Scattering Surfaces in Concert halls

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Abstract

For many years the question of appropriate scattering treatments in concert halls has vexed acousticians and it remains largely unresolved. Whilst subjective surveys indicate that the degree of surface relief in a concert hall is of great importance to the aural experience, there has been little research to inform contemporary designs. A new International Standard provides methods to quantify the sound dispersion by different surfaces in terms of diffusion and scattering coefficients.

This paper reviews potential applications for these different coefficients and presents the first systematic research of how varying surface relief influences the sound field in concert halls. Details are given for an acoustic physical scale model of a concert hall, with modular panels to allow changes to the surface relief. Four different types of scattering surface used in the model are described. Measurements are analysed for various configurations of the scattering surfaces. The location of scattering treatments is shown to strongly influence the sound field diffusivity and degree of back-scattering in the model.

Introduction

Traditionally, concert halls tended to be very ornate with significant surface relief that scatters sound.

Designers often attribute very favourable audience responses in some older halls to the 'diffusion' arising from this surface relief. This view has gained support from research by Haan and Fricke [1].

Beranek [2] showed that there is a rough relationship between the rank -ordering for subjective preference of 31 concert halls and the estimated surface diffusivity index (SDI), with the best liked halls having the highest SDI. However, no substantive analysis has yet been presented to support this conclusion and Fricke [3] has demonstrated many difficulties in the use of the SDI.

Despite the lack of robust research, it is commonly believed that surface relief contributes to acoustic quality, and consequently a range of modern surface profile designs have been tried in some of the more recent concert halls. For example, Benaroya Hall in Seattle has significant surface relief with a contemporary style.

Modern surface profiles have generally been designed without rigorous analysis of the influence on the reflected sound, and designs have been based largely on precedent and estimated effects.

However, over the last decade, there has been significant research effort into surface profiles and there are now both 'diffusion' and 'scattering' coefficients available to quantify the characteristics of reflected sound from a particular surface.

These objective coefficients should offer a significantly more robust approach than subjective SDI estimation.

Although the degree of surface relief can now be quantified, there has been no substantive research that capitalises on this new knowledge by assessing the effect of varied scattering/diffusion on the sound field in concert halls.

The limited research that has been conducted has focused on how scattering coefficients affect the accuracy of computer models rather than the actual changes in the sound field [4,5,6]. The current study was designed to quantify changes to the sound field in a concert hall resulting from different types of scattering surface on the walls and ceiling.

A physical scale model of a generic 'shoebox' concert hall was constructed with modular components to allow many parameters to be altered, including the surface relief.

Four different types of scattering surface were made for the concert hall model and a series of measurements was conducted with different configurations of these four surface types.

Results are analysed below for the same scattering treatment on different surfaces of the concert hall. Further analysis, not included in the current paper, has been conducted for different scattering treatments on the same surface and for combinations of scattering surfaces and balconies.

Scattering and diffusion coefficients

Acousticians are comfortably familiar with random-incidence energy absorption coefficients, and substantial databases exist of measured data.

As a single number quantity, an absorption coefficient has an easily understood physical meaning and is of great use in acoustic calculations.

To describe reflected sound patterns, acousticians have sought a similar coefficient to the absorption coefficient that has served so well. Unfortunately, the infinitely variable characteristics of reflected sound are not easily described by a single number.

There are different possibilities as to which particular reflection characteristics a coefficient should represent and perhaps inevitably acousticians have failed to produce the single coefficient so desired.

Currently, two coefficients have been proposed to describe different aspects of reflected sound: scattering and diffusion coefficients.

Scattering coefficient

When sound is reflected from a surface some energy departs in a specular direction (opposite to the incident sound) and some energy is scattered in other directions by the shape or roughness of the surface.

The scattering coefficient defined in ISO 17497-1 [7] is the proportion of reflected energy that is scattered in a non-specular direction. In older literature this quantity was often referred to as a diffusion coefficient, but thankfully there is now standardisation and consensus on the appropriate use of the terms scattering and diffusion; for the last few years the name scattering coefficient has been universally used for this quantity.

The main application of scattering coefficients is in acoustic computer models. If computer models are based solely on specular reflections then generally they predict unrealistic non-linear decays and give erroneous results.

Conversely, if all reflections are taken as completely scattered then too much energy from the first order reflections will be redirected towards the sound source in the model.

