

## THE CURRENT STATE OF ACOUSTIC DESIGN OF CONCERT HALLS AND OPERA HOUSES

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### ABSTRACT

The key issues for concert halls and opera houses are discussed including the role of objective measures and the unresolved issues relating to spatial hearing in concert halls. The question of diffusion in auditoria has been discussed now for 100 years yet its objective and subjective importance is still far from understood. The issues of computer or scale modelling, concert hall shape, conditions for the performers and opera house acoustics are also covered.

### 1. OBJECTIVE MEASURES OF ACOUSTIC QUALITY

Since the 1950s there have been major efforts to discover objective measures appropriate to the experience of listening to music. Several of the new objective measures have been derived from experiments with simulation systems using many loudspeakers in an anechoic chamber. Two German studies around 1970 using dummy head recordings made in real auditoria helped to establish the relative importance of objective measures that had been proposed [1]. The consensus objective measures have now been included in the standard ISO3382 [2], as follows;

- reverberation time
- early decay time (EDT)
- ratio of early-to-late sound,  $C_{80}$
- early lateral energy fraction,  $L_f$
- total relative sound level (strength)

The early decay time is considered to be more closely related to the perceived sense of reverberation than the traditional reverberation time (RT). In actual halls the mean EDT tends to be a little shorter than the RT [3]. EDT values generally fall significantly under balcony overhangs.

The early lateral energy fraction is now considered to be a measure of perceived source broadening; sound level also influences the magnitude of the effect. High lateral fractions are to be found in narrow halls and sections of halls bounded by reverse-splay walls in plan [4].

ISO3382 also includes the alternative measure for spatial impression or source broadening: the inter-aural cross-correlation coefficient (IACC). Though the ear probably conducts some form of

cross-correlation analysis, the IACC measure is not identical to the process found in our hearing. The lateral fraction has the advantage that it functions well at low frequencies which are known to be important for source broadening, whereas the IACC does not. The link between hall design and lateral fraction is better documented than the IACC.

The total relative sound level, or strength, is a measure of the sound level at an audience position for a known sound power on stage. This obvious quantity was ignored for many years because the variation of level within and between concert halls was considered small relative to the assumed sensitivity of listeners to sound level (5dB for a worthwhile noise reduction, for instance). The measured range of total relative sound level in eleven British concert halls with volumes greater than 11000m<sup>3</sup> is 10dB, the closest receiver point was 10m from the source [5]. It is now clear that listeners are sensitive to level differences of a decibel or so.

The inclusion of the newer objective measures in a Standard is a welcome development. It provides a point of reference for future work as well as a fixed set of measures for measurement and prediction.

## 2. SPATIAL HEARING IN CONCERT HALLS

Until 1967 it was assumed that one of the values of reverberation was the spatial sense it created of sound arriving at the listener from all directions. Apart from the reverberation time, this was never quantified. In 1967 Marshall [6] proposed that early lateral reflections played a prominent role in concert hall listening. The subjective effect of these reflections has most commonly been called **spatial impression**.

In 1989 Morimoto and Maekawa [7] suggested that at least two subjective spatial effects occurred. They provided evidence that a sense of being enveloped by sound was independent of spaciousness (spatial impression caused by early reflections) and that envelopment was linked to incoherence (a low interaural cross-correlation) of the reverberant sound.

Bradley and Soulodre [8] conducting their own experiments basically agreed with Morimoto and Maekawa that there were two spatial effects which had in the past often been confused. Bradley and Soulodre called the two effects: **source broadening** and **listener envelopment** (LEV). Source broadening can be measured by the perceived apparent source width (ASW). Their experiments showed that ASW is predominantly determined by the early sound, whereas envelopment is governed by the late sound. Most earlier work had concentrated on source broadening, referring to it as spatial impression. Just as perceived source broadening is influenced by sound level, so Bradley and Soulodre also found sound level to be significant for LEV.

