Research Article

Improved Sound Absorption Properties in Polyurethane Foams by the Inclusion of Al$_2$O$_3$ Nanoparticles

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At present, the scale of China's power grid is becoming larger and larger, and the control of low-frequency noise in substations (especially for transformers) is very important. The sound-absorbing materials have become one of the important ways to control low-frequency noise. The single polyurethane material cannot satisfy the requirements for reducing low-frequency noise, so it is very necessary to study its composite with other materials. In the paper, the flexible polyurethane foam and Al$_2$O$_3$ nanoparticle composites were obtained by the impregnation method. The method was simple, safe, and easy to control. The morphology and sound absorption coefficient of the foam materials before and after filling were analyzed. Single-hole acoustic cavity models of PU and Al$_2$O$_3$-PU composite were established through the finite element. The absorption and dissipation process of sound pressure for single hole was studied to understand the energy dissipation process. Meanwhile, through studying acoustic energy storage and acoustic energy dissipation, the loss factor of a single hole was obtained, which can predict the change rule of the sound absorption coefficient for PU foam and Al$_2$O$_3$-PU.

1. Introduction

With the development of national economic and social progress, the accompanying environmental issues have attracted more and more attention from the country and the people. At present, four pollution problems are concerned, such as water pollution, air pollution, solid waste, and noise pollution. Among them, noise pollution has an increasing impact on people's lives [1]. How to control noise pollution and reduce the harm of noise to the human body is concerned by scientific researchers [2]. The treatment of low-frequency noise in substations has received lots of attention, and using sound-absorbing materials to reduce noise has become one of the important ways to control low-frequency noise [3–6]. Polyurethane (PU) is a sound-absorbing material with excellent performance, which is composed of solid polyurethane skeleton and holes [7–9]. Meanwhile, there are many tiny holes in the internal structure of porous sound-absorbing materials. Thus, sound waves can be transmitted in the gaps and microholes, which will produce

friction and some viscous resistance between the material and the hole wall for consuming sound energy.

The sound absorption performance of a single sound-absorbing material is limited. The soft PU foam has better sound absorption performance for medium- and high-frequency noise. However, the low-frequency sound absorption performance is not high. In order to improve the low-frequency sound absorption performance, nanoparticles can be added to improve its performance. Sung et al. [6] used magnesium hydroxide fillers to prepare polyurethane syntactic foam to improve its acoustic properties, which not only increased the damping motion of the fillers but also increased the number of partial openings, thereby improving the sound absorption efficiency. When the open porosity was 0.63, the noise reduction coefficient was about 70% higher than that of no fillers. Khanouki and Ohadi [7] used polyurethane foam as the base material and added silica (SiO$_2$) nanoparticles to improve its acoustic damping. In the frequency range of 500–1000 Hz, the sound absorption properties of PU foam samples containing only 0.05 wt% nanoparticles increased

greatly (over 90%), but the sound-absorbing performance in the low-frequency range was not much improved. Baek and Kim [10] manufactured PU composite foam containing silicone-acrylic filler particles to test the sound absorption performance. When the content of nanoparticles was 2 wt%, the maximum value of sound absorption coefficient was increased by 0.12 compared with the PU foam without addition. When the frequency was 1000 Hz, the sound absorption had not much improved, and its sound absorption coefficient was about 0.2. In addition, other materials can also be used to fill the PU foam. Chen and Jiang [11] proposed a new type of acoustic material, by adding different content (2%, 4%, 6%, and 8%) of bamboo slices or bamboo stems to prepare PU foam composite materials to improve the acoustic performance of PU foam. Experiment results showed that the composite foam significantly improved its sound absorption performance, especially in the low-frequency region (100 Hz–630 Hz).

In recent years, different theoretical models had been reported to predict the sound absorption performance of porous absorbent materials. One of the most commonly used models was the fiber absorbing material model based on a large number of impedance tube measurements and curve fitting proposed by Delany and Bazley [12]. This model provided a good estimate of the characteristic impedance and propagation constant at frequencies above 250 Hz. However, there was a significant error in prediction at lower frequencies. Further updates and improvements were suggested by Miki [13, 14]. Gibson and Ashby [15] introduced dynamic permeability and dynamic tortuosity factor to study the low-frequency and high-frequency sound propagation characteristics of the pore structure in 1987. Meanwhile, the viscous characteristic length of pore was defined to predict the high-frequency asymptotic behavior of the dynamic shape of pore structure. Allard and Champoux [16–18] derived the expressions of effective density and effective bulk elastic modulus of porous sound-absorbing materials in 1991 and introduced the thermal characteristic length of pores to study the problem of heat dissipation at the boundary layer of porous saturated media. Then, in 1992, the Johnson–Champoux–Allard semiempirical equivalent fluid model (JCA equivalent model) was established to characterize the propagation of sound waves in rigid porous materials. The experimental test results verified that the empirical model can be used to accurately estimate the characteristic impedance and material propagation coefficient.

