Hindawi
Shock and Vibration
Volume 2024, Article ID 3820651, 16 pages
https://doi.org/10.1155/2024/3820651

Research Article

Study on Sound Absorption Properties of Polyvinyl Chloride (PVC) Film Multicavity Structure Materials

Tingying Zhang, Jiyang Zhang, Pengxuan Zheng, Hong Hou, and Ying Xu

School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, Shaanxi, China

Correspondence should be addressed to Hong Hou; houhong@nwpu.edu.cn and Ying Xu; xuying@nwpu.edu.cn

Received 3 November 2023; Revised 23 January 2024; Accepted 20 February 2024; Published 2 April 2024

Academic Editor: Arcanjo Lenzi

Since the development of industry, sound absorption and noise reduction have gradually become an urgent problem to be solved. Lightweight polymer film materials are very effective in response to sound waves, and sound waves can easily cause vibration of the film, which can convert sound energy into vibration and film friction to achieve sound absorption. The application conditions of the film material are very harsh, that is, a support body is required to fix the film and the film needs to be tensioned. The film is very thin and easy to damage. The idea of this research is to transform the film into a bubble structure and use a large number of film bubbles to form a cavity structure material. As a unit of the sound absorption structure, bubbles can avoid damage to the film. In this paper, commercial polyvinyl chloride film bubble materials are used to prepare two kinds of film multicavity structure materials, and the sound absorption performance of this film multicavity structure material is studied. The research results show that this film multicavity structure material has very excellent broadband sound absorption performance, which changes the narrow band sound absorption properties of the usual film single cavity. The average sound absorption coefficient can reach 0.84 in frequency range from 500 Hz to 6400 Hz. This structural material has a single peak sound absorption curve at the middle and low frequency bands, which is the characteristic of resonance sound absorption. And at the middle and high frequency bands, it exhibits the characteristics of broadband sound absorption. The film multicavity structure material has both cavity sound absorption and broadband sound absorption characteristics.

1. Introduction

The increasing noise pollution has significantly influenced people's lives since the industrial evolution, ranking the second among all environmental pollution [1–4]. Industrial noise and social life noise will affect human hearing and psychology. At the same time, high intensity noise will cause the aging of mechanical equipment and cause harm to buildings [5–7]. Therefore, sound absorption and noise reduction have gradually become an urgent problem to be solved [8, 9].

During the past few decades, two methods have been widely investigated to alleviate noise pollution: passive and active noise control [10, 11]. Passive noise control indicates reducing noise by using sound absorption materials and structures [12, 13]. Sound absorption materials and structures mainly include porous sound absorption materials [14–16] (i.e., foam plastics, metal foams, and fiber porous materials) and resonance sound-absorbing materials (i.e., microperforated plate sound absorption materials [17, 18], membrane sound-absorbing materials [19, 20], Helmholtz resonance sound absorption structures [21, 22], and film cavity sound absorption structures). Porous sound absorption materials are composed of a large number of pores, cracks, or cavities, allowing sound waves to enter the material [23, 24]. The sound energy is dissipated by the heat loss caused by the friction between air molecules and the pore wall, and the viscosity of the airflow in the material causes the viscosity loss, the sound energy can be greatly reduced, and the porous material exhibits broadband sound absorption at 1000–6000 Hz [25–27]. The resonant sound absorption material is mainly a cavity resonance structure, and the sound absorption frequency band is narrow. When the sound wave propagates to the surface of the material, the air inside the material vibrates with the vibration of the sound wave. When the frequency of the incident sound wave is close to the natural frequency of the structure, the air in the cavity vibrates violently and resonates [28–30]. In the resonant sound absorption material, the film cavity structure shows the advantages of light weight, low cost, and simple ways of manufacturing.

Under the excitation of sound, the film causes vibration and absorbs sound waves. The sound absorption of the film cavity structure is affected by the film surface density and cavity depth [31]. However, this structure is unlikely to achieve broadband absorption as only a single film cavity structure is applied. Thus, many recent studies have been carried on in order to achieve broadband sound absorption by the film cavity structure, such as film with mass structure [32, 33], film with cavity structure [34, 35], and honeycomb film metamaterial structure [36]. Acoustic metamaterials composed of film and mass block were used to absorb low-frequency sound waves [37–40], and the sound absorption coefficient at 100–1000 Hz can reach more than 0.6 [41–44]. The finite element method was used to analyze the vibration mode of this structure, and the sound absorption principle was explained [45, 46]. The influence of the geometrical and material factors of the structure on the propagation loss was investigated [47, 48]. By changing the position and quantity of the masses and the shape, density, and prestress of the film structure, the position and bandwidth of the sound wave transmission peak can be effectively controlled, improving the sound wave absorption capacity [49–51]. At the same time, the sound insulation performance of this structure was investigated, the finite element simulation results showed that this structure can achieve effective sound insulation in the 0–300 Hz frequency band, and the sound insulation can reach 24 dB at 157 Hz [52]. Langfeldt proposed that the peak value of sound insulation at anti-resonance was more than the corresponding mass-law 25 dB [53, 54]. And a theoretical analysis model using point coupling analysis method is proposed to analyze the film with mass structure, and a relationship is obtained, indicating that the sum of the incoming acoustic wave (complex number) pressure amplitudes (averaged over the membrane area) must be equal to the outgoing waves. By using this relationship, and without considering any details of the wave solution, it was shown that the maximum achievable absorption for single side incidence is 50%, while the maximum absorption for back-reflecting surfaces is up to 100% [55, 56]. The acoustic properties of the film with cavity structure could be adjusted by compressing the air between two films. The study results showed that the sound absorption bandwidth of double layer film structures with cavities is 400 Hz higher than that of single layer film structures [57, 58]. Adhering a film to the micro-perforated plate was also proposed. The film had a significant influence on the acoustic impedance. A higher absorption peak than a single-layer micro-perforated panel can be achieved by adjusting the size of the film cells, increasing from 0.76 to 0.97 [59]. By comparing and analyzing the acoustic performance of honeycomb metamaterials with and without film, the results showed that the acoustic performance of the film structure was greater at low frequencies and the sound insulation at 500 Hz–2500 Hz was greater than that of metamaterials without film. The frequency position of the acoustic reflection peak can be effectively controlled by changing the density parameters and structural parameters of the film [60, 61]. A bubble structure of locally resonant acoustic metamaterial that can reach the transmission peak at 1480 Hz was designed [62]. And a theoretical model to predict the resonant behavior of bubble-based metamaterials was developed. An analytical expression for resonant frequencies of bubble meta-screens using self-consistent approximation method [63].

