Acoustic Metamaterials

Michael R. Haberman

Postal:
Applied Research Laboratories and
Department of Mechanical Engineering
The University of Texas at Austin
P.O. Box 8029
Austin, Texas 78713-8029
USA

Email:
haberman@arlut.utexas.edu

Andrew N. Norris

Postal:
Mechanical and Aerospace Engineering
School of Engineering,
Rutgers University
Piscataway, NJ 08854
USA

Email:
norris@rutgers.edu

Acoustic metamaterials expand the parameter space of materials available for new acoustical devices by manipulating sound in unconventional ways.

Introduction

Why have acoustic metamaterials (AMMs) appeared on the scene in the last few years, and what are they? The original defining property of a metamaterial is that it achieves effects not found in nature as a means to address long-standing engineering challenges in acoustics. Can one, for example, create ultrathin acoustic barriers whose performance surpasses currently existing technology? Is it possible to eliminate scattering from an acoustic sensor and minimize the influence the device has on the field being measured? Can spatially compact acoustical lenses be created whose resolution surpasses the diffraction limit? These are but a few examples of the problems AMM research strives to address. The common theme of the many AMM devices is an apparent defiance of the intuitive laws of physics, which often require strange concepts such as negative density and negative compressibility. Negative effective properties underlie behavior such as negative refraction that, in turn, enables acoustic lens designs that beat the diffraction limit.

AMM research was originally motivated by parallel developments in electromagnetics, such as negative refraction and cloaking (Norris, 2015). The first to study these topics quickly found that the available materials were not up to the task of providing the necessary properties for cloaking or negative refraction. A straightforward reaction to this problem was to simply create new materials. Although not simple, the creation of new materials has been, and continues to be, the fundamental driving force for the study of AMMs. This has led to concepts that could not be anticipated from electromagnetics, such as pentamode materials (exotic materials that only resist one mode of deformation, analogous to how fluids only resist volumetric change), to address AMM challenges (Norris, 2015). The challenge in developing new materials has been significantly aided by steady improvements in technology, primarily computer simulation and additive manufacturing. Those technologies combined with ingenious ideas from the acoustical research community have helped drive rapid advances in AMMs over the last decade, some of which we describe in this article.

For acoustical applications, dynamic material properties are of interest and may open the door to more exotic behavior. The focusing/beamforming from the fatty lobe of a dolphin, known as the melon, is a case in point (Yamato et al., 2014). Dynamic properties are not the same as their static counterparts that we learn about in introductory courses on mechanics. Thus **Figure 1** displays the design space of AMMs, a range that includes negative values for both density and compressibility, that is explained in detail in this article. At this stage, it is sufficient to note that the effective density and compressibility provide a helpful way to view the overall response of an engineered structure as an effective medium rather than using the impedance of a complex system. This is consistent with the metamaterial paradigm that seeks to expand the available parameter space available to people designing acoustic systems and devices to control acoustic waves.

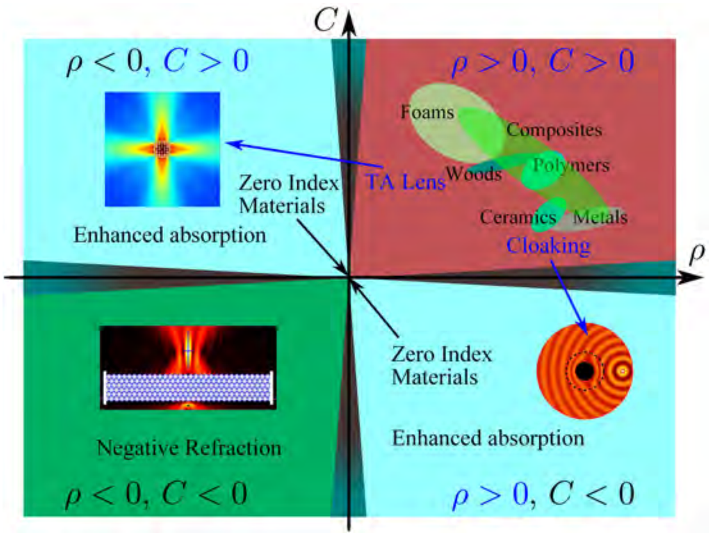


***Figure 1**. The material design space for acoustic metamaterials, density (ρ) versus compressibility (C), with example applications. Top right quadrant is the space familiar in normal acoustics. The other quadrants have one or both parameters with negative values. Negative density or compressibility can only be achieved dynamically. For instance, Helmholtz resonators driven just above their frequency of resonance lead to negative dynamic compressibility. The three devices shown employ the metamaterial effects of negative refraction, transformation acoustics (TA), and cloaking, all of which are described in the text.*

Our objective is to demonstrate the broad range of AMMs in terms of some seemingly "unnatural" effects such as negative density and compressibility, nonreciprocal wave transmission, and acoustic cloaking. The interested reader can delve further into the technical aspects both in the original papers cited and through several accessible reviews by Kadic et al. (2013), Ma and Sheng (2016), Cummer et al. (2016), and Haberman and Guild (2016). Detailed expositions on AMMs can be found in edited texts such as Craster and Guenneau (2013) and Deymier (2013). On specific topics, Hussein et al. (2014) survey phononic crystals and applications; Chen and Chan (2010), Fleury and Alù (2013), and Norris (2015) provide overviews of acoustic cloaking; and Fleury et al. (2015) review nonreciprocal acoustic devices. We begin with the negative acoustic properties and their application.

