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Review of Phononic crystals and acoustic metamaterials

Qiqi Chen¹, Bo Zhang^{1,2,*}, Yutian Bai¹, Liheng Wang¹ and M R M Rejab³

¹ School of Mechanical Engineering, Ningxia University, China

² CAE Key Laboratory for Intelligent Equipment of Ningxia, China

³ Faculty of Mechanical and Manufacturing Engineering, Universiti Malaysia Pahang, Malaysia

*Corresponding author: zhangb@nxu.edu.cn

Abstract. As a new type of acoustic functional material, phononic crystal has great research value and application environment. It is a periodic structure of two or more elastic materials, which are derived from photonic crystals. The main research work on phononic crystals focuses on the two band gap formation mechanisms of Bragg scattering and local resonance, and some new methods of vibration reduction and noise reduction can be obtained by studying its banding mechanism. Similarly, a "metamaterial" has been proposed for the ability to achieve new vibration reduction and noise reduction, which is a composite structure or material with physical properties not available in natural materials. By analysing the acoustic metamaterials of various structures, in this work we can understand how to achieve vibration reduction and noise reduction under the local resonance mechanism.

Keywords. Phononic crystals; Band mechanism; Metamaterial; Vibration reduction; Local resonance.

1. Introduction

The phononic crystals introduced in the 1990s are conceived for controlling elastic waves from the geometric structure. In fact, the phononic crystal is a type of periodic artificial acoustic functional material that prevents the propagation of elastic waves within a certain frequency, i.e. within the band gap [1]. Moreover, the local resonant phononic crystal structure proposed in 2000 has superior low-frequency band gap characteristics particularly, which brings another breakthrough for the subsequent research progress, and opens up a new situation for the application of phononic crystal in low-frequency shock reduction and noise reduction. In terms of the structural periodicity in three orthogonal directions and in Cartesian coordinate system, phononic crystal can be divided into three forms: one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) phononic crystals. The typical structures are shown in figure 1.



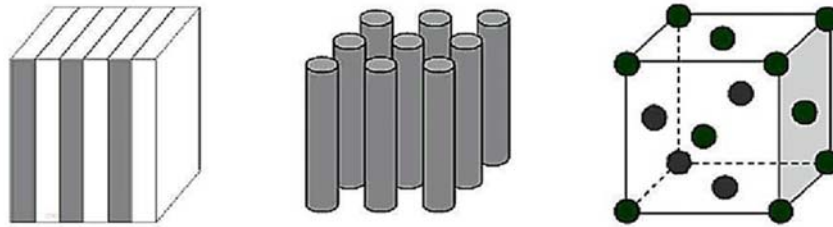


Figure 1. Schematic diagram of one-dimensional, two-dimensional and three-dimensional phononic crystals.

The concept of acoustic metamaterial is put forward later than phononic crystals, but it also exhibits an excellent potential in practical engineering of noise reduction. The term metamaterial originated from the Latin word "meta", which is more than intended, and is generally considered by the academic community to be composed of sub-wavelength artificial microstructure units. Usually it consists of two or more different dielectrics and magnetic media materials, which can exhibit special characteristics not available yet in natural materials. As sound waves or elastic waves propagate inside the materials, some distinct physical properties or functions may be demonstrated, which were ever not found in traditional materials, such as negative refraction, plane focus, acoustic stealth, etc.

2. Research status of phononic crystals

The concept of phonon crystal has been put forward for only 20 years. After more than 20 years of development, phonon crystal has made great progress in theoretical research, experimental testing and sample fabrication. In general, the research on phonon crystals in or out of China mainly includes the formation mechanism of elastic band gap, calculation method of elastic band gap, localization of waves caused by surface and internal defect, negative refraction and its application. Because of its potential application prospect, the corresponding researches have drawn the attention of scholars around the world. International research groups such as Kushwaha in Mexico, Sigalas in the United States, Vasseur in France, Torres in Spain, Khelif in Belgium. In China, Wen Xisen, Liu Youyan of South China University of Science and Technology, Liu Zhengyou of Wuhan University, Wang Yuesheng of Beijing Jiaotong University, Shen Ping of Hong Kong University of Science and Technology, Wu Zhengzhong of Taiwan University and Nanjing University have done a lot of research work in the field of phononic crystals. Of course, there are still many problems to be solved in the calculation method of phononic crystals, band gap mechanism and characteristics, application exploration and so on.

