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Review Paper

Acoustic Metamaterials

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This review article is concerned with metamaterials, i.e. specifically engineered structures with special properties for interaction with sounds. The research on and practical design of these materials have gained momentum in the last decade, when 3D printing techniques provided the possibility to fabricate such geometrically complex structures. We briefly describe the history of research on AMMs and group them into active and passive metamaterials. For each of these groups of AMMs, we discuss the most notable construction achievements and outline the main applications. We conclude this review with a discussion of possible directions for further research and main applications of AMMs such as noise attenuation, acoustic lens, and the cloaking phenomenon.

Keywords: acoustic metamaterials; metasufraces; tunability; 3D printing.

1. Introduction

Metamaterials are artificial, man-made materials of unique properties and structures that do not occur in nature. A significant growth in interest and development of metamaterials has taken place over the last two decades. Generally, the concept derives from the studies attempting to control electromagnetic waves in a more effective way than it was possible with the then available materials. Historically, numerous efforts have been made to manipulate electromagnetic waves in a way that is similar to what optical devices do with light waves. Note that the first use of optical lenses was in Ancient Egypt and dates back to over two millennia BC (ENOCH, 1999; GRUBER, TEW, 1998). However, manipulating light waves with "natural" materials only has some significant limitations such as those resulting from the principles of wave propagation, e.g. diffraction (BORN, WOLF, 1980). Resolution of conventional lens is limited by diffraction of light waves. It is a physical limit where the resolution of the rendered image is inversely proportional to the light wavelength and proportional to the lens size. Two decades ago, prof. John PENDRY (2000) presented a paper in which he described a "perfect lens" which inherently goes beyond diffraction limits. He proposed a way to build a lens able to focus waves in the entire visible spectrum. Such an ambitious goal called for unique properties of the lens material. However, the material sought by Pendry did not exist in nature. It had to have negative permeability (μ) as well as negative permittivity (ε) coefficient at the same time. Earlier, a similar concept was put forward by a Russian physicist Victor Veselago. In 1968, he published a pioneering work on the theoretical analysis of materials featuring negative ε and μ coefficients (VESELAGO, 1968). Such materials are called "left-handed" or doubly negative substances.

The year 2000 was crucial for metamaterials not only because of Pendry's contribution. The same year SMITH *et al.* (2000) published a paper in which they numerically analyzed a structure featuring negative permittivity and permeability coefficients. Smith with his coworkers built a structure based on a periodic array of resonators and a net of wires that together formed a left-handed substance for electromagnetic waves. They used Split Ring Resonators (SRR) with uniformly placed metal wires underneath. The resonators were made on a printed circuit board (PCB) with a thin copper layer. The shape of the resonator was such that for a predefined range of frequencies its permeability was negative. At the same time, the mentioned net of wires had permittivity ε below 0. The transmitted signal of the net alone was below the noise level. Thus, adding a net of wires to the PCB of resonators resulted in introducing negative permittivity of the resonator ($\varepsilon < 0$) for a certain frequency range. Experimentally, a passband spectrum was achieved within which both the μ and ε coefficients were negative (Smith *et al.*, 2000).

There were other researchers who undertook to study left handed materials. Previously, such substances were not called metamaterials. The term was used for the first time by Roger Walser in 1999, during DARPA workshops (Ziolkowski, 2014). As Walser (2001) explains in his later work, the name is composed of the word 'meta' (gr. $M\varepsilon\tau\acute{\alpha}$ – beyond). The intention was to emphasize that the properties of such substances go beyond the properties of other materials existing in nature.

Although, the pioneering studies carried out by Veselago (1968) and Pendry (2000) were fundamental in the history of metamaterials, there were other investigations which concentrated mainly on electromagnetic (in a microwave range) and optical metamaterials. Both authors focused their efforts on building a 'super' (also referred to as 'perfect') lens. A properly engineered structure of left-handed substance can have the refractive index at near zero or even negative values. The device in question can surpass the diffraction limit, which is a theoretical resolution limit for optical devices. Obviously, it is possible to observe even smaller objects with electron microscopes, those, however, are very complex and expensive devices.

The research on metamaterials has enabled investigation of intriguing phenomena of cloaking. Generally, the term cloaking refers to the idea of making objects invisible to the external world. Pendry *et al.* (2006) and Leonhardt (2006) published articles suggesting that invisibility may be possible with the use of metamaterials.

Veselago, Pendry, and Smith paved the way for further studies of metamaterials. While their work was oriented to microwave range of frequencies, metamaterials can be designed for other wavelengths, from nanometer to meter scale. Generally, our world is filled with different types of waves such as electromagnetic or mechanical waves. While some of them can spread in vacuum, mechanical waves (e.g. sound waves) can propagate through a physical medium only.

The last two decades have led to strong insights into our understanding and potential novel applications of electromagnetic doubly negative substances. Nevertheless, the concept of double-negative materials can also be applied to mechanical waves such as acoustic waves, not just to electromagnetic waves, although they are quite different.

Acoustic waves are ubiquitous in everyday life, e.g. they play an important role in human communication, but they can also be utilized for imagining, sensing, medical diagnosis and treatments etc. (Sarvazyan *et al.*, 2013). Acoustic waves are not only the sounds that the human ear can hear and perceive as audible (assumed frequencies between 20 Hz and 20 kHz). Their spectral range extends much further. As they are longitudinal waves, they are different from electromagnetic waves which are transverse waves and are comprised of electric and magnetic components. Interestingly, with some assumptions the Maxwell and Helmholtz equations (see Table 1 describing electromagnetic and acoustic waves) are similar (Fang *et al.*, 2018; Zhang, 2010).

