Acoustic Cloaking

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It might drive bats batty, but there is no fundamental physical limitation on developing acoustic cloaking devices.

Introduction

An *acoustic cloak* is a shell surrounding an object so that sound incident from any direction passes through and around the cloak, making the cloak and the object acoustically "invisible." We do not experience acoustic cloaking because the materials required are exotic and, as far as we know, not found in nature. Yet there is no fundamental physical restriction on acoustic cloaking. Implementation is a matter of developing *metamaterials* with very unusual properties. Acoustic cloaking is in fact more likely to be achieved before its electromagnetic (EM) counterpart. The reason is that the cloaking material must have structure on sub-wavelength scales. Specific examples will be explained below. Acoustic wavelengths are typically orders of magnitude larger than optical wavelengths, meters vs. microns, which makes the acoustic problem easier, in principle.

This review attempts to explain the physics behind acoustic cloaking. No complicated mathematics is necessary to understand the concept of *transformation acoustics*, which defines the type of metamaterial required. We will see that acoustic cloaking is not an analog of EM cloaking but has unique features. Other cloaking methods based on passive and active *wave cancellation* are discussed. Practical realizations are reviewed. This survey does not discuss some related topics, such as negative dynamic properties. However, comprehensive technical reviews are available: Chen and Chan (2010) provide an early overview; Kadic et al. (2013) review acoustic metamaterials; Fleury and Alù (2013) give a recent review of cloaking and invisibility. Detailed reviews specific to acoustics can be found in (Craster and Guenneau, 2013).

Cloaking is an admittedly fantastic concept, well represented in popular culture (The Invisible Man, Invisible Woman, Harry Potter, etc.) using ingenious "technologies." The Cloaking Field Generator in Star Wars is an example of an active de-

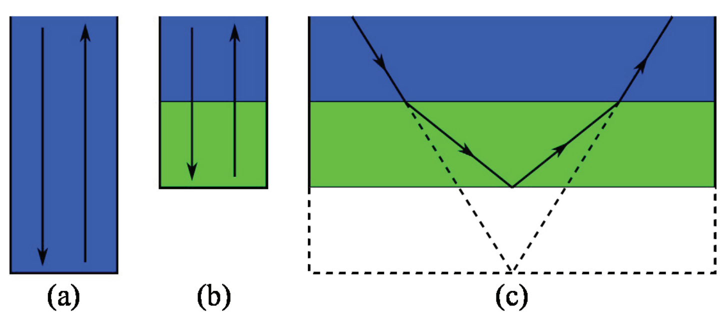

Figure 1. *Some space is made available in (b) by shrinking a region of (a) into the transformed green material. As explained in the text, the original and transformed ray paths in (c) imply that the transformed medium must display acoustic anisotropy. The wave speed in the horizontal direction is unchanged while the vertical speed is lower than the original.*

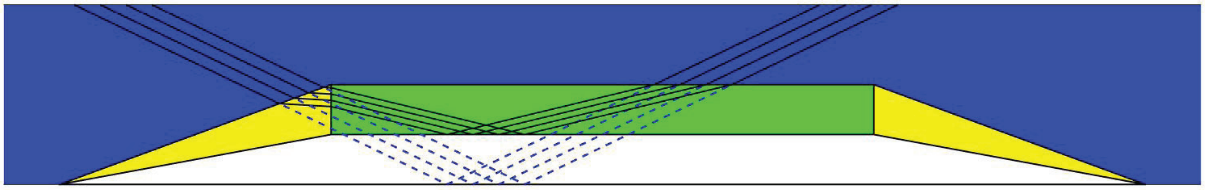

Figure 2. *A carpet cloak. The white region is freed up by squashing the entire white+green+yellow region into the green and yellow segments. The green region is a one dimensional compression, as in Figure 1. The transformation in the yellow region depends on both the vertical and horizontal coordinates, resulting in a compression and an extension in orthogonal directions not aligned with the coordinates axes (Craster and Guenneau, 2013, Ch. 7).*

vice requiring a power supply (*"They can't have disappeared. No ship that small has a cloaking device."* Lorth Needa). Dr. Who's famous Tardis, which is much larger inside than it appears from the outside, uses "transdimensional engineering" to make the interior and exterior exist in different dimensions (!). Yet, this is not too far removed from the actual basis for passive cloaking devices, described next.

Transformation Acoustics

The trick in passive acoustic cloaking is to somehow shrink the object and cloak from the observer's viewpoint, so that the object appears to be vanishingly small. This geometrical metamorphosis of a large virtual region into a smaller physical one is called *transformation acoustics* (TA). The technical details of TA convert the acoustic wave equation from one coordinate system to another, which can quickly obscure the concepts.

