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Sound absorption of several various nickel foam multilayer structures at aural frequencies sensitive for human ears

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Abstract: Using the three-dimensional reticular nickel foam as experimental material, the sound absorption performance was investigated for several various multilayer structures in the frequency range of 2000−4000 Hz, which is aurally sensitive for human ears. The results showed that the 7.5 mm-thick foam sample, which was formed by piling of 5-layer foam plate (thickness: 1.5 mm; porosity: 96%; average pore-diameter: 0.65 mm) could exhibit an excellent sound absorption effect at 4000 Hz, with the absorption coefficient about 0.8. Constituting alternate air gap with the total thickness of about 18.5 mm can greatly improve the absorption performance at relatively low frequencies of 2000−3150 Hz, with the absorption coefficient up to about 0.5 or more. In addition, the research showed that alternate piling up the perforated plate inside the foam plates can also achieve a quite good effect of sound absorption at relatively low frequencies.

Key words: reticular nickel foam; composite structure of sound absorption; aurally sensitive frequency sound absorption

1 Introduction

At present, noise pollution is one of the major public hazards all over the world, which could be reduced mainly by using sound absorption materials [1]. Most sound absorption materials are of porous structure, and their sound absorption performances are largely studied theoretically in Refs. [2−4] and recently in Ref. [5]. Porous sound absorption materials are commonly of fibers and foams [6−9]. Though organic fiber sound absorption materials behave better in the intermediate and high frequency ranges, their usages are still limited in most applications due to their poor fire resistance and low anticorrosion and moistureproof performances. Inorganic fiber sound absorption materials are lightweight, anticorrosion and incombustible, but they are brittle and easy to break, resulting in the flying dust to damage the skin, pollute the environment, and influence the breathing. Foamed materials are usually superior to fibered ones in the overall properties. Nevertheless, the plastic foam will be fast aging with weak fireproofing, the glassy foam has low strength to be easily damaged, and the ceramic foam is of low toughness to be difficult for moving and installing. As a comparison, metal foams may have the merits simultaneously: high strength, good toughness, fireproofing, moistureproofing, high-temperature stability, and non-toxicity. Such foams are easy to be assembled and recycled, and may be widely applied in transportation, construction, electronics and aviation industries [10−12]. Although there have been some studies on the sound absorption performance for metal foams, the relevant works were mostly concentrated on the cellular aluminum foam [3,11−15]. Currently, the majority of metal foams on the market are closed-cell aluminum foams, but open-cell foams are more appropriate for some applications [14]. It is commonly believed that the noise reduction may be well realized by cellular foams with an abundant pore surface, so little interest has been in the sound absorption performance for reticular metal foams with a low air flow resistance.

With good ductility and toughness, metallic nickel is chemically quite stable to withstand weak acid, strong alkali, and air oxidation at a relatively high temperature (up to 1073 K). Large quantities of nickel foams, mainly used as electrode materials, are produced through the electrodeposition method in a number of countries. This

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kind of nickel foam is of reticulated thin plate structure with the sound absorption effect far worse than that of cellular open-cell foam structure, so the researches are very limited on the acoustic performance [16]. Human ears respond to audible sounds in the frequency range of 20−20000 Hz, with the most important range of 500−4000 Hz. In our previous work [17], the sound absorption was primarily explored for the porous structure based on the three-dimensional reticular nickel foam in a low frequency range of 200−2000 Hz. In this work, the sound absorption performance in a higher frequency range of 2000−4000 Hz was further investigated on several different composite structures of the nickel foam. A good sound absorption effect was expected to achieve by adjusting the assembling way and the structural factor for these composite structures, and this nickel foam was found to be well used as the sound absorption material at the relevant sound frequencies.

2 Experimental

2.1 Sample preparation

A 3-D reticular nickel foam sample was employed as the experimental material, which was produced by widely used electrodeposition process [18]. For this nickel foam, the electrical and mechanical properties have been reported in Refs. [19−21]. This foam sample is about 1.5 mm in thickness, 96% porosity, and 0.65 mm in the average pore-diameter, which was cut into a circular slice of 50 mm in diameter, as shown in Fig. 1.

