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Wide-band underwater acoustic absorption based on locally resonant unit and interpenetrating network structure*

Jiang Heng(姜 恒)[a)b)], Wang Yu-Ren(王育人)[b)†], Zhang Mi-Lin(张密林)[a)], Hu Yan-Ping(胡燕萍)[b)], Lan Ding(蓝 鼎)[b)], Wu Qun-Li(吴群力)[c)], and Lu Huan-Tong(逯还通)[c)]

[a)] *Key Laboratory of Superlight Materials and Surface Technology, Ministry of Education, Harbin Engineering University, Harbin* 150001, *China*

[b)] *Key Laboratory of Microgravity Science, Institute of Mechanics, Chinese Academy of Sciences, Beijing* 100190, *China*

[c)] *BSWA Technology Co., Ltd., Beijing* 100029, *China*

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The interpenetrating network structure provides an interesting avenue to novel materials. Locally resonant phononic crystal (LRPC) exhibits excellent sound attenuation performance based on the periodical arrangement of sound wave scatters. Combining the LRPC concept and interpenetrating network glassy structure, this paper has developed a new material which can achieve a wide band underwater strong acoustic absorption. Underwater absorption coefficients of different samples were measured by the pulse tube. Measurement results show that the new material possesses excellent underwater acoustic effects in a wide frequency range. Moreover, in order to investigate impacts of locally resonant units, some defects are introduced into the sample. The experimental result and the theoretical calculation both show that locally resonant units being connected to a network structure play an important role in achieving a wide band strong acoustic absorption.

Keywords: underwater acoustic absorption, wide frequency, locally resonant unit, interpenetrating networks

PACC: 6265, 8160H, 4330

1. Introduction

Acoustics is an interdisciplinary science, having extensive applications in areas such as industrial manufacture, daily life and social activities, etc. In the past decade, extensive efforts have been devoted to the locally resonant phononic crystal (LRPC) with better acoustic qualities and a unique structure.[1−13] In the LRPC, the sound band gap can be generated at a certain frequency. The LRPC material is produced by periodically embedding the metallic balls with the soft polymer coating layer into a hard polymer matrix, in general. The elastic modulus ratio among the metallic ball, soft polymer coating layer and hard polymer matrix plays an important role in adjusting the LRPC property. Furthermore, theoretical calculation indicates that enhanced sound absorption can be obtained when considering viscoelastic deformation.[14,15] A robust underwater acoustic absorbing material is urgently needed for its important applications in both military and commercial uses, such as sonar evasion by stealthy coating and underwater acoustic communication system.[16−22] In this paper, viscoelastic LRPC units are utilized as building blocks of a new underwater acoustic absorbing material to attenuate the acoustic wave strength in water, while these LRPC units are physically connected by interpenetrating networks of polymers and metallic foam. It should be noticed that the composite materials owning an interpenetrating network structure are usually found to exhibit unexpected merit due to the cooperative interaction among their component materials, such as bones and muscles in animals and the trunks and limbs in plants. The same effect is expected to work efficiently in sound energy attenuation due to the enhancing multiple scattering of sound in the network structure.

The most striking difference between traditional LRPC and the new material is that the resonant units in the LRPC have the same size and distribute discretely in the polymer matrix, while units in the new

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†Corresponding author. E-mail: yurenwang@imech.ac.cn

material have a wide size distribution and complicated geometry in shape. Contrary to the aim of producing a narrow band gap in phononic crystal at some frequency, theacoustic absorbing material usually needs to be designed to have a strong absorbance in a wide range of frequencies. It is reasonable to deduce that a broad size distribution and multiple morphologies of resonant units are helpful for the realization of the wide band acoustic absorption. In this paper, we report the strong underwater acoustic absorption of a new composite material. The study is focused on the sound attenuation mechanism in this new material. It should be noticed that these resonant units are different from the traditional LRPC building blocks both in shape and in constitution. Therefore, the acoustic absorbing effect should be carefully investigated.

