

Establishment of Method for Optimizing Multi Specifications for Sound-proof Packages

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ABSTRACT

This paper describes an optimization method for designing a vehicle sound-proof package. This method enables the achievement of an optimum balance between lower weight and higher absorption performance. In order to propose a sound-proof package in the early stages of vehicle development, it is necessary to assess the number of sound-proof elements required and to select the optimum design specifications for weight and absorption performance. However, it is difficult to achieve conflicting objectives simultaneously, and acoustic engineers therefore require special technical knowledge. The research discussed here developed a new automated optimization method that resolves these issues. The new method enables detailed sound-proof package specifications to be obtained, including the thickness distribution for each part. These specifications can be easily transferred to drawings. The method was successfully used to reduce the sound pressure level of a vehicle cabin, providing verification of its accuracy.

1. Introduction

Increasing the quietness of automotive cabins is an important element in enhancing commercial performance. The achievement of weight savings is also an indispensable element in ensuring fuel efficiency. However, in many cases increased quietness (enhanced acoustic performance) and the attainment of weight savings are contradictory objectives.

It is necessary to determine specifications from the initial stages of a development project in order to develop efficient sound-proof packages^{(1), (2)}. The flow of the process of determining specifications is as follows:

- (1) Determine the targets for in-cabin sound pressure level.
- (2) Determine the targets of individual vehicle components for achieving the overall in-cabin sound pressure target using SEA parameters of damping loss factor (DLF) and coupling loss factor (CLF).
- (3) Determine the targets of each sound-proof component based on absorption coefficient and transmission loss for achieving the targets of individual vehicle components.
- (4) Establish the material, thickness, and area coverage for each layer of each component in the sound-proof package for achieving targets.

Techniques are already available using the SEA method for items (1)-(3)^{(1), (2)}. However, a number of parameters, including acoustic material choice, thickness and application area, should be considered in order to decide on the specifications in item (4), and it is therefore challenging to determine specifications in a short period of time.

The purpose of the study discussed in this paper was to propose a method for optimizing multi-objective specifications for sound-proof packages that enables optimum specifications satisfying in-cabin sound pressure level targets. In addition, for verification, a comparison is made between the near-optimal and optimal results proposed by this method. In the result, the essence of this optimization technique can be verified by acoustic performance.

2. Analysis Method

Sound-proof package used in automotive applications is composed of layers of several different materials. Figure 1 shows an example of this structure, which will be referred to as a “multi-layered” structure in this paper.

The acoustic performances (absorption coefficient,

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transmission loss) are determined by the material specifications of each layer of the multi-layered structure, the thickness of these materials, and their surface area. These items are referred to as the sound-proof package specifications.

Figure 2 shows the flow of the process of designing sound-proof package specifications to satisfy in-cabin sound pressure level targets. This process is discussed in detail below.

(1) Specifying material and equivalent thickness in element

Limitations are placed on the potential thickness of the acoustic materials by other aspects of the layout, including the shape of the body panels, the air-conditioning ducts and the harnesses. Based on these restrictions, the acoustic materials are divided into a number of elements. Each layer of the multi-layered structure of each element is treated as being formed from a uniform material, and the layers are treated as being of equivalent thickness. Specifications for materials and the thickness of materials that satisfy the in-cabin sound pressure level targets are determined for each element. At the same time, the

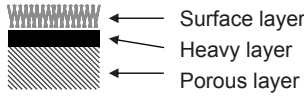


Fig. 1 Multi-layer sound-proof package

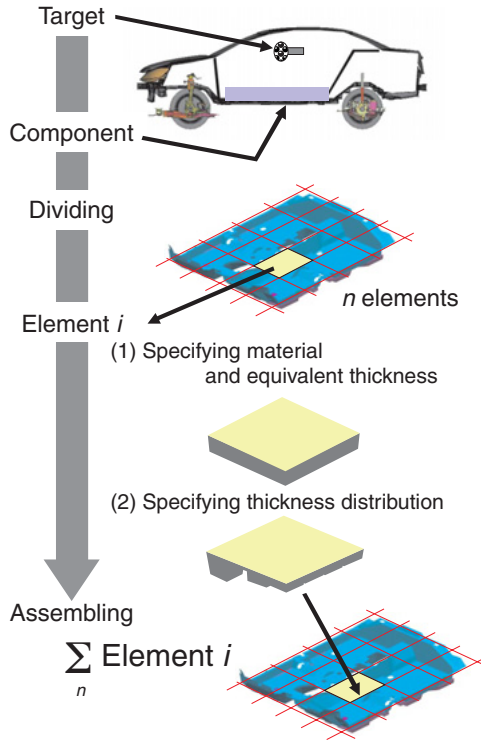


Fig. 2 Procedure for design of optimized sound-proof package

acoustic characteristics (absorption coefficient, $\bar{\alpha}_{if}$, and transmission loss, $\overline{TL}_{if}$) are calculated. Here, f is the center frequency of the 1/3 octave band.

