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ON THE PARAMETERS CONTROLLING DIFFUSION CALCULATION IN A HYBRID COMPUTER MODEL FOR ROOM ACOUSTICS PREDICTION

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1. INTRODUCTION

Computer modelling has been continuously applied to room acoustics in various forms incorporating different algorithms based on the ray tracing method [1], the image method [2,3], and the hybrid ray tracing/image method [4,5]. These algorithms generally have two basic assumptions in common: sound is modelled only as energy; and the propagation of the sound is modelled by straight-line geometrical acoustics. Clearly these assumptions are not entirely true in a real hall, and can only be considered as necessary compromises to enable predictive modelling of complex sound fields in auditoria. A particularly important problem is that real life walls generally do not produce purely specular reflections. The scattering of sound away from the specular reflection angle creates partially diffuse reflections. Successive diffuse reflections make it increasingly inappropriate to describe high order reflections by purely geometrical means. This could introduce large error in the geometrical models' calculation of reverberation especially in enclosed spaces such as a concert hall in which the absorption is concentrated on only one surface (the audience).

The importance of modelling of diffuse or partially diffuse reflections has become apparent in recent years [6] and has prompted several researches into various methods of introducing such phenomena into the basic geometrical models [6-10]. In here mainly the method of Naylor [8] as implemented in the hybrid model ODEON version 2.0 will be investigated. This will also be compared to a modified form of the method described in Ref.[6], which is implemented into an earlier versions of ODEON. The method suggested by Heinz [9] is considered too computationally time consuming to be used in this comparison, while the approaches used by Nakagawa *et al* [10] and Dalenbäck [7] have theoretical similarity to those used by Naylor and Rainy.

The performance of the diffusion calculation methods is investigated against acoustic data obtained by physical scale model measurements on a total of seven physical scale models. These physical models have different sizes and shapes which are intended to cover a wide range of concert auditoria. By using such a variety of auditoria the accuracy of methods under various hall conditions can be examined.

2. DIFFUSION METHOD IN ODEON VERSION 2.0

The ODEON computer model is based on the hybrid ray tracing/image method. Detailed descriptions of the model have been given elsewhere [5] and will not be repeated here. The ODEON version 2.0 approach for diffuse reflections has also been described in Ref.[8]. In summary the calculation is separated into two parts; early and reverberant. The transition between the two parts is defined by a transition order of reflection. Reflections with orders lower than the transition order are calculated by the purely geometrical hybrid method. No diffuse reflection is calculated for these early reflections. Reflections with order higher than the transition order are reverberant reflections. They are treated as energy packets as in a normal ray tracing method. However at each subsequent wall reflection a secondary impulse source is created at the reflection point. This source is then considered to radiate into a hemisphere inside the room as an elemental area source in order to determine the contribution of this particular reflection to the sound field. The energy is then re-grouped back into the primary ray which generated this secondary source. This primary ray is then traced forward in a direction given by a randomization process depending on the wall's diffusion coefficient. There are two potential problems with this approach. Firstly the transition order is not physically satisfactory. One would expect diffuse reflections to occur even at the very first reflection rather than suddenly being switched on at the transition order. Since this order is defined as a calculation parameter by the user, a guideline to its choice has to be clear established for it to be useful. Secondly the wall's diffusion coefficient is used as a probability determinator. It has a statistical rather than a straightforward physical correspondence to the amount of scattered energy.

In the following investigation, the basic calculation parameters set for the hybrid ray tracing/image calculations are 4000 rays, 10000/s maximum reflection density, and 3s ray runtime. With the reverberant tail of the impulse response calculated by the diffuse method, the accuracy of the calculations is relatively insensitive to the number of rays and maximum reflection density, provided that they are sufficiently high to cover the early part of the impulse response. The accuracy of the prediction is more sensitive to the calculation parameters which control the diffuse calculation. Attention will first be given to the effect of the transition order and diffusion coefficients on the accuracy of the ODEON version 2.0. Later on results from a different approach of diffusion calculation, which does not have the problem of transition order, will be compared.

3. PHYSICAL SCALE MODELS

The seven physical scale models used in this work are in 1:50 scale and are designed to be simple so that their acoustics can be readily analyzed, while at the same time maintaining all the important design criteria of modern auditoria. This also enables the evaluation of the accuracy of the computer prediction to be carried out in a deterministic way, so that the sources of errors and possible improvements can be identified. One should however be reminded that ODEON was developed to predict acoustics of real halls which are generally more complex than our physical models. The error characteristic of ODEON in real hall situations may be different from that found in our physical model comparisons. The validation of ODEON in real hall situations is currently a subject of our on-going research.