The simple example of acoustic wave reflection in **Figure 1** captures the essence of TA. The incident wave reflects from a fixed boundary at the bottom of the uniform fluid (**Figure 1(a)**). The same response is obtained from a non-uniform acoustic medium (**Figure 1(b)**), if (i) the time taken for the sound to travel back and forth is unchanged, and (ii) there is no reflection except at the bottom of the medium, assumed to be rigid. These conditions clearly constrain the acoustic speed and impedance in the green section. The no-reflection condition is then met if the green slab has the original acoustic impedance. Let f be the fractional ratio of the length of the green fluid to the original, the time constraint is then satisfied if the green index of refraction is $1/f$. The relative density and compressibility are therefore both $1/f > 1$. The lesson of this simple mirage (Norris, 2009) is that the transformed acoustic parameters depend upon the *geometrical* quantity f. One can already gain some appreciation for the difficulties in the full cloaking problem. In order to achieve a sizable effect the value of f must be significantly different from unity. A fluid of much greater density and compressibility is necessary to "squeeze" the original fluid into a much smaller space ($f \ll 1$), freeing up a relatively large amount of space. Extreme phenomena require extreme physical properties.

Acoustic anisotropy distinguishes cloaking from everyday acoustics. Consider the mirage in two dimensions, (**Figure 1(c)**). The index of refraction determined above implies a travel time for the transmitted ray (solid line) different from the original (dashed line). The only resolution is to allow for directional wave speed dependence, also known as anisotropy. For a wave incident near glancing the travel time condition requires that the green wave speed is the same as the original, hence the horizontal index of refraction is unity as compared to $1/f$ for normal incidence. A full analysis shows that the index of refraction (i.e. slowness) in any other direction describes an ellipse with major and minor axes corresponding to the normal and glancing incidence values.

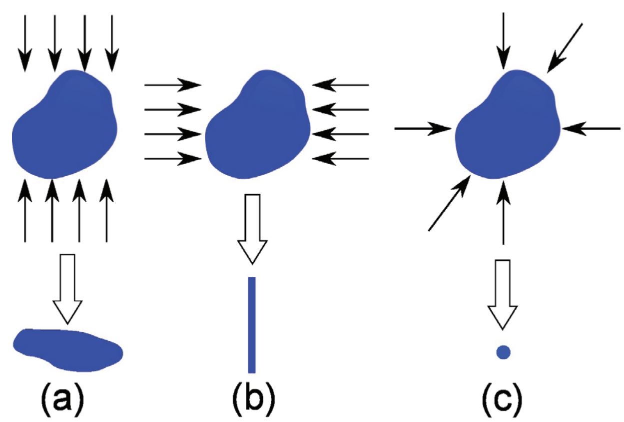

Figure 3. *(a) The cloaked region is flattened by a one dimensional-like mapping. (b) The cloaked region has the scattering cross-section of a thin cylinder. (c) A fully 3D transformation; the cloaked region scatters like a point.*

Transformation in more than one dimension (1D) follows the same principle of squeezing a virtual region into a smaller physical volume. The *carpet cloak* (aka ground-plane cloak) (**Figure 2**) frees up a finite volume. The anisotropy in the green part is like that of **Figure 1**, with faster vertical wave speed and unchanged horizontal speed. In the yellow section the principle axes for the wave speeds are rotated from the vertical and horizontal, one faster and the other slower than the background speed. The difference in properties is evident from the ray paths (**Figure 2**). Each ray is the transformation of the straight rays in the virtual region, the dotted lines in **Figure 2**. As long as the bottom surface of the carpet cloak is the same as the virtual region, the net effect of the carpet cloak is to make the cloaked region appear to be infinitely thin. The general carpet cloak transformation (**Figure 3 (a)**), is suitable for hiding in "plain sight" against a flat surface. But in the absence of a flat boundary to provide camouflage, TA must reduce the combined cloak and the cloaked region into an infinitesimally small scatterer with zero scattering cross-section.

