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Design and manufacture of metal membrane microperforated panel absorbers

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Abstract. Metal Membrane MPP (Microperforated Panel) is a kind of promising acoustic absorber due to its steady absorption performance and the convenience in process. In order to reveal the effects of pivotal parameters on absorption coefficient, an acoustic model of MPP is derived based on classic theory. The optimized parameters are found using genetic algorithm by the aid of this model. The MPP samples made of aluminum are manufactured by laser drilling and then the absorption coefficient is measured in impedance tube. The result shows that the theoretical model can predicted the absorption behavior of metal MPP relatively accurately. And the peak absorption coefficient, peak frequency, and the half-absorption band width are about 0.9, 2000Hz and 3200Hz respectively.

1. Introduction

Noise control has attracted great attention in the modern mechanical and environmental engineering [1-3]. Countless kinds of materials have been developed to alleviate the adverse effect of noise. Due to the unique acoustic characteristics, MPP (microperforated panel) absorbers became a research focus since its first appearance over forty years ago [4-5]. As compared to traditional sound absorber, MPP are often made of relatively simple materials without the addition of fiber or foam for the general case. Thus, as far as MPP absorber is concerned, there is almost no need to worry about the problems of material deterioration and particle dislodging over time [6-7]. And as a result, the air pollution caused by fiber or foam can be well controlled for indoor applications. Maa [8-10] and his collaborators carried out the pioneering works of MPP based on the research of Rayleigh on the theory of sound wave propagation in small cylindrical tube [11]. And the practical application of MPP absorbers in the plenum of the Deutscher Bundestag in Bonn, Germany is an undoubted successful premiere to show the enormous potential of MPP [12]. Furthermore, absorption of broadband noise by sonic crystals consisting of microperforated cylindrical shells is proposed and experimentally demonstrated by Wave Phenomena Group, Universitat Politècnica de València of Spain [13].

It has been a long time that glass and plastic are commonly used in MPP fabrication. But the processing of both of them suffers from difficulty in thickness thinning since the thickness of MPP is often lower then 1mm. For glass membrane, the problem is the fragility. And it is not easy to manufacture a thin enough plastic MPP with proper stiffness due to its inherent physical properties. Thus, the application of metal in MPP fabrication is more and more popular. And due to its excellent mechanical characteristics and unique antirust property, aluminum is a proper material for MPP manufacturing.

However, at the beginning of the development of MPP, the holes within MPP were several millimeters even centimeters in diameters because of the limitation of manufacturing method at that time. The absorption coefficient of this kind of MPP absorbers was very low and corresponding frequency band was narrow. In other words, the acoustic characteristics could not be satisfactory for practical application.

Along with the progress of manufacturing technology, the micro holes on the order of submillimeters can be achieved nowadays. Mechanical machining (micro-drilling), electric discharging and even chemical etching are eligible techniques by which holes with the diameters of several micrometers can be realized for MPP. But for these methods, manufacturing flexibility is relatively low because one set of equipment (drilling bit, discharging electrode, etching mask, etc.) is only designed for one fixed diameter. Therefore the processing cost will increase greatly if diameter changes. In this case, laser drilling is a better choice since its focal spot can be adapted to different diameters conveniently.

Based on the properties of materials and manufacturing techniques, MPPs made of aluminum are designed. Corresponding pivotal parameters are investigated and optimized. The samples processed by laser drilling are tested in a standing wave tube. The result shows that the aluminum membrane MPP after optimized design has satisfactorily high absorption coefficient and wide frequency band.

2. Fundamental theory

A typical MPP structure consists of a perforated membrane, an air cushion and a rigid wall as shown in Figure 1(a). Every perforated hole and the part of air cushion just underneath constitute a tube cell which can be regarded as a Helmholtz resonator as shown in Figure 1(b). Therefore entire MPP is considered as a combination of all the tube cells. The thickness of perforated panel is t. The cavity depth (thickness of air cushion) is D and interval between holes is b.