2.2 Measurement

The sound absorption examinations were performed on a sound absorption coefficient measurement system developed by Beijing Century Jiantong Technology Development Company. Sound absorption coefficient of the sample was measured by the way of the stationary wave tube [22]: the sound wave, which is generated from a speaker, will move in the form of plane wave in the tube, and a standing wave field will be established when the incident wave reflects from the sample surface, presenting an alternate distribution of the sound pressure maximum (p_{max}) and minimum (p_{min}) along the tube axis. The sound pressure distribution was examined by a mobile detector in the tube, and the corresponding sound level maximum L_M and minimum L_m could be recorded, giving the sound absorption coefficient (α) at normal incidence for the sample:

$$\alpha=\frac{4\times 10^{(L_M-L_m)/20}}{\left(1+10^{(L_M-L_m)/20}\right)^2}=\frac{4\times 10^{\Delta L/20}}{\left(1+10^{\Delta L/20}\right)^2} \tag{1}$$

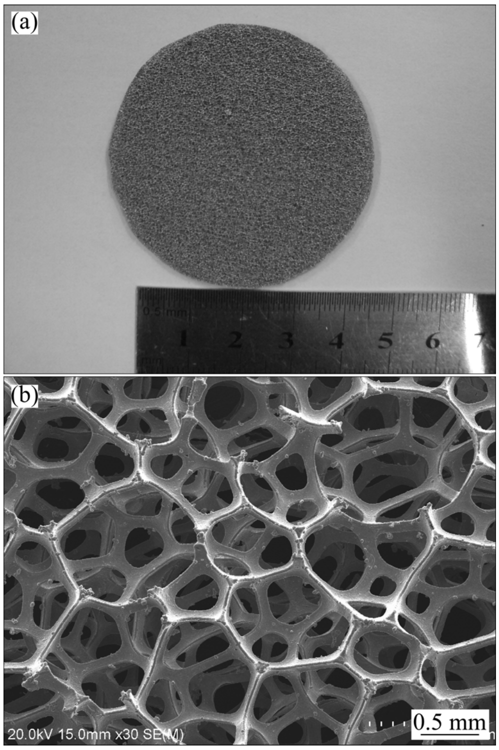

Fig. 1 Nickel foam sample for measuring sound absorption coefficient: (a) Macroscopic circular sample; (b) Magnified pore structure

Audible sound wave is in the frequency range of 20−20000 Hz, in which the intermediate range of 2000−4000 Hz is the most important for the sense of human hearing [2]. In the present work, the sound absorption performance was investigated for the above-mentioned nickel foam structure at 2000−4000 Hz. The absorption coefficient was measured following the 1/3 octave rule in the stationary wave tube. According to this rule, the measurement was performed selectively at four frequency points of 2000, 2500, 3150, and 4000 Hz. Initial decibel value of the sound signal was tuned to the sound level, of which the maximum L_M and minimum L_m were recorded in the same period. With the repeated measurement at different initial decibel values, the average of L_M-L_m (ΔL) could be obtained to calculate the sound absorption coefficient by using Eq. (1).

3 Results

3.1 Laminated structure of nickel foam and multilayer structure of nickel foam with air gap

Five layers of the nickel foam sample (Fig. 1) were laminated together to get a total thickness of 7.5 mm (see Fig. 2), and then loaded into the sample tube, against the rigid wall. Figure 2 presents the sound contacts of samples: the boundary between different sample layers cannot be easy to find unless the cut edge inwards retreats due to the cutting force for sample preparation, for example, the boundary between the fourth and fifth layers close to the graduated ruler. Sound level maximum L_M and minimum L_m were measured at the four center frequencies of 2000, 2500, 3150 and 4000 Hz in 1/3 octave range, and the sound absorption coefficients of the samples were then calculated by Eq. (1). Two samples were measured at each center frequency, and the average values were taken, as listed in Table 1.