By using scattering coefficients, computer models are able to simulate an appropriate balance between specular and scattered reflections.

The scattering coefficient is a very simple quantity that does not describe the detail of a particular reflection, but as computer models are not able to simulate detailed reflection characteristics anyway, the scattering coefficient is sufficient. However, the fact that current computer models do not simulate real reflection patterns is a significant limitation.

Diffusion coefficient

A hypothetical surface that reflects all energy in a single non-specular direction would have a scattering coefficient of unity. Another hypothetical surface that dispersed all reflected energy equally in all directions would also have a scattering coefficient close to unity.

Clearly, these two reflection characteristics are very different but if a designer had specified this hypothetical surface solely on the basis of a scattering coefficient they would have no control over which of these two (or other) surfaces would be used.

To resolve this issue, an Audio Engineering Society working group (AES SC-04-02) devised the diffusion coefficient, which provides a measure of the directional uniformity of scattering. This diffusion coefficient will soon be standardised in ISO 17497-2 [8].

The diffusion coefficient should enable designers to compare and specify surface treatments.

As both scattering and diffusion coefficients are new quantities there is limited measurement data available for different surfaces. This shortage is compounded by complicated and expensive measurement procedures for both coefficients and in particular for the diffusion coefficient.

These issues are discussed in detail by Cox and D'Antonio [9]. As scattering coefficients can at least be measured at model scale, more data has been published and some of these are given below for the surfaces in this study.

Capacity	Volume	Length	Width	Height
1800 seats	18,000 m^3	45 m	22 m	18 m

Table 1 Internal dimensions of a typical shoebox concert hall

Concert hall model

A model of a generic shoebox shaped concert hall was constructed at a scale of 1:25. To avoid confusion, results and discussion below are always for the full size equivalent frequencies and distances. Nineteen rectangular concert halls, detailed by Beranek [2], were studied and the dimensions in Table 1 were established as being typical of these auditoria.

The shoebox model was based on the data in Table 1. The floor level in the model varies as the stalls seating is slightly raked. Figure 2 is a photograph of the inside of the concert hall model taken from the stage.

Orchestra members can be seen in the foreground (out of focus). At the rear of the hall an adjustable balcony is in place for this photograph, although no balcony was present during any of the measurements reported below. On the walls and ceiling of the model there are a total of twenty-five removable panels to allow different scattering treatments to be quickly interchanged between the surfaces of the model.

The scattering panels are described below. The default condition was for the panels to be flat and flush with the concert hall walls/ceiling.

The use of physical scale modelling is an established technique in room acoustics and the University of Bath has a sophisticated measurement system. The system uses spark sources, 1/8" microphones, 1/4" preamplifiers and computer acquisition.

All normal room acoustics parameters are obtained using standard reverse integration but with tail correction to extend the dynamic range available.

Measurements are made in air with numerical corrections for absorption from ISO 9613-1 [10]. To provide sufficient dynamic range over five octave bands (125 Hz to 2 kHz full-size) two spark sources were used: one for each half of the frequency range.

All results presented below are average values for the 500 Hz, 1 kHz and 2 kHz octave bands.

Scattering surfaces

There are twenty-five removable panels in the model: nine on the ceiling, five on each of the side walls, three on the stage wall and three on the rear wall. Each panel is 6 m by 12 m (full-size). There are twenty-five plain flat panels so that all of the concert hall surfaces can be smooth.

A total of twenty-four scattering panels were constructed with a variety of different surface profiles. Randomly distributed hemispheres and randomly spaced parallel rectangular battens were selected as two basic forms of scattering to be investigated in this study.

The hemispheres were chosen as they scatter sound across a wide solid angle with relatively uniform distribution. The battens were chosen as a surface that scatters sound predominantly in one axis; the battens are scattering in cross section but not long section.

Extensive measurements of the scattering coefficients of hemispheres have been conducted by Jeon et al [11].

From these results it was decided to use 20 mm radius hemispheres at coverage densities of 50% and 25%, which should have average scattering coefficients of approximately 0.7 and 0.5 respectively. Eight panels were made with hemispheres at each of these densities.

