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Comparisons between Computer Simulations of Room Acoustical Parameters and Those Measured in Concert Halls

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Abstract

11 European concert halls were surveyed in 1989[1]. In this paper, comparisons are made between the room acoustical parameters measured and those obtained from computer simulations using the ODEON[2), 3)] program version 5.0 on these 11 concert halls. Four kinds of models each concert hall are produced in computer simulation. The one is computer simulation model with high geometrical fidelity and three kinds of models with simplifications to geometry are made by reducing the number of the surfaces and by controlling scattering coefficient of the surfaces. Various acoustic parameters in each model are calculated by using ODEON program to compare with those measured in each concert hall. The relative errors of each acoustical parameter between measurement data and simulated data are calculated. By comparing between relative errors for four kinds of models, the approximate abilities of computer simulations are examined.

Keywords: Computer simulation, Room acoustical parameter, Relative error, Scattering coefficient

1. Introduction

For sound simulation of large rooms such as concert and opera halls, geometrical methods such as Ray-tracing or the Image source method are commonly used. These methods being based on high frequency assumptions, the basic assumption is that reflecting surfaces in the modelled geometry are infinitely large or at least reasonably large compared to the wavelengths of interest. As surfaces are indeed not of infinite size, scattering is introduced in room acoustics software such as Odeon[2), 3)], in order to take into account the limited size of the surfaces causing diffraction as well as the non-specular behaviour of various surface materials.

There is an obvious contradiction between including all geometric features, which may have influence on the acoustics in a concert hall and at the same time respecting the laws of geometric acoustics. On one hand, if the geometry of the room is simplified too much, the acoustic behaviour of the room to be investigated might no longer be present in the model, on the other hand, if including too many details in the model it will not be consistent with high frequency methods such as the Image source method.

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So what is the optimum way to model the geometries of concert hall for calculations in a high frequency method, should the geometry be modeled in detail in or can some details be left out or simplified. It is not only interesting to make simplifications to the geometries in order to obtain better room acoustic predictions, indeed a lot of time can be saved in the modelling process if there is no need for including small geometric features in the models – creating the room models for the simulations is probably the most time consuming task in the process.

In this study, 11 concert halls are modeled in computer simulation. Though the authors have already modeled and investigated four of 11 concert halls in previous papers[4), 5)], two kinds of simulation models for each concert hall were produced. Four kinds of simulation models for each concert hall are produced in this study. The one is the model with high geometrical fidelity. Three kinds of models with simplifications to geometry are also made by reducing the number of the surfaces and by controlling scattering coefficient for the surfaces. Various acoustic parameters for each model are calculated by using ODEON program to compare with those measured in each concert hall. The relative errors of each acoustical parameter between measurement data and simulated data are calculated. By comparing between relative errors for four kinds of models, the approximate abilities of computer simulations are examined.

2. Geometrical Data from Computer Simulation

2.1 Modeling of Concert Halls

11 European concert halls were surveyed in 1989[1)]. In this paper, these 11 concert halls are modeled by computer simulation. They are shown in **Table 1**.

Four kinds of models in **Table 2** for each concert hall

Table 1 11 Concert Halls

Country	Concert Halls	Volume [m³]	Number of Seats	Number of Surfaces CH/CS/CSP/CSA
Germany	Liederhalle, Stuttgart	15,000	1,944	544/120/509/155
	Gasteig Philharmonie, München	30,000	2,387	287/202/266/263
Austria	Musikverein, Wien	15,000	1,600	461/239/410/298
	Grosses Festspielhaus, Salzburg	15,500	2,168	403/103/263/243
England	St.Davids Hall, Cardiff	22,000	1,952	1,351/499/1,311/539
	Usher Hall, Edinburgh	16,000	2,548	2,330/243/1,920/651
	Barbican Concert Hall, London	17,750	2,026	252/106/238/120
	Royal Festival Hall, London	21,950	2,901	427/270/398/299
	Derngate, Northampton	13,500	1,398	376/312/362/326
Holland	Concertgebouw, Amsterdam	18,700	2,040	1,042/258/647/662
Sweden	Göteborg, Koncerthus	11,900	1,286	218/85/183/120

Table 2 Computer Simulation Models

Abbreviation	Four kinds of computer simulation models
CH	Computer simulation model with high geometrical fidelity
CS	Simplified model, that simplifies the platform and the audience area of CH
CSP	Simplified model, that simplifies the platform of CH
CSA	Simplified model, that simplifies the audience area of CH

are produced in computer simulation. The first one is computer simulation model with high geometrical fidelity abbreviated to "CH". The others are the simplified models of CH. The second model is the most simplified one that simplifies the platform and the audience area of CH. It is abbreviated to "CS". The third model is the one that simplifies the platform of CH. It is abbreviated to "CSP". The fourth model is the one that simplifies the audience area of CH. It is abbreviated to "CSA".

The geometrical details and the numbers of the surfaces for four kinds of models for each concert hall are also shown in **Table 1**. Four kinds of models for Liederhalle in Stuttgart are shown in **Fig.1**. CH and CS for the other 10 concert halls are shown in **Figs.2-11**