According to the statistics of works in literatures worldwide, Bragg scattering and local resonance are two mature photonic band gap formation mechanisms. It has been found that the band gaps of phonon crystals are successfully explored by means of Bragg scattering mechanism, as shown in [2-4]. The current studies showed that provided that the medium in matrix is a type of fluid, the centre-frequency of the lowest acoustic band gap of the phonon crystal can be given by the combination of matrix sound velocity c and lattice constant a , namely $c/2a$. The relationship between wavelength and lattice constant is similar to X-ray diffraction behaviour in crystals discovered by Bragg, so the formation of such band gaps is termed as Bragg scattering mechanism, as seen in [1]. It is noted that this mechanism emphasizes the effect of periodic structure on wave's propagations. However, the minimum frequency range of the band gap generated by this mechanism is related to the lattice constant, and the elastic wave length corresponding to the minimum band gap frequency is the same order of magnitude as the lattice constant. In theory, larger size structure is therefore needed to produce lower frequency band gap, yet which is not conducive to the application of phonon crystal devices in low frequency range.

On the other hand, the discovery of local resonance mechanism has also changed this situation, as in [5]. Different from Bragg scattering mechanism, local resonance mechanism paid more attention to motion mode of a single cell. And through appropriate construction, a soft coating is added among the

substrates and the scatterers to make a series of acoustic oscillators formed by the original cells resonate locally in the frequency range corresponding to the lattice scale wavelength, and block the propagation of ongoing waves in crystals, as in [6]. For locally resonant phonon crystals, the band gap mechanism is not sensitive to the periodicity of the structure, and even the random arrangement of scatterers may produce band gaps also. Local resonance mechanism makes the generation of low-frequency band gap without the help of relatively large size structure, which has an important theoretical significance and great practical application prospect, as in [5-7]. Figure 2 gives a cell diagram of the ideal two-dimensional Bragg scattering phonon crystal and two-dimensional local resonant phonon crystal, as well as their respective can-band structure diagrams.

