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Development of Sound Absorption Coefficient Prediction Tool of Laminated Ultrafine Fibers

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Abstract. This report describes research regarding a sound-absorption coefficient prediction technique for laminated ultrafine fiber. As the sound-absorption material used for interior noise reduction in automobiles, we considered fiber with a diameter of several μm. When the fiber diameter decreases, the sound-absorption coefficient typically increases., but it is necessary to laminate it whether it is fiber materials with the fiber diameter and several levels to some extent that rigidity becomes small when fiber narrows and is destroyed. We calculated an acoustic feature from fiber diameter, fiber density, thickness, materials density in extra-fine fiber materials this time. In addition, in combination with Transfer Matrix method, we developed other fiber materials and the plural technique that we could predict when we laminated it. We compare the experimental and calculation results, and verify the usefulness of this technique. The prediction of the sound absorption coefficient of the product before the sample making in this way enabled it.

1. Introduction

Generally, that the sound absorption is good is known about the same weight to the extent that the fiber diameter is attenuate. Fig. 1 is the picture which photoed the ultrafine fiber with a diameter about 2 [μm] by SEM (Scanning Electron Microscope). Fig. 2 shows the measuring result of the normal sound absorption coefficient of four fiber materials. These thickness are 10 [mm] and 300 [g/m^2] In the case of the same thickness and the same density, an absorption coefficient is so high that the diameter of a fiber is thin. Because a characteristic varies according to frequency, as for the sound absorption coefficient of fiber materials, it is difficult to produce a product with the acoustic absorption performance of the aim in the spectrum of the aim. In addition, laminating with different fiber is necessary, but the acoustic absorption performance changes by the laminating pattern. Demanding the frequency characteristic of the sound absorption coefficient from the enormous sample manufacture and number of the measurements by a calculation when is going to find the most suitable fiber diameter, laminating pattern every frequency for experimental measurement because it is of this study aimed.

In the past, the normal incidence absorption coefficient which is the sound absorptivity of the laminated fibers were obtained using the transfer matrix method from the characteristic impedance and propagation coefficient which used the measuring result by impedance tube [1]. I developed the technique to compute an absorption coefficient from the fiber diameter, the fiber density, the sample thickness and the sample density not to need the measurement of the impedance tube [2]. When the fiber diameter was equal to or more than 20μm, there was a tool which estimates an absorption coefficient from the fiber diameter, the fiber density, the sample density and the sample thickness [3] but less than 4μm, the predictability was bad. As for this calculation technique, only the absorption coefficient computation in case of it supported but when using actually as the acoustic material of the car, it must make the fiber material which is used to secure the thin bonded-fiber fabric and the thickness which protects a surface from the past and so on the aliquation. Therefore, in this research, it reviewed the absorption coefficient prediction tool of the laminated fibers which contains ultrafine fiber.

Like condition, it made it apply the calculation technique which was developed before [4] to the transfer matrix method of 2×2. It reports on the result of comparison of the calculation technique and the experiment.

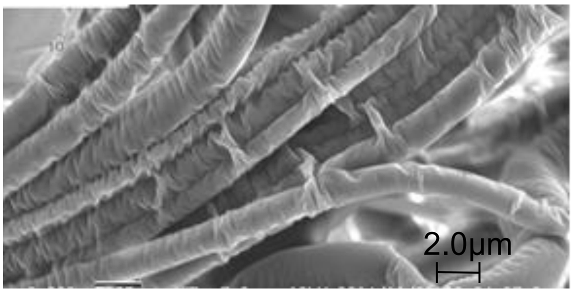


Fig. 1 Ultrafine fibers (fiber diameter : about 2.0μm)

