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THE ACOUSTICS OF SEGERSTROM HALL AT THE ORANGE COUNTY PERFORMING ARTS CENTRE IN CALIFORNIA

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1. INTRODUCTION

Segerstrom Hall (named after its major benefactor) is a 3000 seat multipurpose auditorium at the Orange County Performing Arts Centre in California. It was formally opened on 29 September 1986 and caters for performances of orchestral music, opera, musicals and drama.

The architect was Charles Lawrence who, together with theatre consultant John von Szeliski, formed a design team with the acoustical consultants Harold Marshall, Jerald Hyde and Dennis Paoletti. A remarkable aspect of this collaboration is that the acoustical requirements were the dominant factor in defining the geometry of the auditorium.

These acoustical requirements were principally to provide listening conditions for various types of music which would have a high degree of clarity coupled with ample reverberance and a sense of spaciousness or envelopment. To satisfy these requirements the design has made considerable use of knowledge developed over recent years about the subjective impression of sound in enclosed spaces.

This paper starts with a brief review of the developments in subjective acoustics over the past 30 years or so illustrating how the knowledge gained has influenced concert hall design. The acoustical design of Segerstrom Hall is then described, and the results of subjective and objective measurements in the completed hall are presented.

The overall aim of this paper is to place Segerstrom Hall in the context of the evolution of concert hall design over the last three to four decades, in particular those designs that have been influenced by developments in subjective acoustics. In this respect, Segerstrom Hall is undoubtedly a prime example.

2. BRIEF REVIEW OF DEVELOPMENTS IN CONCERT HALL DESIGN

2.1 The Royal Festival Hall

The Royal Festival Hall was opened in 1951 and pre-dates the new research initiatives in subjective acoustics which began in earnest around the mid 1950's. However, the acoustical design was based on all the knowledge that was then available and therefore represents a starting point against which the designs of subsequent halls can be compared. Moreover, it is relevant that the audience capacity of the Royal Festival Hall, namely 3000, is the same as that in Segerstrom Hall because this presents an intriguing opportunity of comparing the different approaches to the acoustical design of each hall.

The main aims of the acoustical design of the Royal Festival Hall were to achieve reasonably uniform acoustics over the whole audience area and to provide "fullness of tone" for music [1]. The plan shape of the hall was chosen to be rectangular since this avoided the occurrence of curved surfaces and, furthermore, recognised the acoustical success of the classical nineteenth century halls. With regard to uniformity, a concern was that listeners at the rear of a large hall might feel remote because of the weakness of the direct sound. To compensate for this reflectors were used above the orchestra to reflect sounds towards the back of the hall. For "fullness of tone" the reverberation time was to be as long as possible.

When the hall was opened, comments about the acoustics showed that the "clarity" is high but that the "fullness of tone" is not sufficient for certain types of music. This was reinforced by measurement of the reverberation time, the only measure of practical use at that time, which was 1.5 seconds at mid-frequencies.

The short reverberation time in the Royal Festival Hall (which was subsequently lengthened electronically [2]) is unfortunate because in other respects the design based on the rectangular plan shape was acoustically successful. With the knowledge that is now available regarding the importance of early (lateral) reflections it is fortuitous that a rectangular plan shape was adopted at that time. It is interesting to note that the designers may have had an inkling of this knowledge when they suggested that cross-reflection of sound in a rectangular hall may give added "fullness" [1].

2.2 The Berlin Philharmonie

An auditorium which marks the beginnings of the new research initiative in subjective acoustics is the Berlin Philharmonie which opened in 1963. This is also a large concert hall and has a seating capacity of 2600. In the acoustical design, attention was paid to providing early reflections to all the seats, particularly those that are in the centre of the main floor and thereby distant from the main walls and ceiling [3]. This was achieved by subdividing the audience into small blocks arranged on terraces. These subdivisions provide many additional vertical surfaces in the midst of the seating which act as local sound reflectors.

This concept of providing plentiful local reflections has proved very influential on subsequent auditorium design.

2.3 Early Lateral Reflections

In the years following the opening of the Berlin Philharmonie, research was conducted to determine whether the direction of these local reflections was important. In 1967 Marshall [4] proposed that early reflections from a sideways or lateral direction are a component of the acoustics of the best concert halls.

The link between Early Lateral Reflections (as they are called) and acoustical quality was proved by the careful psychoacoustic experimentation of Barron [5] and has since been reaffirmed by others [6].

Early lateral reflections produce a sensation of spaciousness, called 'spatial impression', or an apparent broadening of the sound source. This gives the listener the desirable sensation of being 'enveloped' by the music.

