Article

Sound Absorption Principle of Fibrous Materials

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Abstract

By applying the energy conservation theory and considering the vibration characters of sound and structure characters of fibrous material, we propose theory and formula for the fibrous material sound absorption coefficient and spectrum formula. After analysis and comparison, we find that the theory proposed in the paper is able to correctly reflect the characteristics of the empirical sound absorption coefficient laws of fibrous materials found in noise control literature.

Key Words: fibrous material, sound, vibration, sound absorption coefficient, spectrum formula.

1. Introduction

Since the founding of architectural acoustics, scientists have done a vast amount of work devoted to the construction of the sound absorption theoretical model for the sound absorption of porous materials. However, the current theory remains to be under discussion on the sound absorption principle which is not able to be used in practice. The reason is that the sound absorption coefficient equation obtained according to the conventional theory has no applicable solution, failing to make the quantitative analysis on the material sound absorption properties [1-7， 10-17].

Through analysis and argumentation, the author has worked out an idea - that is, the sound absorption of the fibrous material comes from the vibration of the material under the action of the sound wave. Based on this idea, the author establishes a sound absorption coefficient formula according to the energy conservation theory.

2. Porous Material Sound Absorption Model

As shown in Fig. 1, suppose that the sound wave air which is considered as a rigid body with mass *m* acts on the material, the mass of the material is *M*. Again suppose that the material is a perforated material, its single pore area is *A*. The material makes back and forth motion when pushed by the sound wave. Its moving speed is v_2. According to the kinetic energy

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conservation law, we have

$$\frac{1}{2}mv^2 = \frac{1}{2}Mv_2^2 + \frac{1}{2}mv_1^2 \quad (1)$$

Suppose that the sound absorption of the material is derived completely from the forced vibration of the material itself. Then, the sound absorption coefficient can be defined as

$$\alpha = \frac{\frac{1}{2}Mv_2^2}{\frac{1}{2}mv^2} = \frac{M}{m}(\frac{v_2}{v})^2 \quad (2)$$

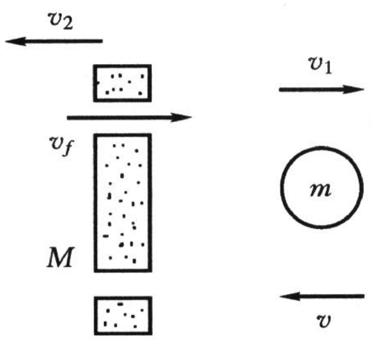

Fig. 1 The action process for sound wave to material

Let's look at v_2. In Fig. 1, the fluctuating speed of the material and the air flow speed v_f are equal in magnitude but opposite in direction, namely

$$v_2 = -v_f \quad (3)$$

In hydromechanics, the relation between the pressure difference on both sides of the pipe and the air flow speed is [5]

$$p = -\frac{8\eta L v_f}{R^2},$$

where p - pressure difference on each side of the pipe (in which it is considered that the pressure difference does not change with the distance in the pipe), L - pipe length, R - pipe diameter, η - viscous coefficient.

If $B = \frac{8\eta L}{R^2}$, we get $p = -Bv_f$. Supposing that the air in the pipe is regarded as a rigid body, according to Newton's Second law, the pressure difference can also be expressed as

$$p = \frac{F}{A} = \frac{m_p}{A}\frac{dv_f}{dt},$$

In which m_p - air mass in the pipe, A - pipe cross section area. Then,

$$\frac{m_p}{A}\frac{dv_f}{dt} = -Bv_f .$$

This is a first-order differential equation. Solving the equation gives

$$v_f = Ce^{-\frac{B}{m_{pa}}t}, \text{ where } m_{pa} = \frac{m_p}{A} .$$

Solving the above equation yields

$$v_f = v_{af} e^{-\frac{B}{m_{pa}}t} \qquad (4)$$

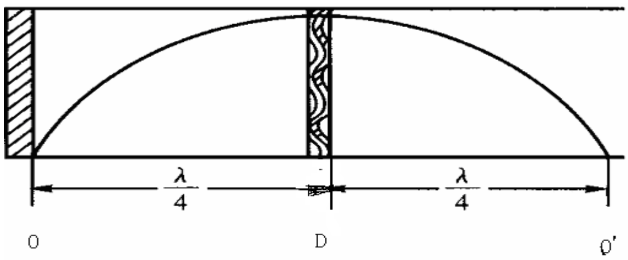

Fig. 2 Sound wave particle vibration process

What is expressed in Eq.(1) and Eq.(2) is actually a process of the instant that the air layer collides with the material. At the moment of the collision action, $t = 0$, from Eq.(4),we have

$$v_f = v_{af} \qquad (5)$$

Then, v_{af} is the flow speed maximal value.

Assuming that the energy transfer is instantaneous, substituting both Eq.(3)and Eq.(5) into Eq.(2) gives

$$\alpha = \frac{M}{m}\left(\frac{v_f}{v}\right)^2 = \frac{M}{m}\left(\frac{v_{af}}{v}\right)^2 \qquad (6)$$

The above equation is an energy transfer equation of air mass to the materials after once collision.

The vibration of the sound particles when there is a rigid wall behind the material is analyzed in the following. Suppose that the point where the amplitude of a sound wave particle with a certain frequency is zero is just the point 0 of the rigid reflection wall. Then, the change of the amplitude of the sound wave particle is shown by the curve in Fig. 2. This is just the situation of the standing wave vibration in the standing wave tube. Let's discuss the situation in the standing wave tube. In Fig. 2, the material is in the middle position, the rigid wall is at the point 0 on the left side and the distance between point 0 and the material is D.

In the scope of 1/2 wave length, the 0' point on the right side of the material is equal to a sound source start point. Then, at this time, the amplitude function of the particle is $|\sin(\omega t) = \sin(2\pi f t) = \sin(2\pi ct/\lambda)|$, where c, f, λ denote the sound speed, frequency and wave length separately. The moving direction of the sound is from 0' to the left side. Then, for $ct = \frac{\lambda}{2} - D$, the above equation changes into $|\sin(\pi - 2\pi D/\lambda)| = |\sin(2\pi D/\lambda)|$ and the corresponding particle speed function is $|\cos(\pi - 2\pi D/\lambda)| = |\cos(2\pi D/\lambda)|$.