In summary, the study of film materials in sound absorption or sound insulation mainly uses skeletons or supports to form a film cavity structure recently. Due to the small surface density of the film, it is easy to cause vibration and change the acoustic performance of the film structure. The main research results are that the good narrow frequency band acoustic performance can be found in medium and low frequencies.

The application conditions of the film material are very harsh, that is, a support body is required to fix the film, and the film needs to be tensioned. Because the film is very thin and easy to damage, it is difficult to apply the film to noise control in practice. The idea of this research is to transform the film into a small structure, such as a bubble structure, and use a large number of film bubbles to form a cavity structure material. The advantage is that the film can be flexibly used for structural design after the film is transformed into a bubble structure. As a unit of the sound absorption structure, bubbles can avoid damage to the film. Even if it is damaged, it is a small number of bubbles that will not affect the structure of the overall film cavity material.

Commercial packaging polyvinyl chloride (PVC) film bubbles laid the foundation for this research, which is used for packaging and reducing vibration to prevent damage of products. This material will be thrown away as waste after being used, causing environmental pollution. The second use of this material is conducive to environmental protection. The structure of this commercial PVC film bubble is favorable to the response of sound waves, that is, it is easy to convert sound waves into vibrations, thereby eliminating noise. Using this single layer film bubble, two types of film cavity materials can be prepared, the multilayer film PVC bubble structure (PB) and the frame filled by PVC bubble structure (FPB). Three effects on sound absorption performance are studied, including film bubble material thickness, bubble diameter and porosity.

This film bubble structure has the advantages of ultra-lightweight, easy preparation, easy installation, convenient use, and the secondary utilization of discarded commercial bubble materials, which is beneficial to environmental protection. It can realize the application of film materials in sound absorption materials. It is a new type of sound absorption material with a broad application prospect.

2. Experiment

2.1. Sample Preparation. Two kinds of samples were made with waste PVC film bubbles used in commercial packaging.

The first structure is to cut the ordinary waste PVC bubble material into discs required for the sample, and paste the multi-layer film PVC bubble (PB) sample, as shown in Figures 1(a) and 1(b).

The second structure is to cut the packaging bubble material into a single film bubble, the bubble is intact. The thickness of the bubble film is 0.01 mm, and the diameter is 5 mm, 10 mm, and 25 mm. The design frame is cylindrical, and the front and back are restricted by narrow strips, which width is 2 mm and spacing is 3~4 mm. The complete frame is made by 3D printing technology. The diameter of the frame is 99.6 mm and 29 mm respectively. The material of the frame is polytetrafluoroethylene resin. The film bubbles are packed into the frame to form frame filled by PVC bubble materials (FPB), as shown in Figures 1(c) and 1(d). When preparing FPB samples, the porosity of the sample can be controlled by changing the mass of bubbles filled. The porosity can be calculated using formula.

$$\varphi = 1 - \frac{m/V}{\rho_{\mathrm{PVC}}}, \tag{1}$$

where m is the mass of bubbles filled, V is the volume of sample, and ρ_{PVC} is the density of the PVC film bubbles.

2.2. Sound Absorption Performance Test. The Danish B&K 4206 two-microphone impedance tube is used in this experiment, and the sound absorption coefficient of the samples are measured according to GB/T 18969.2-2002. The test system consists of an impedance tube, two microphones, a power amplifier, a data analyzer, and computer software. The diameter of the tested sample is 99 mm and 29 mm, and the test frequency range is 150–1600 Hz and 500–6400 Hz.

3. Experimental Results

3.1. Results of Sound Absorption Performance of Multilayer Film PVC Bubbles (PB). A single piece of commercial film PVC bubble material is used, cut into discs, and PB samples are made by gluing the discs of PVC bubble material. The average sound absorption coefficient is the average value of the sound absorption coefficient from 150 to 1600 Hz. The starting frequency is the lowest frequency at which the sound absorption coefficient reaches 0.2. The sound absorption curve is shown in Figure 2.

It can be seen from Figure 2(a) that the PB structure material has an obvious resonance peak in the frequency range of 150–1600 Hz. The resonance peak moves to low frequency with the increase of the material thickness, which is similar to the sound absorption characteristics of the cavity resonance structure. The sound absorption curve has a single peak sound absorption characteristic, which is due to the resonance sound absorption caused by the cavity. Generally speaking, for cavity sound absorber, the greater the depth, that is, the greater the thickness of the sample, the more the absorption peak moves to low frequencies.

It can be seen from the experimental results that when the thickness of the sample increases, the sound absorption curve of the sample moves to low frequencies. The average sound absorption coefficient increases, and the starting frequency decreases. When the thickness is 10 mm, the sound absorption coefficient of the PB sample reaches the maximum at 1600 Hz, which is 0.75, and there is no peak; When the thickness is 20 mm, the sound absorption coefficient of the sample reaches its maximum at 1170 Hz, which is 0.99, showing obvious single peak sound absorption characteristics; When the thickness is 30 mm, the sound absorption coefficient of the sample reaches its maximum at 746 Hz, which is 0.98, also showing obvious single peak sound absorption characteristics. Moreover, the single peak at this sample moves 424 Hz to the low frequency, which is caused by the increase in sample thickness.

The sample thickness of 30 mm is selected, and PB samples with film bubble diameters of 5 mm, 10 mm, and 25 mm are prepared respectively. It can be seen from Figure 2(b) that in the frequency range of 150–1600 Hz, the three diameter film bubbles have little effect on the resonance peak of PB material. And the resonance absorption peak is almost at the same position, which means that the thickness of the sample determines the position of the resonance peak. When the thickness is constant, the depth of the cavity has been determined, and the position of the resonant absorption peak has been determined. When the film bubble diameter is larger, the sound absorption coefficient is higher. When the bubble diameter is 10–25 mm, the average sound absorption coefficient is basically the same, and the sound absorption frequency band is wider; when the bubble diameter is 5 mm, the average sound absorption coefficient is the minimum and the sound absorption band becomes narrower. It can be seen that the diameter of the film bubble should be larger.