2.4 Directed Reflection Sequence Halls

Marshall proceeded to implement his ideas about early lateral reflections in concert hall design and has done this so far in three halls. He has called these halls - Directed Reflection Sequence Halls [7].

The first of these was for the city of Christchurch in New Zealand which opened in 1972 [8]. This hall has a large volume based on an elliptical plan shape with a seating capacity of 2600. Within the volume large reflectors are suspended which are appropriately angled to provide early reflections (including early lateral reflections) for the audience.

The result is musical performances with clarity and a strong feeling of envelopment. Moreover there is a sensation of ample reverberance, which stems from the overall large volume providing a reverberation time of 2.3 seconds.

The second hall in the evolutionary line was the Michael Fowler Centre in Wellington, New Zealand, which was completed in 1983 [9]. This hall adopted a similar design philosophy but an important new feature was introduced. The large reflectors suspended within the volume were made highly diffusing because it was considered that diffuse early lateral reflections were subjectively preferable to specular ones. This high degree of diffusion was achieved by constructing the surfaces of the reflectors as a series of channels of different depths as shown in Figure 1. The theory behind this was proposed by Schroeder [10] who has demonstrated that certain sequences of numbers, for example quadratic residues, when realised physically as a surface consisting of a series of wells of different depths, will scatter incident sound within a certain frequency band to the maximum possible extent.

Figure 1. Cross section of diffusing panel based on quadratic residue sequence

The acoustics of the Michael Fowler Centre again resulted in a high degree of clarity with a sense of reverberance together with the feeling of envelopment in the sound.

The acoustical design concepts that Marshall had successfully implemented into these two halls were now applied to the design of the auditorium at the Orange County Performing Arts Centre [11]. However, the constraints for this hall were more severe since not only was it to be large but also multipurpose and with a proscenium stage.

3. ACOUSTICAL DESIGN OF SEGERSTROM HALL

3.1 General requirements and their influence on the basic plan shape

The requirements for the auditorium were for a large multipurpose space with at least 3000 seats. These were all to be on one side of a proscenium stage which was to provide for a broad range of performing arts including symphony, opera, musicals and ballet [12].

These requirements forced the initial plan shape of the auditorium into a fan. This ensures that all the seats have good sightlines and are as close to the stage as possible. As the rearmost seats were not to exceed 43m (a criterion for largescale musical and operatic presentations) balconies had to be incorporated. However, the arrangement of 3000 seats in a fan shaped space resulted in a width at the rear of around 50m. The acoustical implications of this are serious, particularly for the seats near the centre which are a long way from the sidewall boundaries. The ceiling is also distant because a large ceiling height was necessary to achieve adequate reverberation.

For the centre third of the seats, the delay of the first early reflections occurs in the range 60-95ms whereas they should preferably be within 80ms. This means that without corrective measures, the balance between early and late sound would be biased too far towards late sound for symphonic music.

3.2 Acoustical design solutions

To reduce the delay of early reflections and increase their level, the seating was subdivided into four tiers which provides extra vertical surfaces in the centre of the fan. These extra surfaces act as "sidewalls" and in each case are appropriately angled to direct early lateral reflections to the seating tier below. The reflection paths are shown on the seating plans in Figure 3. Thus the seats near the centre of the overall fan shape are aurally in a narrower room of 20-25m where the spatial impression is enhanced. Early lateral reflections are also provided by the sidewalls of the fan which are broken up into steps and appropriately angled.

Additional early reflections arrive from the large reflectors suspended within the volume of the auditorium; these reflections have a time delay in the range 20-80ms. Figure 2 shows the paths of these reflections and illustrates that by appropriate angling of the reflectors, many of the reflections arrive from lateral directions. Those reflectors nearest the stage are made diffusing, according to Schroeder's quadratic residue method, so that the numerous lateral reflections from these surfaces are diffuse rather than specular.
An additional feature which provides some variability in the acoustics is the use of banners which can be extended or retracted. These are located beyond the main reflectors from the listeners' viewpoint so that they do not

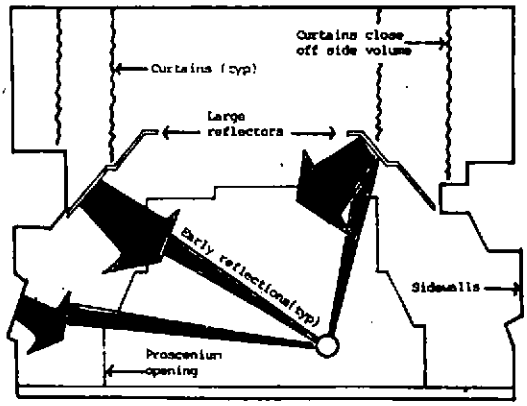

FIGURE 2

Transverse section of Segerstrom Hall showing early reflection paths (after J.R. Hyde)