Scattering coefficients of parallel

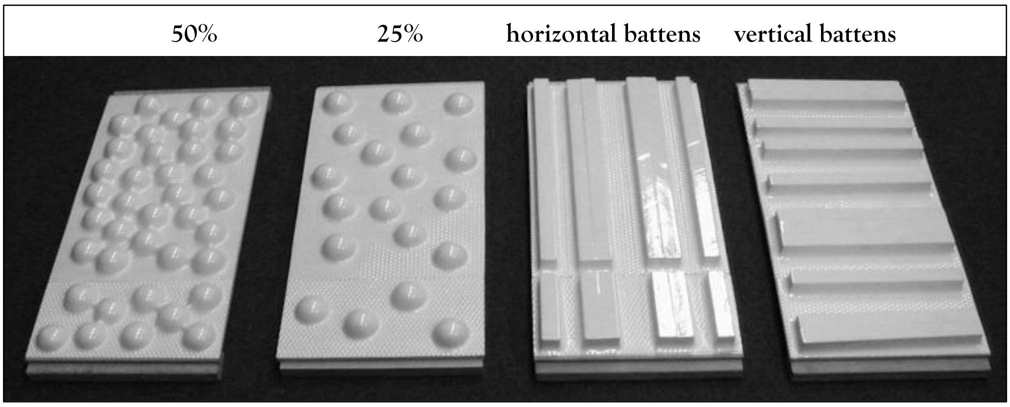

Figure 1 Photograph of the four types of scattering panels

battens were measured by Vorländer and Mommertz [12] and from these measurements it was determined that 20 mm square battens would have a scattering coefficient of approximately 0.4 across the measurement frequencies.

Four panels were made with horizontal battens and four with vertical battens. The four different types of scattering panels are shown in Figure 1. All four types of scattering treatment were 20 mm deep. The panels were mounted with a 10 mm recess so the average depth was approximately level with the main concert hall walls. Therefore there was no significant change in the concert hall volume or average width when the flat panels were replaced with scattering panels.

Figure 2 Photograph of the concert hall model with scattering panels on the side walls

Figure 2 is a photograph of the model with scattering panels on the side walls: horizontal battens in the lower positions and hemispheres at a coverage density of 50% in the upper positions.

Results

Sound decays

A key characteristic of a sound decay is the rate of decay. This is expressed by the following objective measures as the time that would be taken for the level to fall by 60 dB. In this analysis, the reverberation time (T_{20}) was evaluated over 20 dB of the decay curves from -5 dB to -25 dB.

The T_{20} was used as there was often insufficient dynamic range from the model measurements to determine the T_{30}, which is evaluated from -5 dB to -35 dB. The scatter of T_{20} values is given by the relative standard deviation of the reverberation time: $\sigma(T_{20})/T_{20}$. The rate of decay at the start of a curve is also important for subjective responses, and the early decay time (EDT) is evaluated from the slope of the initial 10 dB of the decay curve.

The first tests were for the extreme configurations of all flat panels (configuration A) and the maximum possible scattering (configuration B).

In configuration B, all twenty-four scattering panels were randomly distributed on the different surfaces, covering approximately 54% of the total wall and ceiling areas.

Reverberation times and EDTs for configurations A and B are included in Table 2.

The theoretical mid-frequency reverberation time is the same for both configurations and is approximately 3.0 s using the Sabine formula or 2.6 s using the Eyring formula.

The T_{20} measured in configuration A is higher than both the Sabine and Eyring values, whereas in configuration B, the T_{20} matches the Eyring value. In configuration B the T_{20}, EDT and relative standard deviation of reverberation time are substantially lower than in configuration A and the EDT/T_{20} ratio is significantly higher (closer to unity).

With no scattering (configuration A)

(*Continued on page 27*)

Configuration	A	B	C	D	E	F
Hemispheres	—	—	**front**	**Rear**	**ceiling**	**sides**
T_{20}	3.9 s	2.6 s	3.2 s	3.2 s	3.5 s	3.2 s
$\sigma(T_{20})/\overline{T}_{20}$	6.5%	2.3%	2.5%	3.8%	7.8%	3.8%
EDT	3.5 s	2.6 s	2.9 s	3.0 s	3.1 s	3.1 s
EDT/T_{20}	0.88	1.00	0.91	0.93	0.91	0.96

