Sound and vibration of periodic structures have been investigated for decades because of the numerous applications of periodic structures in various engineering areas. Many types of periodic structures have been examined, such as multi-storey buildings, multi-supported beams, lattice structures, stiffened plates/shells, space trusses, etc. While recently, wave propagation in artificial periodic structures known as phononic crystals and acoustic metamaterial, consisting of a periodic array of elastic scatters embedded in a host medium, has received renewed attention. The focus was placed on the investigation of novel wave phenomena and wave physics. In the past decade, the Vibration and Acoustics Research Group (VARG) at National University of Defense Technology has devoted in the investigation of sound and vibration of artificial periodic structures. The interest is focused on implementing the idea of phononic crystals and acoustic metamaterials into the design of engineering structures and materials for the purpose of controlling sound and vibration. The purpose of this paper is to presents a brief review of the research contributions from the VARG, with the attention particularly placed on the development of various types of artificial periodic structures, including locally resonant periodic structures for vibration suppression, periodically shunted beams and plates for vibration attenuation, acoustic metamaterials for sound insulation, locally resonant sonic materials for underwater sound absorption, periodic pipes/shells conveying fluid for sound and vibration reduction, and acoustic cloak/anti-cloak devices.

1. Introduction

Sound and vibration of periodic structures have been investigated for decades because of the numerous applications of periodic structures in various engineering areas. Many types of periodic structures [1] have been examined, such as multi-storey buildings, multi-supported beams, lattice structures, stiffened plates/shells, space trusses, etc. While recently, wave propagation in artificial periodic structures known as phononic crystals (PCs) [2, 3] and acoustic metamaterial (AMs) [4-6], consisting of a periodic array of elastic scatters embedded in a host medium, has received renewed attention. The focus was placed on the investigation of novel wave phenomena and wave physics. In the past decade, we have devoted ourselves to the study of theory and application of artificial periodic structures. Our effort is mainly focused on introducing the idea of PCs and AMs into the design of engineering structures and materials for the purpose of sound and vibration control. This
paper is intended to make a brief review of the research contributions from our research group (Vibration and Acoustics Research Group, VARG). In what follows, six topics will be addressed, including the locally resonant periodic structures for vibration suppression, periodically shunted beams and plates for vibration attenuation, acoustic metamaterials for sound insulation, locally resonant sonic materials for underwater sound absorption, periodic pipes/shells conveying fluid for sound and vibration reduction, and acoustic cloak and anti-cloak devices.

2. Locally resonant periodic structures for vibration suppression [7-19]

In the area of PCs, two types of band gap formation mechanisms have been revealed. One is known as the Bragg scattering mechanism, and another one is known as the locally resonant (LR) mechanism. The LR mechanism was first demonstrated by Liu et al.[4], who proposed a 3D PC consisting of arrays of binary resonant microstructures embedded into a host matrix. Due to the locally resonant behavior of the embedded binary microstructures, the proposed LR PC can achieve band gaps in a much lower frequency range than conventional Bragg-type PCs with the same lattice constant. In addition, recent studies show that LR PCs may exhibit unusual properties such as negative mass density, negative modulus and double negative properties, thus they can be designated as AMs[4-6].

LR PCs and AMs are always constructed by periodic arrays of resonant units embedded in a host matrix material. We introduce such an idea into the design of LR engineering structures by attaching periodic arrays of local resonators onto structural waveguides such as such as rods, shafts,
beams, and plates. As an illustrative example, Figure 1 shows the basic physical model of an LR plate made of a periodic array of spring-mass resonators attached to a homogeneous thin plate, which is proposed in Ref. [13].

![Experimental and Theoretical Vibration Suppression Performance](image)

Figure 3. Comparison of (a) experimental and (b) theoretical vibration suppression performance of an LR plate [18]. The shaded frequency region represents the theoretically predicted complete band-gap range in Figure 2.

We have demonstrated both theoretically and experimentally that various types of LR periodic structures can be constructed to achieve elastic wave band gaps at frequencies below, around or higher than the lowest Bragg frequencies, showing significant vibration suppression for the associated host structures [7-19]. As an illustration, Figure 3 shows the band gap behavior of an LR plate proposed by us recently [18], and the vibration suppression performance of the LR plate is shown in Figure 3.