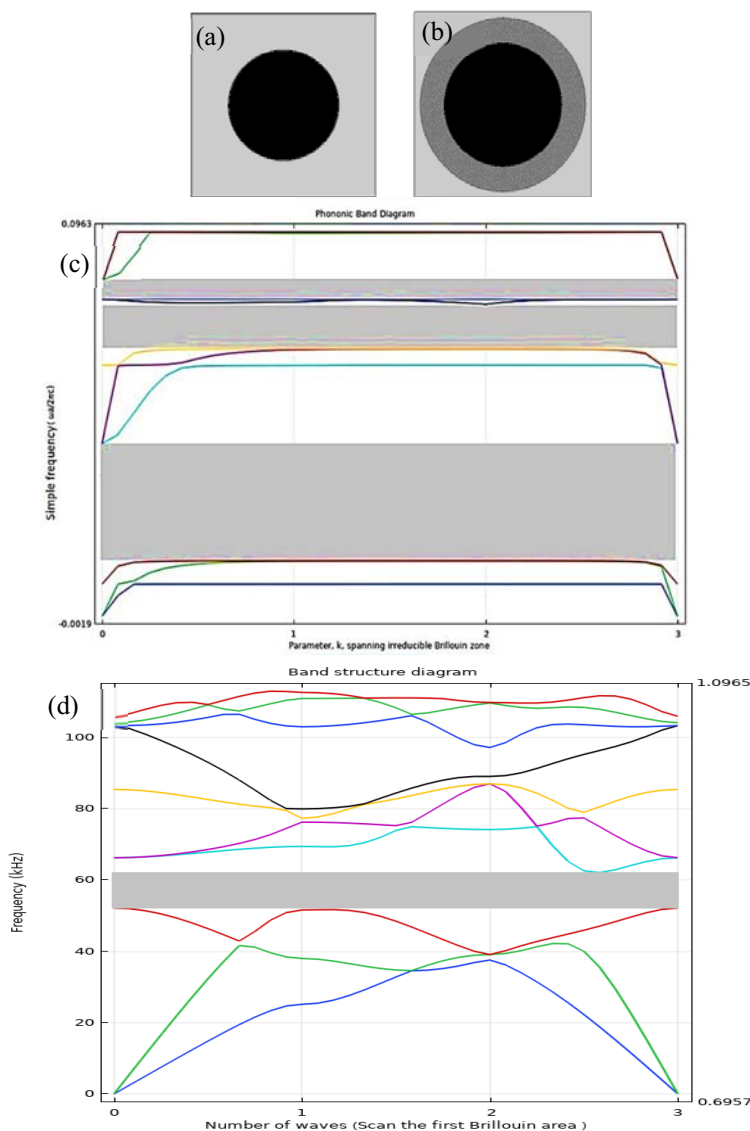


Figure 2. (a) Schematic diagram of ideal 2D Bragg scattering phonon cell structure; (b) Schematic diagram of 2D locally resonant phonon crystal cell structure; (c) Schematic diagram of band structure of ideal 2D Bragg scattering phonon crystal; (d) Schematic diagram of band structure of 2D locally resonant phonon crystal.

It can also be seen from the band structure curve that the local resonance phononic crystal is obviously different from the Bragg scattering phononic crystal. Specifically, the band gap frequency is much lower than the Bragg band gap of the same lattice size, which realizes "small size control large wavelength"; there is a flat band in the band structure, and there is a local resonance phenomenon in the internal wave field; the band gap is determined by the local resonance characteristics of a single scatterer, which has nothing to do with their arrangement.

Whether it is Bragg scattering phononic crystal [2-4], or locally resonant phononic crystal [5-7], whether it is one-dimensional [8-9], two-dimensional [10-11] or three-dimensional structure, whether it is ideal phononic crystal [11], or beam or plate with limited aperiodic direction [9], whether it is for high or low frequencies, whether it is for general elastic waves coupled with longitudinal waves, or only longitudinal wave, volume or surface waves, in practical engineering applications, most of all, one need to construct a structure or artificial matrix that can generate band gap. Then, by changing the lattice type, material parameters, scatterer shape, filling rate, etc., the rules of the factors affecting the band gap are summarized, so as to obtain a wider band gap with a smaller volume. For example, one-dimensional phononic crystals with acoustic band gaps can be constructed by using a tube with periodically varying diameter. The acoustic band gap can also be generated by installing periodically arranged branch tubes on the tubes. The acoustic band gap can also be generated when the tube is connected to an asymmetric ring and its period is connected together. Ultra-wide acoustic bandgap can also be obtained by using these structures. As long as the different tubes which can produce bandgap are connected together, the bandgap range will be widened by linear superposition. In the same way, one-dimensional layered phononic crystals with ultra-wideband gap can be constructed as well. For two-dimensional and three-dimensional fluid-type phononic crystals, materials with low density as scatterers are more likely to produce wide acoustic band gaps, such as water column in mercury, air column in water, and air bubble in water, as stated in [4]. For three-dimensional solid phononic crystals, regardless of the shape of the scatterer, the widest band gap can be obtained under the face-centred cubic arrangement; if confined to face-centred cubic or body-centred cubic arrangement, the wider band gap can be obtained provided that spherical scatterer is selected; if simple cubic arrangement, the wider band gap can be obtained by using cubic scatterers.

3. Advances in acoustic metamaterials

Acoustic metamaterials originate from locally resonant phononic crystals, in 2004, Li and Chan et al. [13] first proposed the concept of acoustic metamaterials. They studied the periodic structure of soft silicone rubber scatterer embedded in water. The solid-liquid phonon crystal has the equivalent negative mass density and negative volume modulus in a certain frequency range. That is so-called "double negative" parameter characteristics. Fang et al. [14] studied a periodically arranged Helmholtz resonator array in 2006. It was found that it has a negative equivalent bulk modulus in the resonant frequency band, and the experimental verification was given, as shown in figure 3. These studies show that the superphysical effects of electromagnetic wave metamaterials also exist in the field of elastic waves.