Table 2 Reverberation times and EDTs for different hemisphere locations

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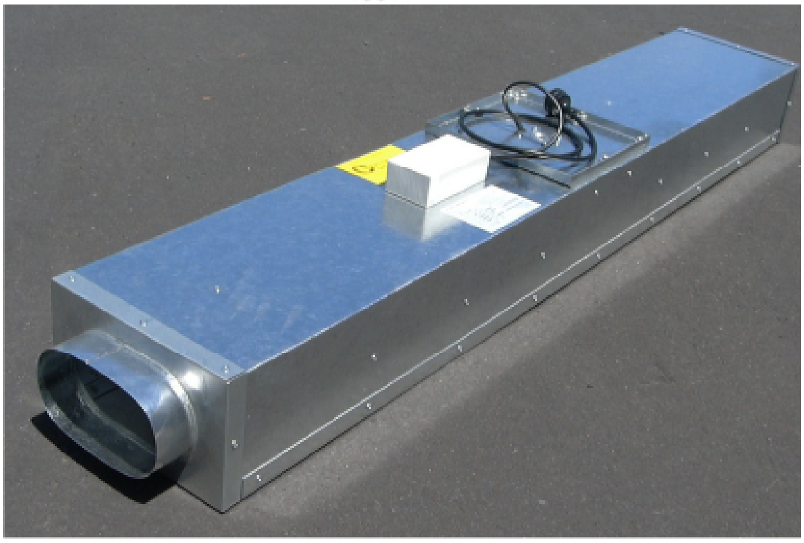
Compartment Unit

Type AFA150

The AFA150 unit incorporates a fan with integral inlet and outlet silencers. This one piece unit gives quiet airflow from 25l/s up to 100l/s. Flexibility is such that it can be configured to run in a two speed mode for 'trickle' and 'boost' in bathroom extract type applications.

The one piece design means that the fan is enclosed in a steel casing thus reducing fan radiated noise - all important for 'in ceiling' uses.



LOW NOISE

The AFA150 is very quiet. It can be configured to deliver 100l/s airflow with intake noise at **NC38** with radiated noise (via a Gib ceiling) at a remarkable **NC20**.

At lower flow rates of 25-50l/s noise from the AFA150 is ***barely audible*** even with low ambient background noise levels.

Applications for the AFA150 include apartment outside air supply, bathroom and toilet extracts. The AFA150 low noise levels allow for installation in domestic houses.

EASY INSTALLATION

The one piece AFA150 makes installation simple and straightforward. Just couple up 150mm diameter inlet and outlet flexible ducts and plug it in.

Reduces on-site time spent with fans, flexible couplings, silencers, speed regulators etc.

COMPACT DIMENSIONS

Measuring just 250mm wide by 150mm deep and 1500mm long the AFA150 is compact.

Its low profile is ideal for tight in-ceiling applications

FLEXIBLE PERFORMANCE

Airflow performance of the AFA150 unit is between 20 -100l/s and can easily be tailored to each application by simply changing a capacitor.

The AFA150 can also be set up to run in a low speed 'trickle' mode of 25l/s continuously and switched to full speed 'boost' of 100l/s. This is an ideal setup for bathrooms where the continuous low speed mode provides ventilation and the high speed 'boost' mode is used during showers to extract excess steam.

(Continued from page 25)

it was expected that reflections would be predominantly specular from the walls and ceiling. Considering a ray tracing model with purely specular reflections, some rays can remain in a particular plane being reflected from only four of the six principle surfaces.

Rays travelling between the reflective walls in a predominantly horizontal plane will decay much slower than rays in a vertical plane, which will be mainly absorbed when they hit the stalls seating.

For configuration A the significant difference between the T_{20} and EDT is indicative of non-linear decays that result from such behaviour. The comparatively high relative standard deviation of reverberation time $(\sigma(T_{20})/T_{20})$ in configuration A implies that decays are not uniform throughout the space, which in turn is also an indication of non-linearity.

In configuration B with all scattering panels, sound should be reflected in all directions from most surfaces, regardless of the angle of incident sound. Individual rays should no longer be 'trapped' in a predominantly horizontal or vertical plane. The sound decay should be more linear and more uniform throughout the space.

In configuration B, the mid-frequency T_{20} was the same as the EDT and the relative standard deviation of reverberation time was significantly reduced compared to configuration A. This is consistent with the expectation of more linear and uniform sound decays.