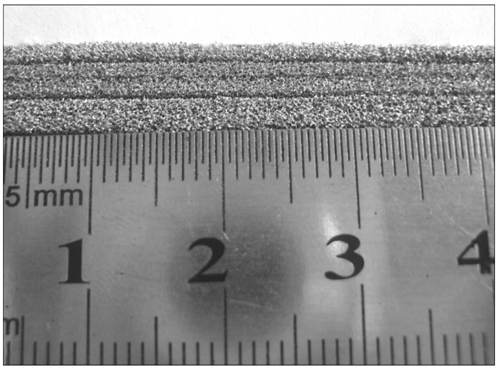

Fig. 2 Sidelong photograph of combined samples of 5-layer nickel foams

Based on the above operation, an air gap was arranged between the sample and the rigid wall of the sample tube. The 18.5 mm-thick air gap was structured by five 3.7 mm-thick polymethyl methacrylate (PMMA) rings with the inner and outer diameters of 40 mm and 50 mm, respectively, as shown in Fig. 3. The measured results are also listed together in Table 1.

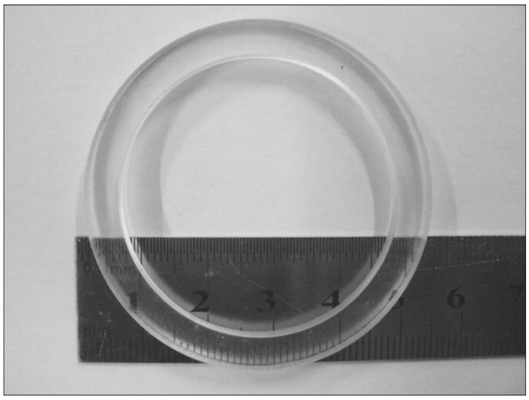

Fig. 3 PMMA ring for constructing air gap

In order to investigate the combined effect of the air gap and the nickel foam sample, the 1.5 mm-thick nickel foam sample and the 3.7 mm-thick air gap were laminated alternately to form a five-layer structure, with the total thicknesses of the nickel foam samples and the air gap to be 7.5 mm and 18.5 mm, respectively. The measured results are listed in Table 2.

3.2 Laminated structure of nickel foam and perforated plate

Matching the nickel foam sample, the 304 stainless steel perforated plate was also made into a round one with diameter of 50 mm (Fig. 4). These perforated plates are about 1 mm in thickness, and 4 mm in diameter for their holes with the density of about 1/cm^2. The

Table 1 Sound absorption coefficients at normal incidence for multilayer structure of 5-layer nickel foam samples with and without air gap at different sound frequencies

No.	Sound frequency, f/Hz	Foam thickness/mm	Air gap thickness/mm	ΔL/dB	α	Average value of α
1	2000	7.5 (5 layers)	0	21.7	0.281	0.21
2	2000	7.5 (5 layers)	0	28.4	0.141	0.21
3	2500	7.5 (5 layers)	0	17.9	0.401	0.29
4	2500	7.5 (5 layers)	0	26.3	0.176	0.29
5	3150	7.5 (5 layers)	0	19.2	0.356	0.29
6	3150	7.5 (5 layers)	0	23.9	0.226	0.29
7	4000	7.5 (5 layers)	0	7.7	0.827	0.79
8	4000	7.5 (5 layers)	0	9.4	0.756	0.79
9	2000	7.5 (5 layers)	18.5 (5 layers)	17.9	0.401	0.38
10	2000	7.5 (5 layers)	18.5 (5 layers)	18.9	0.366	0.38
11	2500	7.5 (5 layers)	18.5 (5 layers)	15.1	0.509	0.51
12	2500	7.5 (5 layers)	18.5 (5 layers)	15.1	0.509	0.51
13	3150	7.5 (5 layers)	18.5 (5 layers)	14.8	0.521	0.54
14	3150	7.5 (5 layers)	18.5 (5 layers)	13.7	0.568	0.54
15	4000	7.5 (5 layers)	18.5 (5 layers)	8.9	0.777	0.80
16	4000	7.5 (5 layers)	18.5 (5 layers)	7.9	0.819	0.80

assembled details of the nickel foam and the perforated plate are listed in Table 3. Sound absorption coefficients at 2000, 2500, 3150, and 4000 Hz were measured and listed in Table 4.