Cloaking in free space requires a vanishing target strength; the virtual image of the cloaked region must shrink to a point (**Figures 3 (a), (c)**). As in the 1D case, the TA mapping is not unique. **Figure 4** shows an example where the outer surface of the cloak is an oblate spheroid, while the cloaked region is a prolate ellipsoid (egg shaped) (Norris, 2008). Some of the transformed region must be rotated in addition to stretching/compression as in the examples of **Figures 1 and 2**. The rays shown for horizontal wave incidence are the transformed versions of straight lines in the virtual domain. The rays around the central cloaked region, which is the image of a point in the virtual domain, must have infinite wave speed. Conversely, the wave speed perpendicular to the inner boundary is zero, which explains the sharp curvature of the rays near the "stagnation" point. Thes extreme effects, infinite speed, infinite slowness and ray bifurcation, are a consequence of the fact that the transformation is much more severe than in **Figures 1 and 2**. In **Figure 1** the virtual region 0 < x < 1 transforms to the physical one $1-f < x' < 1$. Consider a simple linear mapping, $x' = 1-f+fx$. The analogous mapping in 2 or 3-dimensions is $r' = 1-f+fr$ where $0 < r < 1$ and $1-f < r' < 1$ define the virtual and physical radii. Volume elements transform as $dV' = \left(\frac{r'}{r}\right)^{d-1} f\,dV$ where $d = 2$ or 3 is the dimension (Norris, 2008). The singularity as $r \to 0$ reflects the fact that a finite area or volume is compressed to a point, leading to infinite values of speed and slowness. These are clearly unattainable implying that the perfect cloak is impossible in 2 and 3 dimensions, the best one can achieve is a "near cloak" in which the cloaked region is the image of a small but finite area/volume.

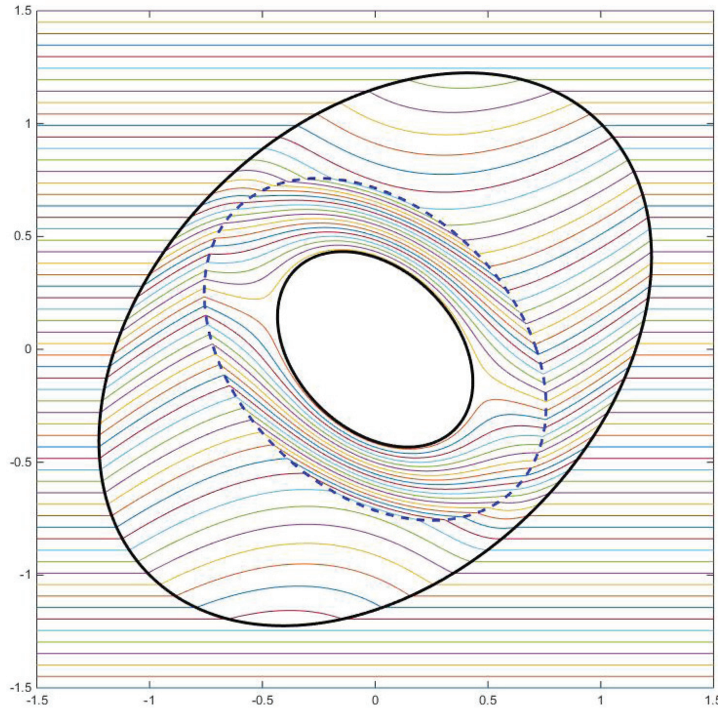

Figure 4. Ray paths through a non-radially symmetric cloak. The solid curves are the inner and outer surface of the cloak.

The original motivation for TA and acoustic cloaking came from the remarkable observation of Pendry et al. (2006) that singular transformations provide cloaking of EM waves. However, in a sense TA preceded cloaking, because the idea of mapping the acoustic wave equation has been used for decades in simplifying numerical problems. One application is the surface flattening transformation for rough surface scattering (Beilis and Tappert, 1979); by mapping the rough surface to a flat one the numerical geometry becomes simpler to mesh, at the expense of an inhomogeneous wave equation and more complicated boundary conditions.

Anisotropic Density or Stiffness?

How can acoustic anisotropy be achieved in practice? It is not observed in natural acoustic fluids where wave propagation depends on density ρ and compressibility C. At least one more parameter is required; this could be introduced by allowing density or compressibility to be tensors (i.e., matrices). Tensorial density means that the force per unit volume $\rho\mathbf{a}$ is not necessarily aligned with particle acceleration $\mathbf{a}$. This is not ruled out on fundamental grounds and in fact a physical mechanism for anisotropic inertia exists. Schoenberg and Sen (1983) showed that the inertia tensor in a layered fluid is transversely isotropic with elements $\langle\rho\rangle$ normal to the layering, and $1/\langle\rho^{-1}\rangle$ in the transverse direction, where $\langle\cdot\rangle$ is the spatial average. Anisotropic effective density can arise from other sub-wavelength microstructures, such as

Acoustic cloaking is more achievable than its optical counterpart because of the much larger wavelengths involved.

arrays of rigid cylinders in water (Torrent and Sánchez-Dehesa, 2008b). The anisotropic wave speed follows from the force balance $\rho\dot{\mathbf{v}} = -\boldsymbol{\nabla}p$ and the pressure relation $C\dot{p} = -\boldsymbol{\nabla}.\mathbf{v}$ Eliminating particle velocity v yields the wave equation $\boldsymbol{\nabla}.(\rho^{-1}\boldsymbol{\nabla}p) - C\ddot{p} = 0$ which is anisotropic by virtue of the tensor ρ^{-1}.

