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Effect of wall admittance distribution on a quiet zone in a three dimensional enclosure

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Abstract

This study aims to generate a quiet zone in a three dimensional enclosure by controlling its boundary condition. It is well known that the boundary condition affects the enclosure sound field. This implies that we can modify the sound field by changing a wall's acoustical property, e.g. admittance. Attaching absorptive materials on a wall can fulfill this alteration. In this context, a theoretical analysis is performed to understand the influence of the absorptive material arrangement on the interior sound field. Then, to find its optimal arrangement, a simulation program that combines BEM and genetic algorithm is developed. The program has following features. The arrangement of absorptive materials is expressed as a vector form. The vector is defined as an AMA (absorptive material arrangement) vector. In addition, for the practical application, the program determines the element of the AMA vector from the predefined set of available absorptive materials. We believe that the newly defined vector certainly provides a way to understand the role of a sound absorptive material's arrangement on making a quiet zone in an enclosure.

1. Introduction

There have been a few researches that related to the quiet zone generation by altering the boundary condition of an enclosure. Bernhard and Takeo [1] have optimized the internal and radiated acoustic energy from two dimensionally modeled printer. Yang, Tseng and Ling [2] has performed the optimization of the internal acoustic potential energy of three dimensionally modeled car cabin. Martin and Bodrero [3] executed the optimization of impedance locations on the wall of a three dimensional cavity.

In order to make a quiet zone in an interior sound field, two methods can be applied. The one is ANC (active noise control) and the other is PNC (passive noise control). The ANC controls the strength and phase of additional sound sources. On the contrary, the PNC determines the optimal

arrangement (size, location) and admittance of absorptive materials. In this study, a PNC system that determines the optimal arrangement of available absorptive materials is proposed.
Whatever the performance of the PNC system is good; it is useless if the optimal admittance is not available or the practical arrangement is too complex to materialize. In this context, the proposed PNC system assumes that the available absorptive materials and its workable size are predefined. Therefore the control variable of the proposed PNC is only the location.
Proposed PNC system is composed of two analysis tools. The one is BEM simulation soft ware. This tool is used to evaluate a cost function, i.e. acoustical potential energy density in a quiet zone. The other is a genetic algorithm. [4] This optimization algorithm searches the best boundary condition by referencing the fitness value of selected boundary condition. The fitness value is evaluated from the BEM simulation.
To verify the proposed PNC system, it is applied to a parallelepiped enclosure of Figure 3, because of its simplicity. The interior SPL (sound pressure level) under the optimal boundary condition is measured experimentally. Then, the measured interior SPL is compared to the result from BEM simulation.

2. Cost function and control variable

The proposed PNC system optimizes the location of available absorptive materials. The optimization procedure requires a pertinent cost function and control variables. The selected cost function is

$$\varepsilon_p = \frac{1}{4\rho c^2 V_q} \int_{V_q} |p(\vec{r})|^2 dV \qquad (1)$$

where ε_p is the acoustic potential energy density, ρ is the density, c is the wave speed, V_q is the quiet zone volume and $p(\vec{r})$ is the field pressure. The control variable of the cost function is the admittance on the enclosure wall. The admittance does not show explicitly in the equation (1). However the interior pressure field of an enclosure such as Figure1 is related to the admittance like as

$$c(\vec{r})p(\vec{r}) = \int_V f(\vec{r}')G(\vec{r}\,|\,\vec{r}')dV - \int_S \left(jk\beta(\vec{r}')p_s(\vec{r}')G(\vec{r}\,|\,\vec{r}') + p_s(\vec{r}')\frac{\partial G(\vec{r}\,|\,\vec{r}')}{\partial n} \right) dS \qquad (2)$$

where $c(\vec{r})$ is the solid angle, $f(\vec{r})$ is the source function, $G(\vec{r}\,|\,\vec{r}')$ is the free field Green function and $\beta(\vec{r})$ is the admittance at $\vec{r}$ on the wall. The equation (2) is the Kirchhoff-Helmholtz integral equation in case of locally reacting wall.