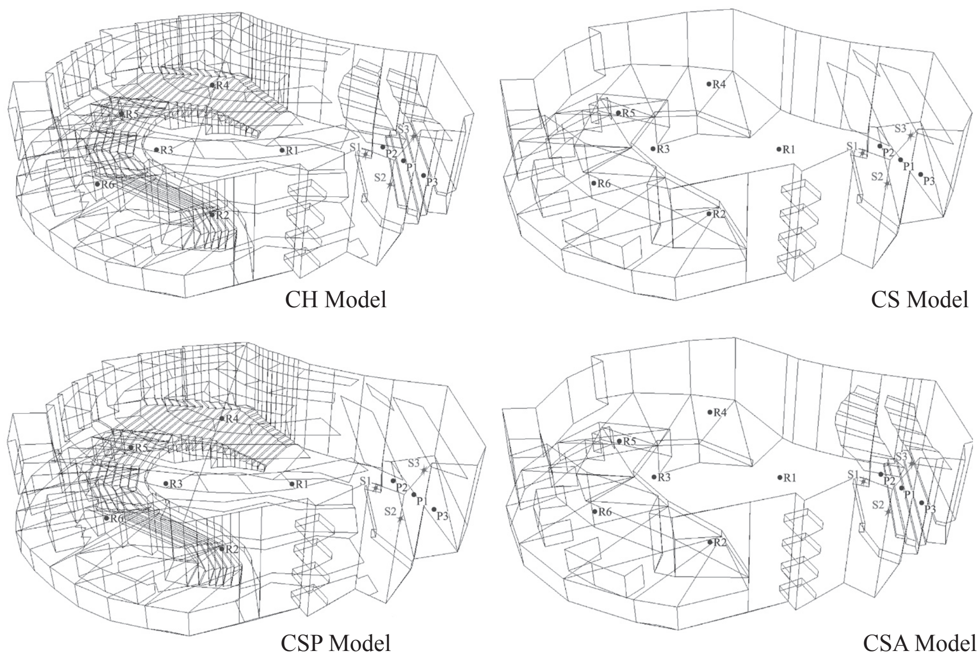


Fig. 1 Model of Liederhalle

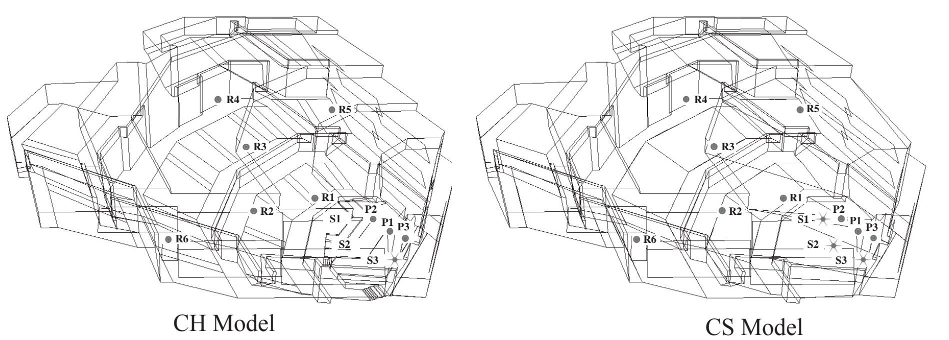


Fig. 2 Model of Gasteig Philharmonic

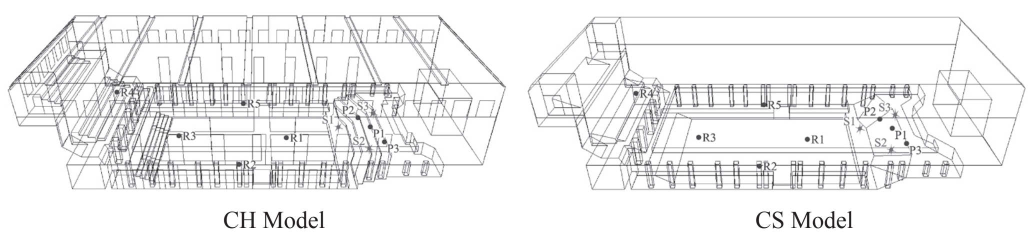
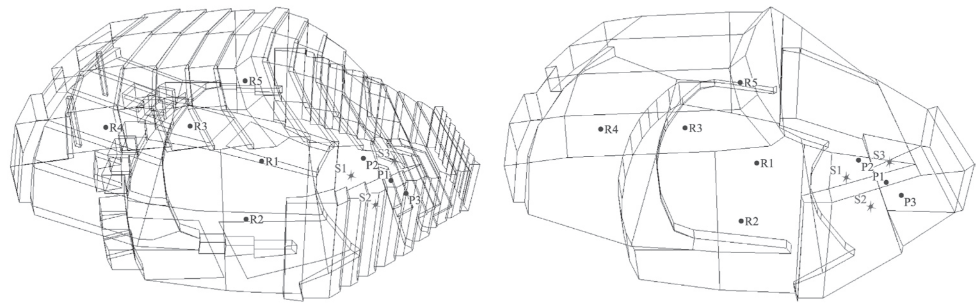
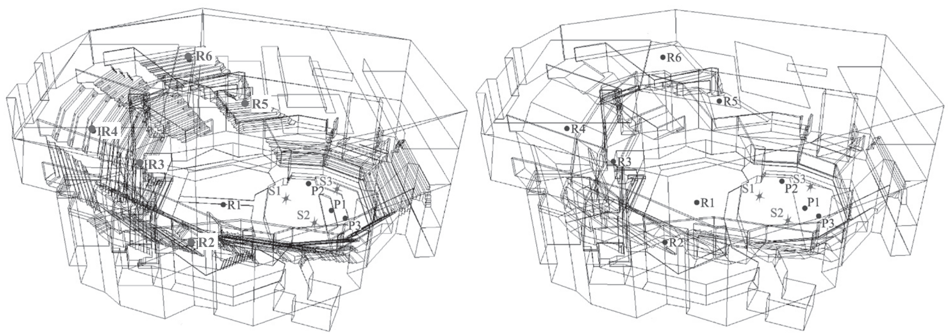