The first papers on acoustic cloaking assumed anisotropic mass density. Cummer and Schurig (2007) noted the analogy between the EM wave equation with anisotropic permittivity and the acoustic equation with a density tensor to describe a 2D cylindrically symmetric cloak. Chen and Chan (2007) proposed a spherically symmetric cloak with anisotropic density. Most subsequent acoustic cloaking literature is based on anisotropic inertia, what we call *inertial cloaking (IC)*. Particular realization of ICs are in principle feasible using layers of isotropic fluid (Torrent and Sánchez-Dehesa, 2008a), a strategy which has proved very successful in realizing carpet cloaks, as discussed below. However, fully enveloping cloaks require extreme anisotropy near the inner boundary that can only be achieved by alternating layers of fluids with extremely small and large densities. At the same time, the compressibility must be such that the homogenized value is that of TA. The cylindrical or spherical layered cloak does not seem to be possible with existing fluids. Models such as (Torrent and Sánchez-Dehesa, 2008a) require hundreds of fluids with different properties, some with very large compressibility and density. One possible solution is to take advantage of the non-uniqueness of TA and find the best possible transformation for a given set of fluids (e.g. 2 or 3 (Norris and Nagy, 2010)) but this also requires that the constituents have widely disparate properties not found in available materials.

Another possibility exists: anisotropic wave speeds can be achieved with anisotropic bulk modulus rather than density. It turns out that TA is fundamentally different from its EM counterpart where the transformation uniquely defines the EM material and, for instance, the tensors of electric permittivity and magnetic permeability display the same level of anisotropy for a transformation of the vacuum. In acoustics, by contrast, there is a wide range in material properties that can yield a given transformation. The non-uniqueness comes from the freedom to introduce an arbitrary positive definite symmetric divergence free matrix S into TA (Norris, 2008; Norris and Shuvalov, 2011). The inertial cloak corresponds to S=I, the identity, which partly explains why this degree of freedom in TA had not been noticed earlier. Any other choice of S leads to anisotropic stiffness in the sense of elasticity, however it is a special type of elastic material known as a *pentamode material* (PM). An elastic solid is characterized by six modes of deformation, a PM is the limiting case where five of the six are "soft" modes (Milton and Cherkaev, 1995) with one stiff mode. PMs generalize the property of an acoustic fluid that it can shear without effort but resists hydrostatic compression with a stress $-pI$, where ρ is acoustic pressure. The PM stress is proportional to S.

Pentamode cloaks have, in principle, distinct advantages over ICs. For instance, cylindrical or spherical cloaks with isotropic density are possible, in which case the total cloak mass is simply the mass of the original, virtual region (Norris, 2009). In contrast, the mass of a perfect IC becomes unbounded (Norris, 2008). The PM in the cloak must still have continuously varying properties defined by TA. Scandrett et al. (2010) examined the effect of piecewise layering in a spherical cloak, and found that an optimized three layer PM cloak provides better target strength reduction than a 3-layer IC. The best performance was found by combining both properties in a PMIC cloak. Scandrett and Vieira (2013) showed that the dominant scattering from heavily fluid loaded thin shells in the mid- and high-frequency regimes can be essentially eliminated by PM cloaking.

The current limitation on PM cloaking is fabrication. Solid materials with five soft modes and one stiff mode with desired stress state S can be achieved with periodic foam-like networks in which the microstructure lattice members only support axial forces. In practice, this means thin members that are flexible in bending but stiff in compression. Fabrication of such microstructured lattices is possible using rapid prototyping and related technologies; for instance Bückmann et al. (2014) designed and fabricated a PM "unfeelability" cloak, essentially a static cloak for elastic fields. The difficulty as far as cloaking sound in water is concerned is to achieve just the right properties. In order to get density and stiffness values similar to those of water using thin lattice members of low volume fraction the structural material must be very dense and stiff relative to water. Metals provide the appropriate reservoir of density and stiffness. The first realization of a metal-based microstructure with 2D PM behavior close to water, called "metal water" (Norris and Nagy, 2011), was an Aluminum lattice with hexagonal unit cells. The metal lattice model has also been studied by Layman et al. (2013) who simulated a slab of PM designed to provide a 2D acoustic illusion of **Figure 1**.