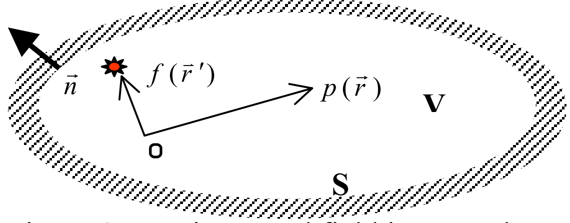


Figure 1: Interior sound field in an enclosure

The admittance function is a continuous function. However, to integrate the equation (2) numerically, we need a BEM scheme, therefore requires discrete admittance values at each finite element. This means that the control variable, i.e. admittance can be expressed in terms of a vector. This vector represents a boundary condition of an enclosure. The vector is denoted as the AMA (absorptive material arrangement) vector.

2.1 AMA vector, AMA Matrix and admittance vector

Figure 2 shows the case of which three kinds of absorption panels are attached on an enclosure wall. The wall is divided into 6 equal areas so that the 6 absorption panels are required. In this case, the AMA vector $\bar{\mathbf{b}}$ is

$$\bar{\mathbf{b}} = [\beta_1 \quad \beta_2 \quad \beta_1 \quad \beta_3 \quad \beta_1 \quad \beta_2]^T \tag{3}$$

where the β_i (i=1,2,3) are the admittances of available absorptive materials.

If we assume that available absorptive panels are three, then absorptive panels can also be represented as a vector, that is

$$\bar{\mathbf{a}} = \left[\beta_1 \quad \beta_2 \quad \beta_3\right]^T \tag{4}$$

The relation between $\bar{\mathbf{b}}$ and $\bar{\mathbf{a}}$ can expressed as a transformation matrix $\mathbf{A}$, i.e.

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}^T \tag{5}$$

Therefore, the AMA vector $\bar{\mathbf{b}}$ can be written as

$$\bar{\mathbf{b}} = \mathbf{A}\bar{\mathbf{a}} \tag{6}$$

The vector $\bar{\mathbf{a}}$ is denoted as an admittance vector and the matrix $\mathbf{A}$ is denoted as an AMA matrix, respectively. The AMA matrix $\mathbf{A}$ also represents the boundary condition of the enclosure wall. The element of $\mathbf{A}$ has the value of 0 or 1. This characteristic enables us to use it as a chromosome in the genetic algorithm.

#1 (β_1)	**#2 (β_2**	**#3 (β_1)**
#4 (β_3	**#5 (β_1)**	**#6 (β_2)**

Figure 2: Absorption panel arrangement on a wall that is divided to 6 equal areas.

3. Genetic Algorithm

In order to use the AMA matrix $\mathbf{A}$ as a chromosome of genetic algorithm, the crossover operation and mutation is newly devised. The crossover operation is defined as the exchange of the elements below the row number that is randomly selected. The mutation is defined as the cyclic shift operation as much as randomly chosen number.

3.1 Crossover operation example

In case of the crossover operation at 4th row between chromosomes $\mathbf{A}_1$ & $\mathbf{A}_2$ is defined as

$$\mathbf{A}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ \hline 1 & 0 & 0 \end{bmatrix} \mathbf{A}_2 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ \hline 0 & 0 & 1 \end{bmatrix} \xrightarrow{\textbf{Crossover}} \mathbf{A}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{A}_2 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

where * indicates the crossover position.

3.2 Mutation example

In case of 1 bit mutation of the 1st row of $\mathbf{A}_1$ is

$$\mathbf{A}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \xrightarrow{\textbf{Mutation}} \mathbf{A}_2 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

where * indicates the mutation position.