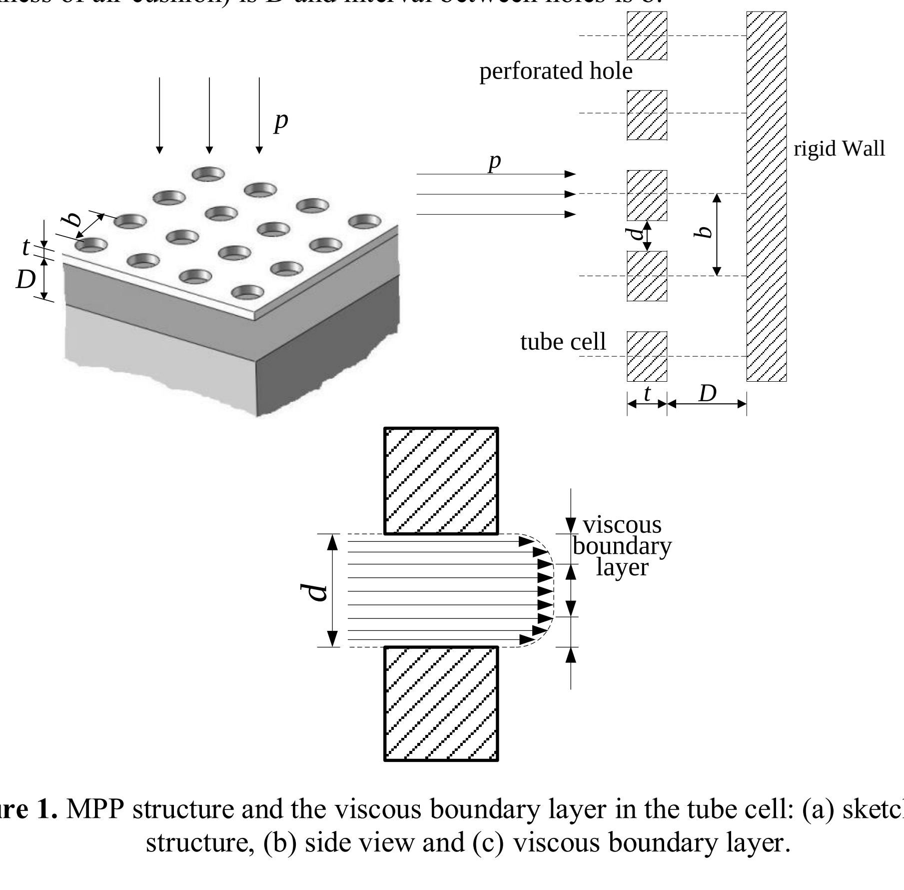

Figure 1. MPP structure and the viscous boundary layer in the tube cell: (a) sketch of the structure, (b) side view and (c) viscous boundary layer.

Based on this structural characteristic, Maa developed the fundamental mathematic model of MPP [8-10]. The acoustic impedance Z of every tube cell is

$$Z = j\omega\rho_0 t\left[1-\frac{2}{x\sqrt{-j}}\frac{J_1(x\sqrt{-j})}{J_0(x\sqrt{-j})}\right]^{-1} \tag{1}$$

Where ω, ρ_0, t are the angular frequency, air density, panel thickness respectively. The symbol x is a dimensionless friction parameter which presents the relationship between the tube radius and thickness of viscous boundary layer which is shown in Figure 1(c) .

$$x = d\sqrt{\frac{\omega\rho_0}{4\eta}} \tag{2}$$

The symbol η represents the viscosity of air. J_0, J_1 are the zero and first order of Bessel's function of the first kind respectively. A reasonable approximation of Eq.1 is

$$Z = \frac{32\eta t}{d^2}\sqrt{1+\frac{x^2}{32}} + j\omega\rho t\left(1+\frac{1}{\sqrt{3^2+\frac{x^2}{2}}}\right) \tag{3}$$

The Eq. 3 is the sound impedance of one micro tube. When perforation rate p (area ratio of holes to total panel) is low (typically 1%-5%), the interval between holes is much larger than the diameter. Thus the interference of adjacent holes can be ignorable. The relative acoustic impedance of the MPP is

$$z = \frac{Z}{p\rho c} = r + j\omega m \tag{4}$$

where c is the sound velocity in air and ρc is the characteristic impedance. The relative acoustic resistance r with end correction r_{ec} can be expressed as

$$r = \frac{32\eta t}{p\rho c d^2}\left(\sqrt{1+\frac{x^2}{32}} + r_{ec}\right) \tag{5}$$

And relative acoustic mass m with end correction m_{ec} is

$$m = \frac{t}{pc}\left(1+\frac{1}{\sqrt{3^2+\frac{x^2}{2}}} + m_{ec}\right) \tag{6}$$