(2) Specifying thickness distribution in element

As Fig. 3 shows, there is a range of variation in the thickness of the acoustic materials that are used in mass-production vehicles from thick to thin. This is termed the thickness distribution.

Because of the restrictions imposed by the shape of the panels and other aspects of the layout, even the elements into which the materials have been divided for optimization of specifications are unable to be assigned a constant thickness. Therefore, specifications for material thickness that reflect the design layout are determined, while maintaining the acoustic characteristics of the elements with materials of equivalent thickness divided in the study conducted in step (1). The relationship between the acoustic characteristics of the elements with materials of equivalent thickness and the elements with a thickness distribution reflecting the design layout is given by Eqs. (1) and (2).

$$\bar{\alpha}_{if} = \frac{\sum_j^n A_{ij} \cdot \alpha_{ifj}}{A_i} \quad (1)$$

$$\overline{TL}_{if} = 10 \times \log \left(\frac{1}{\bar{\tau}_{if}} \right)$$

$$\bar{\tau}_{if} = \frac{\sum_i^n A_{ij} \cdot \tau_{ifj}}{A_i}, \quad TL_{ifj} = 10 \times \log \left(\frac{1}{\tau_{ifj}} \right) \quad (2)$$

Here, A_i is the surface area of the element i , A_{ij} is the surface area of the material of constant thickness j in element i , α_j is the absorption coefficient, and τ_j is the transmission loss.

The method of optimizing the materials and the thickness distribution in each element is discussed below.

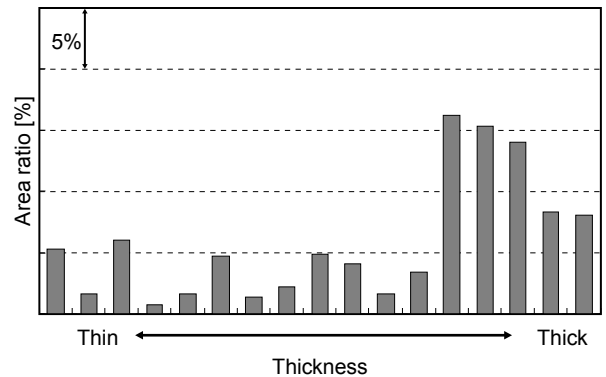


Fig. 3 Thickness distribution of mass produced floor carpet

2.1. Element Material and Equivalent Thickness Optimization

This section will discuss the flow of the procedure employed to optimize the specifications of the elements of the sound-proof package and the algorithm used in this procedure.

2.1.1. The optimization process

Figure 4 shows the process flow for calculating the optimum specifications for the elements of the sound-proof package. The details of each procedure can be summarized as follows:

- (1) The sound-proof package is divided into n elements, and an analytic SEA model is constructed treating the material used in each layer of the multi-layered structure of each element and equivalent thickness of each layer as design variables.
- (2) For each element, the thickness of the overall structure, the equivalent thickness of each layer, the analytic frequencies, and constraints for in-cabin sound pressure level are set.
- (3) The total weight of the sound-proof package and in-cabin sound pressure level are set as objective functions.
- (4) Optimum specifications are searched under the conditions described above.
- (5) Optimum acoustic performance (absorption coefficient, $\bar{\alpha}_{ij}$, and transmission loss, $\bar{T}L_{ij}$) are calculated⁽³⁾ for each satisfactory element determined in step (4).

2.1.2. Algorithm for optimization

A non-dominated sorting genetic algorithm (NSGAI)⁽⁵⁾ is used to search optimum design variables that satisfy the multiple objective functions (total weight of sound-proof package and in-cabin sound pressure level) set in step (3) above. However, because there are numerous design variables and an extensive search time is required, the variables are restricted in two stages. The methods

employed are discussed below⁽⁶⁾.