3. Periodically shunted beams and plates for vibration attenuation [20-25]

With the advantages such as light weight, facility and good performances, piezoelectric (PZT) shunting has been used as an attractive technique for vibration and noise control. Recently, periodic arrays of passive shunted PZT patches are employed to control wave propagation and vibration transmission in beams and plates.

We have paid our attention to improve the modeling and understanding of periodically shunted beams and plates, as well as to improve the vibration attenuation performance of such structures [20-25].

For example, in order to enhance the locally resonant band gaps caused by the passive resonant shunting circuit (RSC), we involve an active strategy in the 1D PCs composed of a flexible beam and periodic array of shunted PZT patches (Figure 4(a)) [20]. Numerical model based on the transfer matrix methodology are developed to predict the band structure, attenuation factors as well as the transmissions of vibration in the proposed periodic smart structure. Vibration experiments are also conducted in order to validate the theoretical results. In Figure 4(b), it is shown that the enhanced RSCs can evidently increase the attenuations around the locally resonant band gaps compared with the passive RSCs. Wider attenuation frequency ranges can be gained by combination of different RSCs [20].
4. Acoustic metamaterials for sound insulation [26-30]

One of the most promising application areas of acoustic metamaterials is sound insulation. We have proposed some new ideas for the design and characterization of several types of acoustic metamaterials for air-borne sound insulation applications [26-28] or underwater sound insulation applications [29, 30].
same surface mass density) at frequencies within the mass-law region (Figure 6) and the coincidence region (Figure 7).

Figure 6. Diffuse field STL of LR metamaterial plates with N (=1, 2, 3, 4) attached resonators in each unit cell (mass-law region)[26]. The host plate and the total resonator mass for each case are chosen the same.

Figure 7. Diffuse field STL of LR metamaterial plates with N (=1, 2, 3, 4) attached resonators in each unit cell (coincidence region region)[26]. The host plate and the total resonator mass for each case are chosen the same.

5. Locally resonant sonic materials for underwater sound absorption [31-37]

Locally resonant sonic materials (LRSMs) are generally known as composite epoxy embedded with various heavy spheres coated by soft rubber with periodic or random position. It has been shown that the soft coating layer and the heavy core are responsible for a band gap at low frequency about two orders of magnitude lower than that predicted by Bragg’s condition. Much effort has focused on air sound isolation induced by the gaps of different LRSMs.

Our investigations in acoustic dissipation by LRSMs have shown the low frequency acoustic absorption while considering the damping of the components. Motivated by understanding of the en-
ergy dissipation in LRSMs, the locally resonant scatterers (LRSs) are introduced to improve the low-frequency acoustic absorption of the water impedance-matched polymer.

Experimental measurement for acoustic absorption of viscoelastic polymer slabs embedded with LRSs has been reported (Figure 8)[33]. The fundamental mechanism operating in localized resonance for acoustic absorption has been investigated by referring the mode conversions during the Mie scattering of a single scatterer. The relationship between the resonance modes described with the displacement contours of one unit cell and the corresponding absorption spectra is discussed in detail[34]. The shape of the scatterers has also been taken into account.

Figure 8. (a) Schematic of the sample of LR underwater absorption material; (b) Comparison of the theoretical and experimental absorbances [33].

We find that LRSMs can exhibit low frequency underwater acoustic absorption while the damping of the components is considered. The fundamental mechanism operating in localized resonance for acoustic absorption has been investigated by referring the mode conversions during the Mie scattering of a single scatterer. The absorption band of viscoelastic polymer slabs embedded with LR scatterers is generally narrow. To get a wider absorption band at low frequency range, the first two resonance modes have been considered. And an optimization scheme, a general genetic nonlinear constrained algorithm, is utilized to enhance the low-frequency underwater acoustic absorption of an acoustic slab with several layers.

The absorption band of viscoelastic polymer slabs embedded with LRSs is generally narrow. To obtain a wider absorption band at low frequency range, the first two resonance modes have been considered. And an optimization scheme, a general genetic nonlinear constrained algorithm, is utili-
ized to enhance the low-frequency underwater sound absorption of an acoustic slab with several layers. The effects of the steel slab backing on the acoustic absorption are discussed [35, 36]. What investigated about the new viscoelastic composites may be widely used in underwater constructions or vehicles to absorb unwanted sounds for practical application.