Dynamic Negative Density and Compressibility

Many AMM devices are based on negative acoustic density and/or compressibility (inverse of bulk modulus). The speed of sound, more precisely the phase speed, is the square root of the bulk modulus divided by the density. If either quantity is negative, then the phase speed is imaginary, corresponding to exponential decay, and hence no transmission. When both acoustic parameters are negative, the phase speed is again a real-valued number, implying wave propagation, although with a twist: the energy and phase velocities are in opposite directions. This response provides AMMs with the capability to produce "unnatural' effects like negative refraction that is discussed below. How are negative properties obtained? The concept of negative impedance is familiar, such as a tuned vibration absorber that oscillates in or out of phase with the force when the drive frequency is below or above the resonance frequency, respectively. Negative inertia can therefore be thought of as an out-of-phase time harmonic motion of a moving mass; see http://bit.do/negm.

The first and probably most widely known AMM (Liu et al., 2000), designed to isolate low-frequency sound much more efficiently than the classical mass law, was a composite containing microstructural elements comprising heavy masses surrounded by a soft rubber annulus arranged periodically in a three-dimensional solid matrix. Many subsequent air-based devices employing negative inertia have used tensioned membranes as the moving mass (e.g., Lee et al., 2009). Although negative inertia is common in vibrations, it is not as obvious how to achieve negative values of compressibility (inverse of bulk modulus). Recall that positive pressure in naturally occurring materials results in a volume decrease. Negative compressibility therefore requires that an applied pressure yield a positive expansion. This can be realized in close proximity to a well-known acoustical element, the Helmholtz resonator, above its resonance frequency where the cavity volume acts as a dynamic volume source. Combinations of these types of resonators can yield one or both negative properties in a finite frequency range.

To understand how a double-negative AMM works, consider the simplest example of an acoustic duct with alternating sprung masses and Helmholtz resonators, as in **Figure 2**. The resonators are defined by impedances that relate acoustic pressure (p) with volumetric flow velocity (U), according to $p_M = Z_M U_M$ and $p_H = Z_H U_H$. The effective acoustic properties can be calculated by first considering the reflection and transmission of an isolated element at a given frequency (**Figure 2**). It is then standard procedure to combine the reflection/transmission coefficients to determine the 2 × 2 matrix that describes how waves propagate across a single period of the transmission line. The Bloch-Floquet condition for determining the effective wavenumber (k_e) is then equivalent to finding the matrix eigenvalues. This gives $\sin k_e b = \omega b \sqrt{\rho_e C_e}$, where ω is the radial frequency, b is one-half the period length, and the effective density and compressibility are $\rho_e = \rho + 2SZ_M / (-i\omega b)$ and $C_e = C + 1 / (-i\omega b 2SZ_H)$, respectively, where ρ and C are the fluid density and compressibility, respectively, and S is the duct cross section.

A simple example is given by the limiting case of a hole in the duct which reduces the Helmholtz resonance frequency to zero and yields negative effective compressibility C_e below a finite cutoff. Conversely, C_e is positive above the cutoff, which is a result well known in musical acoustics: tone holes in a flute are a high-pass filter.

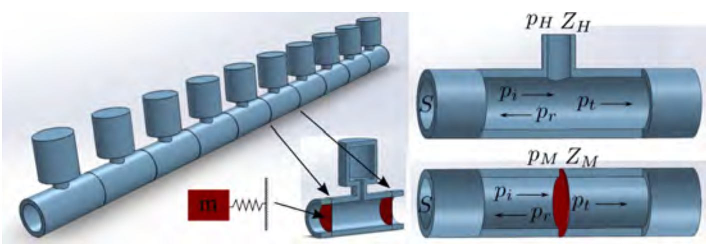


Figure 2*. An acoustic duct with alternating membrane masses and Helmholtz resonators. The resonances of the two elements produce negative effective density and effective compressibility in certain frequency ranges. Simultaneously negative density and compressibility, a "double-negative material," can be obtained by matching the resonances. See text for details.*