In this paper, the PU foam filling with alumina (Al_2O_3) nanoparticles was prepared. The morphology and sound absorption coefficient of the foam materials before and after filling were analyzed. In addition, the model of micro single hole was established in ANSYS Workbench. Most of the simulation research was to study the macro-sound absorption performance through the impedance tube, but there was little research on the micro single hole. Thus, a microscopic single-hole model was established in the paper. The single-hole model can observe the internal sound absorption and energy dissipation process, and the loss factor was also studied.

2. Experiment

2.1. Raw Material. In the paper, a soft polyurethane foam (PU foam) purchased from Ganzhou Yongjia sponge products company was a low-density foam with a thickness of 20 mm and a diameter of 100 mm. Ethanol was purchased from the Sinopharm Group Co., Ltd. The nano Al_2O_3 suspension (with a particle size of 300 nanometers) was purchased from Shanghai Physical and Chemical Analysis Equipment Company.

2.2. Preparation of Foam. Typically, the PU foam was cleaned for 15 min under the solvent of alcohol and water volume ratio of 1 : 3 and then put it in oven to dry at 80°C. The dried PU foam was placed in a Petri dish and soaked in a Al_2O_3 suspension. The foam was completely immersed in suspension and was soaked for about 1 h. Then, the foam was dried at 80°C until it was completely dry. The density and porosity of PU foam were 14.08 kg·m^{-3} and 0.892, respectively. The density and porosity of Al_2O_3-PU foam were 31.21 kg·m^{-3} and 0.704, respectively.

2.3. Test Instruments. X-ray diffraction (XRD) patterns were recorded with a Rigaku D/max 2250 V diffractometer operating with Cu Kα radiation. The operation voltage and current were set as 40 kV and 100 mA, respectively. Scanning electron microscope (FESEM) images were acquired using S-4800 operated at an acceleration voltage of 5 kV. Sound absorption coefficient was explored by 4206 impedance tube. All samples had a thickness of 20 mm and a diameter of 100 mm, and the tested frequency range was 0–1250 Hz. The American MacPritice AutoPore Iv 9510 mercury porosimeter was used to detect and analyze the porosity of foam materials.