Bradley and Soulodre [8] propose as an objective measure for LEV the **late lateral sound level**,  $LG_{80}^{\bar{v}}$  or more simply **GLL**:

$$LG_{80}^{\bar{v}}(\text{GLL}) = 10 \log_{10} \frac{\int_{0.08}^{\bar{v}} p_F^2(t) \cdot dt}{\int_0^{\bar{v}} p_A^2(t) \cdot dt} \text{ dB}, \quad (1)$$

where  $p_F(t)$  is the pressure measured at a listener position with a figure-of-eight microphone with the null pointing at the source and  $p_A(t)$  is the response to the same source at a distance of 10m in a free field. Time  $t$  is measured relative to the arrival time of the direct sound. The late lateral sound level is measured at four octave frequencies (125 - 1000Hz) and averaged.

There is one aspect of listener envelopment about which there is not universal agreement: the significance of sound from behind. Bradley and Soulodre found that sound from behind had no special influence on the subjective effects they were studying. On the other hand, Morimoto and Iida [9] provide evidence that the ratio of front-to-back energy does have an influence on the sense of envelopment. To this author, a listener can perceive whether he/she hears sound from behind in a concert hall and its absence in a concert hall is detrimental to acoustic quality.

A further query about the late lateral sound level (**G<sub>LL</sub>**) being a measure of listener envelopment arises when one observes measured values of the quantity [10]. **G<sub>LL</sub>** can be expressed as the sum of a directional term (the late lateral energy fraction converted into decibels) and the late level **G<sub>L</sub>**. The directional element, the late lateral energy fraction, is found not to vary much and to take a mean value of 0.31, which is very close to the theoretical value for a diffuse sound field of 0.33. When the directional and level components are combined for the **G<sub>LL</sub>**, the directional component is found to contribute to only 17% of the total variation of the **G<sub>LL</sub>**. The level component **G<sub>L</sub>** contributes the remaining 83%. In other words the proposed objective measure for listener envelopment is predominantly determined by the level of the reverberant sound. The principal determinant of the late level is the total acoustic absorption of the auditorium.

The design implications of the proposed measure are that small halls offer a high degree of envelopment whereas in large halls the sense is much reduced.

### 3. THE STATE OF DIFFUSION

The question of diffusion in rooms and concert halls has been discussed ever since W.C. Sabine's work 100 years ago. A diffuse sound field is a requirement for accurate prediction by the standard reverberation equations but this of course does not mean that it is necessary subjectively. Our directional sensitivity is precise for localisation but imprecise for reflected sound. One spatial characteristic of a diffuse sound field is likely to be a sense of envelopment, of feeling surrounded by sound. The necessary sound components for envelopment remain to be confirmed (previous section).

One area of potential confusion is distinguishing between diffusing surfaces and a diffuse sound field. Diffusing surfaces can of course lead to a diffuse field. There are situations where reflections off plane surfaces cause undesirable audible effects. Reflections off diffusing surfaces are considered to be subjectively preferable because they avoid (or at least minimise) false localisation and tone colouration (comb filter effect). Tone colouration tends to be most severe with strong discrete overhead reflections.

The case for diffusing room surfaces and a diffuse sound field is supported by the nineteenth century halls which have such good acoustic reputations. It is the rectangular halls from this period which have tended to survive, such halls as the Musikvereinssaal, Vienna, and the Amsterdam Concertgebouw. The diffusing wall surfaces were a characteristic of the architectural style of the time but the acoustic performance of these surfaces was an accident.

Modern architecture tends to favour clean lines with relatively undecorated surfaces, so that inclusion of diffusing surfaces tends to be a conscious decision. Halls for which Cyril Harris has been acoustic consultant in America have included highly diffusing walls and ceilings, as for instance in Benaroya Hall, Seattle of 1998.

The problem with success in a multi-dimensional situation is that one cannot easily establish the relative importance of the various possible contributions to that success. Is the success of the Musikvereinssaal due for instance to its narrow cross-section (small width) or the diffusing character of its surfaces? An interesting experiment [11] was made with the Beethovenhalle, Bonn, of 1959 which has diffusing walls and ceiling inspired by the example of nineteenth century halls. The consultants for this hall were Erwin Meyer and Kuttruff, both at Göttingen. In 1967 Damaske, also working at Göttingen, discovered from subjective experiments that sound from only four distributed directions was sufficient to give the impression to the listener of sound arriving from nearly all directions. In other words a uniform spatial distribution for arriving sound was not necessary for listeners.

