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THE ACCURACY OF ACOUSTIC SCALE MODELLING AT 1:50 SCALE

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1 INTRODUCTION

Both acoustic scale and computer simulation modelling have reached a certain maturity. There are few recorded accounts of their accuracy in practice, though Bork has reported on a computer round robin [1]. This paper compares measured results in a full-size concert hall with the scale model of the hall tested during the design. In addition a brief account is given of some difficulties encountered with computer modelling of a different concert hall auditorium. The comments here on these two auditoria are limited to accuracy of modelling, rather than any assessment of their acoustic performance as concert halls.

2 ACOUSTIC SCALE MODELLING AND COMPUTER SIMULATION MODELLING OF AUDITORIA

Scale modelling was first investigated in the 1930s in Germany but, as a serious design aid, more objective measures than reverberation time were needed [2]. By the 1970s, objective measures were in place and testing techniques available (predominantly analogue, employing tape recorders for temporal transposition). Further understanding of how to use the objective measures made scale modelling a powerful design aid [3]. Two further developments deserve mention: the development of modelling at smaller scales such as 1:50 [4] made scale modelling more economical and easier to incorporate in a design programme. The second development was the use of digital analysis, which makes the measuring more efficient.

The above refers to using models for objective testing; subjective testing with music ‘played’ through the model has also been used on several projects. Larger scale models are generally needed for subjective testing and assessment is not trivial. For complex issues where two or more design solutions are compared, subjective testing using scale models can be valuable.

The earliest published computer simulation dates from 1968 [5] using a main-frame computer. However the basis of computer models is not waves, as with scale modelling, but rays as if sound behaved like light. Beams of various cross-section shapes have in many cases replaced rays, but introducing wave behaviour is problematic, in particular in the cases of diffusion and diffraction. Considerable progress has been made in the case of diffusion with the introduction of scattering coefficients. Diffraction is more complex but inclusion of the recent findings of Svensson *et al.* [6] in computer simulation programs is likely to be a major step forward.

Improved speed and capacity of PC computers has brought computer simulation to all consultancies and most contemporary auditorium designs are probably tested in this way. Auralisation of course allows one to listen to the acoustic character of the proposed design, though with limitations. As well as the problems found with subjective testing of scale models, there are in addition those associated with whatever limitations there might be in the computer simulation model.

Some consultancy firms currently prefer to rely on scale modelling for major auditorium projects.

3 ASSESSING MODELLING ACCURACY

The accuracy of modelling in terms of acoustic behaviour, by either scale or computer models, is rarely precise enough for it to be obvious what is the best method for quantifying that accuracy. For instance, when measurements are made at a series of receiver positions, differences at one of the positions of 2dB between the model and full-size hall for an objective measure are not uncommon. The person analysing the model results needs to ask whether this is a coincidence, a fiction produced by the modelling or a characteristic of a particular seating area. Ideally one would like to be able to determine that values are following a pattern. As an example of a pattern that one would look for, there is the behaviour of sound under balcony overhangs (first observed in scale models and then recognised in actual auditoria [7]). In particular the late sound level decreases as one moves beyond a balcony overhang.

In quantitative terms, scatter diagrams comparing model and full-size behaviour are valuable coupled with a correlation analysis. However a good correlation is a necessary but not sufficient assessment. Correlation is basically a technique for determining whether two quantities are related rather than the extent to which they are the same; correlation allows for a difference of mean and for slopes other than unity. Looking at mean differences is important but the scatter in agreement also needs to be considered. To express modelling accuracy in a single value, the rms error has much to commend it. The rms error is simply related to the mean and standard deviation of the error. The mean square error is approximately equal to the sum of the squared mean error and the variance. If x represents individual errors for n results, the mean error is $\bar{x}$ and the standard deviation of the error is σ, then

$$rms\ error = \sqrt{\Sigma x^2 / n} \approx \sqrt{\bar{x}^2 + \sigma^2}$$

The approximation is due to a term n/(n - 1), which tends to unity for large numbers of results.

