

Prediction of Vehicle SEA Model Input Parameters for a Sound Package

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ABSTRACT

This paper describes a method for the prediction of automotive sound package acoustical characteristics. This method is based on the transfer matrix approach and is applied to calculate the transmission loss (TL) and absorption of multi-layered insulation components from the acoustical impedance of each layer. The predicted results are necessary as fundamental input parameters of SEA vehicle models. The accuracy of this method was verified by comparing the predicted TL and absorption values of trimmed components with measurement results.

1. Introduction

Statistical energy analysis (SEA) has come into wide, general use for analysis of high-frequency sound propagation, especially through air. A key point in constructing SEA models related to air-propagated sound is to find coupling loss factors (CLF), which express the acoustic insulation characteristics between acoustic fields, and the damping loss factors (DLF), which express the acoustic absorption characteristics of a single acoustic field. It is possible to calculate the CLF and DLF from the acoustic characteristics (transmission loss, absorption coefficient) of a sound package. It is also possible to measure the acoustic characteristics of a sound package, but this is not realistic in an automobile at the development stage. In order to accomplish both weight savings and sound-proofing of an automobile in a short time frame and at low cost, it is necessary to have the technology for predicting the acoustic characteristics of a sound package and for creating SEA models of the situation in an actual vehicle at stages when no test vehicles yet exist (initial stages of development).

The CLF and DLF of an acoustic system are especially important for setting the specifications of noise insulation. Therefore, in this study, a method was proposed for predicting the transmissibility τ (for the transmission losses TL) and the absorption coefficient α from the specifications of multi-layered automotive trim (composition, thickness and material characteristic). The validity of the method was verified by comparing predicted values with measured values.

2. Relationship between Acoustic Characteristics of Noise Insulation and SEA Parameters

The CLF between acoustic fields η_{12} can be found using Eq. (1) with the transmissibility τ_{12} found using the method described in this paper. Here, A is the area of the interface between acoustic fields V the combined volume of the acoustic fields. Additionally, c_0 is the speed of sound in air and ω is the angular velocity of the sound.

- CLF of acoustic fields:

$$\eta_{12} = \frac{A \cdot c_0}{4\omega V} \tau_{12} \quad (1)$$

In the same way, the DLF of an acoustic field η can be found using Eq. (2) with the absorption coefficient α found using this method and the area A and volume V of the acoustic field.

- DLF of acoustic system:

$$\eta = \frac{A \cdot c_0}{4\omega V} \alpha \quad (2)$$

Using these expressions allows investigation of the sound-insulating specifications of the floor, and sound-absorption specifications of various acoustic cavities in the automobile. Knowing these parameters can permit efficient reduction of road noise in the initial stages of development of an automobile.

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3. Method for Prediction of Acoustic Characteristics of Multi-layered Trim

Prediction of the acoustic characteristics of multi-layered trim is based on the transmission matrix method. This allows prediction of the acoustic characteristics of multi-layered trim consisting of both porous materials and vibration-damping materials. In this method, a model consisting of the subject trim material is constructed of multiple areas, of which each can be considered a laminated body of uniform thickness. The transmission losses TL_i and the absorption coefficient α_i of trim layer i are calculated. Then, the calculated values of TL_i and α_i are used to find the mean TL and mean α for the whole area.

3.1. Method for Estimating Transmission Losses in Multi-layered Trim of Uniform Thickness

As shown in Fig. 1, the structure of a general multi-layered trim of uniform thickness is a triple lamination, consisting of the first layer, an impervious barrier; the second layer, a porous medium; and the third layer, a plate.

p_i is the acoustic pressure of the incident wave, ϕ is the incident angle, and p_T is the acoustic pressure of the transmitted wave. The impedance of each interface is found in sequence.

