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Investigation of locally resonant absorption and factors affecting the absorption band of a phononic glass

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Abstract We experimentally and theoretically investigated the mechanisms of acoustic absorption in phononic glass to optimize its properties. First, we experimentally studied its locally resonant absorption mechanism. From these results, we attributed its strong sound attenuation to its locally resonant units and its broadband absorption to its networked structure. These experiments also indicated that the porosity and thickness of the phononic glass must be tuned to achieve the best sound absorption at given frequencies. Then, using lumped-mass methods, we studied how the absorption bandgaps of the phononic glass were affected by various factors, including the porosity and the properties of the coating materials. These calculations gave optimal ranges for selecting the porosity, modulus of the coating material, and ratio of the compliant coating to the stiff matrix to achieve absorption bandgaps in the range of 6–30 kHz. This paper provides guidelines for designing phononic glasses with proper structures and component materials to work in specific frequency ranges.

1 Introduction

Recently, locally resonant sonic materials (LRSMs) have attracted much attention for their promise in applications such as acoustic/elastic filters, acoustic mirrors, and sound insulators/absorbers [1–7]. In our previous works, we fabricated networks of locally resonant phononic crystals (LRPCs) to produce a new sound-absorbing material called a "phononic glass" [8–10], which exhibited good sound absorption over a wide frequency range as well as good compressive properties [10]. The bandgaps of these materials, calculated using lumped-mass methods, suggest that their wideband absorption originates from multiple locally resonant modes. However, it has been difficult to identify the absorption mechanisms in this complex composite, challenging our ability to find acoustic-absorption regularity [9].

In LRSMs, locally resonant absorption coincides with viscoelastic deformation [11–18]. The sound-absorption region in LRPCs was first found using the multiple-scattering approach; these results showed that a conversion from longitudinal mode to transverse mode near the locally resonant frequencies effectively enhanced the anechoic performance of these materials [7, 14]. Subsequent reports used finite element methods (FEM) to study the dynamic modes and corresponding sound absorption of localized resonance [17, 18]. The displacement contours calculated in these reports showed that localized resonance caused the absorption peak. Note that these reports studied sonic crystals, in which scattering normally occurred from isolated spherical or ellipsoidal inclusions, and the structure of these LRPCs were radically different from that of phononic glass. In phononic glass, a metal skeleton is substituted for the spherical scattering centers, and the three component materials are connected in a network [10]. The mechanism of locally resonant absorption is more complicated in phononic glass than in LRPCs. Also, while previous reports have studied the impact of defects in phononic glass, it remains unclear how the sound-absorption properties of phononic glass vary with material properties, including

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structural properties such as porosity [9]. More experiments are needed to investigate the mechanism of locally resonant absorption in phononic glass, and more calculations are needed to investigate how acoustic-absorption regularity changes with various factors.

Theoretical calculations of LRPC behavior mainly use multiple-scattering (MS) methods [19, 20], plane-wave-expansion (PWE) methods [21], the finite-difference time-domain (FDTD) methods [22], transfer-matrix methods [23], and lumped-mass methods [24, 25]. Lumped-mass methods are simple and effective for studying the performance of various LRSMs [24, 25]. In previous reports, we studied the mechanisms of broadband absorption in phononic glass using lumped-mass methods and a mass-spring model [9, 10]. In the present paper, we further investigate the mechanism of locally resonant absorption in phononic glass by experiments and then use lumped-mass methods to study the factors that influence the anechoic performance of phononic glass, finding that the onset frequencies of the absorption bands changed with various factors.

