New breakthroughs in Acoustic Metamaterials enable acoustic clocking, super-lensing , sound focusing and confinements

Acoustic metamaterials are artificially fabricated materials designed to control, direct, and manipulate sound waves. More recently, the metamaterial concept has been extended to acoustic waves in a variety of scenarios of interest such as acoustic clocking, super-lensing and sound focusing and confinement.

Acoustic metamaterial is defined as an artificial composite material displaying novel acoustic properties unavailable in naturally occurring materials and radically different from those of any of the constitutive components. The novel acoustic properties derive from closely spaced constituent elements with specifically chosen geometrical and mechanical characteristics.

They in particular have shown great promise in the field of sound attenuation. Acoustic metamaterials composed of thin elastic membranes decorated with or augmented with designed patterns of rigid platelets, have been utilized to absorb large percentage of acoustic waves and can be made to create acoustically “dark” materials as well as vibration dampening devices

Some of the military applications of these materials are acoustic isolator (acoustic diode), acoustic circulator, acoustic switch, acoustic cloaking, acoustic sensors and thermal management.

Acoustic Metamaterials

Acoustic waves are a type of longitudinal waves that propagate by means of adiabatic compression and decompression. Longitudinal waves are waves that have the same direction of vibration as their direction of travel. Important quantities for describing acoustic waves are sound pressure, particle velocity, particle displacement and sound intensity. Acoustic waves travel with the speed of sound which depends on the medium they're passing through. According to the oscillation frequency, acoustic waves have been classified to different fields that cover the audio, ultrasonic and infrasonic frequency range, or seismic waves at much larger scale which are waves of energy travelling through the Earth's layer.

The material properties of interest for acoustic metamaterials are the effective mass density ρ and the effective bulk modulus κ, which is analogous to a spring's stiffness. Of particular interest for acoustical applications is the ability to manipulate an acoustic wave's speed. Because acoustic metamaterials have a broad range of effective properties, they can produce propagating waves with extremely high, zero, or even negative speeds, not to mention the purely imaginary values that correspond to nonpropagating evanescent waves.

Materials with either negative mass density and positive bulk modulus or positive mass density and negative bulk modulus are called single negative. Single-negative materials cannot support propagating waves, so any acoustic wave in those materials will exponentially decay. That makes them superior sound absorbers.

Double-negative acoustic metamaterials enable significantly improved refractive properties through negative refraction. ”They permit us to construct superlenses that amplify evanescent waves and provide subwavelength resolution for acoustic imaging devices. Double-negative materials can also be fabricated into hyperlenses, which use a hyperbolic dispersion relation between frequency and wavenumber, rather than the elliptical dispersion found in traditional anisotropic materials, to produce negative group velocity and a negative index of refraction. Hyperlenses provide a different means to improve the resolution of acoustic imaging devices. They can also be constructed from single-negative anisotropic acoustic metamaterials, but those hyperlenses lack certain advantages arising from negative refraction," write Michael R. Haberman and Matthew D. Guild in Physics today.

Recent advances in acoustic metamaterials have made it possible to design engineered metamaterials and associated structures for practical applications. Transformation acoustics provides precise control over acoustic wave propagation and this coupled with metamaterials gives unprecedented control in controlling, manipulating and directing sound waves. This coupled with advent of fabrication technology and development of simulation techniques such as finite element method (FEM) and finite difference time domain method (FDTD) have led to a revolution of metamaterials in controlling and manipulating acoustic waves in new ways not previously imagined . For instance, in acoustics, it is now possible to design acoustic lenses for sub-diffraction imaging or design acoustic cloaking which is able to make an object acoustically invisible by bending the waves. Also, an assembly of rubber-coated spheres into a bulk metamaterial can exhibit locally designed resonant structures.

Acoustic Metamaterial applications

Lightweight material in theory translates to a high sound transmission, particularly at low frequencies. Chinese researchers, including Ms. N. Sui and Y. Jing, have designed and experimentally demonstrated a lightweight and yet sound-proof honeycomb acoustic metamaterial. The use of no-massattached membrane-type acoustic metamaterials leads to excellent acoustical performance with minimum weight-penalty.

The proposed metamaterials can be used to build the core material of the sandwich structures which are experimentally proven to be significantly more sound-proof particularly at low frequencies with an extremely low weight penalty. The proposed metamaterial is promising for constructing structures that are simultaneously strong, lightweight, and sound-proof, which can be extremely useful for aerospace and other transportation industries.

Recently Researchers from the University of Maryland A. James Clark School of Engineering directed by Miao Yu, have developed a new acoustic metamaterial that dramatically amplifies acoustic signals, more than 10 times past the detection limit of conventional sensors.

They developed a novel metamaterial having “graded refractive index” or GRIN for short, that would compress and amplify a sound wave before detection by a sensor. Unlike other cutting-edge technologies in acoustic amplification, the GRIN material is relatively broadband and highly compact, with a theoretical length of only 2 to 4 wavelengths of the incident wave. Applications of the research could include improving the capabilities of sonar devices and medical imaging that detects cancer.