Table 2 Sound absorption coefficients at normal incidence for composite structure with alternatively laminated foam sample and air gap at different sound frequencies

No.	Sound frequency, f/Hz	Foam thickness/ mm	Air gap thickness/ mm	ΔL/ dB	α	Average value of α
1	2000	7.5 (5 layers)	18.5 (5 layers)	15.9	0.476	0.49
2	2000	7.5 (5 layers)	18.5 (5 layers)	15.0	0.513	0.49
3	2500	7.5 (5 layers)	18.5 (5 layers)	14.9	0.517	0.52
4	2500	7.5 (5 layers)	18.5 (5 layers)	14.9	0.517	0.52
5	3150	7.5 (5 layers)	18.5 (5 layers)	14.6	0.529	0.54
6	3150	7.5 (5 layers)	18.5 (5 layers)	14.2	0.546	0.54
7	4000	7.5 (5 layers)	18.5 (5 layers)	9.8	0.739	0.75
8	4000	7.5 (5 layers)	18.5 (5 layers)	9.5	0.752	0.75

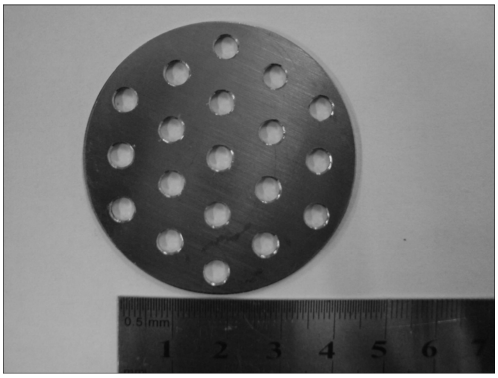

Fig. 4 Stainless steel perforated plate

Table 3 Assembled details of nickel foam piece and perforated plate

No.	Structure	Total thickness of nickel foam piece/mm	Total thickness of perforated plate/mm
1	6*(A)	9.0 (6 layers)	0
2	6*(A)	9.0 (6 layers)	0
3	BAAAAAA	9.0 (6 layers)	1
4	BAAAAAA	9.0 (6 layers)	1
5	2*(BAAA)	9.0 (6 layers)	2
6	2*(BAAA)	9.0 (6 layers)	2
7	3*(BAA)	9.0 (6 layers)	3
8	3*(BAA)	9.0 (6 layers)	3

A is nickel foam piece; B is perforated plate; x*(BA) means x pieces of (BA), i.e. (BA) repeats x times; the nickel foam piece or the perforated plate denoted by the left letter was near the rigid wall

4 Discussion

4.1 Laminated structure of nickel foam and multilayer structure of nickel foam with air gap

4.1.1 Air gap effect on sound absorption

Sound absorption mechanisms of metal foams mainly include the viscous dissipation from the friction between the pore wall and the fluid inside the pores, and the damping attenuation of the materials themselves. Each mechanism plays different roles depending on different material structures and application environments [2,22−24]. When the sound wave enters the open-cell foam, the air in the pores will vibrate, and the friction will occur between the air and the pore wall. The friction and the viscous force will convert a considerable part of the sound energy into heat energy. Also, the heat exchange between the air and the pore wall will cause some heat loss. In addition, the diffuse reflection of the sound wave will occur on the pore surfaces to result in an interference silencing.

After sound waves propagate into the metal foam, the low frequency wave, with small amplitude, will generate an elastic collision on the pore wall to result in a small energy loss, presenting a low absorption coefficient. The high frequency waves, with large amplitude, will generate a non-elastic collision, and a high absorption coefficient can be expected. A good sound absorption effect can achieve if there is a resonance between the system and the sound wave.

As seen from Table 1, the sound absorption system, assembled by five layers of the nickel foam without air gap, preformed a poor sound absorption at 2000, 2500 and 3150 Hz. The sound absorption coefficient increased as the sound frequency increased, but it was still quite low and less than 0.3. However, when the frequency reached 4000 Hz, the porous system had the sound absorption coefficient rapidly approaching 0.8, and became an efficient sound absorption one.

Porous absorption system is a multi-resonator with a number of resonance frequencies [2,25]. It can be concluded that 4000 Hz should be or be close to a resonant frequency of the present porous system, and this frequency point is located in the range sensitive to the human ear. Therefore, if the noise source covers around 4000 Hz, the porous system can get a good sound absorption and noise reduction.