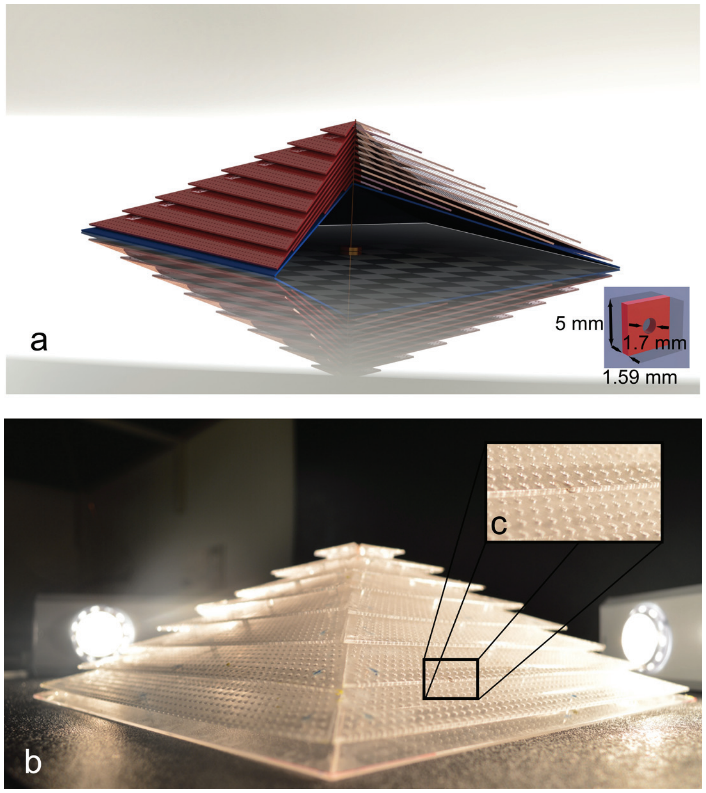

Figure 5. The pyramidal acoustic carpet cloak of Zigoneanu et al. (2014). Reprinted with permission.

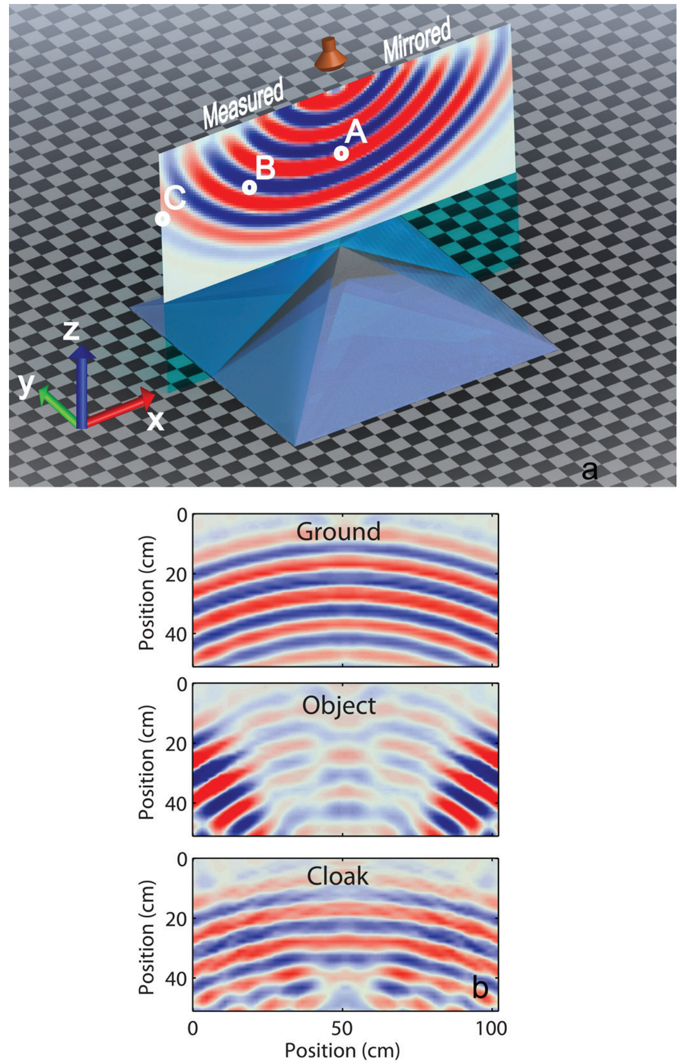

Figure 6. (a) The setup for the 3D carpet cloak of Figure 5. (b) Measured reflected pressure fields for three cases: ground only, object, object+cloak. Reprinted from (Zigoneanu et al., 2014) with permission. (Movie version https://www.youtube.com/watch?v=k13L8u2tACY)