A membrane attached to the sides of the duct behaves as a mass (m) constrained by a spring (**Figure 2**) with $Z_M = -i\omega m\,[1 - (\omega_0/\omega)^2]/(2S)^2$ and therefore acts as a high-pass filter. In this way, Lee et al. (2009) demonstrated negative effective inertia in a periodic array of membranes in air by observing transparency above 735 Hz and very low transmission below that. By contrast, the low-frequency absorber of Liu et al. (2000), with impedance $Z_M = -i\omega m\,[1 - (\omega/\omega_0)^2]^{-1}/(2S)^2$ is a low-pass device whose cutoff frequency $\omega_0/2\pi$ can made very low (400 Hz) by increasing the mass of the internal oscillator. By selecting the resonance frequencies properly, it is clear that it is possible to simultaneously achieve negative density and negative compressibility over a finite range of frequencies. As mentioned above, the phase and energy propagation directions are then opposite; a situation known as negative group velocity (group and energy propagation velocities are almost always the same, except in the case of large absorption that is not applicable here). To see this, note that energy travels in the direction of the acoustic energy flux ($p\mathbf{v}$), where $\mathbf{v}$ is particle velocity. A plane wave with dependence $\cos\omega\left(\frac{x}{c} - t\right)$ has phase velocity c, which is real-valued because both the effective density and compressibility are negative. The pressure and particle velocity are related by the dynamic impedance (ρc) and therefore, because ρ is negative, the energy flux direction must be opposite to the phase velocity.

AMMs take advantage of negative properties in a variety of ways, including radiation/sensing in leaky wave antennae (LWAs) and focusing in phononic crystals. LWAs are one-dimensional transmission line devices, like the duct considered above, designed to radiate sound into a surrounding fluid much like a long flutelike instrument with the sound emanating from the tone holes. The coupling to the exterior fluid is particularly strong if the compressibility element is an open hole. LWAs are of interest because of the possibility to refract acoustic waves at different angles using the frequency-dependent phase speed within the waveguide. Positive and negative effective properties allow the angle to range over 180°, from the forward direction with phase and energy velocities aligned to the negative direction where the energy in one direction in the fluid couples with the LWA wave with the phase velocity in the opposite direction. Naify et al. (2013) demonstrated radiation depending on excitation frequency with positive, negative, and zero refractive indexes, using a structure made of periodically arrayed subwavelength alternating membranes and open vents. The LWA performs just as well sensing incident acoustic waves as it does radiating, which is a consequence of acoustic reciprocity under time reversal. The LWA property to discriminate direction using frequency therefore allows directionality detection of incoming sound using a single microphone in place of beamforming using multiple sensors (Esfahlani et al., 2016).

If both effective density and compressibility become zero at the same frequency, then the phase speed remains real as this frequency is crossed because the properties are double positive on one side and double negative on the other. Such zero index materials are of interest because the phase speed becomes infinite (index is zero), which allows for devices that can steer acoustic energy in unusual ways, such as unidirectional transmission and cloaking (Ma and Sheng, 2016).

The above model of membrane masses and Helmholtz resonators obviously allows for this possibility.

Negative index AMMs also rely on the negative relationship between phase and group velocity to achieve what appears to be a radical violation of normal physics. Recall that a plane wave incident at a flat interface between two materials produces reflected and transmitted waves such that the components of the directions of propagation relative to the interface are equal for the incident and reflected waves and are of the same sign for the transmitted wave, with the magnitude given by the Snell-Descartes law of refraction. If one blindly uses the standard formula with a negative index (inverse of speed) for the transmitted wave, then the sign of the transmitted component becomes opposite to that of the incident wave. As a result, the transmitted wave appears to reverse its direction relative to the incident wave, hence negative index material (NIM). Unlike the one-dimensional LWA, the negative index phenomenon is two- or three-dimensional because it requires the transmitted wave to have a negative group velocity for all incident directions.

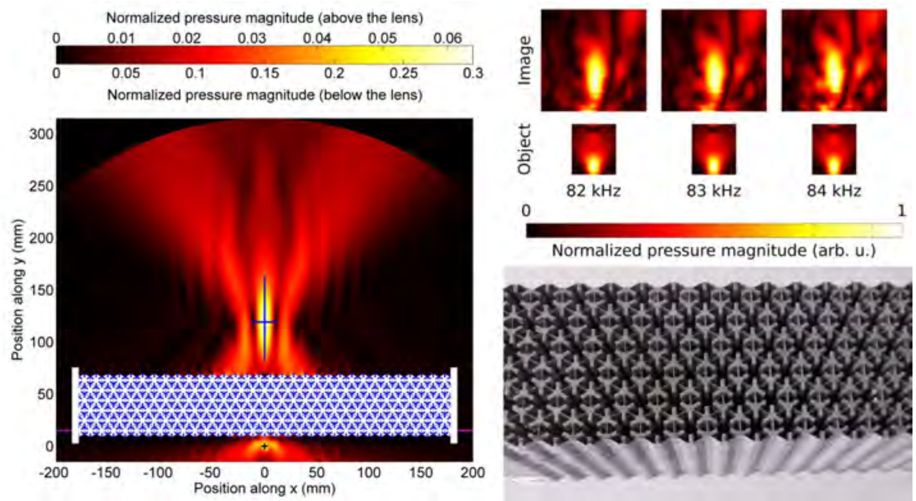


Figure 3. A rectangular slab of a negative index material can act as a near-perfect lens because of the negative refraction and near-field effects (Pendry, 2000). The simulated response of a point source below a negative index material (NIM) lens in water (left) shows the expected separation between the source and the focal point equal to twice the lens thickness. Top right: Measured pressure field in the source and the focal regions (Hladky-Hennion et al., 2014). Bottom right: Close-up view of the lens, an aluminum lattice designed to have effective static density and compressibility matched to water, hence called metal water.