The classical expressions for reverberation time can be derived using average values for surface absorption and the mean free path length of sound rays. If there are significant deviations from this average theoretical behaviour, the reverberation time formulae are no longer valid. In configuration A, sound rays can remain in a predominantly horizontal plane and these deviate substantially from average behaviour with both long path lengths and low absorption at surface reflections.

Therefore, it is not surprising that the measured mid-frequency reverberation time for configuration A is higher than the Sabine and Eyring values. The Eyring formula correctly predicts the reverberation time in configuration B when all surfaces are scattering.

Most users of room acoustic prediction software do not have reliable scattering coefficient data so often repeat simulations to assess the sensitivity to different scattering coefficients.

A commonly reported artefact of computer models is that as scattering coefficients are increased the reverberation time decreases. The measurements in configurations A and B have shown that in this respect computer models are thus representing real sound behaviour; the concert hall model with scattering surfaces has a lower reverberation time than when all the surfaces are flat.

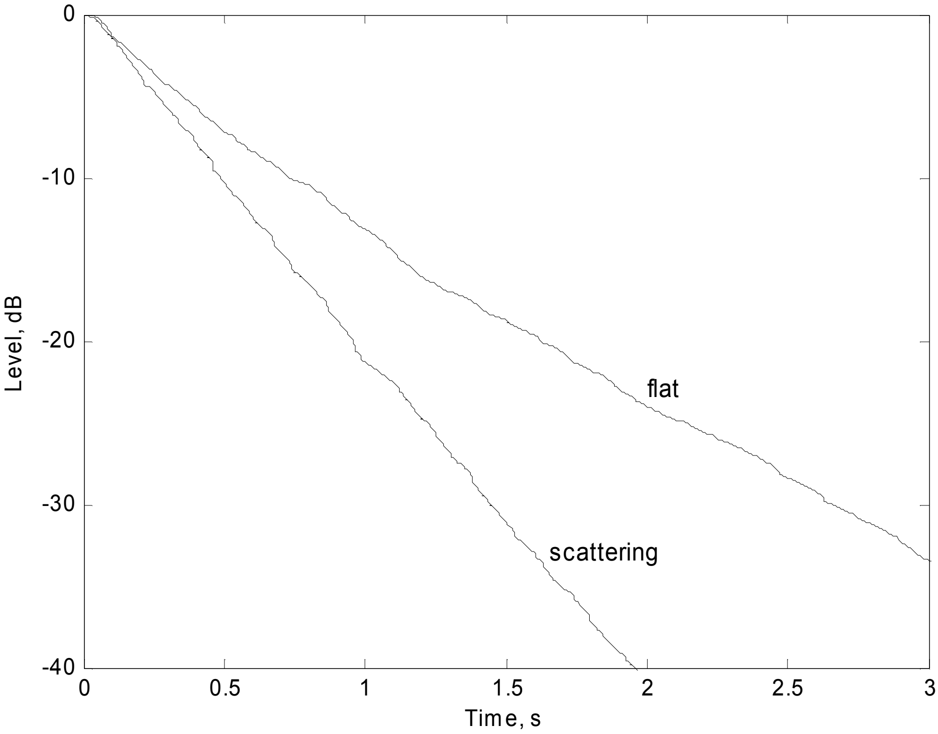


Figure 3 Decay curves with flat and scattering surfaces on the walls and ceiling

The differences in the sound decays discussed above are also illustrated in Figure 3. This figure shows reverse integrated sound decay curves for the 500 Hz octave band in configurations A (flat) and B (scattering).

The decay curves are for a receiver located about three quarters of the way back in the stalls and in the central block of seating. In Figure 3 the difference between the decay rate (and hence reverberation time) in the two configurations is obvious.

It can also be seen that the decay for configuration A (flat) is particularly non-linear, with a noticeable change in the rate of decay at approximately 1.2 seconds.

Scattering location

The next set of tests used just the eight scattering panels with hemispheres at a coverage density of 50%.

These eight panels covered 18% of the total wall and ceiling areas. For configurations C to F these eight panels were located: on the three walls and ceiling at the front of the hall (C), on the three walls and ceiling at the rear of the hall (D), on the ceiling (E) and finally on the side walls (F).

Reverberation time and EDT data for these configurations are given in Table 2. For all four configurations with scattering panels (C to F) the reverberation times and early decay times are less than the values in configuration A (all walls flat) but not as low as the values in configuration B.