Table 1. Acoustic and electromagnetic equations analogy.

	Acoustic waves	Electromagnetic waves
1	$\frac{\partial P}{\partial x} = -i\omega\rho_x v_x$	$\frac{\partial E_z}{\partial x} = -i\omega\mu_y H_y$
2	$\frac{\partial P}{\partial y} = -i\omega\rho_y v_y$	$\frac{\partial E_z}{\partial y} = i\omega\mu_x H_x$
3	$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = -i\omega\beta P$	$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = i\omega\varepsilon_z E_z$

where P – acoustic pressure, E – electric field, H – magnetic field, x, y, z – spatial coordinates, μ – permeability, ε – permittivity, ρ – dynamic density, u – particle velocity, ω – angular frequency, β – dynamic compressibility.

Analogies between electromagnetic and acoustic waves have interested researchers as far back as the 17th century. Robert Hooke believed that light and sound waves are similar in nature. Two centuries later, James Maxwell and Lord Kelvin have used the analogies (mathematical, physical) to explore the wave phenomena in both type of waves (Carcione, Robinson, 2002). The analogies were analyzed and described by many authors, Carcione and Cavallini (1995), Nicolas *et al.* (1998) but Fang *et al.* (2018) and Zhang (2010) have presented those in a form of descriptive list (Table 1). It presents mathematical parities between acoustic waves and electromagnetic waves if such are analyzed on a plane. Note that in 2D case the equations assume scalar formulation (only one polarization mode). Therefore, it can be described by the electric field E_z and the magnetic field components H_x, H_y. Sound as a longitudinal wave is determined by acoustic pressure P and particle velocity v_x, v_y. Due to above assumptions, the third component v_z is skipped.

With that said, specifically engineered structures of materials should act on acoustic waves in a manner similar to that in which they do on electromagnetic waves. They are called Acoustic Metamaterials (AMM). Acoustic metamaterial structures are also reported to have novel properties, including a cloaking effect (Li *et al.*, 2015) or negative refractive index (Li, Chan, 2004), similar to Veselago's medium properties defined for electromagnetic waves. Li and Chan (2004) proved the existence of AMMs, and presented many analogies to electromagnetic metamaterials (EMM).

While considering electromagnetic structures, as left-handed medium we refer to those characterized by negative permittivity and permeability coefficients. Meanwhile, in the case of acoustics, a double-negative structure is termed a material characterized by negative effective mass density and bulk modulus. Consequently, metamaterials have unprecedented properties beyond the capabilities of traditional metamaterials. In the case of optics and EMMs, this was for example surpassing the diffraction limits for light. In the case of acoustics, it is also possible to break the diffraction limits with AMMs, and what might be equally interesting, it is possible to overcome the mass density law. This feature has the potential to significantly affect the construction of mid- and low-frequency acoustic isolations where transmission loss is dependent on the mass of the baffle (1). In general, to obtain more mass, the dimensions of the barriers are consequently increased. As described in next chapters, metamaterials provide better insulation with significantly smaller barrier dimensions (Long, 2014)

$$TL = 20\log(fm_s) - K_{TL}, \tag{1}$$

where f is frequency [Hz], m_s is surface mass density [kg/m^2], K_{TL} is numerical constant (47.3 dB in metric units).

Figure 1 presents classification of the materials in terms of the effective mass density and the bulk modulus. Natural materials are characterized by positive values of both parameters (Fig. 1c). All other categories (Fig. 1a, 1b, 1d) with one or two negative coefficients have unprecedented natural capabilities and are therefore called metamaterials.

The properties of traditional materials may appear to be sufficient for many applications. However, AMMs due to their outstanding properties, can provide strong noise attenuation with much lower dimensions. Nevertheless sound absorption is not the only exceptional property of acoustic metamaterials. Note that AMMs can be used for controlling sound propagation, focusing or dispersing acoustic waves, as well as for acoustic cloaking.

A significant development of such AMM has been observed since additive manufacturing became more accessible and affordable. New technologies were introduced as well as new raw materials for printing. Moreover, currently used methods are constantly being improved and used for fabrication of metamaterials. 3D printing techniques enabled the fabrication

