Finite element sound field analysis for correction of absorption coefficient in reverberation room

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ABSTRACT

In this study, sound fields for the measurement of sound absorption coefficient by reverberation room method are analyzed by time domain finite element method. This study shows effectiveness of the analysis for investigation on causes of variation in the measurement results and improvement methods of the measurement. To evaluate an actual sound field for the measurement, the ratio of incident sound energy to the test material in those to all boundary of the measurement sound field is calculated from results of the finite element sound fields analysis. First, square sound pressure amplitudes of plane sound wave incident on absorption material are calculated in one-dimensional sound field. Next, the calculation method of the ratio of the measurement sound field is described. Finally, relationship among the ratio, shape of the measurement room, and characteristics of the test material is investigated, and it is shown that the bigger normal incident sound absorption coefficient of test material, the larger the change of the ratio for decay sound field regardless of room shape and surface area of test material.

Keywords: Finite element method, Computational simulation of sound field in room, Measurement of absorption coefficient in reverberation room, Diffuseness of sound field
I-INCE Classification of Subjects Number(s): 75.3, 72.7.1, 73.3

1. INTRODUCTION

The sound absorption coefficient by reverberation room method 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 (1).

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 (2,3). Meanwhile, non-steady state analysis has become practical (4) and Tachioka e*t. al.* (5) calculated absorption coefficients in reverberation rooms using finite-difference time-domain method, though no investigation of the factors described above was carried out. 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 by

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reverberation room method.

In this study, the sound fields for the measurement of the sound absorption coefficient by reverberation room method are analyzed by time domain finite element method (TDFEM). This study shows effectiveness of the analysis for investigation on causes of variation in the measurement results and improvement methods of the measurement. To evaluate an actual sound field for the measurement, the ratio of incident sound energy to the test material in those to all boundary of the measurement sound field is calculated from results of the TDFE analysis. First, square sound pressure amplitudes of plane sound wave incident on absorption material are calculated in one-dimensional sound field. Next, the calculation method of the ratio of incident sound energy to the test material in those to all boundary of the measurement sound field is described, and the ratios are calculated in three sound fields with no test material. Finally, relationship among the ratio, shape of the measurement room, and characteristics of the test material is investigated.

2. CALUCULATION OF RATIO OF INCIDENT SOUND ENERGY TO TEST MATERIAL IN ONE TO ALL BOUNDARY IN MEASUREMENT SOUND FIELD

2.1 Incident Sound Pressure Amplitude of Plane Sound Wave on Absorption Material

Assuming that plane wave enter a boundary with complex sound pressure reflection coefficient R, θ denotes incidence angle of the plane wave, then

$$R = \frac{z_n \cos\theta - 1}{z_n \cos\theta + 1}, \tag{1}$$

where z_{n} is surface normal acoustic impedance ratio of the boundary. In this case, a sound pressure amplitude $|p(x,y)|$ of an arbitrary point (x,y) is determined by the summation of the amplitudes of the incident and reflection sound wave,

$$|p(x,y)| = \hat{p}_0[1 + |R| + 2|R|\cos(2kx\cos\theta + \chi)]^{\frac{1}{2}} \exp(-iky\sin\theta). \tag{2}$$

Where $\hat{p}_0$ is incident sound pressure amplitude of a plane sound wave, k and χ are wave constant and phase of R respectively. From this equation, square of sound pressure amplitude at point (x,y) = (0,0) on the boundary is given as

$$|p(0,0)|^2 = \hat{p}_0^2(1 + |R|^2 + 2|R|\cos\chi). \tag{3}$$

At first, to confirm accuracy of $\hat{p}_0$ to the boundary obtained by time-domain finite element method (TDFEM), relationships between $\hat{p}_0$ and sound absorption characteristics on an absorption material in a tube shown in Figure 1 are investigated. One end of the tube is assumed absorption material, normal incident absorption coefficient α_{n} of which is 0.01, 0.2, 0.4 or 0.8, and another end and sidewalls of the tube are assumed to be rigid. A sound source is placed at a center of the rigid end of the tube. Impulse response of IIR filter (Butterworth type band pass filter with third octave band, center frequency f_{m} = 500 Hz) is used as the sound source. In this case, sound pressure amplitude of plane sound wave incident to the absorption material dose not change until 0.06 s (sound speed c = 340 m/s), even if absorption coefficient of the absorption material changes.