3. Results and Discussion

3.1. XRD Pattern and SEM Analysis of Foam. Figure 1 shows the XRD images of PU foam and Al_2O_3/PU composite foam. According to the experimental results, the PU foam had a wide steamed bread peak at 20°. All the diffraction peaks of Al_2O_3/PU composite foam can be indexed as amorphous PU and Al_2O_3 with the space group R-3c (167) (JPCD NO.10-0173). The lattice constants of Al_2O_3 were $a = b = 4.758$, $c = 12.991$ Å, $\alpha = \beta = 90°$, and $\gamma = 120°$. No other impurity peaks were observed, which indicated that the samples were only composed of PU and Al_2O_3. Figure 2 shows the SEM images of PU foam and Al_2O_3/PU composite foam at different magnifications. The selected magnifications were 20 times and 5000 times. The existence of Al_2O_3 can be seen from the change of diffraction peak intensity. When the magnification was 20 times, it can be seen that the foam was composed of many small single pores similar to a tetradecahedron model (6 squares and 8 regular hexagons). When the magnification was 5000 times, it can be clearly observed that the Al_2O_3 nanoparticles were well attached to the foam skeleton and the distribution was relatively uniform.
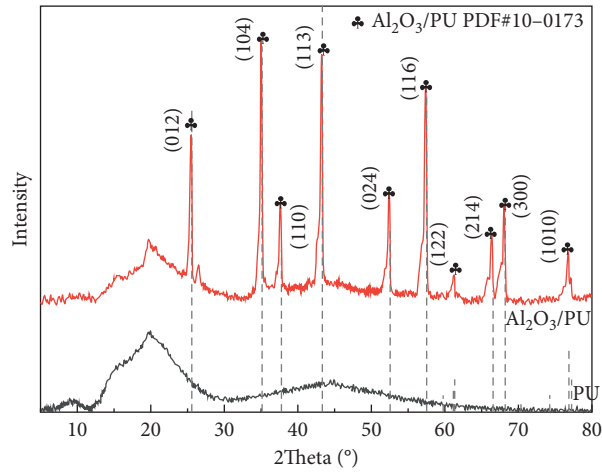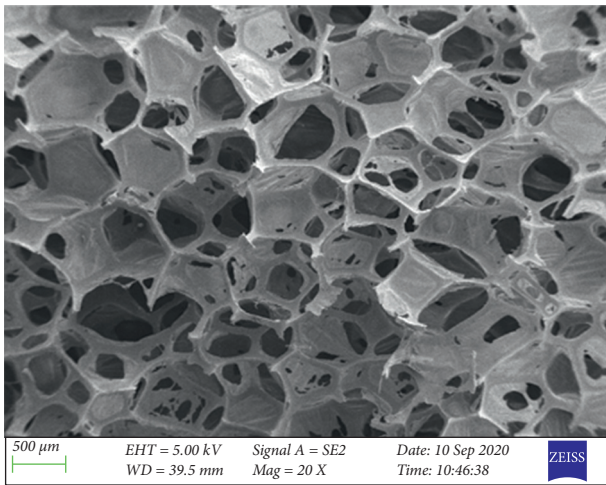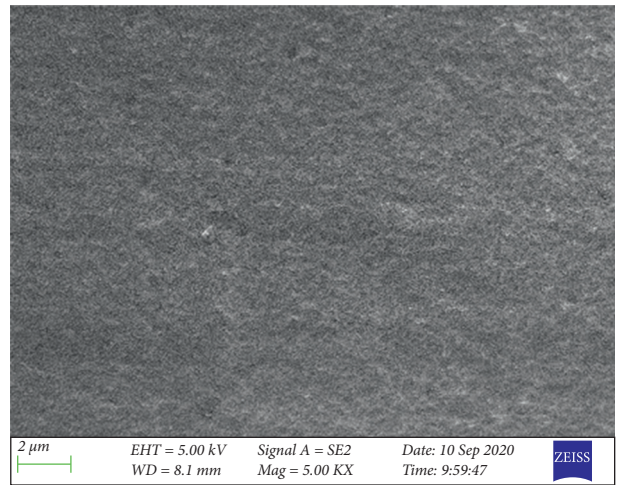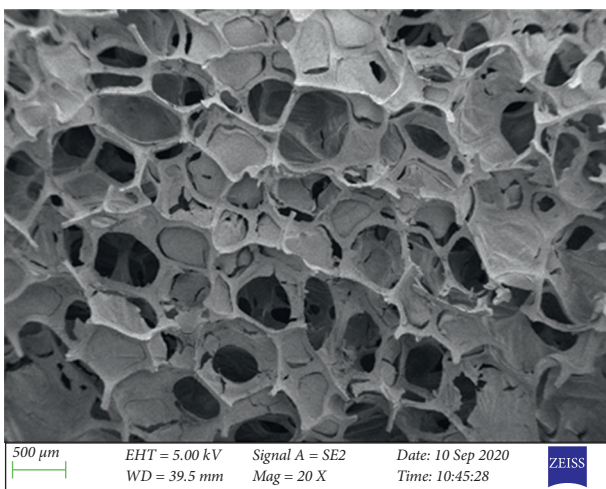
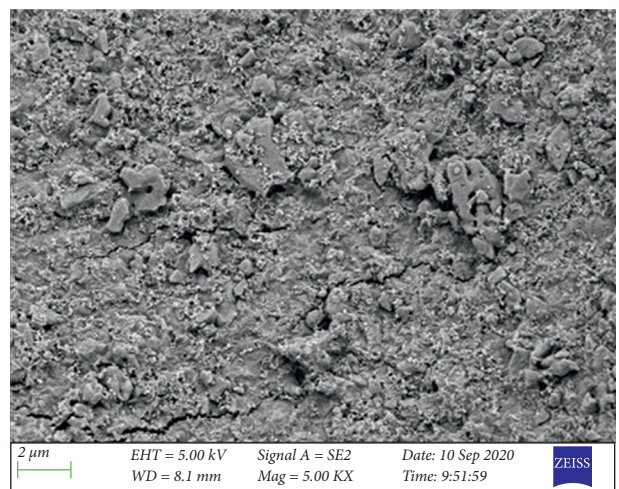FIGURE 1: XRD pattern of PU foam and Al$_2$O$_3$/PU composite foam.

