is the concept of transformation acoustics (TA) which is the basis of wave bending systems such as acoustic cloaking. The fundamental concept behind transformation acoustics is that:

i. The sound wave equation can be modified because of coordinate transformation.

ii. The physical characteristics in the transformed region are influenced by the new equation using the transformed coordinates.

The approach of transformational acoustic borrows inspiration from transformation optics, where the resulting characteristics are a result of the material constitutive parameters and the coordinate transformations [31]. The primary difference when it comes to acoustics is that the transformation follows the invariance of the equation of sound waves under a certain set of coordinate transformations [32,33]. The most notable application utilising the principles of transformation acoustics is acoustic cloaking, where the design of the acoustic metamaterials can bend acoustic waves around objects within multidimensional spaces [34,35][17,18]. Acoustic ground cloaks using transformation acoustics is another possibility as demonstrated by Popa *et al.* [36] that user perforations dictate the material characteristics required.

For a spherical acoustic cloak, the transformation between a thick and thin fluid ring dictates the overall acoustic characteristic of the metamaterial. This means that if the thin ring can mimic the wave equation of the thick ring, then the whole device act as a cloak concealing core through scattering. Consequently, the resulting characteristics of the acoustic metamaterial is that of wave transformation that makes the cloaking construct to transmit the acoustic wave faster in the azimuthal direction in comparison to the exterior fluid. During this time, the wave propagation slows down in the radial direction because of the reduced thickness. This results in an anisotropic property where the sonic velocity is dependent on the direction of transmission [37–39].

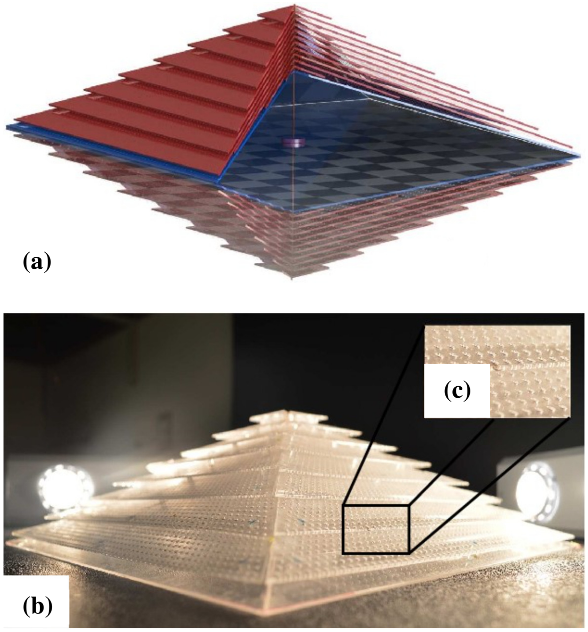


Fig. 3. Acoustic cloak put forwarded by Zigoneanu *et al.* [40] showing (a) the design (b) fabricated cloaked, and (c) perforations.

Although the criteria of wave propagation in regular fluids are quite different, the anisotropy of wave propagation can happen in materials that feature fluids arranged layer-by-layer. In such a construct, inertial anisotropy can occur given the thickness of the layers are at subwavelength under different fluid densities. From an acoustic metamaterial perspective, the spherical cloak demonstrates the complexity of acoustic anisotropy that is required for effective cloaking. Although simpler constructs such as the acoustic ground cloak can be conceived with comparatively small anisotropic complexity as shown by Zigoneanu *et al.* [40] (Fig. 3).

2.4. Acoustic surface evanescent waves

In addition to the physical response of acoustic metamaterials, the existence of surface states of sound waves and their unique characteristics are another aspect. When the energy of a sound wave is restricted at the surface level, the resulting amplitude reduces drastically in the third direction. As a result, the in-plane acoustic wave vector features an effective wavelength that is smaller at a slower sonic velocity. This in turn offers acoustic characteristics that can be applied to chip-scale acoustic devices. The approach when it comes to describing acoustic surface evanescent waves is that they can be evoked at the interface of semi-infinite homogeneous fluids featuring different elastic characteristics. The condition for the existence of such an acoustic surface evanescent wave is similar to the equation governing the presence of surface plasmon polaritons at the interface between metal and dielectric media as discussed by Lu *et al.* [1].