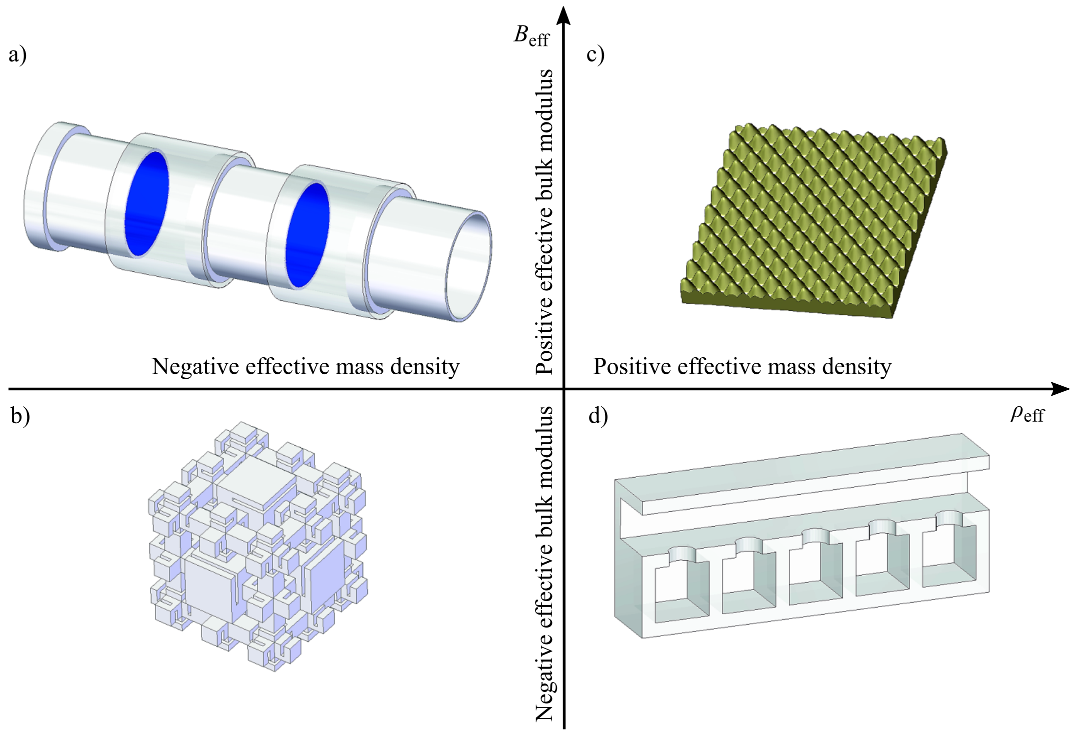

Fig. 1. Classification of materials with regard to the effective mass density and the bulk modulus: a) negative effective mass density acoustic metamaterial; it is a visualization model of an array of meta-units concept inspired by Lee *et al.* (2009), the blue parts are membranes glued to the edges of tube subunits; b) double negative acoustic metamaterial, values of effective mass density acoustic and effective bulk modulus are negative; simulation model of Liu *et al.* (2020) presenting an idea of combining Menger cube with the zigzag channeling; c) 'ordinary' materials such as metals or polymers, including naturally or artificially made porous materials; d) negative bulk modulus acoustic metamaterial; presented waveguide is composed of an array of Helmholtz resonators, as presented by Fang *et al.* (2006).

of complex structures and models that were otherwise impossible to build. Zieliński *et al.* (2020) indicate that prototype acoustic materials, including acoustic metamaterials are already being fabricated. Such novel structures can be then empirically verified. 3D printing is a very flexible production method, allowing for not only complex but also detailed manufacturing, in a relatively cheap and quick way.

Acoustic metamaterials can be categorized in many ways. They can be grouped by their construction, function etc. We propose a subdivision of AMMs as shown in Fig. 2.

Acoustic metamaterials are one of the branches in a general group of artificially designed composites with unique properties. Looking back at the history of AMMs, a surge of interest in this field began in year 2000, when Liu *et al.* (2000) demonstrated a milestone result in sound absorption. Over the next years, a number of studies were conducted, until some limits of passive AMMs were reached. This led to investigation of the so called active acoustic metamaterials, which initially were based on passive ones with an external control. Therefore, the proposed division is with regard to the activeness or passiveness as presented in Fig. 2. A similar approach was applied in a review carried out by Zangeneh-Nejad and Fleury (2019).

Acoustic metamaterials are part of a metamaterials family and include active and passive ones. Also, the whole family can be subdivided according to the structural complexity and interaction in specific directions of wave propagation. Thus, we can distinguish linear metamaterials – 1D, metasurfaces – 2D or spatial metamaterials – 3D. Each of these subgroups obviously further includes active as well as passive structures. Also worth mentioning is a classification based on the properties of the material, i.e. values of effective mass density and bulk modulus. Finally, active acoustic metamaterials can be divided with respect to the type of external control, e.g. magnetic or electric stimuli. On the other hand, passive devices may be categorized by their built (construction): resonant structures and transmission line acoustic metamaterials.

A few reviews on acoustic metamaterials have been published during last decades. However, they focused mostly on individual single aspects. These articles concentrated either on general ideas and theoretical investigations (Cummer *et al.*, 2016), through sound absorption (Zhang *et al.*, 2020), to sophisticated AMMs constructions (Zangeneh-Nejad, Fleury, 2019).

This paper is structured as follows. In Sec. 2, two major types of acoustic metamaterials are defined, namely active and passive metamaterials, and their key application areas are outlined. In Sec. 3, simulation software packages are discussed which can be used for design and numerical simulation of metamaterials. Next, Sec. 4 was provided for the future outlook dis-