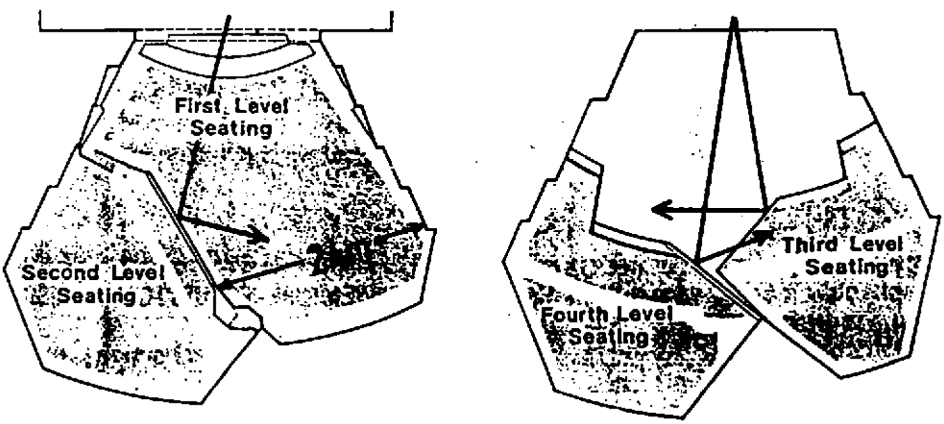

FIGURE 3

Seating Plans of Segerstrom Hall showing early reflection paths (after J.R. Hyde) interfere with the early reflection sequence (see Figure 2). With the banners extended the 'early' sound remains essentially the same whereas the late sound is reduced thus providing the higher clarity suitable for opera and speech.

3.3 1:10 scale model tests

The innovative design of the hall meant that it was appropriate to test it beforehand at model scale and a 1:10 scale model was built for this purpose. Initially the model was used for optical studies which enabled the point of arrival of reflections to be mapped out on the seating area. This proved to be a very valuable exercise in the design process since areas of strong and weak coverage could be detected and adjustments to reflecting surfaces made where necessary.

Acoustic testing of the model began with careful selection of model materials, in particular the seating, which was modelled on full scale measurements. Other materials for modelling curtains and carpet were also based on full scale measurement results. Following this careful scaling of model materials, the RT in the model was remarkably close to that predicted previously by Sabine's equation. This was a valuable confirmation that the design RT was likely to be realised in practice. Furthermore, it was possible to predict using the model the changes in RT that could be obtained by adjusting the variable curtains (see later).

Recordings of speech and music were made in the model according to the Spandöck technique [13] which had been updated by the Cambridge modelling group [14]. Although the authenticity of these recordings is not yet 100% they are useful for comparing the relative sound quality between seats.

Objective measurements besides RT were based on both steady state and impulsive signals. These gave values for total sound level, ratio of early-to-late energy and early lateral energy fraction. The averaged results are shown in Table 1 where they can be compared with subsequent full scale measurements. It is evident that the agreement between model scale and full scale results is good confirming the validity and accuracy of using 1:10 scale models.

The general conclusions of the model tests are that the optical study was valuable in checking and adjusting the alignment of reflecting surfaces. Furthermore, the reverberation and absorption studies provided a welcome confirmation of the RT predictions. Other objective measurements indicated a high degree of clarity and reverberance, suitably high loudness and a strong sense of envelopment.

4. TESTS ON THE COMPLETED HALL

Prior to the official opening on 29 September 1986 a comprehensive acoustic test programme was carried out consisting of both objective and subjective testing as in the model.

4.1 Objective tests

The objective measures listed below were evaluated at 20 receiver positions throughout the auditorium when it was unoccupied. Alongside each measure an indication is given of its relationship with subjective impression.

Reverberation Time, RT, s - [Reverberance, full decay]
Early Decay Time, EDT, s - [Reverberance, initial decay]
Ratio of Early-to-Late Energy, C_{80}, dB - [Balance between Clarity/Reverberance]
Early Lateral Energy Fraction, LE_{80} - [Spatial Impression]

Total Sound Level (re direct at 10m), L_T, dB - [Loudness]

Table 1 presents the results in terms of a mean value for each type of measurement. Comments on the results follow this.