Fig. 3 Model of Musikverein



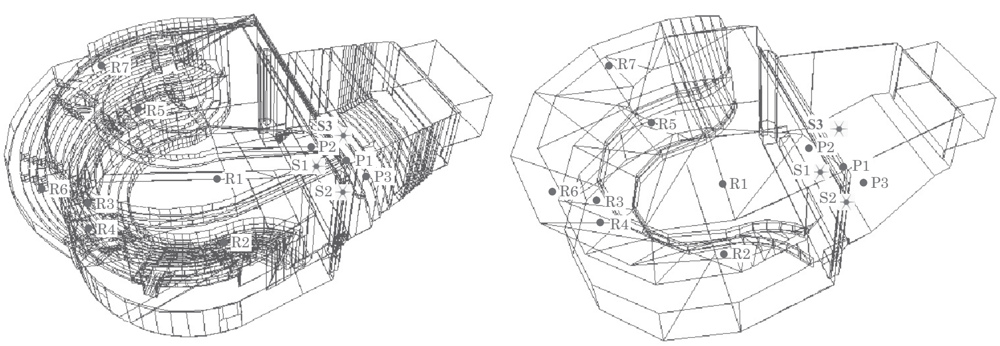
CH Model CS Model

Fig. 4 Model of Grosses Festspiehaus



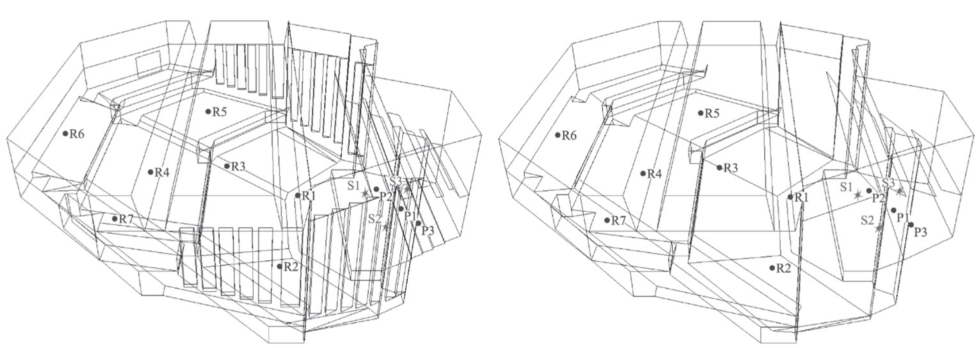
CH Model CS Model

Fig. 5 Model of St.Davids Hall



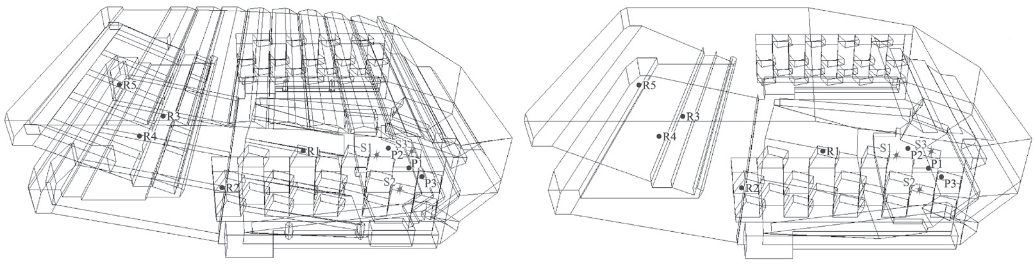
CH Model CS Model

Fig. 6 Model of Usher Hall



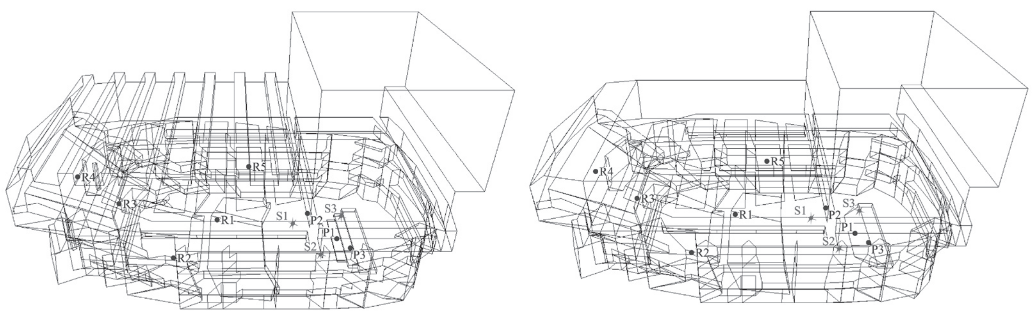
CH Model CS Model

Fig. 7 Model of Barbican Concert Hall



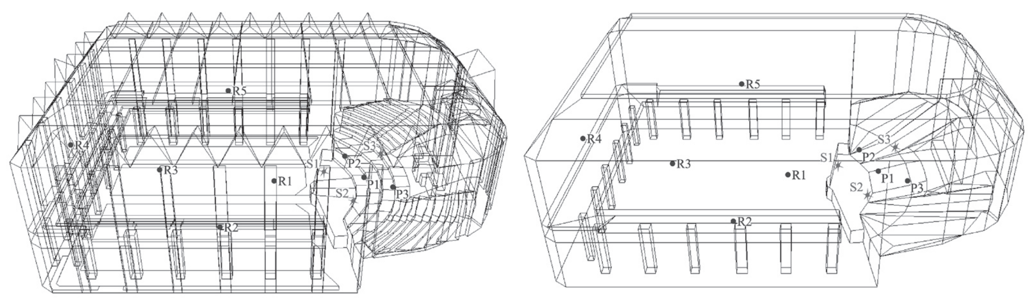
CH Model CS Model

Fig. 8 Model of Royal Festival Hall



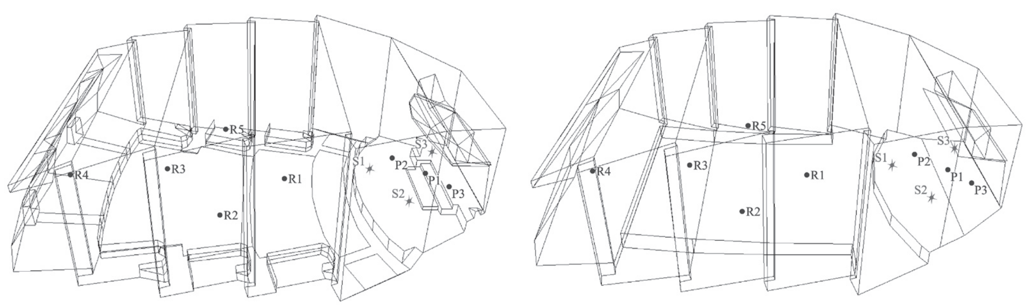
CH Model CS Model

Fig. 9 Model of Derngate



CH Model CS Model

Fig. 10 Model of Concertgebouw



CH Model CS Model

Fig. 11 Model of Göteborgs

2.2 Sound Source and Receiver Positions

Sound source and receiver positions in simulation models are defined according to the survey in 1989. S1 (the typical soloist position), S2 (the middle of right side strings between violas and cellos) and S3 (far left in second row of the wind) are sound source positions. P1 (the normal position of solo oboist), P2 (the middle of left side strings between the first and second violins) and P3 (far right in second row of the wind) are the receiver positions on the platform for each source position. The distance of S2-P2 is about 8 meters. The distance of S3-P3 is about 6 meters. S1-S3 and P1-P3 positions are one meter above the floor. R1-R5, R6 or R7 are receiver positions in the audience area. These positions are 1.2 meters above the floor.

3. Acoustical Parameters

Six acoustical parameters, which are Reverberation Time "RT", Early Decay Time "EDT", Level "L", Clarity "C", Center Time "Ts" and Lateral Energy Fraction "LEF", were measured for each concert hall in 1989. These are also calculated for each model to compare with those measured. The calculation method for each acoustical parameter in this sound simulation follows ISO3382.

4. Accuracy Rating of Acoustical Parameter

For examining accuracy rating of acoustical parameter, the relative errors of each acoustical parameter between measurement data and simulated data are calculated on the each measurement points. The average of the relative errors for each acoustical parameter on the audience area and the platform area are respectively calculated from the formula (1) for RT and EDT and the formula (2) for C, L, Ts and LEF on each frequency.

The formula for RT and EDT is as follows.