In this way, the material speed expression will be

$$v_f = v_{af}\left|\cos(\frac{2\pi D}{\lambda} - \phi)\right| \tag{7}$$

in which, $-\phi$ denotes the phase difference between the speeds of material vibration and air vibration. And the air particle speed is

$$v = v_a\left|\cos(\frac{2\pi D}{\lambda})\right|$$

Then, we get

$$\alpha = \frac{M}{m}(\frac{v_f}{v})^2 = \frac{M}{m}(\frac{v_{af}\left|\cos(\frac{2\pi D}{\lambda} - \phi)\right|}{v_a\left|\cos(\frac{2\pi D}{\lambda})\right|})^2 = \frac{M}{m}(v_{af}\frac{\cos(\frac{2\pi D}{\lambda} - \phi)}{v_{af}\cos(\frac{2\pi D}{\lambda})})^2 \tag{8}$$

Because it is forced to oscillate, the material stays in the rest state before vibration. At $D = \lambda/4$ point, the amplitude of the particle is the greatest whereas the speed is the least. As a result, the phase difference of the vibration speeds between the air particles and the material will be the smallest. And vice versa, at $D = \lambda/2$ point, the phase difference of the vibration speeds between the air particles and the material will be the greatest. In this way, such a term can be expressed as

$$\phi = 2\pi(\frac{\lambda}{4} - D)/\lambda = \frac{\pi}{2} - \frac{2\pi D}{\lambda}$$

Substituting above equation into Eq.(8) gives

$$\alpha = \frac{M}{m}\left(\frac{2v_{af}\sin\frac{2\pi D}{\lambda}}{v_a}\right)^2 \quad (9)$$

The air particles are evenly distributed in the space. If the particle amplitude is the greatest at the $D = \lambda/4$ point, then the point-acquisition scope of the vibrating particles will be great - that is, the number of the vibrating particles acting on the material will be numerous. This is equal to the fact that the greater is the air mass. On the contrary, the particle amplitude is the least at the $D = \lambda/2$ point, and then the point-acquisition scope of the vibrating particles will be small - that is, the number of the vibrating particles acting on the material will be small. This is equal to the fact that the smaller is the air mass. As a consequence, the air mass acting on the material can be expressed as

$$m = m_a\left|\sin\left(\frac{2\pi D}{\lambda}\right)\right| \quad (10)$$

where, m_a - the greatest air mass acting on the material.

Suppose that p_a is the sound pressure in air and $\rho_0 c_0$ is the specific acoustic impedance. Then, as per the sound transfer theory [6], we obtain

$$v_a = \frac{p_a}{\rho_0 c_0},$$

in which v_a is the greatest speed of the motion of the sound wave particles, and the acceleration with which the particle increases the speed from zero to v_a will be

$$a = \frac{v_a}{t}$$

(where the acceleration is assumed to be unchanged). The time the particle uses to increase the speed from zero to v_a is

$$t = \frac{1}{4f}$$

(in which f is the sound wave frequency). Then, we get

$$a = 4fv_a.$$

According to the Newton's Second Law,

$$p_a = \frac{m_a}{S} a = 4 f m_{sa} v_a \,,$$

where, S is the area that the air mass acts on the material. In this way, it is possible to work out that the greatest air mass acting on the material in a unit area is

$$m_{sa} = \frac{p_a}{4 f v_a} = \frac{\rho_0 c_0}{4 f} \qquad (11)$$

Substituting this equation into Eq.(10) yields

$$\frac{m}{S} = m_s = m_{sa}\left|\sin(\frac{2\pi D}{\lambda})\right| = \frac{\rho_0 c_0}{4 f}\left|\sin(\frac{2\pi D}{\lambda})\right| \qquad (12)$$

Where,

$$m_s = \frac{m}{S}$$

is the unit area mass of air body.

Substituting Eq.(12) into $m = m_s S$, then taking m into Eq.(9), we get

$$\alpha = \frac{16 f M_s v_{af}^2}{\rho_0 c_0 v_a^{\ 2}}\left|\sin(\frac{2\pi D}{\lambda})\right| \qquad (13)$$

where

$$M_s = \frac{M}{S}$$

is the unit area mass of the material.

3. The Sound Energy Transmission Equation and Sound Absorption Spectrum Formula of Porous Material

The larger percentage of perforation of material, the less fluctuated air mass imposed on the material. Therefore, the sound energy absorbed by the material will be reduced, and the sound absorption coefficient will be declined, and vice versa. The detailed formula derivation is made as follows. According to the energy transmitting progress

$$\frac{\frac{1}{2} M v_2^2}{E_0} = \frac{\sigma E_0}{E_0} + \frac{E_m}{E_0} \qquad (14)$$

In this equation,

$$E_0 = \frac{1}{2} m v^2$$

is the incident sound energy, E_m is the sound absorption energy of material, the items in left side of equal sign reflect the energy transmission of material layer (including the material and pore in it). σ represents the percentage of perforation. Then, the first item in right side of equal sign reflects the energy transmission of air in the layer, and the second item represents the energy transmission of material in the layer. It is assumed that the sound absorption coefficient of material is α_m, and that of the material layer is α_l, the above formula will be as follows:

$$\alpha_l = \sigma + \alpha_m \qquad (15)$$

Namely,

$$\alpha_m = \alpha_l - \sigma \qquad (16)$$

Considering

$$\alpha_l = \alpha = \frac{16 f M_s v_{af}^2}{\rho_0 c_0 {v_a}^2} \left|\sin(\frac{2\pi D}{\lambda})\right| ,$$

yields

$$\alpha_m = \frac{16 f M_s v_{af}^2}{\rho_0 c_0 {v_a}^2} \left|\sin(\frac{2\pi D}{\lambda})\right| - \sigma \qquad (17)$$

In Eq. (17), σ is not constant. When the cavity depth equal to 1/2 incident sound wavelength the sound wave amplitude at the position of material is zero. That means that the sound wave air particle will not pass the pores of material. When the cavity depth equal to 1/4 wavelength of incident sound the sound wave amplitude at the position of material reach maximum value. In this case, σ is greatest. Then, σ can be expressed as

$$\sigma_{(s)} = \begin{cases} \sigma \left|\sin(\frac{2\pi D}{\lambda})\right| , & s < y \\ 0 , & s > y \end{cases} \qquad (18)$$

where , s, y are amplitude of material and sound wave separately.

