SOME CURRENT ISSUES IN COMPUTER MODELLING FOR ROOM ACOUSTIC DESIGN

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ABSTRACT: This paper deals with several aspects of the application of computer modelling in room acoustic design in order to promote understanding of this design tool. The first section of the paper describes the results of the three international round robin tests of the validity and limitations of current computer modelling techniques. The second and last sections are concerned with the validity of computer modelling and auralization for the prediction of the acoustic quality of two concert halls in Australia. The importance of assigning suitable values of diffusion coefficients to obtain reliable prediction results, and the validation of computer generated auralizations compared with real recorded music in actual halls, are also investigated.

1. INTRODUCTION

Room acoustic computer modelling has developed greatly since the first trial by Krokstad et al. [1] and has been widely adopted in both research and consulting work. Despite several advantages of computer models over physical models, such as being flexible and cost and time effective, there are some problems with current computer modelling techniques and the selection of suitable input values for these models. These result in unreliable predictions which have been reported in international verification tests [2, 3, 4]. Another issue concerning computer modelling is the validation of auralization techniques. If the prediction results of computer models compared with measurements are within the subjective difference limen, then auralization is likely to be a reliable prediction tool for determining the acoustic quality of a room. Therefore, the validation of computer generated sounds compared with real recorded sounds in actual halls is important for the assessment of current auralization techniques. Such an assessment does not appear to have been carried out previously.

This paper deals with several aspects of current computer modelling techniques in room acoustic design and presents a guide to the software users on how to achieve reliable prediction results. The main issues covered in the following sections are:

- Feedback from three international round robin evaluations.
- The importance of assigning suitable diffusion coefficient values.
- The comparison of computer generated auralizations with recorded sounds.

2. THREE INTERNATIONAL ROUND ROBIN ON ROOM ACOUSTICAL COMPUTER MODELLING

The accuracy of various computer models has been checked, in independent verification tests, to examine their reliability and reproducibility. In this section, the testing procedure and findings of three international round robins on room acoustical computer modelling [2, 3, 4], which were undertaken by the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, are briefly summarized.

The first international round robin was carried out on the PTB lecture hall (1,800 m^2, 274 seats) by sixteen participants from seven countries in 1993 - 94 [2]. Eight acoustical parameters were considered: reverberation time (T_{30}), early decay time (EDT, which is a 60 dB decay time extrapolated from the first 10 dB of the impulse response, corresponding to a subjective impression of reverberance); strength (G, which compares the sound pressure level of an omnidirectional source, at some distance in the room, to that of the same source at 10 m in anechoic conditions); clarity (C_{80}, which is the balance of early (<80 ms) to late (>80 ms) sound energy in the impulse response); deutlichkeit (D_{50}, also known as ' definition' , which is similar to clarity and is related to speech intelligibility); centre time (TS, the centre of gravity of the squared impulse response); and early lateral energy fractions (LF and LFC, which are ratios of lateral to omnidirectional sound energy in the first 80 ms of the impulse response). These were calculated in the 1 kHz octave band for ten different combinations of two source positions and five receiver positions. These parameters are defined in ISO 3382 [5], key aspects of which are reproduced in AS/NZS 2460 [6]. The measurements were then carried out by seven different teams for the comparison with the calculated data.

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The test was carried out in two phases. The first phase tested with the information on the room geometry data and surface material descriptions given in words, so that the participants had to estimate absorption coefficients based on their experience and skill in acoustics. After the measurements in the PTB lecture hall had been made, absorption and diffusion coefficients of the hall were estimated and distributed to the participants. In the second phase, the simulations were repeated using these estimated absorption and diffusion data.