(1) Grouping

Elements possessing an identical multi-layered structure are grouped, and the design variables are restricted.

(2) Examination of objective function sensitivity to design variables

Using the orthogonal experimental method, the equivalent thickness of the layers in the multi-layered structures of the elements (which represent design variables) are converted to three levels; the design variable with the lowest sensitivity to in-cabin sound pressure level is used as an initial value, and design variables are restricted.

2.2. Element Thickness Distribution Optimization

This section will discuss the optimization process for thickness distribution of the elements of the sound-proof package and the algorithm employed in the process.

2.2.1. The optimization process

Figure 5 shows the flow of the process of searching optimum results for the thickness distribution of the elements. The following procedures are used:

- (1) The optimum acoustic characteristics of element i (absorption coefficient, $\bar{\alpha}_{ij}$, and transmission loss, $\bar{T}L_{ij}$) are set as objective functions.
- (2) The surface area of element i is termed A_i , and the surface area of the material of fixed thickness j in element i is termed A_{ij} . The ratio of each of these fixed thicknesses is expressed as A_{ij}/A_i , and is set as a design variable. Variations in this ratio of surface areas are treated as the thickness distribution.
- (3) Under these conditions, the optimum thickness distribution that achieves the optimum acoustic performance at the lowest weight is searched.

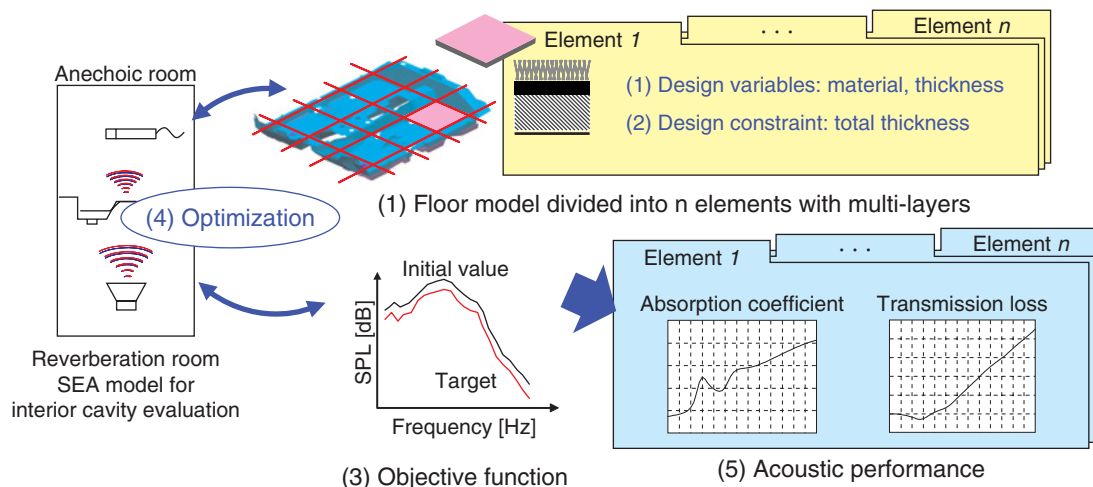


Fig. 4 Optimization process for design variables in elements

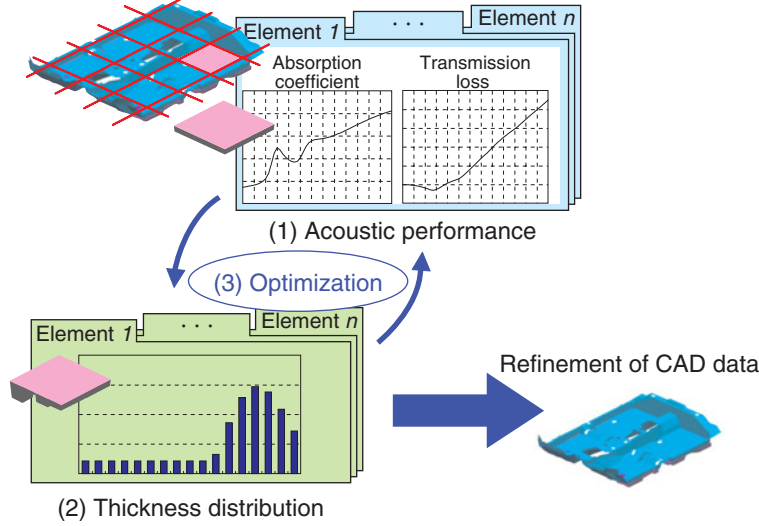


Fig. 5 Optimization process for thickness distribution

2.2.2. Algorithm for optimization

It is desirable that an optimum thickness distribution is realized in an actual vehicle, and that the search time is short. To satisfy these requirements, the three items discussed below are incorporated into the search algorithm.

