Metamaterials for Acoustic Noise Filtering and Energy Harvesting

Subjects: Acoustics

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The twenty-first century's vision for Factory 4.0 requires more advanced methods for noise filtering while creating much safer and healthier environment. From various perspectives of physics, noise filtering capabilities could be addressed in multiple ways. The physics of noise control is first dissected into active and passive control mechanisms. Further different physics are categorized into different geunere to visualize their respective physics, mechanism, and target of their respective applications. Beyond traditional passive approaches, the comparatively modern concept for sound isolation and acoustic noise filtering is based on artificial metamaterials. These new materials demonstrate unique interaction with acoustic wave propagation exploiting different physics. A few multi-functional metamaterials were reported to harvest energy while filtering the ambient noise simultaneously. It was found to be extremely useful for next-generation noise applications where simultaneously, green energy could be generated from the energy which is otherwise lost.

Keywords: metamaterials ; acoustic metamaterials ; topological acoustics

1. Introduction

A worldwide spike in industrialization has led to an increasing amount of noise and noise pollution. Noise pollution is defined as the unwanted propagation of sound energy creating physiological problems. Airborne sound travels through the air. It can transmit, reflect, or be absorbed by obstructions. At times, it is difficult to track sound since it is invisible. As a result, the methods and instruments used to track and filter the sound are difficult to develop. Hence, constant research dollars are spent at various scales to tackle the sound. As a result, innovative and efficient materials are being designed as noise barriers to filter unwanted noise in various environments that reduce noise pollution.

Energy is a vital element in the growth of modern society. From a light bulb to outer space missions, we need energy everywhere. Some energy is visible to us, such as light, but most of the existing energies in nature are not visible. Among such energies, electrical energy is the most commonly used form. Due to the high demand for electricity, different measures are being utilized to convert other forms of energy to electricity. The process which derives energy from external sources is called Energy Harvesting. The converted or harvested energy can be stored in a capacitor or battery for later use. This stored energy can work as a power source for low-energy electronics. In recent years, phenomenal interest has been shown in the harvesting of ambient vibrational energy and converting it into electrical power. The motivation of the research is to power wireless remote sensors, which are usually powered by batteries. Batteries possess the disadvantage of having a finite lifespan which creates problems of frequent replacement, especially during emergencies. In certain situations, it is not feasible to replace batteries either because of the complicated structural situation or due to extra-sensitive circuits with the risk of damage and increased costs. Therefore, in these complicated situations, if ambient energy in the atmosphere can be utilized to harvest electric potential to power these batteries concurrently, then most of the existing problems could be solved. Various transduction mechanisms can be employed to harvest this kind of energy. One such mechanism involves the use of piezoelectric materials to harvest energy from the unused, trapped, or lost vibrational energy of the host structure.

Not only the ambient vibration but the sound and noise created by modern machinery and vehicles can also be used to harvest the energy by trapping them in a medium. In recent years road traffic has increased tremendously. It is, without a doubt, one of the most widespread sources of noise annoyance. Industries with heavy machinery introduce a significant amount of noise into the atmosphere. In such cases, acoustic noise barriers can be developed and incorporated to reduce the outbreak of such unwanted noises. However, the efficiency of these noise barriers has been a big question for a long time. Researchers are constantly working on improving the efficiency of the barriers, but to date, the maximum reported efficiency of noise barriers is around ~50%. Concerning traditional industrial barriers, new materials and designs are combined to create a more effective noise-filtering system. Sound-absorbing materials are being used to trap the sound inside the material and, thus, decrease the reflection of noise. The law of conservation of energy states that energy can neither be created nor destroyed—only converted from one form of energy to another. Hence, the energy that the sound barriers absorb is trapped inside the cells. This trapped energy is not being utilized anywhere. The trapped acoustic energy can be wisely harvested if certain measures or ways can be incorporated serving this purpose, resulting in 'energy harvesting'.

Conventional materials do not show promising output for all these special applications. Therefore, metamaterials can be used for such applications. Metamaterials are engineered materials that possess unique properties that cannot be found in naturally occurring materials. Metamaterials can be constructed by assembling multiple materials or polymers. The properties of the metamaterial are different from the constitutional material properties, and they originate from the design assembly of the pieces. Acoustic metamaterials are metamaterials that are designed to control, direct, and manipulate sound waves, as these might arise in gases, liquids, and solids. The acoustic metamaterial follows the theory and outcome of negative index material. Since acoustic metamaterial is one of the branches of metamaterials, the basic principle of acoustic metamaterials is quite similar to the principle of fundamental metamaterials. These metamaterials usually derive their properties from the structure rather than the material composition, utilizing the inclusion of small inhomogeneities to enact effective macroscopic behavior. A negative refractive index of acoustic materials can be attained by manipulating and controlling the bulk modulus and mass density.