Due to the fact that s is too small comparing to the sound wave amplitude y, the first formula is practical. Considering σ has been replaced by $\sigma_{(s)}$ in Eq.(17) and taking Eq.(18) into Eq.(17), we get

$$\alpha_m = (\frac{16 f M_s v_{af}^2}{\rho_0 c_0 v_a^2} - \sigma) \left|\sin(\frac{2\pi D}{\lambda})\right|$$

Setting

$$A = \frac{16 f M_s v_{af}^2}{\rho_0 c_0 v_a^2} - \sigma \tag{19}$$

leads to

$$\alpha_m = A\left|\sin(\frac{2\pi D}{\lambda})\right| \tag{20}$$

This is the sound absorption spectrum formula of porous material.
At the

$$D = \frac{\lambda}{4} \text{ point, } \quad \sin(\frac{2\pi D}{\lambda}) = 1,$$

which are the maximal value, expressing maximal sound absorption.
At the

$$D = \frac{\lambda}{2} \text{ point, } \quad \sin(\frac{2\pi D}{\lambda}) = 0,$$

which are the minimal value, expressing minimal sound absorption .

The above conclusions tally completely with the change law of the measured sound absorption coefficients of the porous materials quoted in References [2, 5, 10, 11, 12, 15].

4. The Air Permeability and Peak Sound Absorption Coefficient Formula of Material

In this part, the peak sound absorption coefficient A in Eq.(20) will be determined practically by applying a structure parameter of textile.

In the research of textile materials, there is a parameter expressing the permeation performance of the material, named as air permeability Q. The definition is that when the pressure difference on both sides of the material is $49p_a$, the permeability Q is the air flow passing through the unit area of the material per unit time, the unit is $m^3/(sm^2)$. The permeability can be measured with the standard test methods (GB/T5453-1997,test area is 33.6 cm^2) [8，9].

As the % open area σ (percentage perforation) is defined as the percentage of the pore's area which take up in the total area of the material. In such a case, there should be a corresponding relation between the air permeability and % open area. Table 1 and Fig.3 shows the relation between the air permeability and % open area of the fabric. It can be seen that there is a good corresponding relation between the air permeability and % open area, and its related equation can be written as

$$\sigma = 9.35\ln Q - 27.0 \quad (21)$$

where Q – air permeability $L/(s\cdot m^2)$; σ - % open area (%)

Table 1. Relation between the air permeability and % open area of the fabrics

Parameters / Materials	Thickness mm	Unit area Mass (g/m^2)	Air permeability Q ($L/(s\cdot m^2)$)	% open area (%)	Cover Factor (%)
Gabardine fabric #11	0.56	269	29.7	0.5	99.5
Gabardine fabric #13	0.48	259	30.6	5.1	94.9
Shuofeng fabric #8	0.37	208	34	1.1	98.9
Gabardine fabric #12	0.56	267	36.3	5.1	94.9
Single face fabric #10	0.47	215	42.5	8.6	91.4
Serge fabric 14	0.43	290	47.6	13.9	86.1
Serge fabric 15	0.48	234	69.2	13.9	86.1
Plain fabric #4	0.36	203	156	22.4	77.6
Valitin #3	0.36	188	182	24.5	75.5
Plain fabric #1	0.33	180	188	24.5	75.5
Slub fabric #6	0.39	212	208	27.4	72.6
Slub fabric #5	0.41	217	252	27.4	72.6
Plain cotton fabric #50	0.38	131	320	26.9	73.1
Plain cotton fabric #54	0.38	138	325	24.9	75.1
Plain cotton fabric #46	0.39	131	376	27.6	72.4
Slub fabric #7	0.35	166	555	31.2	68.8
Plain cotton fabric #42	0.4	122	600	29.2	70.8
Plain cotton fabric #38	0.4	120	630	30.3	69.7

Note：In this table, except those of plain cotton fabrics, all the fabrics are wool-like fabrics which are woven by midfibre yarn made of polyester and viscous.

Decimalizing Eq.(21)and taking it into Eq.(19)，we obtain

$$A = \frac{16 f M_s v_{af}^2}{\rho_0 c_0 {v_a}^2} - 0.0935\ln Q + 0.27 \quad (22)$$

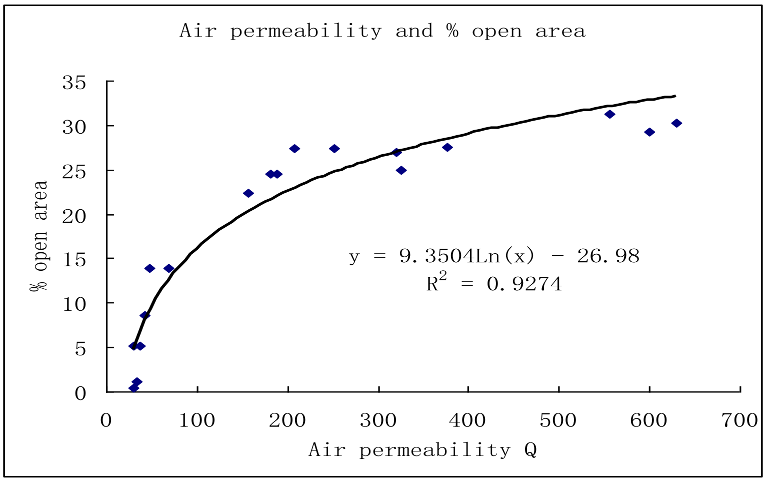

Figure 3. Relation between the air permeability and % open area of the fabrics

Now we discuss M_s in Eq.(22). As we have assumed above that the sound wave is regarded as a rigid body. This body interacts with the surface of material (at D position in figure 2) instantaneously. That means, only the surface of layer of material take part in the interaction and the surface layer's thickness is defined. If we assume that the surface layer's thickness is constant, the effect of the change of M_s can be ended in the change of σ. According to Eq.(21), it can also be ended in air permeability Q.

