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Basic investigation on boundary shape modeling for sound field analysis of rooms using time domain finite element method

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ABSTRACT

With the rapid progress of computer technology, numerical simulations based on the wave equation such as FEM and BEM have come to be powerful tools for acoustical design process. The authors have been developing a system of large scale finite element sound field analysis in both time and frequency domains in order to analyze sound fields in rooms with complicated boundary conditions. One of the problems to use the numerical simulations for design process is how to model the complicated geometries of architectural spaces. Typically, architectural spaces have several uneven structures like window, door and light fixture and so on. Although it is possible to model geometry of the structures including small details such as a window frame, a simulation using FE model with detailed room geometry requires a large computational cost. From a practical point of view, therefore, the use of simplified FE model that does not affect acoustics of rooms is desired. In this paper, a series of simulations using FE model with different approximation level of room geometry are conducted to reveal the influence of the use of FE models with different geometry representations on the simulated sound field of rooms. A small office with the volume of 55 m^3 is selected for the simulation and four FE model are created. The impulse responses and several room acoustical parameters such as T_{30}, EDT and D_{50} obtained from each simulation are compared at frequencies of 125–1k Hz.

INTRODUCTION

Numerical analysis methods based on the wave equation such as FEM, BEM and FDTD method are indispensable tools in order to predict sound fields in rooms accurately with complicated boundary conditions. Generally, these methods require large computational cost in the calculations of sound fields in rooms with practical sizes as well as practical frequency ranges. However, the situation is changing quickly along with the rapid progress of computer technology and development of the efficient method. Among the numerical techniques, the authors have been developing a system of large scale finite element sound field analysis and also have presented the applicability of time- and frequency-domain formulations [1, 2, 3, 4].

One of the problems to use FEM for a design process on an architectural space is how to model the complicated room shape. Although it is possible to create detailed room shape model with fine structures of building elements, numerical analysis using the detailed model leads to significant increase of computational time and memory because of increase of DOF of FE model. From a practical point of view, therefore, the use of simplified model that does not affect acoustics of rooms is desired. However, how does the simplification of room shape affect computed sound fields remains unclear and the simplification may result unexpected error.

This paper investigates the influence of simplification of room shape on the simulated sound field of rooms. A series of numerical simulations using time-domain finite element method (TDFEM [3, 4]) are conducted as a preliminary study.

METHODOLOGY AND FE SETTINGS

Method

The sound field in an office room(Volume, $V \approx 55$ m^3, Surface area, $S \approx 100$ m^2) is analyzed using TDFEM. The four models (M_{ori}, M_{simp1}, M_{simp2} and M_{simp3}) with different level of geometry approximation illustrated in Fig. 1 are created. M_{ori} is an original model and $M_{simp1} \sim M_{simp3}$ are the simplified models with different levels of simplification of the room shape. The simplifications are performed manually. The band-limited impulse responses with four octave bands from 125 Hz to 1k Hz and several acoustical parameters, i.e. T_{30}, EDT, D_{50} and TS, are respectively calculated using the models. Then, the band-limited impulse responses and acoustical parameters computed using the simplified models $M_{simp1} \sim M_{simp3}$ are respectively compared with those computed using the original model, M_{ori}. The details of all models are as follows.

- M_{ori}: The original model.
- M_{simp1}: A simplified model. Small details of building elements are simplified and the geometries of building elements are modeled simply as rectangular geometry.
- M_{simp2}: A more simplified model than M1. Relatively small geometries of building elements are modeled simply as planes.
- M_{simp3}: The most simplified model. The geometries of all building elements were modeled as planes.

The detailes of building elements of all models are illustrated in Fig. 2.

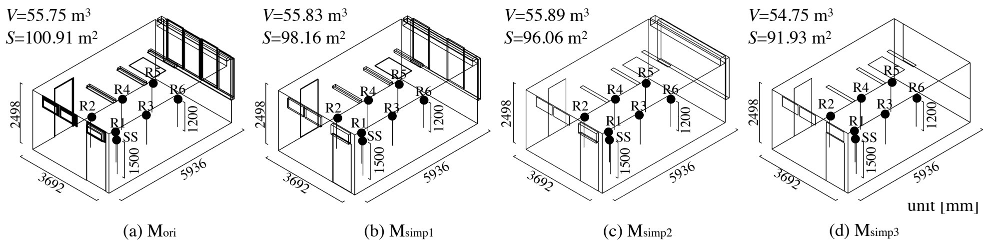

Figure 1: Schematic drawings of four office models to be analyzed. The dots, R1∼R6 represent computed points of sound pressure responses.