2. Noise Control

2.1. Noise Control Mechanism

2.1.1. Active Control Mechanisms

Modifying and canceling sound field by electro-acoustical approaches is called active noise control. There are mainly two methods for active control mechanisms. First, utilizing the actuators as an acoustic source to produce completely out-of-phase signals to eliminate the disturbances. The second method involves the use of flexible and vibro-elastic materials to radiate a sound field, interfering with the disturbances and minimizing the overall noise intensity. A passive noise control mechanism is good for high-frequency noise sources; for noises with lower frequencies, active noise control mechanisms work better.

Control of Acoustic Sources

Control of acoustic sources is also known as Active Noise Control (ANC). This concept uses three basic components—speaker, microphone, and controller, as reported by Elliott [1]. In this method, the noise created from a primary source is passed through a controller to generate an anti-phase signal. This anti-phase signal is transmitted by a secondary source in the controller. Here, the microphone is regarded as a primary source and the loudspeaker as the secondary source. This method works best in an enclosed environment. An increased number of primary and secondary sources can improve the noise reduction efficiency of the system. However, total noise cancellation is impossible due to various technical reasons such as phase lag and others.

Active Damping Mechanism

From the discussion in the previous section, it is evident that ANC systems have various drawbacks. To overcome these flaws, a new system is proposed that not only controls cabin noise but also works toward structural vibrational reduction. The main difference between this mechanism is that it controls the noise indirectly, whereas the ANC controls noise directly. Sensing accelerometers are used to measure the vibration level, which is sent to the controller. Another set of accelerometers is placed near the control region to provide feedback and minimize the error. The entire process runs in a loop and, thus, reduces the sound developed from specific locations. This active damping mechanism is also known as Active Structural Acoustic Control (ASAC).

Like the acoustic source control mechanisms, ASAC has also been studied rigorously since the late 1980s. The initial fundamental work on such systems was published by Fuller and Jones [2], where they achieved a cabin noise reduction of around 20 dB. The study was extended by a few other researchers considering an actual aircraft cabin [3][4]. This extended research had some loopholes because it did not consider the effect of the actuator position. Later this issue was addressed in a comprehensive study conducted on a rectangular enclosed space. The study suggested that the actuator location need not be limited to a specific location [5][6][7].

2.1.2. Passive Control Mechanisms

Passive noise control refers to those methods that aim to suppress sound by modifying the environment close to the sound source. As no input power is required in these methods, passive noise control is often cheaper than active control. However, the performance of the passive system is limited to mid and high frequencies. Active control works well for low frequencies, and hence, the combination of two methods may be utilized for broader bandwidth noise reduction.

Helmholtz Resonator

Helmholtz resonators are referred to as fluid-filled (usually air) hollow containers with a narrow neck system. The Helmholtz resonator effect is caused by the motion of the air at its neck. The fluid inside acts as a spring, which helps the neck air to oscillate, thus, resulting in a spring-mass system. This phenomenon of air resonance in a cavity with a narrow neck is known as Helmholtz resonance. The Helmholtz resonator and its effects on acoustic media have been studied for a very long time, but around three decades ago, Fahy and Schofield [8] presented some disagreement with the existing designs. They experimentally proved the existence of two modes on either side of the resonator's fundamental frequency. The study is considered a foundation for Helmholtz resonator design.

Acoustic Metamaterial

In the past two decades, huge progress has been made in the field of acoustic metamaterials. These materials have demonstrated tremendous potential for absorbing wider noise frequencies. Owing to the promising advancement, the designs developed by researchers so far can be used in practical settings for effective noise reduction in various environments. Acoustic metamaterials use a few basic physics to attenuate sound waves and filter noise. The section below discusses the five widely used physics for noise filtration.

Bragg Scattering

Let us consider two identical scatterers at a distance of Δx. There is a time lag or phase difference between the incident and the radiated wave. The scattered waves interfere destructively with respect to each other. The distance between the scatterers leads to a strong destructive effect on wave propagation. This phenomenon is called 'Bragg scattering'. Bragg scattering can be observed. It happens at the heart of the phononic crystal. In a crystal, at the frequencies where the Bragg condition meets, a frequency window is created through which no waves can propagate.

Local Resonance

From the research conducted so far, it is evident that periodic structures have an influence on the propagation of waves. For instance, if considering two oscillators, the coupling between them is strongest if they are degenerate. The coupling is expected to split the degenerate system of the wave and the local resonator onto the dispersion of waves. This effect is strongest at the point where two frequencies come across. Additionally, similar to the Bragg scattering effect, a window is present through which no wave propagation is possible. The frequency is not directed by the spacing of the periodic array; rather, the local oscillator's frequency dominates it. The propagation of the waves can be modified in the vicinity of a specific frequency by coupling the wave to a local resonance with a similar frequency. This local resonance phenomenon is widely used for designing noise-filtering acoustic metamaterials. Manipulation of the design parameters can help achieve the desired bandgaps in a specific frequency range.