Prof Katia Bertoldi of Harvard University also studies strange, elastic materials like this, which have a negative “Poisson ratio”. This means that when you compress them, instead of squashing out to the sides and getting both flatter and wider, they actually shrink in all directions.

Then when stretched, they expand in all directions. Prof Bertoldi’s team has engineered various useful properties into such materials, including making them absorb sound at different frequencies when squeezed. The Poisson ratio can also affect fatigue in a metal – so she has worked with Rolls Royce to design engine components with complex slits wound into them, which withstand many more cycles of compression before breaking.

Acoustic Cloaking

Acentech has completed a three year, $750,000 U.S. Navy research project, which sought to evaluate the possible application of metamaterials, especially those forming an acoustic cloak for underwater naval vehicles. A cloak is a layer surrounding an object that bends incident acoustic wavers around it, and reconstructs the incident waves on the opposite side. A cloaked object could thus be invisible to active sonar at any angle.

Duke engineers have built world’s first 3-D acoustic cloaking device, from metamaterials under research supported by Multidisciplinary University Research Initiative grants from the Office of Naval Research and Army Research Office. Cummer and his team built a pyramid structure from perforated sheets of plastic, that could alter the trajectory of sound waves striking the structure, so as to appear to have bounced off from a flat surface beneath it.

The acoustic cloaking device works in all three dimensions, no matter which direction the sound is coming from or where the observer is located, and holds potential for future applications such as sonar avoidance and architectural acoustics. The technology could allow any object, for example a submarine, to become inaudible by bending sound waves, such as sonar signals, around the object.

Active Metamaterials

A major limitation of current acoustic metamaterials is that their acoustic properties are either locked into place once fabricated or only modestly tunable, tying them to the particular application for which they are designed.

Researchers from Department of Electrical and Computer Engineering, Duke University presented a design approach that yields active metamaterials whose physical structure is fixed, yet their local acoustic response can be changed almost arbitrarily and in real-time by configuring the digital electronics that control the metamaterial acoustic properties.

They demonstrated experimentally by designing a metamaterial slab configured to act as a very thin acoustic lens that manipulates differently three identical, consecutive pulses incident on the lens. The slab can be configured to implement simultaneously various roles, such as that of a lens and beam steering device. The slab is suitable for efficient second harmonic acoustic imaging devices capable to overcome the diffraction limit of linear lenses. These advantages demonstrate the versatility of this active metamaterial and highlight its broad applicability, in particular to acoustic imaging.

French scientists are using metamaterial technology to create earthquake “shields” that can deflect acoustic waves like those generated in an earthquake

Designing silent metamaterials

Duke University, alongside MIT, University of California, Berkeley, Rutgers University, and the University of Texas at Austin, forms part of a five-year research program sponsored by the US Office of Naval Research to develop new concepts for acoustic metamaterials with effective material parameters that can be fabricated in the real world. Steve Cummer, professor of electrical and computer engineering at Duke University, said: “Mathematical models are the starting point. The acoustic metamaterial designs are optimized through numerical simulations, which we then translate into modern fabrication techniques and experimentally test.”

One focus of the group’s current research efforts is on developing acoustic metamaterial structures that can be used in water-based environments, including the human body, to arbitrarily transform and control incoming sound waves. Acoustic cloaking structures have proven a useful testbed for demonstrating the arbitrary control enabled by transformation acoustics. Designing for aqueous environments represents a shift in metamaterial research, which has evolved from electromagnetic cloaking and transformation optics, to acoustic cloaking and transformations in 2D and then 3D structures in air.

Cummer explained: “To arbitrarily control sound using transformation acoustics, we first apply a coordinate transformation to describe how you would like to bend or twist or deform the sound field in a particular device. Once you’ve defined that coordinate transformation, then you can derive the effective material parameters you need to create that particular deformation of the sound field.”

Attention has now shifted to getting acoustic metamaterials to work in an aqueous environment, such as underwater or inside the human body. Multiphysics modeling is used as the primary design tool to first map the previously designed structures and run simulations in order to test how they will perform in water.

The problem is that the mechanical properties of air are dramatically different from those of water. Cummer explained: “That’s why in air we can get away with building acoustic metamaterials in plastic, or whatever solid is convenient, as the solid can act essentially as a perfectly rigid structure to control the sound field flow. It doesn’t really matter what it is made of.”

But the mass density and compressional stiffness of water are not so different from solid materials. “When sound waves hit a solid structure in water, the mechanical properties of that solid start to matter a lot. We need to come up with new techniques in the design phase to be able to control how that sound wave energy interacts with the solid so that we can maintain the properties we want,” he added.

The ability to easily merge acoustics and structural mechanics is essential, especially when we’re dealing with structures in water where we can’t ignore the mechanical responses of the solid material that we’re using to build the metamaterial. In airborne acoustics, we can get away with treating the solid as a material that is infinitely rigid, which is easy and computationally efficient, but for the water-based material it is essential to be able to consider fluid-structure interaction.

References and resources also include:

http://spectrum.ieee.org/computing/software/manipulating-and-controlling-sound-the-development-of-acoustic-metamaterials