The Development Of A Star-Shaped Lattice Structure For Use In The Design Of An Acoustic Superlens

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Abstract

With a single metamaterial architecture, unusual acoustic properties like acoustic transparency, ultrasonic beam focusing, an acoustic band gap, and super lensing can be shown. In the scientific literature, there have never been any examples of these traits that haven't been written down before. When conventional metamaterials focus an ultrasonic beam on a certain wavelength, they distort the surrounding sonic frequencies. This makes the output wave fields at those wavelengths look bad. Because the frequencies of ultrasonic waves and sonic waves are so different, it is very rare for a metamaterial to focus ultrasonic waves by having negative refractive index and being transparent at sonic frequencies at the same time. Ultrasonic frequency (37,3 kHz) has been shown to be a good way to focus a beam without distorting the waves, and a metamaterial with a bunch of thin, butterfly-shaped ring resonators has been made. This will let the building keep working the way it should.

Some keywords that should be in this article are single-phase metamaterials, exotic acoustics, and star-shaped lattice structures.

1.Introduction

In the last 20 years, the word "metamaterial" has come to mean a group of man-made composite materials that were made on purpose. As composite metamaterials become more common, they are likely to be used in a wide range of real-world situations, making it possible to control waves in new ways. In both photonics and phononics, periodic structures can have a big effect on how waves move through the host medium. This rule applies to both of these technologies. Because of this, a lot of scientists were inspired to come up with new ways to change wave fronts by using structures that repeat. Wave focusing, sound isolation, energy harvesting, ultrasonography, and other things can all be done with this technology. On the other hand, most of the research was done on how to control acoustic waves at specific frequencies. Periodic metamaterial structures not only create a unique feature at the designed frequency, but they also change the wave fields inside and outside the metamaterial at off-designed frequencies, which are frequencies outside the band of a specific designed frequency, in a way that was not planned and cannot be controlled. Periodic metamaterial structures In the long run, there will be a limit to how metamaterials can be used in high-frequency applications. In this article, one solution is to build the periodic structures so that the metamaterial system doesn't affect the wave field until the frequency that was planned for is reached. This answer is given as a possible answer to the problem. Unless it acts in a certain way, the metamaterial system should behave like an acoustically transparent medium, which in this case is the air it is housed in. This frequency is set by how the metamaterial system is supposed to act. There is a range of frequencies where waves can pass through without being affected. This range is called the "Acoustically Transparent Range." On the other hand, the researchers were inspired to make acoustic phononic lenses by the idea of using metamaterials to focus elastic waves. In order to get the look that was intended, these lenses are made with small changes in the way the host material is shaped. The same methods that were used to make electromagnetic lenses were also used to make photonic lenses. Acoustic flat lenses can be shown well by putting phononic crystals in a pattern that repeats itself. Wave propagation phenomena like single and double negative refraction, orthogonal wave transportation, non-diffracting Bessel beam sub-wavelength scale wave focusing, and multiple wave scattering have been seen in a wide range of periodic structures. Recent research in the field of underwater imaging has led to the successful building of a two-dimensional acoustic lens that is optimised from a topological point of view. Even though metamaterials have been fully used in biomedical imaging and surgery, focusing acoustic waves at ultrasonic frequencies may have a bigger effect. It has been shown that the resolution of traditional flat lenses is limited by diffraction. This limitation is caused by a part of waves that disappears as they move. Because of this, it is important to know if metamaterials can be used to get information about subwavelengths. The ability of metastructures with phononic crystals to bend light in the opposite direction has been suggested as a way to make superlenses. There's no question that this is a very good plan. Super-lenses were first made for the field of photonics, but they are now also used in the field of acoustics. Scientists who were interested in the phenomenon of acoustic wave modification thought that an acoustic metamaterial design should be able to do many things and work in different ways. A butterfly-shaped metamaterial made of stainless steel split rings embedded in an epoxy matrix has been suggested as a way to get the wave modulations described above. It is thought that the Butterfly metamaterial can show different acoustic properties at different frequencies, such as acoustic transparency, wave focusing, and superlensing, all at the same time by using one meta structure orientation. This is done with a single meta structure orientation. Individual full-ring and split-ring resonators are put together in a butterfly shape to make the sound qualities and create interdependence at many frequencies. This makes the shape of a butterfly. If you want to see through the meta structure at low frequencies, the global meta structure needs to behave in a way that is almost the same everywhere. On the other hand, wave focusing and superlensing behaviour require local anisotropy. The proposed model's shape and orientation are made to split and focus acoustic waves when the geometry (like the thickness of the ring) and the number of repeating unit cells are made for low frequency acoustic transparency. So, the shape and orientation of the model are chosen to make it easier for acoustic waves to split apart and for the wave field to focus. Another reason for superlensing is that the structure's ability to focus waves controls its ability to bend light in the wrong direction. You can see that it is split into four parts. In the first Brillouin zone, it was said that an eigenfrequency analysis had found that the butterfly structure's dispersion behaviour could be seen. To do this, the eigenfrequency of the building was compared to a reference frequency. In the second step, we looked at the frequency domain to see if the arrangement we had simulated worked in the real world. At the band gap frequencies, a material block with a butterfly shape completely blocked the wave. No waves should go across the gaps between the bands. This section also shows how transparent the proposed construction is to sound and how it looks in the frequency domain below 18 kHz. In the third stage of research, modes with a frequency of about 37 kHz are found and their ability to cause waves to split and focus is predicted. After a frequency domain analysis was done to prove the wave focusing phenomenon, the next step was to make a spectrum of the focusing frequencies. In the last parts of this study, negative refraction and the proposed butterfly structure's ability to act as a superlens are looked at.