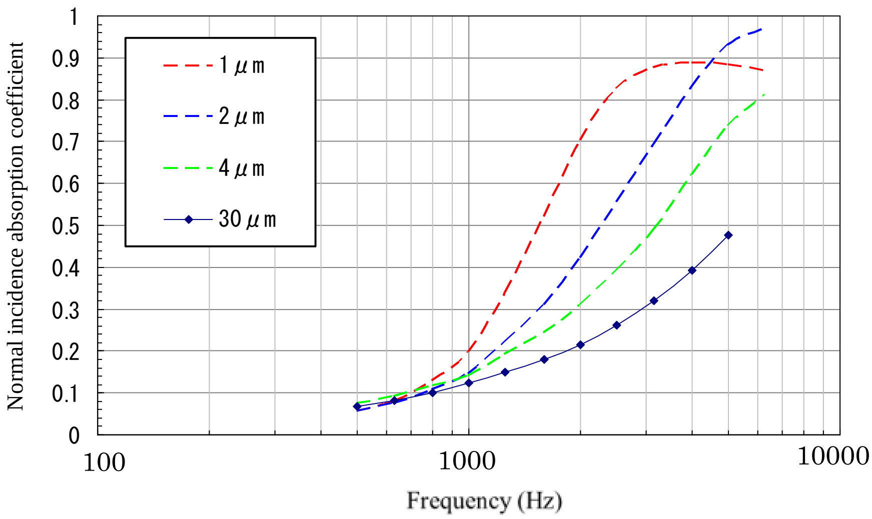


Fig. 2 Sound absorption coefficient of fibers (300 [g/m^2], thickness:10 [mm])

2. Calculation Method of Sound Absorption and Insulation Properties

The insulator stricture consisting of body panel, insulator material, and interior is assumed to be a laminated structure consisting of the element of m layers shown in Fig. 3. To be specific, this is an issue of vibro acoustic coupling of laminated structure with elastic body (panel), viscoelastic body (damping material, resin, etc.), porous body (felt, urethane form, etc.), and air. First, properties of individual layer (sound wave transmission inside the material and reflection properties on the surface) are expressed by transfer matrix. Then, the individual properties are combined in the order of actual lamination to obtain the sound transmission properties of the entire lamination structure.

2.1 Sound Absorption and Acoustic Feature of the Laminate Surface

From the relation between incident sound P_i and reflected sound P_r, sound absorption coefficient α is calculated, which is a parameter showing difficultness of reflecting sound of the laminated structure. Normal sound absorption coefficient α_θ is calculated by (1).

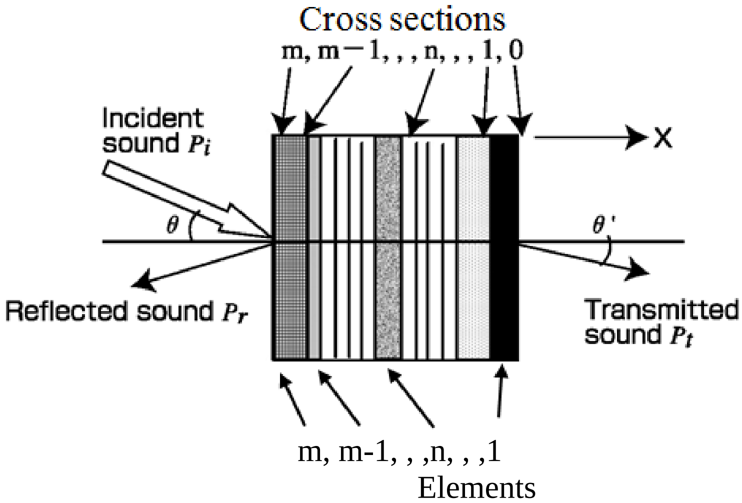


Fig. 3 Model of sound insulation material

$$\alpha_\theta = 1 - \left| \frac{P_r}{P_i} \right|^2 \tag{1}$$

Θ indicates incidence angle of sound wave to the surface of laminated structure.

The relation of the incidence sound P_i and the reflected sound P_r in (1), sound pressure P_m, particle velocity u_m, and acoustic impedance Z_m at the sound source side surface of the laminated structure (cross section *m*) will be determined. When the balance of sound pressure at the laminated structure surface in x direction is considered, the relation of P_i, P_r, P_m, u_m, and Z_m is expressed as (2).

$$P_i + P_r = P_m = Z_m u_m \tag{2}$$

From the continuity of particle velocity in x direction,

$$\frac{P_i - P_r}{\rho c_x} = u_m , \quad c_x = \frac{c}{\cos\theta} \tag{3}$$

c_x is an effective sound velocity in *x* direction. From (2) and (3), the relation of P_i, P_r, and Z_m is expressed as (4).

$$\frac{P_r}{P_i} = \frac{Z_m \cos\theta - \rho c}{Z_m \cos\theta + \rho c} \tag{4}$$

The relation of the incidence sounds P_i and transmitted sound P_t in (1), sound pressure P_m, partied velocity u_m, acoustic impedance Z_m at the sound source side surface (cross section m) of laminated structure, sound pressure P_0, particle velocity u_0, and acoustic impedance Z_0 at the sound receiving surface (cross section *0*) will be determined.