2 Experiments

According to the formation mechanisms reported in our previous papers, we fabricate phononic glasses with three kinds of materials, each with a different elastic modulus [8–10]: stiff polyurethane (PU), compliant PU, and aluminum foams with varying porosity. The storage modulus of stiff PU and compliant PU are 30 and 1.3 MPa, respectively. And the density of stiff PU and compliant PU are 1,076 and 898 kg/m^3, respectively. To further confirm the locally resonant absorption mechanism, we prepare composites of the aluminum foam filled with one kind of PU. To investigate the effect of porosity, we fabricate phononic glasses using aluminum foams with porosities of 50, 65, and 80 %. To keep the original configuration invariant, the PU foam is fabricated by etching the aluminum from the phononic glass. To reduce sound reflection from the surface, all samples are coated with stiff PU to match the characteristic impedance of water. Because the tested absorption coefficients have a great relationship with backing materials [26], for consistency, the absorption coefficients are all measured and calculated using a pulse tube system in air back mode at the Institute of Acoustics of Chinese Academy of Sciences under Chinese National Standard GB/T 5266–2006. All samples are fabricated with the same dimensions and a diameter of 56 mm.

3 Experimental results and discussion

The LRSMs were usually composed of three types of materials, forming a stiff/flexible/stiff structure [27]. To further study the locally resonant absorption mechanism, we compare materials by removing one of component materials to break the stiff/flexible/stiff structure. Figure 1 shows the acoustic-absorption coefficients as a function of frequency of the phononic glass and the two-component materials, which are only filled with one kind of PU. The phononic glass exhibits excellent acoustic absorption in the tested frequency range, exhibiting an average absorption coefficient >0.9 for 12–30 kHz. In contrast, neither two-component materials exhibit a sound-absorption coefficient >0.6 at any frequency. The two kinds of two-component materials have similar sound-absorption curves: smooth with small fluctuations. All three materials exhibit the wideband effect; however, the underwater acoustic absorption of the phononic glass is much better than those of the two-component materials over the measured frequency range.

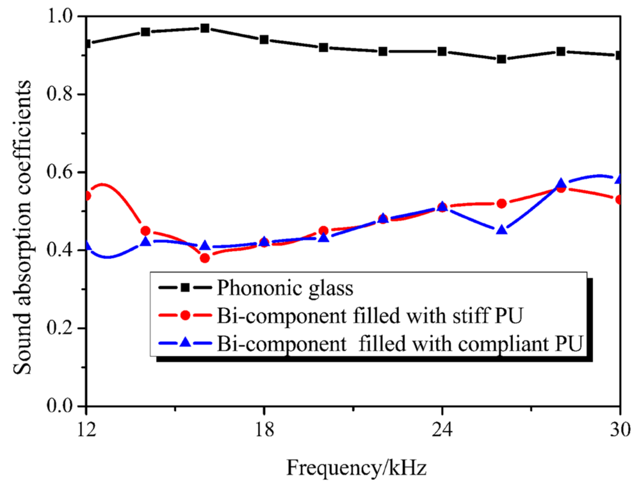

Fig. 1 Underwater absorption coefficients of two-component materials and phononic glasses with porosity of 80 % and thicknesses of 1 cm in 12–30 kHz

These results suggest that LRPC-like units are critical to sound absorption and that locally resonant absorption does exist in phononic glass. In traditional LRSMs, the dynamic modes calculated by FEM suggested that localized resonance caused the absorption peak and that the transition from longitudinal to transverse waves enhanced the energy dissipation [28]. In phononic glass, the stiff/compliant/stiff structure acting as the LRPC units consists of three materials with different elastic moduli, and the mass-spring system provides an effective way to dissipate the sound energy when consider the viscoelastic deformation. Meanwhile, the network structure in phononic glass provides more interfaces between three different materials, enhancing the energy dissipation by increasing the number of effective conversion mode. The two-component materials have only a stiff/compliant or stiff/stiff structure, because they lack one component, meaning that no LRPC-like units exist. Lacking local resonance, dissipation of sound energy in two-component materials only depends on the PU and the mode transitions at interfaces, sharply decreasing sound absorption. In addition, the acoustic-absorption capability of phononic glasses is much better than that of the component materials, as described in previous works [10]. To construct a phononic glass, it is essential to use three kinds of materials with different moduli. The local resonances produced by the stiff/compliant/stiff structure are critical to good sound absorption.