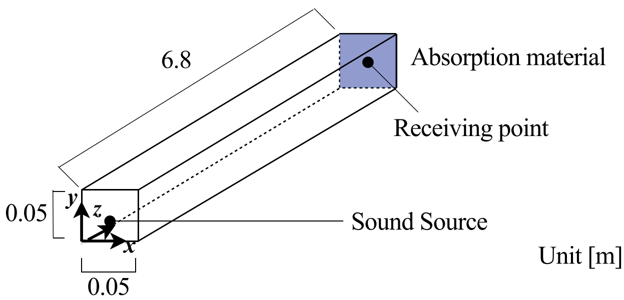


Figure 1 – Geometry of simulated tube.

Sound pressure amplitude of plane sound wave incident on the absorption material is calculated from sound pressure on the absorption material obtained by TDFEM and equation (3). Comparison of the sound pressure amplitudes incident on the absorption material, α_n of which is 0.01, 0.2, 0.4 and 0.8, is portrayed in Figure 2. It is confirmed that the sound pressure amplitudes incident on the absorption material don't change even if the absorption coefficient of the material changes.

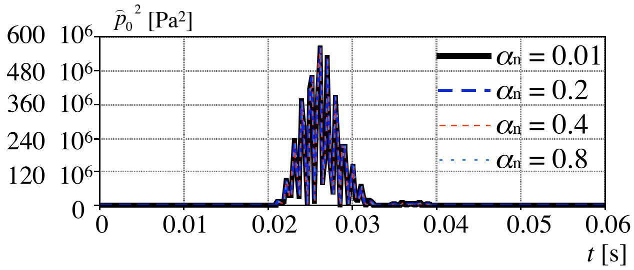


Figure 2 –Comparison of sound pressure amplitudes of plane sound wave incident on the absorption material of the band pass filtered impulses centered at f_m = 500 Hz.

2.2 Measurement Sound Field for Absorption Coefficient in Reverberation Room

When a diffuse sound field is assumed, square of incident sound pressure amplitude at point $(x,y) = (0,0)$ on boundary with R is given as

$$\hat{p}_0^2 = \frac{|p(0,0)|^2}{\frac{1}{2\pi}\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} \left|1+|R|^2+2|R|\cos\chi\right| \sin\theta \, d\theta}. \tag{4}$$

A sound field of measurement for the absorption coefficient in reverberation room is assumed to be diffuse sound field. Then, the measurement sound field is analyzed by TDFEM, and the incident sound pressure amplitude on boundary is calculated from sound pressure of each time step on boundary obtained by TDFEM and equation (4). Assuming that square of the incident sound pressure amplitude on boundary is proportional to incident sound energy to the boundary, the ratio of incident sound energy to the test material in those to all boundary in the measurement sound field is calculated as follows.

$$r(t) = \frac{\int_{\Gamma_{abs}} \int_t^{\infty} \hat{p}_0^2(\tau)\, d\tau \, d\Gamma}{\int_{\Gamma_{all}} \int_t^{\infty} \hat{p}_0^2(\tau)\, d\tau \, d\Gamma}. \tag{5}$$

When $\hat{p}_0(\tau)$ is incident sound pressure amplitude of a plane sound wave at time τ, Γ_{abs} is test material, and Γ_{all} is all boundary, respectively. If the sound field of the measurement is sufficiently diffused, $r(t)$ equals the ratio of the surface area of test material s in one of all boundary S (s/S).