2. Experiments

According to the LRPC formation mechanism, three kinds of materials with different elastic modulus were employed to produce the new material. They were aluminum foam, soft polyurethane (PU) and hard polyurethane (PU). Soft and hard PU were synthesized by referring to the method reported in the literatures.[23,24] The aluminum foam (the average pore size had 4 mm in diameter and the porosity was 81%, i.e., the relative density was about 0.19) was used in the experiments. In order to reduce the sound reflection from the surface of the new material, hard PU of characteristic impedance matching with water was chosen as viscoelastic coating. A schematic of synthesis route and structure morphology is shown and described in Fig. 1(a) and its caption. Volume ratio of hard PU, soft PU and aluminum is 2:2:1. Underwater acoustic absorption coefficients were tested by the pulse tube in the air back mode in the Institute of Acoustics, the Chinese Academy of Sciences. The scanning electron microscopy (SEM) images were obtained by using a HITACH-S570 scanning electron microscope.

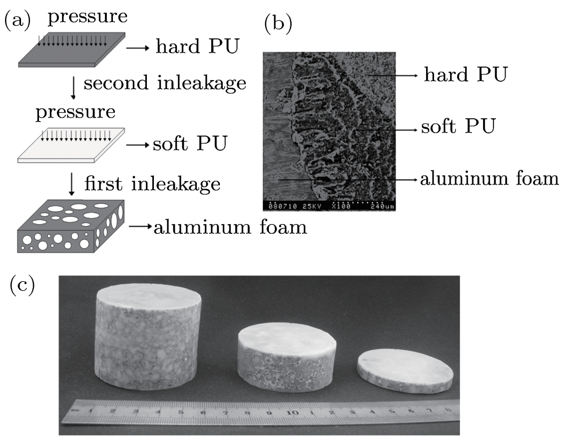

Fig. 1. Schematic diagram of synthesis and structure of the new material. (a) Synthesis scheme. First, the uncured soft PU was infiltrated into the aluminum foam which induced formation of a thin coating layer with thickness of about 0.3–0.6 mm on the interior wall of porous aluminum. After totally drying, the uncured hard PU was filled into soft PU coated aluminum foam. (b) The SEM image shows clearly the three-layer structure of building block inside the material. (c) The optical photo shows that samples of different thickness are homogeneous solid materials.

Figure 1(b) shows typical hard-soft-hard multilayer structure existing in the material. We have fabricated samples of different thicknesses, as shown in Fig. 1(c).

In order to investigate impact of locally resonant units on underwater acoustic absorbance, we have artificially introduced some defects into the sample of 2-cm thickness shown in Fig. 2(b), while figure 2(a) shows cross section of the defect-free sample of 0.5-cm thickness as reference.

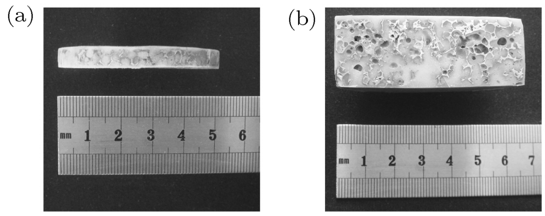

Fig. 2. Optical images of defect-free sample of 0.5 cm thickness and defective sample of 2-cm thickness. (a) The new material of 0.5-cm thickness has internal random interpenetrating network phase microstructure and multiscale inverse locally resonant units. (b) When defects are artificially introduced, locally resonant units of sample are destroyed.

3. Results and discussion

Figure 3 illustrates the changes of sound absorption coefficients for three samples of different thickness as a function of frequency. It can be seen that the line profiles of sound absorption curves for defect-free samples are different from that for the defective sample. For defect-free samples, strong absorptions can be achieved in a wide frequency range, started from some onset frequencies. However, there exists a broad absorption peak in the absorption curve of the defective sample in a low frequency region, after which the sound absorption coefficient decreases gradually with the increase of frequency. The phenomenon that the onset frequencies move to the low frequency region with the increase of sample thickness has been found and studied in previous literatures.[25,26] It can be readily understood that the resonant absorbing frequency changes with the sample thickness. However, the big difference in line profiles for defect-free and defective samples cannot be interpreted by the conventional sound absorption theory.