Also, the EDT/T_{20} ratio was closer to unity in all configurations with scattering panels compared to configuration A.

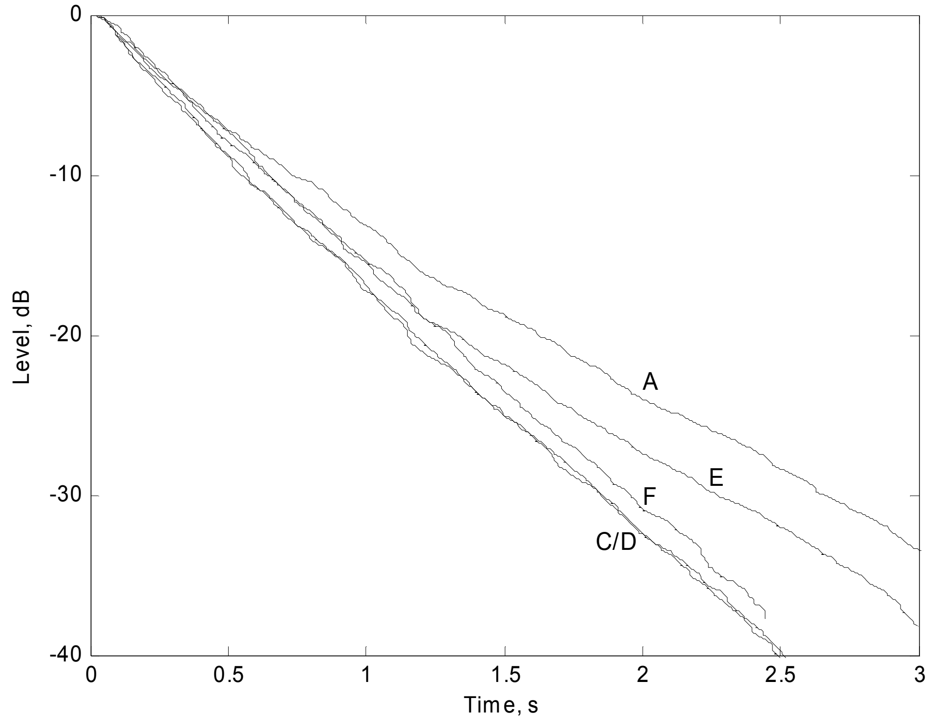


Figure 4 Decay curves for different hemisphere locations

The EDT values in configurations C to F are close to the Sabine reverberation time (3.0 s) and for configurations C, D and F, the values of T_{20} are also relatively close to the Sabine reverberation time.

Practitioners have found that the Sabine reverberation time formula is a reliable design tool for real concert halls. The EDT and T_{20} measurements in configurations C to F are close to the Sabine value and, if these configurations represent a typical amount of scattering for a real concert hall, this demonstrates the validity of the Sabine formula.

If there were a greater degree of scattering in real concert halls then the reverberation time would be expected to be below the Sabine value and closer to the Eyring value as in configuration B.

With scattering surfaces on 18% of the walls and ceiling configurations C to F have an SDI of approximately 0.25, which is unrealistically low when compared to the concert hall data presented by Haan and Fricke [1].

However, it is thought that the SDI is not adequately representing the diffuse conditions in the scale model

