World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:9, No:9, 2015

Development of Prediction Tool for Sound Absorption and Sound Insulation for Sound Proof Properties

Yoshio Kurosawa, Takao Yamaguchi

***Abstract*—**High frequency automotive interior noise above 500 Hz considerably affects automotive passenger comfort. To reduce this noise, sound insulation material is often laminated on body panels or interior trim panels. For a more effective noise reduction, the sound reduction properties of this laminated structure need to be estimated. We have developed a new calculate tool that can roughly calculate the sound absorption and insulation properties of laminate structure and handy for designers. In this report, the outline of this tool and an analysis example applied to floor mat are introduced.

***Keywords*—**Automobile, acoustics, porous material, Transfer Matrix Method.

I. Introduction

THE interior comfort as part of vehicle performance is emphasized in these days. Since the design considering interior quietness is required from the design concept stage, the development of CAE prediction technologies has been encouraged.

High frequency interior noise above 500 Hz considerably affects passenger comfort and conversation. This noise is mainly airborne noise such as engine noise, tire pattern noise, or wind noise transmitting through the body. In order to reduce the interior noise, sound insulation material is often laminated on body panels or interior trim panels. For example, floor area of a vehicle is securely sound insulated because this area highly contributes to the interior noise. The floor panel was made with a steel sheet in the required shape by press forming, and damping material of viscoelastic is laminated for the purpose of reducing the vibration level. On top of that, insulation material (porous material) made by felt or urethane and mat made of resin sheet are laminated. The insulation properties of this laminated structure cannot be predicted from the insulation properties of individual materials and members [1]-[4]. Furthermore, the thickness of insulation material varies, some material is absent, or combination of them is different depending on the place due to other parts or space limitation.

In recent years, the Statistical Energy Analysis (SEA method) is used for high frequency interior noise analysis including the prediction of the laminated insulation structure performance. However, tins method has some disadvantages such as it requires special analyst since there are too much know-how for modeling, and an exclusive measurement device is needed for measuring insulation material data. Under this circumstance, we developed a simple tool for design engineers that readily calculate the insulation properties (absorption and insulation properties) of the complex laminated structure. This is a tool based on spreadsheet in which absorption coefficient (Abs) and transmission loss (TL) of laminated members are calculated using the transfer matrix method with high speed (about few seconds) by a laptop computer. Specifically, calculation results can be graphed only by entering laminated patterns, material, and thickness etc. in the sheet. Material data of insulation material can be identified about ten minutes per sample using the measurement result of impedance tube.

This paper introduces the content of the tool and analysis for floor area as an example.

Y. Kurosawa is with the Department of Mechanical and Precision Systems, Teikyo University, Utsunomiya, CO 327-8551 Japan (phone: +81-28-627-715; fax: +81-28-627-7131; e-mail: ykurosawa@mps.teikyo-u.ac.jp).

T. Yamaguchi is with the Mechanical System Engineering Department, Gunma University, Kiryu, Japan (e-mail: yamagme3@gunma-u.ac.jp).

II. Calculation Method of Sound Absorption and Insulation Properties

This chapter describes the calculation method of the developed tool. The method is based on the method developed by Ota et al. [1]-[2].

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. 1. 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.

A. Sound Absorption Coefficient and Transmission Loss

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. Statistical incident sound absorption coefficientα_r is calculated by (1).

$$\alpha_r = \frac{\int_0^{\frac{\pi}{2}} 2\pi\alpha_\theta \sin\theta\cos\theta d\theta}{\int_0^{\frac{\pi}{2}} 2\pi \sin\theta\cos\theta d\theta} \tag{1}$$

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

Θ indicates incidence angle of sound wave to the surface of laminated structure. Where sound absorption coefficient is 0 (α=0), it is a perfect reflection. This condition is close to the acoustic field of room surrounded by concrete walls. Where the sound absorption coefficient is 1 (α=1) it is no reflection. This condition is close to the acoustic field of anechoic room. The sound insulation properties (sound transmission loss: TL) are expressed by (2) from the relation between the incident sound P_i and the transmitted sound P_t to the laminated structure as shown in Fig. 1.