The results showed that smaller differences between the measured and calculated data were obtained in the second phase (with estimated input data) than in the first phase (without estimated input data), but the differences were still large compared with the standard deviation of the average measurement results and with the just noticeable difference (JND) for the eight acoustical parameters. It was found that only three participants were able to give reliable prediction results that were approximately within the subjective difference limens. Some participants gave 5-6 times higher prediction errors than the subjective limens for TS, EDT and C. Further information on the averaged prediction errors relative to the subjective difference limens for the eight acoustical parameters can be seen in [2], p.692, Figure 4. The main reason for this appeared to be that diffusion effects needed to be taken into account in the simulation programs. It also appeared that the attenuation of sound at grazing incidence at the audience seats should be implemented in the simulation software if good agreement with measurements was to be achieved.

The second round robin test was carried out in the ELMIA multipurpose hall (11,000 m^2, 1,100 seats) in Jönköping, Sweden, in 1996 - 98 [3]. There were thirteen participants from nine countries in the second test. Nine acoustical parameters referred to in ISO 3382 (T_{30}, EDT, D_{50}, C_{80} TS, G, LF, LFC and IACC), were calculated in six octave bands (125 Hz - 4 kHz) for twelve different combinations of two source positions and six receiver positions. IACC is the absolute value maximum coefficient of the normalized inter-aural cross correlation function (assessed using lag times within ±1 ms, which is roughly the time difference between the arrival at the two ears of a wave from the right side or left side of the head), measured using a model of a human head [7]. Hence, IACC assesses the difference between the sound at the two ears, and has been related to aspects of auditory spatial impression. The measurements were then carried out by three teams for the comparison with the calculated data.

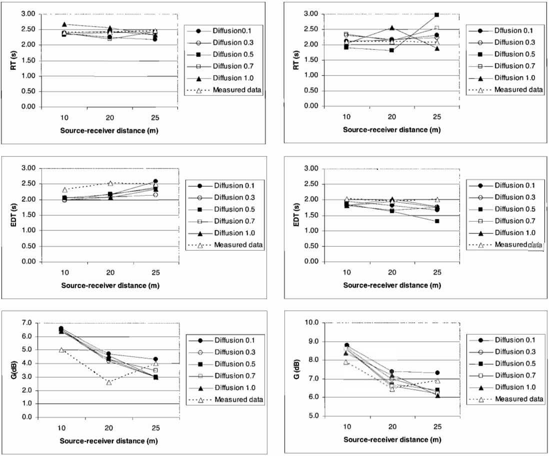
Like the first round robin, the test had two phases. The first phase of modelling was undertaken with geometrical and descriptive data for the hall (e.g. photographs, drawings and verbal descriptions of the surface materials) to examine the influence of software quality and user' s skill on the calculation results. The second phase was undertaken with given absorption and diffusion values, from the organizer, that had been estimated from room measurements, to find out to what extent the different software approaches influenced the accuracy of the calculations.

The results again showed that smaller prediction errors were obtained in the second phase (with estimated input data) than in the first phase (without estimated input data). The prediction errors were approximately 2-3 times higher than the subjective difference limens [see ref. [3], p.953, Figure 11]. One reason for this was due to measurement error as reported in [8] but the main reason was almost certainly due to the computer programs and the associated input data. Overall, the results of the second round robin were much improved on those of the first round robin, but still systemic errors due to the calculation algorithms gave unreliable predictions, especially in the 125 Hz frequency band.

The third round robin was carried out in the PTB music recording studio (400 m^2) by twenty-one participants from 14 countries in 1999 - 2002 [4]. Nine acoustical parameters (T_{30}, EDT, D_{50}, C_{80} TS, G, LF, LFC and IACC) were calculated in six octave bands (125 Hz - 4 kHz) for six combinations of two source positions and three receiver positions. The measurements were then carried out by five teams for the comparison with the calculated data.

The test was carried out in three phases. In the first phase, the studio was modelled to have seven plain walls with all geometrical data and absorption and diffusion values given (without measurement). In the second phase, the measured absorption and diffusion coefficients were given without changing the geometry. In the third phase, all design details and surface geometrical data were added into the modelling. The aim of this phase was to find out whether presenting detailed geometrical data for room modelling improves the calculations or decreases the accuracy of the model.