3.2. Results of Sound Absorption Performance of Frame Filled by PVC Bubbles (FPB). The structure of FPB is to put film bubbles into a frame, to form a tightly connected structure between the film bubbles, and the thickness of the FPB is controlled by the outer frame, as shown in Figure 1. Three effects on sound absorption performance of FPB materials are investigated respectively, including sample thickness, film bubble diameter and porosity.

3.2.1. The Effects of Thickness on the Sound Absorption Performance of FPB. The film bubble diameter of 10 mm and porosity of 0.975 are selected, and FPB samples with thickness of 10 mm, 15 mm, 20 mm, 25 mm and 30 mm are prepared respectively. It can be seen from Figure 3(a) that in the frequency range of 150–1600 Hz, a wider resonance absorption peak is occurred obviously in FPB structure. The resonance absorption peak becomes more complicated, but it is still resonance absorption. The sound absorption curve of FPB moves to low frequency with the sample thickness

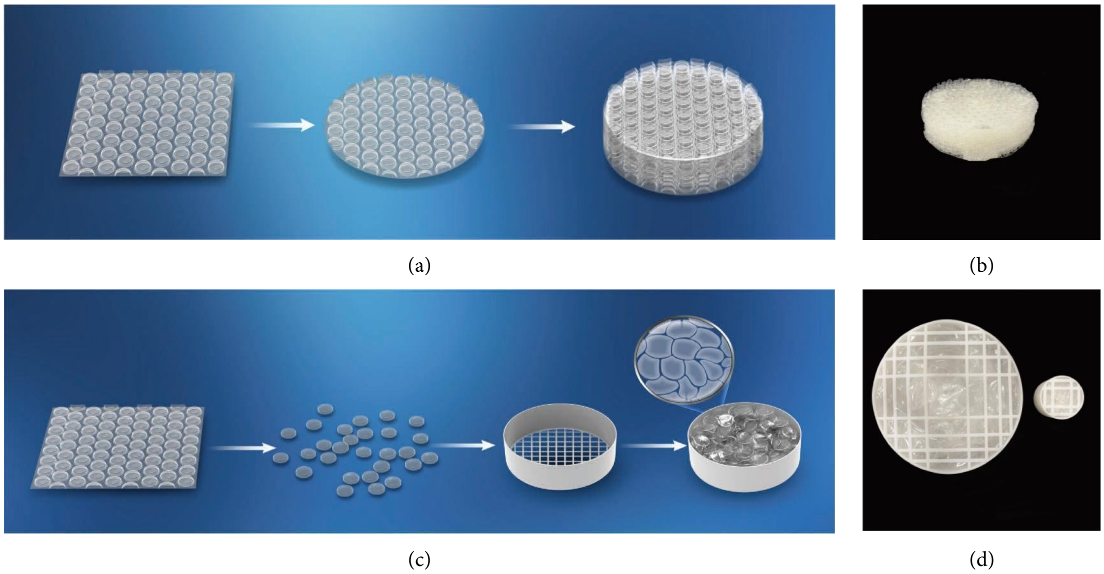

Figure 1: (a) PB sample preparation. (b) PB sample. (c) FPB sample preparation. (d) FPB sample.

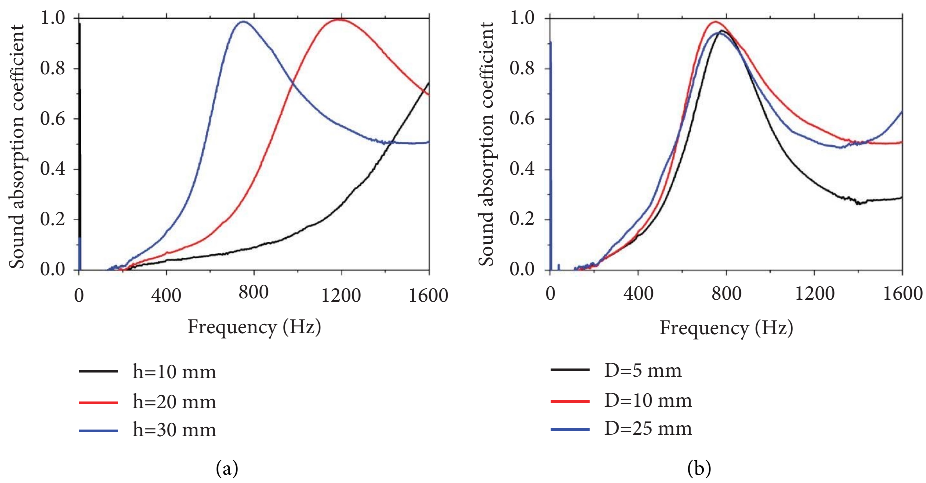

Figure 2: (a) Sound absorption curve of PB samples with different thicknesses and (b) sound absorption curve of PB samples with different film bubbles diameters.

increases. When the sample thickness is 10 mm, the sound absorption coefficient reaches the maximum at 1600 Hz, which is 0.75, and there is no resonance absorption peak; when the sample thickness is 15 mm, the sound absorption coefficient reaches the maximum at 1600 Hz, which is 0.85, and the resonance absorption peak still does not occur; when the sample thickness is 20 mm, a resonance absorption peak occurs, which frequency is 908 Hz, and the sound absorption coefficient is 0.86; when the sample thickness is 25 mm, the first resonance sound absorption frequency is 782 Hz, and the sound absorption coefficient is 0.93; when the sample thickness is 30 mm, the sound absorption coefficient of FPB structure can reach 0.94 at 754 Hz. The sound absorption frequency band moves 154 Hz to low frequency with the sample thickness increases from 20 mm to 30 mm. And the morphology of the peak is basically the same. Compared with the PB structure, the absorption peak morphology of FPB structure is more complex and wider. The sound absorption coefficient of FPB with a thickness of 30 mm and a film bubble diameter of 10 mm is 0.54, which is slightly larger than 0.52 of PB.

In Figures 3(b) and 3(c), when the sample thickness increases from 10 mm to 30 mm, the average sound absorption coefficient of sample increases and the starting frequency decreases gradually.