The concept of negative refraction is difficult to appreciate, and the authors of this article are the first to admit to having trouble understanding it. One way to think about negative refraction is that at an interface, it is the phase of the wave that is matched, phase rules so to speak. Hence, if the group velocity is parallel to the phase velocity on one side and antiparallel on the other, the energy flow along the interface must switch direction as the wave crosses into the NIM. If this is too far-fetched to comprehend, you do not have to believe us but can watch the movie instead (see http://bit.do/negref).

One of the primary motivations for interest in NIMs is their ability to achieve higher resolution in imaging compared with classical lenses. Pendry (2000) showed that a rectangular slab of NIM acts, in principle, as a perfect lens, which provided a major stimulus in the development of metamaterials. This interactive program (see http://bit.do/NIMlens) allows you to get a feel for the NIM lens. Phononic crystals (PCs) are periodic structures designed to display specific dispersion properties and are at present the method of choice for realizing NIMs. However, it is a delicate balancing act to obtain approximately constant phase and group velocities for all wave numbers at a given frequency (equifrequency contours) while also ensuring uniform transmission. In practice, to act as the perfect lens, the slab should be of infinite extent, the equifrequency contours must be circular and the transmission amplitude independent of wave number. The PC water-based flat lens device of Hladky-Hennion et al. (2014) in **Figure 3** achieves the first two constraints well but not the third. Despite this limitation, the lateral focus achieved is superior to a normal acoustic lens, making this arguably the most effective acoustic NIM lens to date.

Transformation Acoustics

The second concept driving the development of AMMs is transformation acoustics (TA) that provides the basis for acoustic cloaking and other wave steering systems. The fundamental idea behind TA is that (1) a change of coordinates, the transformation, modifies the acoustic equations, while (2) the coefficients in the new equations are the physical parameters in the transformed region. For instance, a spherical acoustic cloak uses the transformation of a thick annular region of fluid into a thinner one so that the original central volume is enlarged. If the thinner annulus, the cloak, faithfully mimics the equations of acoustics in the original annulus, then, to an outside observer, the cloak plus whatever is placed in the large central volume scatters acoustic waves like a much a smaller heterogeneity. The crucial condition is that the new material in the cloak steers the acoustic energy around the “hidden” object, which requires the cloaking material to propagate sound faster in the azimuthal direction than in the exterior fluid while simultaneously slowing propagation in the radial direction relative to the background value because of the reduced thickness. As a result, the sound at a given point in the cloak behaves anisotropically, and the speed depends on the propagation direction. This is certainly not the situation in normal fluids. However, acoustic anisotropy is possible in systems comprising layers of different fluids arranged like a sandwich. Significant inertial anisotropy can be achieved if the layer thickness is subwavelength and the fluid densities are quite different. The spherical cloak is an extreme example in that it requires acoustic anisotropy levels that are not reachable at present. The acoustic ground cloak, also known as a carpet cloak, can be realized with relatively small anisotropy. Thus, Zigoneanu et al. (2014) used parallel layers of balsa wood in air to get just the right properties (see http://bit.do/acousticcloak). The recent *Acoustics Today* article on acoustic cloaking (Norris, 2015) provides a more comprehensive overview of this and related developments.

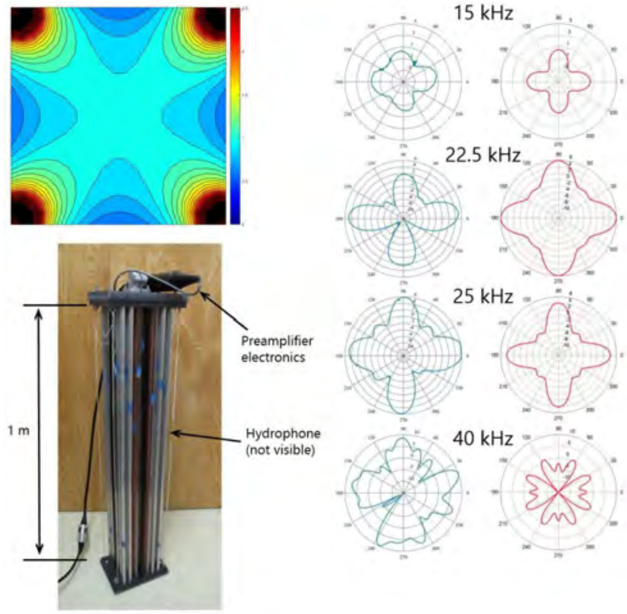


Figure 4*. TA, which underlies cloaking effects, also enables efficient and accurate acoustic lenses and radiators. Bottom left: Device is designed to radiate a monopole source preferentially in four directions. The square array of 7 × 7 cylindrical tubes uses 9 different materials ranging from brass to polymer selected to approximately match the bulk modulus (top left) defined by transforming a circular region of water to a square. Radiation patterns at four frequencies are also shown, with simulation on the right and underwater measurements on the left (Titovich et al., 2016).*