The case for diffusing room surfaces and a diffuse sound field is not straightforward. But two recent pieces of evidence support the value of the diffuse field. Haan and Fricke [12] (see also

Beraneck, Appendix 3 [13]) conducted a survey of musicians' and conductors' views of their preferred world concert halls. The performers' acoustic quality index was compared with geometrical factors for the halls. Rather than specific dimensions or reverberation time being critical, the highest correlation was found to be with the degree of surface irregularity, or degree of surface diffuseness. This survey can be criticised for several reasons, including the fact that musicians are not typical listeners and that subjective judgements were based on memory. But even though the survey cannot explain why diffusing surfaces are valuable, it has refocused attention on this ambiguous aspect of concert hall design.

The second piece of evidence comes from a recent English concert hall in Manchester, the Bridgewater Hall, which opened in 1996. The architect of this hall favours the smooth surfaces of the modern architectural movement. Though in objective terms (reverberation time, early lateral energy fraction etc.) the hall behaves well, its sound quality has been criticised by some with faults which may be linked to a lack of diffusion. The acoustic consultant [14] has indicated that the hall might benefit from more high frequency diffusion.

#### **4. ACOUSTIC SCALE AND COMPUTER MODELS**

It is now standard practice to give consultancy advice on an auditorium with the aid of a model of some sort. Computer models have become popular since the arrival of programs that can run on standard personal computers.

##### Computer Simulation Programs

Though much effort has been devoted to computer programs, it is important to appreciate their limitations. The limitations are usually hidden from the user when confronted by the standard output of numerical data or colourful contour plots. Nearly all computer programs start from a visual model with either rays or beams radiating out from a source. The following situations present problems for computer models:

- a) diffusing surfaces
- b) curved surfaces
- c) diffraction at reflection
- d) transition from discrete early reflections to reverberation

The question of diffusion has received considerable attention recently and most programs permit the specification of diffusion coefficients as well as absorption coefficients for each surface in the room. This is obviously a step forward but diffusion coefficients assume that reflected sound is split into either a specular (mirror) reflection or a fully diffuse reflection, which is obviously a simplification. For a computer program, a reflection off a diffusing surface turns a single sound ray into a multitude of rays. This links to the problem already listed of transition from discrete reflections to reverberation, because the number of rays to be considered grows exponentially. An algorithm for tackling this problem is necessary; some program solutions are more successful than others.

For curved surfaces, most programs suggest substituting it by a series of plane surfaces. In this case the calculation will be incorrect and this may be significant for critical auditorium situations.

The problem of dealing with diffraction seems the most intractable for computer models. A fairly simple algorithm exists for dealing with reflection from a finite size freely suspended surface. Freely suspended surfaces are however the exception rather than the rule in auditoria. The problem of diffraction when a finite surface is joined to other surfaces is so far beyond the capabilities of computation.

The last difficulty listed, transition from discrete early reflections to reverberation, has been apparent from the early days of computer models. Some ingenious solutions, such as [15], have been developed to tackle it.

There is a further limitation in computer modelling which is even more fundamental. Computer programs can only deal with surfaces and objects which can be described in terms of planes with absorption and diffusion coefficients. Modelling of some of the suspended objects one finds in modern auditoria, such as lighting grids, is not simple!

Validation of modelling systems is not easy; a model may work in one space and not in another. Two round-robin exercises have been so far conducted in which many computer programs were tested for a single room. In the first exercise the room was a modest lecture theatre; three programs were deemed to have correctly predicted acoustic behaviour [16]. These computer programs are however intended for use in rooms where acoustic performance is difficult to predict. The space used for the first round-robin would fall into the category of a room unlikely to present acoustic problems due to its small size.

The second round-robin [17] used a real concert hall space, an 11000m<sup>3</sup> auditorium at Jönköping in Sweden. Results of the study have yet to be published in full but the analyst concluded that only one program predicted with sufficient accuracy.