3.2.2. The Effects of Film Bubble Diameter on the Sound Absorption Performance of FPB. The thickness of 30 mm and porosity of 0.975 are selected, and FPB samples with film bubble diameter of 5 mm, 10 mm, and 25 mm are prepared, respectively. It can be seen from Figure 3(d) that the resonance absorption peak in the sound absorption curve changes obviously, when the diameter of the filling PVC film

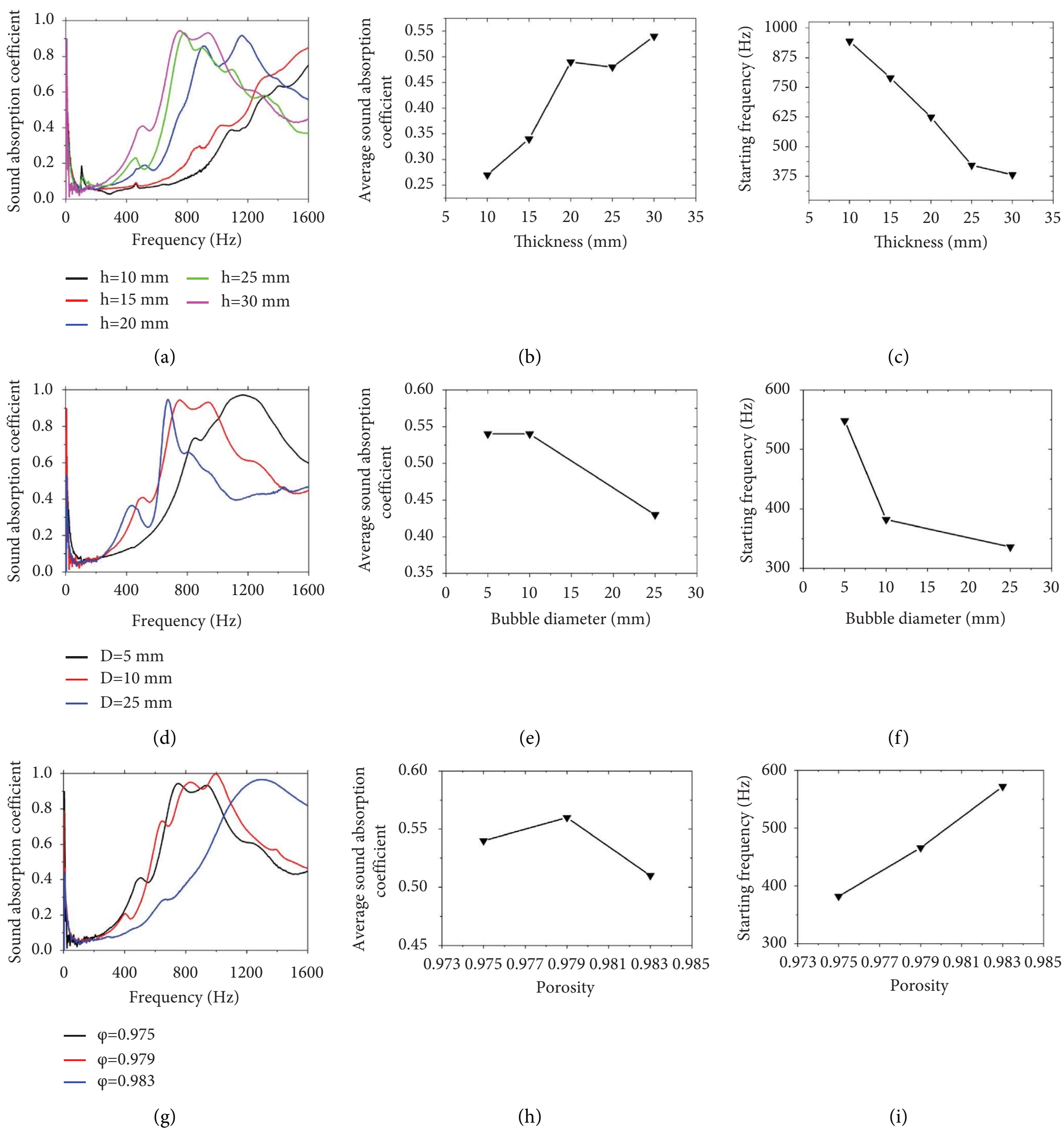

Figure 3: (a) Sound absorption curve of FPB samples with different thicknesses, (b) the effect of thickness on average sound absorption coefficient, (c) the effect of thickness on starting frequency, (d) sound absorption curve of FPB samples with different film bubbles diameter, (e) the effect of film bubbles diameter on average sound absorption coefficient, (f) the effect of film bubbles diameter on starting frequency, (g) sound absorption curve of FPB samples with different porosities, (h) the effect of porosity on average sound absorption coefficient, and (i) the effect of porosity on starting frequency.

bubbles is different. The curve moves to low frequency, the sound absorption frequency band becomes narrow, and the sound absorption coefficient decreases as the diameter of the film bubble increases. When the diameter of film bubble is 25 mm, the sound absorption frequency band becomes the narrowest, and the sound absorption coefficient is the minimum 0.43. When the diameter of film bubble is 10 mm, the sound absorption coefficient is 0.54, the sound absorption frequency band becomes wider and the starting frequency is 382 Hz, which has excellent sound absorption performance.

It can be seen from Figures 3(e) and 3(f) that as the film bubble diameter increases, the average sound absorption coefficient and the starting frequency of the sample decrease slightly. When film bubble diameter is 5 mm and 10 mm, the average sound absorption coefficients of samples are the same, both are 0.54. When the diameter of film bubble is 25 mm, the FPB sample has better low frequency sound absorption performance. In comprehensive comparison, when the film bubble diameter is 10 mm, the sample has the most excellent sound absorption performance.

3.2.3. The Effects of Porosity on the Sound Absorption Performance of FPB. The thickness of 30 mm and film bubble diameter of 10 mm are selected, and FPB samples with porosity of 0.975, 0.977, 0.979, 0.981 and 0.983 are prepared, respectively. It can be seen from Figure 3(g) that when the porosity of the FPB structure increases, the resonant absorption peak of the sound absorption curve moves to high frequency. That is, the larger the porosity, the worse the low frequency sound absorption performance of the FPB structure. When the porosity is 0.975, the sound absorption coefficient of FPB structure can reach 0.94 at 754 Hz; When the porosity is 0.983, the sound absorption coefficient of FPB structure can reach 0.96 at 1284 Hz.

It can be seen from Figures 3(h) and 3(i) that as the sample porosity increases, the average sound absorption coefficient changes from 0.49 to 0.56, and the starting frequency increases significantly.