Table 1. General geometrical design data of the physical model halls. The width dimensions shown in brackets are the different width values of the fan shaped halls.

Name	Shape	Interior Dimensions (Length x Width x Height)	Volume (m^3)	Capacity (seats)	Balcony
RECT-1	Rectangular	50mx36mx20m	29500	3018	Yes
RECT-2	Rectangular	43mx31mx17m	19900	2165	Yes
RECT-3	Rectangular	34mx25mx13.5m	10620	1012	No
RECT-4	Rectangular	27mx20mx10m	5050	529	No
FAN-1	Fan	48mx25(60)mx17m	29880	3422	Yes
FAN-2	Reversed Fan	48mx60(25)mx17m	29910	3127	Yes
FAN-3	Hexagonal	48mx25(48)(36)mx17m	27680	3215	Yes

The design and the acoustics of the physical models has been described in details in a PhD thesis [11]. A brief description of the model halls is given in Table 1. The models are constructed mainly from hard, varnished plywood. The model seating is constructed from angled steel strips covered with an absorptive fabric. The absorption coefficient of the model seating compared very well with those of full-scale upholstered seating obtain in several modern auditoria [12]. The values at 1 kHz are 0.05 for the walls and 0.7 for the seating.

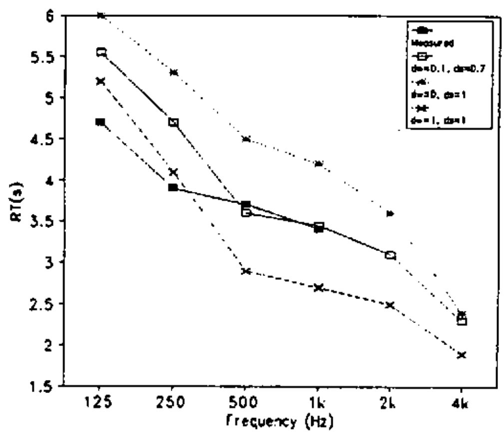

Figure 1 The effect of diffusion coefficients on the prediction of RT in RECT-1.

The physical model measurements were carried out by means of a computer based data acquisition system: Salford University Model Measurement System (SUMMS) [11]. The system is based on an EISA PC. The data acquisition is via a type EISA-A2000 hardware card from National Instrument. The card is capable of a sampling rate of 1 MHz. The actual upper frequency of the measurements is however limited by the frequency range of the transducers available for 1:50 scale measurements. With a spark source and a 1/8" microphone the measurement is limited to the octave frequency band of 50 kHz, which corresponds to the 1 kHz band in real scale. The operating principles of SUMMS are the same as those of the system described by Polack [13], except that in SUMMS the direct sound energy is determined by anechoic measurements instead of from the first few ms of the impulse response.

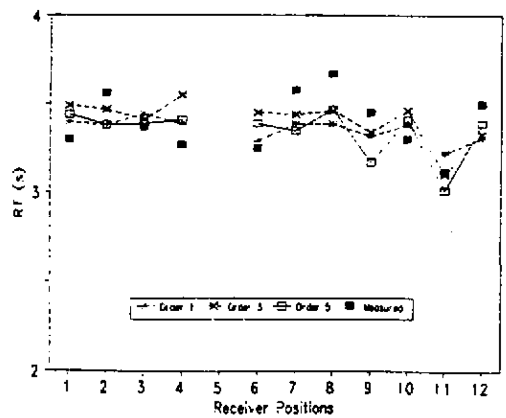

Figure 2 The effect of transition order on the predicted RT at 1kHz, source 3 in RECT-1.

The receiver positions in the physical models are numbered as follows: (a) in the rectangular models, receivers 1 to 4 are in the front seating, 5 and 6 are on the side stage, 7 to 9 are under balcony, and 10 to 14 are on the balcony; and (b) in the fan models, receivers 1 to 4 are in the front seating, 5 to 7 are under balcony, 8 is on the side stage, and 9 to 12 are on the balcony. For the source positions, source 1 is in the front, 3 is at the back, and 2 and 4 are in the middle of the stage. The acoustics of the physical model halls has been described in detail in Ref.[11].