(a)

(b)

(c)

(d)

FIGURE 2: SEM images of (a, b) PU foam and (c, d) Al$_2$O$_3$/PU composite foam.

3.2. Sound Absorption Coefficient. The sound coefficient of different PU foam samples was varied with frequency as shown in Figure 3. It can be seen that the sound absorption coefficient of PU foam and Al_2O_3-PU foam materials generally increased with the increase of frequency in the low-frequency range (50 Hz–1250 Hz). The sound absorption performance was unstable between 50 Hz and 250 Hz, and sound coefficient α had a tendency to vibrate up and down. The PU filled with Al_2O_3 nanoparticle composite material had better sound absorption performance than the pure PU foam. The α difference value between PU and PU/Al_2O_3 increased with the increase of frequency, which reached the maximum difference value of 0.11 and increased about 70% at 1250 Hz. It can be seen that filling PU foam with Al_2O_3 nanoparticles could effectively improve the sound absorption performance in the low-frequency range.

3.3. Simulation Calculation of Single Hole. The macroscopic sound absorption performance of porous materials was determined by the microstructure, and its microstructure must be analyzed. Based on PU foam SEM images, a single-hole geometric model was established. The established model was essentially a Kelvin model, which was the predecessor of the Voronoi model. The air temperature was set at 20°C, and the density and porosity were entered according to the test values. According to the empirical formulas of the JCA equivalent model, the sound absorption process of single hole was simulated.

Figure 4(a) shows the SEM image of the PU foam. From the image, the microstructure distribution of the foam can be seen more clearly, which can be indexed as tetradecahedron (6 squares and 8 regular hexagons). The regular tetradecahedron model was constructed (Figure 4(b)), and then the shell was removed to extract the skeleton structure, as shown in Figure 4(c). Then, the model was analyzed in ANSYS Workbench to form the single-hole acoustic cavity model, as shown in Figure 4(d). Figure 4(e) shows the model after meshing. It should be divided evenly and finely, and the part where the acoustic cavity model contacted with the single-hole skeleton required a predefined boundary layer grid. The finite element acoustic cavity model was established to simulate the sound absorption and the loss factor of sound waves in the foam structure.

When the sound wave passed through the porous foam material, the sound pressure on each surface of the single-hole acoustic cavity was approximately the same. Therefore, the sound pressure of 1 Pa was applied to each surface of the single-hole regular tetradecahedron acoustic cavity, and there was a plane wave outside. We set the thermal viscosity boundary on the surface of the skeleton. Figures 5(a) and 5(b) show the acoustic cavity (PU and Al_2O_3/PU) with the skeleton removed. The model was cut in the middle, so that the image change of the single-hole sound absorption can be better observed from the sound pressure diagram. It can also be clearly seen that the sound pressure changed with frequency, and the selected frequencies were 125 Hz, 375 Hz, 625 Hz, 875 Hz, 1125 Hz, and 1250 Hz. From the average sound pressure change curve in the low-frequency range
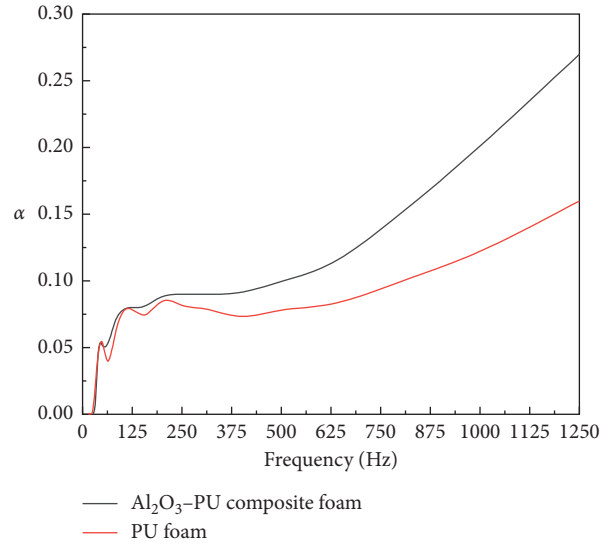

FIGURE 3: Sound absorption coefficient (α) diagram of PU foam and Al_2O_3-PU foam.