3.3. Comparison of Sound Absorption Performance Results of PB and FPB Samples. PB and FPB samples with a diameter of 29 mm are prepared. In order to further study the sound absorption performance of the film cavity structure material, the test is carried out in a wider frequency band, and the test range is 500–6400 Hz. The average sound absorption coefficient is the average value of the sound absorption coefficient from 500 to 6400 Hz. The resonance frequency is the frequency at which the sound absorption coefficient reaches its maximum. The starting frequency is the lowest frequency at which the sound absorption coefficient reaches 0.2. In Figure 4(a), the PB structure material has broadband sound absorption and excellent sound absorption performance. At less than 1600 Hz, the same as the previous test results, the resonance absorption peak frequency is basically the same. In the range greater than 1600 Hz, broadband sound absorption characteristics appear, and there is no obvious resonance absorption peak. For medium and high frequencies, the sound absorption properties of porous materials appear. It can be seen that the average sound absorption coefficient of No. 1 sample with a film bubble diameter of 10 mm is 0.75, and the average sound absorption coefficient of No. 2 sample with a diameter of 25 mm is 0.72. Therefore, for the PB structure, a film bubble with a smaller diameter can be selected to improve its sound absorption coefficient.

In Figure 4(b), the FPB structure has broadband sound absorption. The average sound absorption coefficient of the No. 1 and No. 2 sample is 0.84, while the starting frequency of the No. 2 sample is low, which is 416 Hz. When the sample porosity is 0.98 and the film bubble diameter is 25 mm, the bubble volume is large, the number of bubbles is less, and the friction between the film bubbles is less. It can be seen from curve No. 2 that the first resonance peak is a narrow and smooth single peak. It shows that the contact between the film bubbles is small, and the friction between the bubbles is less. When the bubble diameter is 10 mm, there are more small bubbles and the first resonance peak becomes wider, indicating that the contact between the small bubbles is more, the friction between the films is more, and the sound absorption performance of the middle and low frequency is higher than that of No.2 sample with diameter of 25 mm.

In Table 1 and Figure 4(c), the PB and FPB film cavity samples both have broadband sound absorption characteristics. When the frequency is less than 1600 Hz, both have resonance sound absorption characteristics, and when it is greater than 1600 Hz, both have porous sound absorption characteristics. The average sound absorption coefficient of FPB is greater than PB, therefore, the sound absorption performance of FPB is better than PB. The starting sound absorption frequency of PB is lower than FPB, and the low frequency sound absorption performance of PB is slightly better than FPB.

The sound absorption properties of film multicavity structure materials are compared with commonly used sound absorption materials. The material parameters and sound absorption test results are shown in Table 2, and the sound absorption curve is shown in Figure 5.

It can be seen from Table 2 and Figure 5 that when the thickness of the four materials is 30 mm, the average sound absorption coefficient of FPB structure is the largest, 0.84. The average sound absorption coefficient of polyurethane foam is the smallest, 0.66. PB and FPB structures exhibit cavity resonance sound absorption characteristics at frequencies below 1600 Hz, with better low frequency sound absorption performance. The average sound absorption coefficient of melamine foam is 0.82, but its price is expensive. PB and FPB structure is the secondary use of discarded commercial film bubble materials, which is light and conducive to environmental protection.

4. Discussion of Experimental Results

4.1. Result Analysis of Sound Absorption Performance of the PB Structure. The film bubble structure is mainly composed of a cavity and a film, the cavity occupies a large volume, and the film occupies very little volume. The function is that the bubble cavity provides the reflection space of the sound wave, the film generate heat and dissipate sound energy by vibration and friction with sound waves. The structure of PB is neat, as shown in Figure 1(a). It is made up of multiple layers film bubbles and the porosity remains unchanged. The bubbles are independent of each other and have less interaction. The external appearance is similar to periodic structure. It exhibits typical sound absorption characteristics of film cavities below 1600 Hz. As shown in Figure 2, the sound absorption coefficient curve presents a smooth resonant single peak morphology.

When the sound wave radiates to the surface of the PB structure, it causes the film with a small area density to vibrate, which converts the sound energy into the film vibration and consumes a part of the sound energy. At the same time, the sound wave radiates into the inside of the PB material due to the film vibration, and the sound wave encounters each surface of the film will reflect causing cavity resonance and film friction will consume sound energy. When the film bubble layer increases, the effect between the film bubble and the sound wave increases, so the sound absorption coefficient increases. The thicker the PB, the

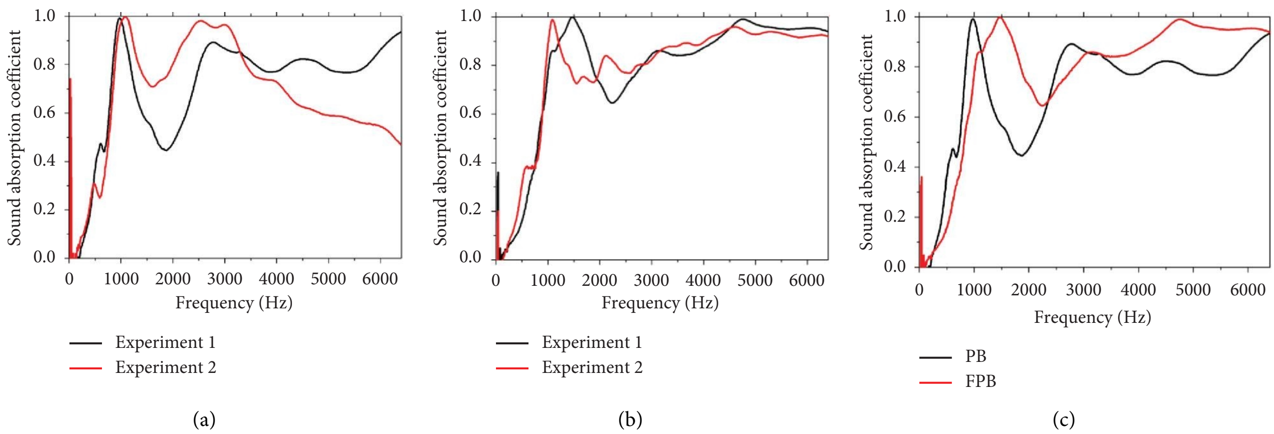

Figure 4: (a) The sound absorption curve of PB samples, (b) the sound absorption curve of FPB samples, and (c) comparison of sound absorption curve of PB and FPB samples.