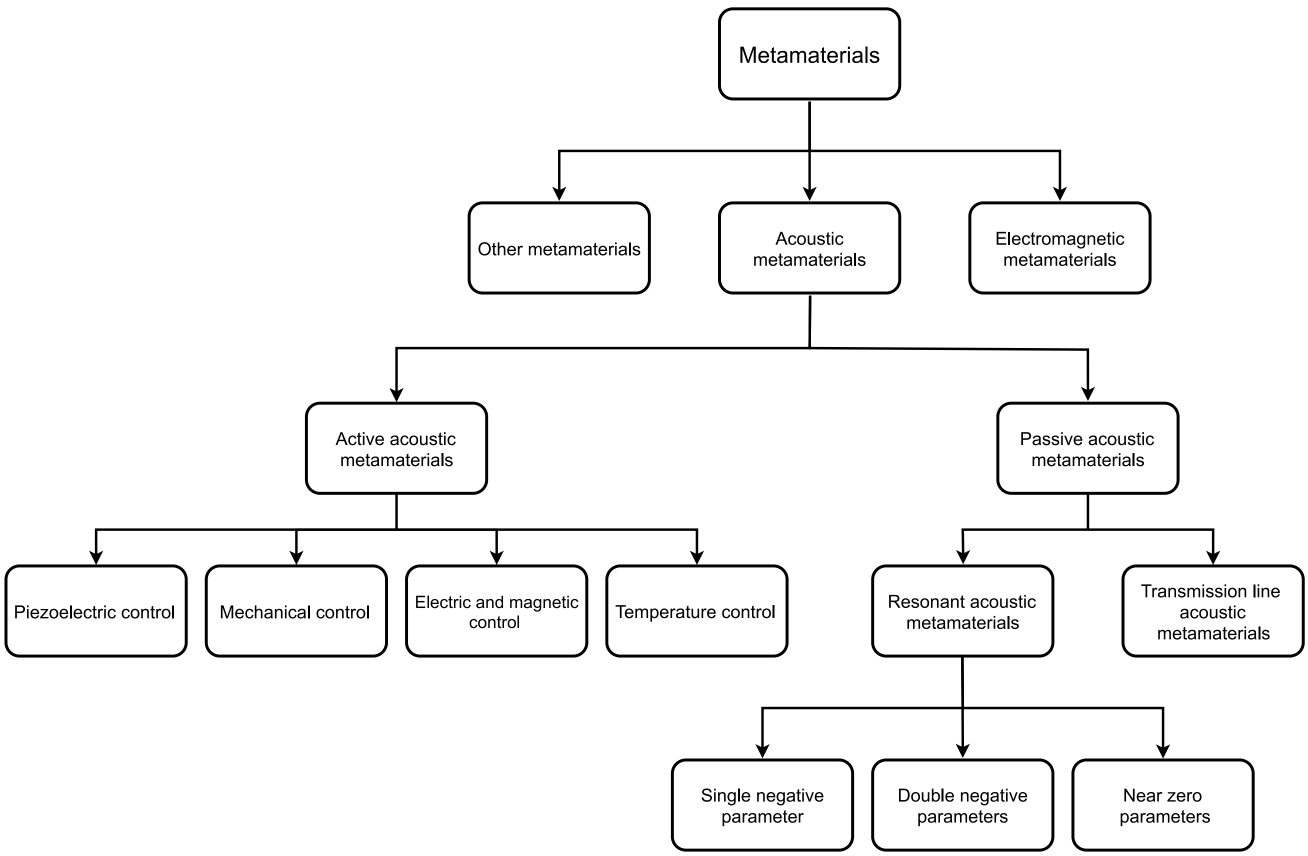

Fig. 2. The classification diagram of acoustic metamaterials.

cussion. Finally, in the concluding section, the review is summarized and main future developments of metamaterials and their exceptional potential applications are pointed out.

2. Types and applications of AMMs

Our classification of acoustic metamaterials is general and describes devices that can be interpreted as working in one dimension with respect to the propagating wave (1D), 2D (metasurfaces) as well as in 3D interaction with acoustic waves (Zangeneh-Nejad, Fleury, 2019). Other criteria based on which the AMMs are categorized, as presented in the following sections, are the structure and type of external excitation's source. Namely, in the case of passive structures, they are divided according to the operation mechanism. Interestingly, in this group one can distinguish transmission line structures and those with resonating parts. On the other hand, in the case of active metamaterials, the mechanism of external control is pointed out. Finally, the values of relevant acoustic parameters, i.e. effective mass density and bulk modulus, are taken into account in the review.

2.1. Passive acoustic metamaterials

Two decades ago, in 2000, researchers reported sound attenuation in excess of 60 dB for a 400 Hz tone, effected with a 2 cm thick material (Liu *et al.*, 2000). They created a medium with locally resonant structural units and achieved negative mass density. The experiment covered measurements of an $8 \times 8 \times 8$ meta-atoms cube, in which a single unit was a small lead ball covered with silicone (Fig. 3).

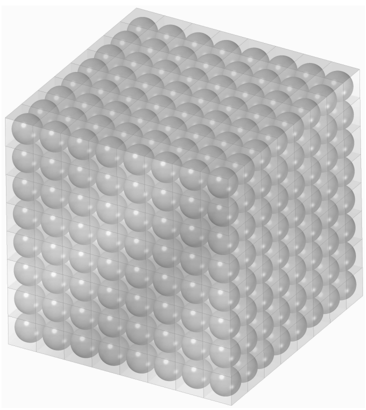

Fig. 3. Model of the AMM cube consisting of metal spheres covered with silicone, as suggested by Liu *et al.* (2000).

Each worked like a mass on a spring to model a mass-spring resonator. All of those small meta-atoms worked as subwavelength scatterers. Their out of phase oscillations above the resonance frequency were used to produce destructive interference. Although, the edge length of the cube was about 10 cm it turned out that spatial periodicity was not affecting that interference, and it was possible to build a material of about 2 cm thickness to attenuate the acoustic wave of a length of approx. 77 cm.

Another example of a structure characterized by a negative effective density factor was reported by Lee *et al.* (2009), who presented an acoustic metamaterial based on very thin flexible membranes at the end of rigid tubes (Fig. 1a). The authors obtained a critical frequency at 735 Hz below which the sound wave was blocked by a system of array of resonators. The experimental results agree with those foreseen by theoretical analysis.

Six years after Liu's work, Fang and co-workers (2006) demonstrated a negative bulk modulus in an experiment with an array of the Helmholtz resonators connected to a waveguide. Although, it was only a one dimensional wave propagation model, the work paved the way for further studies on multidimensional arrays of the Helmholtz resonators. Mahesh *et al.* (2011) published a paper on the study of acoustic metamaterials with negative bulk factor. He used eight Helmholtz resonators to build a one-dimensional waveguide. The experimental results were compared to the simulation carried out in the Comsol finite element simulation environment. Although, the experimental results differed slightly from the simulated values, a considerable attenuation of sound near the resonance frequency was confirmed in both approaches.