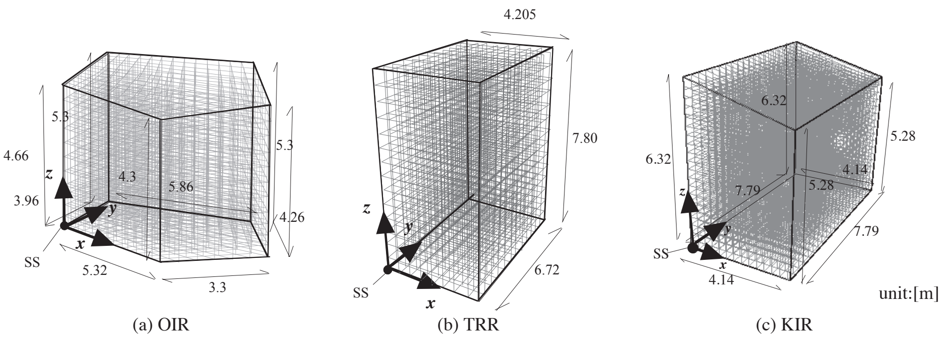


Figure 3 – Reverberation room to be analyzed: (a) heptahedral irregularly shaped room (OIR), (b) hexahedral regular shaped room (TRR), (c) hexahedral irregularly shaped room (KIR).

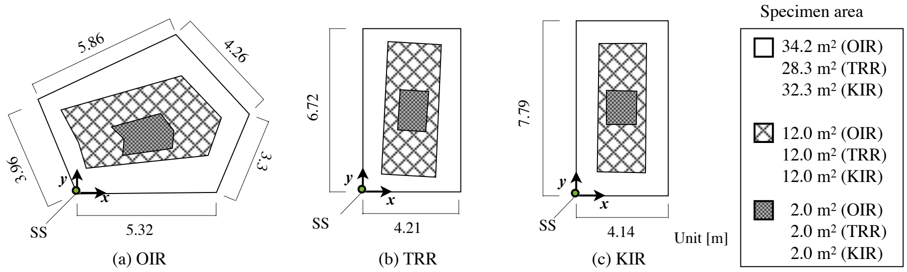


Figure 4 – Location and surface area of specimens in: (a) OIR, (b) TRR, (c) KIR.

3. TIME DOMAIN FINITE ELEMENT ANALYSIS OF MEASUREMNT SOUND FIELD FOR ABSORPTION COEFFICIENT IN REVERBERTION ROOM

3.1 Analyzed room and setup of TDFE analysis

Figure 3 shows analyzed reverberation rooms, which are a heptahedral irregularly shaped room (OIR, V = 168 m^3, S = 180 m^2), a hexahedral regular shaped room (TRR, V = 220 m^3, S = 227 m^2), and a hexahedral irregularly shaped room (KIR, V = 187 m^3, S = 204 m^2). In the analysis, we used three installing pattern of the test material in each room, and locations and surface areas of the materials are shown in Figure 4 respectively.

The sound source (tone burst signal of nine waves) is placed at a corner of the room as shown in Figure 3 and 4. Center frequencies of the sound source f_m 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 (6). The meshes satisfy a requirement that $\lambda/d > 4.8$ (6), where λ and d are upper limit frequency and maximum nodal distance of elements. Receiving points are placed at 1.0 m apart from any room surface and 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 α_n is given as a boundary condition of a test material, α_n = 0.01, 0.2, 0.4 and 0.8. For other boundaries except in the material, in real number corresponding to α_n = 0.01 is given as boundary condition.

3.2 Sound Field in Measurement Room without Test Material

As the mentioned above, if the sound field is sufficiently diffused, $r(t)$ equals the ratio of the surface area of test material s in one of all boundary S (s/S), and sound energy in the sound field constantly decay regardless of time, i.e. $r(t) = s/S = r_{\mathrm{ideal}}$ regardless of time in the case of diffuse sound field.

The three measurement rooms at f_m = 500 Hz with 12 m^{2}test material, α_n of which is 0.01, i.e. α_n of all boundary is 0.01, are analyzed by TDFEM and $r(t)$ are calculated in the three rooms. Figure 5 shows comparisons between $r(t)$ and r_{ideal} in each room. It can be seen that $r(t)$ in all rooms hardly changes with time, and $r(t)$ in OIR are better corresponding to r_{ideal} than those in TRR and KIR. Mean values of difference between $r(t)$ and r_{ideal} are 0.003 in OIR, 0.02 in TRR, and 0.01 in KIR.