It is confusing that the expression of r_{ec} has two different versions. According to early analysis of Maa [4-6], the correction of acoustic resistance due to the friction loss caused by the air flow near the inlet and outlet of micro tube is $2(2\omega\rho\eta)^{1/2}$. If this correction is used, r_{ec} should be

$$r_{ec} = \frac{\sqrt{2}}{8}x\frac{d}{t} \tag{7}$$

This result had been accepted over several decades. Even today it is still used in some articles. However, this expression of r_{ec} was found too high when x was large [9]. As a result, extra error would be introduced. Then the correction of acoustic resistance was modified by Maa himself to $(1/2)(2\omega\rho\eta)^{1/2}$ [9]. And correspondingly, the expression of rec was revised to

$$r_{ec} = \frac{\sqrt{2}}{32}x\frac{d}{t} \tag{8}$$

As to end correction m_{ec}, the compensation of acoustic mass is $0.85d$, thus,

$$m_{ec} = 0.85\frac{d}{t} \tag{9}$$

And the *r*, *m* should be, respectively,

$$r=\frac{32\eta t}{p\rho c d^2}\left(\sqrt{1+\frac{x^2}{32}}+\frac{\sqrt{2}}{32}x\frac{d}{t}\right) \tag{10}$$

$$m=\frac{t}{pc}\left(1+\frac{1}{\sqrt{3^2+\frac{x^2}{2}}}+0.85\frac{d}{t}\right) \tag{11}$$

The absorption coefficient of MPP for normal incidence sound, α is

$$\alpha=\frac{4r}{(1+r)^2+(\omega m-\cot(\omega D/c))^2} \tag{12}$$

From Eq. 12, when ωm-cot($\omega D/c$)=0, the peak of absorption coefficient α_p can be deduced as

$$\alpha_p=\frac{4r}{(1+r)^2} \tag{13}$$

The corresponding approximation of frequency was given in Maa's article [4] as

$$f_p=\frac{1/2\pi}{\sqrt{(m+\mathrm{D}/3c)(\mathrm{D}/c)}} \tag{14}$$

When α is $1/2\alpha_p$, there are two half-absorption frequencies. The difference between these frequencies is half-absorption band width which can be deduced approximately as,

$$\Delta f=\frac{1+r}{2\pi(m+D/3c)} \tag{15}$$

Now along with the development of computers and mathematical software, the numerical solutions of these variables with higher accuracy are available.

3. Experiment

3.1. Parameters Design

It is almost impossible to find a parameters combination of MPP which has high absorption coefficient, wide absorption frequency band and proper peak absorption frequency at the same time. Thus, according to the application of this MPP, the design target is to find the most appropriate parameters combination for the frequency range of 1kHz to 5kHz. Genetic algorithm method is used to search the optimized results of parameters combination. Based on the analysis above, searching ranges of *t*, *d*, *p*, *D* are 0.02mm to 1.00mm, 0.1mm to 0.5mm, 0.1% to 10.0% and 5mm to 200mm, respectively. The 1/3-octave bands frequency of 1000Hz，1250Hz，1600Hz，2000Hz，2500Hz，3150Hz，4000Hz，5000Hz are chosen as inspection points for the searching. And in order to enhance the constraint, the 1/6-octave bands frequency (1125Hz, 1450Hz, 1800Hz, 2250Hz, 2900Hz, 3600Hz, and 4500Hz) are also included as inspection points. Among these 15 points of frequencies, if there are 12 (i.e., 80%) or more points at which the absorption coefficient is higher than 50% (half-point), the corresponding parameters combination of MPP is regarded a reasonable result. The searching results are shown in Table 1.

According to the searching results, there are 7 eligible parameter combinations. The numbers of half-point of combination no.1 and no.3 are 13 which is one more than that (12 half-points) of others. However, the thickness for both of them is higher than their diameters. In this case, on one hand, the thermal effect is not ignorable and the distinct error will be introduced. On the other hand, the relatively high aspect ratio will lead to the difficulty in processing. And for those combinations except no.1 and no.3, the parameter values concentrate on a narrow range (*t*: 0.104-0.106mm; *d*: 0.100-0.107mm; *p*: 0.02994-0.03000; *D*: constant 30mm). In order to realize convenient processing, the parameters are decided as 0.100mm, 0.100mm, 0.03000 and 30mm for t, d, p, D respectively. And for this optimized combination, there still are 12 half-points as shown in Figure 2.

Table 1. Searching results of parameters combinations.