When modelling the acoustics of a space, it is only when the full-size space can be tested that the accuracy of modelling can be assessed. There is often a period of several years separating testing the model for design purposes and the completion of the building. In qualitative terms, the modelling should be sufficiently accurate that the correct design decisions are taken. In other words certain inaccuracies may be acceptable, up to a threshold beyond which changes to the design might be considered. An understanding of the interplay between auditorium geometry and acoustic behaviour is very valuable here.

4 COMPUTER MODELLING OF A CONCERT HALL

The 1340-seat Thessaloniki Megaron Concert Hall in Greece opened in 2001 and has been well received. It has an auditorium volume of 16500m^3. The acoustic consultants to the client were Müller BBM, while Fleming & Barron and Theodore Timagenis were consultants to the contractors, GEK. A decision was taken that the design should be studied by computer model; this was undertaken by Fleming & Barron using a well-known computer simulation program.

The form of the hall is basically parallel-sided, tapering slightly in plan at both ends. The ceiling is made of segments that rise in level from the stage end to the rear of the seating. Seating is divided into stalls, a balcony opposite the stage and two rows of boxes along the side walls, Figure 1. Two problems arose with the computer simulation modelling.

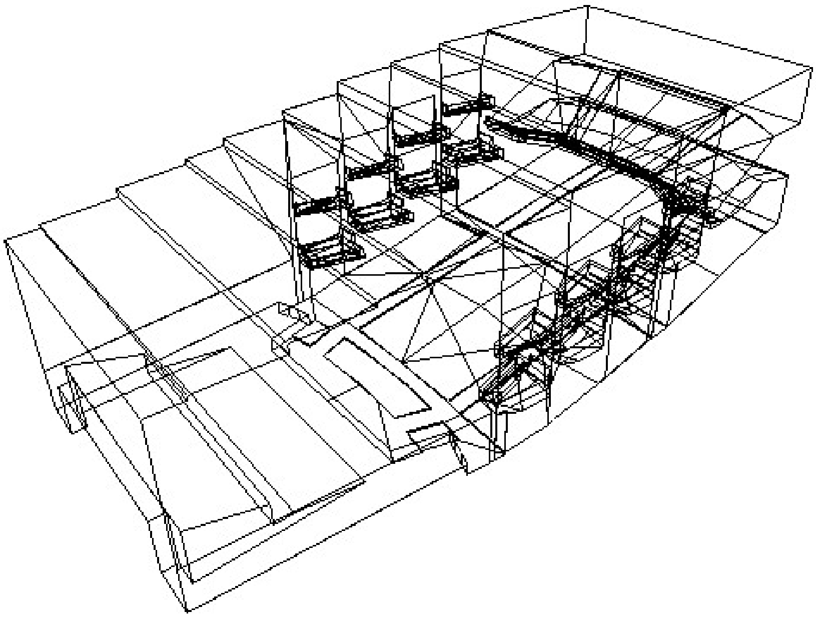

Figure 1. Computer model wire diagram of the Thessaloniki Megaron Concert Hall

The first problem concerned modelling the ceiling, which contains downstand elements running across the hall, Figure 2. The downstands when viewed from the stage end are 200mm deep, whereas they have a range of depths when viewed from the rear of the hall. Behaviour at high frequency of these elements will be different to that at low frequencies. One is advised in a computer model not to include too much detail in the acoustic model, but it is difficult to know how to respond to this advice. How should one simplify this geometry? Perhaps a different geometrical model is appropriate for low and high frequencies. If this were done, what would the appropriate transition frequency be? If the downstand elements were removed for the low frequency computer model, what scattering coefficient would be appropriate for the ceiling?

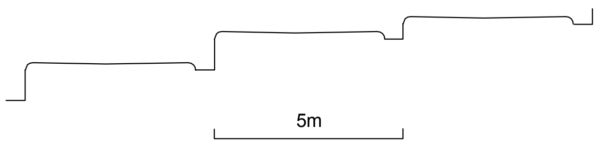

Figure 2. A segment of the ceiling line as viewed on a long section. The stage is on the left.