(1) Expression by function of thickness distribution

As Fig. 3 shows, the thickness distribution of divided elements in mass-production vehicles is affected by the shape of the panels and other layout constraints. The thickness distribution tends to describe a smooth curve centering on a specific thickness. In the proposed method, the thickness distribution A_{ij}/A_i , which enables this tendency to be reproduced, is expressed as a function like Eq. (3).

$$A_{ij}/A_i = K_1 \cos(k_1 \times j) + L_1 \sin(l_1 \times j) + K_2 \cos(k_2 \times j) + L_2 \sin(l_2 \times j) + M \quad (3)$$

Here, the factors K_1 , k_1 , L_1 , l_1 , K_2 , k_2 , L_2 , l_2 and M in Eq. (3) are variables enabling determination of A_{ij}/A_i .

(2) Restriction in thickness distribution

Certain thicknesses, j , can generate surface area ratios that vary considerably from others in the thickness distribution A_{ij}/A_i expressed as a function for element i . These surface area ratios are issues to realize in the actual sound-proof package. To ensure that surface area ratios do not vary widely, constraints are placed on the surface area ratio of thickness j and the surface area ratios of the contiguous thicknesses $j-1$ and $j+1$. As an example, Fig. 6 shows constraints of 5% and 10% applied to $j-1$ and $j+1$ respectively. This ensures that the search for a thickness distribution is able to generate a result that can be realized in practice.

(3) Two-step optimization process

The absorption coefficient and transmission loss,

treated as objective functions, are independent indexes with no correlation. Because of this, there is the possibility that the algorithm employed will search for a local optimal result close to the initial value and ignore global optimal results.

In this project, the use of an algorithm combining NSGAII for global optimization, and sequential quadratic

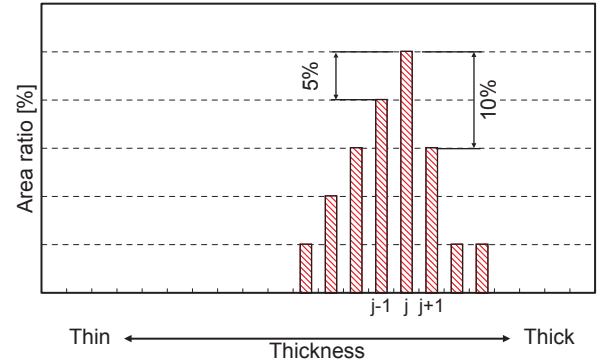


Fig. 6 Constraint for thickness distribution

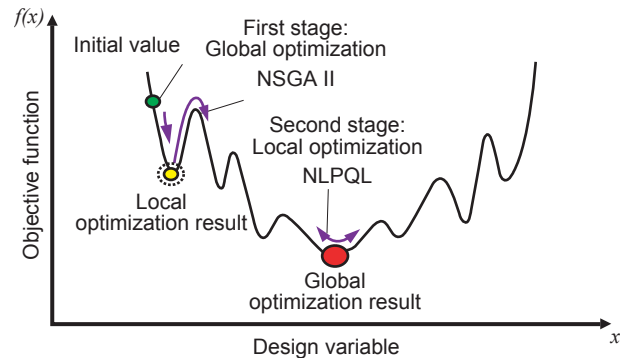


Fig. 7 Results of local and global optimization

Table 1 Optimization variables for elements

Objective component	Floor carpet divided along with floor panel shape into 50 elements
Design variables	Each layer thickness in multi-layer
Constraints	Total thickness of multi-layer in each part
Objective functions	Interior cavity sound pressure level in O.A. and high frequency range 1.25-5 kHz

Table 2 Target for floor optimization in interior cavity sound pressure level and floor carpet total weight

	High-frequency range 1.25-5 kHz	O.A.	Total weight
Target	1.0 dB reduction	1.0 dB reduction	Lighter than initial weight

programming (NLPQL)⁽⁴⁾ for local optimization, accomplished the method to search for global optimal results as shown in Fig. 7.