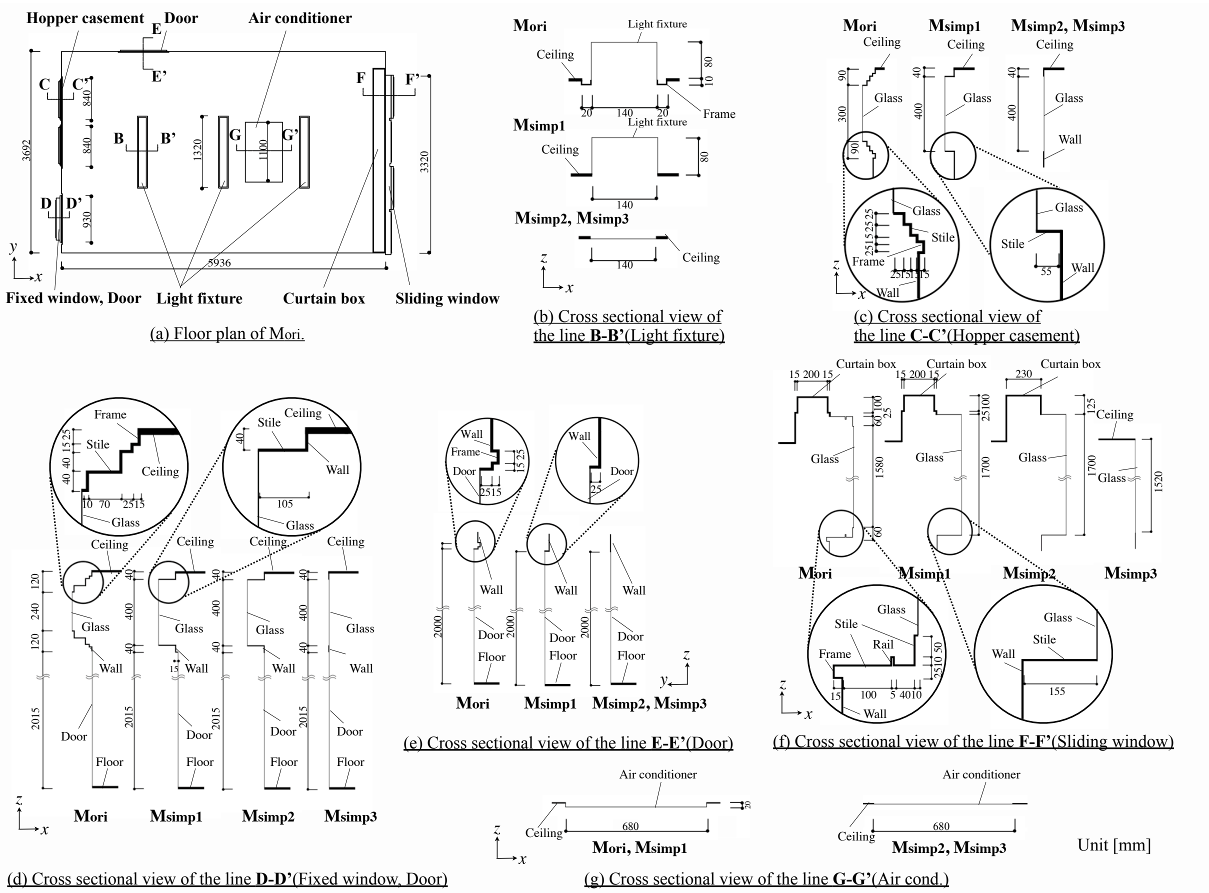

Figure 2: Floor plan of M_{ori} and cross sectional views of building elements of four office models.

Table 1: Boundary condition of FE analysis.