4. Quiet zone in an parallelepiped enclosure

The proposed PNC method is applied to a parallelepiped enclosure that is depicted in Figure 3. The parallelepiped is a width of 50cm, a length of 80cm and a height of 10cm in size. The quiet zone is established as

$$3\text{cm} \le x \le 77\text{cm},\ 2\text{cm} \le y \le 48\text{cm and } 1\text{cm} \le z \le 9\text{cm} \qquad (7)$$

There are 10 locations on the side walls (#1~#10) where the boundary condition is altered by arranging the absorptive panels. The other surfaces of the enclosure wall have the fixed boundary condition of rigid wall. In this example, we limited to put the absorptive material to 4 locations (#4 ~#7). The other locations are settled to have a rigid wall boundary condition. The #11 location has a constant velocity panel of 1mm/s at 2kHz.

Table1: Impedance value of the four absorptive materials at 2kHz

Specimen	A	B	C	D
Impedance	1332.9 +j564.3	545.8+j332.2	443.2 +j333.9	∞

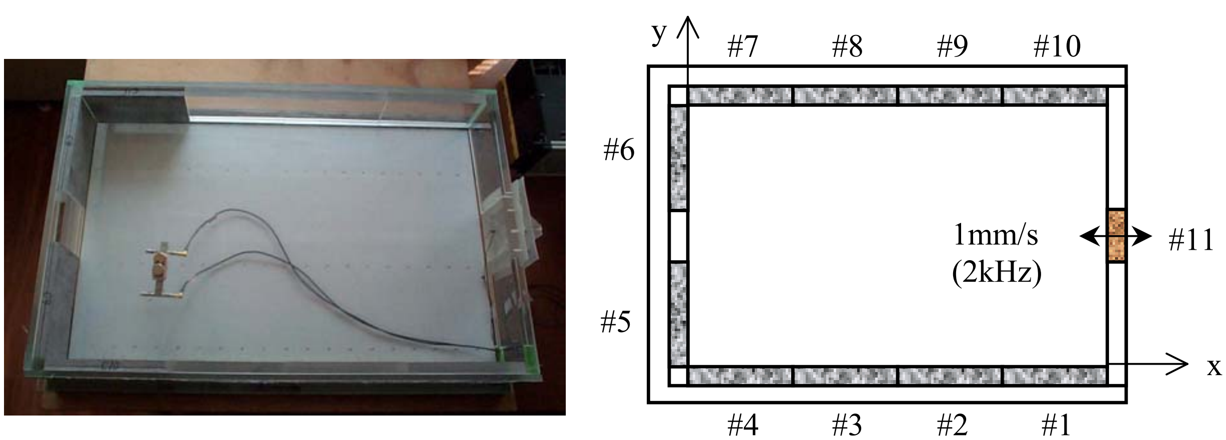


Figure 3: A parallelepiped enclosure (a width of 50cm, a length of 80cm and a height of 10cm)

Four kinds of absorptive material are assumed to be available. Therefore the possible number of boundary conditions is 4^4 (=256). Table 1 shows the impedance value of four absorptive materials at 2kHz. The absorptive material denoted by D means a rigid wall. An acrylic panel of which reflection coefficient is 0.97 at 2kHz makes the rigid wall condition of the experiment.

4.1 Direct evaluation of all cases

The BEM simulation is performed for all 256 boundary conditions. Figure 4 shows the ε_p of the quiet zone that is evaluated from the BEM simulations. In the Figure 4, the x-axis corresponds 256 kinds of AMA vector.

From the BEM simulations, the AMA vector $\bar{\mathbf{b}}_{\min}$ at minimum ε_p is determined as

$$\bar{\mathbf{b}}_{\min} = [D \quad D \quad D \quad C \quad D \quad D \quad C \quad D \quad D \quad D]^T \tag{8}$$

From the BEM simulations, the AMA vector $\bar{\mathbf{b}}_{\max}$ at maximum ε_p is determined as

$$\bar{\mathbf{b}}_{\max} = \left[D \quad D \quad D \quad C \quad C \quad C \quad C \quad D \quad D \quad D\right]^T \tag{9}$$

