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OBJECTIVE SURVEY OF UK CONCERT HALLS

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INTRODUCTION

Research during the last 30 years has indicated a series of objective measures which appear to relate to subjective response in concert hall listening [1]. In addition to the ubiquitous reverberation time (R.T.), the following appear likely contenders: ratio of early to late energy, centre time, early decay time, early lateral energy fraction or early cross-correlation coefficient and total sound level. However measured values of these qualities are few and virtually no information is available which indicates the link between auditorium design and the behaviour of these new measures. This absence prompted the extensive measurement exercise in 41 British auditoria of all types. This paper will discuss the results of measurements in concert halls only. It will also limit itself to omni-directional measurements.

The majority of these new objective measures are based on energy measurement. A convenient subdivision which is significant both subjectively and objectively is temporally between an early and a late sound component. The sum and difference of these components are measured in the total sound level and the ratio of early to late energy. The discussion below suggests an improvement in the traditional prediction techniques for these two measures based on a simple but realistic model of sound decay in a space.

Prediction of an objective acoustic measure is though an academic exercise unless it can be used to predict subjective response. The analysis discussed here indicates certain design details which cause objective deviations from the mean behaviour. Examples of some individual halls are discussed, with reference to subjective responses during our parallel subjective survey.

Extensive objective measurements have been made in 17 concert spaces in Britain. The measurements used omni-directional sources and receivers at on average ten seating positions. Both impulse measurements and steady state measurements with a calibrated source were undertaken [2]. Data has been processed in the five octaves between 125Hz and 2kHz. For the majority of the following discussion the mean of the mid-frequency octave results will be considered (500-2kHz) and results of measurement locations below balcony overhangs are omitted.

For this discussion the impulse response is divided into three components: the direct sound, the early sound before 80 ms after the direct sound, and the late (reverberant) sound after 80ms. The latter two components can also be combined as the reflected component.

TOTAL SOUND LEVEL

The traditional theory for predicting total sound level in a space subdivides the sound into a direct and a reflected component. The direct component is presumed to behave according to an inverse square law; measurements in auditoria [3] indicate that this is valid and that excess attenuation due to propagation over audience seating is minimal at mid-frequencies. The traditional theory predicts the reflected sound component as being constant throughout the space. Measured values in auditoria of the reflected sound level (=total - theoretical direct) are not, however, independent of position. In all halls it is found that the reflected sound level decreases with increasing distance from the source and in the majority of halls the level vs. distance relationship is a linear one. The mean decrease with distance is 1dB per 10m linear distance. When coupled with the variation in direct sound level, the total level change in a large hall between 10 and 40m from the source is typically 4.5dB. A difference of this order is almost certainly significant subjectively.

As well as the behaviour within halls, the mean measured reflected sound level in each hall can be compared with the traditional theoretical value (= 10 log 4W/A, where W is the sound power and A the total acoustic absorption). These mean measured and theoretical values for the 17 halls are plotted in Figure 1. The slope of the regression line is very close to unity but there is a discrepancy of 2dB between mean measurement and theory. This result, when combined with the previous one of a level decrease with distance of 1dB per 10m, leads to the extrapolation that the measured reflected sound level agrees with theory at zero source-receiver distance.

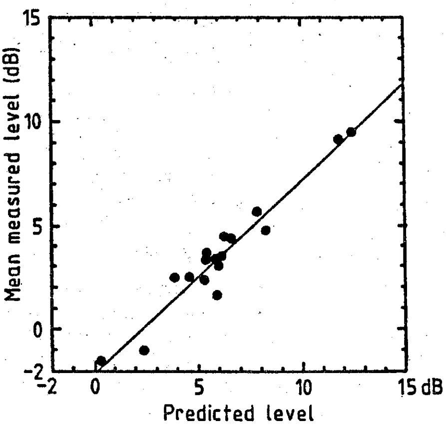

Figure 1. Mean measured total sound levels in 17 concert halls compared with traditional prediction.