2. Related work

(Gao, H. et al. , 2022) It is thought that a square acoustic metamaterial (SHAMLRAS) with local resonant Archimedean spirals can be used to reduce single-phase vibration while keeping the structure's light weight. By changing the spiral control equation, SHAMLRAS structures can be given different geometry parameters that are not tied to the spiral control equation. With mode forms, dispersion surfaces, and group velocities, you can study how low-frequency bandgaps form and how in-plane elastic waves weaken in certain directions. The width and location of the low-frequency bandgap, as well as the effect of the spiral arrangement and changes to the equation's parameters, are all being talked about separately right now. In addition, transmission loss experiments and numerical simulations are done along with a rational period design of the SHAMLRAS plate structure to measure how well the filtering works. According to the study results, many Archimedean spirals have enough local resonance for acoustic metamaterial design, and several low-frequency bandgaps can be made with the right parameter control. These bandgaps happen at frequencies lower than 500 Hz.

(Li, Zuyu, et al. , 2021) Pentamode metamaterials are a new type of three-dimensional lattice composites that are made on purpose. There are many different kinds of pentamode metamaterials, and all of them are heavily based on ad hoc design principles. But there hasn't been a systematic design strategy for these materials yet. In this paper, a good topological optimization method will be shown so that many different types of unique pentamode lattice microarchitectures can be found. These microarchitectures can be used for a wide range of useful material properties, such as thermal conductivity. In the first step of the method, an elastically orthotropic pentamode micro lattice is made that meets the necessary and sufficient conditions for the elasticity constants. This must be true before the elasticity constants can be found. In the second stage of this project, a universal mathematical paradigm for designing and optimising pentamode micro lattices is being made. Third, an orthotropically symmetric ground structure is built in three dimensions. Because of the way the structure is made, the truss bars on the ground structure can't meet or overlap.

Narisetti, R. K., et al.(2011) In this paper, we look at how waves spread out in two-dimensional periodic lattices with weakly nonlinear symmetry. For nonlinear effects on dispersion and group velocity, you can get a closed-form answer by using a perturbation approach that was first made for one-dimensional systems and was then made more general. These formulas are used to figure out amplitude-dependent bandgaps and wave direction in a non-isotropic environment. In an anisotropic setting, there is no symmetry. Using lattice equations of motion and numerical integration, it is possible to check how accurate perturbation approach forecasts are. For waves with a small amplitude, there has been a lot of agreement on how dispersion and directionality work. Simulations show that there are "dead zones" in the response of anisotropic nonlinear lattices that depend on the amplitude.

Manktelow, K., et al. (2021) By first finite-element discretizing a single unit cell and then doing a perturbation analysis on the resulting data, one can look at how waves move through structures with weak nonlinearities that are periodic and continuous. The dispersion analysis has been combined with commercial finite-element analysis (FEA) software to speed up the nonlinear analysis of unit cells with complicated shapes. Here, a simple continuous multilayer system is used to show the key parts of the technique. The example shows how flexible the method is by using a periodic membrane structure supported by nonlinear elastic supports. The group velocities and bandgaps of these diagrams depend on the amplitude, and the band diagrams are not linear. The nonlinear dispersion analysis method shown here can be used with standard FEA software to learn more about how waves move through a wide range of difficult-to-draw nonlinear periodic structures.