3. Analysis Results

The floor section was adopted as an example, and optimum specifications were searched for the sound-proof package using the proposed methods of optimizing materials specifications and thickness distribution. The details of each process are discussed below.

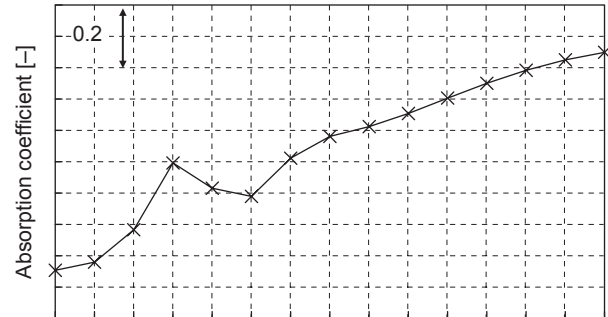
3.1. Element Material and Equivalent Thickness Optimization

A target was set for the effect on in-cabin sound pressure level to be achieved as a result of measures applied on the floor section, and materials specifications were searched for the floor elements, enabling this target to be satisfied. Table 1 shows the variables established for optimization of materials specifications.

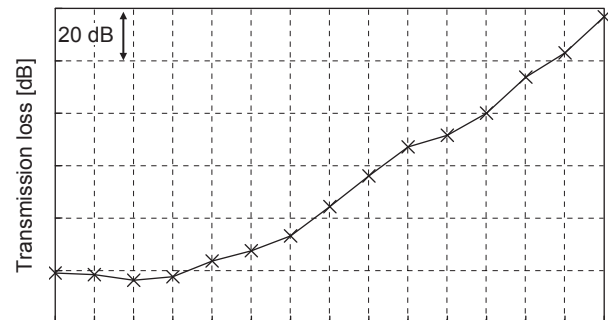
Table 2 shows the targets for the optimum specifications.

As Fig. 8 shows, using grouping and examination of objective function sensitivity, the approximately 100 design variables established in Table 1 are reduced to approximately 20.

Next, using the reduced design variables, the specifications of the elements that satisfied the conditions were optimized. An example of the optimum specifications determined by the method is shown in Fig. 8. The absorption coefficient, $\bar{\alpha}_f$, and transmission loss, $\overline{TL}_f$, of the optimum package are shown in Fig. 9.



(a)



(b)

Fig. 9 Sound-proof performance of optimal sound package: (a) absorption coefficient and (b) transmission loss

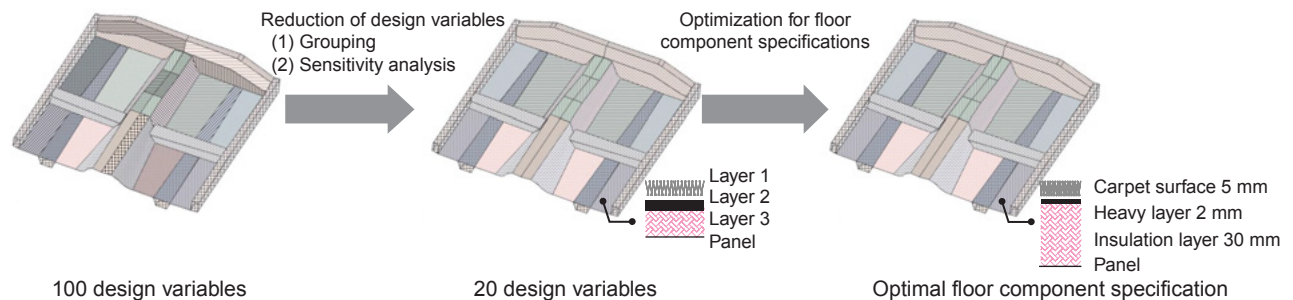


Fig. 8 Reduction of design variables and optimal result

Table 3 Optimization variables for thickness distribution

Design variables	Thickened in 2 mm pitch from 7 mm to 41 mm in an element
Constraints	Coefficients in Eq.(3) restrained as follows; $-10000.0 \leq K_1, L_1, K_2, L_2 \leq 10000.0$ $-10000 \leq k_1, l_1, k_2, l_2 \leq 10000$ $0 \leq M \leq 10000$
Objective functions	Absorption coefficient and transmission loss of the element

3.2. Element Thickness Distribution Optimization

An additional examination was conducted to determine a more attainable thickness distribution while maintaining the optimal acoustic performance (absorption coefficient, $\bar{\alpha}_{if}$, and transmission loss, $\overline{TL}_{if}$) of the elements as shown in Fig. 9.