$$\text{Error} = \frac{\sum \dfrac{\left|AP_{measured} - AP_{simulated}\right| \times 100}{AP_{measured} \times SL}}{N_{Pos}} \tag{1}$$

The formula for C, L, Ts and LEF is as follows.

$$\text{Error} = \frac{\sum \dfrac{\left|AP_{measured} - AP_{simulated}\right|}{SL}}{N_{Pos}} \tag{2}$$

$AP_{measured}$ = Measured value of the current acoustic parameter

$AP_{simulated}$ = Simulated value of the current acoustic parameter

SL = The subjective limen for the current acoustic parameter

N_{Pos} = Number of measuring positions

The subjective limens for each acoustical parameter to calculate the relative error are shown in **Table 3**[6]. The more the relative error of this calculation value and measurement data approaches zero, the more both of them are in good agreement.

Table 3 Subjective Limens of Room Acoustical Parameters (SL)

Parameter		Subjective Limen	
RT	[s]	5	[%]
EDT	[s]	5	[%]
Level	[dB]	1	[dB]
Clarity	[dB]	1	[dB]
Ts	[ms]	10	[ms]
LEF	[-]	0.05	[-]

5. Results

5.1 Audience Area

All of the relative errors of LEF at 2kHz and 4kHz are not calculated as they were not measured in 1989. The relative errors for acoustical parameters at 500Hz and 2kHz in the audience area where receiver positions are R1-R5, R6 or R7 of each concert hall are shown in **Figs. 12-22**.

According to **Fig. 12** for Liederhalle, the relative errors for CH or CSP are the smallest in four kinds of models except that of EDT, less than 2 sub. limen. The differences between the relative errors of EDT for four kinds of models are small. Those are about 2-3 sub. limen. The relative errors of Ts for CS at 500Hz and 2kHz and CSA at 2kHz are over 3 sub. limen.

According to **Fig. 13** for Gasteig Philharmonie, the differences between the relative errors for four kinds of models are small. The relative errors of Level and LEF at 500Hz are about 1 sub. limen. The relative errors of all of Ts and EDT for CH at 2kHz are about 3 sub. limen.

According to **Fig. 14** for Musikverein, the relative errors of Level are the smallest in acoustical parameters, less than 1 sub. limen. The differences between the relative errors for four kinds of models are small. All of the relative errors at 500Hz except those of Ts are

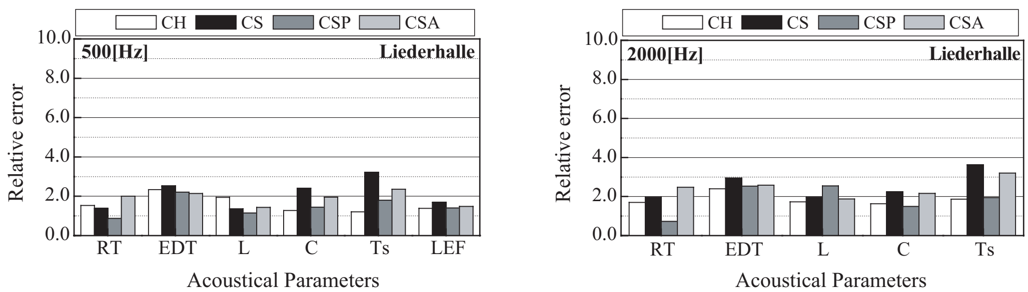


Fig.12 Relative errors in units of subjective limens at 500Hz and 2000Hz in Liederhalle

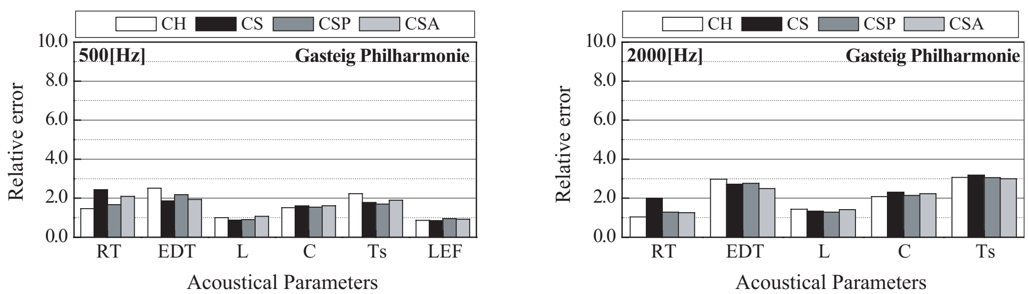


Fig.13 Relative errors in units of subjective limens at 500Hz and 2000Hz in Gasteig Philharmonie