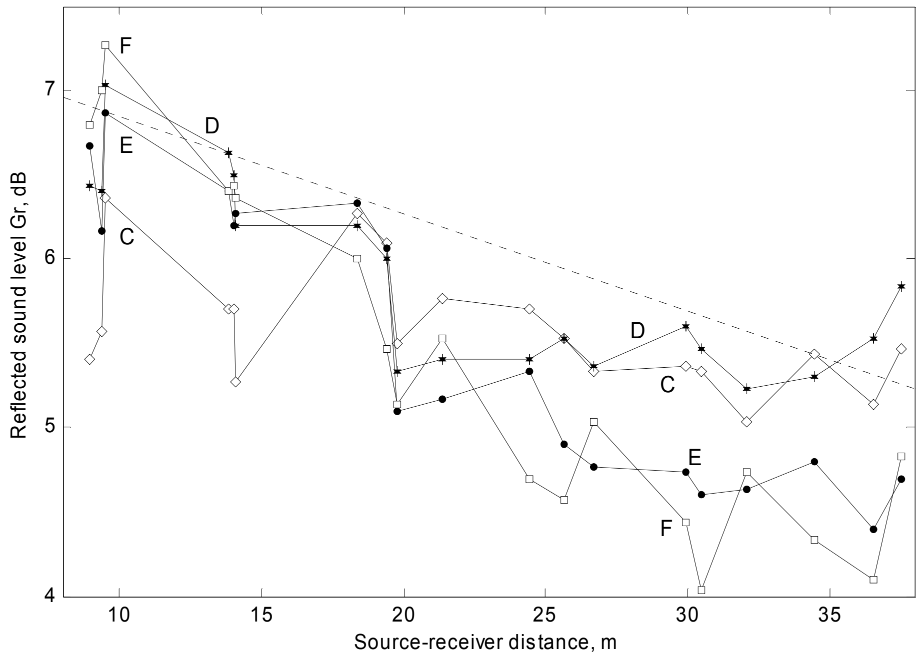


Figure 5 Reflected sound levels for different hemisphere locations

and this shows a further weakness in the procedure for the subjective determination of SDI.

Configurations C, D and F have either five or eight scattering panels located on the side/end walls.

Configuration E has scattering panels only on the ceiling and the walls are all flat. Therefore, in configuration E sound can still remain in a predominantly horizontal plane with minimal absorption by the reflecting walls. In Table 2 it can be seen that in this configuration there is the smallest reduction in T_{20} compared with configuration A, which is consistent with the hypothesis that sound in a predominantly horizontal plane is decaying at a slower rate.

The relative standard deviation of reverberation time is even higher for configuration E than for configuration A. For all other configurations with scattering panels the relative standard deviation is lower than configuration A.

In both configurations A and E the sound travelling in a horizontal plane causes non-linear decays and a non-diffuse sound field. Figure 4 shows decay curves for configurations A and C to F using the same receiver and frequency (500 Hz octave band) as Figure 3.

The non-linear decay for configuration E can be clearly seen in this figure.

Configuration F has hemispheres on both side walls but not on the end walls. Therefore, some sound paths may involve repeated reflections from just the end walls and energy could remain in this predominantly horizontal plane taking longer to decay.

However, most sound paths in a horizontal plane, such as in configurations A and E, include reflections from the side walls. These paths will be disrupted by the scattering in configuration F.

For the receiver used in Figure 4 it can be seen that the decay for configuration F is more linear than for configurations A and E but less linear than for configurations C and D. However, the data in Table 2 is similar for both configurations D and F.

Sound level behaviour

The reflected sound levels measured in configurations C to F are shown in Figure 5 plotted against source-receiver distance. (The reflected sounds levels are expressed in decibels relative to the direct sound at 10 m from the source).

Classical statistical theory erroneously predicts a uniform reflected sound level in a concert hall. However, measurements in real halls show levels generally decrease with increasing source-receiver distance and are usually well predicted by revised theory [13].

The dashed line in Figure 5 is the theoretical value for the reflected sound level according to revised theory. Measured levels in configurations C and D are reasonably close to the revised theory prediction (the discrepancy at short source-receiver distances in configuration C is discussed below), but in configurations E and F there are significant deviations.

For configurations E and F, Figure 5 shows the sound levels were substantially lower than revised theory at larger source-receiver distances but reasonably close to revised theory at shorter source-receiver distances.

This effect is attributed to back-scattering of early energy. Early reflections that were predominantly specular would be reflected by the ceiling and side walls in a direction away from the source on the stage.

However, in configurations E (ceiling) and F (side walls), part of this energy is scattered back towards the source so that the early and therefore total reflected sound levels are reduced at the rear of the hall.

The energy scattered back towards the front of the hall arrives significantly later than the direct sound so has less influence on the total reflected sound levels at short source-receiver distances.

The back-scattering of early energy leads to less favourable acoustic conditions in configurations E and F than for configurations C and D, as the distribution of energy becomes distorted between the front and back of the hall.

In configurations E and F the reduced early energy at the rear of the hall leads to a reduction in the clarity index, C_{80}.

Near the stage in all concert halls, the clarity index is generally satisfactory as the strong direct sound results in relatively high early sound levels and a correspondingly high C_{80}. Further from the stage, it is more important to provide sufficient early reflections to maintain a reasonable early sound level and hence clarity index.