Constructing a 18.5 mm-thick air gap behind the above laminated nickel foam structure, the sound absorption coefficient of the resultant system could be close to 0.4 at the frequency of 2000 Hz, and even above 0.5 at the frequencies of 2500 and 3150 Hz, presenting a significant increase of the absorption effect. The variation of absorption coefficient became slow above

Table 4 Sound absorption coefficients at normal incidence for different combinations of nickel foam and perforated plate at various frequencies

Sample No.	2000 Hz			2500 Hz			3150 Hz			4000 Hz		
	ΔL/dB	Mean ΔL/dB	α	ΔL/dB	Mean ΔL/dB	α	ΔL/dB	Mean ΔL/dB	α	ΔL/dB	Mean ΔL/dB	α
1	23.7	24.1	0.22	25.7	22.5	0.26	24.1	22.2	0.27	9.2	9.2	0.76
2	24.4	24.1	0.22	19.3	22.5	0.26	20.3	22.2	0.27	9.2	9.2	0.76
3	23.4	25.1	0.20	24.4	22.5	0.26	19.8	21.9	0.28	8.8	8.3	0.80
4	26.8	25.1	0.20	20.6	22.5	0.26	24.0	21.9	0.28	7.8	8.3	0.80
5	20.7	19.5	0.35	15.7	15.9	0.48	12.9	15.8	0.48	7.1	10.9	0.69
6	18.2	19.5	0.35	16.1	15.9	0.48	18.8	15.8	0.48	14.7	10.9	0.69
7	19.7	20.0	0.33	17.3	16.3	0.46	14.2	14.2	0.55	8.2	10.2	0.72
8	20.3	20.0	0.33	15.2	16.3	0.46	14.2	14.2	0.55	12.2	10.2	0.72

the frequency of 4000 Hz. Therefore, it can be concluded that the sound absorption performance could be greatly improved in the low frequency range by including air gap, and it could be still good in the intermediate frequency range.

The effect of air gap on the absorption performance of the system should be mainly due to tuning the resonance parameters of the whole system, and increasing the number of mutual reflection and oscillation of the sound wave on the surface and the rigid cell-wall of the porous body. The mechanical damping thus increased in the composite structure.

The resonance absorption is mainly from the Helmholtz type structure, which makes use of the resonance resulted from the incident sound wave in the structure to consume a lot of sound energy [26]. The sound absorption effect would become better with air gap behind the porous material. Viscous loss and heat loss are two main dissipation mechanisms without air gap, and the Helmholtz resonance absorption will also play an important role with air gap [2]. It is found that the connected pores in the metal foam are equivalent to the resonator tubes, which can constitute a great deal of Helmholtz resonators, with the back air gap together. These resonators will locate their resonant frequencies generally in the low frequency range. Because of these complex resonators, most of the low frequency acoustic waves can be dissipated when the sound wave enters the material to cause the resonance of the metal foam structure.

The resonance between the sound wave and the system increases not only the damping of the material itself, but also the viscous loss of the fluids, and the friction loss between the air and the pore wall. A very high absorption coefficient can be expected at the resonance frequency.

4.1.2 Relationship between air gap thickness and sound absorption performance

According to Refs. [24,25], the sound absorption coefficient of the system composed of the perforated plate and the air gap under the condition of normal sound incidence can be expressed as

$$\alpha_{\mathrm{N}}=\frac{4r}{(1+r)^2+[\omega m-\cot(\omega D/c_0)]^2} \tag{2}$$

where r is the relative acoustic impedance rate of the perforated plate; ω is the incident wave angular frequency (rad/s), and it equals $2\pi f$, here f is the incident wave frequency (Hz); m is the relative acoustic quality of the perforated plate, and ωm is the acoustic reactance ratio of the perforated plate; D is the thickness of the air gap, i.e., the distance between the perforated plate and the rigid wall; c_0 is the propagation speed of the sound wave in air, and it equals 340 m/s at room temperature; $-\cot(\omega D/c_0)$ is the acoustic resistance ratio of the air gap.

