The absorption coefficient in reverberation room is used in the practice of room acoustics and noise controls. However, it is well known that measurement results of the coefficient vary according to a room shape of the measurement and area of the measurement material, i.e. diffuseness in the measurement room and the area effect. This study shows effectiveness of a non-steady state analysis by computational method for investigation on causes of variation in the measurement results and improvement methods of the measurement. Uncertainty of mean reverberation times of the measurement sound fields for the absorption coefficient in reverberation room due to combinations of different sampling points are investigated on Monte Carlo method. First, 72 sound fields for the measurement of absorption coefficient in three reverberation rooms are analyzed by time domain finite element method (TDFEM). Next, relative frequencies of mean reverberation times in the each sound field are calculated from the results obtained by TDFEM to use the investigation. In addition, cumulative relative frequencies of the mean reverberation times, which are difference within 2.5 % from an expectation values of mean reverberation times in each room, are also calculated from the results. Finally, coefficients of variation of mean reverberation times at all receiving points in each sound field are calculated from the results of the analyses, and relations between the cumulative relative frequencies and the coefficients of variation are investigated.

Keywords: Finite element sound field analysis, Sound absorption coefficient in a reverberation room, Monte Carlo method, Reverberation Time, Diffuseness of sound field

1. Introduction

The absorption coefficients in a reverberation room are most representative measure for evaluating absorption performance of architectural materials. However, the absorption coefficients are affected by some factors such as fluctuations in temperature and moisture during the measurement,
diffuseness of sound fields and area effect (1). Numerical analyses based on wave acoustics are effective tools to investigate these factors on absorption coefficient measurement in reverberation room. For an example, Kawai has conducted an investigation on area effect using steady state boundary element method (2). To improve the measurement, however, it is necessary to clarify characteristics of practical non-steady state sound fields in the reverberation rooms.

On the other hand, numerical analyses based on the wave equation have been intensively used to explore many kinds of acoustic problems. Among the analyses, the finite element method (FEM) is has the following advantages: (i) Distributions of temperature and moisture can be considered in the analysis, (ii) sound pressure of entire region is obtainable at the same time, and (iii) easy to treat of complex geometry. Considering these strong points of FEM, the authors have been conducted some investigations such as comparison of the steady state sound pressure distribution computed using FEM with measured values, and diffuseness of the sound fields (3,4). Meanwhile, non-steady state analysis has become practical (5,6) and Tachioka et. al. (7) calculated absorption coefficients in reverberation rooms using finite-difference time-domain method. From results of these non-steady state analyses, it might be able to clear details of decay sound field of the measurement for the sound absorption coefficient in reverberation room.

In this study, sound fields for the measurement of absorption coefficient in reverberation room are analyzed by time domain finite element method (TDFEM). Uncertainty of mean reverberation times of the measurement sound fields due to combinations of different sampling points are investigated on Monte Carlo method. First, relative frequencies of mean reverberation times in the each sound field are calculated from the results obtained by TDFEM to use the investigation. In addition, cumulative relative frequencies of the mean reverberation times are also calculated from the results. Next, coefficients of variation of mean reverberation times at all receiving points in each sound field are calculated from the results of the analyses, and relations between the cumulative relative frequencies and the coefficients of variation are investigated.

Fig. 1 Reverberation rooms to be analyzed: (a) heptahedral irregularly shaped room (OIR), (b) hexahedral regular shaped room (TRR) and (c) hexahedral irregularly shaped room (KIR).

Table 1 Room and setting of TDFEM simulation

<table>
<thead>
<tr>
<th>Room</th>
<th>$V$ [m$^3$]</th>
<th>$S$ [m$^2$]</th>
<th>Specimen area [m$^2$]</th>
<th>Number of receiving points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>small</td>
<td>large</td>
<td></td>
</tr>
<tr>
<td>OIR</td>
<td>168</td>
<td>2.1</td>
<td>12.1</td>
<td>10136</td>
</tr>
<tr>
<td>TRR</td>
<td>220</td>
<td>2.0</td>
<td>11.8</td>
<td>9208</td>
</tr>
<tr>
<td>KIR</td>
<td>187</td>
<td>2.1</td>
<td>12.0</td>
<td>8556</td>
</tr>
</tbody>
</table>
2. Analyzed room and setup of FE analysis

Figure 1 shows analyzed reverberation rooms, which are a heptahedral irregularly shaped room (OIR), a hexahedral regular shaped room (TRR) and a hexahedral irregularly shaped room (KIR). Table 1 lists room volume, surface area of room, surface area of specimen and number of receiving points for analysis of each room. In the analysis, we used two installing pattern of the specimen in each room, and locations of the specimen are shown in Fig. 2 respectively.