In configurations E and F, the back-scattering works counter to this basic requirement. When normalised to a reverberation time of 3.0 seconds, the average value of C_{80} in the rear 14 rows of seats (7 measurement positions) is 0.7 dB lower in configurations E and F than configurations C and D.

According to Cox et al [14], the subjective difference limen for the clarity index varies between 0.4 and 0.9 dB depending on the source material. Therefore, the average difference of 0.7 dB between configurations C and D and configurations E and F might be significant.

However, it is unlikely that a reduction in clarity of 0.7 dB alone would be particular cause for concern when designing a concert hall.

Configurations C and D both contain the same arrangement of scattering panels but at opposite ends of the hall.

In Figure 4, decay curves for the particular receiver used are very close for these two configurations. However, in Figure 5 there are differences visible between the two configurations at shorter source-receiver distances, with lower reflected sound levels in configuration C than in configuration D.

Analysis showed that the reduced reflected sound levels for configuration C could be entirely attributed to reduced late reflected sound levels as the early sound levels were comparable with configuration D.

These are slightly curious effects for which only a partial explanation is put forward. With flat surfaces, sound from second order reflections off the ceiling and rear wall (and possibly side walls as well) will be travelling downwards from the rear to the front of the concert hall.

If the surfaces around the stage are also flat, this sound would undergo a specular reflection from the wall at the back of the stage and might arrive at audience seats near the stage. When the surfaces around the stage are scattering, these reflections will be dispersed, resulting in weaker sound at the seats near the stage.

The geometry of the hall does not give rise to the same effect in reverse for scattering surfaces around the rear of the hall.

The above discussion has focussed on certain aspects of sound behaviour resulting from scattering panels in the simple concert hall model. The parameters considered are thought to have illustrated the most important factors in relation to concert hall design.

However, there are numerous other criteria against which the effects of the panels could have been judged, and one limitation of the scale model testing is that the spatial distribution of reflections at receivers could not be assessed.

Further studies at a larger model scale would be required to address this important issue. A significant assumption in the above discussion is that a linear sound decay is better than a non-linear sound decay. In many cases, a non-linear decay may not adversely affect subjective responses to sound in a concert hall, but for this model the non-linear decays are indicative of undesirable effects such as repeated reflections in a horizontal plane and poor uniformity of the sound field.

Conclusions

In the introduction it was explained how there has been no substantive research into the effects of scattering surfaces on the sound fields in concert halls. It is believed that the measurements reported above form part of the first systematic study in this area.

Whilst there remains enormous scope for further research, this study has established some fundamental trends, which should be of great value to auditorium designers.

The first conclusion from these measurements is that scattering surfaces anywhere in a concert hall will: increase the linearity of the sound decay curves, reduce the reverberation time, reduce the standard deviation of reverberation time and increase the EDT/T_{20} ratio to bring it closer to unity.

All of these effects are related to the existence of a more diffuse sound field with the scattering surfaces. In a real concert hall unavoidable structural/architectural features may also fulfil this purpose.

In the scale model it was shown that a comparatively small area of scattering surfaces (eight panels) was need to achieve a significant improvement in diffusion of the sound field. Eight panels covered only 18% of the total wall and ceiling areas.

This finding appears to be slightly at odds with the work of Haan and Fricke [1], which suggests that a substantially greater area of scattering is optimum. However, this discrepancy is thought to be primarily due to the inadequacy of the surface diffusivity index, SDI.

It was found that a potential disadvantage of adding scattering surfaces to the concert hall model was back-scattering of early energy towards the stage.

Back-scattering significantly decreases the reflected sound level and objective clarity at the rear of the hall. The degree of back-scattering was shown to depend on the location of the scattering surfaces.

Scattering surfaces solely on the ceiling were not particularly effective at producing a more diffuse sound field and this scattering could be considered detrimental as it caused the most back-scattering of early energy.

Scattering surfaces on the side walls produced a more diffuse sound field than scattering surfaces on the ceiling but they also gave rise to a significant back-scattering effect. Scattering surfaces at either end of the concert hall appear to produce a diffuse sound field and avoid back-scattering.

There is some evidence that scattering at the front of the hall reduces the reflected sound levels near the stage so scattering at the rear of the hall may be preferable.

Acknowledgements

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