The second problem concerned predicted results that emerged from the modelling. Some very low values of around –6dB for the early-to-late index (C_{80}) were predicted for the balcony seating (opposite the stage). Rather than present results in terms of C_{80}, it is more valuable to divide the received sound into early (pre-80ms) and late (post-80ms) components [8]. These two components are derived from the ratio between them, C_{80}, and the sum, the total sound level, G, also known as the Strength.

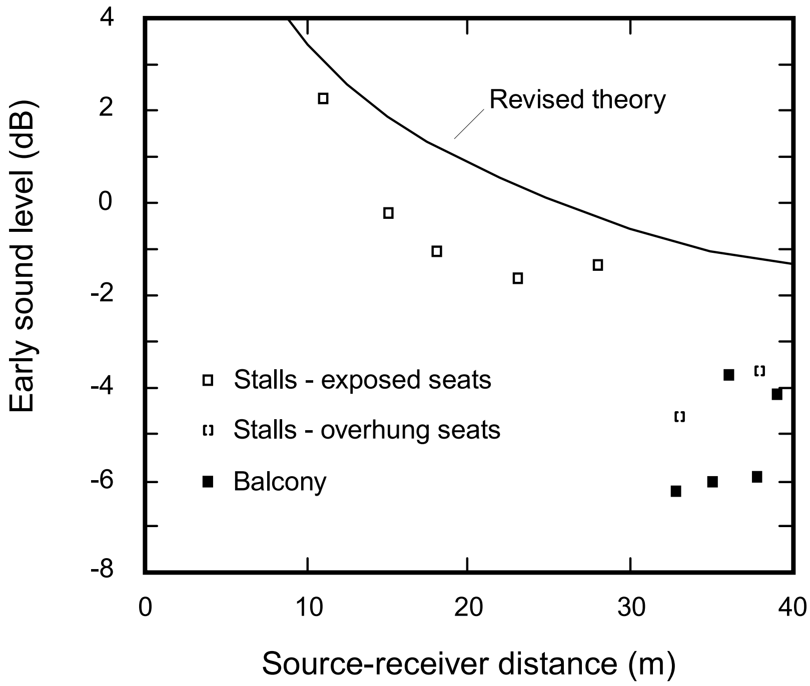

Figure 3. Predicted values by computer program for the early sound as a function of source-receiver distance for the Thessaloniki Concert Hall

Figure 3 shows the values of the early sound predicted at mid-frequencies (500 - 2000Hz) in the Thessaloniki Concert Hall. When interpreting these figures, it is the magnitude of the divergences that are important (auto-scaling of the y-axis can conceal their significance). Comparisons of measured values can be made either with absolute criteria or with expectations for instance taken from revised theory which is based on reverberation time and source-receiver distance [8]. In Figure 3 one sees particularly low values for the early sound in some balcony locations. The lowest values were in the front and centre of the Balcony; higher values were measured near the side wall away from the balcony front. Minimum measured values of the early level for the 'quietest' British halls are listed in Table 1 for comparison with the Thessaloniki Hall predicted result.

Table 1. Minimum measured values of early level in halls.

Concert Hall	**Minimum early level (dB)**
Thessaloniki Concert Hall predicted	*-6.2*
Royal Albert Hall, London	-6.1
Barbican Concert Hall, London	-4.1
St. David's Hall, Cardiff	-4.0
Fairfield Hall, Croydon	-3.5
Royal Festival Hall, London	-3.3

The Royal Albert Hall is of course an extreme hall with low sound levels because of the large seat capacity. These values for the early sound were clearly unacceptable, since as already mentioned they lead to C_{80} of –6dB and G (total level) of around 1dB. The criterion for G is that values should be greater than 0dB so for this measure there is no serious problem. However in the case of C_{80} the criterion range is between -2 to +2dB [8] and these predicted values are unacceptable.