$$r=\frac{32\eta\delta}{\theta\rho_0 c_0 d^2}[\sqrt{1+(k^2/32)}+\sqrt{2}kd/(32\delta)] \tag{3}$$

$$m=\frac{\delta}{\theta c_0}(1+1/\sqrt{9+k^2/2}+0.85d/\delta) \tag{4}$$

where η is the dynamic viscosity of the air, and $\eta \approx 1.85\times10^{-5}$ kg/(m·s) at room temperature; δ is the thickness of the perforated plate; θ is the ratio of the total area of holes and that of the plate; ρ_0 is the static air density, and ρ_0=1.2 kg/m^3 at room temperature; d is the diameter of the hole on the perforated plate; k is a constant of the perforated plate, and

$$k=d\sqrt{\omega\rho_0/4\eta} \tag{5}$$

Pores in the metal foam could be often treated as connected straight holes for simplifying the relevant deduction. If open-cell metal foams are treated as a perforated plate with the equivalent diameter of d, the sound absorption coefficient of the three-dimensional reticulated nickel foam with air gap can also be approximately estimated by Eq. (2). The cotangent function in Eq. (2) is a periodic one with the period of π, so the variation of the air gap thickness D has an influence on the porous structure of sound absorption periodically under the same conditions. The most reasonable structure requires the maximum sound absorption coefficient of an absorption system occupying the minimum space, so the optimal value of the air gap thickness D is based on Eq. (2):

$$D=c_0\times[\mathrm{arccot}(2\pi fm)]/(2\pi f) \tag{6}$$

According to Eqs. (4)−(6), the optimal value of the air gap thickness is related not only to the frequency of the absorbed sound, but also to the thickness, the porosity and the pore size of the porous absorption body. Therefore, the frequency range should be firstly considered to design this kind of sound absorption structure. Based on this, the appropriate thickness, porosity and pore size would be selected for the porous absorption material, and the optimal value of the air gap thickness could be calculated finally.

4.1.3 Combination mode effect on sound absorption

As shown in Table 2, the sound absorption coefficient is close to 0.5 at 2000 Hz for the alternate nickel foam plate and air gap structure mode with total thickness of 26.0 mm and five layers of nickel foams. The absorption performance has an evident improvement compared with the above-mentioned structure of laminated five layers of nickel foam plates with 18.5 mm-thick air gap, and a more improvement on that of only five layers of nickel foam plates without air gap. There was almost no difference of the absorption effect between two systems of the alternate air gaps and the large air gap at 2500 and 3150 Hz. In conclusion, the alternate system could be in favor of sound absorption only at low frequencies, but could not at intermediate frequencies.

4.2 Laminated structure of nickel foam and perforated plate

As shown in Table 4, the average absorption coefficient of the laminated structure of six-layer nickel foams is lower than 0.27, and that of the laminated sample with a backed layer of the perforated stainless steel plate is almost the same at 2000, 2500 and 3150 Hz. As the frequency continues to increase, the absorption coefficients begin to increase and reach 0.76 and 0.8, respectively, for the above two kinds of combined samples at 4000 Hz. It is found that the absorption performance of the nickel foam was very poor in low frequency range, and it became relatively high only above 3150 Hz, with the peak that should come forth over 4000 Hz. This is not ideal for the actual noise reduction. The absorption effect could not be improved by a perforated plate next to the rigid wall for the laminated nickel foams. Judging with the absorption mechanism, the viscous dissipation plays a major part to absorb sound energies for the laminated sample without the perforated plate. The small resonant air gap would form by adding a perforated plate behind the nickel foam, and the resonance dissipation and the impedance matching effect would bring forth, but the absorption improvement was quite poor due to a small air gap volume.

When two layers of perforated plates were respectively located at the bottom and in the middle of the nickel foam layers, the absorption coefficient was significantly improved at 2000, 2500, and 3150 Hz. The absorption coefficient rose up to 0.35 at 2000 Hz, and above 0.45 at 2500 and 3150 Hz. But it was nearly the same as that of samples 1−4 at 4000 Hz. From the change trend of the absorption coefficient, the absorption peak frequency of the samples with two layers of perforated plates should be lower than that of samples 1−4, and the average absorption would be better.