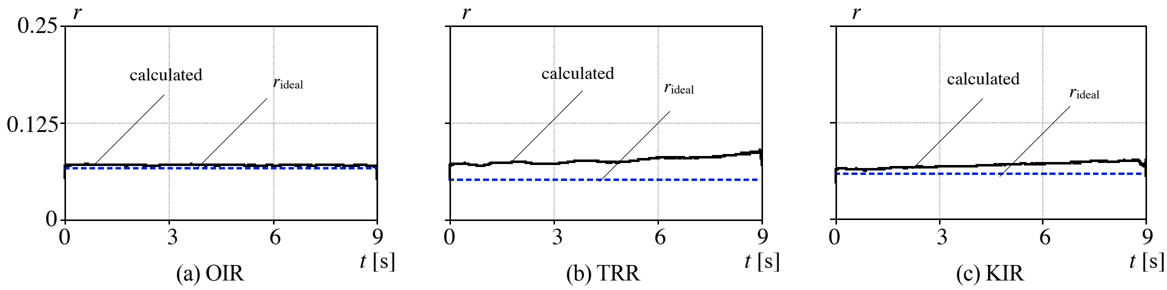


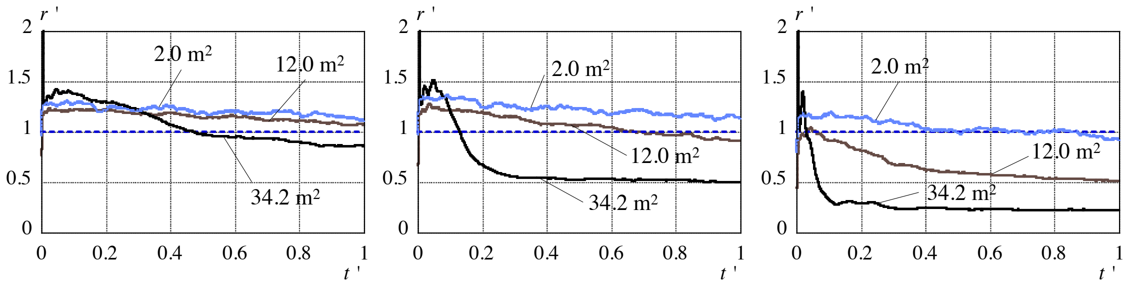
Figure 5 – $r(t)$ curve at f_m = 500 Hz and r_{ideal} (= s/S): (a) OIR, (b) TRR , (c) KIR.

3.3 Sound Field in Measurement Room with Test Material

In this section, relationship among $r(t)$, shape of the measurement room, and characteristics of the test material is investigated. In order to make comparison of $r(t)$ in each sound field easier, t and $r(t)$ are divided by the reverberation time and s/S in each sound field, and are expressed as t' and $r'(t')$ respectively.

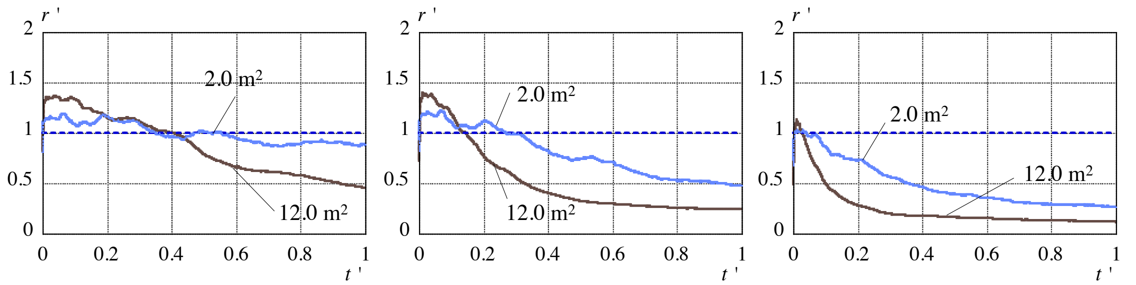
Figure 6 shows comparison among $r'(t')$ in case that s = 2.0 m^2, s = 12.0 m^2, and s = 34.2 m^2 at f_m = 500 Hz calculated in OIR. It is noted that $r'(t')$ of sound field in OIR with 34.2 m^2 test material are small and constant values, i.e. the sound expect to hardly enter the test material, for late part of decay sound field. On the other hand, $r'(t')$ of sound field in OIR with 2.0 m^2 test material are larger than 1.0 for most of decay sound field, i.e. it is expected that the area effect has occurred.