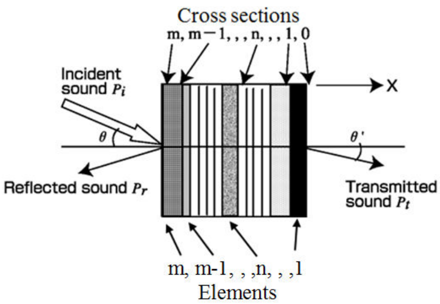

Fig. 1 Model of sound insulation material

$$\tau_\theta = \left|\frac{P_t}{P_i}\right|^2$$

$$\tau_r = \frac{\int_0^{\frac{\pi}{2}} 2\pi\tau_\theta \sin\theta\cos\theta d\theta}{\int_0^{\frac{\pi}{2}} 2\pi \sin\theta\cos\theta d\theta} \tag{2}$$

$$TL = 10 Log_{10}\left(\frac{1}{\tau_r}\right)$$

The larger transmission loss TL (unit: dB) is, the more we can reduce sound transmitting through the laminated structure.

B. Sound Absorption Properties and Acoustic Properties on Laminated Structure Surface

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 (3):

$$P_i + P_r = P_m = Z_m u_m \tag{3}$$

From the continuity of particle velocity in x direction,

$$\frac{P_i - P_r}{\rho c_x} = u_m$$

$$c_x = \frac{c}{\cos\theta} \tag{4}$$

c_x is an effective sound velocity in *x* direction. From (3) and (4), the relation of P_i, P_r, and Z_m is expressed as (5):

$$\frac{P_r}{P_i} = \frac{Z_m \cos\theta - \rho c}{Z_m \cos\theta + \rho c} \tag{5}$$

C. Sound Insulation Properties and Acoustic Properties on Laminated Structure Surface

The relation of the incidence sounds P_i and transmitted sound P_t in (2), 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 (3) and (4), the relation between the incidence sound P_i and the sound pressure P_m at the section m is expressed as (6):

$$P_i = \frac{P_m(Z_m + \rho c_x)}{2Z_m} \tag{6}$$

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 (7) and (8) from the sound pressure balance and the continuity of particle velocity.

$$P_t = Z_0 u_0 = P_0 \tag{7}$$

$$\frac{P_t}{\rho' c'_x} = u_0 \tag{8}$$

$$c'_x = \frac{c'}{\cos\theta'}$$

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 (7) and (8):

$$P_t = P_0 \qquad Z_0 = \rho' c'_x \tag{9}$$

D. 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 (10) and (11) using the elements transfer matrix $T_{n,n-1}$ [3].

$$\begin{Bmatrix} P_n \\ u_n \end{Bmatrix} = T_{n,n-1} \begin{Bmatrix} P_{n-1} \\ u_{n-1} \end{Bmatrix} \tag{10}$$

$$T_{n,n-1} = \begin{bmatrix} T_{n,n-1}^{(1,1)} & T_{n,n-1}^{(1,2)} \\ T_{n,n-1}^{(2,1)} & T_{n,n-1}^{(2,2)} \end{bmatrix} \tag{11}$$

$T_{n,n-1}^{(1,1)}, T_{n,n-1}^{(1,2)}, T_{n,n-1}^{(2,1)}, T_{n,n-1}^{(2,2)}$: 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 (12) as the product of transfer matrix of each layer (element).

$$T_{m,0} = T_{m,m-1} \cdot T_{m-1,m-2} \cdots T_{n,n-1} \cdot T_{n-1,n-2} \cdots T_{2,1} \cdot T_{1,0} \tag{12}$$

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 (13) and (14) respectively:

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

$$\frac{P_m}{P_0} = T_{m,0}^{(1,1)} + \frac{T_{m,0}^{(1,2)}}{z_0} \tag{14}$$

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.

E. 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 $n+1$.

$$T_{n,n-1} = \begin{bmatrix} \cosh(\gamma_n l_n) & w_n \sinh(\gamma_n l_n) \\ \frac{1}{w_n} \sinh(\gamma_n l_n) & \cosh(\gamma_n l_n) \end{bmatrix} \tag{15}$$

$$w_n = \frac{w_{nR}}{\cos\theta_n} + \frac{j w_{nI}}{\cos^2\theta_n}$$

$$\gamma_n = a_n + \frac{j k_n}{\cos\theta_n}$$

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 mean 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 (Fig. 2) are used (improved two cavity method: [5], [6]). Compares to the SEA method, it requires less parameters to be measured and measurement time is only ten minutes or so per one sample.