Traditional LRPCs only have two sound-absorbing peaks [17], while a wide absorption band appeared at 12–30 kHz in the phononic glass. The locally resonant absorption mechanism differs between the phononic glass and LRPCs. In phononic glass, because of the multi-sized LRPC units and the cooperative effect from the interpenetrating network, there are many modes of the localized resonance in the phononic glass, with many fewer modes in LRPCs. The sound absorption of the phononic glass in the range of tested frequencies is greatly enhanced by the network of local resonances. In addition, the performance of the two-component materials differs from the two-component phononic crystals: There is only a Bragg gap or subfrequency gap in the two-component phononic crystals [29], where the flat absorption curves of two-component materials cross the tested frequencies. Although the sound absorption decreases sharply in two-component materials, the broadband effect still exists because of their networked structure. Thus, we attribute the strong sound attenuation to analogous LRPC units and the broadband effect to the networked structure.

Considering the calculation and the locally resonant theory, the resonant frequency f in an LRPC is determined by the following equation [30]:

$$f = \frac{1}{\pi}\sqrt{\frac{ES}{ML}} \tag{1}$$

where E is the modulus of elastic coating layers, S is the stressed area of scatterer, L is the thickness of coating layer, and M is the mass of the scatterer. We speculate that the acoustic-absorption peak shifted to the lower frequency with increasing the mass of scatterer in LRPC. Similarly, the same law also applies in phononic glass. Figure 2 shows the acoustic-absorption coefficients of the phononic glass with varying porosity as a function of frequency. As the porosity decreased, the maximum acoustic-absorption coefficients tend to shift to lower frequencies and the acoustic absorption at high frequencies degrades. The mass of the metal part also increases; according to LRPC theory, the decrease in porosity will cause the sound-absorption peak of the phononic glass to shift to lower frequencies. These results also demonstrate that a locally resonant absorption mechanism does exist in phononic glass. Note

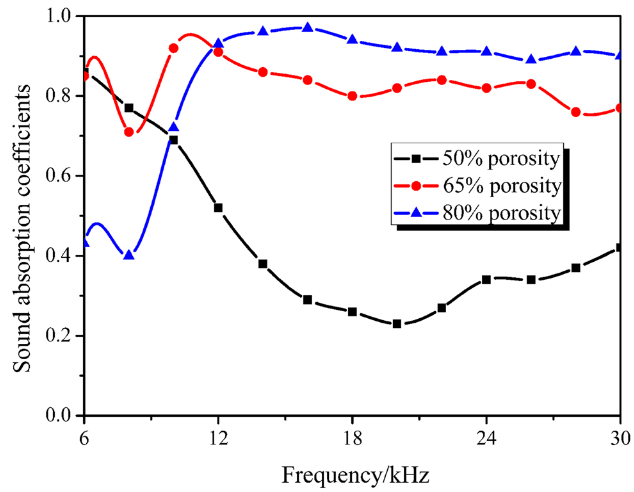

Fig. 2 Underwater absorption coefficients of phononic glasses with different porosities and thicknesses of 1 cm in 6–30 kHz

that the samples with many different porosities (except 50 %) achieve broadband absorption at the measured frequencies. Because of the limitations of the preparation technology used to make the metal skeleton, the samples with higher porosity have more LRPC units in the direction of thickness. The sample with 80 % porosity and a thickness of 1 cm has four or more LRPC units in thickness direction, while the sample with 50 % porosity only has one or two units. More LRPC units in the thickness direction lead to more LRPC modes capable of dissipating energy at different frequencies. Thus, phononic glass with greater porosity can more easily achieve broadband absorption because of cooperation from the interpenetrating network.