A further conclusion from Figure 1 is that design aspects other than the total acoustic absorption (i.e. in general, the absorption by the audience) have little effect on the mean reflected sound level.

A SIMPLE THEORETICAL MODEL

This divergence from the traditional theory for total sound level can be accommodated by a simple model. This simple model is based on consideration of the decay trace at difference receiver positions. Indeed this consideration makes it difficult to account for the prediction of the traditional theory! It is assumed that the sound arriving at a listener is composed of a direct component and an exponentially decaying component. The instantaneous level at late time throughout the space is assumed uniform. The late decay traces at all seats are thus superimposed. However, since the exponential decay begins at a time determined by the source-receiver distance, the integrated reflected energy will be larger at receiver points close to the source. The theoretical decay traces for three receiver positions are plotted in Figure 2. The decay rate is assumed to be that corresponding to the reverberation time.

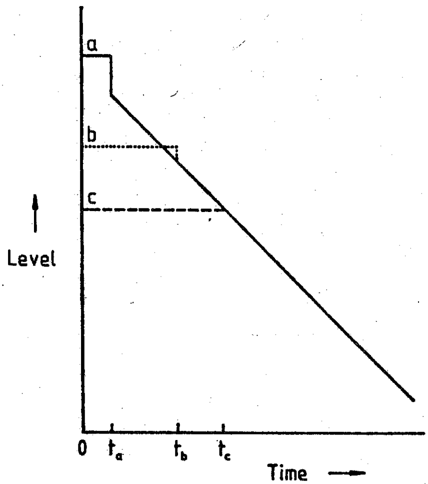

Figure 2. Theoretical decay traces at three receiver positions: a,b and c. Position a is closest to the source. Sound pulse emitted at t=0.

This simple model for the shape of the decay trace is combined with the figure for the total reflected sound level, taken as the traditional theoretical value (= 10 log 4W/A) but at zero source-receiver distance. This enables calculation of the individual components of the sound fields such as the early and late component before and after 80ms [4]. The components parts are functions of three variables: source-receiver distance, the reverberation time and the volume. This model substantially accounts for the measured behaviour of the total reflected sound level and predicts the total sound level in halls with an overall r.m.s. error of 1.0dB [4].

CLARITY INDEX (RATIO OF EARLY TO LATE ENERGY)

One of the fundamental measures in concert hall acoustics for many years has been the ratio of early to late energy. This has generally been expressed in dB. The time limit for the early energy was initially taken as 50ms, but 80 ms is now generally used for music. The traditional prediction of the ratio assumes a simple exponential decay, so that the ratio, C, is just a function of the reverberation time, T :

$$C_{th} = 10 \log (e^{1.1/T} - 1) \qquad (1)$$

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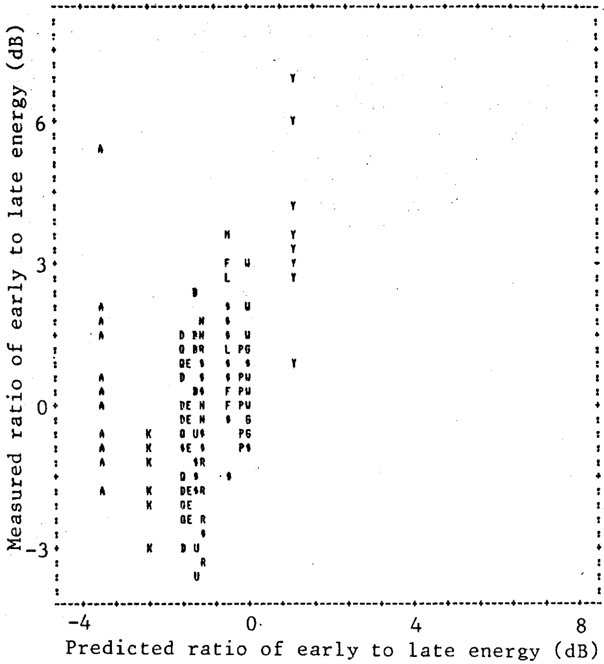


Figure 3. Measured vs. predicted ratio of early to late energy. Predicted according to R.T., equation (1).