3. Emerging characteristics of acoustic metamaterials

3.1. Nonlinear behaviour

While the previous acoustic metamaterial characteristics exhibit linear behaviour, there are cases when nonlinearity from a material perspective can be exploited for developing acoustic metamaterials. In most cases, the difficulty in conceiving acoustic metamaterial is in the inception of constructs where the constitutive pressure-volume curve $(p - v)$ features areas of nonlinearity. Nonlinearity in an acoustic metamaterial is achieved through the pre-processing of structures using techniques that induce $p - v$ oscillations for enhanced material nonlinearity. A representative case is shown in Fig. 4 where the linear response is about two different configurations ($= 0$ and $= {}_{pre}$).

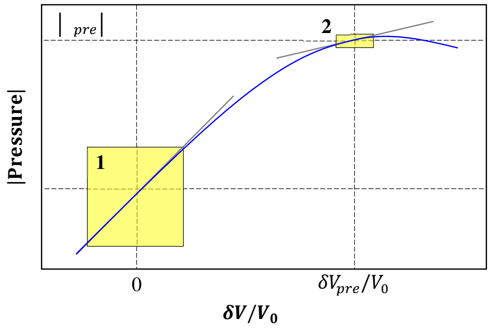


Fig. 4. Linearity as an approximation at two different configurations as highlighted. Adapted from Haberman [19]. A representative example of a case involving pre-pressurisation (P_{pre}) is demonstrated. The dotted lines show the $p - v$ oscillations. The first configurations highlighted configuration is where the change in pressure and volume is zero, the second case a state of pre-pressurisation. Nonlinearity has a higher significance at lower amplitudes of sound pressure for the P_{pre} configuration as indicated by the 2nd highlighted section in comparison to 1st.

Nonlinear characteristics in material as shown in Fig. 4 can be conceived by subwavelength geometries of features like the dynamic architecture causing $-$ and $-k$ as discussed in the previous section. This results in a nonlinear equation as shown in Eqn. (3):

$$C_0 p = x + \frac{B}{2A}x^2 + \frac{C}{6A}x^3 + \cdots with\ x = \frac{{}^{\prime}}{{}_{0}} \tag{3}$$

where is the sound pressure, C_0 and ${}_0$ are ambient compressibility and density, respectively. ${}^{\prime}$ is the density perturbation from ambient, and B/A and C/A are the effective parameters of nonlinearity. The characteristic results of such a construct is that of significant nonlinear effects that lead to higher harmonics. Such effects are favourable when it comes to improving the resolution of imaging techniques and for the creation of nonreciprocal sound transmission which otherwise is inconceivable [41–43].

3.2. Nonreciprocal acoustic metamaterials

When an acoustic wave travels through conventional media, wave motion obeys a fundamental property, reciprocity, that describes the symmetry in wave transmission between two points in space. Reciprocity guarantees that wave propagation always occurs symmetrically. If waves can make their way from a source to an observer, the opposite propagation path, from the observer to the source, is equally possible and the transmission is symmetric [44–46]. Reciprocity is a concept so natural that its validity is taken for granted in everyday lives. For example, when the neighbours can be heard through a common wall, it should be assumed that the reverse is equally possible [47,48].

According to Fleury [49], in the field of theoretical acoustics, reciprocity can be challenged under certain conditions; the presence of fluid in motion is an example [50,51]. Furthermore, research carried out by Liang *et al.* [52] and Boechler *et al.* [53] show engineered devices with strongly nonreciprocal responses. These devices force the acoustic energy to flow only in one direction and thereby create a one-directional nonreciprocal acoustic system.

In general, nonlinear acoustic metamaterials may have several undesirable features for practical applications such as:

i. Bulky and large isolation ratios
ii. Acoustic isolation may be related to specific (high) levels of input acoustic power
iii. Frequency conversion that significantly alters the incident acoustic signal.