(Figure 5(c)), it can be seen that the average single-hole sound pressure for PU foam showed a trend of rising first and then falling in 50–1250 Hz. The highest point was about 812.5 Hz, but it had not yet reached the lowest point. The single-hole average sound pressure showed a trend of rising first, then falling, and rising again for Al_2O_3/PU foam. In addition, the highest point was around 593.75 Hz, and the lowest point was around 937.5 Hz. In terms of sound pressure, the sound absorption process of a single hole was a process of absorption and dissipation. Meanwhile, the absorption and dissipation process of Al_2O_3/PU foam was faster than that of PU foam. It can be inferred that this cycle was repeated at a later frequency.

The total energy dissipation of PU and Al_2O_3/PU foam could be divided into acoustic potential energy dissipation and acoustic kinetic energy dissipation, as shown in Figures 6 and 7. From the cloud diagram of the acoustic cavity model (Figure 6), the acoustic potential energy dissipation was mainly concentrated in the central area, and the kinetic energy was dispersed between the central and the outer edge to form a ring, in which the red area was the maximum value. In Figure 7(a), the left axis represented acoustic energy storage, and the right axis represented acoustic energy dissipation. It can be seen that the acoustic energy storage of PU/Al_2O_3 composite was lower than that of PU foam, while the acoustic energy dissipation of PU/Al_2O_3 composite was higher than that of PU foam. Figure 7(b) shows the loss factor for single-hole sound absorption. The sound loss factor was the ratio of system energy dissipation and energy storage. Both energy dissipation and energy storage would fluctuate continuously with changes in frequency. The loss factor of single-hole sound absorption could be obtained by calculation, which had an important influence on the vibration response of the predictive structure. It tended to change with frequency or temperature, showing a trend similar to the sound absorption coefficient. Zhang et al. [19] designed and successfully
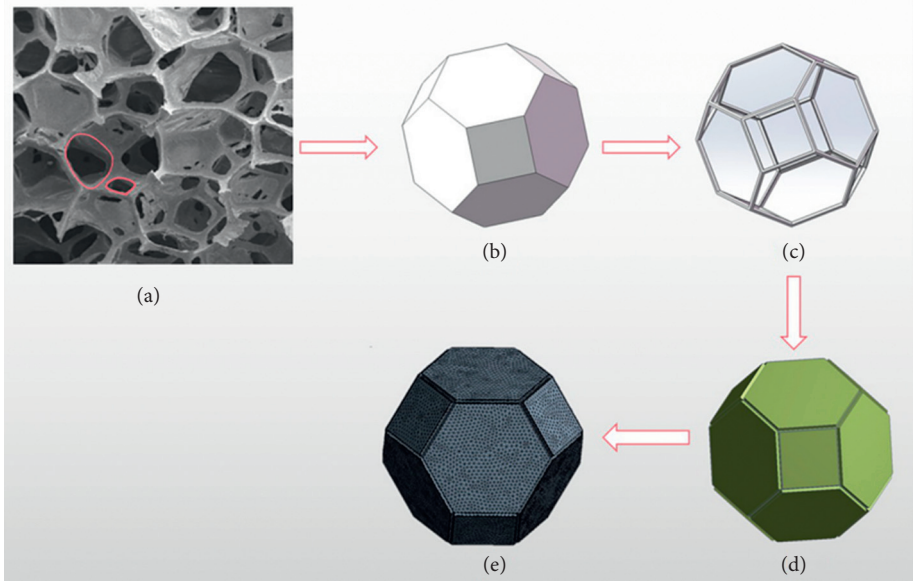
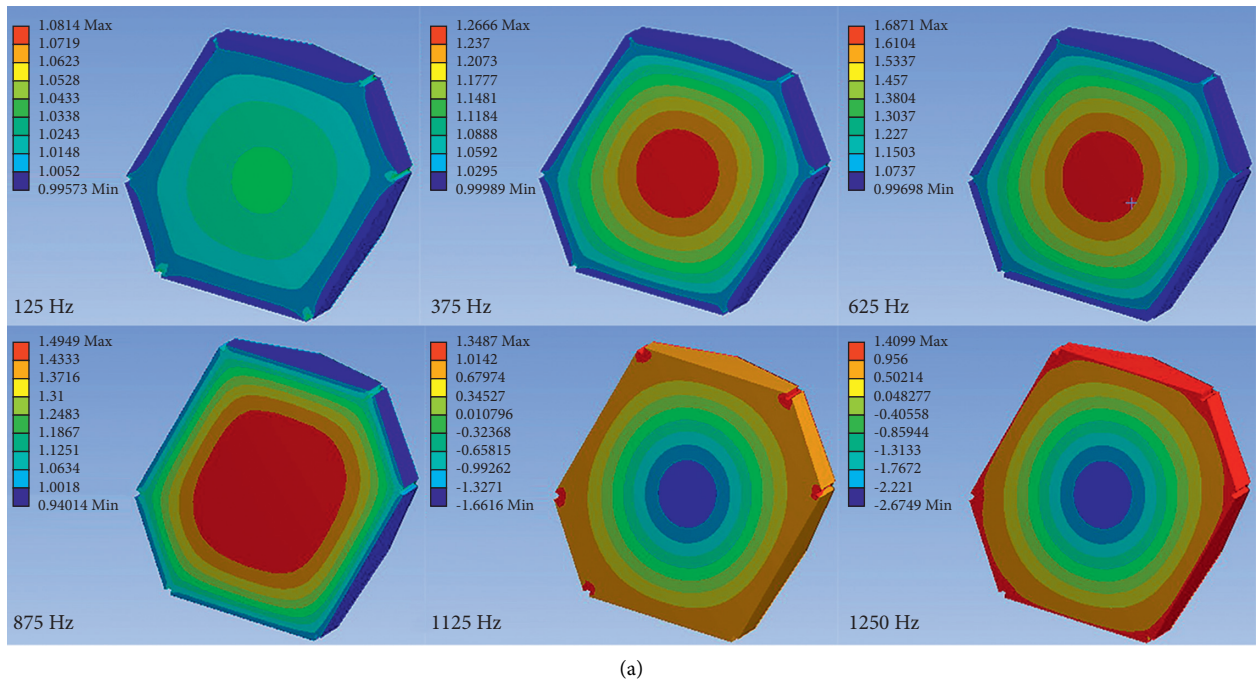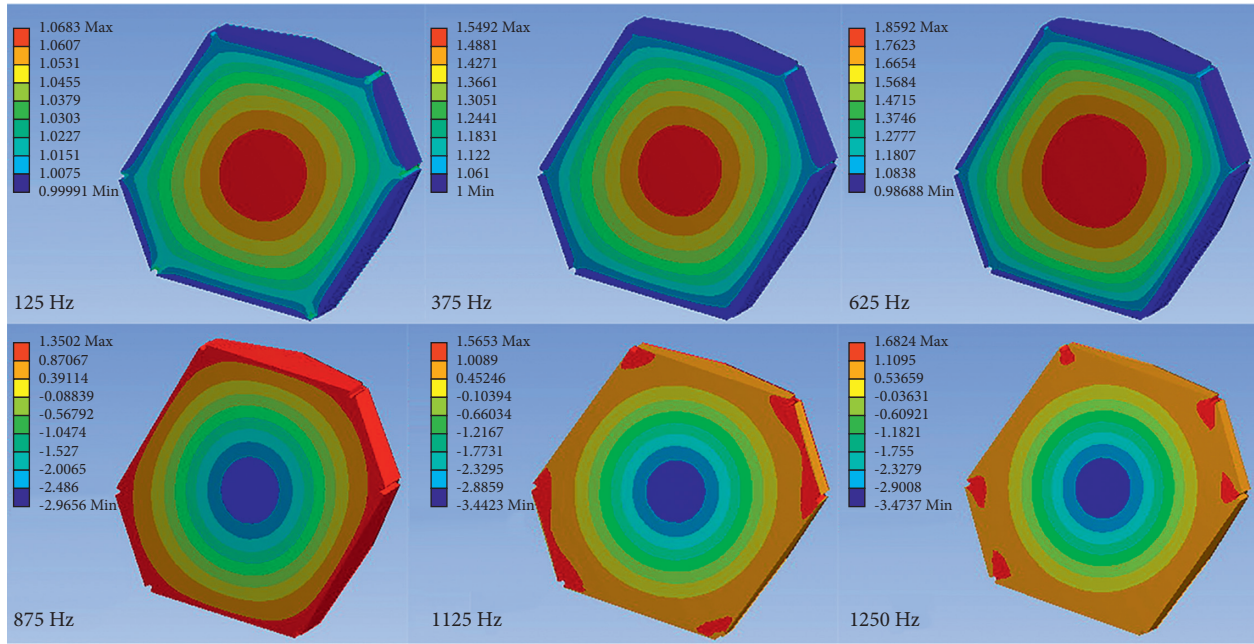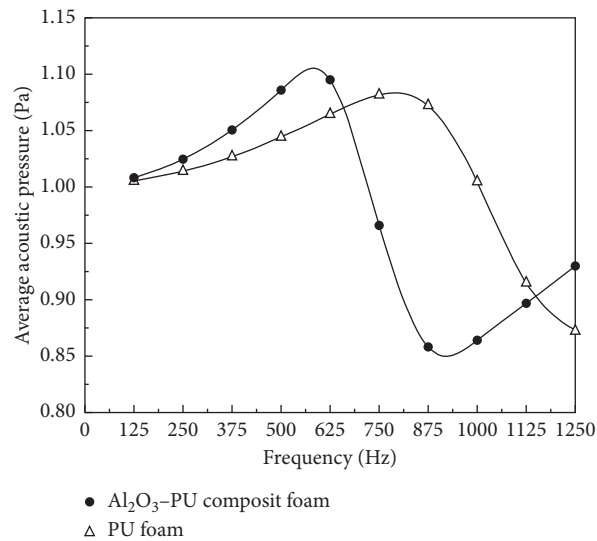FIGURE 4: The process of establishing a single-hole acoustic cavity model.