Fig.4 and Table 2 give the data and curve of the relation between some materials' air permeability Q and their unit area mass M_s. These materials have the same thickness approximately.

From Fig.4 it can be seen that, for the fabric with same thickness, there is a good corresponding relation between the fabric's air permeability Q and its unit area M_s. Its related equation can be written as

$$\ln Q = -0.043(M_s - 100) + 7.32 \text{, or } M_s = -23.76 \ln Q + 270.23$$

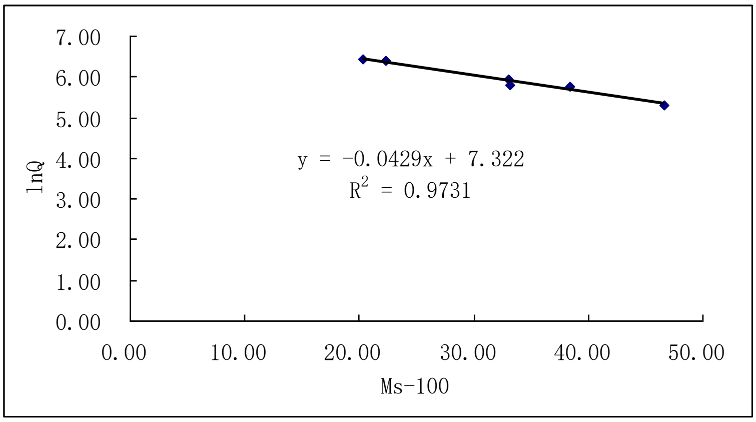

Fig.4 The curve of the relation between the material's air permeability and its unit area mass (For being shown in middle of the chart, the abscissa is M_s -100 g/m^2)

Table 2 The relation between material's air permeability and their unit area mass

Parameters / Materials	Thickness (mm)	% open area (%)	Air permeability Q ($L/(s\cdot m^2)$)	Unit area mass M_s (g/m^2)
Plain cotton fabric #58	0.38	27	200	146.6
Plain cotton fabric #54	0.38	30	325	138.4
Plain cotton fabric #50	0.38	33	321	133.2
Plain cotton fabric #46	0.39	37	376	133.0
Plain cotton fabric #42	0.40	40	601	122.3
Plain cotton fabric #38	0.40	41	624	120.3

The normal relation equation can be written as

$$M_s = -K\ln Q + H \qquad (23)$$

Inserting Eq.(23) into Eq.(22) yields

$$A = -(\frac{16fKv_{af}^2}{\rho_0 c_0 v_a{}^2} + 0.0935)\ln Q + \frac{16fHv_{af}^2}{\rho_0 c_0 v_a^2} + 0.27$$

Where, K, H are just determined by the material's quality. Hence, they are constant here. $\rho_0 c_0$ is constant. If we set

$$\frac{16K}{\rho_0 c_0} = u \quad \text{and} \quad \frac{16H}{\rho_0 c_0} = \upsilon,$$

u, υ are constant either. Then,

$$A = -(uf\frac{v_{af}^2}{v_a{}^2} + 0.0935)\ln Q + \upsilon f\frac{v_{af}^2}{v_a^2} + 0.27 \qquad (24)$$

According to general knowledge of vibration, in the situation of low frequency, the speed phase shift between the sound wave and the materials is small; while in the situation of high frequency, the speed phase shift between the sound wave and the materials is great. In other words, the difference between ν and ν_2 (see Fig.1) varies with the frequency. Then, the maximal value ν_a and ν_{a2} vary following the frequency.
Considering

$$|v_{a2}| = |v_{af}|$$

(see Eq.(3,4,5)) and $\frac{v_{af}}{v_a}$ is below 1, and because the more speed phase shift which is correspond high frequency, the more the speed difference, the increase of f will be offset by the decrease of $\frac{v_{af}}{v_a}$, and vice versa. Thus, $f\frac{v_{af}}{v_a}$ can be considered as constant. If we set

$$uf\frac{v_{af}^2}{v_a^{\ 2}}+0.0935=F \quad \text{and} \quad \upsilon f\frac{v_{af}^2}{v_a^2}+0.27=G,$$

F and G are constant either. Then, we get

$$A=-F\ln Q+G \tag{25}$$

It is seen that there is linear correlation between A and ln Q. Table 3 and Fig.5 give the measurement data and curve of the relation between the peak sound absorption coefficient of material A and its air permeability Q. From table 3 and Fig.5, the experimental correlation between A and ln Q is exactly linear. This fact justifies the theoretical model put foreword by the author above.