Although cloaking is the most dramatic manifestation of TA, the underlying concept of coordinate invariance also allows us to view classical effects like focusing in a new light. The convex lens, for instance, is based on the short wavelength approximation of ray acoustics. A superior image is guaranteed if the lens itself transforms the wave equation according to TA so that the focusing is independent of frequency. TA therefore opens up new possibilities for improved efficiency of passive acoustic devices. As an example, the circle-to-square lens converts a monopole cylindrical source at the lens center into a fourfold plane-wave radiation pattern. Conversely, a plane-wave incident from one of the four directions will focus at the center. TA achieves this by mapping a circular region of acoustic medium into a square using a conformal map. Conformal TA is special in that it maintains isotropy, and, furthermore, the density is unaltered; only the compressibility is modified (one might expect using ray acoustics that the impedance is constant but that is not the case!).

Figure 4 shows the required distribution of the bulk modulus along with the fabricated lens device and comparisons of numerical simulations and experimental measurements (Titovich et al., 2016). The variation in compressibility is obtained to a good approximation using a grid of parallel tubes, each selected to match the density of water and to have the required effective compressibility. Using properties ranging from those of polymers to metals, the lens of **Figure 4** was constructed with nine distinct materials. Distributed among the 7 × 7 cells of the lens, these simple elements were sufficient to provide a broadband effect as shown in **Figure 4.**

Emerging Areas in AMMs

Nonlinear Materials

All of the previous AMM examples rely on linear behavior. There are, however, a multitude of acoustical applications where material nonlinearity can be used advantageously. The challenge for AMM researchers is to devise materials whose constitutive curve (pressure versus volume change) includes regions that are highly nonlinear. Most nonlinear AMMs achieve this using structures that can be preconditioned, usually with static prestress, such that pressure-volume oscillations about the preconditioned state generate elevated levels of material nonlinearity. The concept is represented in **Figure 5** where the linear response is about two different configurations ($p = 0$ and $p = p_{pre}$).

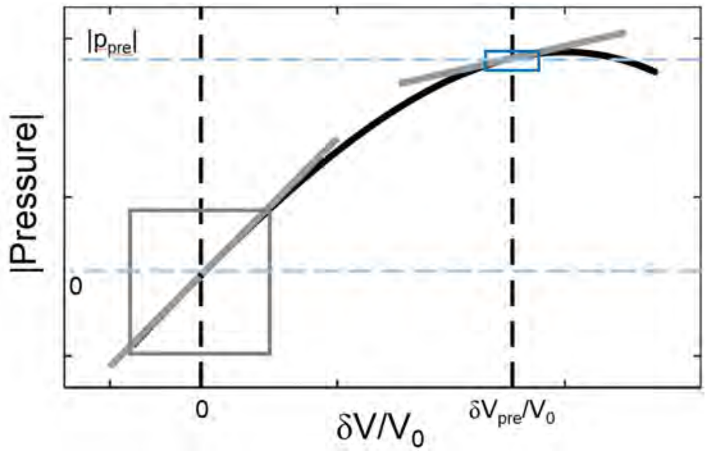


***Figure 5**. The use of nonlinear effects is an emerging area of acoustic metamaterial research. One possibility is to control the linear acoustic response by imposing a state of prepressurization (p_{pre}). The idea is based on the schematic nonlinear pressure-volume change (solid black line). Boxes: Approximate linear responses about two different reference configurations. The configurations are (1) zero pressure, zero volume change (gray box) and (2) a state of prepressurization (blue box). Pressure perturbations associated with acoustic waves are well approximated by the gray tangent lines. Nonlinear effects become important at much lower acoustic pressure amplitudes for the prepressurization configuration as indicated by the vertical extent of the blue box relative to that of the gray box.*

Material nonlinearity like that in **Figure 5** can be produced by subwavelength, microscale geometric nonlinear mechanisms, much in the same way that the dynamic linear microstructure leads to effective negative material parameters. The result is a nonlinear effective equation of state

$$C_0\, p = x + \frac{B}{2A} x^2 + \frac{C}{6A} x^3 + \ldots \text{ with } x = \rho'/\rho_0$$

where p is the acoustic pressure, C_0 and ρ_0 are ambient compressibility and density, respectively, ρ' is the density perturbation from ambient, and B/A and C/A are the effective parameters of nonlinearity. This results in strong nonlinear effects, including generation of higher harmonics, which can be used to improve imaging resolution and even to produce nonreciprocal wave propagation as discussed next.

Elevated material nonlinearity has been achieved using several mechanisms, including buckled structures (Klatt and Haberman, 2013), patterned holes in soft media (Shim et al., 2015), active elements (Popa and Cummer, 2014), and granular media. A simulation of a "sound bullet" generated by granular chains can be seen at http://bit.do/soundb. In all but the granular media, the structures studied can produce equations of state with multiple stable configurations, analogous to phase transformation in solids. This is of interest to reconfigurable AMMs discussed later.