Design and Realization of TA Devices

We follow the progression of **Figure 3**, starting with carpet cloaking. Popa et al. (2011) demonstrated the first acoustic carpet cloak in air using a 2D inertial design. Anisotropic density was realized with thin, heavy (relative to air) plates perforated to allow the air to permeate the plates stacked with air gaps between them, giving a mass density ratio of about 5 to 1 in orthogonal directions. Scanned microphone measurements showed good cloaking for incident waves of center frequency 3 kHz with a 3 dB bandwidth of 1 kHz. The broadband nature of the device can be ascribed to the long wavelength, 10 cm at 3 kHz in air, compared with the lattice constant for the perforations (5 mm) and the plate spacing, yielding good effective medium properties.

Zigoneanu et al. (2014) fabricated a fully 3-dimensional omnidirectional carpet cloak based on the same design principles. A pyramidal structure (**Figure 5**) rendered a region of space three wavelengths in diameter invisible to sound. Experiments were performed using a Gaussian pulse of 600µs half-amplitude duration modulated with a 3 kHz sinusoid. The measured response is shown in **Figure 6.**

Kan et al. (2013) presented an experimental demonstration of an acoustic cloak designed to hide an object in a corner. The device used thin slabs in air separated to provide a mass anisotropy ratio greater than 6 at 1700 Hz operating frequency. This design could, in principle, be adapted to manipulate the acoustic field near boundaries of arbitrary curved geometry.

Zhang et al. (2011) gave the first demonstration of cylindrical cloaking in water at ultrasonic frequencies. The design is unique in that it uses a 2-dimensional network of 1D channels in the radial and circumferential directions, where each channel is an acoustic circuit of TA-defined lumped parameters.

Passive Cancellation and Directional Cloaking

More "traditional" techniques have been proposed using passive sound cancellation. The idea is to coat an object with a layer that eliminates the scattered sound. In the long wavelength, low frequency limit, this can be achieved by eliminating the monopole and dipole scattered terms, which amounts to making the cloak plus the target have effective density and compressibility of water (Zhou and Hu, 2007; Guild et al., 2011) so the scatterer behaves as a "neutral acoustic inclusion." Omnidirectional cancellation can be achieved at finite frequencies using optimization methods to determine the coating properties (Guild et al., 2011). Martin and Orris (2012) proposed a hybrid design combining TA with scattering cancellation and showed that it outperforms both a cancellation layer and a discretized TA design over a broad frequency range in cloaking an Aluminium cylinder in water.

Guild et al. (2014) used the fact that cancellation eliminates the scattering in the exterior fluid without removing the field inside the object, to consider non-scattering sensors. This would enable the sensor to detect sound without disrupting the acoustic field. Simulations of a scattering cancellation cloak made of two fluid layers surrounding a piezoelectric sensor showed a 20-to-50 dB scattering strength reduction compared to the uncloaked sensor over the typical frequency range of operation.

Directional cloaking (as opposed to omnidirectional) can be achieved for specific directions of incidence using simpler cancellation designs. Thus, García-Chocano et al. (2011) demonstrated a 2D narrow band cloak in air comprising 120 aluminum cylinders of 1.5 cm diameter surrounding the cloaked cylinder of diameter 22.5 cm. The 120 positions were determined by optimization at an operating frequency of 3061 Hz, yielding good cloaking over a bandwidth of 100 Hz. Sanchis et al. (2013) used the same design strategy to experimentally characterize a 3D acoustic cloak in air that significantly reduces scattering for a unique incidence direction. The cloak consists of 60 tori made by 3D printing, arranged concentrically around the 4 cm radius cloaked sphere. Measurements show an approximately ten-fold scattering reduction at operating frequency 8600 Hz with a bandwidth of 200 Hz.

Urzhumov et al. (2012) proposed a uni-directional cloak comprising a spherical shell of isotropic (i.e. normal) acoustic material. The cloak, designed to operate in transmission mode, uses a conformal mapping (the only case of TA that does not require anisotropy) to yield an *eikonal cloak*, a cloak which partially preserves the ray structure of TA in the desired direction but without the necessary impedance. Conversely, Hu et al. (2013) designed and tested a 2D unidirectional cloak that specifically reduces backscattering by surrounding an object with layers of perforated plates that make the target appear narrow in reflection. Measurements show at least 20 dB reduction in sound pressure level near the backscatter direction over a frequency range 1500 to 2200 Hz.