The sound source (tone burst signal of nine waves) is placed at a corner of the room as shown in Fig. 1. Center frequencies of the sound source ($f_n$) are set to 125, 250, 500 Hz, respectively. Sampling frequency and time interval are respectively 44.1 kHz and 0.02 ms. Finite element meshes used here are constructed by using hexahedral 27 node elements using spline polynomial function for shape function (8). The meshes satisfy a requirement that $\lambda d > 4.8$ (8), where $\lambda$ and $d$ are upper limit frequency and maximum nodal distance of elements. Receiving points are placed at (a) 1.0 m apart from any room surface and at (b) 2.0 m apart from sound source, based on ISO 354 and JIS A 1409. In this investigation, all materials are assumed to be local reaction and are given a normalized surface impedance ratio $z_n$ in the TDFE analysis. The $z_n$ of real number corresponding to a normal incidence absorption coefficient $\alpha_n$ is given as a boundary condition of a specimen, $\alpha_n = 0.2, 0.4, 0.6$ and 0.8. For other boundaries except in the material, in real number corresponding to $\alpha_n = 0.01$ is given as boundary condition.

3. Calculation method for variation of mean reverberation time

In this study, using reverberation times obtained by the FE-analysis of each receiving point, variation of mean reverberation times ($T_{30, \text{rand}, N_{k,i}}, i = 1, 2, \ldots 10,000$) due to combinations of different sampling points are calculated by six steps below on ISO 354 and the Monte Carlo method.

1. Decide number of sampling points ($N_k$: In this case, $N_k = 5 \sim 20$).
2. Divide the space, which satisfies the both (a) and (b) mentioned above, into $N_k$ subspaces.
3. Statistically sample one of the points, reverberation times of which are obtained by the TDFE-analysis, in the subspace.
4. Repeat step 3. for all sub spaces (total $N_k$ points are sampled).
5. Calculate mean reverberation time if all $N_k$ points are distanced from each other more than $\lambda/2$ m in each frequency.
6. Repeat step 3. to 5. 10,000 times of trial number.
Relative deviation of trial \(i (i = 1, 2, \ldots 10,000)\) is calculated by following equation (1).

\[
dT_{30,N_s,i} = \frac{T_{30,\text{rand},N_s,i} - T_{30}}{T_{30}} \times 100 \quad [\%].
\]

Where \(T_{30}\) is mean reverberation times of all receiving points obtained by TDFE-analysis. For comparison among sound fields, relative frequency (RF) of \(dT_{30,N_s,i}\) are calculated counted by 2.5 % width steps from –10 % to +10 %.

4. Results and discussions

4.1 Relationship between frequency of mean reverberation time and sound field

Figure 3 shows RF distribution of \(dT_{30,N_s,i}\) at \(f_m = 125\) Hz, \(s = 12\) m\(^2\) and \(\alpha_n = 0.2\) in each room when \(N_s\) are five, ten and twenty. It is confirmed that the RF of \(dT_{30,N_s,i}\) around 0.0 % in case that \(N_s = 20\) are higher, i.e., the number of \(T_{30,\text{rand},N_s,i}\) near \(T_{30}\) are greater, than those in case that \(N_s = 5\) and 10 regardless of room type. Similar tendency can be confirmed in other sound field.

From the RF distributions of \(dT_{30,N_s,i}\), cumulative relative frequency of \(dT_{30,N_s,i}\) in case that \(|dT_{30,N_s,i}| < 2.5\% (CRF_{2.5})\) is calculated in this paper. When \(|dT_{30,N_s,i}|\) is less than 2.5 %, the variation range of \(dT_{30,N_s,i}\) becomes 5 %.