Table 1: Comparison of sound absorption performance of PB and FPB samples.

Sample	Thickness, h (mm)	Film bubbles diameter, D (mm)	Porosity, ϕ	Average sound absorption coefficient, α	Resonance sound absorption frequency, f_1 (Hz)	Starting frequency, f (Hz)
PB	30	10	0.980	0.75	968	408
FPB	30	10	0.980	0.84	1464	544

Table 2: Comparison of sound absorption properties of four materials.

Sample	Thickness, h (mm)	Average sound absorption coefficient, α	Starting frequency, f (Hz)
PB	30	0.75	408
FPB	30	0.84	544
Melamine foam	30	0.82	432
Polyurethane foam	30	0.63	664

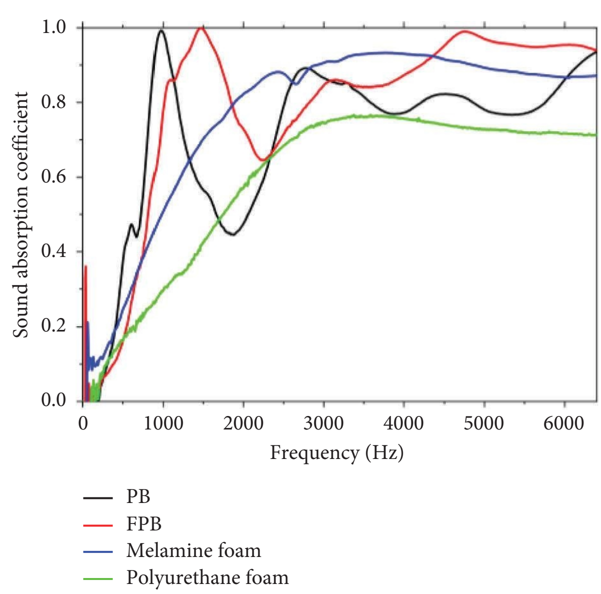

Figure 5: The sound absorption curve of four materials.

deeper the cavity and the more the resonant absorption peak moves to the low frequency.

When the thickness of PB is constant, the film bubble diameter has no significant effect on the resonance frequency. This is because no matter how the diameter of the film bubble changes, the overall cavity volume changes little, the movement of resonance absorption peak is not significant, and the average sound absorption coefficient changes little.

When the frequency is greater than 1600 Hz, the sound absorption curve exhibits broadband sound absorption characteristics, that is, the sound absorption characteristics of porous materials. When the acoustic waves enter the inside of the PB structure, due to the number of film cavities increases, the area of action between the film and the sound waves increases. During the process of sound wave multiple reflections, the sound energy consumed by the film friction also increases, and the sound absorption performance is improved. It can be seen from Figure 2(b) that when the diameter of the film bubbles is small, the number of bubbles per unit volume will increase, and the area of the film will increase, and the effect between film and sound waves will increase.

In summary, the sound absorption characteristics of the PB structure are cavity sound absorption characteristics in the middle and low frequencies, broadband sound absorption characteristics in the middle and high frequencies, and the PB structure generally exhibits broadband sound absorption characteristics. The required resonance peak frequency can be obtained by controlling the thickness of the PB structure, so that the low frequency sound absorption characteristics can be designed. At medium and high frequencies, a broadband sound absorption effect can be obtained by controlling the diameter of the film bubble, and a smaller bubble diameter is beneficial to improve the sound absorption coefficient.

Three ways for PB structure to dissipate sound energy are concluded, including film vibration, cavity resonance, and friction between sound waves and the film surface.

4.2. Result Analysis of Sound Absorption Performance of FPB Structure

4.2.1. The Effects of Thickness on the Sound Absorption Performance of FPB. The FPB structure is more complicated, which is consisted of the multiple individual film bubbles filled into the frame. The bubbles are no longer independent, and the films between the bubbles squeeze each other, as shown in Figure 1(c). The effect of the film increases, so the sound absorption peak becomes more complicated. As shown in Figure 3, the resonance absorption peak is not a smooth single peak, but a broad resonance absorption peak at the frequency range less than 1600 Hz. The morphology of the absorption peak is related to the film bubble cavity structure. The sound absorption curve of the PB structure is a smooth single peak, indicating that the cavity is invariant in the sound wave radiation. The bubbles in the PB structure are independent of each other, therefore, it can be ensured that the cavity of the entire structure will not change. In the FPB structure, the bubbles are mutually squeezed, and the interaction between the film and bubbles is strong. When the sound wave radiates to the surface of the FPB, the film will vibrate due to the sound pressure, which will cause the deformation of the bubble cavity, so the resonance absorption peak changes in morphology.

As the thickness of the FPB sample increases, the sound absorption curve of the sample shifts to low frequencies, and the starting frequency gradually decreases. As the cavity depth increases, the volume of a Helmholtz resonator increases, and the resonance frequency shifts to low frequencies.

As the thickness of the FPB increases, the average sound absorption coefficient increases. This is because the number of film bubble cavities in the sample increases with the thickness increases, the interaction area of sound waves with the film increases, the propagation channel becomes more complicated, the sound wave attenuation increases, and the sound absorption performance improves.

4.2.2. The Effects of Film Bubble Diameter on the Sound Absorption Performance of FPB. The FPB structure is more complicated, the film bubbles squeeze each other, and the film vibration is more complicated. When the thickness is constant, the diameter of the film bubble decreases. When the diameter of the film bubble is 5 mm, it is the smallest bubble diameter in this set of experiments. At this time, the number of film bubbles filled is the largest, the squeezing area between the films is the largest, the friction between the films is the strongest, the resonance absorption peak is widened, and the complex single-peak characteristics are presented, as shown in the sound absorption curve of Figure 3(d). This is because the existence of both the cavity effect and the friction between the films at this time. So, the sound absorption coefficient is the highest.

When the thickness of the FPB is constant, the resonance peak frequency is related to the size of the film bubble cavity. The larger the film bubble cavity, that is, the larger the diameter, the more the resonance peak moves to the low frequency. This is because large bubbles have a large volume and the filled FPB structure has a larger cavity. So, the resonance peak moves to a low frequency as the bubble diameter increases. When the diameter of the film bubble changes from 5 mm to 25 mm, the resonance absorption peak frequency of the FPB structure drops from 1162 Hz to 672 Hz and moves to the low frequency by 490 Hz. It can be seen that the diameter of the film bubble can change the resonance sound absorption frequency of the FPB structure.

