THOUGHTS ON THE ROOM ACOUSTIC ENIGMA: THE STATE OF DIFFUSION

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1 INTRODUCTION

A diffuse sound field is a reference point in room acoustics. Yet defining what is meant by diffuse is problematic. Schultz [1] makes the analogy between defining humour and diffusion: we know what they mean but cannot express them in words. A commonly heard definition is "that in a steady state diffuse sound field there is equal probability of energy flow in all directions and random angle of incidence of energy upon the boundaries of the room" [2]. As Schultz mentions, a definition such as this is probably adequate from a conceptual standpoint, but offers no help from an operational point of view. We cannot measure the quantities contained in the definition.

In the derivation of most reverberation time formulae, it is necessary to assume diffuse sound fields. But in practice few spaces in fact have fully diffuse fields. The only spaces, in which diffuse conditions are sought and in which test results depend on the state of diffusion, are reverberation chambers. Reverberation chambers are however unusual since for their size they contain little sound absorbing material.

The issue of diffusion is beset by questions: how do we measure it? How important is it in certain spaces, such as auditoria? Can one have too much diffusion in a concert hall? How are listeners aware in auditoria of the state of diffusion?

A traditional technique for assessing the degree of diffusion has been to consider the correlation of the sound between two microphones over a range of separations between the microphones [3]. This however is a tedious measurement to implement and has only been applied in laboratory studies [4, 5].

This paper explores the question of how suitable for indicating the degree of diffusion is a measure that is related to reverberation time measurements. Since this study was made in the absence of other measurements relating to the degree of diffusion, we are required to base our assessment on assumptions about diffusion in different spaces.

2 THE STANDARD DEVIATION OF MEASURED REVERBERATION TIME

Davy and colleagues [6, 7] have proposed theoretical equations for the scatter of measured reverberation time. For the traditional interrupted noise method for measuring reverberation time, the variance consists of two basic terms, one associated with the ensemble average of n measurements and the other with spatial variation. When using the integrated impulse method to measure reverberation time, it has been proposed that n be made equal to 10. This allows the formula to be stated in simple terms, with a constant depending on the dynamic range used to extract the reverberation time. For reverberation times based on 20 and 30dB decays:

$$\text{Standard deviation, } \sigma(T_{20}) = 0.96\sqrt{\frac{T_{20}}{B}} \qquad \text{and } \sigma(T_{30}) = 0.59\sqrt{\frac{T_{30}}{B}} \tag{1}$$

As regards the bandwidth, B, Davy and Dunn [8] point out that the statistical rather than the effective bandwidth should be used, which in the case of 5th-order Butterworth filters requires an 11% increase. If f is the centre frequency and octave bands are used, the expressions become:

$$\sigma(T_{20}) = 1.08\sqrt{\frac{T_{20}}{f}} \qquad \text{and } \sigma(T_{30}) = 0.666\sqrt{\frac{T_{30}}{f}} \tag{2}$$

These expressions are relevant to diffuse fields and are quoted in standards (such as the new revision of ISO3382).

To test the accuracy of their formula, Davy *et al.* [6] derive a normalised standard deviation by dividing the measured by the theoretical standard deviation:

$$\text{Normalised standard deviation} = \frac{\text{Measured st. deviation}}{\text{Theoretical st. deviation}} \tag{3}$$

To demonstrate the accuracy of their theory, they have plotted the normalised standard deviation of reverberation time (NSDRT) for a series of reverberation chambers, as reproduced in Figure 1 here. It can be seen that on average the measured standard deviation is close to theory in these spaces, except at low frequencies. Davy [9] proceeded to derive corrections for low frequencies, on the basis that the scatter increases with the lower numbers of modes found at low frequencies.