	Absorption coefficient, α			
Surface / f_m[Hz]	125	250	500	1000
Ceiling	0.26	0.13	0.09	0.05
Wall	0.03	0.03	0.03	0.04
Floor	0.01	0.01	0.02	0.02
Door	0.20	0.15	0.10	0.10
Window	0.18	0.06	0.04	0.03
Air cond.	0.75	0.80	0.80	0.80
Light fixture	0.04	0.04	0.03	0.03
Frame, Rail	0.03	0.03	0.03	0.04

FE-settings

Table 1 lists absorption coefficients, α, of room surfaces with the frequency range of 125 Hz–1k Hz given for the time-domain finite element computation. An omnidirectional point source SS is placed at 1.5 m height as depicted in Fig. 1. For the comparison of impulse response, six receiving points R1∼R6 are located as shown in Fig. 1. On the other hand, except for the places near the source point and boundaries of room, 327∼1,710 sound receiving points in response to analyzed frequency are located on the xy-plane at 1.2 m height for the comparison of several acoustical parameters.

The hexahedral 27-node isoparametric element using the spline function as an interpolation function [5] is used for spatial descretization. Using the element, the FE meshes are created to satisfy the spatial division requirement that $\lambda/d > 4.8$. Here, λ and d respectively denote wavelengths of upper limit frequencies of the octave band and the maximum nodal distance of all the elements. Table 2 lists the DOF of each model.

To calculate the band-limited impulse response, an impulse response of the IIR filter (Butterworth type band pass filter with third order) is given at source point as volume acceleration waveform.

Table 2: Degrees of freedom of FE analysis.

Model	*DOF*			
	125 Hz	250 Hz	500 Hz	1000 Hz
M_{ori}	487,865	596,857	1,002,997	2,285,585
M_{simp1}	54,293	82,555	223,965	864,927
M_{simp2}	32,239	55,411	179,873	744,389
M_{simp3}	15,873	38,399	137,175	649,605

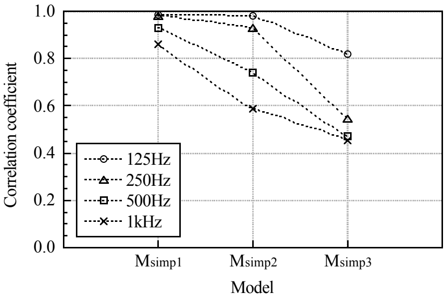

Figure 3: Correlation coefficients of impulse responses between original model and simplified models.

Parallel computations based on the domain decomposition method are conducted to compute the impulse response efficiently. A maximum of 32 processors are employed for the parallelization. The direct time integration method employed here is a constant average acceleration method with the consideration of unconditionally stability [6]. By using unconditionally stable formulation, the problems with very small finite elements can be better handled than conditionally stable formulation. The sampling frequency is set to 44.1kHz. The analyzed time length is 1.5 s which corresponds to 66,150 time steps. Absolute diagonal scaled COCG iterative solver [8, 7] is used in order to solve the linear system of equations at each time step. The convergence tolerance is set to 10^{-6}.

RESULTS AND DISCUSSION

Influence of simplification of room shape on the computed impulse response

In this section, we confirm the influence of simplification of room shape on computed impulse response. The influence is evaluated by calculating the cross correlation coefficient between impulse responses computed using original model M_{ori} and computed using simplified models M_{simp1}~M_{simp3}. The correlation coefficients are presented in Fig. 3. Here, the correlation coefficients are spatial averaged value at six receiving points.

The correlation coefficients decrease at all frequencies as degree of simplification becomes large. It is clear that change of impulse response waveform caused by simplification of room shape becomes larger as the frequency becomes higher. Modeling of building element shapes as planes, i.e. M_{simp3}, has an significant effect on computed impulse response, even if the low frequency region. At 125 Hz and 250 Hz, the correlation coefficients are 0.81 and 0.55, respectively.

Influence of simplification of room shape on the computed acoustical parameters

This section deals with the influence of simplification of room shape on computed room acoustical parameters.

[T_{30}]
The influence of the simplification on computed reverberation

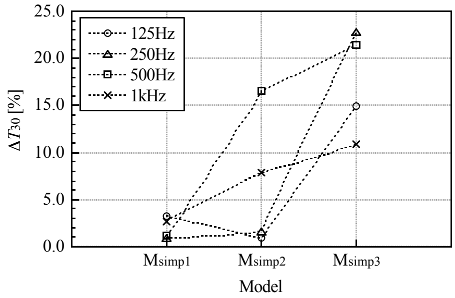

Figure 4: Relative errors of T_{30} between original model and simplified models.