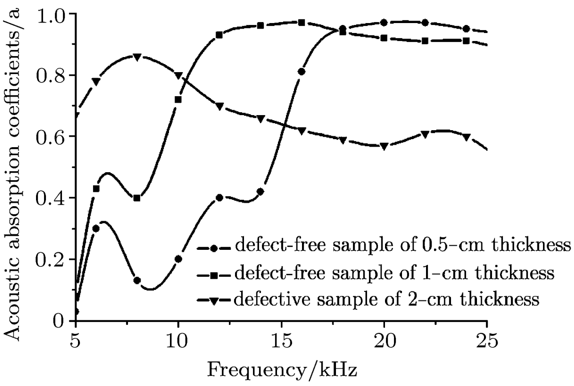

Fig. 3. Underwater absorption coefficients of different samples in 5∼25 kHz. Thicknesses of three samples were 0.5 cm, 1 cm, and 2 cm. Acoustic absorbing coefficients over 0.9 of defect-free sample of 0.5-cm thickness can be clearly seen in the range from 18 kHz to 25 kHz and defect-free sample of 1-cm thickness owns sound absorption coefficients over 0.9 from 12 kHz to 25 kHz. The sample of 2-cm thickness which is artificially introduced defects did not achieve sound absorbing coefficients over 0.9 in 5∼25 kHz.

The LRPC can exhibit an effectively negative elastic constant at a certain frequency due to the existence of sound resonators dispersed in the matrix. The resonant reflection originates from elastic modulus matching among component materials and the geometrical shape of the sound resonator. Therefore, the construction of the sound resonator units is essential for the achievement of phononic crystal property. However, the locally resonant property of the LRPC is independent of periodic arrangement of resonators in the matrix.[1] The new material presented in this paper possesses inverse resonator structure units similar to those in the LRPC, as shown in Fig. 4(a) and illustrated schematically in Fig. 4(b). Hard PU–soft PU–Al laminated structure is constructed in the new material which might guarantee the sound resonant feature.

If viscoelastic scattering in materials is considered, the maximum viscoelastic energy dissipation is generated at a locally resonant frequency.[14,15] It is reasonable to deduce that the strong sound absorbance partially results from this energy dissipation mechanism, even if not totally. As a consequence, the resonant band gaps generateed by the LRPC units can be used to estimate the frequency at which strong absorbance could occur. From a geometrical point of view, resonators in the new material have a broad size distribution and various shapes. This induces the anomalous wide frequency acoustic absorption due to the existence of many overlapped absorption band gaps and affects acoustic wave propagation and attenuation in the synthesized material. To attest to the validity of the hypothesis on the enhanced sound absorption from LRPC units in experiment, we destroy some LRPC units in the thick sample and obtained the so-called defective sample, as shown in Fig. 4(a) and illustrated schematically in Fig. 4(d). Figure 3 clearly shows that the sound absorption ability degrades with the frequency for the defective sample even if the sample thickness is larger than the defect-free samples. It indicates that LRPC units constructed in the new material play an important role in the enhanced sound absorption.

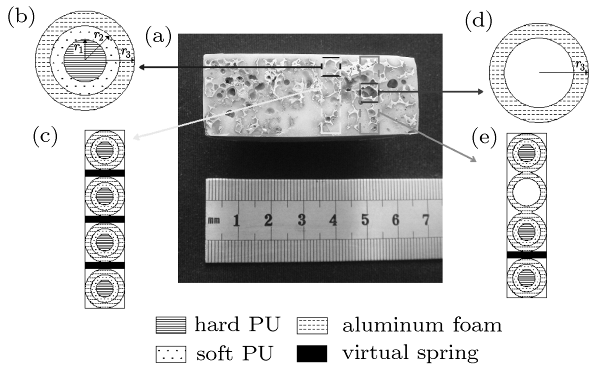

Fig. 4. The model simplification process of the new material. (a) The sample of 2-cm thickness has internal random interpenetrating network phase microstructure and obvious defects. (b) A resonator of the new material could be approximately described as coaxial cylindrical inclusions with two coaxial coating layers. For convenience of calculation, the value of radius of coaxial cylindrical inclusions has been defined as $r_1 = 1.5$ mm, $r_2 = 2.2$ mm and $r_3 = 2.5$ mm in light of volume ratio of three components and the average size of different units. (c) Along the normal incidence direction of sound wave, the sample of 2-cm thickness can be predigested as four vertical units connected by virtual spring. (d) A defect unit of the new material could be approximately described as aluminum cylinder. (e) When considering defects condition, the sample of 2-cm thickness could only be predigested as defect model.