Nonreciprocal Materials

One of the most fundamental ideas in acoustics is that wave propagation is reciprocal in the sense that transmission from a source to observer is identical if they are interchanged. However, it is also known that reciprocity may not hold in specific situations, for instance, in the presence of a moving fluid. Considerable recent effort has been focused on developing nonreciprocal AMM devices because of the exciting potentials, such as the ability to hear but not be heard, sensors that can transmit and receive at the same time, or sensors that have different transmit and receive patterns. The first such device exploited material nonlinearity to generate nonreciprocal acoustic wave behavior (Liang et al., 2009). Other nonreciprocal acoustical systems followed, including a linear device that employed momentum field biasing via fluid motion in a resonant cavity (Fleury et al., 2014) and another that modulated the material properties using electrically active components (Popa and Cummer, 2014).

So how does one generate nonreciprocal behavior? As with the cases of negative dynamic density and compressibility, one must take a closer look at the fundamentals; it is essential to understand what physical principles underpin acoustic reciprocity. A brief description is provided here, but the reader is referred to the recent *Acoustics Today* article on this topic (Fleury et al., 2015) for detailed explanations.

Reciprocity can be formulated for most systems supporting wave propagation (acoustic, electromagnetic, elastodynamic) using the Onsager-Casimir principle of microscopic reversibility. Consider a linear time-invariant medium, possibly inhomogeneous, in which time-harmonic waves are excited at source point A and detected at B. The Onsager-Casimir principle implies $t_{AB}(\omega,\eta,\mathbf{B}) = t_{BA}(\omega,\eta,-\mathbf{B})$ where t_{AB} and t_{BA} are the transmission coefficients for waves propagating from A to B and B to A, respectively, ω is the frequency, η is the material loss factor, and $\mathbf{B}$ is a set of parameters that influence propagation. The proper selection of $\mathbf{B}$, therefore, allows one to break microscopic reversibility and thus produce linear materials that support nonreciprocal acoustic

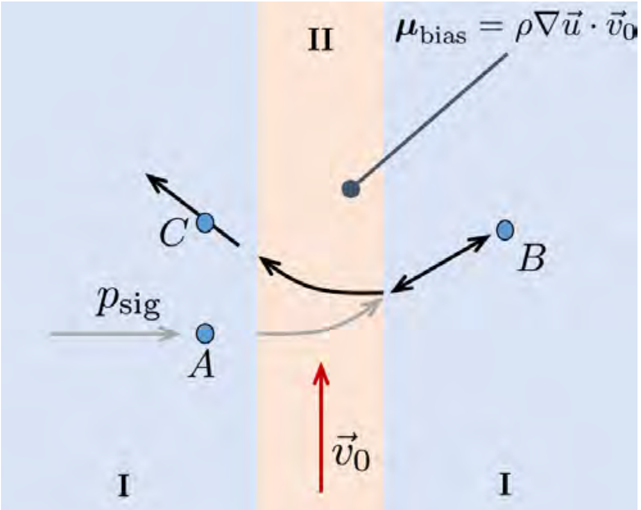


Figure 6. Acoustic signals usually behave in a reciprocal manner, meaning that the response is unchanged if the source and receiver are swapped. The schematic shows how nonreciprocal wave propagation can be induced by transmission through medium II with fluid flow. An acoustic beam (p_{sig}) incident from the left and sensed at A is refracted as it transits medium II. It exits with a different propagation direction than it entered with and is detected at point B. If the acoustic signal is time reversed at B (double arrow), it will be refracted and detected at point C on the other side of medium II. Thus $t_{AB} \neq t_{BA}$ and transmission between any two points on opposite sides of II (A and B or B and C) breaks reciprocity.

propagation. The challenge of creating media and devices displaying nonreciprocal behavior is thus to violate microscopic reversibility. Fleury et al. (2014) achieved this using fluid flow to induce momentum field bias coupled with a resonant cavity; **Figure 6** shows an illustrative schematic of this approach without the cavity.

Another means to break reciprocity is to violate some assumptions of the Onsager-Casimir principle. Nonreciprocal transmission can thus be induced by breaking linearity or time invariance. For instance, Liang et al. (2009) employed narrowband acoustic filters made from periodic plates and a nonlinear medium consisting of contrast agents in water to produce one-way propagation.

Active and Reconfigurable Materials

Active AMMs are heterogeneous media with some constituent components controlled by an external stimulus. A simple example would replace the diaphragms in **Figure 2** used to generate negative dynamic density with piezoelectric membranes. It then becomes possible to control the resonance, and thus the dispersive nature, of the AMMs. The first example of this in the context of AMMs was an active transmission line (Baz, 2010) that injected energy into the system using electromechanically coupled elements to produce tunable negative dynamic density. Another application of active AMMs employs nonlinear electric circuits to control nonlinear acoustic propagation (Popa and Cummer, 2014).