Antisymmetric Deaf Band

Ao et al. reported a design of an acoustic metamaterial that can form a far-field image beyond the diffraction limit [9]. They studied a 2D array of coaxially layered rods in water. They observed transverse modes corresponding to zero effective density. These are labeled as deaf bands since they do not couple with normal incident longitudinal waves. Very recently, Indaleeb et al. [10] reported an acoustic metamaterial where a Dirac cone-like point is introduced. They presented a deaf band-based predictive model which has the potential to achieve an engineered Dirac cone. Their model includes PVC cylinder PnCs immersed in air. They experimentally validated the model to confirm the numerically generated orthogonal wave transport phenomena.

Acoustic Quantum Hall Effect

The acoustic quantum Hall effect is a new phenomenon observed in acoustic metamaterials recently. Under a strong magnetic field, many intriguing phenomena can be observed. Recently, the introduction of graphene has opened the door to quantum transport control by mechanical means. Wen et al. [11] reported the first experimental realization of a giant uniform pseudo-magnetic field in acoustics by introducing a simple uniaxial deformation to acoustic graphene. They proposed a strategy to create a uniform pseudo-magnetic field (PMF) for airborne sound by arranging a 2D sonic crystal array in a triangular lattice and validated the model experimentally. They attained uniform PMF by modifying only one geometric parameter in a single direction.

Topological Effect

In electrodynamics, topological insulators have drawn significant attention due to their unique one-way wave propagation characteristics, which are not affected by defects or disorders in the structures [12][13][14]. In topological insulators, the outer surface is conductive while there is a bandgap-like phenomenon inside the cell which makes it an insulator to the electron flow. Topological metamaterials are developed considering the same physics, and they demonstrate a new vision for the domination of wave propagation aside from Bragg scattering and local resonance. Understanding topological transition by the interaction between these mechanisms is strongly desired to extend the degrees of freedom in the design for this intriguing wave phenomenon. Quantum Spin Hall Effect (QSHE) is one such topological behavior that could be used for acoustic isolation and/or predictive back scattering immune one-way wave propagation along the domain wall.

Spring Mass Damping System

The spring-mass-damper model is the most basic method of suppressing vibration. These models are used widely used to minimize the structural vibration and, thus, reduce the noise. This is the age of metamaterials, and therefore, the traditional spring mass damper system has also entered the metamaterials club for enhanced structural vibration suppression.

Vibration Absorbing Structure

Vibration is one of the major sources of industrial noise. Reducing the vibration of a structure or isolating the vibrating surface will lead to a huge reduction in environmental noise. Ideally, springs are used in most cases to suppress the vibrations. Modern complex problems with vibrational sources have led researchers to develop lattice structures to absorb a wide range of vibrations. Such vibration-absorbing structures fall under the passive noise-controlling mechanism.

2.2. Acoustic Metamaterial with Ventilation

2.2.1. Acoustic Facade Systems

Skyscrapers are very common in big cities, and there are more every day. It has been observed that these skyscrapers are often installed with transparent double-leaf facade systems as their window panels. Researchers have been exploring these facade systems and their structure and materials for effective noise reduction and air ventilation. Bajraktari et al. [15] utilized an acoustic structure with two-faced sheets (primary and secondary facades) along with ventilated openings. The unique structural design and the openings resulted in the circulation of sound and air within the cavity between the structures before the secondary passage. The design caused frictional resistance due to the ventilated openings, thus, resulting in impedance mismatching from the air cavity enabling significant noise reduction and ventilation. This structure displayed a noise reduction of approximately 27–35 dB.

2.2.2. Helmholtz Resonators (HRs)-Based Acoustic Structures for Airflow

The next type of simultaneous noise reduction and air ventilation structure involves the use of Helmholtz resonators. Many researchers have been widely investigating the incorporation of HRs in their design for noise filtration. Kim, Lee, et al. [16] established a prototype of air-transparent soundproof window panels by integrating the 3D arrays of diffraction-type HRs consisting of a central hole having a diameter of subwavelength. The HR contributed to negative bulk modulus and the central hole leading to noise reduction and efficient air ventilation.

2.2.3. Acoustic Metacage Systems

Another interesting design often explored by researchers for effective noise reduction and air ventilation is the acoustic metacage system. These systems mostly comprise acoustic metamaterials installed to the confined sound source in the form of cage-shaped systems. The metacage is usually introduced to the sound source system and, at times, also to the receiver based on the requirement and compatibility.