This influence of porosity of phononic glass on its acoustic performance is similar to the influence of thickness previously reported [8, 9], where the onset frequencies shifted down as the sample thickness increased. This change with thickness can be explained by local resonance theory. In phononic glass, the whole metal part acts as the scatterer in the LRPC, influencing the location of the onset frequencies. The mass of the metal part increases as the sample thickness increases, tending to shift the onset frequencies to lower values. The effects of porosity and thickness on acoustic performance are unique to phononic glass, suggesting that the network locally resonant absorption mechanism is different from traditional LRPCs. This behavior also indicates that the porosity and thickness of phononic glass must be optimized to achieve the desired sound absorption at given frequencies.

We also investigate the acoustic-absorption coefficients of PU foam (Fig. 3), fabricated by erosion of the metal part of the phononic glass. When the metal part of the phononic glass is removed, its acoustic absorption declines sharply.

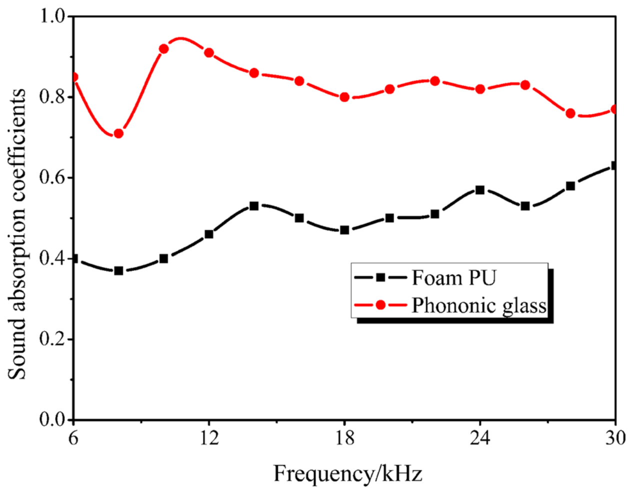

Fig. 3 Underwater absorption coefficients of foam PU and phononic glass with thicknesses of 1 cm in 6–30 kHz

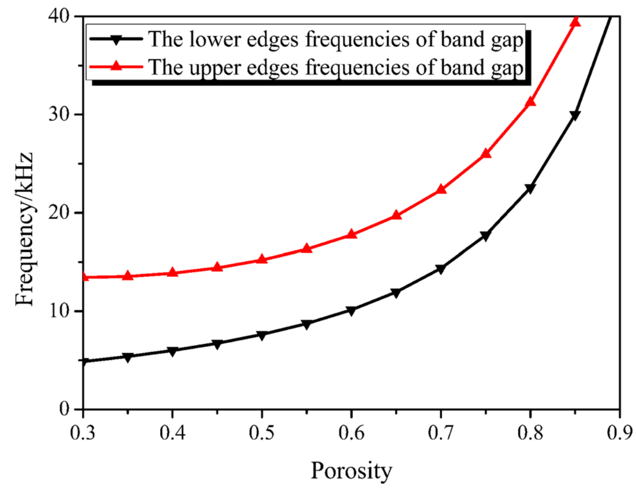

Fig. 4 Bandgap-edge frequency of phononic glass with different porosities and 1:1 ratios of compliant PU to stiff PU

The acoustic-absorption coefficients of the PU foam are only 0.38–0.6 in the tested frequency range; because these samples lack a metal part, they have no LRPC-like units and thus no locally resonant absorption mechanism. These results demonstrate that the metal foam is critical to the excellent acoustic absorption of phononic glass.

4 Calculation results and discussion

To optimize the properties of the phononic glass, we calculate how various factors affect its acoustic performance by finding its resonant bandgaps, which can be used to estimate the frequencies at which it could strongly absorb sound energy. Lumped-mass methods are widely used to find approximate solutions to this problem, simplifying these calculations [24, 25]. In these methods, the mass of the continuous material converges at infinite nodal points; in other words, it transforms the continuous-system problem into a discrete problem. It is difficult to calculate the bandgap of phononic glass using common methods, except for the lumped-mass method, because of its interpenetrating network structure [10].