The calculated results of the second phase compared to the measurements for LF and IACC at source position A1 and receiver position 1 can be seen on the PTB website (**http://www.ptb.de/en/org/1/_index.htm**). Note that although the testing and analysis for the third round robin have been completed, only a few details of the results have been published in ref [4]. Therefore, the results referred to here are directly from the PTB website, where further detailed information about the third round robin can be found. The largest differences between the measured and calculated results were found in the 125 Hz frequency band (excluding one participant result which shows very high LF values compare to others). The difference between the mean measurement values and the computed values was between 10 and 20%. The differences between the calculated and mean measured values in the 500 Hz, 1 kHz and 2 kHz frequency bands were about 8% which was more than the subjective difference limen. Interestingly, the variations in the measurement results were about the same as in the calculated data. The results again demonstrated the importance of the reproducibility of measurements to the evaluation of computer models. A similar trend was obtained for the IACC calculation



(a) Hall A

(b) Hall B

Figure 1. The prediction results for RT, EDT and G at the 1 kHz frequency band as a function of diffusion coefficients in the audience area in the two halls, (a) Hall A and (b) Hall B.

results, although the differences between measured data and calculated values were smaller than those for LF. However, considering that the subjective difference limen for IACC is 0.08, the differences were still large, especially those in the 500 Hz, 1 kHz and 2 kHz frequency bands, which are critical octave bands for this measure. It was also found that well-defined room geometrical data did not improved the accuracy of the prediction results.

The limitations of current room acoustical computer models reported in the three international round robin evaluations can be summarized as follows:

- There are problems with the calculation algorithms especially when dealing with curved surfaces and diffraction effects on finite surfaces;
- The selection of suitable values of input parameters is problematic, especially diffusion coefficients for surface materials; and
- There has been no satisfactory validation of computer generated auralizations – no comparison of computer generated sounds with recorded sounds in real rooms.

3. THE INFLUENCE OF DIFFUSION COEFFICIENTS ON PREDICTIONS

Computer modelling results are strongly dependent on the selection of input parameters, in particular room surface properties. Of those input parameters the particular importance of assigning suitable values of diffusion coefficients for room surfaces, to achieve reliable prediction results, has been reported in the international round robin tests. Although there are standard measuring methods for surface diffusion coefficients devised by two different groups (the International Standards Organization (ISO) and the Audio Engineering Society (AES)), experience in the use of suitable values of diffusion coefficients in computer models is rather limited. As a result, the findings from physical model measurements, e.g. 0.1 for the smooth and plain surfaces and 0.7 for the rough surfaces such as audience areas, have been widely adopted in computer models [9].

In this section, the influence of diffusion coefficients on the prediction results is reported on. Two concert halls in Australia, referred to as Hall A (a large volume hall) and Hall B (a moderate volume hall), were used for the investigation and modelled using the Odeon V.6.0 software [10]. The 3D modelling of the two halls was based on drawings and photographs. Some simplifications for the audience seats, the ceilings and the pipe organ were made in the computer models of the two halls. The absorption coefficients were selected from the material library provided with the program. As described previously, the assumptions from physical model measurements were used for assigning the diffusion coefficients in this study. The calculations were made using 12966 rays for Hall A and 9774 rays for Hall B. The transition order (the number of reflections modeled using the image-source method, after which ray tracing is used) was set at 1 for both halls. The calculated impulse response length was 2.5 s long.

Figure 1 shows the prediction results for RT, EDT and G in the 1 kHz frequency band when different diffusion coefficients for the audience area in the two halls are used. The results at three receiver positions (10 m, 20 m and 25 m distance from the centre stage source) in the stalls in each of the two halls are presented. The variations in the prediction results depend on the hall and the seat position. Overall, larger differences are shown in Hall B than in Hall A and for the more distant seats. The variation in parameter values at a particular seat seems to be an almost random function of the audience diffusion coefficient used. This issue requires further investigation.