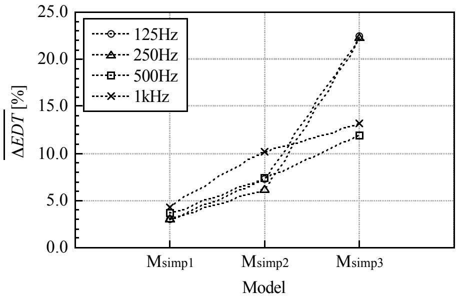

Figure 5: Mean of relative errors $\overline{\Delta EDT}$ between original model and simplified models.

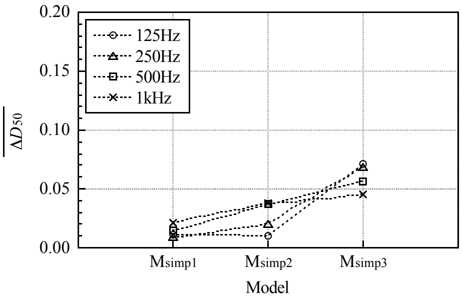

Figure 6: Mean of absolute errors $\overline{\Delta D_{50}}$ between original model and simplified models.

time is evaluated by calculating the relative error ΔT_{30} given as

$$\Delta T_{30} = \frac{|T_{30,\mathrm{ori}} - T_{30,\mathrm{simp}}|}{T_{30,\mathrm{ori}}} \times 100[\%], \qquad (1)$$

where $T_{30,\mathrm{ori}}$ and $T_{30,\mathrm{simp}}$ respectively represent spatial averaged reverberation times at all receiving points computed using original model and computed using simplified models.
The relative errors, ΔT_{30}, are presented in Fig. 4. Overall, ΔT_{30}s become large with increasing degrees of simplification. When using most simplified model M_{simp3}, ΔT_{30}s are greater than 10% at all frequencies. Particularly, ΔT_{30}s at 250 Hz and 500 Hz are 23% and 21%, respectively. For M_{simp2}, ΔT_{30}s are less than 2% at low frequencies below 250 Hz and are greater than 8% at higher frequencies. ΔT_{30}s of M_{simp1} are less than 4% at all frequencies.

[EDT]
The influence of the simplification on computed early decay time is evaluated by calculating the mean value of relative error $\overline{\Delta EDT}$ given as

$$\overline{\Delta EDT} = \frac{1}{N}\sum_{i=1}^{N} \frac{|EDT_{i,\mathrm{ori}} - EDT_{i,\mathrm{simp}}|}{EDT_{i,\mathrm{ori}}} \times 100[\%], \qquad (2)$$

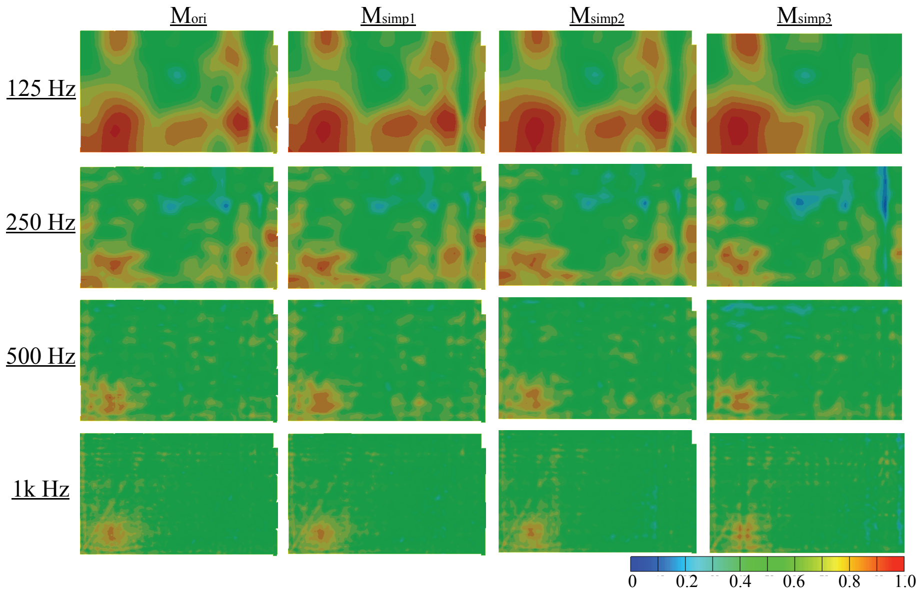

Figure 7: Comparison of spatial distributions of D_{50} calculated using four models.