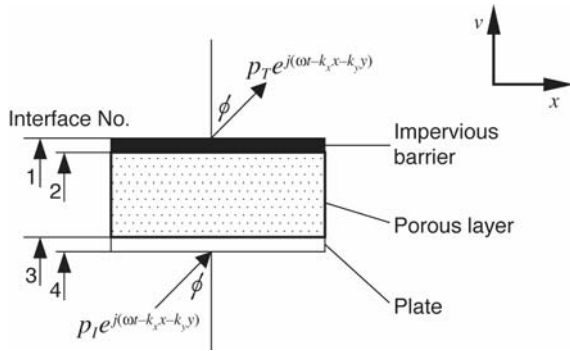


Fig. 1 Three layers in contact in a multilayer material

First, the impedance Z_1 of the first interface (at air) is calculated using Eq. (3) and (4). Here, k is the wave number.

$$k_x = k_0 \sin \phi \quad (3)$$

$$Z_T = Z_1 = \frac{\rho_0 c_0}{\cos \phi} \quad (4)$$

Next, the impedance Z_2 of the second interface (at impervious barrier) is calculated using Eq. (5), (6), (7) and (8). Here, the surface density, thickness, Young's modulus, Poisson's ratio, and loss factor at each interface are denoted by ρ , t , E , ν and η , respectively.

$$Z_2 = Z_1 + j \left[\omega \rho_s - \frac{D^c k_x^4}{\omega} \right] \quad (5)$$

$$P_x = P_{BTB} \quad (6)$$

$$D^c = D(1 + j\eta_B) \quad (7)$$

$$D = \frac{E_B t_B^3}{12(1 - \nu_B^2)} \quad (8)$$

The impedance Z_3 at the third interface (at porous barrier) is calculated using Eq. (9), (10), (11) and (12). The subscript 'PL' indicates that the variable applies to the porous layer; R_{PL} is the flow resistance of the porous layer.

$$Z_3 = Z_0 \frac{K}{k_y} \frac{\left(1 + \frac{Z_0 K}{Z_2 k_y} \right) e^{jk_y t_{PL}} + \left(1 - \frac{Z_0 K}{Z_2 k_y} \right) e^{-jk_y t_{PL}}}{\left(1 + \frac{Z_0 K}{Z_2 k_y} \right) e^{jk_y t_{PL}} - \left(1 - \frac{Z_0 K}{Z_2 k_y} \right) e^{-jk_y t_{PL}}} \quad (9)$$

$$Z_0 = \rho_0 c_0 \sqrt{1 - j \frac{R_{PL}}{\rho_0 \omega}} \quad (10)$$

$$K = k_0 \sqrt{1 - j \frac{R_{PL}}{\rho_0 \omega}} \quad (11)$$

$$k_y^2 = K^2 - k_x^2 \quad (12)$$

The impedance Z_4 at the fourth interface (at plate) is calculated from Eq. (13), (14) and (15).

$$Z_l = Z_4 = Z_3 + j \left[\omega \rho_s - \frac{D^c k_x^4}{\omega} \right] \quad (13)$$

$$P_x = P_{pT} \quad (14)$$

$$D^c = D(1 + j\eta_p) \quad (15)$$

The transmission loss in a multi-layered trim of uniform thickness, $TL^{w/trim}$, is found in Eq. (16) – (22) using impedances $Z_1 - Z_4$:

$$\tau_R^{w/trim}(\omega) = \int_0^{\pi/2} \tau_R^{w/trim}(\omega, \phi) \sin 2\phi d\phi \quad (16)$$

$$TL^{w/trim} = 10 \log \frac{1}{\tau_R^{w/trim}(\omega)} \quad (17)$$

$$\text{Here, } \tau_R^{w/trim}(\omega, \phi) = \frac{|p_T|^2}{|p_I|^2} \quad (18)$$

$$p_T = p_1 = \frac{Z_1}{Z_2} p_2 \quad (19)$$

$$p_2 = \frac{p_3}{2} \left[\left(1 + \frac{Z_0 K}{Z_3 k_y} \right) e^{-jk_y t_{PL}} + \left(1 - \frac{Z_0 K}{Z_3 k_y} \right) e^{jk_y t_{PL}} \right] \quad (20)$$

$$p_3 = \frac{Z_3}{Z_4} p_4 \quad (21)$$

$$p_4 = \frac{2\alpha}{\alpha+1} p_i, \quad \alpha = \frac{Z_l}{Z_T} = \frac{Z_4}{Z_1} \quad (22)$$

(p_i is the acoustic pressure at each interface)

3.2. Method for Estimating Acoustic Absorption Coefficient in Multi-layered Trim of Uniform Thickness

Here, the method for finding the absorption coefficient α in a multi-layered trim of uniform thickness is explained. The multi-layered trim of uniform thickness used as the object of this analysis is shown in Fig. 2.