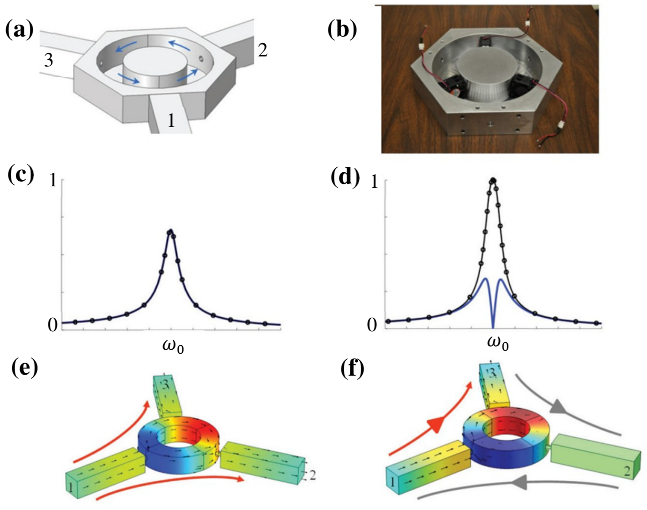


Fig. 5. A nonreciprocal acoustic metamaterial circulator based on angular-momentum biasing through a circulating fluid [54]. (a) Circulating air through a fan linked to three separate waveguides, (b) resulting from the physical prototype. (c) acoustic transmission in the absence of fluid circulation. (d) Transmission at ports 2 and 3 for excitation from port 1 with air circulation and at the circulator frequency $\boldsymbol{\omega_0}$. (e) Acoustic pressure in the system (surface color) and power flow (vector plot) at the cavity resonance without fluid circulation. Red arrows indicate the direction of sound transmission. (f) Same as panel (e) but the fluid motion is applied. The red arrow indicates the one-way direction of sound transmission for excitation at port 1. The grey arrows indicate the direction of one-way sound transmission if the sound were incident from port 2 or 3.

This led to the development of a linear nonreciprocal acoustic device [54] in the form of a subwavelength acoustic circulator metamaterial as shown in Fig. 5a. The design uses air as the fluid of choice and the directional circulation was achieved using fans as shown in Fig. 5b. The cavity was symmetrically coupled to three acoustic waveguides, which formed the input and output channels of the device.

When the fluid in the cavity is not circulating, the structure operates as a reciprocal sound splitter, which equally divides the input power to the output ports. Consider the case where the structure is excited from port 1 with frequency ω. When the signal enters the cavity, it follows closed paths in opposite directions with a length equal to the average circumference of the cavity l. Every time the signal passes in front of an output hole, a small part leaks out to the corresponding waveguide. To achieve significant transmission at the output waveguides, the multiple circulations of the signal in the cavity should interfere constructively, which happens if $l\omega/c = 2 \quad \pi$, where c is the speed of sound and   is an integer.

This equation essentially provides the resonant frequencies of the cavity modes, which are pairs of counter-rotating modes with azimuthal dependence $\mathrm{e}^{\pm im\varphi}$, where "plus" and "minus" signs correspond to waves propagating in the right- and left-handed directions, respectively, and φ is the polar angle. The above condition leads to constructive interference for each of the modes individually, while different modes appear at the output ports with a phase difference of $2\pi/3$ or $4\pi/3$ concerning each other for odd and even , respectively. This phase mismatch results in a slight reflection at the input port equal to 1/9 of the incident power, which can be shown from power conservation and reciprocity to be the minimum reflection that can be achieved in any rotationally symmetric three-port system [55].

If the fluid in the cavity starts rotating with velocity v in the right-handed direction, the frequencies of the signals propagating in the right- and left-handed directions are shifted by $-\omega v/c$ and $\omega v/c$ concerning the input signal, respectively, due to the Doppler effect [56]. In this case, it is evident that both waves have a detuned resonance condition, with the right- and left-handed modes being up- and downshifted by $\omega_0 v/c$ with respect to the static cavity resonance ω_0. The fact that the resonance frequencies of the rotating modes are symmetrically located concerning ω_0 allows one to completely cancel the phase mismatch between counterrotating modes at one of the output ports for a particular circulation velocity. This leads to unity transmission at one port and perfect isolation at the other.

For rotation in the right-handed direction, unitary and zero transmission happen at ports 3 and 2, respectively. Under the same rotation condition but for excitation from waveguide 3, power is transmitted to port 2 instead of port 1, providing clear evidence of nonreciprocity. Likewise, power from port 2 is transmitted to port 1. Interestingly, power flows in the direction opposite to the cavity fluid bias, highlighting that the circulation is not a simple "dragging" of the acoustic wave by the moving fluid but rather a wave interference phenomenon.