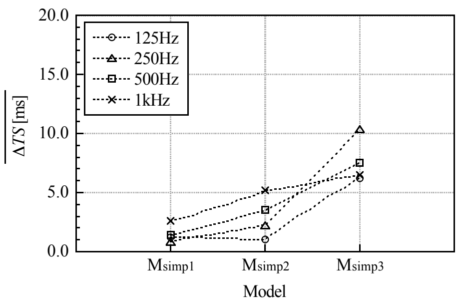

Figure 8: Mean of absolute errors $\overline{\Delta TS}$ between original model and simplified models.

where $EDT_{i,\mathrm{ori}}$ and $EDT_{i,\mathrm{simp}}$ respectively represent the early decay times at receiving point i calculated using original model and calculated using simplified models. N is number of receiving points.

The mean of relative errors, $\overline{\Delta EDT}$ are presented in Fig. 5. Again, $\overline{\Delta EDT}$s increase at all frequencies with increasing degrees of simplification. When using $\mathrm{M_{simp3}}$, $\overline{\Delta EDT}$s greater than 10% are observed at all frequencies. In the low frequencies below 250 Hz, $\overline{\Delta EDT}$s become about 20%. $\overline{\Delta EDT}$s of $\mathrm{M_{simp2}}$ in the frequency below 500 Hz are 6∼7% and are 10% at 1k Hz. $\overline{\Delta EDT}$s of $\mathrm{M_{simp1}}$ are less than 5% at all frequencies.

[D_{50}]
The influence of the simplification on computed definition is evaluated by calculating the mean value of absolute error $\overline{\Delta D_{50}}$ given as

$$\overline{\Delta D_{50}} = \frac{1}{N}\sum_{i=1}^{N} |D_{50,i,\mathrm{ori}} - D_{50,i,\mathrm{simp}}|, \qquad (3)$$

where $D_{50,i,\mathrm{ori}}$ and $D_{50,i,\mathrm{simp}}$ respectively represent definitions at receiving point i calculated using original model and calculated using simplified models. N is number of receiving points.

The mean of absolute errors, $\overline{\Delta D_{50}}$ are presented in Fig. 6. $\overline{\Delta D_{50}}$s increase at all frequencies with increasing degrees of simplification. For $\mathrm{M_{simp3}}$ $\overline{\Delta D_{50}}$s are greater than 0.05 at all frequencies except at 1k Hz. For $\mathrm{M_{simp2}}$ and $\mathrm{M_{simp1}}$, $\overline{\Delta D_{50}}$s are respectively less than 0.04 and 0.02 regardless of frequency. As a reference, a comparison of spatial distributions of D_{50} at 1.2 m height calculated using four models are illustrated in Fig. 7. It is observed that the distributions between $\mathrm{M_{simp3}}$ and the others are different at frequencies below 250 Hz.

[TS]
The influence of the simplification on computed center time is evaluated by calculating the mean value of absolute error $\overline{\Delta TS}$ given as

$$\overline{\Delta TS} = \frac{1}{N}\sum_{i=1}^{N} |TS_{i,\mathrm{ori}} - TS_{i,\mathrm{simp}}|[\mathrm{ms}], \qquad (4)$$

where $TS_{i,\mathrm{ori}}$ and $TS_{i,\mathrm{simp}}$ are center times at receiving point i calculated using original model and calculated using simplified models, respectively. The mean of absolute errors, $\overline{\Delta TS}$ are presented in Fig. 8. $\overline{\Delta TS}$s increase at all frequencies with increasing degrees of simplification. For $\mathrm{M_{simp3}}$, $\overline{\Delta TS}$ is greater than 10 ms at 250 Hz. For other frequencies, the values are less than 7 ms. $\overline{\Delta TS}$s of $\mathrm{M_{simp2}}$ and $\mathrm{M_{simp1}}$ are respectively less than 5 ms and 3 ms at all frequencies.