To elucidate the effect of newly constructed LRPC units in physics, the lumped-mass method[27−32] is employed to estimate possible sound resonant band gaps occurred in defect-free and defective structures. The fully elastic scattering condition is used for the simplification of calculations. It should be kept in mind that the calculated band gaps can be considered to correspond to resonant absorbance frequencies if viscoelastic scattering was taken into account. Though this method is relatively simple and rough, it can distinguish the difference between the absorption of defect-free samples and that of defective sample.

In our calculation, an ideal LRPC resonant absorbing unit in the new material can be predigested as a hard-PU cylinder with two coaxial layers (inner soft PU layer and outer aluminum layer), as shown in Fig. 4(b). The radius of the cylinder and the coating layers are determined according to the volume fractions of three components. In another aspect, we have introduced the defective LRPC unit to simulate the damage of the sample. A defective LRPC unit can be abstracted as a hollow aluminum cylinder pipe with diameter $r_3 = 2.5$ mm.

According to lumped-mass method,[27−32] an LRPC unit can be represented by the spring-mass model, as shown in Fig. 5(a). Two vibration blocks with masses m_1 and m_2 are connected by a virtual spring with stiffness coefficient k. Basically speaking, m_1 is the mass of central hard-PU core and m_2 is the mass of outer aluminum shell. The main effect of inner soft-PU layer is to provide kind of pliable connection between the hard-PU core and the Al shell. Therefore, the inner soft-PU layer is dealt with as a virtual spring in the calculation. However, its mass has to be assigned to the surrounding medium. The mass of a part in Fig. 5(a) is added into mass m_1 in the calculation. The treatment for the b part is a little bit cumbersome. Appropriate fraction of b part mass is added into the mass of outer Al shell m_2, while the rest b part mass is assigned to the hard-PU core m_1.[32] The masses m_1 and m_2 can be calculated through the following formulas:

$$m_1 = \rho_{\mathrm{H-PU}} \cdot \pi r_1^2 + m_b \cdot \frac{1}{1 + \dfrac{m_b + \rho_{\mathrm{H-PU}} \cdot \pi r_1^2}{\rho_{\mathrm{S-PU}} \cdot \pi\left(r_2^2 - r_1^2\right) + \rho_{\mathrm{Al}} \cdot \pi\left(r_3^2 - r_2^2\right)}}, \tag{1}$$

$$m_2 = \rho_{\mathrm{Al}} \cdot \pi\left(r_3^2 - r_2^2\right) + m_a + m_b \cdot \frac{\dfrac{m_b + \rho_{\mathrm{H-PU}} \cdot \pi r_1^2}{\rho_{\mathrm{S-PU}} \cdot \pi\left(r_2^2 - r_1^2\right) + \rho_{\mathrm{Al}} \cdot \pi\left(r_3^2 - r_2^2\right)}}{1 + \dfrac{m_b + \rho_{\mathrm{H-PU}} \cdot \pi r_1^2}{\rho_{\mathrm{S-PU}} \cdot \pi\left(r_2^2 - r_1^2\right) + \rho_{\mathrm{Al}} \cdot \pi\left(r_3^2 - r_2^2\right)}}, \tag{2}$$

where m_a and m_b are masses of a part and b part. They can be calculated through the following formulas:

$$m_a = 2\rho_{\mathrm{S-PU}} \int_{r_1}^{r_2} 2\sqrt{r_2^2 - x^2}\,\mathrm{d}x = 2\rho_{\mathrm{S-PU}}\left[\arccos\left(\frac{r_1}{r_2}\right) \cdot r_2^2 - r_1\sqrt{r_2^2 - r_1^2}\right], \tag{3}$$

$$m_b = \rho_{\mathrm{S-PU}} \cdot \pi\left(r_2^2 - r_1^2\right) - m_a, \tag{4}$$

where $\rho_{\mathrm{Al}} = 2700$ kg/m^3, $\rho_{\mathrm{H-PU}} = 1076$ kg/m^3, $\rho_{\mathrm{S-PU}} = 898$ kg/m^3.