No.	t: mm	d: mm	p	D: mm	Number of half-points
1	0.123	0.100	0.02974	30	13
2	0.104	0.107	0.02999	30	12
3	0.521	0.100	0.02999	30	13
4	0.104	0.102	0.02999	30	12
5	0.104	0.107	0.03000	30	12
6	0.104	0.100	0.02994	30	12
7	0.106	0.100	0.02999	30	12
Optimized	0.100	0.100	0.03000	30	12

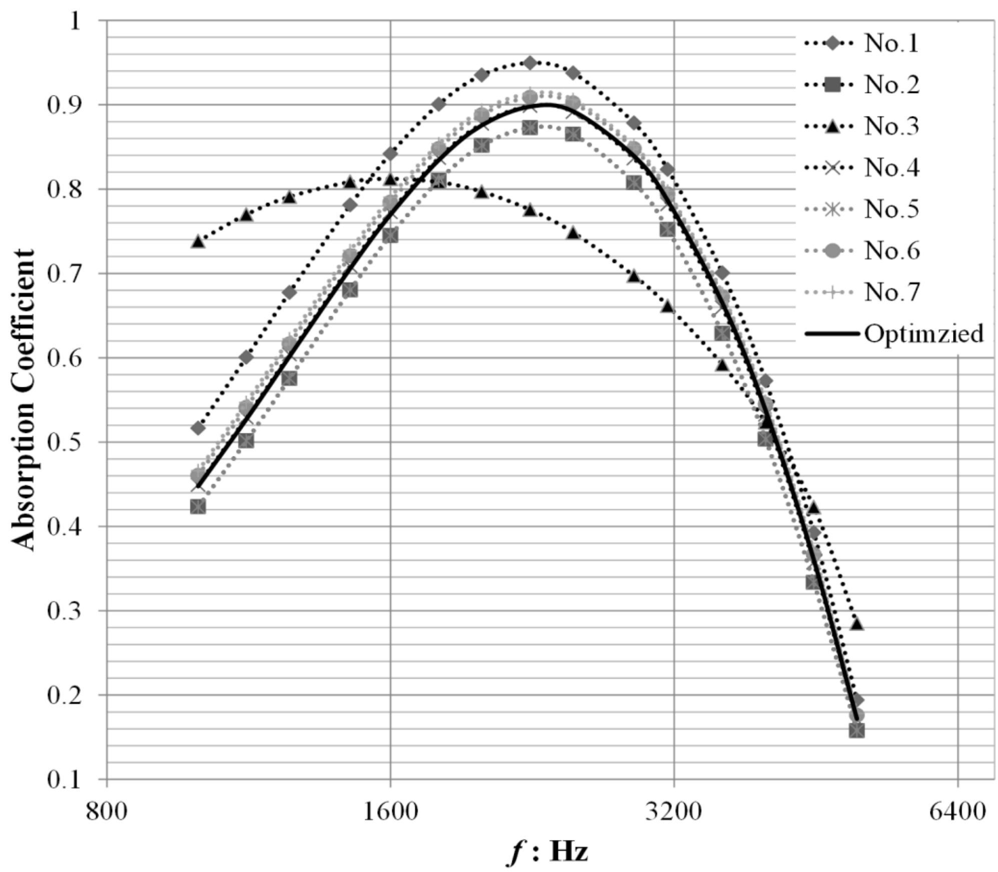

Figure 2. Absorption coefficients of searching results of parameters combinations.

3.2. *Metal MPP manufacturing*

Because of the characteristics of antirust, low density and ease of processing, aluminum is used as panel material. The thickness of aluminum panel is 0.1mm on which through holes are drilled by a picosecond laser machine and the processed sample is shown in Figure 3.

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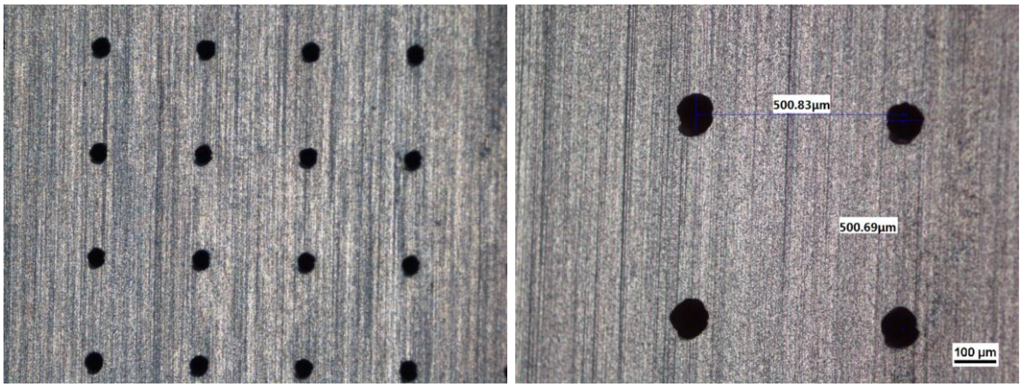

Figure 3. The aluminum panel of MPP: (a) array and (b) through holes.