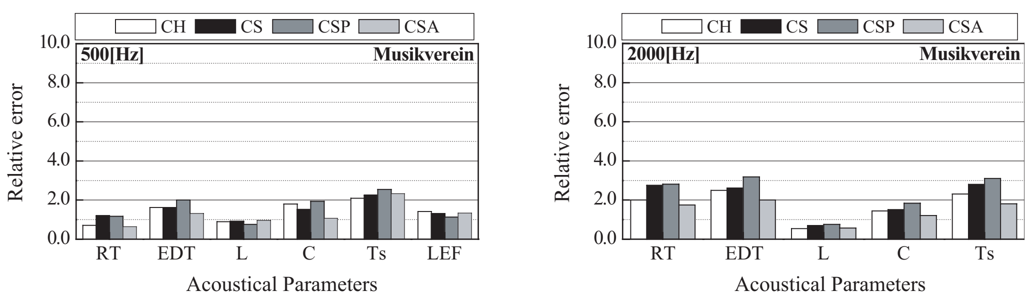


Fig.14 Relative errors in units of subjective limens at 500Hz and 2000Hz in Musikverein

less than 2 sub. limen.

According to **Fig. 15** for Grosses Festspielhaus, the relative errors for CS or CSA are the smallest in four kinds of models, less than 2 sub. limen. The relative errors of RT, EDT and Ts for CH and CSP at 500Hz are especially larger than those for CS and CSA. Some of them are over 5 sub. limen.

According to **Fig. 16** for St. Davids Hall, the relative errors for CH or CSP are the smallest in four kinds of models, less than 2.5 sub. limen. The relative errors for CS and CSA at 2kHz are larger than those of CH and CSP. Some of them are over 4 sub. limen.

According to **Fig. 17** for Usher Hall, the relative errors of RT except that of CSA at 500Hz are the smallest in acoustical parameters, less than 1 sub. limen. The differences between the relative errors for four kinds of models are small except those of RT and EDT at 500Hz. The relative errors of EDT and Ts at 2kHz are about 3-4 sub. limen.

According to **Fig. 18** for Barbican Concert Hall, the

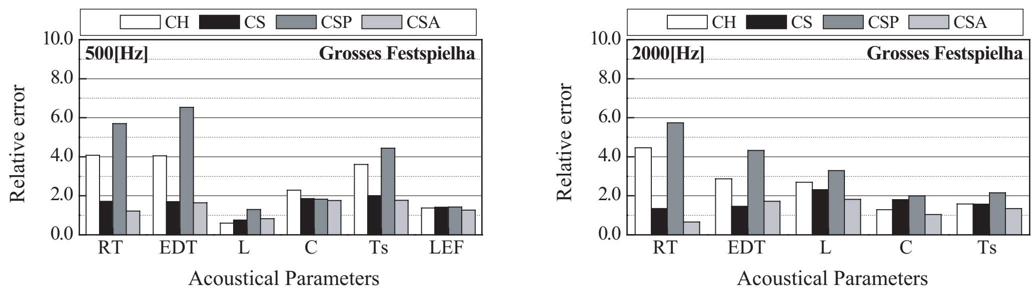


Fig.15 Relative errors in units of subjective limens at 500Hz and 2000Hz in Grosses Festspielhaus

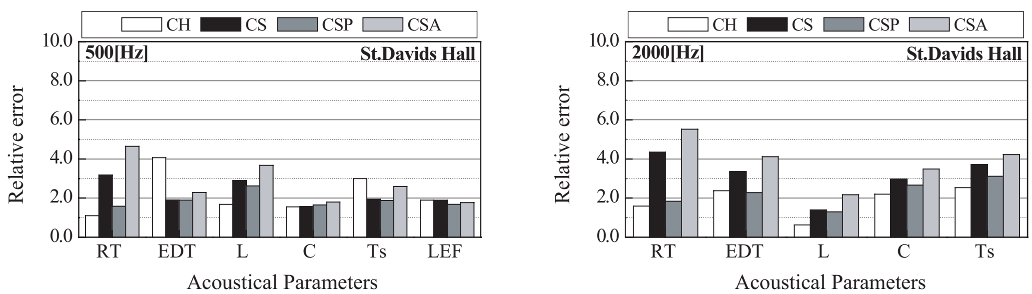


Fig.16 Relative errors in units of subjective limens at 500Hz and 2000Hz in St. Davids Hall

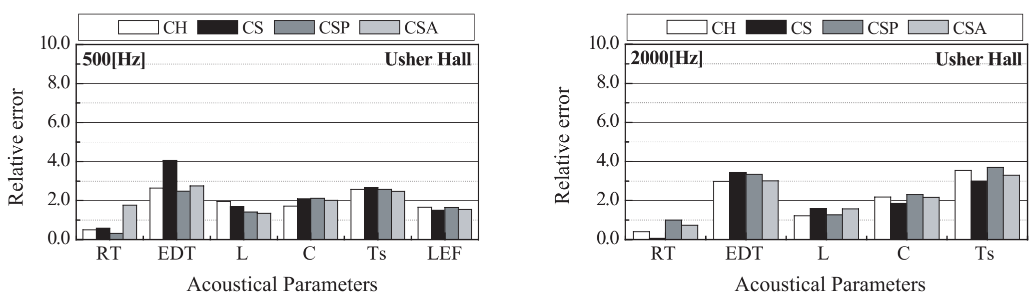


Fig.17 Relative errors in units of subjective limens at 500Hz and 2000Hz in Usher Hall

differences between the relative errors for four kinds of models are small except those of RT, EDT and Ts at 500Hz. The relative errors of RT, EDT and Ts for CH and CSP at 500Hz are larger than those of CS and CSA. Some of them are over than 4 sub. limen. All of relative errors for CS except that of EDT at 500Hz are less than 2 sub. limen.