But was this prediction realistic, was the design of this concert hall so extreme that these values were expected? Comparison with results from British halls suggested that the acoustic predictions of the model might be inaccurate.

The reason for low values of early sound in the Balcony were not difficult to discover: the lower line of boxes was preventing side wall reflections reaching the Balcony. A view of the long section of the hall makes this clear since the row of boxes lie behind the line of sight from seats in the Balcony to the stage. This effect has been recorded from another rectangular auditorium with stepped side wall boxes (ref. 8, p. 81). This box arrangement along side walls is to be found in several concert halls world-wide yet this design detail has not attracted a reputation for poor acoustics.

Various simple modifications to the computer simulation model were tried, but with balcony fronts tilted down, no first order reflection can reach the Balcony via the boxes. A major parameter change within the program was necessary to produce more realistic values for the early sound in the Balcony.

Measurements have now been made in the completed Thessaloniki Concert Hall by Müller BBM. These show that the early levels in the Balcony are indeed lower than one expects from revised theory. The maximum difference however is -2.6dB rather than -4 to -5dB predicted by the computer model and in terms of 'perceived' parameters, C_{80} and G, measured values are basically within accepted criteria. We are not aware of criticisms of the acoustic quality in these seats.

What is worrying about this experience is that, if we had believed the predictions of the computer simulation model, we would have felt it necessary to make a major change to the design of the concert hall. In the event, we disbelieved the model and leaving the design as it was proved to be the appropriate response. The computer program had difficulty dealing with objects (in this case boxes) which reflected a significant amount of energy by diffusion and diffraction.

5 SOME CONSIDERATIONS RELEVANT TO OBJECTIVE MEASURES IN SCALE MODELS

5.1 Scale Model Testing and Reverberation Time

The aim of modelling is of course to reproduce full-size conditions as precisely as possible. There will always however be small inaccuracies and techniques to deal with this are required. The principal difficulty is to match full-size absorption coefficients. The major problem for computer modelling of matching scattering properties can usually be tackled in scale models by accurate geometrical scaling.

Scale models are most commonly built of varnished timber or plastic materials. These will have an absorption coefficient of around 0.06 independent of frequency; this may be slightly more than the full-size absorption by some wall surfaces, such as concrete. In an auditorium the major absorbing material is generally audience seating or audience. Accurate reproduction of chair or audience absorption is obviously important, though usually model versions will represent typical audience seating. A decision on the actual seats to be used is in any case often taken at a later stage of the design process.

All major absorbing materials should be reproduced in a scale model in order to have a correct distribution of absorbing and reflective surfaces. This distribution is likely to be more important than matching the predicted reverberation time (RT); in other words one does not want to be adding absorption to a model simply to get a better agreement for the RT.

Most room acoustic consultancy involves calculation of the reverberation time by a reverberation time formula. In the scale model the absorbing materials can be added progressively with the reverberation time being measured at each stage. By making checks on whether the reverberation time is behaving according to prediction for the model materials, the validity of the reverberation formula being used for this auditorium can be established.

Several objective quantities likely to be measured in a model are influenced by the reverberation time; these include the early decay time, the Clarity Index (C_{80}) and total sound level or Strength, G. In recent years, three independent correction methods have been proposed. Barron's proposal (ref. 9, Appendix A) for C_{80} and G is that, since average behaviour follows revised theory, divergences from it are likely to remain the same when the RT changes. This correction method takes account of reverberation times and source-receiver distance. Bradley [10] gives equations that use the reverberation time ratio alone for correction. Hidaka, Nishihara and Beranek [11] derive alternative correction formulae based on traditional theory for exponential decays. For small RT changes, these various methods are likely to give similar corrections.

This extended discussion of matching the reverberation time and correcting other measures for RT discrepancies has been given since it is central to the exercise of assessing scale modelling accuracy. Errors in scale modelling can be divided into two components: errors linked to inaccuracies in modelling the RT and errors in other measures following correction for RT. The accuracy of RT modelling is limited by the accuracy of measurement, as would normally be expressed by the standard deviation of measured reverberation time. Of the two standard methods for measuring RT [12], the integrated impulse method is clearly superior to the interrupted noise method in terms of accuracy of measurement. In scale models, the integrated impulse method can be easily implemented with spark sources [3].