Cloaking of Elastic and Other Waves

Elastic waves present a greater challenge for cloaking because of the two wave types as compared with one in acoustics. Theoretical analyses (Brun et al., 2009; Norris and Shuvalov, 2011) show that even more exotic material properties are required for TA in the presence of waves with transverse and longitudinal polarization. The cloak material must display significant stress asymmetry, which is not found in natural solids and difficult to achieve with microstructure. Asymmetric stress is a feature of small-on-large elasticity, the type of linear elasticity found in hyperelastic solids after large static strain, offering one possible cloaking mechanism (Norris and Parnell, 2012).

One area of elastic waves has seen practical cloaking: flexural (or bending) waves in thin plates are polarized in a single direction (normal to the plate) and satisfy a Helmholtz-like equation similar to acoustics. Stenger et al. (2012) adapted the TA design proposed by Farhat et al. (2009) to make a flexural wave cloak comprising 20 concentric rings of PVC and PDMS machined into a 1 mm thin PVC plate. The cloak was demonstrated at acoustic frequencies (**Figure 7**). This device exhibits the largest measured relative bandwidth (more than one octave) of reported free-space acoustic cloaks.

Cloaking has been demonstrated for gravity waves in water (Farhat et al., 2008) which satisfy a wave equation amenable to TA. Modifications of acoustic cloak design to include convective effects for moving objects and cloaks was considered by Huang et al. (2014). Thermal effects have even been proposed for 2D acoustic cloaking in air. García-Chocano et al. (2012) simulated cylindrically layered anisotropic density by controlled heating or cooling of cylinders. Numerical results showed reduced acoustic backscatter in certain frequency bands using this exotic mechanism.