Profunser, D. M et al, (2009) Using pulsed ultrashort optical excitation and detection, surface acoustic wave propagation on a microscopic two-dimensional phononic crystal made of a square lattice of holes can be seen in two dimensions and in real time at frequencies up to 1 GHz. The crystal is small because it only has two dimensions. The spatial-temporal Fourier dispersion relation makes it clear that surface waves moving in the direction of the phononic crystal axes open stop bands when they reach the zone boundaries. Our results show that there are strong Bloch harmonics above the stop band and that the spatial mode distributions depend on the frequency. Phonon collimation can also be seen at frequencies where the surfaces with constant frequency take on a square shape.

3. Methodology

Using pulsed ultrashort laser stimulation and detection, surface acoustic wave propagation on a microscopic two-dimensional phononic crystal made of a square lattice of holes can be seen in two dimensions and in real time at frequencies up to 1 GHz. This can be done at a frequency of no more than 1 GHz The crystal is very small because it can only live in two dimensions. For example, it is clear that surface waves that move from one zone to another can open stop bands at the edges of zones because of a spatial-temporal Fourier dispersion relation. The data we collected show strong Bloch harmonics above the stop band, as well as spatial mode distributions that change with frequency. Also, phonon collimation can be seen at frequencies where the square-shaped constant-frequency surfaces can be seen.

3.1 Locally Resonant Sonic Materials

Adding a resonance unit to the basic building block of a phononic crystal makes it possible to make locally resonant sound materials. This is an important step toward making acoustic metamaterials. The main difference between this sonic material and a phononic crystal is that each unit cell in this material is in the deep subwavelength range, while the resonance frequency is in the shallow subwavelength range. The mass density and bulk modulus of this material are useful because they show how different it is. For the structure to stay stable, it needs to have a positive static elastic modulus and density. However, the dynamic effective acoustic characteristics are spread out and can have a negative value at the point of resonance. This means that the bulk modulus of a material could be negative when the resonance-induced scattered field dominates the incident fields in the background. This causes a change in volume that is out of phase with the dynamic pressure that is applied. If the acceleration was out of sync with the dynamic pressure gradient, a negative mass density effect would be seen. Scientists covered heavy spheres with soft silicon rubber and then put epoxy around them to show how localised resonance works. Because of an acoustic dipolar resonance at a low sonic frequency, it was possible to make something with a negative effective density. Not Bragg scattering, but a strong connection between the moving elastic wave in the host medium and the localised resonance caused these strange things to happen. When applied to the long wavelength limit, the effective medium technique gives a valid evaluation and a clearer, more intuitive understanding of this complicated system. It has been shown that putting together two different kinds of structural units makes an acoustic metamaterial with a negative bulk modulus and mass density. [Needs citation.] [Needs a citation] Negative bulk modulus is caused by monopolar resonances, while negative mass density is caused by dipolar resonances. Both types of resonance are good for the whole system.

3.2 Acoustic Circuits

Electrical current and sound move through a system of pipes or chambers in ways that are very similar. A lumped-parameter model is the best choice when the size of the area where sound travels is smaller than the wavelength. In this case, it is important that the phase stays the same across the system, so it must be kept that way.

3.3 Acoustic Impedance of a Pipe

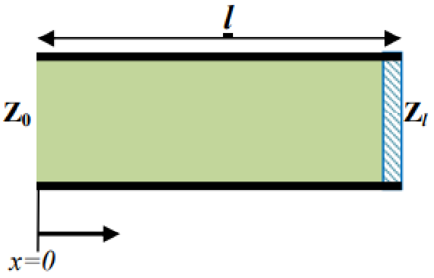

Figure 1 A tube with rigid side wall terminated with acoustic impedance Zl

$$v_i = v_{ai}e^{j(\omega t-kx)}$$
$$v_r = v_{ar}e^{j(\omega t+kx)}$$

Think about a hollow, cylinder-shaped tube with an impedance Zl, one open end, and one closed end. The coordinate system starts at the end of the tube, where there is an opening. Using this assumption, we can figure out if waves with flat wave fronts can move down the tube in a straight line. This claim can't be checked unless the diameter of the tube is bigger than about 6. An initial wave moving in the positive x direction spreads out until x=l, where it usually changes into a reflected wave that moves in the opposite direction. The speed of the particles that make up this wave can be described as:

Where $v_{ai} = \frac{p_{ai}}{\rho_0 c_0}, v_{ar} = -\frac{p_{ar}}{\rho_0 c_0}$

The total pressure in the tube at any point is

3.4 Acoustic Inductance

Think about the water inside a tube with a length of l and a surface area of S. We'll assume that the tube has a rigid acoustic structure because both ends are open. When the size of the tube is smaller than the wavelength it corresponds to, all the numbers are in phase. When an unbalanced force is applied, the tube moves as a whole. Because the part has open ends, it can move freely without putting any noticeable pressure on the other parts.