According to **Fig. 19** for Royal Festival Hall, The differences between the relative errors for four kinds of models are small except those of RT and EDT. The relative errors of RT and EDT for CS and CSA are larger than those of CH and CSP. Some of them are about 3-4 sub. limen. The relative errors for CH or CSP except that of EDT at 2kHz are less than 2 sub. limen.

According to **Fig. 20** for Derngate, All of the relative errors for CSP except that of Level at 2kHz are smallest in four kinds of models. The relative errors of Level at 2kHz are about 1 sub. limen. The relative errors of EDT, Level and Ts at 500Hz and RT at 2kHz are over 3 sub. limen. Some of them are over 4 sub. limen.

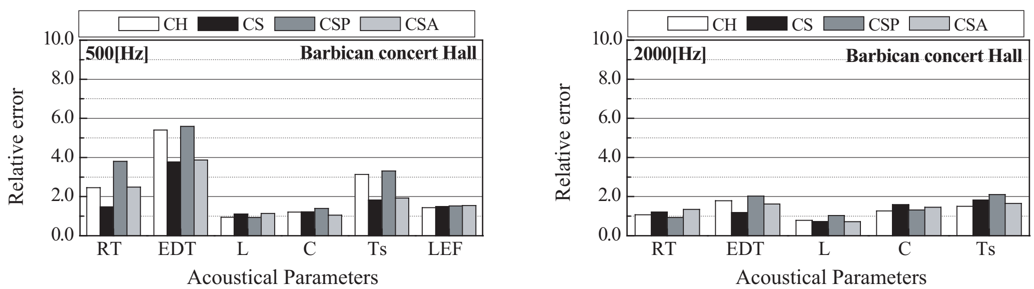


Fig.18 Relative errors in units of subjective limens at 500Hz and 2000Hz in Barbican Concert Hall

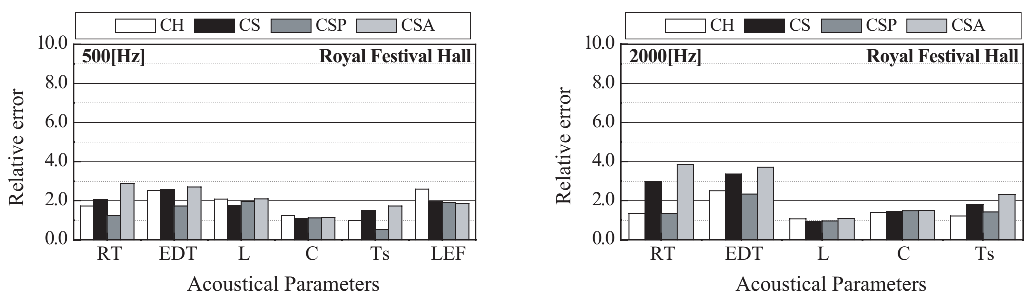


Fig.19 Relative errors in units of subjective limens at 500Hz and 2000Hz in Royal Festival Hall

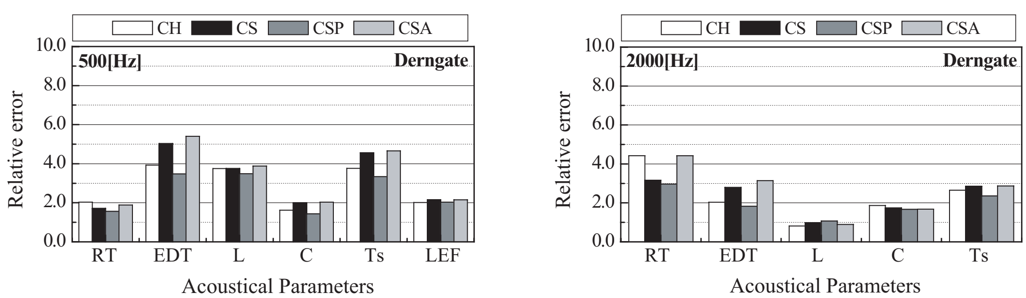


Fig.20 Relative errors in units of subjective limens at 500Hz and 2000Hz in Derngate

According to **Fig. 21** for Concertgebouw, the relative errors for CH or CSP are the smallest in four kinds of models. All of CSP except those of Clarity and Ts at 500Hz are less than 2 sub. limen.

According to **Fig. 22** for Göteborg Koncerthus, the relative errors for CH and CSP except those of EDT at 500Hz are less than 2.5 sub. limen. The relative errors of EDT for four kinds of models at 500Hz are about 4-5 sub. limen.

The averages of the relative errors for 11 concert halls at 125-4kHz of each acoustical parameter (125-1kHz of LEF) for the audience area where receiver positions are R1-R5, R6 or R7 are shown in **Figs. 23-28**.

The relative errors in **Fig. 23** for RT except those at 125Hz are about 2 sub. limen. Those at 125Hz are about 3 sub. limen. All of the relative errors at 125Hz in **Fig. 24** for EDT are over 5 sub. limen and those at the other frequencies are about 3-4 sub. limen. The relative errors in **Fig. 25** for Level except those at 4kHz are the smallest in acoustical parameters, about 1-2sub. limen and those at 4kHz are 2.5-3 sub. limen. The relative errors in **Fig. 26** for Clarity except those at 125Hz are about 2 sub. limen and those at 125Hz are about 2.5 sub. limen. The relative errors in **Fig. 27** for Ts except those at 125Hz are about 2-3 sub. limen and those at 125Hz are 3.5-4 sub. limen. The relative errors in **Fig. 28** for LEF are about 2 sub. limen.