(a)

FIGURE 5: Continued.

(b)

(c)

FIGURE 5: (a) PU foam and (b) Al$_2$O$_3$/PU foam acoustic cavity section sound pressure topography in 125 Hz, 375 Hz, 625 Hz, 875 Hz, 1125 Hz, and 1250 Hz. (c) The average sound pressure change curve of PU foam and Al$_2$O$_3$/PU foam.

prepared a high-damping polyurethane/hollow glass microsphere sound insulation material and measured the loss factor of the polyurethane composite material. In the range of −80 to 60°C, the loss factor first increased and then decreased. The highest point was at −20°C, and the sound absorption performance was the best. Moradi et al. [20] measured the loss factor by studying the different ratios of PU and PMMA polymers. Thus, the loss factor of single-hole sound absorption can reflect the sound absorption coefficient of porous materials. From Figure 7, it can be

seen that the loss factor of single hole first rose to the highest point and then decreased with the increase of frequency. The loss factor of Al$_2$O$_3$-PU reached the highest point earlier than that of PU in the frequency range of 0–6000 Hz, and the highest points were 2750 Hz and 3500 Hz, respectively. Meanwhile, the loss factor of Al$_2$O$_3$-PU was higher than that of PU from 500 Hz to 4500 Hz. It can be predicted that the change rule of the sound absorption coefficient for PU foam and Al$_2$O$_3$-PU was similar to that of the loss factor.
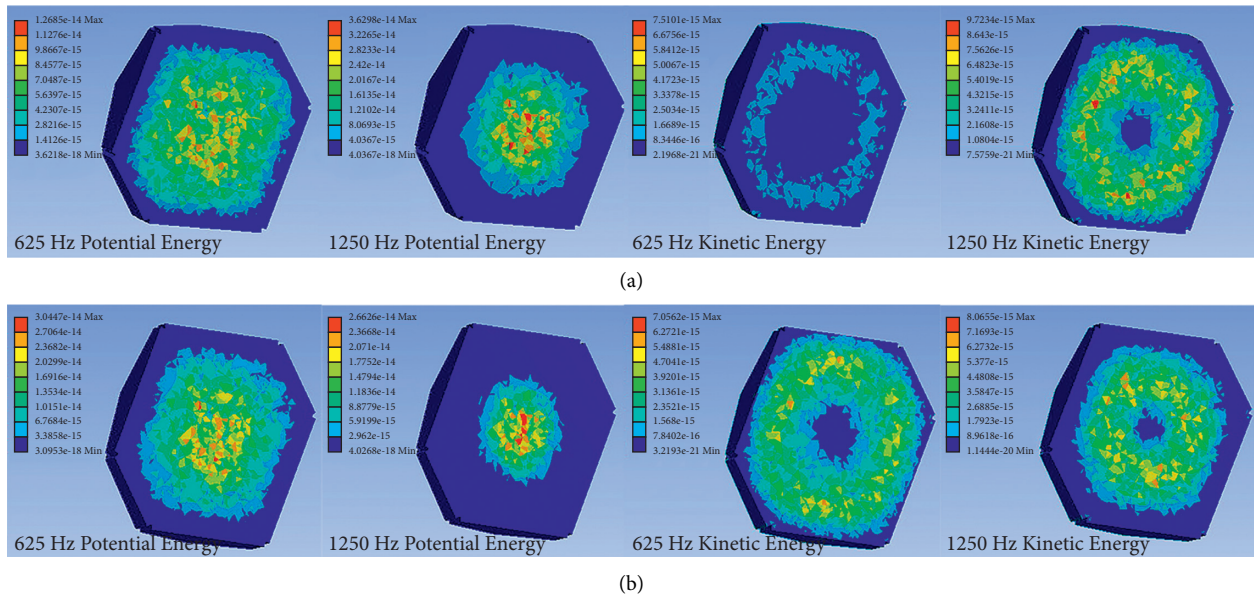
(a)