4. Result and discussion

The aluminum MPP is put into an impedance tube so that the absorption coefficient can be measured. The theoretical absorption coefficient of optimized design and corresponding measurement result of aluminum sample. It is obvious that the absorption coefficient of aluminum sample matches the theoretical model relatively well. Therefore the absorption characteristics of aluminum MPP can be predicted by the model derived in section 2. The measurement shows that the peak absorption coefficient is about 0.9 and corresponding frequency is approximate 2000Hz. Since the half peak absorption coefficient is 0.45, the half-absorption band width can be deduced from Figure 4 and the value is about 3200Hz.

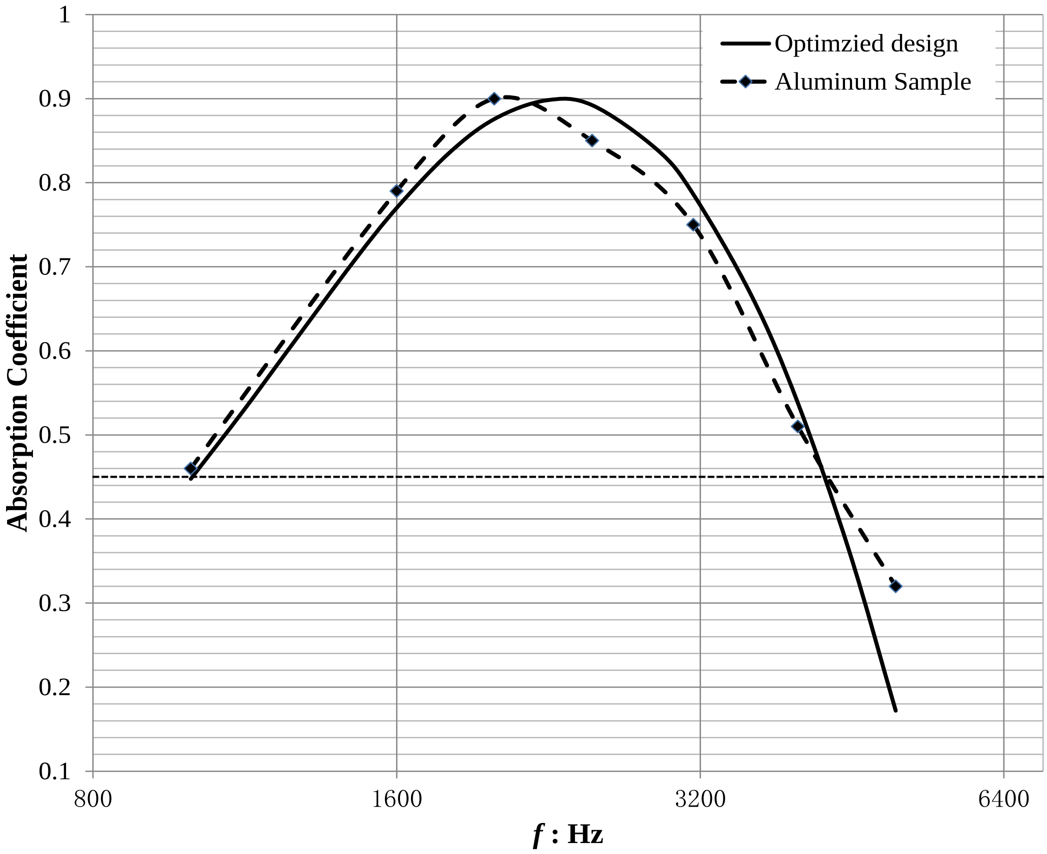

Figure 4. Theoretical absorption coefficient of optimized design MPP and experimental result of aluminum sample.

As to the reason for the error, the deviation of laser drilling is the most possible factor. It is very difficult for laser beam to drill a perfect cylinder through aluminum panel to form a micro perforated hole. Therefore the critical parameter, namely the diameter of micro hole, cannot be controlled precisely. And due to the accuracy of moving stage of laser drilling machine, there is also deviation of the interval between these holes. Thus it is easy to understand there always be the error between theoretical model and experimental result.

5. Conclusions

MPP is a commonly used material in noise control application. Because of steady acoustic absorption performance and the convenience in process, metal MPP attracts more and more attention. Based on the research of classical MPP theory, the acoustic model of metal MPP is presented and the relationship between critical parameters and absorption characteristics is revealed by concrete analysis. Thus, the optimized design of MPP parameters is deduced by the aid of genetic algorithm. The aluminum is determined as the panel materials due to the antirust property and corresponding samples are manufactured. The absorption coefficient of aluminum MPP sample is measured in impedance tube. The measurement result proves that the model can predict the variation of absorption coefficient along with the increase of frequency. And the absorption performance of aluminum MPP is good enough for practical application.

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