The earlier discussion of engineered nonlinear acoustic media opens the door to the concept of a reconfigurable AMM. Reconfigurable here implies that one can somehow alter the medium (actively or passively) in a way that fundamentally changes its dispersive properties. Analogues are deployable structures used in aerospace applications or the everyday example of a deployable structure, the umbrella. An umbrella is highly compliant and dense (i.e., contained in a small volume) before expanded into its "usable" configuration. When deployed, however, the structure is considerably stiffer and less dense. A reconfigurable metamaterial is one that employs similar structural concepts on the subwavelength scale to produce a material that can control acoustic waves in dramatically different ways depending on the configuration.

To date, most reconfigurable AMMs have employed perforated buckling elastomeric structures (Shim et al., 2015). This area of research is very new, however, so it is highly probable that different methods for producing reconfigurable acoustic media will be found.

Finally, it is important to highlight that many nonlinear AMMs represent the flipside of the reconfigurable AMM coin. The interest in reconfigurable AMMs is to support wave propagation in two or more regimes with large linear regions and then to vary the linear properties by switching between configurations. Nonlinear AMM design, on the other hand, seeks to optimize configurations whose constitutive behavior does not require large-amplitude acoustic pressures to generate nonlinear behavior. For this reason, it is possible that the same structure can be used to create both nonlinear and reconfigurable AMMs.

Conclusions

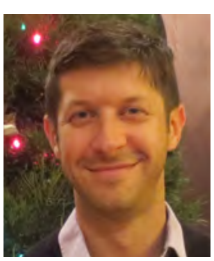
Although many of the topics of AMM research sound exotic, it is important to recognize that acousticians have a long history of designing subwavelength structures to control acoustic waves. Examples include the design of bass traps to absorb low-frequency sound in performance spaces, Helmholtz resonators to limit acoustic wave propagation in ducts, and contrast agents to improve ultrasonic imaging capabilities. Nature provides exquisite prototypes; the subwavelength spatial filter known as the human cochlea springs to mind. Although these examples are not usually referred to in the context of AMMs, they exploit the same physical principles as individual AMM elements and can easily be considered precursors to AMMs. Indeed, one can comfortably state that many AMM concepts have been hiding in plain sight waiting for us to stumble on them. We are fortunate to have finally come to appreciate and realize what properly designed subwavelength structures can provide to the field of acoustics.

In the span of just over a decade, AMMs have developed from several disconnected research efforts into a well-established, wide-ranging, and expanding field that encompasses ideas like negative refraction, super resolution, cloaking, enhanced absorption, nonreciprocity, active control, and material tunability. Concepts introduced in AMM research challenge acousticians to rethink what is possible and offer potential solutions to long-standing problems in acoustics. We are confident that new ideas hatched in AMM research, coupled with the expanding technologies of computational simulation and additive manufacturing, will produce the next generation of acoustical materials and devices.

Acknowledgments

We are grateful to Arthur Popper for suggesting this timely article and to Xiaoshi Su for graphical assistance. We thank all of our colleagues for their ideas, suggestions, and patience in helping us come to understand acoustic metamaterials. This work was supported by Office of Naval Research Multidisciplinary University Research Initiatives Grant N000141310631.

Biosketches



Michael Haberman is a Research Scientist at the Applied Research Laboratories and Department of Mechanical Engineering at The University of Texas at Austin. He received a BS in mechanical engineering from the University of Idaho in 2000, MS and PhD degrees from the Georgia Institute of Technology in 2001 and 2007, respectively, and a Diplôme de Doctorat in engineering mechanics from the Université de la Lorraine in Metz, France, in 2006. His research interests include wave phenomena in complex acoustic and elastic media, acoustical materials design, ultrasonic nondestructive testing, and acoustic transducers. He serves as an Associate Editor of *The Journal of the Acoustical Society of America*.

Andrew Norris received a BSc and MSc in mathematical physics from University College Dublin and a PhD from Northwestern University in 1981. After a postdoc at Exxon Research and Engineering Corporate Laboratories, he joined Rutgers University where he is Professor of Mechanical and Aerospace Engineering. He has worked on geophysical, structural, and ultrasonic nondestructive evaluation wave problems. His current interests are in metamaterials that exhibit extraordinary wave-bearing properties. He is editor of *Wave Motion*, an Associate Editor of *The Journal of the Acoustical Society of America*, and a Fellow of the Acoustical Society of America. In his off time, he enjoys reading, running, and the great outdoors.

References

Baz, A. (2010). An active acoustic metamaterial with tunable effective density. *Journal of Vibration and Acoustics* 132, 041010. doi:10.1115/1.4000983.

Chen, H., and Chan, C. T. (2010). Acoustic cloaking and transformation acoustics. *Journal of Physics D: Applied Physics* 43, 113001. doi:10.1088/0022-3727/43/11/113001.

Craster, R. V., and Guenneau, S. (Eds.). (2013). *Acoustic Metamaterials*. Springer, Netherlands.

Cummer, S. A., Christensen, J., and Alù, A. (2016). Controlling sound with acoustic metamaterials. *Nature Review Materials* 1, 16001. doi:10.1038/natrevmats.2016.1.