4. DIFFUSION COEFFICIENTS

The ability of a surface to produce diffuse reflections generally depends on both the material properties and physical dimensions of the surface. A suitable definition of a diffusion coefficient to characterise this ability is still not standardized. Hence it will be difficult at this stage to determine precisely the diffusion coefficients of the physical models' walls by direct measurements. Instead, this investigation looks at the effect of changing the diffusion coefficients in the calculation.

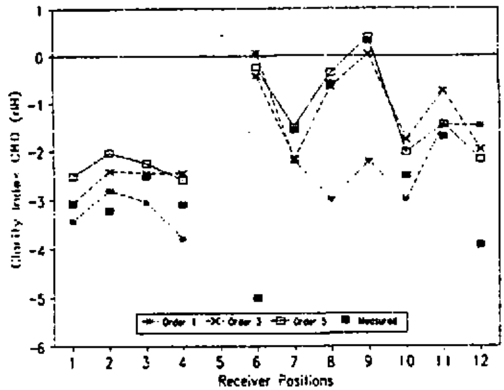

Figure 3 The effect of transition order on the predicted C80 at 1kHz, source 3 in RECT-1.

The interior surfaces of the physical models are predominantly of two types: smooth wooden walls and uneven seating areas. The surfaces are generally large and it may be assumed that the effect of size on the diffusion coefficients will be small in the models. Hence only two coefficients need to be used: one, dw, for the smooth wooden walls and another, ds, for the uneven seating areas. It is expected that the smooth walls will have a diffusion coefficient much smaller than that of the seating areas.

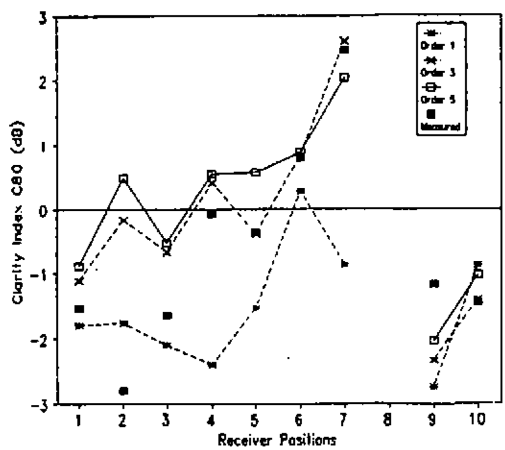

Figure 4 The effect of transition order on the predicted C80 at 1kHz, source 2 in FAN-1.

Figure 1 shows the predicted RT, averaged over all source and receiver positions, in RECT-1 using various combinations of diffuse coefficients. Without diffusion on the wall, represented by the case of dw=0, the prediction overestimated the average RT by almost 1s at frequencies up to and including 1 kHz. Assigning a diffusion coefficient of 1 to all surfaces, which is equivalent to maximum diffusion, produced a prediction which significantly underestimated the RT at mid frequencies. In the end it was found that using dw=0.1 and ds=0.7 gave a good prediction on the average RT at the mid frequencies (500 and 1000 Hz). At frequencies below 250 Hz larger diffusion coefficients gave better predictions. This indicates that, as may be expected, the diffusion property of a surface is a function of frequency. At lower frequencies diffraction effects will be stronger and a larger diffusion coefficient should be used. However even using the maximum diffusion coefficient value of 1 for all surfaces still over-predicted the RT. It is believed that the large amount of wood panels used in the construction of the models might have contributed to the larger than expected low frequency absorption in the models. In the following sections only mid frequency results will be discussed and the diffusion coefficients used for the predictions are therefore 0.1 for the wooden walls and 0.7 for the seating areas.

5. TRANSITION ORDER

All the predictions shown in Figure 1 used a transition order of 5. This order is suitable for the above estimation since the transition order has very little effect on the prediction of RT in RECT-1, as can be seen in Figure 2. This is because RT is determined by the whole decay process and is therefore rather insensitive to the transition changes in the first few order of reflections. On the other hand the prediction of objective parameters which depend heavily on the early energy, such as C80, will be affected significantly by the choice of the transition order. Figures 3 and 4 show comparisons of predicted and measured C80 in RECT-1 and FAN-1 respectively. In the rectangular model the transition order, with a variation between 1 to 5, has surprisingly little effect on the prediction except at the lowest order of transition, i.e. 1. With a transition order of 1 the prediction accuracy deteriorated significantly and the details of the spatial pattern were lost. Other values of transition order produced similar predictions which compare well with measurements. It should be noted that the very low C80 value at receiver 6, which is on the side stage, is caused by a destructive interference of the direct sound by the first order reflection from the hard stage floor. This was picked up by the measurement but not by the energy based prediction.