From (2) and (3), the relation between the incidence sound P_i and the sound pressure P_m at the section m is expressed as (5).

$$P_i = \frac{P_m \left(Z_m + \rho c_x \right)}{2 Z_m} \tag{5}$$

while the relation of the sound pressure P_0 at the cross section *0*, particle velocity u_0, and acoustic impedance Z_0 is expressed as (6) and (7) from the sound pressure balance and the continuity of particle velocity.

$$P_t = Z_0 u_0 = P_0 \tag{6}$$

$$\frac{P_t}{\rho' c'_x} = u_0 \quad , \quad c'_x = \frac{c'}{\cos\theta'} \tag{7}$$

where ρ' is the density of sound field of sound receiving side, c' is the sound speed of sound field of receiving side, c'_x is the effective sound velocity in x direction in which sound transmits to the receiving side.

The following equation is obtained from (6) and (7):

$$\begin{aligned} P_t &= P_0 \\ Z_0 &= \rho' c'_x \end{aligned} \tag{8}$$

2.2 Acoustic Transfer Properties of the Entire Laminated Structure and Each Layer

The relation between the transfer characteristics of sound wave in element $T_{n,n-1}$ and the transfer characteristics of the entire laminated structure $T_{m,0}$ will be determined as follows. In addition, $T_{n,n-1}$ is element transfer matrix, and $T_{m,0}$ is the transfer matrix between sound pressure P_m, particle velocity u_m at sound source side surface (cross section m) of laminated structure and sound pressure P_0, particle velocity u_0 at the sound receiving side surface (cross section *0*) of the entire laminated structure.

Assuming plane wave, the relation between sound pressure P_n, particle velocity u_n, sound pressure P_{n-1}, particle velocity u_{n-1} at cross section n and n-1 respectively will be expressed as (9) and (10) using the elements transfer matrix $T_{n,n-1}$. [4]

$$\begin{Bmatrix} P_n \\ u_n \end{Bmatrix} = T_{n,n-1} \begin{Bmatrix} P_{n-1} \\ u_{n-1} \end{Bmatrix} \tag{9}$$

$$T_{n,n-1} = \begin{bmatrix} T^{(1,1)}_{n,n-1} & T^{(1,2)}_{n,n-1} \\ T^{(2,1)}_{n,n-1} & T^{(2,2)}_{n,n-1} \end{bmatrix} \tag{10}$$

$T^{(1,1)}_{n,n-1}\ T^{(1,2)}_{n,n-1}\ T^{(2,1)}_{n,n-1}\ T^{(2,2)}_{n,n-1}$ Complex constant which makes up transfer matrix $T_{n、n-1}$.

The transfer matrix of the entire laminated structure (all m layers) $T_{m,0}$ is expressed as (11) as the product of transfer matrix of each layer (element).

$$T_{m,0} = T_{m,m-1} \cdot T_{m-1,m-2} \cdots T_{n,n-1} \cdot T_{n-1,n-2} \cdots T_{2,1} \cdot T_{1,0} \tag{11}$$

when $T_{m,0}$ is used, the acoustic impedance Z_m and sound pressure P_m at the laminated structure surface (cross section *m*) are expressed as (12) and (13) respectively.

$$Z_m = \frac{P_m}{u_m} = \frac{T_{m,0}^{(1,1)} z_0 + T_{m,0}^{(1,2)}}{T_{m,0}^{(2,1)} z_0 + T_{m,0}^{(2,2)}} \tag{12}$$

$$\frac{P_m}{P_0} = T_{m,0}^{(1,1)} + \frac{T_{m,0}^{(1,2)}}{z_0} \tag{13}$$

where $z_0 = \frac{\rho c}{\cos\theta'}$ is acoustic impedance of cross section *0*, ρ is air density, *c* is sound velocity, and θ' is transmission angle of sound wave.

2.3 Transfer Matrix of Element

In this program, the following two types of elements are used to obtain the transfer characteristics between the cross section *n* and the cross section *n+1*.