We attribute the excellent sound absorption of the phononic glass to the multiple LRPC units and the cooperative effect of the interpenetrating network. To study this cooperative effect, we introduced a suppositional spring to investigate the impact of defects and the broadband effect, as in previous works [9, 10]. In the present paper, we focus on the LRPC units to study how various factors affect the absorption bandgaps. For convenience of calculation, we only consider one LRPC unit. The phononic glass has inverse LRPC-like units, each of which can be abstracted as a cylindrical core with two coaxial coating layers [10]. When considering one unit, it can be further simplified by the spring-mass model, where continuous materials with great inertia and stiffness such as stiff PU and metal are approximated as lumped masses, while the continuous materials with poor inertia and stiffness such as complaint PU are approximated as springs. We model the entire system as two vibration blocks with masses m_1 and m_2 connected by a virtual spring with a stiffness coefficient k; these variables can be calculated using an equation similar to that previously reported [9, 10].

Similar to the behavior of traditional LRPCs, the vibration mode of the lower bandgap edge is the vibration of a metal ring considered as one particle; a fixed delay in the phases of the vibrations between adjacent lattices is kept to maintain the dynamic balance of the whole system [25, 26]. In contrast, the vibration mode of the upper bandgap edge is the vibration of the host media with the reversed phase of the metal ring. Thus, the frequencies of the bandgap edges can be evaluated with.

$$\omega_1 = \sqrt{\frac{k}{m_2}} \tag{2}$$

$$\omega_2 = \sqrt{\frac{k(m_1 + m_2)}{m_1 m_2}} \tag{3}$$

Using Eqs. (2 and 3), the bandgaps of phononic glass can be obtained and the sound-absorption performance can be evaluated.

The metal foam is a crucial constituent material to enhance the acoustic performance of phononic glass. The porosity is also an important structural parameter and relates directly to the mass of the blocks. When investigating the effect of porosity, the radius of the metal ring r_3 as well as the outer and inner radii r_2 and r_1 can all vary.

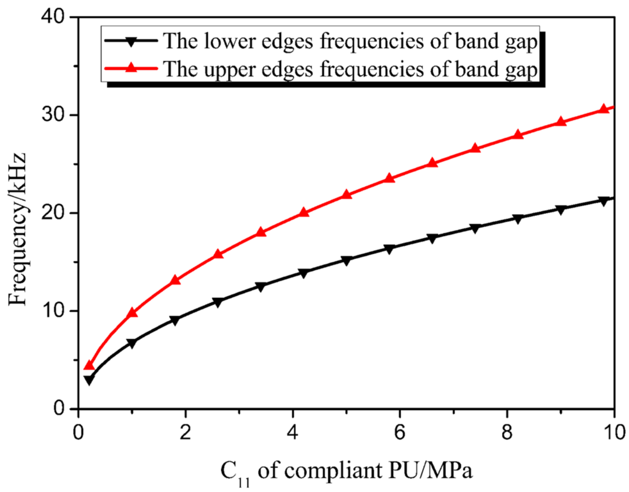

Fig. 5 Bandgap-edge frequency of phononic glass as a function of the C_{11} of the compliant PU to stiff PU

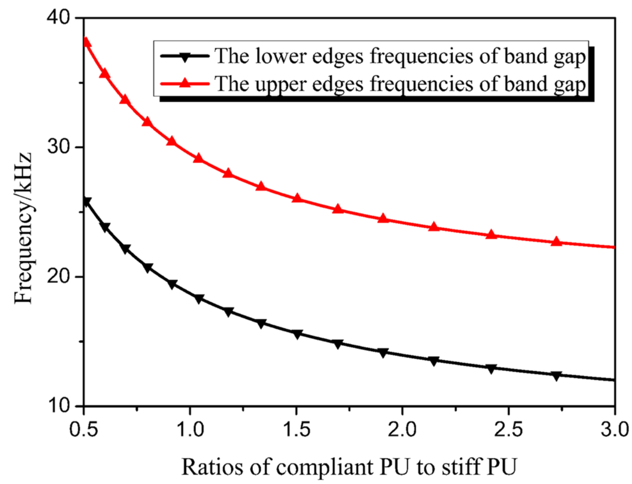

Fig. 6 Bandgap-edge frequency of phononic glass with different ratios of compliant PU to stiff PU