From Fig.5, the experimental formula of the peak sound absorption coefficient is

$$A=-0.30\ln Q+2.43 \tag{26}$$

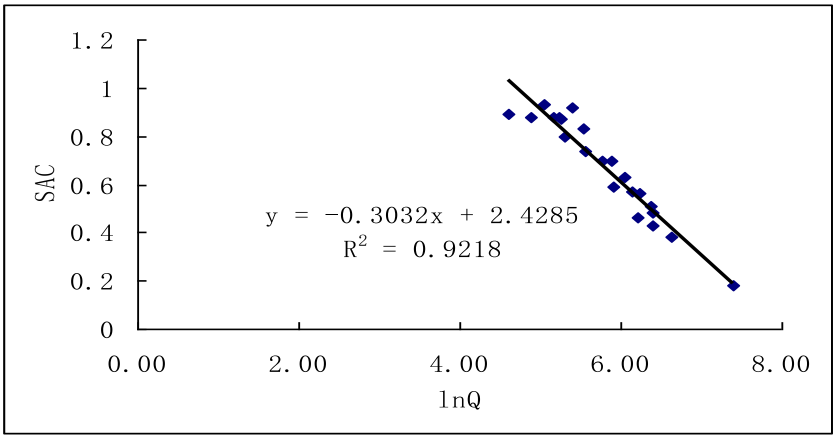

Fig.5 The experimental correlation between A and ln Q (SAC=A denotes the peak sound absorption coefficients at the cavity depth of 20cm)

Now we study the situations of thick porous layer and low frequency. In the low frequency, comparing to the wavelength of sound, the fluctuation range of material is obviously small. When the sound wave pushes material to get the maximum amplitude, the sound wave has not got the maximum amplitude at the same time. In this way, the sound wave will travel forward continuously. As for the material with greater percentage of perforation, part of the sound wave air particle can travel through the pores of material and travel forward continuously, and other air particles will be blocked by the material. At this time, due to the too large wavelength, the fluctuated air within 1/4 wave length can't be regarded as an integer body. Namely, only the front part of the air acting on the material can be regarded as the rigid body. That is, the sound absorption just occurs at the moment that the front sound wave interacts with material. When the back sound wave reaches the material the material has been pushed to the maximal amplitude and will reflect the sound energy as a rigid wall. As a result, the actual sound absorption coefficient for material in the low frequency is lower than the theoretical value.

Table 3. The experimental relation between sound absorption coefficients (A) and ln *Q*

Parameters / Materials	Thick-ness （mm）	Unit area mass （g/m^2 ）	A	Air permeability *Q* （$L/(s\cdot m^2)$）	lnQ
Cotton khaki drill	0.40	150	0.89	101	4.62
Figured cloth （ yellow texture）	1.70	361	0.88	131	4.88
Wool-like plain fabric #4	0.36	203	0.93	156	5.05
Wool-like valitin	0.39	208	0.88	174	5.16
Wool-like plain fabric #2	0.35	185	0.88	186	5.23
Polypropylene nonwovens #8	2.25	337	0.87	192	5.26
Plain cotton fabric #58	0.38	148	0.8	200	5.30
Wool-like slub fabric #5	0.41	216	0.83	252	5.53
Polypropylene nonwovens #7	1.97	300	0.74	261	5.56
Plain cotton fabric #50	0.38	131	0.7	321	5.77
Polypropylene nonwovens #2	2.00	215	0.7	363	5.89
Valitin	0.28	143	0.59	367	5.91
Polypropylene nonwovens #6	2.00	231	0.63	423	6.05
Polypropylene nonwovens #4	1.75	212	0.57	465	6.14
Glass fiber nonevents #6	0.28	63.9	0.46	500	6.21
Polypropylene nonwovens #3	2.15	223	0.56	515	6.24
Polypropylene nonwovens #5	1.88	217	0.51	585	6.37
Plain cotton fabric #42	0.39	121	0.48	601	6.40
Glass fiber nonwovens #3	0.31	68.2	0.43	603	6.40
Glass fiber nonwovens 2	0.26	60.6	0.38	748	6.62
Glass fiber nonwovens #1	0.21	30.3	0.18	1616	7.39

Note：The A(SAC)-sound absorption coefficients tested in this table is in the state that cavity depth is 20cm、frequency is 400Hz.

However, the thick porous layer can be regarded as the superimposition of multi-layer of thin layers. Most of the fibers in the thick fibrous layer are arranged loosely, if it is divided into multi-layer thin porous layers, the percentage of perforation of single layer for most materials is much larger, which will facilitate the sound wave to travel through. When these single layer materials are superimposed the irregular arrangement of material fiber can cause that the sound wave air of traveling through the front layer of material is resisted by the inner layer of material, thus the energy when the sound wave passes through the inside of material will be consumed layer by layer, the back part of sound wave(to the wave, the part that interacts with the material at beginning is called the "wavefront part", and the part after that is called the medium part or back part) will interact with the material surface. In this way, the interaction between the sound wave and material is equal to that multi-layer material interacts with the sound wave air particle within a certain range at the same time. Then, the sound absorption coefficient in low frequency is higher than the thin material with the same percentage perforation. In other word, the thin material with the same percentage perforation only acts with the material on the wavefront part. As for the long wavelength in low frequency, the back part within 1/4 wavelength of sound wave doesn't involve in the interaction of material. As a result, the sound absorption coefficient of thin material in low frequency must be lower than that of the thick material layer.

5. Sound Absorption Coefficient Formula of Porous Materials

In Fig.1, the structure character of materials is not considered. That means, this theoretical model is suitable to all the porous materials. Combining above discussion (Eq.(21) and Eq.26), we get

$$A = -0.30\ln Q + 2.43 = -0.032\sigma + 1.56 \qquad (27)$$

We have discussed the affection of frequency to the sound absorption coefficient. It is held that the frequency has no effecting (as we have discussed above(part 3). However, if the material is thin, it will be more free to vibrate and its moving speed is grater and the increase of f will not be offset by the decrease of

$$\frac{v_{af}}{v_a}.$$

Then, from Eq.(24), the frequency will influence the sound absorption coefficient. In fact, for the thin material layers, the tested sound absorption coefficient is slightly increased following the increase of frequency.

Two kinds of materials have been measured. The peak sound absorption coefficients of different frequency have been shown in table 4. The experimental low can also be seen in Fig, 6.