Table 3 shows the variables established for the search for optimal results for the thickness distribution of the elements.

Under these conditions, a search was conducted for an optimum thickness distribution for the elements. A thickness distribution was determined that both maintained optimum acoustic performances and could be practically implemented on the vehicle. These results for optimum thickness distribution are shown in Fig. 10.

4. Verification of the Technique

The appropriateness of the proposed optimization process is verified with the optimized acoustic package. Moreover, applying the optimum specifications determined for the floor carpet to an actual vehicle, the majority of the proposed optimization process is verified.

4.1. Element Material and Equivalent Thickness Optimization

Optimum specifications were searched for using design variables that had been restricted in two steps. The $\times$ marks in Fig. 11(a) show the relationship between in-cabin sound pressure level in high frequency range and

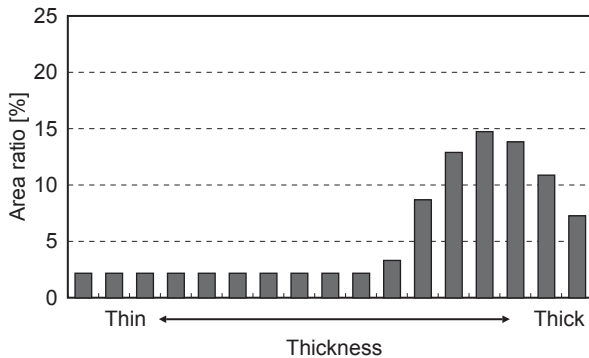


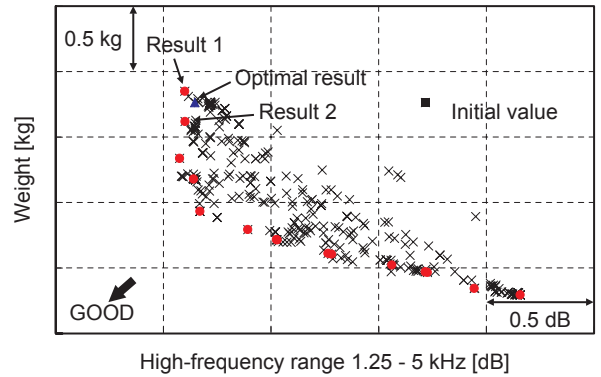
Fig. 10 Optimal thickness distribution for floor element

Table 4 Comparison between optimization results

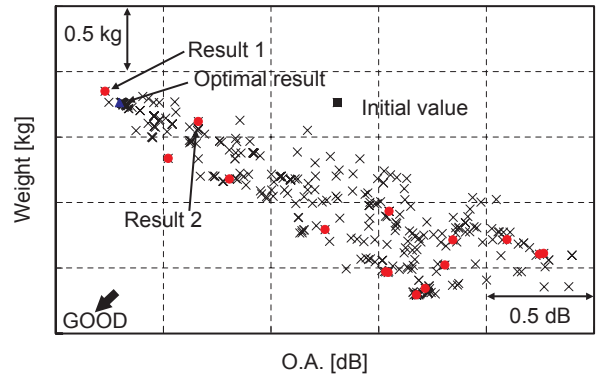
	High-frequency range 1.25-5 kHz	O.A.	Total weight
Target	1.0 dB reduction	1.0 dB reduction	Lighter than initial weight
Optimal result	Achieved	Achieved	Achieved
Result 1	Achieved	Achieved	Not achieved
Result 2	Achieved	Not achieved	Achieved

the weight of the floor carpet for the distributions determined in this process. The results for distribution (pareto solution) of in-cabin sound pressure level in high-frequency range by the lightest carpet weight are shown with circle marks, and the optimum specification by this method is shown with triangle mark. The relationship between the O.A. in-cabin sound pressure level and the weight of the floor carpet at this time is shown with triangle marks in Fig. 11(b).

Table 4 shows a comparison of the relationship



(a)



(b)

Fig. 11 Distribution of samples during optimization: (a) high-frequency range versus weight (b) O.A. versus weight

between the optimal result and target, and the relationship between near-optimal results and the target. As the table shows, while the optimal result satisfies all the pre-established targets, the near-optimal results did not satisfy certain targets.