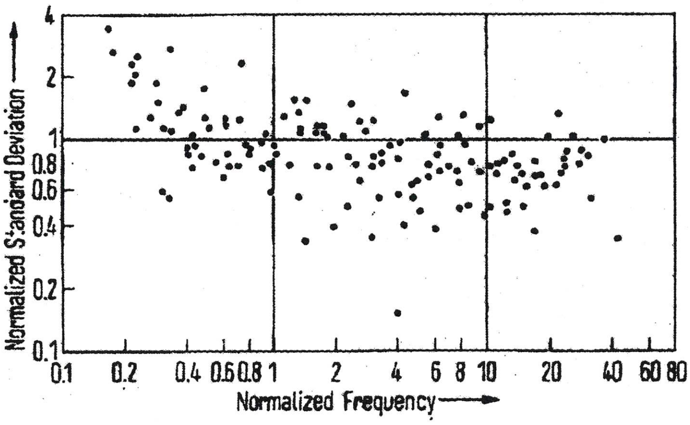

Figure 1. Measured values of the normalised standard deviation of reverberation time in four reverberation chambers. Third-octave centre frequencies have been normalised to multiples of the Schroeder frequency (after Davy [6])

In the following, the normalised standard deviation will be presented for a series of model and a few real spaces. NSDRT values close to unity are assumed to indicate a diffuse sound field, while values significantly greater than one are assumed to indicate poor diffusion. In section 6 this hypothesis will be assessed.

3 MODEL STUDIES IN "DIFFUSE" SPACES

A study of sound behaviour in model diffuse spaces was recently completed [10]. The background to the study concerned sound level behaviour as a function of distance from the source. Measurements in concert halls had shown that, whereas tradition theory of sound level behaviour predicts a constant reflected sound level throughout a space, in practice sound levels decrease for positions further from the source [11]. On average a linear relationship of reflected sound level vs. distance was found to conform to a simple theory, called simply "revised theory". Auditoria are not obviously diffuse spaces, since absorption is concentrated on the floor. The purpose of the model study was to discover whether sound levels behaved according to revised theory in diffuse spaces.

Reverberation chambers are diffuse spaces but, due to the low average absorption coefficient of the wall surfaces, the difference between levels predicted by traditional and revised theory is very small. For these model studies it was necessary to have a higher average absorption coefficient of around $\alpha_{mean} = 0.3$, in order to demonstrate a clear "revised theory effect".

Two models were constructed, which were expected to provide diffuse sound fields. Model 1 had plane surfaces but one from each pair of opposite walls was inclined at 5°. Square patches of absorbing material were distributed on all wall surfaces, Figure 2. Model 2 was rectangular but surfaces consisted of hemispherical diffusers and strips of absorber over an air space, Figure 3.

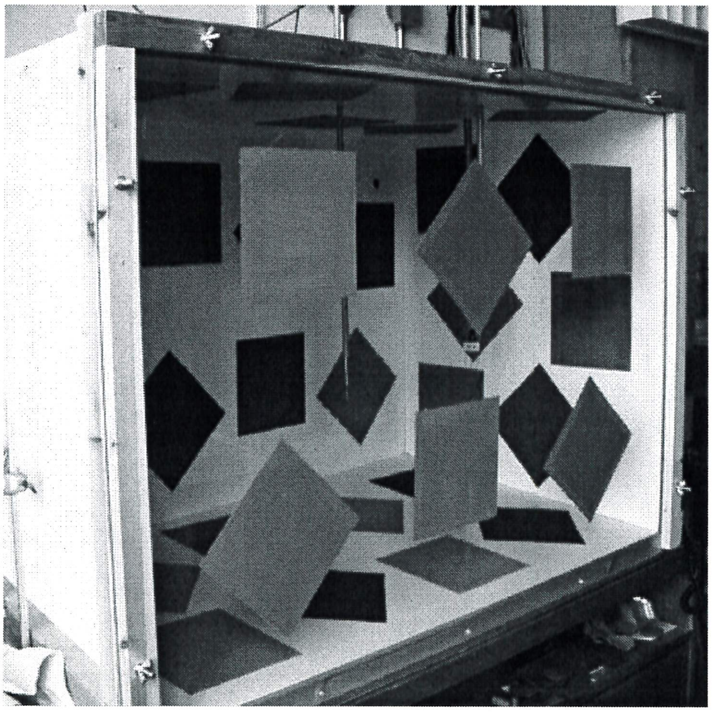

Figure 2. View of Model 1, the front surface is transparent acrylic. Brown squares are absorbent fabric.