One of the potential applications of acoustic metamaterials is noise absorption. Noise can be referred to as any unwanted signal that is received or contaminates the signal of interest. In the modern congested world, acoustic noise is a serious issue. It is produced by any vibrating object in our environment. On behalf of the World Health Organization, Goelzer *et al.* (2020) published a report addressing the threats, control, and prevention of noise and noise-induced hearing problems. Obviously, the best solution is to avoid or prevent noise exposure, however, it is rarely possible. Thus, new damping materials must be developed for sound absorption. Traditional sound absorption materials are usually based on porous structures made to attenuate acoustic waves. Although, it is rather straightforward to cancel out high frequencies, low frequencies are very difficult to control. In general, this results from wavelengths that typically are significantly greater than the diameter of the fibers or pores in the absorbent materials. They have more energy than higher tones, they penetrate deep into the materials and dissipate energy in a slower manner. As predicted by the mass density law, attenuation of low frequency noise requires thick materials, if traditional ones were to be used. Although sound wave absorption was one of the first key features of acoustic metamaterials, new concepts of these structures where ideal absorption is the goal are still being developed. An example is the work of Shao *et al.* (2019) who proposed a metamaterial structure with a near-zero Bulk modulus. They constructed a low-frequency absorber (> 0.99 for 157 Hz) with a thickness about 28 times smaller than the wavelength at which it operates. They created a lattice of oval units with an internal zigzag structure by which the propagation path is much longer than the thickness of the material in a straight line. Inside the structure is a core that connects the two channels together for destructive interference. The results were simulated and further experimentally confirmed. A similar concept has been was presented recently by Long *et al.* (2020) The authors presented an ultra-thin metastructure that they report has significant engineering and scientific contributions. The presented structure is made of a sponge and a metasurface behind it. It provides broadband attenuation of low frequencies. The metasurface combines several different coiled resonators to extend the bandwidth. Combined with the sponge layer, this results in high damping (> 0.8) in the range of about 185 to 385 Hz (over one octave).

Lee *et al.* (2010) fabricated a structure made of an array of membranes and holes. With such a medium, they were able to obtain double negativity for frequencies in the range of 240–450 Hz. It was a milestone achievement in the research on acoustic metamaterials, proving that doubly negative acoustic medium could be fabricated. The authors postulated that such materials should be useful to make super acoustic lenses or could be used to make devices capable of acoustic cloaking. Yang *et al.* (2013) confirmed that a combination of the membrane system and Helmholtz resonators, characterized respectively by a negative mass density and a negative bulk modulus, allows for the construction of a double-negative system. Such a system was constructed from two diaphragms connected by a plastic ring. The double negative coefficients were obtained for the frequency range of 520–830 Hz. The authors point out that this simple system can serve as a meta-unit for the construction of more complicated metamaterial structures.

An interesting structure was presented by Lin *et al.* (2021) presenting a two-layer Sandwich Structure Composed of Resonating Acoustic Metamaterial (SSCRAM). The SSCRAM is a periodic lattice of meta-atoms each built from a surface layer with a hole, and an internal resonant structure with added mass. The goal behind this is to achieve the best possible acoustic isolation. The authors present an analytical model of the presented sandwich structure and show promising experimental results. The increase of STL by about 7–8 dB for low frequencies (370–670 Hz) was obtained.

In another work Liu *et al.* (2020) claim that despite novel applications, such materials bring, e.g. building acoustic lenses and sound control, there is a lack of design and fabrication methodology. Nevertheless, by using a combination of spatial Menger structures (a three-dimensional version of the Sierpinski carpet) and the zigzag channels, they designed a doubly-negative AMM. They simulated the structure using a finite element method and confirmed the results experimentally. It was proved, by simulations and experiment, that for a certain frequency range the presented material has a negative refractive index. Interestingly, there were also frequencies for which the effective mass density assumed zero value. The observed property, named as *density-near-zero* property, allowed them to build a model of a waveguide for bending the acoustic plain wave by 90 degrees. This property opens numerous novel applications.

One of those is an acoustic cloaking. It is as a rule of thumb it is analogical to invisibility cloaks. Thus, it relies on the manipulation of (sound) waves and steering them around an object to make the sound invisible (Li *et al.*, 2015). Zigoneanu *et al.* (2014) demonstrated an almost perfect design of a 3D omnidirectional device invisible to sound. Their design was based on a pyramid consisting of metaunits – small air-filled cubes with a perforated plate inside. A few years later, Esfahlani *et al.* (2016) suggested and numerically verified the concept of skin-like metasurface for acoustic cloaking. By analogy to electromagnetic metamaterials, acoustic ones can be used for super-resolution imagining. That involves building an acoustic lens. In 2020, Chinese researchers developed and investigated a metamaterial with a multilayer structure. With the latest additive 3D printing technologies, they fabricated a biaxal super-resolution metamaterial lens. They also observed that with the structure built enabled duplication of an acoustic beam and performance of composition and decomposition of sound images (Peng *et al.*, 2020).

2.2. Active Acoustic Metamaterials

During the last decade, a few reports have been published on the so called active acoustic metamaterials (AAMM). The AAMMs are, in general terms, acoustic metamaterials but their interaction with acoustic waves can be controlled in an active way. The concept involves any type of external stimuli altering the properties of the material as well as its functionality.