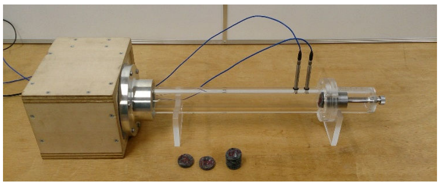

Fig. 2 Impedance tube (φ29mm)

Lumped constant element is applied to nonporous layer such as steel sheet, aluminum sheet, and resin. This element has a function as a vibration sheet or vibration film. The transfer matrix between the cross section n and the cross section $n+1$ is expressed by:

$$T_{n,n-1} = \begin{bmatrix} 1 & Z_{k,n} \\ 0 & 1 \end{bmatrix} \tag{16}$$

$$z_{k,n} = \frac{r_n}{\cos\theta_{n+1}} + j2\pi f m_n \left[1 - \left(\frac{f}{f_{c,n}} \right)^2 \sin^4\theta_{n+1} \right]$$

$$f_{c,n} = \frac{(c_{n+1})^2}{2\pi} \sqrt{\frac{m_n}{B_n(1 + j\eta_n)}}$$

where $Z_{k,n}$ is mechanical impedance of n layer element, $f_{c,n}$ is coincidence frequency of n layer element, m_n is surface density of n layer element, B_n is rigidity of n layer element, η_n is loss coefficient of n layer element, r_n is acoustic resistance of n layer element, c_{n+1} is sound velocity of sound wave transmitting in, $n+1$ layer, θ_{n+1} is sound wave angle transmitting in $n+1$ layer.

Rigid wall element can be expressed by making mechanical impedance infinite.

F. 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:

$$\theta_n = \sin^{-1}\left(\frac{c_n \sin\theta_{n-1}}{c_{n-1}}\right) \tag{17}$$

Using (1)-(17), the sound absorption and insulation performances of the laminated structure are calculated.

III. Calculation Result

A. Calculation Results and Test Verification

First of all, the analysis accuracy of the made calculation tool was check. Fig. 3 shows transmission loss for panel 0.8mm laminated felt 20mm1550g/m^2, resin sheet 2mm 3500g/m^2, felt 5mm 550g/m^2. When the experimental results were compared with the calculation results, it has checked that there agreed about.

B. Calculation of Floor

This chapter introduces the example of calculation by this tool. In calculation the laminated structure of the automotive floor shown in Fig. 4, just enter the following date in the sheet of the spreadsheet software; the number of lamination, material name, permeability, thickness, specific gravity, damping, name of characteristics data. In the actual vehicle, the lamination pattern and thickness vary. In such case, the calculation can be simply done with one calculation by sorting out the lamination patterns based on the thickness distributions, making a sheet for every lamination pattern considering area, and entering the date. Fig.5 shows the calculation result of transmission loss by making the eighteen-lamination patterns. The green thick line indicates the result of the integration of each lamination pattern.

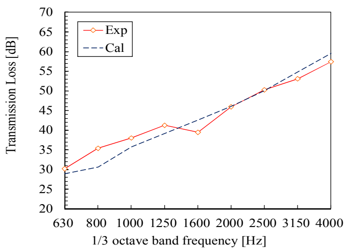

Fig. 3 Comparison of experimental results and calculation results

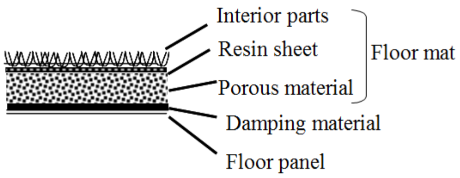

Fig. 4 Cross section of automotive floor

C. Optimum Laminated Structure for Floor Mat

The optimum laminated structure for a floor mat was studied using this tool. It assumes that the floor mat is laminated in a constant thickness in the order of panel, urethane, and resin sheet. With the weight per unit area of the mat (urethane & resin sheet) kept constant (1.5kg/m^2), weight ratio of urethane and resin sheet is changed to compare the transmission loss.

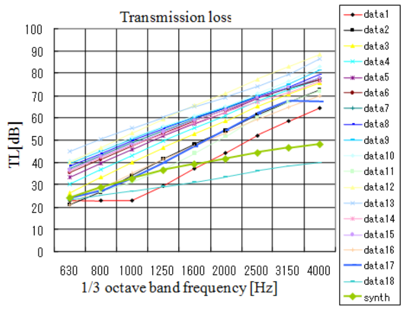

Fig. 5 Calculation results of transmission loss of floor

Urethane of ρ =0.05 g/cm^3 was used. The upper graph of Figs. 6 and 7 show the calculation result of transmission loss where the thickness of urethane and weight of resin sheet were as follows; (1) 0mm, 1.5kg/m^2 (2) 5mm, 1.25kg/m^2 (3) 10mm, 1.0 kg/m^2 (4) 15mm, 0,75kg/m^2 (5) 20mm, 0.5kg/m^2 (6) 25mm, 0.25kg/m^2 (7) 30mm, 0kg/m^2.