As a whole, the differences of the relative errors between four kinds of models are small.

5.2 Platform Area

All of the relative errors at 125Hz and 4kHz are not calculated as they were not measured in 1989.

The averages of the relative errors for 11 concert halls at 250-2kHz of RT, EDT, Clarity and Ts for the

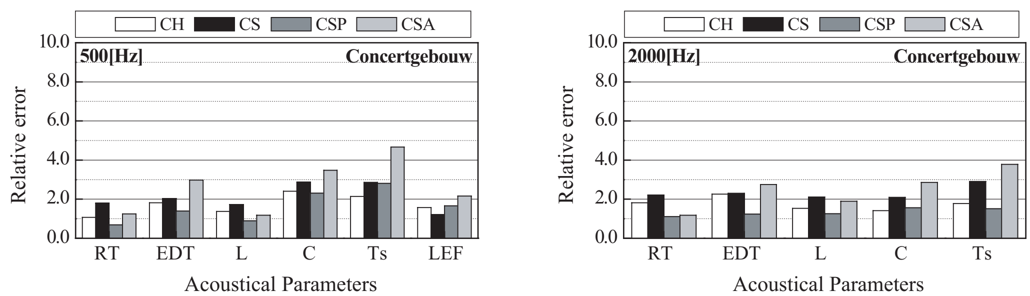


Fig.21 Relative errors in units of subjective limens at 500Hz and 2000Hz in Concertgebouw

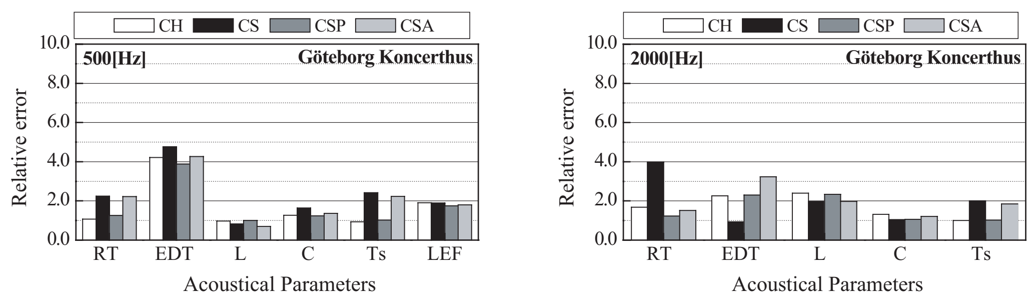


Fig.22 Relative errors in units of subjective limens at 500Hz and 2000Hz in Göteborg Koncerthus

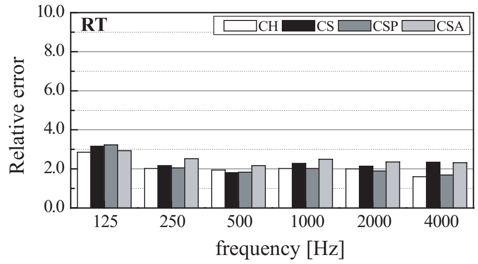


Fig. 23 Relative errors in subjective limens for RT on the audience area

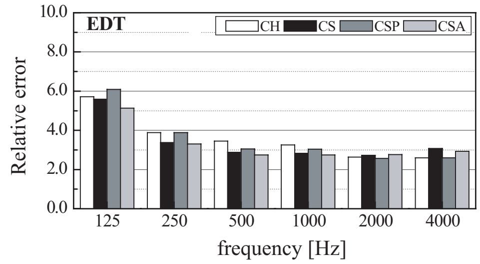


Fig. 24 Relative errors in subjective limens for EDT on the audience area

platform area where receiver points are P1, P2 and P3 are shown in **Figs. 29-32**.

The relative errors at 250Hz in **Fig. 29** for RT are over 3 sub. limen. The relative errors of CH and CSP at 500Hz in **Fig. 29** for RT are larger than those of CS and CSA, about 3 sub. limen. The relative errors of RT at 1kHz and 2kHz are 2-3 sub. limen. The relative errors in **Fig. 30** for EDT are larger than the other acoustical parameters. Those at 250Hz are especially large, over 6 sub. limen and those at the other frequencies are about 4-5 sub. limen. The relative errors in **Fig. 31** for Clarity are about 1-2 sub. limen. The relative errors in **Fig. 32** for Ts are about 2-3 sub. limen.

All of the relative errors of CSP except that at 500Hz of RT are the smallest in four kinds of models.

As a whole, the differences of the relative errors between four kinds of models are small.