3.3. Active and reconfigurable acoustic metamaterials

3.3.1. Piezoelectric control

An active acoustic cloak [57] consisting of fluid arrays separated by piezoelectric boundaries was one of the initial concepts in active and reconfigurable metamaterials. Since then lots of research combining piezo with acoustic metamaterials have been proposed [58–61]. A theoretical analysis of one-dimensional acoustic metamaterials comprising piezoelectric boundaries was discussed by Akl et al. [62].

The use of shunted piezo for acoustic metamaterial research was also demonstrated [63–65] where the resonant frequency can be changed using a piezoelectric patch. The demonstration of such techniques gave rise to tuneable concepts featuring piezoelectric domains such as the one shown in Fig. 6. The construct is formed of a series of identical elements that are manufactured by placing piezoelectric layers on parallel planes of a disk as shown in Fig. 6b. In this manner, the stiffness along the path of acoustic propagation can be tuned for targeted transmission.

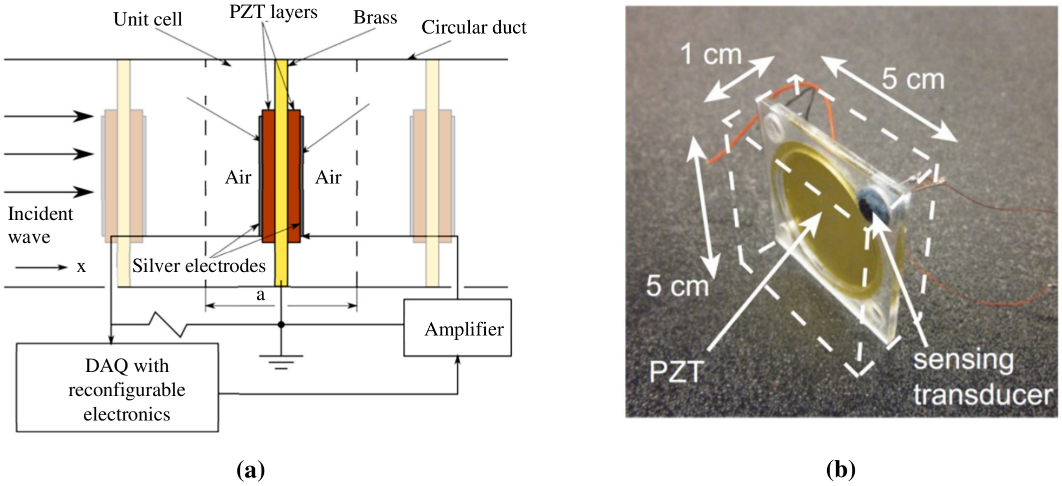


Fig. 6. A one-dimensional (1D) tunable acoustic metamaterial featuring a piezoelectric domain [66] where (a) shows the representative components [67] and (b) physical prototype [68].

3.3.2. Mechanically controlled

The most popular variation of mechanically controlled metamaterial is the plunger-controlled Helmholtz resonator. Here targeted resonance can be created by controlling the resonating fluid in the volume by adjusting a plunger as shown in Fig. 7. Although this approach is theoretically effective, there are significant limitations with this controlled strategy when compared to piezoelectric approach as discussed before. Here the tube distance d only affects the resonance width, this means that it is not effective when it comes to affecting the β_r which is the period of effective compressibility. Meaning active control is possible and the mechanical adjustment is largely passive and once adjusted response-based adjusting is not possible thereby limiting the application.

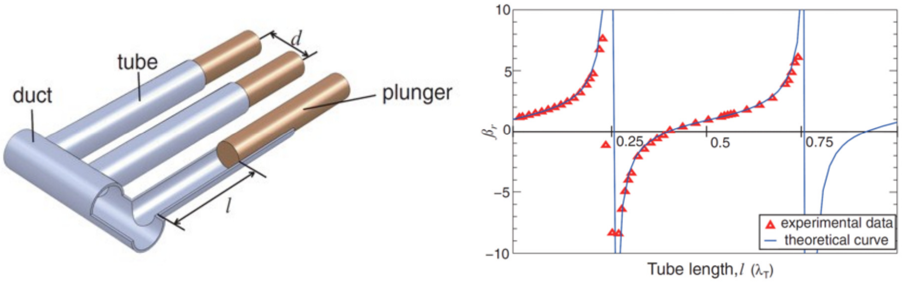


Fig. 7. Mechanically controlled acoustic metamaterial based on variable Helmholtz resonator [2], where (a) shows the tunability and (b) the effective compressibility (β_r) of the duct as a function of the tube length l.