### Acoustic Scale Modelling

The techniques for acoustic scale modelling date back to the 1930s [18] and are now well established. The common method nowadays is to digitise the microphone signal and perform all subsequent analysis of the acoustic signals on a computer [19]. This combination of analogue acoustic and computer analysis is used both for objective testing, to give numerical results, and subjective testing which provides music or speech recordings suitable for assessment by listening test.

The beauty of scale modelling is that it automatically deals with all the basic problems that beset computer modelling. Diffraction, curved surfaces, diffusion and high reflection densities all behave in miniature in an identical way to full-size. The problems of scale modelling are more practical: the greater time and commitment required to build the model. Reproduction of absorbing materials at model scale can also be time consuming. These difficulties can however easily be exaggerated. There should always be sufficient time during the design project for a major auditorium to include scale model construction and testing. The advantage is considerably greater confidence in the final acoustic behaviour of the auditorium.

The choice of scale factor has fluctuated with time. Early models were large using scales of 1:8 or 1:10. Investigations of smaller scales [20] showed that 1:50 scale was feasible for objective measurements up to the 1000Hz octave (full-size equivalent). Several recent models have used intermediate scales of 1:20 or 1:25, which offer the combination of measurements up to the 2000Hz octave with a model of manageable size.

### Modelling In The Future

To this author, the case for including scale modelling in design programmes for large auditoria is clear. No modelling process will be completely reliable, but the risks associated with scale models are substantially smaller than with computer models. In reality, consultants are likely to run a computer analysis in parallel with a scale model and benefit from the superior graphical output etc. that computers provide. Where it is apparent that the computer model is predicting correctly, it can be used to extend the range of measurement conditions.

It is interesting to note that for the refurbishment programmes of two concert spaces in London, scale models are being used for the Royal Albert Hall at 1:12 [21] and for the Royal Festival Hall at 1:20.

## **5. PREFERRED CONCERT HALL SHAPES**

The choice of concert hall form, particularly plan shape, has historically been determined by many different considerations [11]. The key historical events are summarised in the Table.

Date	Development	Significant hall
1870-80s	The rectangular (classical) concert hall	Musikvereinssaal, Vienna etc.
1900	Sabine's reverberation equation	Boston Symphony Hall
1930s	Cinema: the fan-shaped plan	Kleinhans Hall, Buffalo/Salle Pleyel, Paris
1960s	Realisation of the large concert hall problem	Philharmonic Hall, New York
1963	The terraced concert hall	Philharmonie, Berlin
1972	Significance of early lateral reflections	Christchurch Town Hall, New Zealand
1989	Return of the parallel-sided hall	McDermott Concert Hall, Dallas

Dependence on what had gone before, that is dependence on precedent, is a feature which fluctuates from period to period. In the early history of the concert hall the rectangular plan was a fortunate coincidence which became the norm. Different scientific approaches have arrived, been tried and either accepted or rejected. The current situation is that only two solutions for concert halls are popular.

A major realisation around 1960 was that there was a basic conflict involved in concert hall design, which can be called the large concert hall problem. In order to achieve a long reverberation time, the wall and ceiling surfaces tend to move away from the majority of the audience. This can lead to a lack of early reflections for listeners, with resulting loss of clarity, source broadening and loudness.

Since 1950 several strategies have been used to combat the large concert hall problem. In the Royal Festival Hall, London, the over-stage reflector and ceiling profile projected sound to the rear of the auditorium [22]. In the New York Philharmonic Hall of 1962, suspended overhead reflectors famously aimed to maintain clarity and intimacy. Realising that strong overhead reflections were undesirable and lateral reflections desirable, Marshall [23] developed the lateral directed reflection sequence hall for Christchurch in New Zealand.

The two concert hall forms now considered appropriate for the best acoustic characteristics are the terraced concert hall and the parallel-sided hall. The terraces developed for the Berlin Philharmonie were introduced to provide surfaces capable of generating reflections in what would otherwise have been very large continuous areas of audience seating. This approach should be compared with that used in the Festival Hall, where extra reflections were provided from the orchestral reflector, a surface close to the performers. In the terraced hall the 'additional' reflecting surfaces are near the listeners.