Comparison among $r'(t')$ in case that s = 2.0 m^2 and s = 12.0 m^2 at f_m = 500 Hz calculated in TRR is shown in Figure 7, and same comparison calculated in KIR is shown in Figure 8. In both sound fields, it can be seen that $r'(t')$ are smaller than 1.0 even if s = 2.0 m^2, especially $r'(t')$ are smaller than 1.0 regardless of s and α_n of test material in the sound field of KIR. It is confirmed that the incident sound energy to the test material is lower than ideal of diffuse sound field if there is no diffuser panel. In addition, it can be found that the bigger α_n of test material, the larger the change of $r'(t')$ for decay sound field regardless of room shape and surface area of test material. In other words, the reverberation time is difficult to measure because sound decay is expected to be not constant in the measurement sound fields with test material, α_n of which is large.



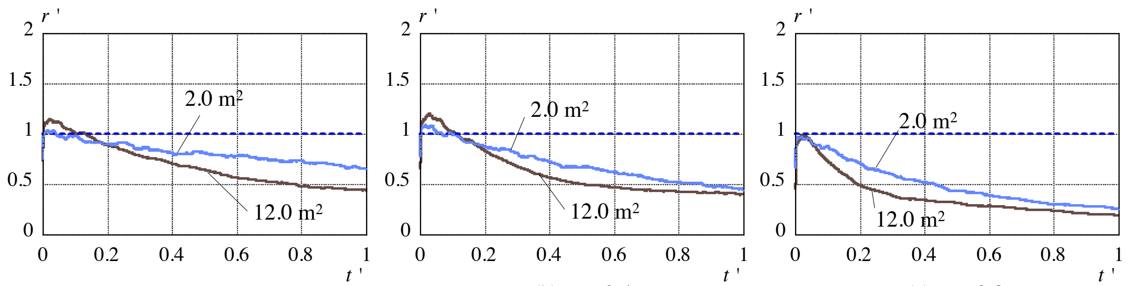
(a) α_n=0.2 (b) α_n=0.4 (c) α_n=0.8

Figure 6 –Comparisons among $r'(t')$ curves in case that s = 2.0 m^2, s = 12.0 m^2, s = 34.2 m^2 (f_m = 500 Hz, OIR) : (a) α_n = 0.2, (b) α_n = 0.4 , (c) α_n = 0.8.



(a) α_n=0.2 (b) α_n=0.4 (c) α_n=0.8

Figure 7 – Comparisons among $r'(t')$ curves in case that s = 2.0 m^2, s = 12.0 m^2 (f_m = 500 Hz, TRR) : (a) α_n = 0.2, (b) α_n = 0.4 , (c) α_n = 0.8.



(a) α_n=0.2 (b) α_n=0.4 (c) α_n=0.8

Figure 8 – Comparisons among $r'(t')$ curves in case that s = 2.0 m^2, s = 12.0 m^2 (f_m = 500 Hz, KIR) : (a) α_n = 0.2, (b) α_n = 0.4 , (c) α_n = 0.8.

4. CONCLUSIONS

Sound fields for the measurement of sound absorption coefficient by reverberation room method were analyzed by time domain finite element method, and it was investigated that ratio of incident sound energy to the test material in those to all boundary of the measurement sound field was calculated from results of the finite element sound fields analysis. At first, it was shown that square sound pressure amplitudes of plane sound wave incident on absorption material were adequately calculated in one-dimensional sound field. Next, the calculation method of the ratio of incident sound energy to the test material in those to all boundary of the measurement sound field was described, and the ratios were calculated in three sound fields with no test material from analytical results obtained by the time domain finite element method. Finally, relationship among the ratio, shape of the measurement room, and characteristics of the test material was investigated, and it could be found that the bigger normal incident sound absorption coefficient of test material, the larger the change of the ratio for decay sound field regardless of room shape and surface area of test material.

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