2.2.4. Acoustic Meta-Absorber Systems

Acoustic meta-absorbers are metamaterials that are capable of high absorption of sound in the targeted frequency range. The phenomena are mostly achieved through the concept of impedance matching, which emphasizes the coupling of incident acoustic energy with the absorbers. Basically, the acoustic impedance complements the air leading to null reflection from the sound absorber metastructure enabling maximum absorption of sound.

3. Energy Harvesting

3.1. Energy Harvesting Based on Sources

3.1.1. Vibration Sources

Based on the vibrational sources, energy harvesting approaches can be classified into two major categories, intermittent and continuous. The continuous source represents the models where the host structure vibrates at specific frequencies or a band of frequencies, such as machine vibration. The intermittent source does not rely on the input frequency; however, the host structure deforms and generates power upon the availability of the source, such as footsteps. One of the major differences between continuous and intermittent sources is their operating principle. While the resonance phenomenon is the key to generating maximum power using the continuous source, the intermittent source uses pure bending mode to harvest energy.

3.1.2. Sound Sources

Generally, acoustic energy is ultimately dissipated into thermal energy at the propagation stage, and the low- and mid-frequency sound waves have attracted the most attention. One of the reasons is that the specified frequency band of noise is usually a significant component of the spectrum. The other reason is that at the low- and mid-frequency range, the corresponding sound wavelengths are longer, making it quite difficult to absorb or isolate them using most engineering structures. Many approaches have been developed to effectively absorb or isolate low- to mid-frequency acoustic sound waves; these include both passive and active approaches.

References

1. Elliott, S. Active noise and vibration control in vehicles. In Vehicle Noise and Vibration Refinement; Elsevier: Amsterdam, The Netherlands, 2010; pp. 235–251.
2. Fuller, C.; Jones, J. Experiments on reduction of propeller induced interior noise by active control of cylinder vibration. J. Sound Vib. 1987, 112, 87A30933.
3. Simpson, M.A.; Luong, T.M.; Fuller, C.R.; Jones, J.D. Full-scale demonstration tests of cabin noise reduction using activevibration control. J. Aircr. 1991, 28, 208–215.
4. Mathur, G.; Tran, B. Aircraft cabin noise reduction tests using active structural acoustic control. In Proceedings of the 15th Aeroacoustics Conference, Long Beach, CA, USA, 25–27 October 1993.
5. Pan, J.; Elliott, S.; Baek, K.-H. Analysis of low frequency acoustic response in a damped rectangular enclosure. J. Sound Vib. 1999, 223, 543–566.
6. Pan, J.; Hansen, C. Active control of noise transmission through a panel into a cavity. III: Effect of the actuator location. J. Acoust. Soc. Am. 1991, 90, 1493–1501.
7. Pan, J.; Hansen, C.; Bies, D. Active control of noise transmission through a panel into a cavity: I. Analytical study. J. Acoust. Soc. Am. 1990, 87, 2098–2108.
8. Fahy, F.; Schofield, C. A note on the interaction between a Helmholtz resonator and an acoustic mode of an enclosure. J. Sound Vib. 1980, 72, 365–378.
9. Ao, X.; Chan, C. Far-field image magnification for acoustic waves using anisotropic acoustic metamaterials. Phys. Rev. E 2008, 77, 025601.
10. Indaleeb, M.M.; Ahmed, H.; Saadatzi, M.; Banerjee, S. Deaf band-based prediction of Dirac cone in acoustic metamaterials. J. Appl. Phys. 2020, 127, 064903.
11. Wen, X.; Qiu, C.; Qi, Y.; Ye, L.; Ke, M.; Zhang, F.; Liu, Z. Observation of acoustic Landau quantization and quantum-Hall-like edge states. arXiv 2018, arXiv:1807.08454.
12. Fu, L.; Kane, C. Superconducting proximity effect and Majorana fermions at the surface of a topological insulator. Phys. Rev. Lett. 2008, 100, 096407.
13. Zhang, H.; Liu, C.X.; Qi, X.L.; Dai, X.; Fang, Z.; Zhang, S.C. Topological insulators in Bi2Se3, Bi2Te3 and Sb2Te3 with a single Dirac cone on the surface. Nat. Phys. 2009, 5, 438–442.
14. Chen, Y.L.; Analytis, J.G.; Chu, J.-H.; Liu, Z.K.; Mo, S.-K.; Qi, X.L.; Zhang, H.J.; Lu, D.H.; Dai, X.; Fang, Z.; et al. Experimental realization of a three-dimensional topological insulator, Bi2Te3. Science 2009, 325, 178–181.

15. Bajraktari, E.; Lechleitner, J.; Mahdavi, A. The sound insulation of double facades with openings for natural ventilation. Build. Acoust. 2015, 22, 163–176.
16. Kim, S.-H.; Lee, S.-H. Air transparent soundproof window. AIP Adv. 2014, 4, 117123.