Reference [12] contains more extensive details on the modelling process. The chosen frequency range for measurement was limited at high frequencies by the directivity of the microphones used; Brüel & Kjaer $^1/_8$ in microphones become directional above about 16kHz. The sound source used for the experiments was a spark source. Spark sources have a maximum output at a high frequency determined by the electrical energy in the discharge, below this frequency their output drops off at about 9dB/octave. A spark source with maximum output close to 16kHz was constructed. The lowest frequency was chosen so that there was still 25dB of decay available for analysis. The final test frequency range covered two full octaves of 4.4 – 18kHz.

Assigning a scale factor for these models is arbitrary. A scale factor of 1:25 was chosen, which implied a measurement range at full-size of the 250 and 500Hz octaves. The model dimensions were up to 1.2m and their equivalent volumes at full-size were 9,800 and 9,500m^3. Measured impulse responses were compensated for excess air absorption during the signal processing.

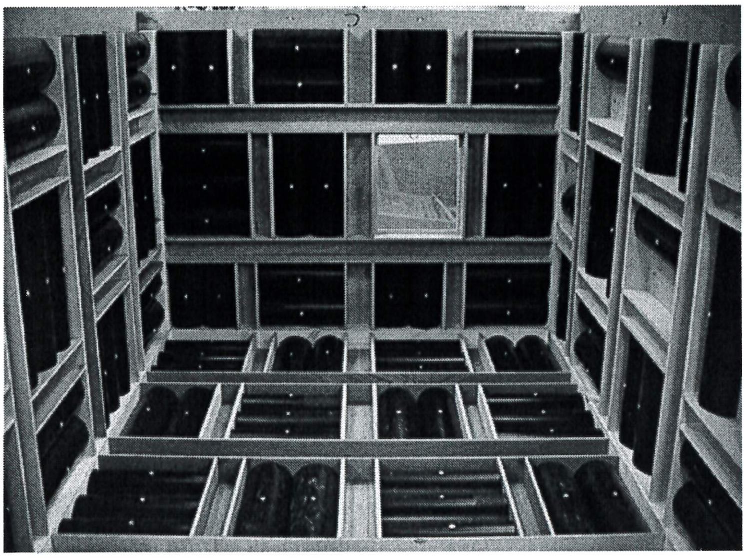

Figure 3. Internal view of Model 2. The channels between areas of hemicylinders were subsequently covered with absorbing fabric to become broadband absorbers.

3.1 Standard deviation of reverberation time in model "diffuse" spaces

In the case of Model 1, measurements were made at several points while the absorbent patches were being added. For this model without any absorption added, the reverberation time at full-size was 16.5 seconds. The normalised standard deviation of reverberation time (NSDRT) in this configuration was 1.68 (in this case only a measurement for the 250Hz octave was possible). It therefore appears that an empty space with no parallel walls has a larger scatter than that predicted for a diffuse space. Adding absorbing patches produced lower NSDRT values, though with all patches in place the NSDRT is still around 1.6.

The measured values of NSDRT in the completed models are plotted in Figure 4. In the case of Model 2, the values are just below unity, suggesting satisfactory diffusion. A simple experiment was conducted in Model 1 by suspending 16 plane surfaces throughout the space, Figure 4. This had the effect of reducing the standard deviation of reverberation time, giving NSDRT values similar to those for Model 2.