According to lumped-mass approach,[32] the stiffness k depends not only on the elastic modulus of soft PU layer, but also on the geometrical shape of b part of soft PU layer. In terms of physics, only the mass of b part (shown in Fig. 5(a)) took part in the resonant reflection. Therefore, the stiffness k can be calculated through the following formulae:

$$k = 4C_{11}\int_0^{r_1} \frac{\mathrm{d}x}{\sqrt{r_2^2 - x^2} - \sqrt{r_1^2 - x^2}} = 2C_{11} \cdot \left[\frac{r_1}{\sqrt{r_2^2 - r_1^2}} + \frac{\dfrac{\pi r_1^2}{2} + r_2^2 \arcsin\left(\dfrac{r_1}{r_2}\right)}{r_2^2 - r_1^2}\right], \tag{5}$$

$$C_{11} = \lambda + 2\mu, \tag{6}$$

where λ and μ are Lame' constants of soft PU layer and their values are taken as 6.2×10^6 Pa and 6.9×10^5 Pa, respectively. The calculated vibration frequency spectra are shown in the right panel of Fig. 5(a). The grey hatched area indicated the phononic band gap which is induced by the LRPC unit. It can be seen that the band gap just can cover a narrow frequency range from 15 kHz to 20 kHz. This is a natural result because only vibration mode from individual LRPC unit is considered in the calculation. In fact, strong connections among LRPC units exist in our samples because the interpenetrating network structure is the main feature in the synthesized material. Neglecting the influence of these physical connections on the resonant vibration mode in the calculation is unreasonable. To estimate the influence from inter-LRPC unit connections, we assume that LRPC units are also linked by the virtual springs of stiffness k in the incident acoustic wave direction. For the normal incident sound wave, the sample of thickness 2 cm contains four LRPC units in the thickness direction, as shown in the left panel of Figs. 5(b) and 4(c). The central panel of Fig. 5(b) shows the corresponding mass-spring model which contains five mass blocks and four virtual springs. The topmost mass block is assigned 4 times mass of m_1 under the consideration that the central hard PU cores are rigidly connected and form a hard PU network matrix in the sample. Therefore, a simple linear superposition for the core mass m_1 is used in the calculation.