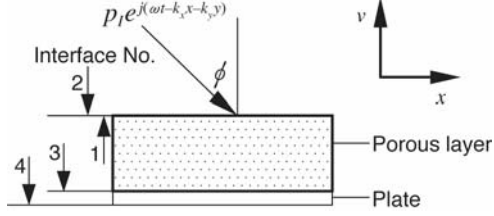


Fig. 2 Two layers in contact in a multilayer material

The first layer of this 2-layer structure is a porous material and the second is a plate. p_i is the acoustic pressure of the incident wave and ϕ is the incident angle.

The absorption coefficient in this case is calculated with the following expression:

$$\hat{\alpha} = 2 \int_0^{\phi_{lim}} d\phi \sin\phi \cos\phi \alpha \quad (23)$$

$$\text{Here, } \alpha = \frac{\text{Absorption energy}}{\text{Incident energy}} = 1 - |R|^2 \quad (24)$$

R : reflection factor

When noise impinges on an interface at a right angle, the reflection factor and absorption coefficient are found using the characteristic impedance Z_2 for perpendicular incident energy in the sound-absorbing layer (Interface 2) and the characteristic impedance Z_1 at the air surface (Interface 1) in the following relation:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (25)$$

Here, Z_2 is found using Eq. (26) – (29).

$$Z_2 = Z_0 \frac{K}{k_y} \frac{\left[1 + \frac{Z_0 K}{Z_3 k_y}\right] e^{jk_y t_{PL}} + \left[1 - \frac{Z_0 K}{Z_3 k_y}\right] e^{-jk_y t_{PL}}}{\left[1 + \frac{Z_0 K}{Z_3 k_y}\right] e^{jk_y t_{PL}} - \left[1 - \frac{Z_0 K}{Z_3 k_y}\right] e^{-jk_y t_{PL}}} \quad (26)$$

$$Z_0 = \rho_0 c_0 \sqrt{1 - j \frac{R_{PL}}{\rho_0 \omega}} \quad (27)$$

$$K = k_0 \sqrt{1 - j \frac{R_{PL}}{\rho_0 \omega}} \quad (28)$$

$$k_y^2 = K^2 - k_x^2 \quad (29)$$

The impedance Z_3 at the surface of the plate (Interface 3) is found in the same way as shown in Eq.(5) shown in Section 3.1.

3.3. Method for Estimating Transmission Loss in Actual Automotive Trim

Here, the method for estimating the transmission loss in a multi-layered trim of uniform thickness shown in Section 3.1 is used to estimate the transmission loss in a real floor carpet of non-uniform thickness.

The following expression (30) is obtained when sections $A_1 - A_n$ of a floor carpet can be assumed to have uniform thickness with transmissibilities $\tau_1 - \tau_n$. Here, τ is the mean floor carpet transmissibility and A is the total floor area.

$$\tau A = \tau_1 A_1 + \tau_2 A_2 + \dots + \tau_n A_n \quad (30)$$

τ is found by the following procedure: τ_i is calculated by the method for predicting transmission losses in multi-layered trim of uniform thickness shown in Section 3.1 for each section of the floor which can be considered of uniform thickness. Then, these are substituted into Eq. (30) and the sum is divided by total floor area A . The overall transmission loss is then found using the mean transmissibility τ and Eq. (16), (17) and (18).

The estimated TL is shown in Fig.4.