3.3.3. Buckling control

Another approach that can effectively utilise buckling deformation to control acoustic transmission was proposed by research carried out by Wang *et al.* [69]. In this approach, a structural matrix featured an elastic membrane surrounding a plate-like structure as shown in Fig. 8. The structs are carefully placed such that enough space is allocated for buckling of the beams under compression ($-\varepsilon$). This results in changing the resonant frequency of the structure resulting in varying acoustic transmittance through the structure. While these types of structure offer a lot of promise, the strain-induced acoustic control is challenging to be performed in an active form.

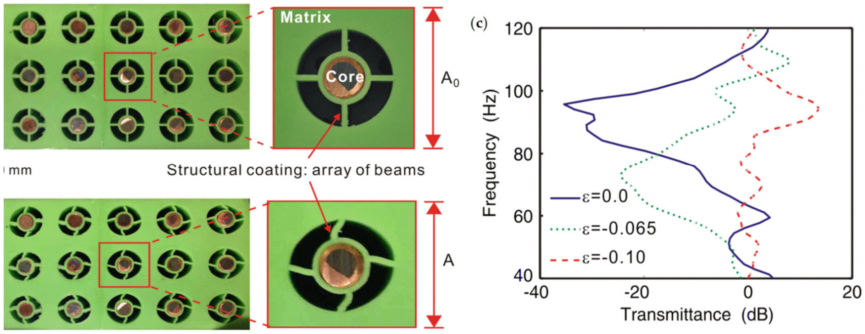
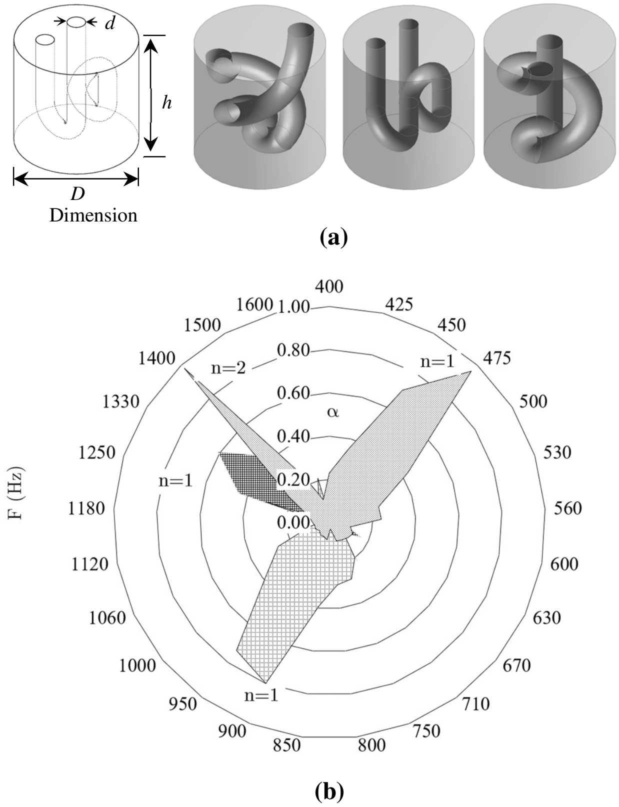


Fig. 8. Buckling induced tunable acoustic metamaterials [69] showing (a) undeformed structured, (b) buckled structure, and (c) change in acoustic transmittance as a function of the strain.

3.3.4. Passive destructive interference-based devices

Carefully constructed geometrical inclusions in the form of waveguides can change the phase of an incident sound wave. Such an out of phase wave at a 180° difference, when added with an incoming wave, can cancel each other to cause acoustic destructive interference. The technique itself is not new and is well established in the form of electronic noise cancellation. But using structural architecture to create targeted passive destructive interference falls within the domain of acoustic metamaterials. One drawback of such constructs is that comparable to technologies that rely on resonance, controlled passive destructive interference often occurs within a small frequency range. However, the performance itself of such constructs is largely unaltered by the bulk material properties making them suitable for applications involving the reduction of frequency-dependent noise pollution [70].