5.2 Influence of Stage Conditions on Auditorium Sound Levels

Analysis of measured values of sound level in British concert halls [13] revealed that absorbing material around a stage will significantly reduce sound levels in the auditorium beyond the effects simply associated with the increase of total absorption. In other words, absorbing material near the stage is more efficient at reducing levels in the auditorium than if placed elsewhere. Prior to this it had been observed in a scale model (but not published) that adding chairs to an empty stage also reduced sound levels at audience seating. A recent measurement of sound level on two different days in Birmingham Symphony Hall [14] showed that the presence of chairs on stage has a significant effect on level.

Measurements of total sound level were made at six audience positions in Birmingham Symphony Hall on two separate days just eight days apart. On the first visit the stage was basically empty, on the second visit there were about 50 chairs and stands on stage. The levels were highly correlated (r = 0.98 with a slope of 1.04) but at mid-frequencies (500-1000Hz) there was a 1.0dB reduction in level with the chairs present.

6 SCALE MODELLING THE WATERFRONT HALL, BELFAST

The Waterfront Hall in Belfast opened in January 1997 [15, 16]. This concert hall has a total seat capacity of 2234 in a substantial volume of 30,800m^3. The architects were Robinson & McIlwaine and the acoustic consultants Sandy Brown Associates. The design is of the vineyard terrace type, with strong similarities to St. David's Hall in Cardiff [8]. The hall has a considerable volume above the seating which allows substantial space for technical equipment, giving flexibility for several different performance configurations. The acoustics of the hall were measured in July 1999.

As part of the design process, Fleming & Barron were asked in 1992 to test two 1:50 scale models of the hall. Following the first test series, several changes were made to the design to improve local acoustic conditions for the audience [3]. The second model tested (Figure 4) closely matched the hall as finally built. It is the results from this model which are used in the comparison below.

Figure 4. View of the interior of the 1:50 scale acoustic model of the Waterfront Hall, Belfast

Between the opening of the Belfast concert hall and the measurements taken two and a half years later, a modification of significance was made to the hall. A proscenium screen was introduced to allow theatrical-type events. When not in use, this screen is lifted up vertically so it sits approximately above the front of the stage, roughly above the source position used for the measurements. This screen is made of dense fabric and has had a measurable effect on the reverberation time in the hall. Since measured values discussed below have been corrected for reverberation time, this effect by itself presents no difficulty. The screen will however influence the sound field in other, unpredictable ways, though its location directly above the source will probably restrict the effects to later reflections.

The question that needs to be addressed is whether due to this proscenium screen the agreement between full-size and model measurements is improved or not. While there is a remote possibility that the screen might improve agreement, there is no logical reason why it should. It seems reasonable to assume that the comparisons quoted here might only be improved if measurements were made with the screen removed from the actual hall.

The model was built of acrylic (Perspex) with the seats accurately reproduced, both geometrically and in terms of absorption. Where appropriate, the model was flushed with nitrogen to reduce air absorption. At the time (1992), model reverberation times were measured using a multi-speed tape recorder for time transposition. Impulse responses were recorded using an 8-bit digital memory. Tests can be conducted at 1:50 scale between 125 and 1000Hz; the comparison made here will be at mid-frequencies averaged over the 500 and 1000Hz octaves. The mean reverberation time (500/1000Hz) in the model was 2.67s, compared to the value in the unoccupied actual hall of 2.12s. The model values have therefore been corrected to a reverberation time of 2.12s.

6.1 Early Decay Times Compared

The early decay time (EDT) has been measured at 16 positions in both the model and full-size hall. To account for the change in reverberation time between model and full-size hall, rather than compare EDT values, it is convenient to look at the ratio between the mean EDT and the RT. (For the mean EDT, positions overhung by balconies are omitted.) This parameter is also valuable as an indicator of the state of diffusion [17]. Indeed when the first model of the hall was tested, there was concern that the values of this parameter were too low [3]. The Mean EDT/RT values are compared in Table 2.