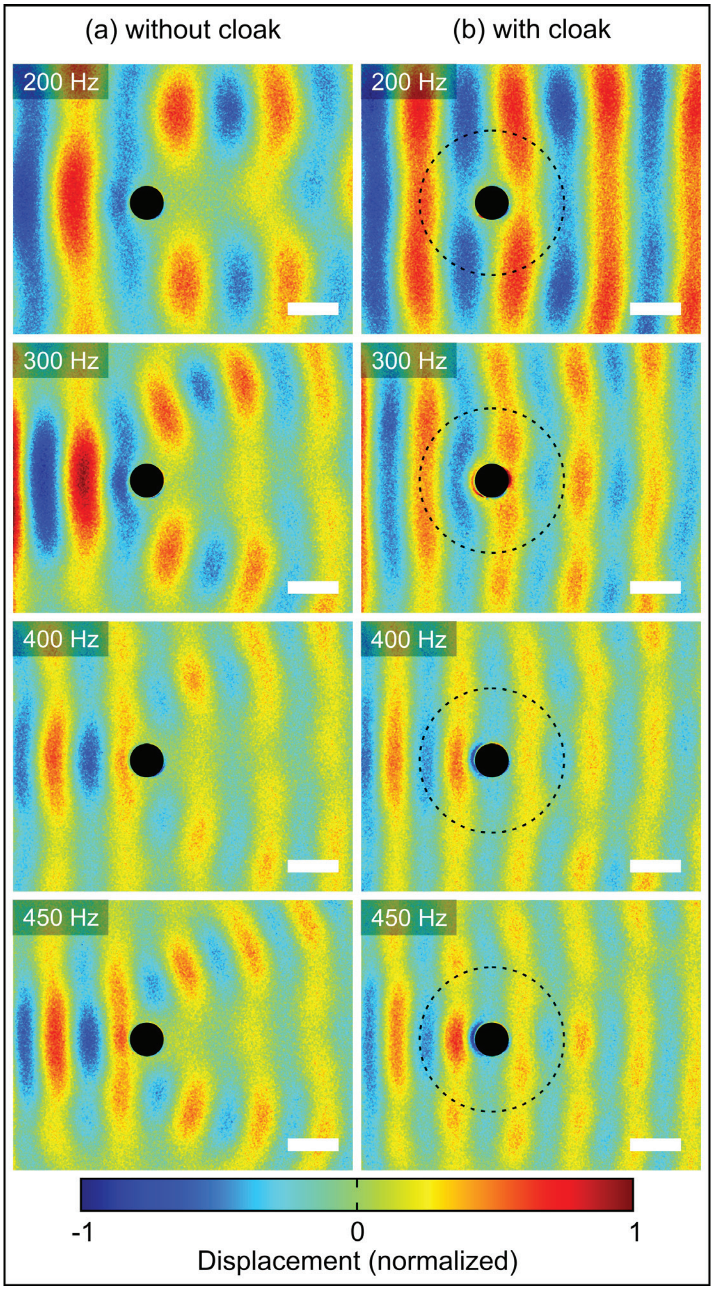

Figure 7. *Cloaking of flexural waves. The black cloaked region of di-ameter 3 cm is clamped, the dashed lines depict the outer boundary of the cloak. Reprinted from (Stenger et al., 2012) with permission. This movie shows experimental results at 200 Hz.* (To view movie please visit *http://wp.me/p4zu0b-MY*)

Cloaking of seismic waves has obvious potential but is essentially a pipe dream, the wavelengths are so long that any structure providing significant cloaking effect would be huge. Nevertheless, several ideas have been floated for cloak-like effects. Kim and Das (2013) proposed attenuating seismic energy using large buried "meta-boxes" with resonance frequencies of the seismic waves. Simulations with boxes of volume ≈ 100 m^2 show significant attenuation at 10 Hz. Brûlé et al. (2014) proposed a phononic crystal design to reflect geophysical surface noise such as pile drivers. Large scale tests were made on a periodic 2D mesh of cylindrical empty boreholes of 0.32 m diameter drilled 5 m into the top soil layer, with a lattice constant of 1.73 m. The configuration was designed to have a bandgap at the operating frequency of 50 Hz. Measurements showed greater than 50% decrease in surface wave amplitude for transmitted waves.

Cloaking by Active Cancellation

The methods discussed so far are passive, reliant on material properties for cloaking. *Active cloaking*, on the other hand, uses sound sources to cancel the incident wave. It is closely related to active noise control and *anti-sound* which creates a zone of silence, although unlike cloaking, the sound is generally not required to be non-radiating. Recent theoretical work on active acoustic cloaking provides insight into the older problem of active sound control.

Miller (2006) proposed cloaking a region by sensing sound on a closed surface while simultaneously exciting sources with amplitudes defined by the measurements. The method relies on the Kirchhoff-Helmholtz integral (Nelson and Elliott, 1992) whereby a continuous distribution of monopoles and dipoles completely suppresses sound. The difficulty with this approach is realizing acoustically transparent sensor and actuator surfaces, replacing the surfaces by a finite number of discrete sensors and sources is preferable. A solution to this problem was provided by Guevara Vasquez et al. (2011) who showed, remarkably, that cloaking requires as few as three active sources in 2D and four in 3D. Norris et al. (2012) subsequently found explicit formulas for the source amplitudes. The catch with this approach is that the sources are multipoles, and full cloaking requires multipoles of all order. Point multipoles are not possible in practice, neither are monopoles or dipoles for that matter. Furthermore, the multipole expansion is divergent, a point noted earlier in anti-sound research (Nelson and Elliott, 1992, pp. 262-4). This motivates truncating the series, limiting accuracy, although numerical simulations indicate that only a small number of multipoles may be required. Despite these difficulties, Guevara Vasquez et al. (2011) provide a rigorous basis for subsequent approximation. Other approaches to active cloaking have been suggested; for instance, Bobrovnitskii (2010) proposed acoustic cloaking using a non-local impedance coating extended reaction.

Conclusion

Cloaking of sound, first proposed only seven years ago, has been shown to be feasible with practical demonstrations appearing regularly and more frequently. How will this emerging acoustic technology impact society? We can expect applications in improved noise reduction, sound absorbtion, architectural acoustics, and envornmental acoustics, not to mention defense interest in underwater sound control.

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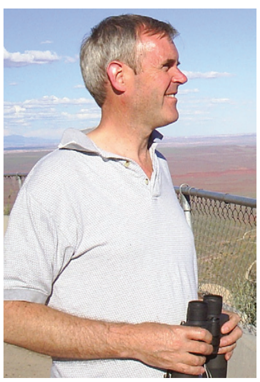
Biosketch



Andrew Norris received the BSc and MSc in Mathematical Physics from University College Dublin, and the PhD from Northwestern University in 1981. Following a post-doc at Exxon Research and Engineering Corporate Laboratories he joined Rutgers University where he is now Professor of Mechanical and Aerospace Engineering. He has worked on geophysical, structural and ultrasonic NDE wave problems. His current interests are in metamaterials that exhibit extraordinary wave bearing properties. He is editor of Wave Motion, an Associate Editor of JASA and a Fellow of the ASA. In his off time he enjoys reading, running and the great outdoors.

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