It is worth commenting on the effect of the plane diffusers on sound level in the model. One of the main issues addressed in the study [11] was the scatter of sound level measurements about the trend line, measured as a standard error of the reflected sound level when plotted against source-receiver distance. To our surprise, the standard error of the reflected sound level was unaffected by having the diffusers in place. This suggests that reverberation time is more sensitive to the state of diffusion than is sound level.

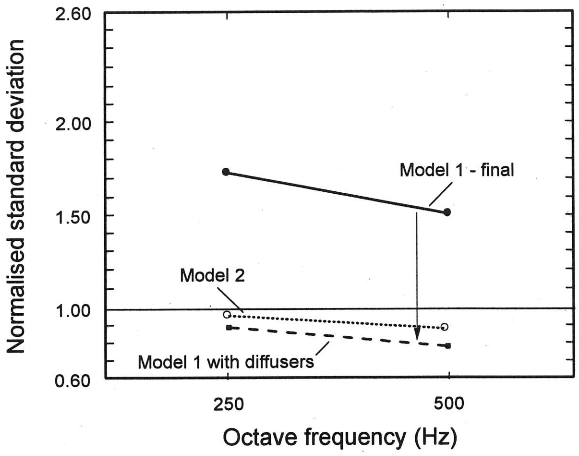

Figure 4. Measured values of the normalised standard deviation of reverberation time in Models 1 and 2. Frequencies are full-size equivalents.

4 MEASUREMENTS IN A MODEL OF A RECTANGULAR CONCERT HALL

A model of a rectangular concert hall was constructed at a scale of 1:25. Figure 5 shows an internal view, but for the tests reported here the balcony in that view was not in place. The internal

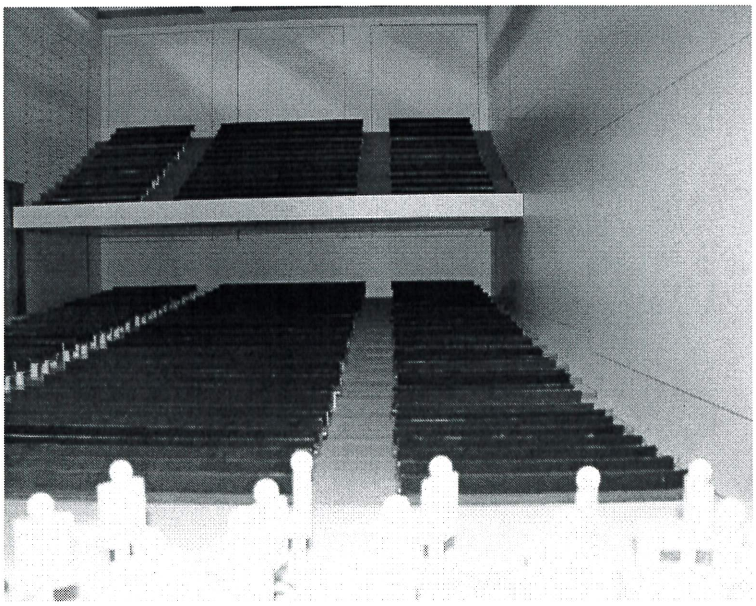

Figure 5. View of concert hall model with plane walls. For the tests reported here, the balcony was not in place.

dimensions of the model were length 45m, width 22m and height 18.2m, giving an internal volume of 18,000m^3. The model included a raised stage containing a model orchestra and correctly modelled seating on a raked floor. A single source position was used on stage.

The walls and ceiling contained removable panels so that tests could be made with scattering or plane walls and ceiling. Suitable scattering profiles were selected guided by the results of Jeon *et al.* [13]. A surface with 50% of the area covered with hemispheres of radius 20mm provides an average scattering coefficient of approximately 0.7 at and above the 250Hz octave (full-size). Equivalent surfaces using horizontal or vertical battens (linear scatterers) were also constructed. Figure 6 shows these panels mounted on the walls of the model.