2.2.1. Mechanical control

One of the most popular meta-atom used in construction of AAMM is the Helmholtz resonator. Since Fang *et al.* (2006), its performance has been studied extensively. It is a powerful device and adopted in many applications. However, it is tuned to a specific frequency range. Based on Fang *et al.* (2006) array of resonators, Lee *et al.* (2012) came up with an idea of a mechanically controlled acoustic metamaterial. Similarly to the previous static designs, they created an array of syringe-like tubes connected to the side of a perpendicular duct. Each of the plungers could be mechanically adjusted and therefore the volume of the resonator could be controlled. The uncommon results included continuous adjustment of compressibility in the range of −8 to 6 relative to air (Lee *et al.*, 2012).

Langfeldt with coworkers (2016) developed a membrane type acoustic metamaterial. The authors put forward an idea of already known membrane materials that could be externally controlled. Their design required at least two membranes to be used as separate structures. Those membranes were spread apart to form a cavity between them, filled with air. With the use of external air pressurization device, air pressure in that cavity could be regulated. Increased pressure acted on the membranes causing their deformation and modifying their stiffness. Finally, the designed acoustic metamaterial was capable of influencing the transmission eigenmodes and transmission loss. Although the built device was externally controlled, which meant that its reconfiguration could be done remotely, there were no attempts to perform live frequency tuning in order to attenuate external environmental noise (Langfeldt *et al.*, 2016).

One of the recently published papers on active metamaterials is by Ning *et al.* (2021). Although, one could categorize the structure presented there into many categories, its performance is based on a mechanical change in the structure. The built structure consists of a frame, an annular gas airbag, and a balancing mass inside it. By changing the pressure inside the balloon, or changing the temperature of the gas inside, the metamaterial is deformed and thus its properties also change. Based on numerical simulations and experiments, the authors conclude that it is possible to manipulate and control very low vibrations in a frequency range of 13–90 Hz.

2.2.2. Electric and magnetic control

Another investigated idea of actively tuned membrane type acoustic materials relied on using the electric field. An interesting concept of applying voltage between two electrodes in the metamaterial was reported by Xiao *et al.* (2015). They modeled a device with a rubber membrane on which a gold coated platelet electrode was fixed. Next, a net like electrode, transparent to the acoustic wave was placed parallel to the first one. The membrane with the electrode on top of it worked like a simple spring-mass resonator. By applying DC voltage to the electrodes it was possible to tune eigenfrequency and phase of incoming acoustic waves. Moreover, an AC current tuned in phase with the membrane excitation has the capacity to enhance the performance of such acoustic metamaterial. AC voltage can introduce additional vibrations to the system and act like an acoustic switch, with the ratio of the transmitted to blocked signals of 21.3 dB.

Pursuing the idea of tunable membrane acoustic metamaterials, a few reports dealt with using electromagnets as external stimuli for controlling properties of metamaterial. Comparable to Xiao *et al.'s* membranes, a similar device was built but with a magnet fixed to the membrane and electromagnet acting on it. By applying a DC current to the electromagnet it was possible to control the vibrations of the membrane (Ma *et al.*, 2018). Yet another idea of taking advantage of electromagnets was proposed by Chen *et al.* (2016). They proposed a design of doubly negative acoustic metamaterial made of membranes and holes. The stiffness of the membranes could be manipulated by applying a current to the electromagnets. The authors highlighted the possibility of extending the bandwidth of double negativity by 40% by applying an electric current of a small value.

An interesting concept was presented by Sirota *et al.* (2021) to achieve real-time active control of a sound beam. The presented metamaterial built from parallel plates uses acoustic transducers placed perpendicular to one them and treat them as a source of acoustic velocity. It is designed to create a specified pressure inside the propagation region. The pressure is continuously monitored by a series of sensors and the system is managed by a controller with an embedded author's algorithm. The presented concept can be called a meta-surface because it gives the possibility to freely direct the wave propagation inside the sound tube. The authors state that such a metamaterial using feedback loop can be used to implement different types of acoustic coupling, and together with dynamical properties all can be programmed.

2.2.3. Piezoelectric control

Another original structure of an active acoustic metamaterial employs piezoelectric patches. Piezoelectricity is a phenomenon of inducing electric charge on the surfaces of some crystals as a result of applied external pressure (stress). Conversely, the same crystals are capable of changing shape under the applied electric field. Moreover, its mechanical parameters can change as well. Making use of the properties of piezoelectric crystals Akl and Baz (2012) were able to obtain a metamaterial of controllable dynamic mass density. They introduced a water-filled cavity with piezoelectric elements. The piezoelectric elements were controlled by using positive or negative feedback in order to modify the effective stiffness of the designed cell. With such a mechanism, the authors proved that the effective density of such a metamaterial can be controlled. The obtained densities varied in the range of

0.72–3.2 gm/cm^3 and were tested on acoustic frequencies on a bandwidth of 100–500 Hz.

In 2021, the same authors presented another work on the studied metamaterial with a dynamically controllable effective density. A real-time control of the experimental sample was achieved. The change of dynamic density of incompressible fluids to 0.35 and 13 × the original density was demonstrated. The authors emphasize that this contribution may change the perception of incompressible fluids such as water from static to dynamic and may pave the way for the era of programmable fluids (Akl, Baz, 2021).

Zhang *et al.* (2016) came up with an idea of an ultra-thin low frequencies acoustic waves insulator based on piezoelectric acoustic metamaterial. They proposed a metasurface that could overcome the mass density law. For frequencies lower than 1 kHz, their metasurface was capable of attenuating sounds by 30 dB. The proposed acoustic metasurface is referred to as ultrathin, since it is made from thin foil with piezoelectric patches whose thickness is much smaller than the length of the processed sound waves (1000 × thinner).