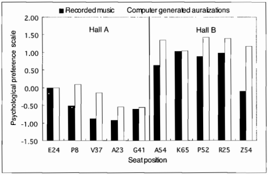


Figure 2. Average subjective preferences obtained from recorded music and computer generated auralization as a function of seat position in the two halls, Hall A (left) and Hall B (right). Note that only the results for five seat positions in each hall which are common for the auralization and recorded music evaluations are plotted.

In Hall A changing diffusion coefficients in the audience area influenced the RT and EDT prediction results. The prediction variations are greater than a subjective difference limen of 0.05 s. The predicted G values are varied within a subjective difference limen of 1.0 dB, except for one receiver position at 25 m from the source. The predicted G value at this position is higher than the others when a diffusion coefficient of 0.1 is assigned to the audience area. More significant prediction variations for RT and EDT are found for Hall B, particularly in the two receiver positions at 20 m and 25 m from the source. Assigning a diffusion coefficient of 0.1 in the audience area results in large prediction variations for G at the 25 m source-receiver distance position.

4. COMPUTER GENERATED AURALIZATIONS COMPARED WITH RECORDED SOUNDS

A recent development of the computer modelling technique is auralization. The term " auralization" can be defined as follows; "*Auralization is the process of rendering audible, by physical or mathematical modelling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modelled space*" [11]. The auralization process can be summarized in the following steps. The Room Impulse Responses (RIRs) for source and receiver positions in a room are calculated using computer simulations. The Binaural Room Impulse Responses (BRIRs) are then computed using a Head Related Transfer Function (HRTF) which is normally taken from a dummy head. Finally, the obtained BRIRs are convolved with anechoic-recorded music or speech. The auralization results are presented to the subjects via either headphones or free field reproduction using loudspeakers with crosstalk compensation [11].

Although auralization has the potential for use as a tool for room acoustic quality evaluation, the validity of the technique is still uncertain due to the limitations of computer modelling and sound reproduction. No international round robin on the comparisons of auralization systems in computer models has been carried out yet. This section reports on a partial validation of computer generated auralizations using dummy head recorded sounds in actual halls.

A subjective assessment of music excerpts was undertaken to examine whether computer auralizations give similar ratings for seats and halls as judgements based on recorded music at the same seats and halls. The recorded music samples were made at seats in the halls referred to in the previous section, Hall A and Hall B. Anechoic recorded music signals [12] were provided from a two channel recorder (ALESIS, Master link ML9600) and emitted by two loudspeakers, a ' Soundsphere' loudspeaker (Sonic systems, model 2212-1) combined with a bass loudspeaker installed with two subwoofer drivers (18 inch diameter 800W P-Audio P180/2242). The music signals obtained from a dummy head microphone (B&K head and torso simulator (HATS) type 4128C) were then digitally stored on a hard disk (ALESIS, ADAT HD24). Impulse response and other measurements (for omnidirectional, dummy head, and B-format microphones) were obtained using the same system. The computer models of the same halls were used to generate computer auralizations at the same seats using the Odeon V.6.0 software [10]. The auralization procedure in the computer models was the same as described previously. The HRTFs used for the computation of the BRIRs were those of the KEMAR dummy head (supplied with the Odeon program). Although the same type of dummy head for recorded and computer generated sounds should be used for the adequate comparison, this could not be undertaken because HRTFs from HATS was not supplied with the program used in this study.

Binaural playback techniques aim to reproduce the sound that was received at in-ear microphones near the listener’ s ears, and as such they provide a level of fidelity attractive for empirical testing. A review of these techniques and their limitations is given by Møller [13]. The most common approach, which is non-individualized binaural reproduction (i.e. not using the listener’ s HRTFs), yields localization errors, with frontal sound sources typically forming auditory images above or behind the listener in headphone reproduction. Although the present work was done using this approach, Azzali et al. [14] have recently shown that non-individualized binaural reproduction using a cross-talk compensation technique with closely spaced loudspeakers (known as ‘ stereo dipole’) yields more realistic sound imagery for auditorium simulations.