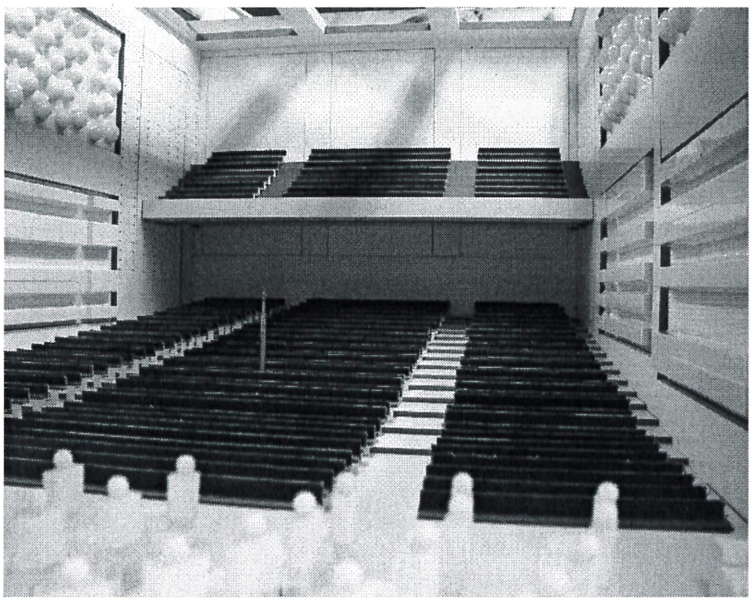

Figure 6. View of concert hall model with scattering panels. For the tests reported here, the balcony was not in place.

A series of six configurations with different amounts and locations of scattering panels was tested, as listed in Table 1. In the case of configuration B, both hemispherical and linear scatterers were used. For configurations C – F, 13 panels with hemispherical scatterers were placed in different locations.

Table 1. Location of scattering surfaces in configurations A – F.

Configuration	Location of scattering panels	Percentage of scattering wall/ceiling surface
A	All surfaces plane	0%
B	All surfaces scattering, using mixed scattering	54%
C	Front wall and front of side walls and ceiling scattering	18%
D	Rear wall and front of side walls and ceiling scattering	18%
E	Ceiling only scattering	18%
F	Side walls scattering	18%

4.1 Standard deviation of reverberation time in the concert hall model

The measured values of NSDRT in the model are plotted in Figure 7. Comparing first of all the extreme scattering conditions, configurations A and B, low values occur for both configurations at 125Hz, while at mid-frequencies the NSDRT is very high for the model with plane surfaces and below unity for configuration B with scattering surfaces on all walls and the ceiling. This result is expected, while some results for the other configurations were not all as predicted. The NSDRT in configurations B, D and F increases at 2kHz relative to values at lower frequencies; this is similar to behaviour found in real concert halls, as described below.

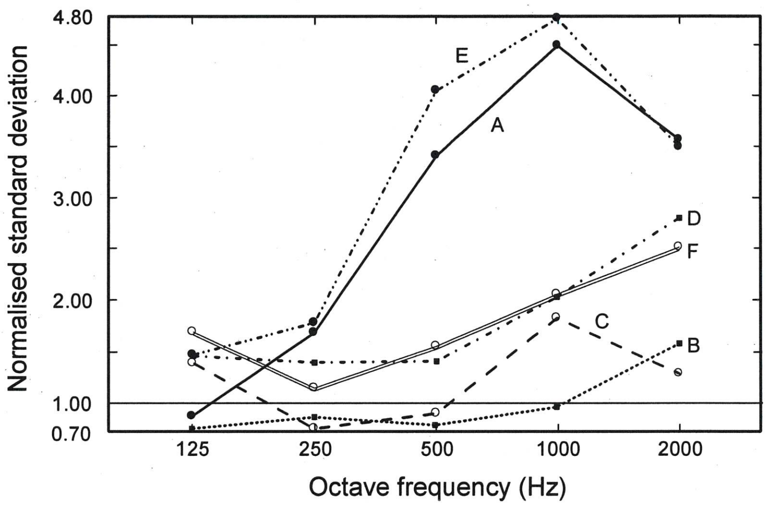

Figure 7. Normalised standard deviations of reverberation time in different configurations of the rectangular concert hall model.