From these results, simplification of building element shape as plane leads to non-negligible errors in the calculations of T_{30} and EDT. On the other hand, we could not observe significant changes in computed acoustical parameters by the simplification from $\mathrm{M_{ori}}$ to $\mathrm{M_{simp1}}$. Thus, if shapes of building elements are simply modeled, the simplification of small details of building elements does not affect the computed acoustical parameters in the given frequency range.

Comparison of computational cost

The computational costs required for FE analyses using each model are compared in this section. The required memory, RM, for TDFEM used here can be estimated as follows [1].

$$RM \approx 1600DOF[\mathrm{Byte}]. \qquad (5)$$

A comparison of RMs for the analyses using each model is presented in Fig. 9. The vertical axis means ratio to memory of FE analysis using original model. From this figure, FE analysis using original model requires large memory compared to

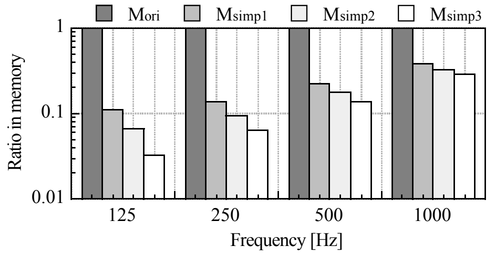

Figure 9: Comparison of memories required for the analyses with each model.

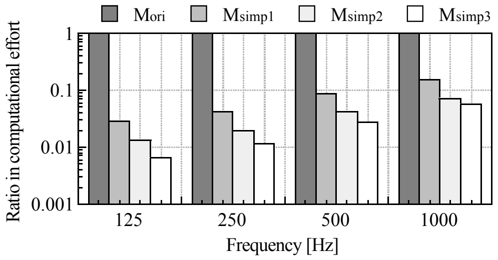

Figure 10: Comparison of computational efforts required for the analyses with each model.

other model at all frequencies. The use of simplified models drastically reduce memories required for the analyses. This means that modeling of small details of building element leads to significant increase of *DOF* of finite element model.

Furthermore, we compare computational efforts required for FE analyses using each model. Instead of computational time, we evaluate the operation required for solving linear system of equations at all time steps. This is computationally time-consuming part in the TDFEM. The operation, *RO*, can be estimated using following equation.

$$RO \approx 65DOF \sum_{j=1}^{N_{\rm step}} N_{mv,j}, \tag{6}$$

where $N_{mv,j}$ is number of iterations of absolute diagonal scaled COCG iterative solver at time step j. $N_{\rm step}$ is total number of time steps. A comparison of *RO*s for the analyses using each model is presented in Fig. 10. The vertical axis means ratio to operation of FE analysis using original model. For all frequencies, FE analysis using original model is much more computationally expensive than FE analysis using simplified models. The computational effort is significantly reduced by using the simplified model. In particular, the reduction rate of *RO* from $\mathrm{M_{ori}}$ to $\mathrm{M_{simp1}}$ is higher than that of *DOF*. This is due to slow convergence of iterative solver for $\mathrm{M_{ori}}$. As a reference, numbers of iterations of absolute diagonal scaled COCG iterative solver for FE analyses using each model at 125 Hz are 85($\mathrm{M_{ori}}$), 23($\mathrm{M_{simp1}}$), 17($\mathrm{M_{simp2}}$), 17($\mathrm{M_{simp3}}$), respectively.

To improve the convergence of iterative solver for the analysis using $\mathrm{M_{ori}}$, we investigate the reduction effect of number of iteration by using IC(0) preconditioning, which is effective preconditioning technique for TDFEM [3]. As a result, the rapid convergence within three iterations is achieved at all time steps by introducing the IC(0) preconditioning. From this result, the use of IC(0) preconditioning is recommended when the detailed model is used.

CONCLUDING REMARKS

In this paper, the influence of simplification of room shape on computed sound field in an office with the volume of 55 m^3 is investigated through the numerical experiments using TDFEM. It is confirmed that change in waveform of impulse response caused by simplification of room shape becomes larger with increasing frequency. In addition, simplification of a building element shape as a plane leads to non-negligible errors in the calculations of impulse response, T_{30} and *EDT* though the simplification is computationally inexpensive. Simplification of small details of building element has an insignificant effect on computed acoustical parameters in the given frequency range when the shapes of building elements are simply modeled.

Further study is required in order to give the guideline of constructing room shape model.

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