Table 2. Derived parameters of the early decay time compared

Measure	500Hz	1000Hz
Mean EDT/RT - model	0.91	0.98
Mean EDT/RT - full-size	0.95	0.98
St. dev. EDT/Mean EDT - model	0.10	0.10
St. dev. EDT/Mean EDT - full-size	0.10	0.11

Another derived parameter of significance for the design of halls is the scatter of EDT measured values divided by the mean EDT, that is the standard deviation of the EDT over the mean EDT. High values of parameter (greater than 0.15) indicate poor acoustic uniformity [17]. This parameter is also listed in Table 2. Agreement for both parameters between model and full-size hall is seen in the table to be very good.

6.2 Total Sound Level Comparison

The total sound level (G) and Clarity Index (C_{80}) have also been measured at 16 equivalent positions in the model and full-size hall. The mean of measured total sound level values at 500/1000Hz are compared in Figure 5. In the case of the model results the values plotted follow corrections for the reverberation time difference between model and full-size as described in section 5.1 above. There is clear agreement between model and full-size, though the model values are generally lower than the full-size ones by on average 0.9dB.

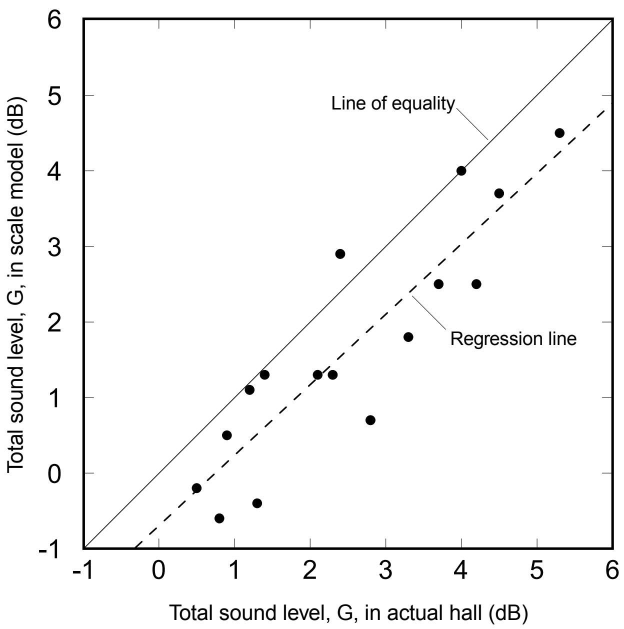

Figure 5. Measured values of total sound level, G, in the model plotted against values measured in the full-size hall.

However the measurements in the full-size hall were made on an empty stage while chairs were included on the model stage. As recorded in section 5.2, from experience elsewhere we expect a difference of this order. For a final comparison to assess the accuracy of modelling, levels will therefore be corrected before calculation of an rms error. The chosen magnitude of the correction has been selected here as 1.0dB, as measured in a full-size hall (section 5.2).

Table 3 gives the mean errors (before and after correction) and the rms error between model and full-size for various energy measures. In the case of the total sound, the rms error is 0.7dB, which compares well with a difference limen of about 1dB for this quantity.

Table 3. Measured errors in dB between full-size values and those measured in the model.

Measure	**Mean error (before correction)**	**Mean error (after correction)**	**rms error (after correction)**
Total sound level, G	0.9	-0.1	0.7
Clarity Index, C_{80}	-0.5	-	1.0
Early level	0.6	-0.4	0.9
Late level	1.2	0.2	0.8

6.3 Clarity Index Comparison

Values of the Clarity Index C_{80} averaged over 500/1000Hz are compared between model and full-size in Figure 6. In this case no correction is made for the change of condition on the stages, since both the early and late levels are affected similarly. Agreement in this case is not as good as with the total sound. The rms error in Table 3 for C_{80} is 1.0dB, again close to the difference limen [18].