Two sets of subjective judgements based on recorded music and computer generated auralizations were carried out. Twelve seats (mainly in the stalls and circles or galleries) in each hall were selected for assessing the subjective judgements using recorded music. Not all of twelve seat positions (only five seats in each hall) were used for the subjective judgements using computer generated auralizations. Although fewer seat positions were used in the subjective judgements using computer generated auralizations, the results still could be used to examine the reliability of the computer generated auralizations for matching sets of seat positions [for more details on the experimental design of the subjective judgements see 15]. Table 1 presents the average values of the measured and calculated acoustical parameters at five common seat positions in each hall.

Table 1. Seat-averaged measured and calculated

Acoustical parameters	Averaged Values			
	Hall A		Hall B	
	Measured data	Calculated data	Measured data	Calculated data
RT (unoccupied)	2.17 s	2.09 s	2.03 s	2.29 s
EDT (unoccupied)	2.23 s	2.05 s	1.91 s	1.83 s
G	3.4 dB	3.2 dB	7.3 dB	7.0 dB
C_{80}	-2.6 dB	-1.7 dB	-0.6 dB	1.0 dB

Note: The acoustical parameters were averaged in the all frequency bands (125 Hz- 4 kHz).

The subjective judgements were obtained using a two alternative forced choice experimental design. Eight subjects aged between 20 and 40 identified which one of each pair of recordings they preferred in terms of the acoustics. The subjects were allowed to listen to the music pairs as often as they wished before giving their judgements. The music samples, 10 s of solo cello (Weber’ s Theme), were presented via a CD player (Denon DN-C630) and given over open headphones (Sennheiser HD600) in an anechoic room.

The psychological scales of overall preference, based on the subjective responses to the recorded music and computer generated auralizations in the two halls, were obtained using the method of Thurstone’ s Case V [16, 17]. Scale units of preference are standard deviations of a normally distributed probability density function. A χ^2 test of goodness of fit showed that the response matrix had significant internal consistency, meaning that the resulting ratings were significantly different to random selection [18]. The averaged preferences of the eight subjects for seat positions in the two halls are plotted in Figure 2. The preference judgements based on recorded music show that most seats in Hall B are more highly ranked in terms of their acoustics than the seats in Hall A. The preference judgements based on computer generated auralizations show similar ratings for the same seats in the two halls as for the recorded music in the same halls: the listeners had a greater preference for seats in Hall B than those in Hall A. Higher preference for seats in the two halls was obtained from computer generated auralizations than recorded music real-hall stimuli. This may be partly because of assessing more seat positions for the subjective judgements using recorded music than the judgements using computer generated sounds. The results of preference judgements made using computer auralizations are in agreement with preference judgements based on recorded music at matching seats. The low subjective ratings for seats in Hall A are in agreement with musician-assessed ratings of the actual halls [19] and even with anecdotal evidence by concert-goers in Australia.

The indirect subjective comparisons of computer generated auralizations with recorded sounds for the evaluation of the acoustics of the two halls were carried out because of the limitation of using different types of dummy head. The preference judgements based on computer generated auralizations give similar rank ordering of seats and halls as the judgements made using recorded sounds. There is evidence [21] to suggest that even though there are errors in computational techniques, it may well be possible to use such techniques to make judgements about the acoustics of concert halls.

5. CONCLUSION

With the development of computer modelling techniques, especially as a result of the feedback of three international round robin evaluations, it is now possible to use them as a tool in room acoustics design. However there are still several uncertainties associated with this technique and there is a need for any user to gain practical experience in assigning suitable input values for surface materials.

Something that the computer modelling cannot do on its own, even with auralization techniques, is to predict the overall acoustic quality of a space, unless subjective judgements are carried out. If the computer modelling is to be reliable, i.e. if it is to give good agreement with measurements or even just give the same rank ordering of subjective assessments as in actual halls modelled, then some other technique, such as neural network analysis [20], could be used in conjunction with the computer modelling to obtain predictions of concert hall acoustic quality.

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