$$Z_{A0} = j\frac{\rho_0 C_0}{S}\tan kl$$

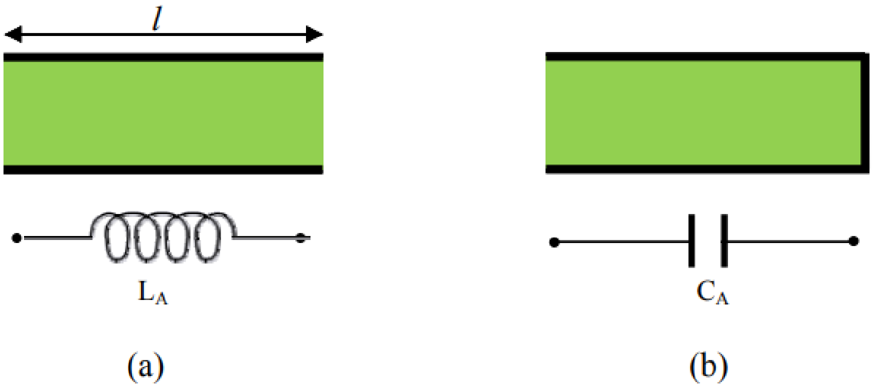

Figure 2 Acoustic Inductance

3.5 Composite Materials.

Periodic layered composites were one of the first things that made people want to learn more about how different materials can be arranged in a one-dimensional periodic pattern., the development of composite materials and the need to test their integrity using nondestructive evaluation (NDE) methods based on the propagation of elastic waves brought back interest in studying these kinds of assemblies. In the 1980s, people became interested in the subject again. Because of this, it's become more popular to study layered composites and make similar models, which are sometimes called "continuum models." A continuum theory was used to study how a laminated composite behaves in motion. Both the reinforcement and matrix layers were said to have two-term extensions of their midplanes. To figure out how accurate the theory is, dispersion curves for waves with polarizations normal and parallel to the layering were looked at and compared to exact curves. In this study, which is part of a series of papers about getting more complicated in layer structures, variational formulas for how harmonic waves move through periodic elastic composites were introduced. In, variational methods for analysing periodic composites are talked about. At the same time, colleagues came up with continuum theories. Since then, they have been working on wave propagation in layered composites and guiding waves in layered composites, both of which have made important contributions to the field of NDE. The transfer matrix approach and other matrix-based calculations that are similar to it have been used to study the properties of dispersion and the way harmonic waves move through the thickness of composites with generally non-uniform behaviour in plane. Many other authors, like, have looked at how mixture theories can be used to figure out the equivalent stiffness and mass of structures with more than one layer. Equivalent, mixture, and continuous theories are still being looked at to see if they can predict how different types of media disperse. Recent investigations on many different levels have looked into this. This has been the subject of a lot of research. Several studies, like those done by Hulbert and his colleagues and by Fish and others, have used the one-dimensional periodic waveguide as a test case to see how well established approximation techniques that are based on multiple scale expansions work. Here are a few of these investigations: Most of the time, the materials that make up the periodic systems that scientists study don't go together very well. Even though they are called "phononic crystals," these periodic patterns are still used. One of the first discoveries in this field is the study of two-dimensional periodic materials and their bandgap properties. This is in contrast to what was seen in "photonic crystals" before. This is a very important discovery in this field.

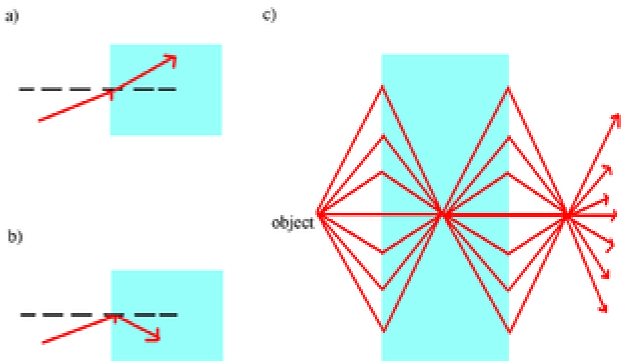

Figure a) A wave that is moving through a vacuum can bend around an object with a high refractive index. When waves travel through a vacuum, they hit things that have a negative index of refraction. To put it another way, the light from an object with n=1 in front of another object is bent twice: once inside the lens and again outside the lens. Imaging at a subwavelength level is now possible.