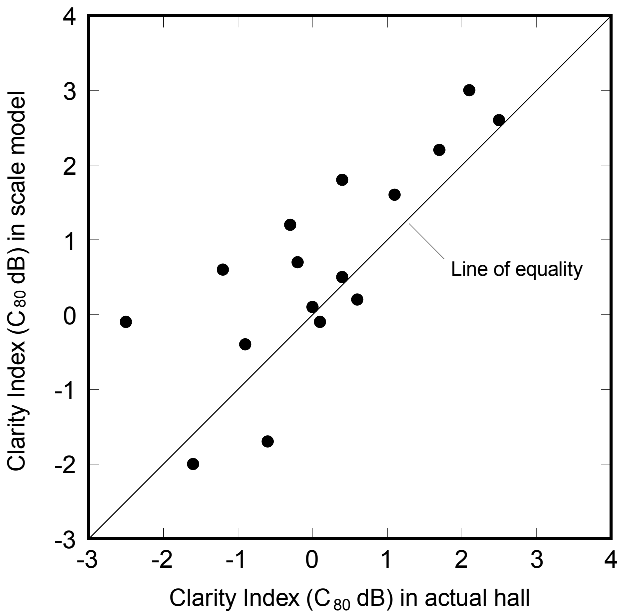

Figure 6. Measured values of Clarity Index, C_{80}, in the model plotted against values measured in the full-size hall.

6.4 Comparison of the Early and Late Levels

The early and late levels have been calculated for results in the model and hall from the Clarity Index and total sound level, as mentioned in section 4. The plots for early and late levels are similar in both cases to Figure 5. The 1dB correction is appropriate for both the early and late level, giving rms errors of 0.9 and 0.8dB (Table 3). There are no corresponding difference limen for the early and late levels but the prediction accuracy by the model was satisfactory.

7 CONCLUSIONS

Accuracy of modelling can be assessed either qualitatively or quantitatively. An example was given in which, following a computer simulation exercise, a design change might have been made to the hall, if the predictions of the modelling had been believed. With the concert hall now built, it is clear that this design change, which was not implemented, was not necessary.

For the case of a 1:50 scale model, comparisons were made between model and full-size measurements of early decay time, total sound level, clarity index as well as the derived early and late levels. Each of these measures is influenced by reverberation time and the accuracy of modelling was assessed following corrections to take account of reverberation time differences. Using the rms error to assess modelling accuracy, the values of the errors were close to subjective difference limen for each measure. For comparison with values presented by Bork [1] for computer simulation programs, the mean absolute errors are 0.8dB (C_{80}) and 0.7dB (G). Direct comparison is difficult because of choices of frequency, but scale modelling appears to be equivalent in accuracy with the best simulation programs.

In two respects, the comparison was compromised. Firstly this was due to the introduction in the full-size hall of a large absorbing screen suspended in the upper ceiling space, that was not contemplated when the model was tested six or so years earlier. Secondly, improved accuracy is now available for objective model measurements, compared with what was used in 1992 for the model measurements reported here. The main change in model measurement technique is due to using 12-bit A-D conversion with no limit on file size. This allows decays from spark signals to be measured with 50dB or more dynamic range [3], allowing reverberation time and other objective measures to be measured with an accuracy that should match full-size measurements.

The greater reliability of scale models compared with computer simulation models for predicting acoustic behaviour in rooms is appreciated by many, but the additional expense and the inconvenience of having to wait for the scale model to be built dissuades many clients from using them. There are though situations in which scale models may give false predictions. It is difficult to be confident about modelling in halls when there are a substantial number of suspended objects in the ceiling space, including such things as lighting grids, luminaires and structure. A good number of halls rely on what are intended to be acoustically transparent screens; as such they are generally not well understood at full-size and their correct modelling is less well understood, other than of course simply scaling them geometrically.

While complex arrays of suspended elements may present difficulties for scale modelling, there is no reliable guidance available to deal with such features with current computer simulation models.

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