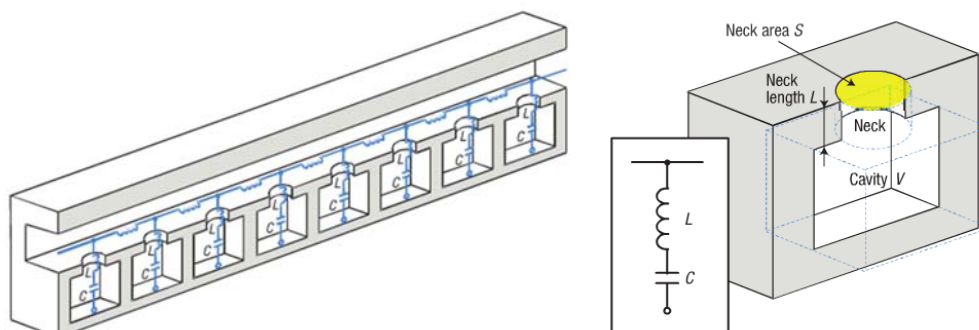


Figure 3. Acoustic metamaterials consisting of Helmholtz resonators arranged periodically [14].

In the past 20 years, the research of acoustic metamaterials has developed into many branches. Researchers have proposed a labyrinth-type acoustic super-surface that can simultaneously control the amplitude and phase of the acoustic front, as shown in figure 4 and [15]. A Metal-water with very similar physical properties and fluids is proposed, which can actively control acoustic metamaterials by adjusting characteristic frequencies and performance parameters, as shown in figure 5. Topological phononic crystals, nonreciprocal acoustic metamaterials, and odd-even time symmetry acoustic metamaterials evolved from topological insulators. Furthermore, applications of above-mentioned artificial materials or structures are also very wider and wider; for example, in addition to shock reduction noise reduction and acoustic stealth, those also can be used for sound focus and imaging, as in [16-17].

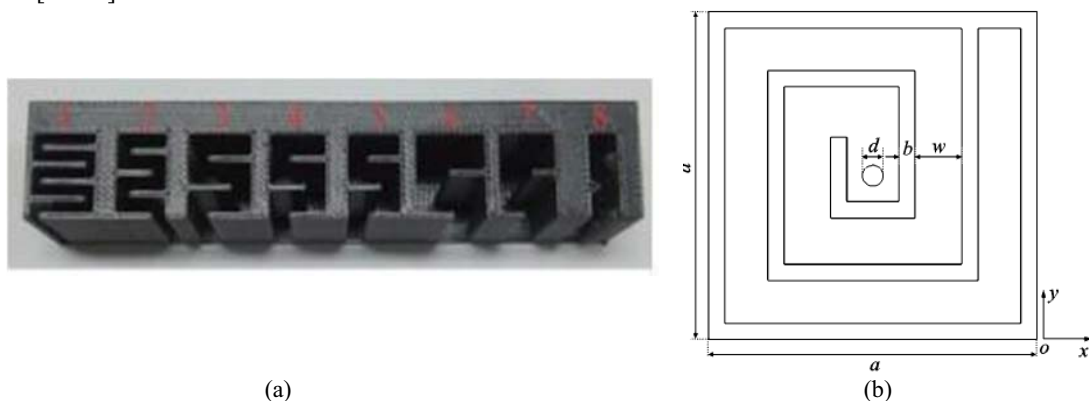


Figure 4. (a): Labyrinth acoustic Super surface; (b): Two-dimensional maze structure [15].