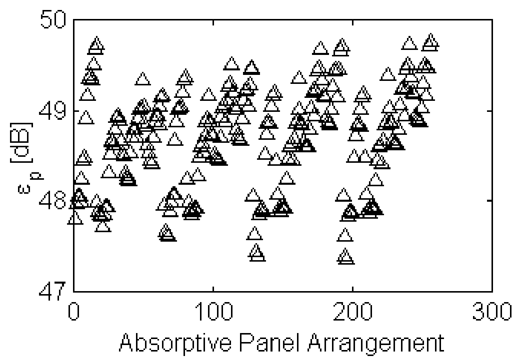
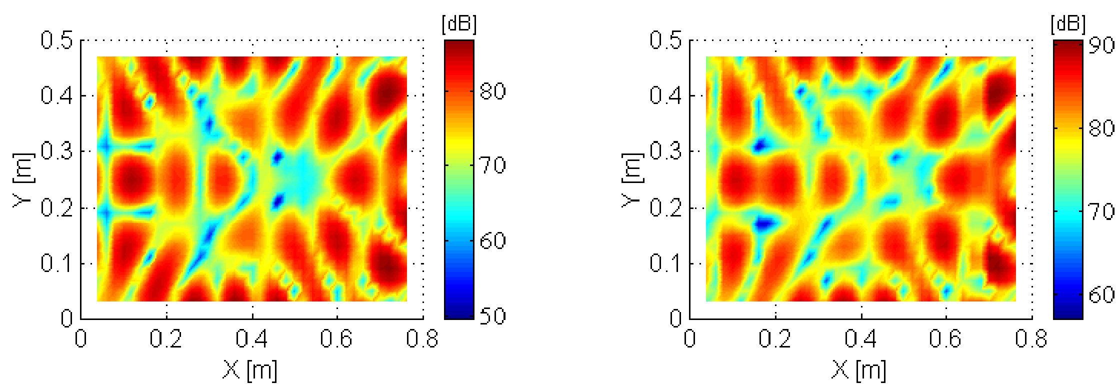


Figure 4: Acoustic potential energy ε_p at each 256 boundary conditions



(a) BEM simulation (b) Experiment

Figure 5: SPL on mid plane from BEM simulation and experiment

4.2 Genetic algorithm

In order to determine the optimal boundary condition by using the direct evaluation, total 256 BEM simulations are needed. However the genetic algorithm find optimal boundary condition from 54 BEM simulations. The optimal boundary condition, i.e. $\bar{\mathbf{b}}_{min}$ from both methods coincides exactly.

4.3 Experimental verification

The genetic algorithm optimization is based on BEM analysis. Therefore the precision of BEM simulation determines the fidelity of the genetic algorithm. In order to assure the precision of the simulation, the measured SPL on the mid plane of the enclosure is compared to the one from the simulation. Figure 5 shows the comparison between them.

5. Conclusion

In order to determine the optimal absorptive material arrangement on the enclosure wall, the combined PNC system of a BEM analysis and a genetic algorithm is proposed. The proposed PNC system is applied to the parallelepiped enclosure. From the application, the PNC system determines the optimal boundary condition. Compared to the direct evaluation, it has computational advantages.

The optimal arrangement of absorptive materials at 2kHz is realized experimentally. From the experiment, the SPL on the mid-plane are measured. The measured SPL is compared with the result from BEM simulation. The comparison shows that SPL distributions of both results are similar. However, the difference in absolute value is not negligible. The difference could be caused by many unknown reasons. Some of them can be an acrylic panel's incomplete rigidity, imperfect sealing of the enclosure and the effect of the 1st flexural mode of the velocity source panel.

As a conclusion, from this study, the PNC system that considers the practical realization of the optimal absorptive material arrangement is proposed. In detail, the vector-matrix notation for the absorptive material arrangement ($\bar{\mathbf{b}}$, $\mathbf{A}$ and $\bar{\mathbf{a}}$) and the genetic algorithm operation (crossover and mutation) for the AMA matrix $\mathbf{A}$ are devised.

Acknowledgements

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