Table 4 The peak sound absorption coefficients of different frequency of two materials

Frequency/Hz	250	630	1000	2000	3150
Material 1	0.32	0.38	0.34	0.42	0.41
Material 2	0.69	0.85	0.80	0.87	0.89

Note: Cavity depth behind the materials is 40cm

Material 1-Glass fiber nonwovens (thickness of 0.26mm, unit area mass of 56.4 g/m^2)
Material 2-Cotton plain fabric (thickness of 0.38mm,unit area mass of 147.0 g/m^2)

In Fig. 6, it is seen that the increasing of the slope of two materials are different. The increasing of the slope of glass fiber nonwovens is small than that of cotton plain fabric. This is because that glass fiber nonwovens is stiff than cotton plain fabric. As a result, its speed is small and the increase of *f* will be offset by the decrease of

$$\frac{v_{af}}{v_a}.$$

Then, the increasing slope of glass fiber nonwovens will be small.

According to Fig.6, without considering the stiffness of the materials, the equation relating sound absorption coefficient and frequency can be estimated as

$$A = 0.05\ln f + W \tag{28}$$

Considering that Eq.(26) is come from the tested results at the frequency of 400Hz ， taking *f*=400 into Eq.(28) and combing Eq.(26) and Eq.(28) yields

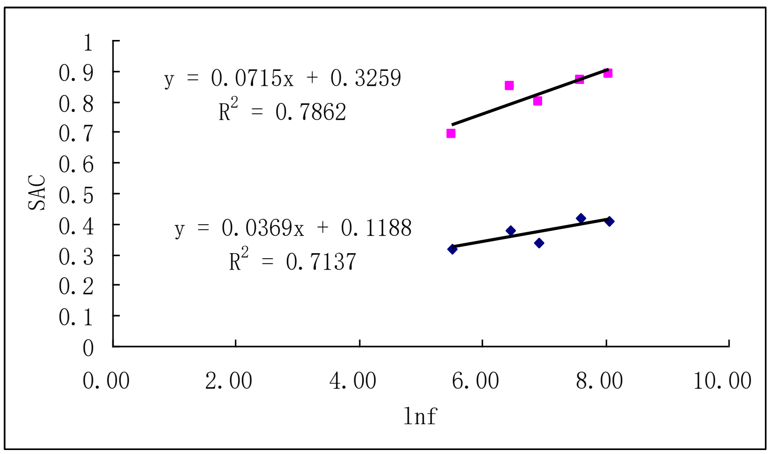

Fig.6. The relation between peak sound absorption coefficients and frequency (The abscissa is the frequency applying the operator of natural logarithm)

$$W = -0.032\sigma + 1.26 = -0.30\ln Q + 2.13$$

which leads to

$$A = 0.05\ln f - 0.033\sigma + 1.26 = 0.05\ln f - 0.31\ln Q + 2.13 \tag{29}$$

We have derived the sound absorption spectrum formula of porous material. That is

$$\alpha_m = A\left|\sin(\frac{2\pi D}{\lambda})\right|,$$

then the sound absorption coefficients formula will be:

$$\alpha_m = (0.05\ln f - 0.30\ln Q + 2.13)\left|\sin(\frac{2\pi D}{\lambda}\right| \tag{30}$$

for the air permeability as the independent variable.

$$\alpha_m = (0.05\ln f - 0.032\sigma + 1.26)\left|\sin(\frac{2\pi D}{\lambda})\right| \tag{31}$$

for the percentage of perforation as the independent variable

The general equation of Eq.(28) can be

$$A = S + W$$

For thin fiber layers such as fabric and nonwovens $S = 0.05\ln f$;for the thick fiber layers, because their peak sound absorption coefficients will not change following the frequency and display the maximal value, we can take the value corresponding highest measurement frequency f =3150Hz, i.e., $S = 0.40$.

Then the sound absorption coefficients formula of porous material will be:

$$\alpha_m = (S - 0.30\ln Q + 2.13)\left|\sin(\frac{2\pi D}{\lambda})\right| \tag{32}$$

for the air permeability .

$$\alpha_m = (S - 0.032\sigma + 1.26)\left|\sin(\frac{2\pi D}{\lambda})\right| \tag{33}$$

For the percentage of perforation

For thin fiber layers such as fabric and nonwovens $S = 0.05\ln f$;for the thick fiber layers, $S = 0.40$. The unit of air permeability Q is $L/(s \cdot m^2)$, the unit of percentage of perforation σ is (%).

To justify Eq.(32), two fiber layers have been measured. One is the polypropylene fiber layer (#1)which has the thickness of 20mm, unit area mass of 1170 g/m^2 and air permeability of

168 $L/(s\cdot m^2)$）.The other is the plain cotton fabric (#2) with the thickness of 0.39mm, unit area mass of 131 g/m^2 and air permeability of 376 $L/(s\cdot m^2)$）.Their tested sound absorption coefficients spectrum have been compared with the theoretical data calculating from Eq.(32) in Fig.7-Fig.13.

In our calculating, taking air permeability of the thick material（#1） into Eq.(32) and setting $S=0.40$， the sound absorption coefficients formula of thickness material（#1）is

$$\alpha_m = 0.94\left|\sin(\frac{2\pi D}{\lambda})\right| = 0.94\sin\left|(2\pi D\frac{f}{c})\right|$$

Taking air permeability of the thin material（#2） into Eq.(32) and setting $S=0.05\ln f$， the sound absorption coefficients formula of thin material（#2）is

$$\alpha_m = (0.29+0.05\ln f)\left|\sin(\frac{2\pi Df}{c})\right|$$

(In later context, the sound absorption coefficients in tables and figures is abbreviated as SAC)