(b)

FIGURE 6: Acoustic potential energy and acoustic energy dissipation diagram at 625 Hz and 1250 Hz for (a) PU foam and (b) PU/Al$_2$O$_3$ foam.
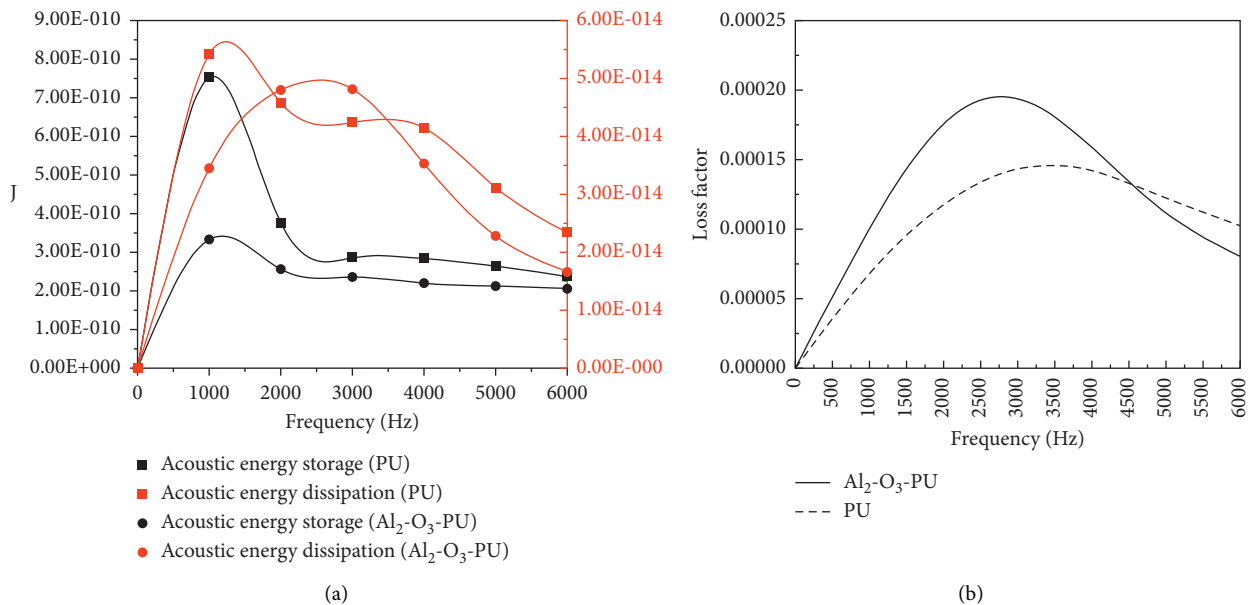

(a)

(b)

FIGURE 7: (a) Sound energy storage and sound energy dissipation of single-hole PU and Al$_2$O$_3$-PU foam. (b) Loss factor for single-hole sound absorption.

4. Conclusion

In this paper, a practical approach for obtaining PU composite foam directly soaked with nano Al$_2$O$_3$ was proposed. The method was easy to operate for preparing composite foams. Compared with pure PU foam, the density and air flow resistivity of the Al$_2$O$_3$-PU composite samples were higher, but the porosity decreased. The sound absorption coefficients of different PU and Al$_2$O$_3$-PU foam samples generally increased with the increase of frequency in the low-frequency range (50 Hz–1250 Hz). It can be seen that filling PU foam with Al$_2$O$_3$ nanoparticles could effectively improve the sound absorption performance in the low-frequency range. In addition, the microscopic single-hole model was established based on SEM images, and the absorption and dissipation process of PU/Al$_2$O$_3$ foam was faster than that of PU foam. Through studying the sound energy storage and sound energy dissipation process, the loss factor can be calculated. The results showed that the loss factor of Al$_2$O$_3$-PU was higher than that of PU from 500 Hz to 4500 Hz, and the highest points of Al$_2$O$_3$-PU and PU foam were 2750 Hz and 3500 Hz, respectively. It meant that the sound absorption properties of Al$_2$O$_3$-PU foam were better, which was consistent with the experimental results.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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