Following the work of Akl and Baz (2012), Allam *et al.* (2017) demonstrated a programmable density acoustic metamaterial. It is an example of a 1D membrane type metamaterial. In such a membrane piezoelectric elements are used with feedback control circuit in order to change the effective mass density of the unit in the range of $-100 \div 100$ kg/m^3.

2.2.4. Thermal control

There have been few studies reported on thermally controlled acoustic metamaterials. Although they are indeed controllable, their response to external stimuli is not immediate and therefore they have not gained noticeable research interest. Naify *et al.* (2020) from the U.S. Naval Research Laboratory explored an acoustic metamaterial that can be actively tuned with an electric current passed through the material. They built a kind of a membrane that was 3D printed from carbon filled conducting material. Their approach is based on the local variation of the temperature of the membrane which can therefore be softened or stiffened. The authors believe that their approach could be beneficial since many acoustic metamaterials are of the membrane type. Results have also been reported which demonstrated an increasing or decreasing frequency response following a change in the temperature of the material.

3. Engineering simulation software

First reports on metamaterials concentrated solely on theory. A notable example is the previously mentioned Veselago's paper based on a theoretical background. A rapid development of this research topic and developing manufacturing aids enabled experiments that validated the unique properties of metamaterials. Technological progress allowed researchers to use computational tools to accelerate the development of metamaterials as well as to design structures of larger complexity and study their properties experimentally. Many currently available simulation software packages offer an option to modify pre-defined equations of the simulated physical structures. Being able to manipulate materials' properties by using computer simulation tools is very consequential for researchers. Especially so in the field of metamaterials because properties of materials can be tested and improved prior to manufacturing.

Simulation software packages have been extensively used in the design of acoustic metamaterials. Specifically, numerical methods have been used to justify unique properties of AMMs. Most of the reports implement finite element method analysis, usually performed with Comsol® and ANSYS® simulation solutions.

Cummer and Schurig (2007) applied numerical techniques to simulate the cloaking effect by acoustic materials. It was one of the first attempts proving, as was the case for electromagnetic metamaterials, that the cloaking effect can be reproduced in acoustic metamaterials. Figure 4 presents a simulation of EM wave propagation prepared with *Anisotropic Cloak FDTD* application in a MATLAB environment (Csernyava, 2021). The figure shows undisturbed propagation of an electromagnetic wave (Fig. 4a), propagation with

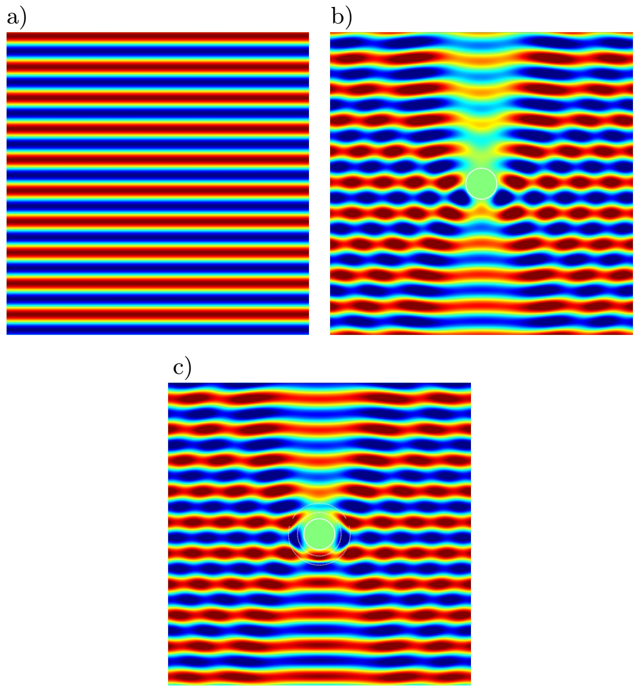

Fig. 4. Simulation of a cloaking effect in EM metamaterials: a) no obstacle, b) obstacle, c) obstacle + metamaterial cloak.

an obstacle (Fig. 4b) and the phenomenon of masking the obstacle – the cloaking effect (Fig. 4c).

Yang *et al.* (2008) performed a series of finite element simulations on their design of a membrane-type metamaterial. Their simulations justified negative mass coefficient at the examined frequency at which a total wave reflection occurs. Similarly, Akl and Baz (2012) presented a concept of how to simulate an actively tunable acoustic metamaterial that implemented piezoelectric transducers. In ANSYS 12.1 environment, they developed an exact model of a cell filled with water and enclosed by bimorphs.

Comsol Multiphysics® is a frequently used software program for numerical simulations. Within the wide portfolio of addons available for this tool, there is an acoustic module designed for acoustic simulations. It was employed by Popa *et al.* (2013) in the analysis of acoustic waves generated by monopole and dipole sound sources.

Simulations are also beneficial in providing a proof of concept before fabrication. The main advantage stems from the fact that fabrication of metamaterials requires complex, time-consuming, and usually expensive technological processes. Whereas with simulations one can reduce the risk of failure, save time or/and money. Further still, simulations can predict the results of the experiments assuming production errors occur. Zigoneanu *et al.* (2014) states that their approach involved computer simulations to check whether production errors will alter material parameters. Their complex model of a three dimensional acoustic cloak would be difficult to manufacture. Therefore, the authors calculated engineering tolerances for which the fabricated cloak should retain its desired properties.

Dong *et al.* (2019) by applying dozens of computer simulations optimized the topology and fabrication of double-negative AMMs. They developed a framework of different shapes or sizes of structures to achieve the widest possible bandwidth (Fig. 5).

a) b)

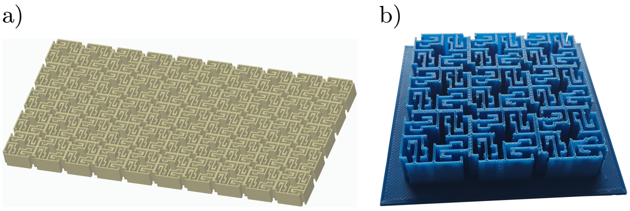

Fig. 5. a) Model of the AMM inspired by Dong *et al.* (2019); b) a fragment of this model produced using 3D printing technology.