Samples 5 and 6 have the same total thickness of nickel foam as the sample with only nickel foam, and the same area of holes in the perforated plate as samples 3 and 4 in Table 3, so it can be believed that the incident wave energy and the viscous dissipation ratio are not increased. The only difference between these two kinds of samples is that a new resonance gap formed between two perforated plates, the sound waves would be absorbed by the nickel foam core after they run into the first layer of the perforated plate, and reflected by the second layer of the perforated plate to form a Helmholtz resonance between these two perforated plates. One dimensional movement system would be built up by the air in the perforated plate and in the nickel foam to cause a resonance for the sound waves. The inner air vibration will be the strongest under resonance.

In the actual cases, each hole in the perforated plate can be considered as a separate Helmholtz resonance cavum constituted with the nickel foam core, and the interference will yield among each resonant air gap. At the same time, the porous structure of the nickel foam core between the perforated plates will reduce the liquidity of the air in the air gap and increase the sound energy loss from the elastic deformation, making a shift of the frequency at which the absorption peak occurs. Near the frequency for the absorption peak of the laminated nickel foam without the perforated plate, the absorption coefficient increased at all frequencies, and the absorption performance greatly improved.

Keeping the total thicknesses of nickel foam constant and adding three layers of perforated plates to the sample, the absorption coefficients are 0.33, 0.46, 0.55 and 0.72 at 2000, 2500, 3150 and 4000 Hz, respectively, which are roughly the same as that for adding two layers of perforated plates.

According to the change trend of the absorption coefficient, the peak of all samples will appear after 3150 Hz, and exhibits a good absorption in the audible range of human ear. Low frequency sound absorption will be evidently enhanced if the perforated plate is included. It can be known from Table 4, the sound absorption of the multilayer structure will increase at a relatively low frequency if more perforated plates are inserted among the nickel foam layers, and its peak will move to the lower frequency.

The relatively poor sound absorption behavior of cellular metallic foams with closed cells is due to the closed porous structure, so a rolling operation is often conducted to decrease the closed porosity. On the other hand, the sound absorption of reticular metallic foams is also very poor, because the porous structure is too open and leads to very low flow resistance. Such absorption may be even much poorer than that of common metallic foams with cellular structures. To overcome this disadvantage of reticular metallic foams, the practical measures may use relatively thick samples and take appropriate composite structures.

5 Conclusions

1) A poor sound absorption was found for the laminated structure of three-dimensional reticulated nickel foam plates, with a total thickness of 7.5−9.0 mm, in the relatively low frequency range (e.g., <3150 Hz), but an excellent one in the intermediate frequency range. For instance, an acoustic resonance could achieve with the sound absorption coefficient of about 0.8 around 4000 Hz.

2) Adding a certain thickness of the air gap to the reticulated nickel foam plate laminated structure with a total thickness of 7.5−9.0 mm, the sound absorption may be greatly improved in the relatively low frequency range. For example, the absorption coefficient at normal incidence can significantly increase to above 0.5 at 2500 and 3150 Hz. If taking the assembling way of alternately overlapping the nickel foam plate and the air gap, a better sound absorption in the low frequency can be obtained, with the absorption coefficient close to 0.5 at 2000 Hz.

3) Adding the perforated plate on the surface of the sample will impact a little on the sound absorption, while adding it inside the laminated structure will improve a lot. When the number of inner perforated plates continues to increase, their overall impact decreases gradually, but may still enhance the sound absorption at low frequencies. From the balance between the structure cost and the performance, the effect of adding the air gap is better than that including the perforated plate.

Acknowledgments

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泡沫镍的几种不同复层结构在人耳敏感区的吸声性能

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摘 要：采用三维网状泡沫镍作为实验材料，探讨几种不同复层结构在 2000~4000 Hz 人耳敏感声频内的吸声行为。结果发现，对于孔隙率为 96%、厚度为 1.5 mm、平均孔径为 0.65 mm 的泡沫镍，五层叠合成总厚度为 7.5 mm 的泡沫样品在 4000 Hz 时表现出优良的吸声效果，其吸声系数达到 0.8 左右。层间交替加入空腔组成总厚度 18.5 mm 的叠层结构，可以大大改善相对较低频段 2000~3150 Hz 的吸声性能，吸声系数提高到大约 0.5 甚至更高。此外，在泡沫板之间交替堆积穿孔板也可在相对较低频段获得较好的吸声效果。

关键词：网状泡沫镍；复合吸声结构；听觉敏感频段吸声

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