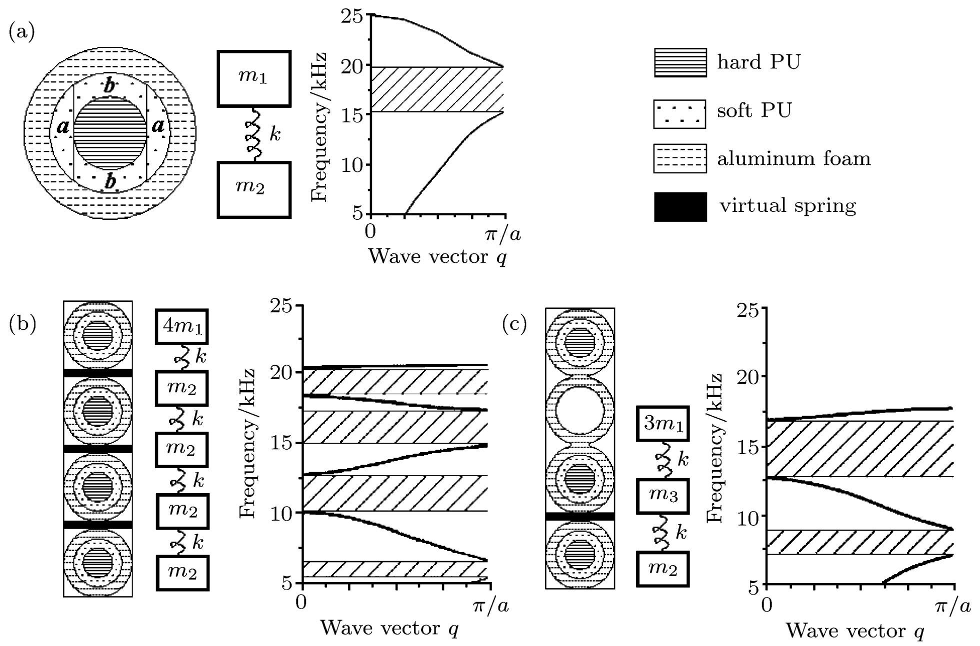

Fig. 5. Schematic diagram of different vibration models and spectral characteristics. (a) Vibration mode of a unit can be simplified as double-oscillator model because it is similar to that of vibration mode of LRPC. Soft PU of every simplification unit may be subdivided into 2 parts (a and b). (b) Taking no account of defect condition, four vertical units connected by virtual spring have relevant four band gaps under full elastic scattering condition. (c) When considering defects condition, four vertical units only have relevant two band gaps under full elastic scattering condition.

Here, the same virtual spring as that in the calculation of an individual LRPC unit vibration mode is also employed to estimate the cooperative vibration among LRPC units. This is due to the consideration that the soft PU layer is uniformly coated on the aluminum skeleton in the sample and forms a soft PU network structure. Therefore, the similar soft PU layer connects the LRPC units as it works in the interior of an individual LRPC unit. Calculated vibration spectra are shown in Fig. 5(b). An obvious character of spectra is that multiple resonant band gaps appeared and covered different frequency ranges instead of a single band gap in Fig. 5(a). Spectral feature implies that the resonant sound reflection would happen in a more wide frequency range if the connections between individual LRPC units are taken into account. It should be noticed that the above calculation is made in the hypothesis of fully elastic sound scattering. As mentioned in the introduction part, LRPC unit will exhibit strong resonant absorption in the band gap frequency region if the viscoelastic scattering is considered.[14,15] From Fig. 5(b) it can deduce that interpenetrating network structures in the present samples produce strong connections among LRPC units and resulted in a broad strong absorption in the acoustic absorption curve shown in Fig. 3. Moreover, this kind of strong connection chain will be broken down if an LRPC unit in the material is damaged.

One of four LRPC units in Figs. 4(c) and 5(b) is changed to a damaged unit in the calculation. In the damaged unit, we assume that only Al wall is preserved and the linkage to the neighbouring LRPC units is totally broken down due to the lost of soft PU layer connection. In Figs. 4(e) and 5(c), the arrangement of damaged unit and the other LRPC units is illustrated. In the arrangement, the system can be described as a large lock with the mass of $3m_1$ connecting to two small blocks with the mass of m_3. Therefore, the stiffness m_3 can be calculated through the following formula:

$$m_3 = 3m_{\mathrm{Al}} + 2\left(m_a + m_b \frac{\dfrac{m_b + \rho_{\mathrm{H-PU}} \cdot \pi r_1^2}{\rho_{\mathrm{S-PU}} \cdot \pi\,(r_2^2 - r_1^2) + \rho_{\mathrm{Al}} \cdot \pi\,(r_3^2 - r_2^2)}}{1 + \dfrac{m_b + \rho_{\mathrm{H-PU}} \cdot \pi r_1^2}{\rho_{\mathrm{S-PU}} \cdot \pi\,(r_2^2 - r_1^2) + \rho_{\mathrm{Al}} \cdot \pi\,(r_3^2 - r_2^2)}}\right). \tag{7}$$

Through two springs of stiffness k the corresponding vibration spectrum is shown in the right panel of Fig. 5(c). It can be seen that only two band gaps can be obtained. This calculated result means that the possible resonant absorption range is greatly decreased even if just one LRPC unit is damaged. In experiment, we found that the sound absorption capability for the artificially damaged sample goes down dramatically with the increase of frequency shown in Fig. 3. This experimental result is consistent with the above calculation. It indicates that well linkage between LRPC units is very important for the wide band acoustic absorption feature.

4. Concluding remarks

Based on resonator units of the LRPC and the interpenetrating network structure, we have developed a new material that can achieve a wide band strong acoustic absorption. The experimental result and the theoretical calculation show that locally resonant units being connected to a network structure plays an important role in achieving a wide band strong acoustic absorption. The present concept of material design can also be extended to make other functional materials.

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