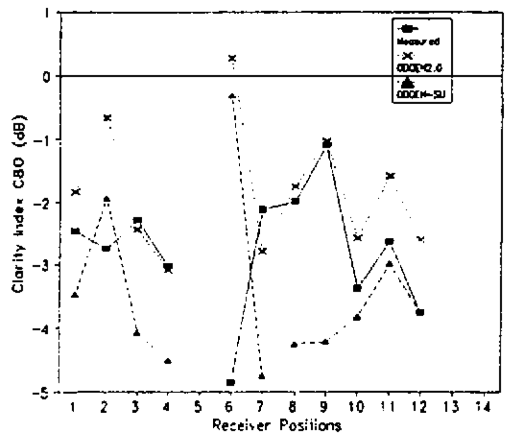

Figure 5 Predictions of C80 in RECT-1 with different diffusion methods.

Results on the fan shape models show a stronger dependence on the choice of transition order. In Figure 4, the clear tendency for the clarity to increase towards the back of the fan shape hall is well predicted by using transition orders of 3 and 5, but not 1. However the absolute values of the C80 were over-predicted by a transition order of 5 but under-predicted by a transition order of 1. Generally a transition order of 3 produced the best prediction at most receiver positions while a lower transition order produced better results at the front of the hall. This behaviour can be explained by considering the number of early reflections received in different part of the halls. In a fan shape hall, most of the early reflections are directed towards the rear of the hall. The front of the hall will therefore have much fewer reflections than the back. In ODEON, reflections are treated as purely specular without diffusion before the transition order. The strength of these reflections will be higher than in real life where some diffusion is inevitable. The energy scattered by the diffusion will eventually come back to the receiver but at a later time, perhaps one or two order of reflections later. In the front of the hall where early reflections are few, the reflections arriving within the 80 ms limit of C80 will be mainly first and second order reflections. In ODEON with a high transition order, these reflections will be treated as purely specular and their strength will be too high. The result is an over-prediction of clarity. With a very low transition order even the first few reflections are diffuse and the predicted clarity agrees better with measurement. At the rear of the hall there are more higher order reflections. In real life this also means that the energy scattered by the lower order reflections would have arrived back at the receiver as well. Thus even with a high transition order the over-prediction of the energy of the lower order reflections in ODEON will be compensated by the arrival of scattered energy in real life. Thus the predictions with higher transition orders agree well with measurement at the rear of the fan halls. This is also the case in the rectangular halls where the distribution of early reflections is more even.

A danger of using too low a transition order is that the geometrical influence of the hall on the reflection direction will be unduly reduced. It can be seen clearly in Figure 4 that a transition order of 1 may not be able to provide adequate prediction on some strong acoustic features of a hall. The use of such a low order should be avoided unless there are reasons to believe that a low density of early reflections is to be expected.

6. A DIFFERENT DIFFUSION CALCULATION METHOD - ODEON-SU

As mentioned earlier, one problem with the diffusion method of ODEON version 2.0 is that the transition between purely specular to diffuse reflection at a single transition order is physically unsatisfactory. The approach described by Ref.[6] avoids this problem by taking scattered energy out of every reflections. This approach is implemented in an earlier version of ODEON (version 1.1) to form a partially new model ODEON-SU which is used to compare with the ODEON version 2.0 approach.

In the ODEON-SU approach, a fraction of the energy, defined by the diffusion coefficient of the wall, is taken out from the specularly reflected ray at each reflection. This diffuse energy is first radiated into the hall as a secondary impulse source on the wall according to Lambert's law. After this first radiation, the energy is grouped into a pool of diffuse energy. The energy in this pool is assumed to decay exponentially at a rate corresponding to the hall's Erying RT, while continuously contribute to the energy density everywhere in the hall according to the usual statistical diffuse field model. To allow for simple shielding effects created by surfaces such as balconies, the contribution of this energy to a receiver depends on the proportion of visible reflective surface seen by the receiver.