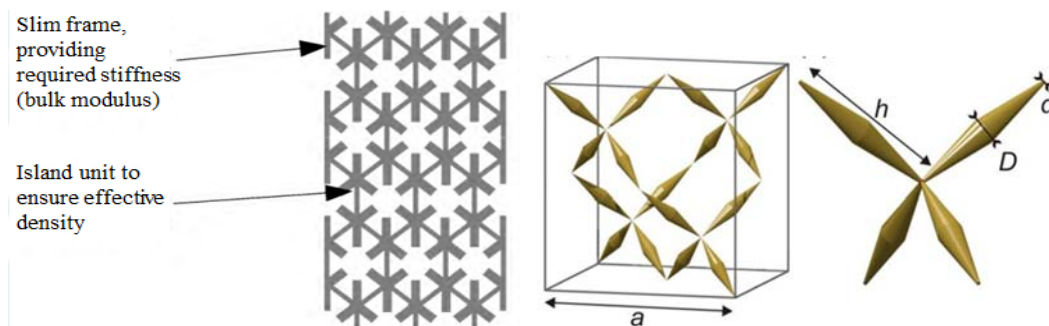


Figure 5. 2-D and 3-D Five-mode material (Metal-Water) structure diagrams [24].

4. Practical application of phononic crystals and acoustic metamaterials

4.1. Application of phononic crystals

Phononic crystal structures have attracted much attention in the field of noise and vibration control due to their designable bandgap characteristics. Since the introduction of phononic crystals in 1993, many people have studied their practical applications. It is well known that noise has an important impact on human health. The development of sound insulation materials or sound absorption structures with strong applicability is one of the important directions for the development of phononic crystals from theoretical research to practical application. In 2008, Chen Tianning et al. proposed a two-dimensional phononic crystal bandgap material with slot characteristic scatterers, as in [18]. In 2010, Ding Weiping et al. invented a compound three-dimensional phononic (3D) crystal automobile exhaust muffler by using the forbidden band characteristics of sound wave propagating in periodic media, as in [19]. Phononic crystals also have potential applications in submarine silencing tile, sonar,

and air flow noise and tree insulation. In the aspect of acoustic functional devices, new filters, waveguides and resonators have been designed by using the defect properties of phononic crystals.

Phononic crystals also provide a new way to solve the problem of vehicle interior noise, but the application research is still at the initial stage of exploration, and there is little research work available worldwide. Shen Li et al. made an attempt to apply phononic crystals to automobile braking noise, and achieved obvious noise reduction effect. The braking noise of the improved brake disc based on Bragg scattering phononic crystal has an average attenuation of 13 dB in 2-2.5 kHz, as reported in [20]. Zhang Sanqiang and Zhou Xiaoqiang applied the periodic damping and thin plate structure to the roof, rear seat floor and shelf of a certain type of car respectively to reduce the noise in the car, and achieved good noise reduction outcomes, as seen in [21-22]. Zuo Shuguang et al. applied the local resonance phononic crystal structure to the vibration reduction of the body roof. The vibration of the roof was suppressed obviously in the frequency range of 200-500 Hz, and the noise radiated from the roof to the car was reduced, as in [23].

4.2. Exploration on the application of acoustic metamaterials

At present, the application of acoustic metamaterials in acoustic wave and vibration control, new acoustic functional devices, acoustic stealth and other aspects has made considerable progress. In the aspect of aeroacoustics, based on the local resonance structure, Helmholtz resonance structure, sound insulation and sound absorption barrier [25], many researchers have obtained the effect of reducing the thickness and frequency band of sound absorption and insulation structure. Zhang et al. [26] proposed a piezoelectric shunt foil-like sound insulation metamaterial in 2016, which consists of a thin metal foil with shunt piezoelectric plates attached to it. It can isolate low-frequency noise efficiently under very light thin conditions. Furthermore, the researchers consider combining acoustic metamaterials with periodic grid structure [27], honeycomb sandwich plate structure (see in figure 6, and [28-30]) to explore the engineering application of light and low frequency metamaterial sound insulation structure, and obtain better sound insulation effect. In vibration control, in 2015, Aravantinos-Zafiris et al. [31] proposed the design of seismic wave isolator based on acoustic metamaterial. In 2016, Mahmoud et al. [32] designed a metamaterial structure with inertial amplification structure, which provides a reference for the design of low frequency and light material vibration isolation devices.