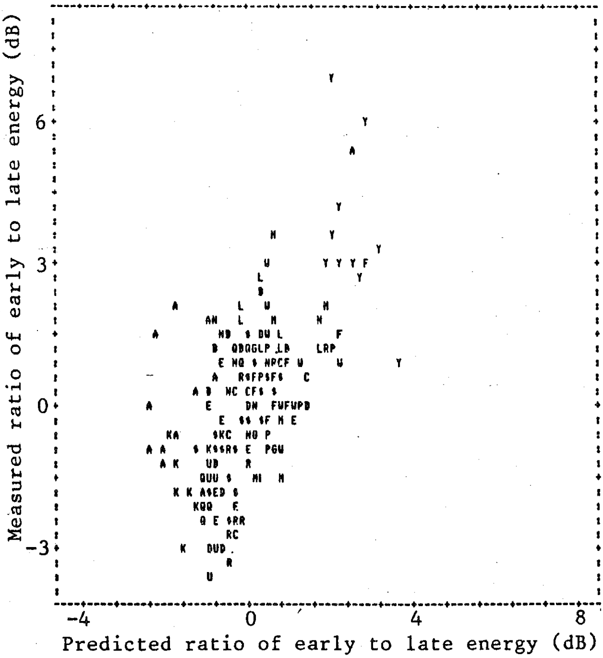


Figure 4. Measured vs. predicted ratio of early to late energy. Predicted according to revised theoretical model.

If the measured values are plotted against this theory, Figure 3, the correlation coefficient is only 0.42. If the theoretical value is based on the model described above, Figure 4, the correlation coefficient increases to 0.63. Eliminating results for five halls in which the early or late component is not linearly related to distance, and introducing elaborations of the theory for three other halls [4], the correlation coefficient increases to 0.84. The 'simple theoretical model' thus appears to be an improvement on traditional approaches. The revised theory predicts higher values for the ratio at positions closer to the source; in other words we expect higher clarity there than at the rear of the hall.

INDIVIDUAL EXAMPLES

A major value of a theory is that it provides a frame of reference against which individual examples can be compared. The first question must be, though, what are the physical characteristics of a hall, in which behaviour conforms with the theory. The first example belongs to this group.

Wessex Hall, Poole

This hall seats 1,500 audience plus 200 choir and is basically rectangular in plan. Several of its details are reminiscent of the Royal Festival Hall, though there is no free-standing reflector above the stage. The surfaces of the hall are moderately diffusing. From an objective point of view the reflected sound level decreases consistently for seats further towards the rear at a rate of 1.1dB per 10m. The ratio of early to late energy is close to theoretical predictions; at mid-frequencies it varies between -0.8 and 1.3dB, which are typical measured values.

Subjectively the hall was liked, with favourable responses on all the questionnaire scales. The acoustics were judged as uniform. Several comments were made though relating to lack of brilliance. Curiously this response did not extend to perceived lack of reverberance because the mid-frequency reverberation time (R.T.) is only 1.6s, but the low frequency R.T. is considerably higher (2.4s at 125Hz).

It seems reasonable to assume that the classical rectangular hall also behaves in line with the simple theory outlined above. Unfortunately, Britain no longer possesses a classical rectangular hall, so that we have no measurements to confirm this. (The differences between the Wessex Hall and classical halls may be limited to effects on lateral reflections due to the cross-section and balconies along the side walls.) The two halls discussed below have behaviour which deviates from the simple theory and which can be expected to produce significant differences between different sections of audience.

Fairfield Hall, Croydon

The Fairfield Hall is similar in size to the Wessex Hall, and is also rectangular in plan. It was completed 11 years after the Royal Festival Hall and its design aimed to reproduce the virtues but avoid the shortcomings of its predecessor. The novel features of the design, which were introduced one presumes for stylistic reasons, with perhaps a nod in the direction of providing diffusion, are the fins separating the boxes which rise most of the height to the ceiling and the transverse roof beams. It appears that these two features influence the objective behaviour in the hall.