This result shows that (4)-(6) have better performance compared to (1) (mass law of resin sheet). This is caused by the effect of the double walled sound insulation structure, which the sound insulator (urethane) is sandwiched by the panel and the resin sheet. There is the optimum lamination pattern depending on material and frequency. The bottom graph of Fig. 6 shows 1kHz, 2kHz, 4kHz calculation. According to it, the optimum combination for 1kHz is (6), and (6) for 2kHz and 4kHz.

In actual vehicle, the sound insulation material is often reduced because of the space limitation and other parts. Figs. 8 and 9 show the result when the same calculation was made if urethane lacks 30% of the total area. This results show that its performance deteriorated more in the high frequency compared to Figs. 6 and 7. This is because the sound insulation effect of the double walled sound insulation structure is very few due to the lack of urethane. It is also found that, in the range of high frequency (above 2 kHz), the performance is slightly better if weight is allocated to resin sheet rather than urethane.

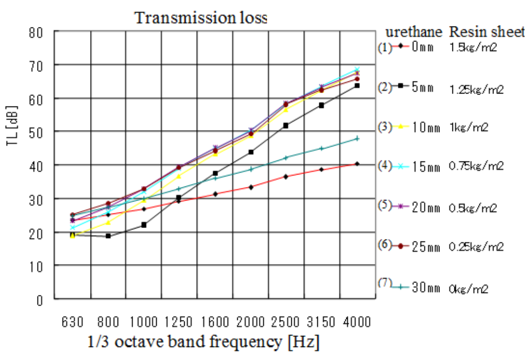

Fig. 6 Calculation results of transmission loss for seven patterns

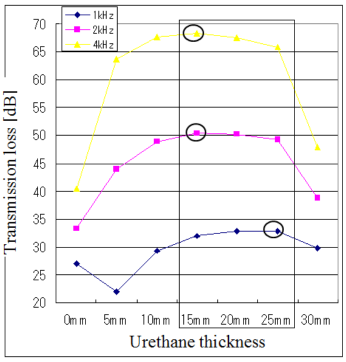

Fig. 7 Optimal lamination structure of floor mat

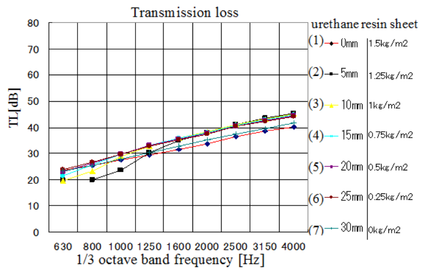

Fig. 8 Calculation results of transmission loss for seven patterns (urethane lacks 30%)

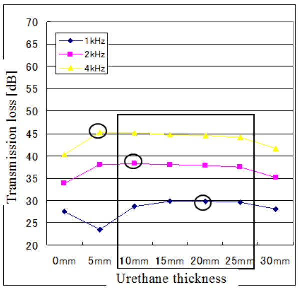

Fig. 9 Optimal lamination structure of floor mat (urethane lacks 30%)

IV. Conclusion

We developed the simple prediction tool for laminated sound insulation structure performance using the transfer matrix method. Using the spreadsheet software, designers can easily estimate the variation of sound performance caused by the changes of material, thickness, and area of sound insulation material. We analyzed the floor in the vehicle by the tool to study the optimum laminated structure.

References

[1] Ohta M., et al, A Unified Theory of Sound Transmission Loss of General Double Walls and its Practical Application to the Double Wall with Sound Absorbent Material in the Cavity, The Acoustical Society of Japan Vol. 34 No.1, 1978, pp.3.

[2] Ohta M., et al, A Unified Theory of Sound Transmission Loss of General Double Walls and its Practical Application to the Double Wall with Sound Absorbent Material in the Cavity, The Acoustical Society of Japan Vol. 35 No.3, 1979, p.118.

[3] Nishimura. K., et al, Experimental Acoustic Duct Analysis Based on Transfer Matrix Method: 1st Report, Transactions of the Japan Society of Mechanical Engineers. C vol. 54 No. 504, 1987, pp.1740.

[4] Shiraki K., et al, Noise Prevention Design and Simulation, O-You-Gijutu Shuppan, 1987.

[5] Utsuno H., et al, Transfer Function Method for Measuring Characteristic Impedance and Propagation Constant of Porous Material, J. Acoust. Soc. Am. vol. 86 No.2, 1989, pp. 637.

[6] Yamaguchi T., Society of Damping Technology, Technology Exchange Forum, 1999, pp. 91-94.