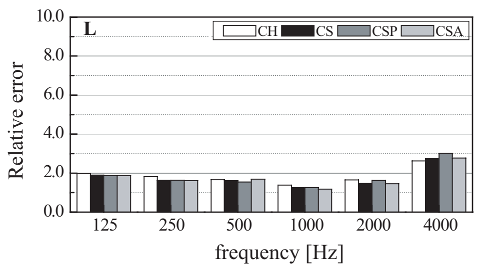


Fig. 25 Relative errors in subjective limens for L on the audience area

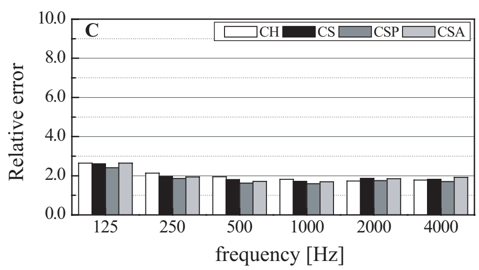


Fig. 26 Relative errors in subjective limens for Clarity on the audience area

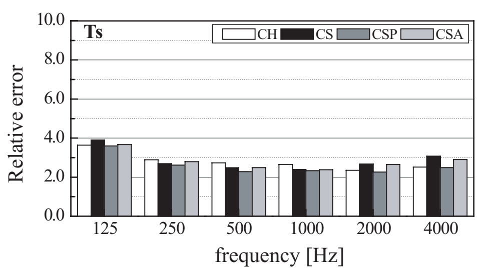


Fig. 27 Relative errors in subjective limen for Ts on the audience area

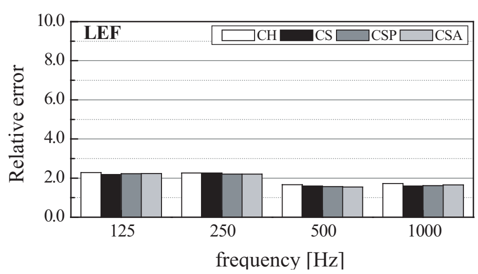


Fig. 28 Relative errors in subjective limens for LEF on the audience area

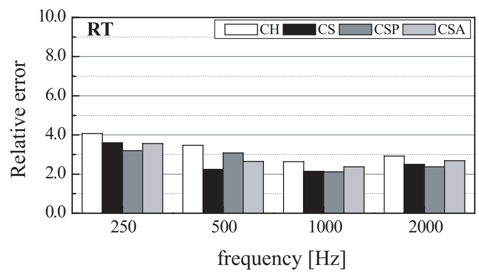


Fig. 29 Relative errors in subjective limens for RT on the platform

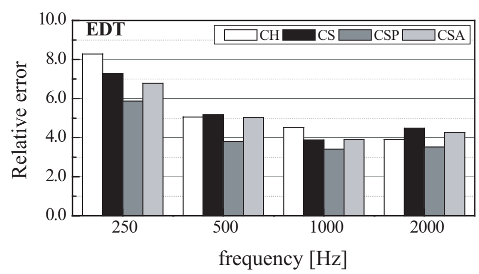


Fig. 30 Relative errors in subjective limens for EDT on the platform

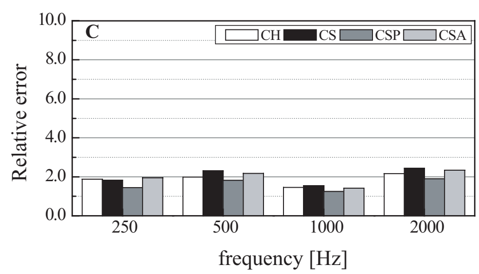


Fig. 31 Relative errors in subjective limens for Clarity on the platform

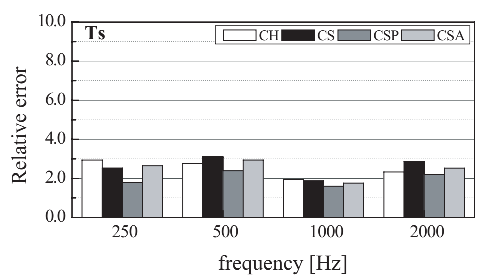


Fig. 32 Relative errors in subjective limens for Ts on the platform

6. Discussions

As a whole, the CSP model that simplifies the platform of CH is the most approximate in four kinds of models except Grosses Festspiehaus and Barbican Concert Hall. The relative errors of CS and CSA for Grosses Festspiehaus and Barbican Concert Hall are smaller than those of CH and CSP. The sideward walls of the platforms for both concert halls spread out like a fan shape and also the ceilings of the platforms for both concert halls are low. The mean ceiling height of the platform for Grosses Festspiehaus is about 8.5m. This is the lowest in 11 concert halls. That of the platform for Barbican Concert Hall is about 9.0m. As above, it is better that the platform area is modeled with simplification to geometry like CSP or CS. It depends upon the shape and the size of the platform whether audience area is also modeled with simplification to geometry to get the high approximate ability.

As the simulation technique of ODEON on the basis of the geometrical method supposes that the room is the diffuse sound field, interference of sound waves is disregarded. However, as there is interference of sound waves in real sound field, it has influence on some measurement data especially at low frequency like 125Hz or 250Hz by the shape and the size of concert hall, so that some relative errors at low frequency are large.

The relative errors of EDT that is calculated from early sound energy decay are the largest in acoustic parameters. Especially, those relative errors of the platform area are larger. However, the relative errors of EDT at 500Hz or 2kHz for CS or CSP of some concert halls are not large, about 2 sub. limen. Therefore, the approximate ability of EDT depends upon the kind of the simulation model.

As a whole, the CSP model that simplifies the platform of CH is the most approximate in four kinds of models. For some concert halls, the models with simplifications to geometry are better than the models with high geometrical fidelity. This means that the model with simplification to geometry like CSP or CS is enough for acoustical simulation by a computer.

7. Conclusion

1) The relative errors of Level are the smallest in the acoustical parameters except those at 4kHz.
2) The relative errors of EDT are larger than those of the other acoustical parameters. Especially, those on the platform are larger.
3) The platform area should be modeled with simplification to geometry like CSP or CS to get the high approximate ability.
4) It depends upon the shape and the size of the platform whether audience area is modeled with simplification to geometry to get the high approximate ability.
5) The simplified model that is made by reducing the number of surfaces and controlling scattering coefficient of surfaces is enough for acoustical simulation by a computer.

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コンサートホールにおける室内音響パラメータの
コンピュータ・シミュレーションによる計算値と測定値との比較

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概　　要

1989年に11のヨーロッパにおけるコンサートホールの音響特性が測定された。本論文では，それら11のコンサートホールにおける室内音響パラメータの測定値とコンピュータ・シミュレーション(ODEONVer.5.0) から得られた計算値とを比較検討している。コンピュータ・シミュレーションでは，それぞれのコンサートホールに対して4種類のモデルが作られている。ひとつは詳細に作られたコンピュータ・シミュレーション・モデルである。さらに，壁面の散乱係数をコントロールし，壁面数を減らすことにより3種類の簡易モデルが作られている。11のコンサートホールにおいて，4種類のモデルにおける音響パラメータが，測定値と比較するために計算されている。また，それらの音響パラメータにおける測定値と計算値との相対誤差が計算されている。4種類のモデルの相対誤差を比較することにより，コンピュータ・シミュレーションのシミュレーション能力を検討している。

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