These results indicate that the proposed method was able to select the optimal result for specifications satisfying in-cabin sound pressure level targets from among multiple specification patterns, thus confirming its validity.

4.2. Element Thickness Distribution Optimization

The distribution of results for acoustic performance during optimization of the thickness distribution of the elements is shown with $\times$ marks in Fig. 12. Acoustic performance at the initial thickness distribution is shown with square marks, and at the optimum thickness distribution with triangle marks.

As the method proceeds for the optimum result, the results become clustered in the lower left-hand corner of the graph, the area in which results match target

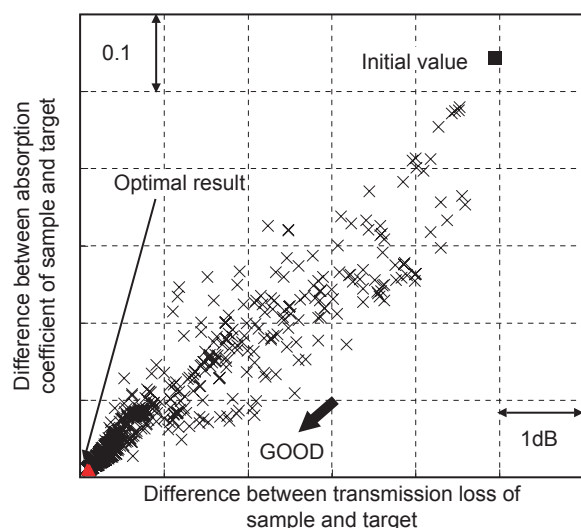


Fig. 12 Distribution of samples during optimization of thickness distribution

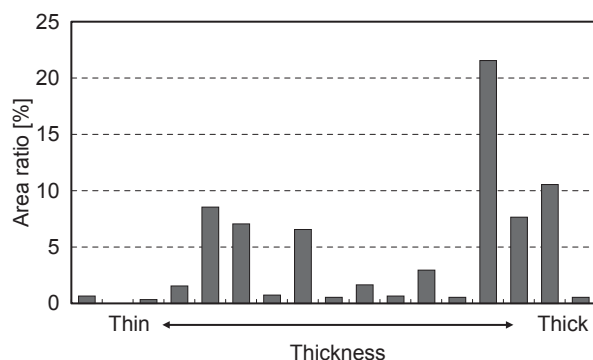


Fig. 13 Optimal random thickness distribution

performance. These results confirm that by using the proposed method, it can be achieved to select the optimum thickness distribution that enables targets for absorption coefficient and transmission loss to be satisfied from among a variety of thickness distributions rendered as functions.

In order to confirm the validity of the thickness distribution function expressed by Eq. (3), thickness distributions were expressed as random numbers without using Eq. (3) and an optimum thickness distribution was searched. The result is shown in Fig. 13. This thickness distribution differs from the distribution shown in Fig. 10 in that it does not describe a smooth curve centering on a specific thickness. The vehicle body panel is, in generally, formed in continuous shapes. The changes in thickness distribution shown in these results indicate the existence of unevenness on the surface of the floor carpet. These results demonstrate that the use of the function given by Eq. (3) to express thickness distributions enables determination of distributions that satisfy the targets for acoustic performance and are practically.

The results discussed above indicate that the new method enables a selection of an optimum result that is practically realizable from among multiple thickness distributions, thus confirming its validity.

4.3. Confirmation of Validity of Method in Actual Vehicle

The optimum specifications for acoustic materials for the floor carpet determined using the proposed method were applied to an actual vehicle. The effect of the use of these specifications on in-cabin sound pressure level satisfies the targets set in Table 2, additionally confirming the validity of the method.

5. Conclusion

A method of determining optimum specifications for sound-proof packages satisfying performance targets has been developed. The validity of this method was studied, and tests confirmed its viability. As a result, the following are stated:

- (1) The optimization procedure requires two steps. The first step is the element optimization of the acoustic package, and the second is the optimization of thickness distribution in elements.
- (2) The validity of the optimal results determined by the method was verified on the basis of the sample distribution maps.
- (3) The accuracy of the optimized specification is verified by comparing the reduction of the interior cavity sound pressure level of a vehicle with the proposed package versus the target.

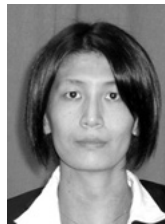
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