Deymier, P. A. (Ed.). (2013). *Acoustic Metamaterials and Phononic Crystals*. Springer-Verlag, Berlin Heidelberg.

Esfahlani, H., Karkar, S., and Lissek, H. (2016). Exploiting the leaky-wave properties of transmission-line metamaterials for single-microphone direction finding. *The Journal of the Acoustical Society of America* 139, 3259-3266. doi:10.1121/1.4949544.

Fleury, R., and Alù, A. (2013). Cloaking and invisibility: A review. *Forum for Electromagnetic Research Methods and Application Technologies* (FERMAT). Available at http://www.e-fermat.org.

Fleury, R., Sounas, D., Haberman, M. R., and Alù, A. (2015). Nonreciprocal acoustics. *Acoustics Today* 11(3), 14-21.

Fleury, R., Sounas, D. L., Sieck, C. F., Haberman, M. R., and Alù, A. (2014). Sound isolation and giant nonreciprocity in a compact acoustic circulator. *Science* 343, 516-519. doi:10.1126/science.1246957.

Haberman, M. R., and Guild, M. D. (2016). Acoustic metamaterials. *Physics Today* 69, 42-48. doi:10.1063/PT.3.3198.

Hladky-Hennion, A. C., Croenne, C., Vasseur, J. O., Haumesser, L., and Norris, A. N. (2014). Focusing capability of a phononic crystal based on a hollow metallic structure. *IEEE Transactions on Ultrasonics, Ferroelectrics,*

and Frequency Control 61, 1314-1321. doi:10.1109/tuffc.2014.3038.
Hussein, M. I., Leamy, M. L., and Ruzzene, M. (2014). Dynamics of phononic materials and structures: Historical origins, recent progress, and future outlook. *Applied Mechanics Reviews* 66, 040802. doi:10.1115/1.4026911.
Kadic, M., Bückmann, T., Schittny, R., and Wegener, M. (2013). Metamaterials beyond electromagnetism. *Reports on Progress in Physics* 76, 126501. doi:10.1088/0034-4885/76/12/126501.
Klatt, T., and Haberman, M. R. (2013) A nonlinear negative stiffness metamaterial unit cell and small-on-large multiscale material model. *Journal of Applied Physics* 114, 033503. doi:10.1063/1.4813233.
Lee, S. H., Park, C. M., Seo, Y. M., Wang, Z. G., and Kim, C. K. (2009). Acoustic metamaterial with negative density. *Physics Letters* A 373:4464–4469. doi:10.1016/j.physleta.2009.10.013.
Liang, B., Yuan, B., and Cheng, J. C. (2009). Acoustic diode: Rectification of acoustic energy flux in one-dimensional systems. *Physical Review Letters* 103, 104301. doi:10.1103/PhysRevLett.103.104301.
Liu, Z., Zhang, Z., Mao, Y., Zhu, Y. Y., Yang, Z., Chan, C. T., and Sheng, P. (2000). Locally resonant sonic materials. *Science* 289, 1734-1736. doi:10.1126/science.289.5485.1734.
Ma, G., and Sheng, P. (2016). Acoustic metamaterials: From local resonances to broad horizons. *Science Advances* 2, e1501595. doi:10.1126/sciadv.1501595.
Naify, C. J., Martin, T. P., Nicholas, M., Calvo, D. C., and Orris, G. J. (2013). Experimental realization of a variable index transmission line metamaterial as an acoustic leaky-wave antenna. *Applied Physics Letters* 102, 203508. doi:10.1063/1.4807280.
Norris, A. N. (2015). Acoustic cloaking. *Acoustics Today* 11(1), 38-46.
Pendry, J. B. (2000). Negative refraction makes a perfect lens. *Physical Review Letters* 85, 3966-3969. doi:10.1103/physrevlett.85.3966.
Popa, B.-I., and Cummer, S. A. (2014). Non-reciprocal and highly nonlinear active acoustic metamaterials. *Nature Communications* 5, 3398. doi:10.1038/ncomms4398.
Shim, J., Wang, P., and Bertoldi, K. (2015). Harnessing instability-induced pattern transformation to design tunable phononic crystals. *International Journal of Solids and Structures* 58, 52–61. doi:10.1016/j.ijsolstr.2014.12.018.
Titovich, A. S., Norris, A.N., and Haberman, M. R. (2016). A high transmission broadband gradient index lens using elastic shell acoustic metamaterial elements. *The Journal of the Acoustical Society of America* 139, 3357-3364. doi:10.1121/1.4948773.
Yamato, M., Koopman, H., Niemeyer, M., and Ketten, D. (2014). Characterization of lipids in adipose depots associated with minke and fin whale ears: Comparison with "acoustic fats" of toothed whales. *Marine Mammal Science* 30, 1549–1563. doi:10.1111/mms.12120.
Zigoneanu, L., Popa, B.-I., and Cummer, S. A. (2014). Three-dimensional broadband omnidirectional acoustic ground cloak. *Nature Materials* 13, 352–355. doi:10.1038/nmat3901.