Distributed constant element is an element used for porous material with good permeability such as felt and urethane and gas such as air. When sound wave runs inside the porous materials or in the air, resistance caused by particle velocity works. At this time, amplitude and phase by particle of sound wave are changed. The effect of this is expressed by the following equations using the transfer matrix $T_{n,n-1}$ between the cross sections *n* and *n+1*.

$$T_{n,n-1} = \begin{bmatrix} \cosh(\gamma_n l_n) & w_n \sinh(\gamma_n l_n) \\ \frac{1}{w_n}\sinh(\gamma_n l_n) & \cosh(\gamma_n l_n) \end{bmatrix} \tag{14}$$

$$w_n = \frac{w_{nR}}{\cos\theta_n} + \frac{j w_{nI}}{\cos^2\theta_n}, \quad \gamma_n = a_n + \frac{jk_n}{\cos\theta_n}$$

where W_n is complex characteristic impedance of sound wave propagating in n later. Characteristic impedance is a constant indicating a reflecting amount at the material surface and the phase change at that moment. Suffixes of *R* means real part and *I* means imaginary part respectively.

γ_n is complex propagation constant of sound wave propagating in n layer. Propagation constant is a constant indicating damping and phase change when sound runs inside the material).

a_n is attenuation constant of sound wave propagating in *n* layer.

k_n is phase constant of sound wave propagating in n layer.

l_n is thickness of *n* layer.

θ_n is angle of sound wave propagating in *n* layer. *j* is imaginary unit.

For W_n, γ_n, and a_n values identified by the experiment with impedance tubes are used (improved two cavity method: [1]).

About the ultrafine fiber, I used Limp frame model [5]. The necessary parameter used technique [3] to identify from fiber diameter, fiber density, sample thickness, sample density.

$$K_{eq} \cong \frac{\gamma P_0}{\gamma - (\gamma - 1)\left[1 + \frac{8\mu}{j\Lambda'^2 B^2 \omega\rho_0}\sqrt{1 + j\rho_0 \frac{\omega B^2 \Lambda'^2}{16\mu}}\right]^{-1}} \tag{15}$$

$$\tilde{\rho}'_{eq} \approx \frac{\tilde{\rho}_{eq} M - \rho_0^2}{M + \tilde{\rho}_{eq} - 2\rho_0}, \ \tilde{\rho}_{eq} \cong \frac{\alpha_\infty \rho_0}{\phi}\left[1 - j\frac{\sigma\phi}{\alpha_\infty \rho_0 \omega}\sqrt{1 + j\frac{4\alpha_\infty^2 \mu \rho_0}{\sigma^2 \phi^2 \Lambda^2}\omega}\right], \quad \phi = 1 - \frac{\rho}{\rho_s}, \quad M = \rho + \phi\rho_0 \quad (16)$$

K_{eq}: the air coefficient of elasticity in fiber, γ: specific heat ratio of the air, P_0: standard atmospheric pressure, μ: loss factor of the air, Λ': thermal characteristic length, B^2: Prandtl number, ω: angular frequency, ρ_0: density of the air, $\tilde{\rho}'_{eq}$: Conversion density of air in fiber, α_∞: tortuosity, ϕ: porosity, σ: flow resistivity, Λ: viscous characteristic length, ρ: sample density, ρ_s: density of fiber

The flow resistivity assumed it the following expressions of relations than a measurement result of a large number of ultrafine fiber [3].

$$\sigma = \left\{85.733 \times (D \times 10^6)^{0.2871}\right\} \times \rho^{2.1922 \times (D \times 10^6)^{-0.2527}} \quad (17)$$

D: mean fiber diameter

The tortuosity often became approximately 1.0 in the fiber [4] and assumed it constant value 1.0.

We demanded a regression curve, and the thermal characteristic length an expression of relations such as expression (18) from a measurement result.

$$\Lambda' = 955.92\rho^{-0.816}\log(\mathrm{D} \times 10^6) + 511.99\rho^{-0.939} \quad (18)$$

The viscous characteristic length used the following expressions of relations to generally consist of fiber [6].

$$\Lambda = \frac{\Lambda'}{2} \quad (19)$$

We applied these to Limp frame model and calculated characteristic impedance and propagation coefficient than the following expressions of relations.

$$W_n = \sqrt{\tilde{\rho}'_{eq} \mathrm{K}_{\mathrm{eq}}}, \quad \gamma_n = \mathrm{j}\omega\sqrt{\frac{\tilde{\rho}'_{eq}}{\mathrm{K}_{\mathrm{eq}}}} \quad (20)$$

2.4 Refraction of Sound Wave at Element Boundary

Sound wave refracts when it encounters material with different sound velocity at the boundary between different materials. This effect is taken of sound wave with the following equation.

$$\theta_n = \sin^{-1}\left(\frac{c_n \sin\theta_{n-1}}{c_{n-1}}\right) \quad (21)$$

Using from (1) to (21) above, the sound absorption and insulation performances of the laminated structure are calculated.