If only some surfaces are to contain scattering, the most efficient location for scattering surfaces to creating diffuse conditions is from Figure 7 at the front of the hall, that is around the performing platform, configuration C. One could argue that in this case the sound is scattered from the earliest reflections.

Configurations D and F behave very similarly to each other with regard to the NSDRT; these configurations have scattering at the rear of the auditorium and on the side walls respectively. Perhaps the greatest surprise occurs when scattering surfaces are limited to the ceiling, configuration E. In this case, the scattering surfaces contribute nothing towards reducing the scatter of reverberation time.

The behaviour shown in Figure 7 suggests the nature of the sound field in configuration A when all the internal surfaces, other than the floor, are plane. It appears that a horizontal sound field is established, which because it is remote from the floor has a longer reverberation time. Figure 8 shows a decay for configuration A that is initially sagging and then after about a second it takes on a slow linear decay. In configuration B the decay is basically linear throughout. The high NSDRT for configuration E with scattering on the ceiling probably occurs because the horizontal field which dominates in later periods is independent of both the floor and the ceiling.

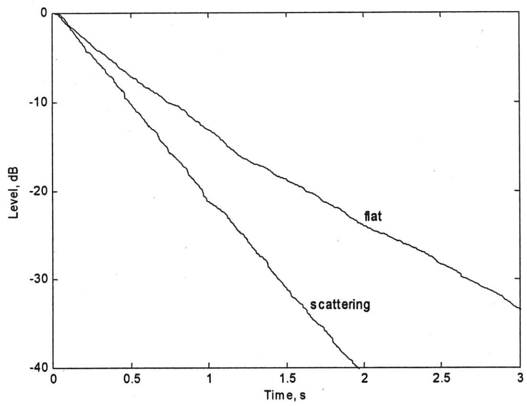

Figure 8. Measured decays in the concert hall model in Configurations A (flat) and B (scattering)

5 REAL CONCERT HALLS

Analysis of measured reverberation times in three recent British concert halls presents further interesting results. The three halls are Birmingham Symphony Hall (1991, 2210 seats), Bridgewater Hall, Manchester (1996, 2400 seats) and the Waterfront Hall, Belfast (1997, 2230 seats). NSDRT values are plotted in Figure 9.

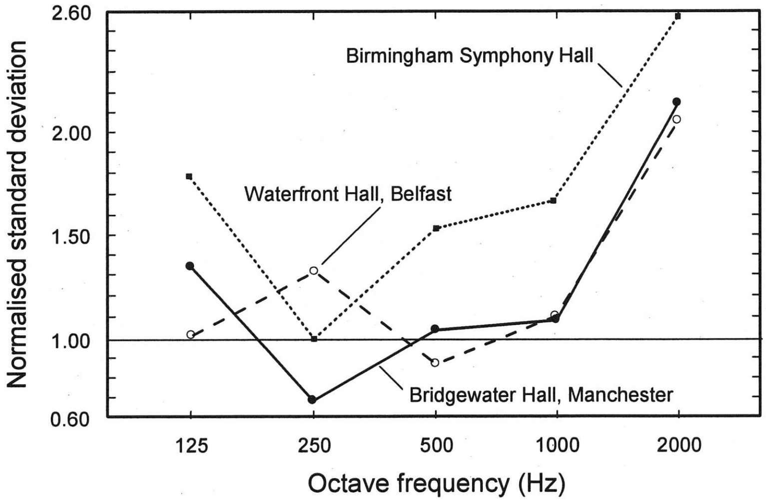

Figure 9. Measured normalised standard deviations of reverberation times in three concert halls.