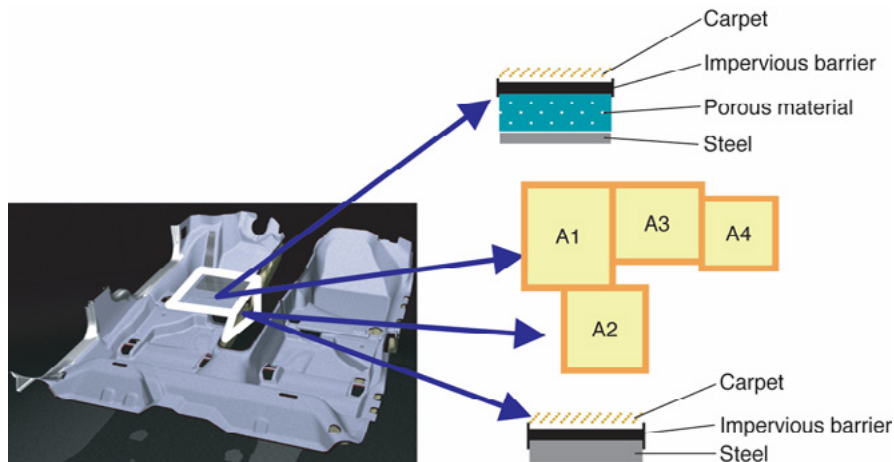


Fig. 3 Definition of the floor carpet model

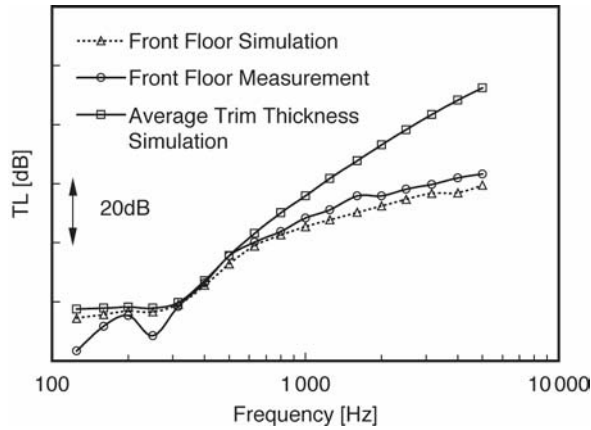


Fig. 4 Measured and simulated TL for the floor

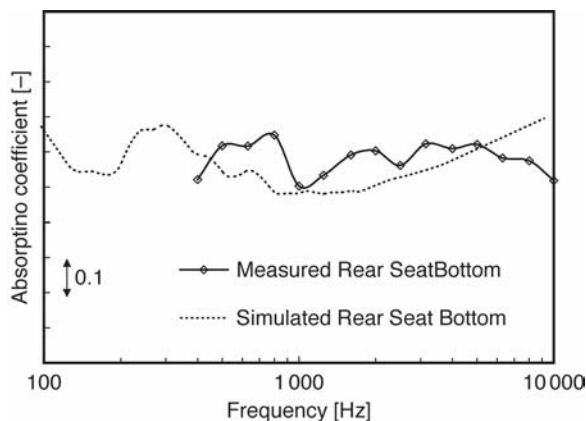
3.4. Method for Estimating Absorption Coefficient in Actual Automotive Trim

Here, the method for estimating the absorption coefficient is shown for a real seat of non-uniform thickness, using the method described in Section 3.2 for estimating the absorption coefficient α in a multi-layered trim of uniform thickness.

Like the method for predicting the floor carpet transmission losses explained in Section 3.3, the following expression (31) can be obtained when areas $A_1 - A_n$ of a floor carpet can be assumed to have uniform thickness with absorption coefficients $\alpha_1 - \alpha_n$, as in the method for transmissibilities. Here, α is the mean absorption coefficient of the seat and A is the total seat area.

$$\alpha A = \alpha_1 A_1 + \alpha_2 A_2 + \dots + \alpha_n A_n \quad (31)$$

α is found by the following procedure: α_i is calculated by the method in Section 3.2 for each section of the seat which can be considered of uniform thickness. Then, these are substituted into Eq. (31) and the sum is divided by total seat area A . The seat absorption coefficient is then found using the mean seat absorption coefficient α and Eq. (23), (24) and (25). The estimated α are shown in Fig. 5.

Fig. 5 Measured and simulated α for the seat

4. Verification of Precision of Estimates of Acoustic Characteristics

4.1. Measurement of Acoustic Characteristics

1) Measurement of transmission loss in floor carpet

The TL values in Fig. 4 observed in an actual floor carpet were measured using the acoustic property measurement equipment shown in Fig. 6. The upper chamber in the equipment in Fig. 6 is the reception cabin (reverberation chamber), and the lower chamber is the emission cabin. The test sample was placed between the two chambers. Noise was generated by the speakers on the floor of the lower chamber, and the transmission loss was calculated from the acoustic pressures in the upper and lower chambers. This equipment was used to measure the TL in the floor carpet shown in Fig. 7. The TL observed in the floor section is shown in Fig. 4.