The ratio of r_1 and r_2 is fixed to maintain the ratio of compliant PU to stiff PU. Using Eqs. (2) and (3), the bandgap of the phononic glass as a function of porosity can be obtained; these results are shown in Fig. 4, revealing that, as the porosity increases, both bandgap-edge frequencies increases and the bandwidth narrows. As porosity increases, the mass of the oscillator decreases, tending to shift the bandgap-edge frequencies toward lower values, according to Eqs. (2 and 3). We speculate that the acoustic-absorption peak shifted to higher frequencies with increasing porosity. The calculated results agree well with experiments, meaning these models and methods are appropriate to forecast the acoustic-absorption performance of phononic glass.

In locally resonant materials, the coating layer serves as a spring, and its elastic modulus determines the stiffness k of the spring. According to Eqs. (2 and 3), the masses of the blocks and the stiffness k determine the edge position of the resonant frequency. When investigating the effect of the modulus of the coating materials, we assess phononic glass with 80 % porosity and a 1:1 ratio of compliant PU to stiff PU. Figure 5 shows how the lower- and upper band-gap-edge frequencies varies with the modulus of the compliant PU, revealing that, as C_{11} increases, both the lower- and upper-edge frequencies increase and the bandwidth broadens. As the modulus of the compliant PU increases, the stiffness k increases and the mass of the oscillator remains the same, leading the bandgap-edge frequencies to tend toward higher values. We speculate that the acoustic-absorption peak shifted to higher frequency as the modulus of the compliant PU increased. The trend of how the acoustic-absorption bandgaps in phononic glass change with the modulus of the coating material is similar to that in traditional LRSMs.

The thickness of the coating material influences the stiffness k and the masses of the blocks, making it crucial to acoustic performance [30]. Keeping the thickness and porosity of phononic glass constant, we study how the ratio of compliant PU to stiff PU affects the bandgap-edge frequencies. When investigating the effect of thickness of the coating material, we fix the radii of the metal ring r_3 and r_2 to keep the porosity at 80 %, and vary the radius of the stiff PU. Using Eqs. (2 and 3), we obtain the bandgap of the phononic glass as a function of the ratio of compliant PU to stiff PU, as shown in Fig. 6.

Both the lower- and upper-edge bandgap frequencies decrease as the ratio decreases, with the bandwidth slightly broadening. As the thickness of the coating materials increases, the stiffness decreases and the mass of oscillator increases, causing the bandgap-edge frequencies to tend to decrease. We speculate that the acoustic-absorption peak shifts to lower frequencies as the compliant PU content increases.

These results indicate that the absorption bandgap-edge frequency tends to decrease as the porosity of metal foam decreases, as the modulus of compliant PU decreases, and as the ratio of the compliant PU increases. Considering low-frequency and broadband absorption, the porosity should be 60–70 % to achieve broadband sound absorption in the frequency range of 6–30 kHz. When considering viscoelasticity, decreasing the modulus of the coating materials is advantageous for low-frequency sound absorption, so the modulus should usually be selected as 1–2 MPa to fit the tested frequencies. According to our calculations and matching to the impendence of water, the ratio of compliant PU to stiff PU should be 1–2 for a frequency range of 6–30 kHz.

5 Conclusion

In summary, we further study the mechanisms locally resonant absorption in phononic glass by experiments and use lumped-mass methods to study how the absorption bandgaps are affected by various factors, including the porosity of aluminum foam and the properties of the coating materials. The experimental results further verify the locally resonant mechanism in phononic glass; they suggest that the strong sound attenuation is caused by analogous LRPC units, while the broadband effect is caused by the network structure. The calculations give selection ranges for the porosity, modulus of the coating material, and ratios of compliant PU to stiff PU. This work provides guidelines for designing phononic glass with proper structure to work in a specific frequency range and to optimize its properties.

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