3. Comparison of Experimental Results and Calculation Results

About the sound absorption material which I laminate nanofiber (thickness 2 [mm]) and PET (polyethylene terephthalate) materials (thickness 4.5 [mm]) of fiber diameter 0.8 [μm] by four pieces like Fig. 4 in turn, and covered up top and bottom with a nonwoven fabric, I show the comparison of the measurement result of the sound absorption coefficient using the sound pipe and the calculation result by this technique to Fig. 5. In Fig. 5 (a), PET materials of mean fiber diameter is 11.6 [μm]. In Fig. 5 (b), PET materials of mean fiber diameter is 28.5 [μm]. In Fig. 5 (c), PET materials of mean fiber diameter is 40.4 [μm]. There was a difference slightly in the high frequencies area more than 2,000 [Hz] when I compared the measurement result with the calculation result, but was able to quite predict a laboratory finding.

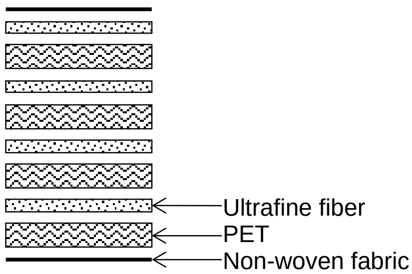
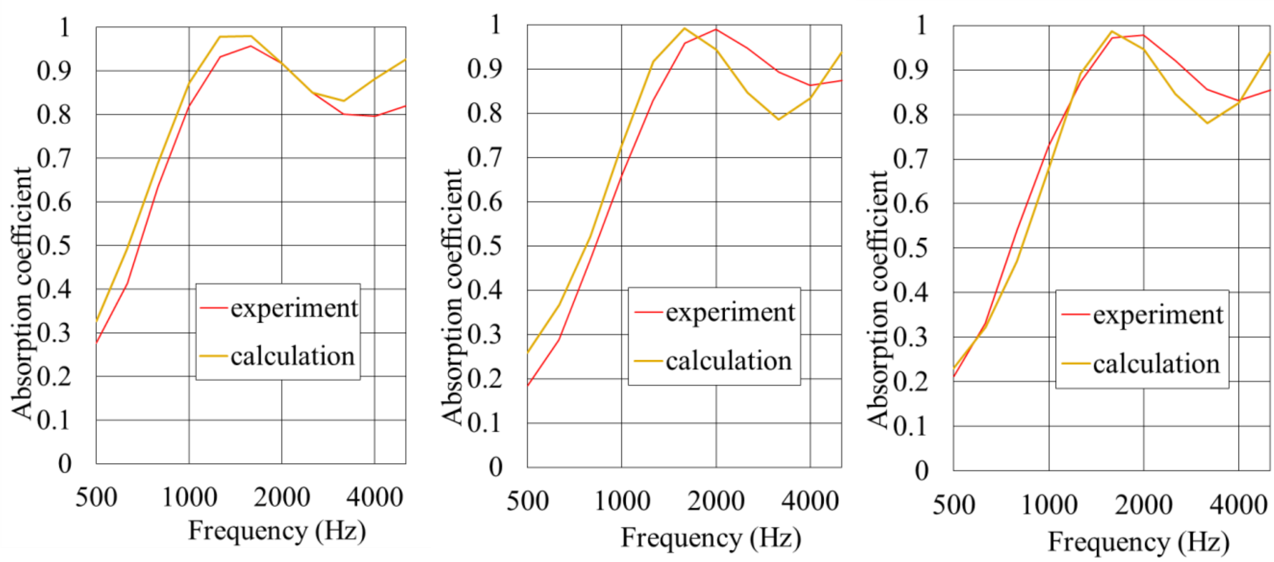


Fig. 4 Sound absorption material laminating pattern



(a) PETφ11.6 [μm] (b) PETφ28.5 [μm] (c) PETφ40.4 [μm]

Fig. 5 Comparison of experimental results and calculation results

4. Conclusion

We developed technique to predict a sound absorption coefficient of the sound absorption material that fiber diameter laminated plural nonwoven fabric and PET materials to nanofiber of 1μm - 4μm. With 2*2 transmission matrix method, we applied a parameter to guidance Limp frame model from an experiment expression of relations. We showed the agreement that was almost better than the sound absorption coefficient measurement result using the impedance tube.

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