One observes in Figure 9 that the low frequency (125 and 250Hz) behaviour is rather mixed, while at 500 and 1000Hz the normalised standard deviation is close to unity in the Manchester and Belfast halls, whereas the value in the Birmingham hall is higher. This behaviour may be as expected, the Belfast hall follows a terraced plan, and one would expect this to be more diffuse than the rectangular Birmingham Hall. The Manchester hall is parallel-sided at the stage end and terraced at the rear; in this case behaviour seems closer to the terraced plan hall in Belfast. From inspection of results for other auditoria, this simple subdivision between parallel-sided and terraced plan halls may not in general be as clear-cut as it appears here.

At 2kHz the normalised standard deviation consistently increases over the 1kHz values. This has also been observed for other data. If this is evidence of less diffusion at high frequencies, the reason for it is not obvious.

6 THE VALUE OF THE NORMALISED STANDARD DEVIATION OF REVERBERATION TIME

In the 'diffuse' scale models, the normalised standard deviation of reverberation time suggests that Model 1 with plane but non-parallel surfaces is not fully diffuse, whereas Model 2 with scatterers on the internal surfaces does have a diffuse sound field.

In the concert hall model, diffuse conditions are again apparent when all surfaces other the floor contain scattering surfaces. In this case, making only the ceiling scattering has no effect on the scatter of reverberation time. In this space it appears that, with plane walls, a horizontal sound field remote from seating becomes established. This may be a common characteristic of rectangular halls, unless efforts are made to scatter sound vertically to break up this dominant horizontal field.

As has been mentioned in section 3, the main thrust of the model studies was to investigate sound level behaviour in spaces. From Figure 7, one concludes that if modest amounts of scattering surface are to be applied, then placing scattering surfaces around the stage (configuration C) is the optimum location. Figure 10 shows sound level behaviour in four of the six configurations. Configuration C has as undesirable drop in level in the 10-15m range from the source. A high degree of diffusion is clearly not the only aspect to consider in concert hall design.

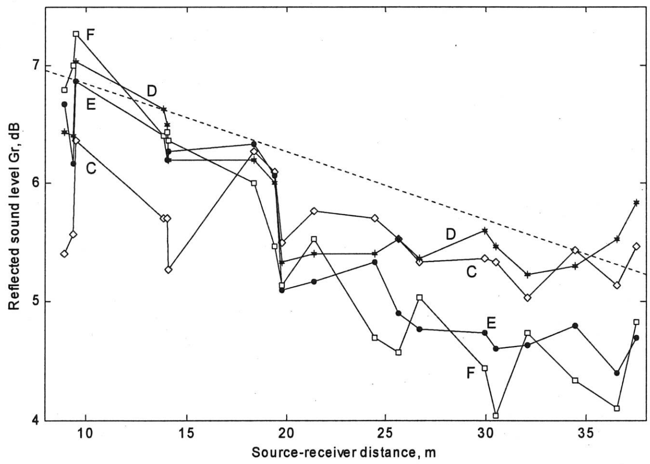

Figure 10. Measured sound levels for configurations C – F of the concert hall model.

In the case of real concert halls, there are several questions relating to variation with frequency which do not have obvious answers, particularly the high values for the normalised standard deviation of reverberation time at 2kHz. At mid-frequencies, on the basis of just three halls the state of diffusion in terraced halls is higher than in a rectangular hall.

On the question of how reliable is the normalised standard deviation of reverberation time as an indicator of the state of diffusion, several examples here suggest that it may be a useful measure. But there may also be exceptions to this hypothesis, which have not been tested here.

The normalised standard deviation of reverberation time looks to be a worthwhile parameter to calculate, particularly since it requires no new measurements (though may require measuring at more positions than one otherwise might). In scale models, it is always possible to add suspended diffusing panels to demonstrate whether full diffusion has been reached or not. One criticism of the normalised standard deviation of reverberation time is that, as a measure, it is completely independent of directions in the sound field, which is the prime consideration in the definition of diffuse sound field.

7 ACKNOWLEDGEMENTS

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