The CRF\(_{2.5}\) can be found to relate with number of sampling points \(N_s\) in Fig. 4 when area and normal incidence absorption coefficient of a specimen are 12 m\(^2\) and 0.4. It is confirmed that the CRF\(_{2.5}\) becomes higher in response to increasing \(N_s\), regardless of frequency and room shape. In OIR, the CRF\(_{2.5}\) are more than 80 % at \(f_m = 250\) and 500 Hz while those are less than 60 % at 125 Hz regardless of \(N_s\). On the other hand, the CRF\(_{2.5}\) are less than 80 % in TRR regardless of frequency and \(N_s\). It can be found that relationship between CRF\(_{2.5}\) and \(N_s\) varies depending on the room even if equivalent sound absorption area of specimen \(A\) is same.

Figure 5 shows relationships between the CRF\(_{2.5}\) and \(A\) for each room in case that \(N_s = 5\). In OIR, the CRF\(_{2.5}\) becomes lower in response to increasing \(A\) and are more than 80 % when \(A\) is larger than 4.0 m\(^2\) at \(f_m = 250\) and 500 Hz while those are less than 80 % regardless of specimens at 125 Hz. In KIR and TRR, although the CRF\(_{2.5}\) shows a tendency to decrease with increase of \(A\), there is no clear difference by frequency. And the CRF\(_{2.5}\) in KIR and TRR when \(A\) is larger than 2.0 m\(^2\) is smaller than those in OIR at \(f_m = 250\) and 500 Hz. In three rooms analyzed by TDFEM in this paper, the CRF\(_{2.5}\) are more than 80 % when \(A\) is larger than 2.0 m\(^2\) at \(f_m = 250\) and 500 Hz.

![Frequency distribution of T30, rand, Ns, i in the case that f_m = 125 Hz, s = 12 m^2 and alpha_n = 0.2: (a) OIR; (b) KIR; (c) TRR.](image-url)
Fig. 4 Relationship between $CRF_{2.5}$ and number of sampling points in the case of $s = 12 \text{ m}^2$, $\alpha_n = 0.4$:
(a) OIR; (b) KIR; (c) TRR.

Fig. 5 Relationship between $CRF_{2.5}$ and equivalent sound absorption area in the case that $N_s = 5$:
(a) OIR; (b) KIR; (c) TRR.

### 4.2 Relationships between cumulative relative frequency and coefficients of variation of reverberation time

Finally, coefficients of variation ($CV\%$) of reverberation times at all receiving points of TDFE-analysis in each sound field are calculated and compared with $CRF_{2.5}$. Figure 6 shows relation between the $CRF_{2.5}$ and the $CV$ in all sound fields in case that $N_s = 5$. Pearson’s correlation coefficient between the $CRF_{2.5}$ and the $CV$ is -0.95. Moreover, the correlation coefficients of each the reverberation room are -0.97 in OIR, -0.97 in KIR and -0.96 in TRR. If $CV$ is grater than 6 %, the $CRF_{2.5}$ can not exceed 60 %, and if the $CV$ less than 3 %, the $CRF_{2.5}$ exceed 90 % in this case.

Fig. 6 Relationships between $CRF_{2.5}$ and $CV$ values in case that $N_s = 5$. 

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5. Conclusions

Uncertainty of mean reverberation times of measurement sound fields for the absorption coefficient in reverberation room due to combinations of different sampling points are investigated on Monte Carlo method. Seventy-two sound fields for the measurement in three reverberation rooms are analyzed by time domain finite element method, and relative frequencies of mean reverberation times in each sound field are calculated from the results obtained by the analyses to use the investigation. In addition, cumulative relative frequencies of the mean reverberation times, which are difference within 2.5 % from an expectation values of mean reverberation times in each room, are also calculated from the results. In three rooms analyzed by the method in this paper, the cumulative relative frequencies are more than 80 % when equivalent sound absorption area of specimen is larger than 2.0 m$^2$ at $f_m = 250$ and 500 Hz. Finally, coefficients of variation of mean reverberation times at all receiving points in each sound field are calculated from the results of the analyses, and relations between the cumulative relative frequencies and the coefficients of variation are investigated. It is shown that if the coefficient of variation less than 3 %, the cumulative relative frequency exceed 90 % in the three rooms.

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