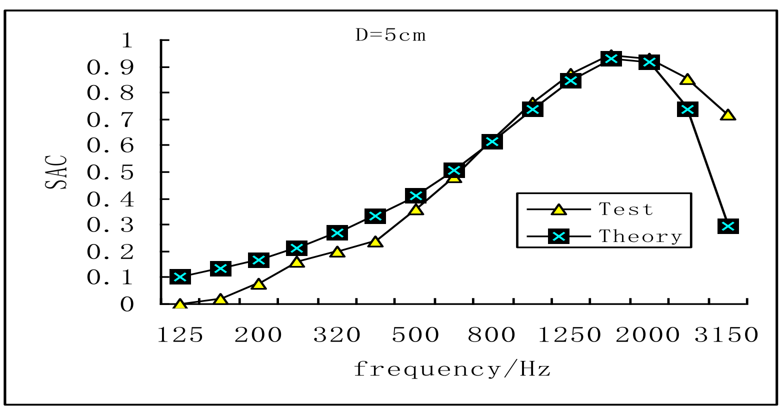

Fig.7 Thick material（#1, 5cm cavity depth

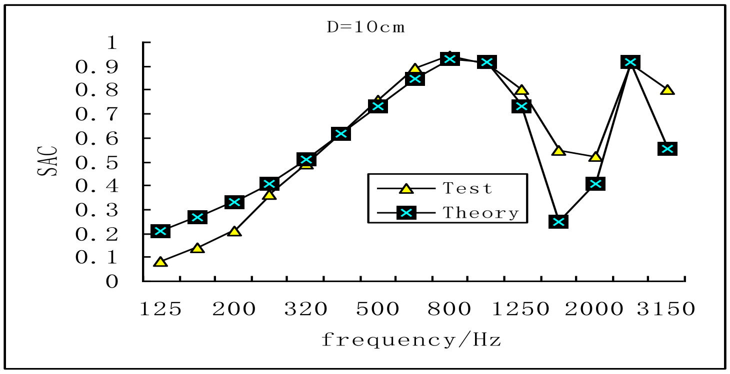

Fig.8 Thick material（#1,10cm cavity depth

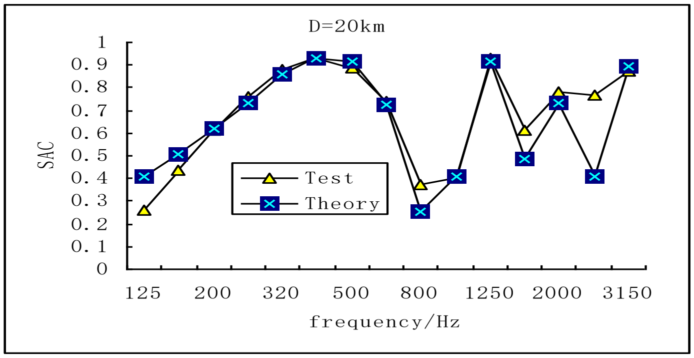

Fig.9 Thick material（#1, 20cm cavity depth

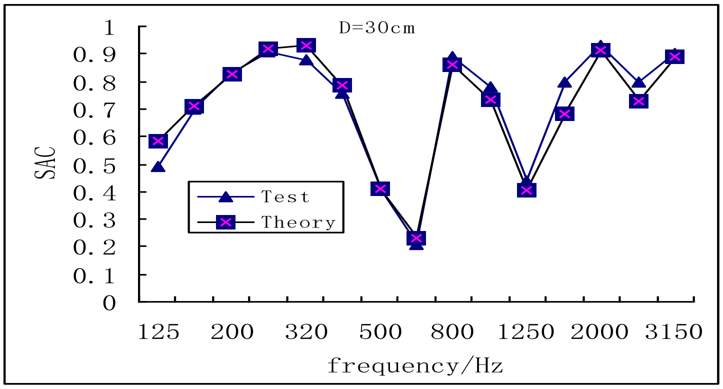

Fig.10 Thick material(#1), 30cm cavity depth

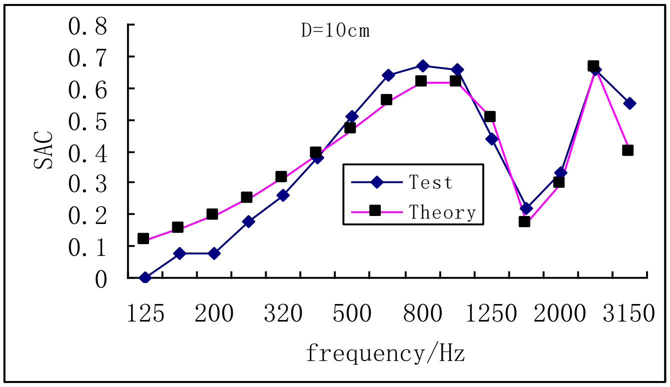

Fig.11 Thin material（#2, 10cm cavity depth

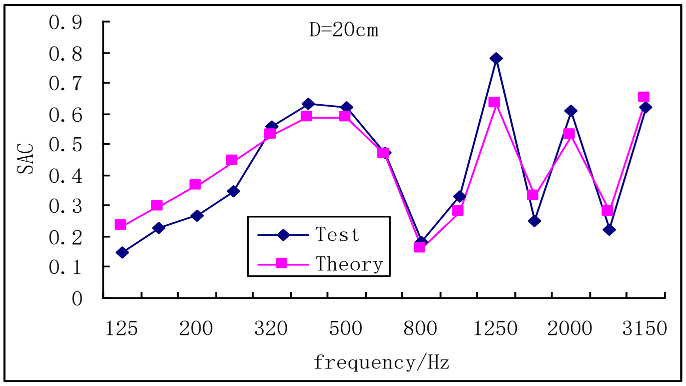

Fig.12 Thin material（#2, 20cm cavity depth

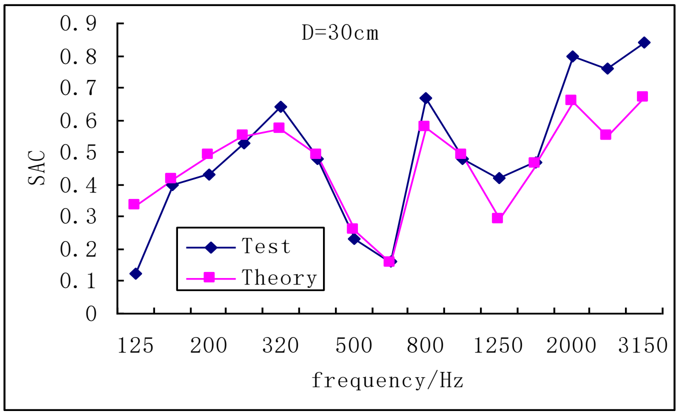

Fig.13 Thin material（#2, 30cm cavity depth

It is obvious from Fig.7- Fig.13 that the measured curves and the theoretical curves of two fibers tally well with each other. Simultaneously, it can also be seen that the sound absorption coefficient and spectra of the thin porous layer (#2) and those of the thick porous layer(#1)almost coincide with each other at higher frequency. This phenomenon has been quoted in German acoustician H. Kuttrufff 's latest edition book "Room Acoustics", he also held that the sound absorption of the thin porous layer is able to obtain relatively high sound absorption effect when taking the place of the thick porous layer[5].