Studies [71–74] have shown that resonators can be arbitrary and still exhibit excellent performance. This offers significant potential for conceiving geometrical inclusions in a material that act as functional interference cavities without large exterior dimensions. Experimental studies conducted by Arjunan [75,76] demonstrated the use of 3D printed cavities to creative passive destructive interference through a geometrically complex architecture as shown in Fig. 9. The principle was to target acoustic destructive interference manipulating the acoustics from a planar source using conformal inclusion architecture similar to the ones shown in Fig. 9a. The change in phase angle of the returning and incoming wave was dictated by the frequency and inclusion length. The model demonstrated the potential for complete acoustic absorption at the mouth of the cavity based on the frequency of inclusion design. Such architecture offers a great opportunity in reducing noise emissions that are tuneable based on geometry without using complex active frameworks.



(a)

(b)

Fig. 9. Acoustic interference cavities [76] showing (a) complex geometrical architecture and (b) influence of cavity length in the frequencies where complete noise cancellation can be achieved.

4. Future perspective

Acoustic metamaterials are an active field of development with numerous efforts being documented in the literature. The rise in additive manufacturing (3D printing) has enabled numerous novel concepts that otherwise would have been challenging to be manufactured. For airborne sound absorption, membrane, cavity, or perforated type metamaterials seems to be most effective. The areas of tuneable acoustic metamaterials are also growing with various potential methods suitable for practical application. Despite the proliferation of research in this area, commercial prototypes of acoustic metamaterial targeted at noise pollution are yet to be realised [77–79]. Furthermore, hybrid metamaterials that bring together multiple concepts into a single construct are also awaiting research studies that can further enhance the prospects of acoustic metamaterials.

Although additive manufacturing offers significant potential for the development of complex acoustic metamaterials through enabling the manufacturing of complex porous architecture, mass production and cost still depend on simplified architecture. Consequently, concepts that feature complex and non-arbitrary features are unlikely to be commercially viable. It is also critical to characterise assessment techniques used for the characterisation of complex acoustic environments the sound source frequency is random [80–82]. Lastly, energy scavenging through acoustic metamaterials is also an area that awaits comprehensive investigations. Although significant progress has been made, many promising directions within the realms of acoustic metamaterials are largely left uncharted. Besides, resonance-based techniques possess significant challenges regarding practical application due to the narrow bandwidth. Accordingly, combining acoustic metamaterial architecture with conventional porous materials to develop functional hybrid structures for broadband acoustics is also an area that demands attention.

5. Conclusion

Although acoustic metamaterial constructs sound futuristic, it is important to recognise that controlling acoustic wave through sub-wavelength structures are part of classical mechanics. Therefore, the studies on acoustic metamaterials have an established theoretical presence where the practical realisation is being enabled by advanced manufacturing techniques. The developments in acoustic metamaterials offer promising ways to achieve sound transmission loss and acoustic absorption suitable for a variety of applications from reducing noise pollution to designing acoustic medical devices. Overall, the fundamental characteristic of acoustic metamaterial is that of wave manipulation to achieve a targeted outcome that is inconceivable through conventional material chemistry. As the research continues, the characterisation of lattice inclusions, layered fluid-structure materials, dynamic microstructure, and surface evanescent waves leading to superior acoustic metamaterials characteristics can be expected. In this regard, the growing literature in the field acts as design guidelines for the future of experimental acoustic metamaterials based on hybrid constructs while increasing the performance bandwidth. However, this requires systematic studies characterising the functionalities of metamaterial constructs conceived over the last decade. Attempts should also be made for transferring acoustic metamaterial research to commercially viable products for a broader impact. Absorption and transmission characteristics of a certain class of acoustic metamaterials offer promising solutions in replacing thick insulating materials for a sustainable future. Although, any industrial-scale implementation of acoustic metamaterials requires cost-benefit evaluation. Acoustic metamaterials are a promising direction that has significantly expanded the material characteristics in wave manipulation.

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