3.6 Periodic Structures.

Using a one-dimensional periodic beam, Cremer and Leilich were the first structural engineers to study harmonic flexural wave motion. The system got its periodicity from basic supports or point masses that were placed at regular intervals. The periodic beam is an example of a monocoupled periodic system, which means that each unit cell can only connect to its neighbours through one degree of freedom. So, the wave properties of this object at any given frequency can be described using only one set of equal and opposite wave modes and propagation constants. Researchers have looked into beam-plate systems, one-dimensional patterns, and two-dimensional grillage structures. [Needs a citation] With a transfer matrix, you can study most of these systems and how they spread in a simple and straightforward way. By doing this for all of the cells in a finite periodic system, you can get an idea of the natural frequencies and mode shapes. A method that will be briefly explained later in this paper lets us estimate the dispersion relationships by looking at just one unit. The study is important because it was one of the first attempts to figure out how to make a transfer matrix. Faulkner and Hong's work, which gives examples for researchers who want to get started, is also important because it was one of the first in this field. Rotationally periodic structures, which seem to be an independent field, have also made important contributions. This topic has gotten a lot of attention because of how important it is in the real world and how hard it is to solve technologically. Rotationally periodic structures include turbomachinery parts like discs with blades. In this industry, the strong responses and localization of vibrations that come with periodic structures have been linked to a number of unique dynamic properties. It has been found that these things are the main reasons why things don't work out.

Mead and his fellow researchers at the University of Southampton, which has been a hub, a number of important contributions to this field of study. Because this essay needs to be a reasonable length, I won't repeat an analysis of their work that has already been done. We'd like to talk about some of the work that Gupta did at Southampton. He found a link between the dispersion properties of beams, stiffened panels, and ribbed plates and their modal content. This section also talks about the modal properties of monocoupled and multicoupled periodic systems. Also, it connects the frequencies of the edges of the propagation zone of systems with only one connection to the frequencies of individual unit cells and finite assemblies. It has been expanded to include multicoupled systems and takes into account the effect of damping. The forced response of periodic systems can be studied with the help of a response function for an infinite, uniform, one-dimensional structure that is hit by a number of harmonic forces or moments. It is taken into account that convective loading could happen at random. In Reference, the use of numerical methods to predict dispersion and the overall dynamic response is talked about. This reference shows how Bloch's periodicity criteria for waves can be applied to both simple supported beams and more complex built-up structures. The goal of this exercise is to help you better understand how numerical techniques can be used to predict dispersion and the overall dynamic response. Thomas and others gave a real-valued form of the eigenvalue problem in the form of an optimization problem for estimating dispersion. Commercial FE packages have modal solvers built in that can help with this problem, as Thomas and others showed later. Periodic structure analysis with FE methods is still a popular topic, as shown by the work of Mace and his colleagues, for example. Consideration of a periodic structure or a uniform structure as the limit of a periodic assembly is helpful in terms of computational cost or being able to use commercial finite element codes to find the dispersion properties of complex structural components like stiffened plates, sandwich panels, or cylindrical shells. Using commercial FE codes to figure out dispersion parameters can save a lot of time and money when it comes to computing. These methods have worked well for studying structures in two dimensions. In the early research at Langley, 2D periodic structural components, such as their directionality and how they behave when they stop and pass, were studied. People are still interested in how topology and geometry affect the way waves travel through structural lattices. When designing vibration-isolating devices, shock absorbers, and impact-absorbing structures, it's important to take banned zones of response into account, as well as the properties of the corresponding anisotropic elastic lattice and how they relate to wave directionality and to each other.

3.7 Phononic Crystals.

As was already said, research on phononic materials and structures is interesting to people from many different fields. While mechanics has focused on composite materials and periodic structures, electromagnetics and photonics have been interested in the idea of artificial periodicity (see the following sentence for an overview of historical advances in these disciplines). In 1987, the idea of what is now called a "photonic crystal" was put forward almost at the same time by two people. It is a dielectric material with different phases and symmetries that are similar to those of crystalline materials on an atomic scale. A crystal made of light (as dictated by the rules of crystallography). The same idea was made for both acoustic and elastic waves, which were later called "sonic crystal" and "phononic crystal," respectively. Because of this, the two ideas were almost the same. In Madrid, the idea was shown to the general public through a huge array of sound sculptures shaped like cylinders. This was a great way to get people interested in the idea.

Conclusion

Metamaterials are man-made structures that are smaller than a wavelength. They have been used to make waves move in strange ways. Because electromagnetics and acoustics have a lot of single and double negative variables, it can be shown that cloaking and superlensing happen in the real world. Controlling how energy is lost is one of the hardest parts of building these devices in the real world. The low friction caused by the membranes moving with the fluid could be one reason why membrane-based metamaterials are so useful. Our negative-density metamaterial made from a membrane could be an important part of an acoustic superlens, hyperlens, perfect lens, or cloak.

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