With each passing year, simulations provide greater and greater accuracy. Shao *et al.* (2020) reported an interesting paper on employing Helmholtz cavities and acoustic metamaterials to build membrane structure muffler. In their work, the authors used finite element simulation to design absorber of low frequency noise. Comsol Multiphysics® was the tool selected to perform simulations that allowed the researchers to observe that changing the number of membranes enabled them to control mass density. Their concept was then experimentally confirmed in a laboratory. For the frequency range where the mass density coefficient was negative for the muffler, a significant 28 dB attenuation was achieved. More interestingly, the authors reported their analytical results to coincide with the experimental transmission loss measurement. However, not all of the calculated/simulated numbers matched the real ones. The peak TL value occurred to be slightly lower than it should compared to the finite element model. A probable cause was that the muffler had not been properly sealed to act correctly on the incident wave during the experiment. It was not taken into consideration during the computer simulation, which led the researchers to suspect it to be the reason (Shao *et al.*, 2020).

4. Future outlook

There is still room for new AMM designs and structures. For example there is still a lack of metamaterials with non-linear acoustic couplings and metamaterials built from inhomogeneous and anisotropic component units. Also, one of the main problems of acoustic metamaterials is the narrow operating bandwidth. Although the presented papers outline studies confirming research work on this issue, it remains a challenging problem to solve. Compressing of individual meta-units interacting with different frequencies may be the method, but a combination of traditional acoustic materials and metamaterials may yield positive results. The continuous increase in available computing power along with available simulation tools allows researchers to design faster and more effectively, and their designs can be conveniently tested without the need for time-consuming lab experiments. One of the challenges in the field of acoustic metamaterials is how to fabricate them. Although, technological development, especially the development and popularization of additive manufacturing, have given impetus to the development of AMMs, there are still problems in practical implementation. 3D printing technologies have opened new perspectives for the fabrication of metamaterials and enabled the validation of sophisticated designs. It is highly likely that additive manufacturing may even be beneficial for commercial production and implementation of AMMs. The promising rapid development of various 3D printing techniques could potentially enable even more sophisticated designs to achieve even better meta-properties. Current accomplishments in building metamaterials for airborne sound frequency range could be spread over to other disciplines. The cloaking effect and other wave control properties of airborne AMMs could possibly be transferred to liquid environments. Any environment other than air demands more sophisticated analysis and experiments due to different densities of and wave propagation in the media. Nevertheless, cloaking phenomena may be advantageous for divers, submarines etc. Additionally, seismic/tsunami wave resistant devices could also benefit from metamaterial research. Last but not least, it is worth mentioning that there are also papers devoted to metamaterial based facilities that are able to reduce destructive energy of earthquakes (Sang Hoon, Mukunda, 2012).

5. Summary and conclusions

Although the foundations of metamaterials were established in the last century, interest in the subject spiked at the beginning of this millennium. Metamaterials are man-made, artificially fabricated structures that do not occur in nature. The emerging development of metamaterials has opened up new ways of looking at material properties as well as novel possibilities to control not only electromagnetic but also mechanical waves. The latter, i.e. acoustic waves, are reviewed in this article. In the early 2000s, Pendry's work sparked the research community to investigate materials with so-called negative coefficients, permeability and permittivity, for electromagnetic materials. Soon after, a novel concept of acoustic metamaterials with negative bulk modulus and negative effective mass density was put forward. However, the biggest limitation to overcome, as Veselago summarized, has been how to fabricate materials of such outstanding properties. Now, almost two decades later, technological progress has made it possible to fabricate metamaterials in laboratories and therefore establish their parameters experimentally.

Acoustic metamaterials with a negative bulk modulus or a negative mass density coefficient obey the mass law and therefore are very efficient in absorbing sound waves. Since the absorption of long acoustic waves, i.e. low frequency waves, is the most problematic issue, acoustic metamaterials provide a serious advantage. Another benefit of metamaterials is the ability to focus or scatter sound. However, the possibilities go far beyond that. We have introduced the idea of acoustic metamaterials as a close relative of electromagnetic metamaterials. Thus, there is still a need for further research and search for important novel applications.

Over the last 2–3 years, there has been a large increase in interest and development of the discipline of acoustic metamaterials. This review article provides an up-to-date overview of recent scientific achievements and trends in the discipline. It contains a comprehensive bibliography and presents the current state of the art, including the literature references and journal papers. A graphically presented flow chart shows the entire family of metamaterials and our proposed classification in terms of metamaterial structure and operation. This review summarizes the discipline in a way that is accessible to readers and researchers, stimulates interest, and provides sources for further studies.

Despite the fact that many documents confirming the beyond natural properties of AMMs have already been published, there is still much to be invented. In this paper we have presented an intuitive classification of acoustic metamaterials that includes the so called passive and active acoustic metamaterials. The passive ones have outstanding properties, including low frequency acoustic wave absorption, while maintaining small dimensions. Those fixed structures are still in the field of interest, although they have evolved into active acoustic metamaterials. AMMs' performance appears be even better; most interestingly, they can be actively tuned. Tunability is a feature not attainable with natural materials. It enables, for example, tuning them in to a desired frequency, which means they could be selective, but it also means the range of usable frequencies is expanded.

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