The parallel-sided hall provides early reflections mainly from the side by restricting the width of the auditorium. The problem with this scheme is that seat numbers become limited. It would be wrong to assume that the parallel-sided hall ever fell out of favour, particularly for smaller halls. Halls in America with Cyril Harris as acoustic consultant have always been basically rectangular in plan; there are also many rectangular plan halls in Japan. The interesting development of recent years has been the shift of Artec Consultants to the parallel-sided plan, first in Dallas 1989 and in Birmingham Symphony Hall, England in 1991. These halls have a ceiling height much larger than the 19th century shoebox halls. They also have seating at the rear arranged as in a traditional opera house.

In Britain we now have an interesting hybrid between the parallel-sided and terrace halls in the 2400 seat Bridgewater Hall, Manchester [14]. The parallel-sides are to be found in the front 2/3 of the hall while the rear follows a terrace arrangement. This hall has already been mentioned under diffusion, section 3.

## 6. CONCERT HALL PLATFORM ACOUSTICS

Ask a concert hall manager what is his main acoustic concern and it is likely to be conditions for the performers not the audience. As a problem, platform acoustics combines not only the subjective aspects that one confronts with listeners (a multi-dimensional experience with different individual priorities) but also different requirements for different musicians.

The most extensive research on stage acoustics has been done by Gade [24, 25] involving subjective experiments with performers in the laboratory and measurements in actual concert halls. Gade established that musicians' main concerns were to hear themselves and to hear each other. He found evidence that these two abilities were linked to the magnitude of early reflections they received. He proposed an objective measure called Support, which in simple terms is the early reflected energy received relative to the direct sound from the performer's own instrument. The magnitude of Support on actual stages was found to be mainly determined by the 'platform volume' (the stage area x height to ceiling or reflectors) [11].

In practice the situation is complicated by instrument directivity and differing output powers. Early reflections are also not the only element which musicians like to hear. Some response from the room is important to feel that "the sound is getting out there". The role of reverberation and reverberation time in this remains somewhat ambiguous. Satisfying the performers in a large auditorium with a full-size platform is far from easy, particularly when an organ is placed behind the platform.

## **7. ACOUSTICS FOR OPERA HOUSES**

For the audience attending an opera performance it is usually the singers that they want to hear most [11]. Yet the singers have to compete on their own with an orchestra of 50 or more musicians. Designing an opera house to enhance the singers' sound but not the orchestra's appears to be a valid response. The surfaces in the area of the proscenium opening prove to be particularly important to optimise the singers' sound.

An interesting opera house design with 1810 seats has recently opened in the New National Theatre, Tokyo [26]. One of the principles behind this design was to include as far as possible an 'acoustical trumpet' in front of the proscenium. Convex surfaces flare out from the proscenium both to the sides and above the pit.

The reverberation times listed as suitable for opera houses are typically 1.3 - 1.8 seconds. The range is much larger than it is for concert halls, partly because different reverberation times are more suitable for operas of different periods and partly due to individual taste. Opera houses with long reverberation times are rare. For the rebuilding of the Semperoper in Dresden in 1985, Reichardt as acoustic consultant chose to increase the reverberation time from 1.3 to 1.6s [27]. The auditorium is also of interest for its highly diffusing surfaces; it is popular among conductors.

More recently the 1300 seat Gothenburg opera house was completed in 1994 with a reverberation time of 1.7 seconds [28]. The design of this house, though built in a modern architectural style, aimed to reproduce as many positive acoustic features as possible of the Dresden house.

## **8. CONCLUSIONS**

Progress in auditorium acoustics is far from linear: a new auditorium revealing interesting characteristics or a new approach to subjective listening are as likely to offer progress as planned research. The standardisation of objective measures provides a valuable reference point for future work. We can be sure that computer simulation models will improve in quality. But one of the most pressing issues about which there is much confusion is the question of the role and importance of diffusion, particularly in concert halls. This is definitely a challenge for the new millennium.

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