Although this approach does not require a transition order, and the diffusion coefficient now has a direct physical correspondence to the scattered energy, it does have a difficulty that many auditoria do not have a diffuse sound field and the re-distribution model may not always work. This problem is illustrated in Figure 5 and 6 in which the ODEON-SU predictions of C80 and Level, averaged over all sources, in RECT-1 are compared with those obtained from ODEON version 2.0 and measurements. It can be seen that although the accuracy of the ODEON-SU is similar to ODEON version 2.0 at positions in the main seating area and on the balcony, it significantly under-estimated the C80 under the balcony. The increase in the C80 under the balcony is due to the balcony's shielding effect which creates a reverberant sound field that is quite different from elsewhere in the hall. Hence ODEON-SU's assumption of a mostly diffuse field over the entire hall for the distribution of diffusely reflected energy will not be able to account for the increase in C80 under the balcony. The simple weighting according to the

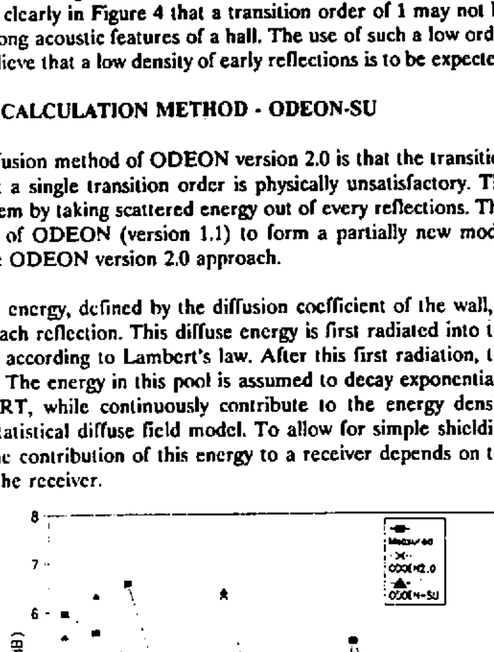

Figure 6 Predictions of Level in RECT-1 with different diffusion methods.

proportion of visible reflective surfaces is not sufficient to correct for this error. However in cases where the balcony shielding is not significant ODEON-SU works quite well. An example is shown in Figure 7 for a hall in which the balconies do not over-shadow the audience.

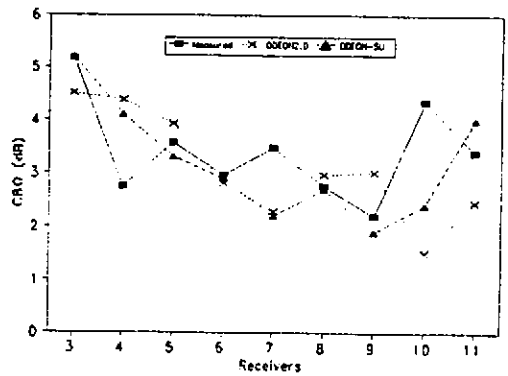

Figure 7 Predictions of C80 in a real hall with different diffusion methods.

7. CONCLUSIONS

It has been shown, by comparisons in seven physical scale model halls of different sizes and shapes, that the inclusion of diffuse reflection is important for a computer model to predict accurately the acoustics of concert halls. The ability of the hybrid model ODEON to predict the acoustic characteristics of a hall depends critically on a proper choice of diffusion coefficients and transition order. The diffusion coefficient has most of its effect on the prediction of the RT time of a hall, while the transition order affects mainly the prediction of the spatial variations of the acoustics parameters. A low transition order should be used in cases where early reflections are few to avoid over-prediction of clarity. A higher order should be used in other cases to preserve the geometrical influences on the acoustics. A transition order of 1 was found to produce too much diffusion and is not recommended except when early reflections are very few, such as when the receiver is very close to the source. One should however be reminded once again that ODEON is intended to predict acoustics of real halls. Some of the above error characteristics, which were obtained in physical models, may be different in real halls. The validation of ODEON in real hall situations is a subject of our on-going research.

One problem with the computer modelling approach used by ODEON is that the transition order does not match what happens physically. In a real halls diffusion occurs at every reflections and there is no physical transition, in terms of a reflection order, from purely specular to completely random reflections. A different diffuse reflection calculation method, ODEON-SU, which resemble the physical situation more closely was compared. It was found that this latter approach can also produce good predictions of room acoustics without the problem of transition order, except at receiver positions where shielding effect is large. Further work is required to solve the shielding problem in this approach.

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