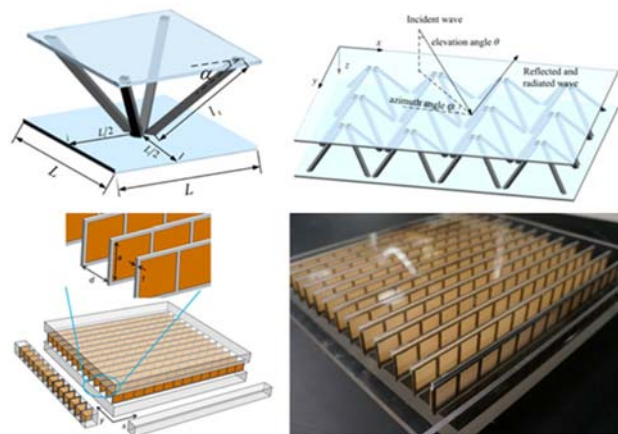


Figure 6. Combination of acoustic metamaterials and sandwich plate structure [28-30].

Stealth technology has great tactical value in modern military. At present, the main means of stealth design are absorbing materials and shape design. Because metamaterials have powerful electromagnetic and acoustic control capabilities, Pendry et al. [33] developed a new stealth technology represented by stealth cloak, which is expected to achieve a great breakthrough in stealth technology. Cummer et al. [34] proposed the concept of acoustic cloak in 2007, which artificially

constructs a distorted space to make the sound wave circumvent the stealth area and restore the stealth, as shown in figure 7. Subsequently, researchers from all over the world have carried out more research on new acoustic stealth principles, such as acoustic illusion design [35], carpet-type acoustic cloak [36], pressure-insensitive cloak [37], and underwater stealth carpet [38]. In 2015, Zhu et al. [39] proposed a unidirectional acoustic cloak for layered background media, the results of which will greatly promote the real applications of an invisibility cloak in inhomogeneous backgrounds. Those studies have further enlarged the application field of stealth design of acoustic metamaterials.

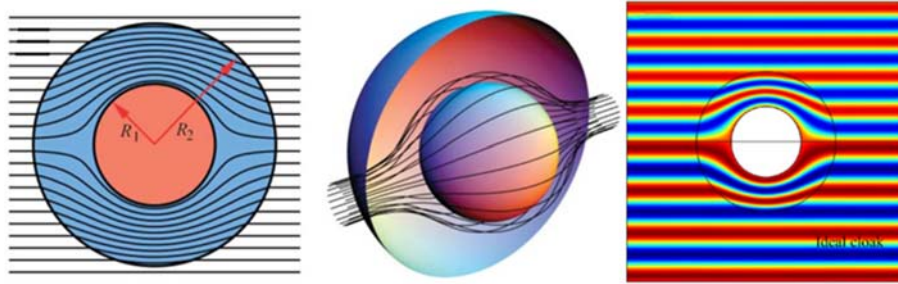


Figure 7. Principle of stealth cloak [33,39].

5. Conclusions

In this paper, the development of phononic crystals and acoustic metamaterials as well as the research work in various fields are briefly reviewed. The research and exploration of phononic crystals are of great significance to vibration and noise reduction, but the traditional structure of phononic crystals cannot meet the practical application of engineering, but only stay in the theoretical stage. Acoustic metamaterials derived from locally resonant phononic crystals have more novel characteristics. They are not limited to the specific structure of artificial period. The response characteristics of different bands and different physical properties can be obtained by adjusting the design and size of the structure. At present, the related research of acoustic metamaterials has become the fastest developing and most intensive research direction in the field of acoustics. It is expected to be applied to the engineering design of traditional vibration and noise reduction and acoustic devices to overcome the existing development bottlenecks of conventional material design, improve its performance and reduce its volume weight. To authors' knowledge, up to now, China's scholars have obtained a number of influential theoretical results, and formed some internationally influential research teams as well, however, more attention should be paid to experimental research.

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