For all the halls measured, the early, late and total sound level has been investigated as a function of source-receiver distance and compared with the theoretical prediction. In the case of the early sound, it is found that the decrease in early sound level with distance is greater than the theory where the ceiling is highly diffusing. In other words in halls with very diffusing ceilings the early sound tends to be deficient at the rear. We find this behaviour in the Fairfield Hall. Though the depth of the transverse roof beams is only 0.75m, which probably does not constitute highly diffusing, the fins in the side walls will act in the same way to reflect sound back to the stage rather than provide useful early reflections at the rear of the auditorium.

From a subjective standpoint, listeners judged the sound as markedly less "intimate" in the Balcony. Though there is normally a tendency for more remote seats to be judged less "intimate", this is not significant statistically. Perceptually in the Balcony one feels more remote than the actual distance from the stage.

Wembley Conference Centre

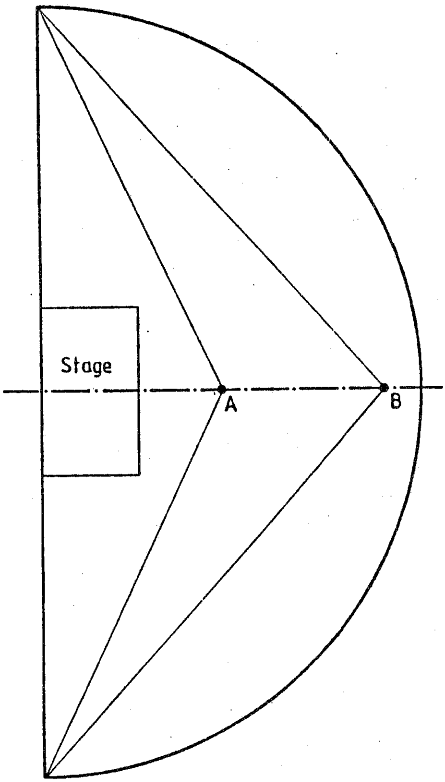
In the previous example the early reflected sound behaved differently from expectation. In the Wembley Conference Centre it is the late or reverberant sound (after 80ms) which behaves differently. The hall is large (24000m^3) with a plan which is semi-circular; the R.T. is only 1.3s. The early sound level behaves close to prediction which is rather surprising since the number of available reflecting surfaces is almost limited to the front wall and ceiling. This limited number of surfaces has a distinct effect on the late sound, which is deficient in remote seats. This effect can be partly attributed to the limited solid angle at remote seats from which reflected late sound can arrive, see Figure 5.

The consequence of this behaviour of the late sound is that the total sound is quieter than normal at distant seats. More signficantly, though, the ratio of early to late energy is very high at these remote seats so that we can expect high clarity but probably very little sense of reverberance at the rear of the hall. We have yet to sample this subjectively.

CONCLUSIONS

Traditional theory predicts the total sound level and the ratio of early to late energy on the basis of reverberation time and hall volume only. Measurements indicate that the total sound level in particular is not constant for different receiver positions. A revised theory introduces the source-receiver distance as an additional parameter. This revision allows better prediction of total sound level and the ratio of early to late energy.

Certain types of hall deviate from this revised theory. Two types of deviation have been mentioned here but there are also further deviations of interest. It is to be hoped that in this way halls can be categorised into groups. Perhaps also this may contribute to an understanding of the subjective significance of auditorium form.



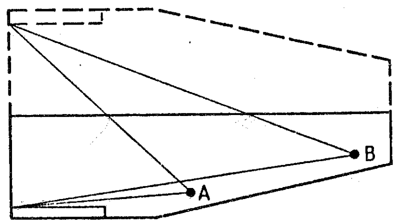


Figure 5. Plan and long section of a semi-circular hall showing angles subtended by the front wall at two receiver positions. Section shows the image of the hall in the ceiling.

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