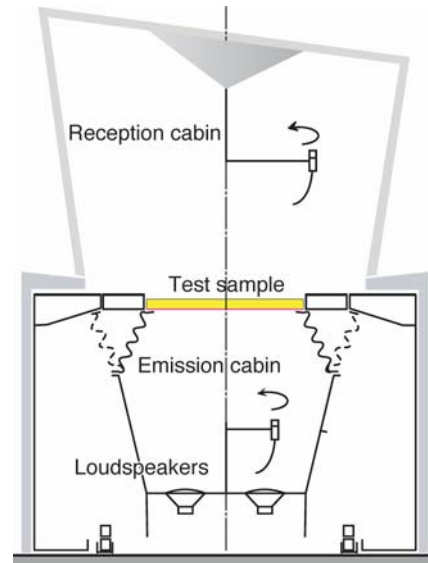


Fig. 6 The acoustic property measurement equipment



Fig. 7 The front floor as an example

2) Measurement of absorption coefficient of a seat

α values were measured in the actual seat shown in Fig. 8 with the equipment shown in Fig. 6, as described in part 1) above. The upper chamber in the equipment in Fig. 6 is the reverberation chamber and the test sample is placed between the two chambers. Noise was generated at the speakers toward the upper chamber, and the absorption coefficient was calculated from the reverberation time. This equipment was used to measure α of the portion of the seat under measurement. The observed α are graphed in Fig. 5.

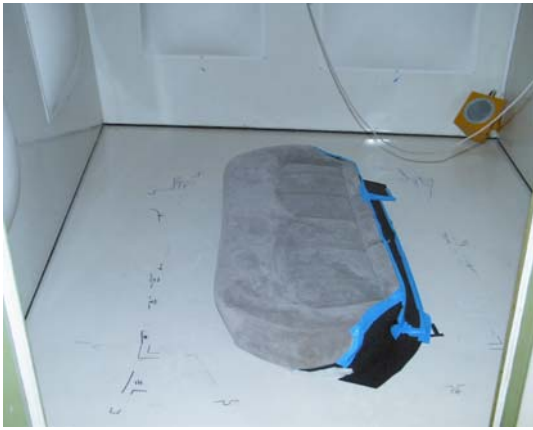


Fig. 8 The rear seat bottom cushion as an example

4.2. Comparison of Predicted Values and Measured Values

1) Transmission losses in floor carpet

The measured values for transmission loss in the floor carpet observed by the method described above are shown in Fig. 4 for comparison with the values predicted by the method shown in Section 3. It is clear that there was over a 10 dB difference between the results for TL using the mean thickness of trim in the floor plate as the equivalent plate thickness and the results for TL using actual plate thicknesses shown in Section 3.3, in the region over 1000 Hz. Also, the latter predicted results matched well with the observed TL in the actual floor plate. The analytical accuracy was within $\pm 3\%$ dB.

Thus, these results indicate that the method of dividing the floor areas into sections which can be considered of equal thickness, calculating the overall mean floor transmissibility from the values for each section, and calculating the floor TL from this transmissibility is superior to the method of calculating TL from average plate thickness.

2) Absorption coefficient of a seat

By comparing the value for seat absorption coefficient estimated by the method in Section 3.4 with the observed absorption coefficient in Section 4.1, it is confirmed that the prediction method proposed in this paper yielded an analytical precision within ± 0.15 (Fig.5).

5. Summary

Methods were presented for estimating the transmission loss characteristics and absorption coefficient of automotive trim with varying thickness and structure. The validity of the methods was verified by comparison with measured values. Accordingly, the following results were found.

- 1) The transmission losses in floor carpet were predicted with an accuracy of ± 3 dB at frequencies over 400 Hz by the demonstrated method.
- 2) The seat absorption coefficient was predicted with an accuracy of ± 0.15 at frequencies over 400 Hz by the demonstrated method.
- 3) This method enables prediction of the SEA parameters CLF and DLF by calculation of transmissibility and absorption coefficient at the early development stage of automobiles, when there are no physical models yet.

- 4) The above results indicate that the demonstrated method is effective for the investigation of specifications of sound packages in the development of automobiles.

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