The larger film bubble diameter can improve the low frequency sound absorption performance, but it is not good for the improvement of the sound absorption coefficient. This is because the friction between the films is reduced, and the sound energy consumption is decreased. In summary, a middle film bubble diameter can be selected.

4.2.3. The Effects of Porosity on the Sound Absorption Performance of FPB. In the FPB structure, the film bubbles squeeze each other, and the film vibration is more complicated. When the porosity of FPB structure increases, the number of film bubbles filled in the frame decreases, the squeeze between the films weakens, the effect of friction between the films changing to sound energy weakens, and the resonance absorption peak becomes a smooth single peak. This is similar to the absorption peak of the PB structure, which is a smooth single peak, as shown in the curve of Figure 3(g). When the porosity is 0.983, the single peak of sound absorption curve is similar to the absorption peak of the PB structure. This is because when the porosity increases to above 0.981, the number of filled bubbles decreases, the friction between the bubbles disappears, and the bubble cavity relatively independent, the cavity resonance absorption peak becomes a smooth single peak. When the porosity is 0.975, the absorption peak morphology is complicated and the sound absorption coefficient increases. This is because as the porosity decreases, the number of film bubbles filled in the frame increases, the friction between the films increases, and the bubbles are no longer independent of each other. So the resonance absorption peak transforms into a wide and complex morphology.

When the porosity is small, the density of film bubbles filled in the frame is high, the bubbles are compressed, and the contact area between the film bubbles increases. When the sound wave radiates to the surface of the FPB material, it dissipates more sound energy, so the sound absorption coefficient increases. When the porosity is large, the density of film bubbles filled in the frame decreases, the effect between the films decreases, the dissipation of sound energy decreases, so the sound absorption coefficient decreases. It can be seen from the change of the sound absorption coefficient that in the FPB structure, the porosity has a suitable value, which should not be greater than 0.980. This can increase the density of film bubbles filled in the frame and the contact area between the bubble films. When the sound wave radiates to material, the dissipation of sound energy can be increases by increasing the friction between the films, and there is also a sound absorption effect of the film cavity at the same time. The FPB structure with excellent sound absorption performance can be obtained with such a joint effect.

In summary, the sound absorption characteristics of the FPB structure are cavity sound absorption characteristics in the middle and low frequencies, broadband sound absorption characteristics in the middle and high frequencies, and the FPB structure generally exhibits broadband sound absorption characteristics. The resonance absorption peak is related to the thickness. The greater the thickness, the more the sound absorption curve moves to low frequencies. When the total thickness is constant, it is related to the size of the film bubble diameter. The larger the film bubble diameter, the more the resonance sound absorption frequency moves to low frequencies.

The morphology of the resonance sound absorption curve is related to the porosity. The smaller the porosity, the more the number of film bubbles filled in the frame, the greater the degree of the bubbles squeezing, the larger the contact area of the films and the wider and more complex resonance peaks. When the porosity increases to a certain value (greater than 0.981), the number of film bubbles filled in the frame is small, the bubbles are independent of each other, and the resonance peak becomes a smooth single peak.

Four ways for FPB structure to dissipate sound energy are concluded, including film vibration, cavity resonance, friction between sound waves and the film surface, and friction between the films.

4.3. Comparison of Sound Absorption Performance of PB and FPB. From the PB and FPB structure, PB structure dissipates sound energy in the following ways: film vibration, cavity resonance, friction between sound waves and the film surface, while FPB structure dissipates sound energy in the following ways: film vibration, cavity resonance, friction between sound waves and the film surface, and friction between the films. It can be seen that FPB dissipates sound energy in one more way than PB, that is, the friction between the films. The ability of FPB structure to dissipate sound energy is greater than that of PB structure, so the sound absorption performance of FPB structure is better than that of PB structure. It can be seen that under the same parameter conditions, the average sound absorption coefficient of FPB structure is 0.84, the average sound absorption coefficient of PB structure is 0.75, and the sound absorption performance of FPB structure is better than that of PB structure. In the middle and low frequencies, the resonant peak of PB structure is a smooth curve, and the resonant peak of FPB structure is wide. This is because the bubble distribution in the two structures is different. The bubbles in the PB structure are independent of each other and arranged regularly, forming a fixed cavity structure, and the resonance peak is a smooth single peak. In the FPB structure, the bubbles are in a squeezed state, and the bubbles are not independent. When the sound wave radiates to material, friction between the bubble films will occur and the shape of the cavity will be changed, so the resonance peak becomes wider and more complicated. The peak-valley value of PB structure is deeper than FPB structure, the resonance peak is more obvious, and the cavity sound absorption characteristics of PB structure are more prominent than FPB structure. Both PB and FPB structure exhibit broadband sound absorption performance at medium and high frequencies, and have a high sound absorption coefficient. This is due to the various ways of dissipating sound energy, such as the friction between the sound waves and the film surface, the friction between the films, and the cavity resonance, etc. There are many ways to transform sound energy, and the sound absorption mechanism is complex, which results in broadband sound absorption characteristics. The summary of the performance comparison between the PB structure and the FPB structure is as shown in Table 3.

In general, both PB and FPB structure have broadband sound absorption performance. It presents the cavity sound absorption characteristics in the middle and low frequencies, and broadband sound absorption characteristics in the middle and high frequencies, and the sound absorption frequency band can be controlled by adjusting the structure

Table 3: Performance comparison of PB and FPB structure.

	Structure	Ways to dissipate sound energy	Morphology of resonance absorption peak
PB	Multilayer film bubbles	Film vibration cavity resonance friction between sound waves and the film surface.	Single peak
FPB	Random filling and squeezing of bubbles	Film vibration cavity resonance friction between sound waves and the film surface friction between the films.	Complex and multipeaks

Table 4: Comparison of the resonance frequency theory and experimental results of the PB structure.

Structure	Sample thickness, h (m)	Experimental results (Hz)	Before revision		After revision	
			Calculation results (Hz)	Error absolute value (Hz)	Calculation results (Hz)	Error absolute value (Hz)
PB	0.01	>1600	1655	—	1655	—
	0.015	1382	1351	29	1351	29
	0.02	1174	1170	4	1170	4
	0.025	1020	1046	26	1046	26
	0.03	746	956	210	733	13
	0.035	656	884	228	661	5
	0.04	600	827	227	604	4
	0.045	560	780	220	557	3
	0.05	510	740	230	517	7

Table 5: Comparison of resonance frequency theory and experimental results of the FPB structure.