6. Periodic pipes/shells conveying fluid for sound and vibration reduction [38-44]

Pipe/shell systems conveying fluid are widely used in many areas. The study of the dynamics of pipe/shell conveying fluid has received considerable attention over the past few decades. Undesired vibration or sound propagation in pipe/shell structure could be eliminated or suppressed by careful design.

One particular structure design technology that has received considerable attention in the last decade is the introduction of periodic configurations into the pipe/shell structure, which can realize impedance mismatch and thus to form elastic wave band gaps in the periodic pipe/shells. Within the band gap frequencies, the vibration and sound propagation through the pipe/shell will be forbidden. In the past few years, we have introduced systematically the idea of Phononic Crystals into the design of pipe/shell structures for sound and vibration reduction [38-44].

![Figure 9. Sketch map of a Bragg-LR periodic pipe/shell structure conveying fluid.](image)

![Figure 10. (a) The FRFs of the Bragg-LR shell/pipe, the three FRF curves a, b, and c is corresponding to the 3 cases of LR oscillator’s ring mass: M, 2M and 3M; (b) and (c) profiles of the pressure distributions for](image)
both the external and internal fluid domains of the periodic shell/pipe. Frequencies (a) 700 Hz and (b) 900 Hz are respectively located in wave pass and stop bands.

Here, as an example, a combined periodic structure of Bragg and LR periodic shells/pipes are addressed, as illustrated in Figure 9. Figure 10(a) shows the frequency response functions (FRFs) of a Bragg-LR periodic fluid-filled pipe; Figure 10 (b) and (c) show the pressure distributions of the periodic shell/pipe for both the external and internal fluid domains. It can be observed that with such a periodic design, both the vibration and the structure-borne sound could be controlled over the band-gap frequency ranges.

7. Acoustic cloak/anti-cloak devices [45, 46]

Work on achieving invisibility of objects to different kinds of waves (electromagnetic, acoustic, biharmonic, etc.) has been the object of increasing attention in recent years. The problem of invisibility, especially to electromagnetic and acoustic waves, is related to protection of various technological objects from detection.

Figure 11. The cylindrical cloak/anti-cloak and its acoustic pressure fields. (a) Sketch of the multilayered cylinder cloak structure; (b) and (c) pressure distribution of two different anti-cloak, respectively. The incident wave coming from the left-hand side is a plane wave at the normalized frequency $k_0a=4.8$, and the surrounding fluid is water, with density $1000 \text{ kg/m}^3$, and velocity of sound $1500 \text{ m/s}$ [45].

Sketch of a multilayered cloak is addressed in Figure 11(a); and the corresponding pressure fields of both the cloak and the anti-cloak are shown in Figure 11(b) and (c) [45]. From these plots, the characteristics of the acoustic cloak / anti-cloak can be seen. The fundamental idea behind achieving an invisibility cloak is the invariance of Maxwell’s equations under a space-deforming transformation if the material properties are altered accordingly. In the construction of an invisibility cloak, the suitable curved coordinate transformation (from a fictitious auxiliary space to the actual physical space) is designed so as to create a “hole”, i.e. a region inaccessible to electromagnetic / acoustic waves, wherein an object can be concealed. However, a perfect cloaking effect can be defeated by adding another kind of transformation medium inside the cloak. Such an effect was accordingly referred to as an “anti-cloak”. An anti-cloak allows the inside object to “see” outside, but to be invisible from outside; whereas a cloak is invisible from outside, but “blind” from inside.
8. Conclusions

In conclusion, we have developed and demonstrated various types of artificial periodic structures for sound and vibration control applications, such as the locally resonant periodic structures for vibration suppression, periodically shunted beams and plates for vibration attenuation, acoustic metamaterials for sound insulation, locally resonant sonic materials for underwater sound absorption, periodic pipes/shells conveying fluid for sound and vibration reduction, and acoustic cloak and anti-cloak devices. Such artificial periodic structures shall provide some new ideas in the field of sound and vibration control.

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