	RT	EDT	C_{80}	LE_{80}	L_T
1:10 Model (occupied)[1]	2.0	-	+1.8	0.23	+2.9
Segerstrom Hall (unoccupied)	2.4	2.1	0.0	0.23	+2.8
Segerstrom Hall (occupied)	2.1[2]	2.0[3]	+1.0[4]	0.23	+2.3[4]

Notes
1. Model seating designed for occupied condition only.
2. Predicted from the empty hall measurement.
3. Estimated from the relation between RT and EDT for the empty hall.
4. Calculated by using the predicted RT for occupied condition.

Table 1. Results of objective measurements in Segerstrom Hall. (See text for details of terms).

Reverberation Time and Early Decay Time

The mean mid-frequency value of RT in the empty auditorium is 2.4 seconds. This value is predicted to fall to 2.1 seconds when the hall is fully occupied. The mid-frequency EDT is slightly shorter than the RT which is to be expected in a directed reflection sequence hall where the early decay is dominated by the sound field between the main reflecting surfaces. Both the EDT and RT are basically flat with regard to frequency.

Early-to-Late Sound Index

Typical values in the empty hall are around 0dB, i.e. an equal balance between early and late sound energy. These are predicted to increase to 1dB when occupied. Both these figures indicate a high degree of clarity.

Early Lateral Energy Fraction

The mean value of 0.23 is high and, moreover, is substantially higher than the Christchurch and Wellington halls. These are respectively 0.15 and 0.17.

Steady State Lavel
Measured levels are all well in excess of the lower criterion of OdB, i.e. the level of the direct sound at 10m, and do not vary much with position.

Objective Effects of Extending Curtains
The RT in the empty auditorium is reduced at mid-frequencies by 14% by extending the curtains, namely from 2.4 to 2.1 seconds. The corresponding change in EDT is 13%. Clearly this is a desirable change for a multipurpose space.

Summarising the objective results, the mean values for all the measures are favourable which is a notable achievement in view of the large audience capacity of Segerstrom Hall. The RT is long and the EDT, although slightly shorter, is still ample. In common with other directed reflection sequence halls, the measured early-to-late sound index is on average higher than expected from the RT but values remain typical for concert halls in general. The proportion of early lateral energy is high and the total sound level is very high for a hall of this capacity.

4.2 Subjective Tests
The arrangements for subjective testing were considerable. Four major sessions were held consisting of the following professional performers: a Mozart ensemble, a solo pianist, vocal soloists with a piano accompaniment and a violin and piano duo. For each session the stage and its enlosure were arranged to suit the performance taking place (see later).

During each session a group of six or more acousticians moved among the selected seats and assessed the acoustical quality by completing questionnaires. This included marking up a number of subjective scales such as clarity, reverberance, loudness etc which had previously been devised by Barron for his acoustic survey of British auditoria [15]. The results of this exercise showed a remarkable consistency of response between the listeners and also between the seats. Particularly noteworthy were the high scores given to envelopment and loudness. For the Mozart ensemble session, the overall response was averaged over all the listeners which gave a rating for the acoustics of Segerstrom Hall as very good at all the seats tested.

Summarising the subjective results, music in Segerstrom Hall can be characterised as having a high level of clarity, reverberance and loudness together with a great sense of intimacy and envelopment. In addition, pianissimo passages were well received at all the seats which probably enhances the sense of intimacy.

Speech, although not tested on a formal basis, remains clear at even the most distant seats using normal voice level. This suggests that a directed reflection sequence design may fulfill more closely the conflicting requirements of a multipurpose hall than other designs.

4.3 Acoustic conditions for performers
Considerable design effort was channelled into providing an appropriate acoustical environment for performers. The stage area and related shell and reflector system can expand or contract to five basic configurations ranging

from solo mode to symphony plus chorus. The stage areas range from $50m^2$ to $300m^2$.

The musicians who played in the four test sessions were questioned about the acoustical conditions for performance. They uniformly commented on the ability to hear each other as well as receiving good support from the hall.

5. CONCLUSIONS

In concluding, it is evident that several new major factors have been introduced into the acoustical design of concert halls in the past 30 to 40 years. These factors stem from the results of careful psychoacoustic experimentation and in some cases from theoretical developments. The main findings, in subjective terms, are that an audience listening to a musical performance requires adequate loudness, clarity, reverberance and envelopment. In objective terms, this means sufficiently high sound level, a long Early Decay Time, and strong early reflections with many arriving from lateral directions.

The implications for concert hall design are that the volume must be sufficiently large to provide the necessary reverberation and that surfaces must be provided within this volume to ensure an appropriate sequence of early reflections where the reflection direction is also taken into account. These early reflections may be provided by reflectors above and to the sides of the seating and also by subdividing the seating areas themselves.

These design concepts have been implemented to the full extent in Segerstrom Hall and both the objective and subjective results support their validity.

6. ACKNOWLEDGEMENTS

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