6. The explanation to the experimental laws which have been quoted by the literature about sound absorption of porous materials

(1) Experimental laws 1: An increase in material thickness is equal to an increase in the thickness of air layer behind（MAA. D.Y., Handbook of Noise and Vibration Control [12], Beijing: Engineering Industry Press, 2002.p410； Zhao S.L., Noise Reduction and Insulation[4], Shanghai: Tongji University Press, 1986，p130）

The explanation: In the above discussions, we have assumed that D = material thickness + cavity depth behind the material. Therefore, with Eq.(32),Eq.(33), an increase in the material thickness is the same as an increase in the cavity depth. In other words, an increase in the material thickness is equal to an increase in the cavity depth.

(1) Experimental laws 2：Thin porous layer is able to obtain relatively high sound absorption（Zhong,X. Z., Architectural Sound Absorption Materials and Sound Insulation Materials[16], Beijing: Chemical Industry Press, ，2005，p307-314；Ingerlev, F., Contemporary Applied Architectural Acoustics[13], Translated by Lu Ruyu, Beijing: China Industrial Press, 1963:101-104; Cavanaugh H, W.J, Wikes, W. J. Architectural Acoustics – Theory and Practice[14], Translated by Zhao Ying, Beijing: Engineering Industry Press, 2004，56-57）.

The explanation：The thick fibrous layer can be regarded as the superimposition of multi-layer of thin fibrous layer. The sound absorption just occurs in the interaction between the wavefront part and surface of materials. The increase of thickness will bring the decrease of the percentage of perforation. That means if the two materials have the same percentage of perforation, they will display the same peak sound absorption as soon as the distance between the surface of materials and the back wall is equal.

(3) Experimental laws 3：When the cavity depth increases, sound absorption spectra move to the direction of low frequency and the sound absorption coefficients of low frequency increase (Zhong, X.Z., Architectural Sound Absorption Materials and Sound Insulation Materials[16], Beijing:Chemical Industry Press, 2005，p59；MAA. D.Y., Handbook of Noise and Vibration Controln[12], Beijing: Engineering Industry Press, 2002. p40).

The explanation: From Fig.7 to Fig.13, in the theoretical calculation and measured results, we can find the phenomenon that sound absorption spectra move in the direction of low frequency when the cavity depth increases. In other words, from the calculation in Eq.(32) it is possible to acquire the result that sound absorption spectra move in the direction of low frequency when the cavity depth increases. With the moves of the spectrum to the low frequency, the sound absorption peak is also moved to the low frequency, which leads the increase of sound absorption coefficients in low frequency.

(4) Experimental laws 4:Sound absorption spectra move in the direction of low frequency when temperature drops (MAA. D.Y., Handbook of Noise and Vibration Control [12], Beijing: Engineering Industry Press, 2002. p413; Zhong,X.Z., Architectural Sound Absorption Materials and Sound Insulation Materials[16], Beijing: Chemical Industry Press， 2005, p60,) ; Zi,A.S.(Japanese), Architectural sound absorption materials(Chinese Translation by Gao,L.T.)[17], Beijing: Architectural industry press of China, 1975: p54.

The explanation：Due to the fact that the sound speed is $c_0 = 331 + 0.6t$ (where c_0, t are the sound speed and temperature separately), when the temperature falls, the sound speed is reduced, which leads the length of the sound wave correspondingly decrease. From Eq.(32), it can be seen that a decrease in the length of the sound wave is equal to an increase in the cavity depth. As we have mentioned above, the increase in the cavity depth will result in the fact that the sound absorption spectra move in the direction of low frequency.

(5) Experimental laws 5：There is an important phenomenon that has been quoted by most of the noise control literature. That is, the sound absorption coefficient get the maximal value when the cavity depth equal to the 1/4 wave length; when the cavity depth equal to the1/2 wave length, there is the minimal value of sound absorption coefficient (MAA. D.Y., Handbook of Noise and Vibration Control [12], Beijing: Engineering Industry Press, 2002.p409; Beranek, Leo L. Noise and vibration Control (2nd ed)[15], 1988，p218).

The explanation：In Eq. (32) and Eq.(33), when D=1/4,function sin has the maximal value，which leads the maximal sound absorption coefficient; when D=1/2,function sin has the minimal value，which leads to the minimal sound absorption coefficient. Here, D = material thickness + cavity depth.

(6) Experimental laws 6：When the density of material is relatively small, with the increase of the density, their sound absorption coefficient will increase (MAA. D.Y., Handbook of Noise and Vibration Control [12], Beijing: Engineering Industry Press, 2002.p409， Zi,A.S., Architectural sound absorption materials[17],1975,p49).

The explanation: The increase of the density of porous materials will follow the decrease of the percentage of perforation. In Eq.(33), the decrease of the percentage of perforation yields the increase of the sound absorption coefficient.

7．Conclusions

The theoretical sound absorption formula of the porous materials obtained in this paper according to the vibration sound absorption principle is consistent with the empirical laws of porous materials.

It should be noted that the material will not breakdown even though the sound wave is regarded as "rigid body" acting on the materials. The reason is that the "rigid body" will not knock against the materials continually because of the wave interval. During this interval the elastic force makes the materials back to its original state. Thus, the energy of the sound wave to the materials will not be piled up and the sound absorption process will be repeated. As a result, the sound absorption coefficients will not change with the increase of time. This conclusion is well known to any acoustic scientist.

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