Structure	Sample thickness D (m)	Experimental results (Hz)	Before revision		After revision	
			Calculation results (Hz)	Error absolute value (Hz)	Calculation results (Hz)	Error absolute value (Hz)
FPB	0.01	>1600	1655	—	1322	—
	0.015	>1600	1351	—	1067	—
	0.02	908	1170	262	915	7
	0.025	782	1046	264	809	27
	0.03	754	956	202	731	23

thickness. However, due to the complexity of the sound absorption mechanism of film multicavity materials, there is currently no good calculation model that can accurately calculate its sound absorption coefficient, and further research is needed in the future.

4.4. Calculation of Resonance Frequency of PB and FPB Structure. The sound absorption curve characteristics of film multicavity structure are cavity sound absorption at the low and middle frequencies, and broadband sound absorption at middle and high frequencies. The resonance frequency of the film multicavity structure at the low and middle frequencies can be obtained by the experimental measurement at 1600 Hz. The PB and FPB structure are analogous to the film cavity resonance sound absorption structure. The resonance frequency of this structure can be calculated by formula:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2}{M_0 h}}, \tag{2}$$

where ρ_0 is the density of air, 1.29 kg/m^3. c is the sound speed in air, 340 m/s. M_0 is the areal density of the film, which is equal to the product of the film thickness and the film density. h is the air layer thickness between the film and the rigid wall. The density of the PVC film is 1.38×10^3 kg/m^3, the thickness of the film is 1×10^{-4} m.

4.4.1. Calculation of Resonance Frequency of PB Structure. According to formula (2), the resonant frequency of the PB film cavity structure is calculated. It can be seen from Table 4 that when the thickness is less than 0.025 m, the theoretical calculation of the PB structure resonance absorption peak frequency is not much different from the experimental measurement results, and the PB structure conforms to the theoretical calculation of the film cavity structure. Therefore, it can be seen that when the thickness is less than 0.025 m, the film bubbles in the PB structure have little effect on the structure. However, when the thickness is 0.03 m, the difference between the theoretical calculation result and the experimental measurement result is about 210 Hz. And as the thickness increases, the resonance peak moves, and the frequency of the movement is basically a same value with the increase in thickness. Therefore, the calculation formula is revised. After the revision, the formula for calculating the resonance frequency of the PB structure is shown below.

$$\begin{aligned} f_0 &= \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2}{M_0 h}}\,(h \le 0.025\text{m}),\\ f_0 &= \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2}{M_0 h}} - 223\,(h \ge 0.03\text{m}). \end{aligned} \tag{3}$$

It can be seen from Table 4 that the resonant sound absorption peak frequency of the PB structure calculated using the revised formula (3) is not much different from the experimental measurement result.

4.4.2. Calculation of Resonance Frequency of FPB Structure. According to formula (2), the resonant frequency of the FPB film cavity structure is calculated. It can be seen from Table 5 that the theoretical calculation of the FPB structure resonance absorption peak frequency is quite different from the experimental measurement result, because the FPB structure is more complicated than the PB structure. The air bubbles in FPB are randomly filled into the frame, and the air bubbles squeeze each other, and the film has a stronger effect, which makes the resonance peak of FPB structure more complicated. At the same time, the resonance peak frequency does not arithmetic change with the increase of thickness, so the formula can be revised. The revised formula is shown below.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2}{(50M_0 h + 1.5)M_0 h}}. \tag{4}$$

After the revision, the theoretical calculation of the FPB structure resonance absorption peak frequency is not much different from the experimental measurement result. This formula can predict the resonance absorption peak frequency of the FPB structure.

Formulas (3) and (4) are obtained, which have practical guiding role in the prediction of the PB and FPB structures resonance frequency, and have guiding significance for the design of PB and FPB sound absorption structure materials.

5. Conclusion

(1) Commercial film bubble materials are used to make a film multicavity structure, which can achieve broadband sound absorption characteristics. This structure greatly improves the ability of the film to absorb sound waves and provides a method for the design of film sound absorption materials.

(2) The PB structure is a multi-layer bubble periodic structure, which is characterized in that each layer of film bubbles are independent of each other, the film bubbles between the layers are bonded to each other, and there are gaps between the bubbles. Three ways for PB structure to dissipate sound energy are concluded, including film vibration, cavity resonance, and friction between sound waves and the film surface. The FPB structure is randomly filled with film bubbles in the frame, the bubbles are squeezed each other, and the bubble films are close to each other. Four ways for FPB structure to dissipate sound energy are concluded, including film vibration, cavity resonance, friction between sound waves and the film surface, and friction between the films. The sound absorption performance of FPB structure is better than that of PB structure.

(3) The sound absorption of PB and FPB structures has two characteristics. It has cavity resonance sound absorption characteristics at medium and low frequencies. In PB and FPB structures, the cavity occupies a very large volume, and the resonance sound absorption of the cavity is single peak characteristics. The sound absorption characteristics are related to

thickness. It has broadband sound absorption characteristics at medium and high frequencies. PB and FPB dissipate sound energy in a variety of ways. The sound energy is dissipated by the friction between the sound wave and the film surface, the friction between the films, and the cavity vibration, etc. The complexity of sound energy transformation leads to broadband sound absorption characteristics.

(4) In PB and FPB structures, the average sound absorption coefficient of FPB samples with a thickness of 30 mm can reach 0.84, and the starting sound absorption frequency is 544 Hz. The average sound absorption coefficient of PB samples with a thickness of 30 mm can also reach 0.75, and the starting sound absorption frequency is 408 Hz. The sound absorption performance of FPB structure is better than that of PB structure.

(5) The film multicavity structure material has excellent broadband sound absorption performance, and has the advantages of ultralight weight, low cost, easy preparation, easy installation, convenient use, and the secondary utilization of discarded commercial film bubble materials, which is beneficial to environmental protection. It is a new type of sound absorption material with a broad application prospect.

Data Availability

The data are available from the first author upon request

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Tingying Zhang was responsible for methodology, investigation, and writing the original draft. Jiyang Zhang was responsible for the conduction of the experiment. Pengxuan Zheng was responsible for validation. Hong Hou reviewed and edited the article. Ying Xu wrote the draft and supervised the study.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant no. 12174314).

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