Proceedings of the International Symposium on Room Acoustics, ISRA 2010

29-31 August 2010, Melbourne, Australia

Whole stage imaging for the control of sound strength in concert halls

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PACS: 43.55.Br , 43.55.Fw, 43.55.Mc

ABSTRACT

The effect of early and late reflected energy upon perceived sound strength in concert halls is well known. In turn the presence of reflected energy throughout a hall may be determined by the adequacy of the design to image the stage at the frequencies of interest for any given seat or group of seats. This approach is in contrast with current ray tracing software which depends upon point to point transmission paths. Is it possible to image the whole stage in such programs are all sections of the orchestra of equal acoustical significance, and finally what design implications may be drawn? Examples from recent and historical experience address these questions.

INTRODUCTION

It is well known that the size and location of reflection surfaces in an auditorium affects the spatial and temporal distribution of reflected sound. This paper discusses the distribution of the early reflections as a result of room geometry, the generation of late and reverberant fields in different room types.

IMAGE SOURCE DISTRIBUTIONS

For simplicity we consider the two dimensional plan view. The narrow shoebox design is known to generate lateral reflections up to high order from the side walls. A source S on stage will generate a direct sound at receiver R, and reflected images S', S'' etc from successive order side wall reflections. Given sufficient size of the side wall surfaces images of the whole stage are generated as illustrated in Figure 1.

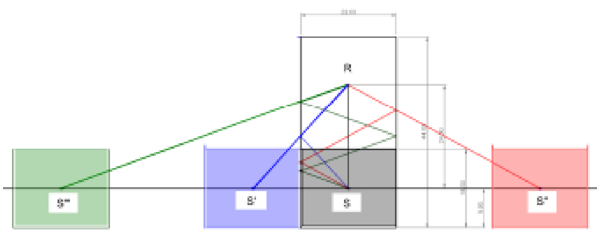

Figure 1. Image sources in shoebox rectangular halls

Due to the parallel side walls of the design the image sources appear on a line perpendicular to the direct path S R. Each successive image source is further from the direct path, and contributes an increasing component to the apparent source width.

For first order early reflections, arriving less than 80ms after the direct sound, we have to satisfy

$$A + A' - D < 80\,\text{ms}$$

where A is the travel time from the source to the side wall, A' is the travel time for the reflection from the side wall to the receiver, and D is the travel time for the direct sound.

This implies that for a reflection to be early, the point of reflection must lie inside the ellipse generated by $A + A' = D + 80\,\text{ms}$, with foci located at the source and the receiver positions as shown in Figure 2 below.

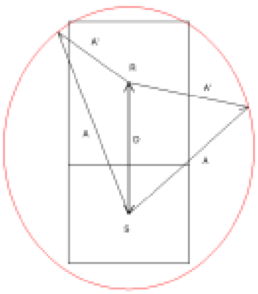

Figure 2. Ellipse showing the position of reflectors generating reflections 80ms after the direct sound for source point S, receiver R

At any given receiver, only the images sources located less than 80ms travel time after the direct sound contribute to the early energy received; those located more than 80ms but less than 180ms away contribute to the late field.

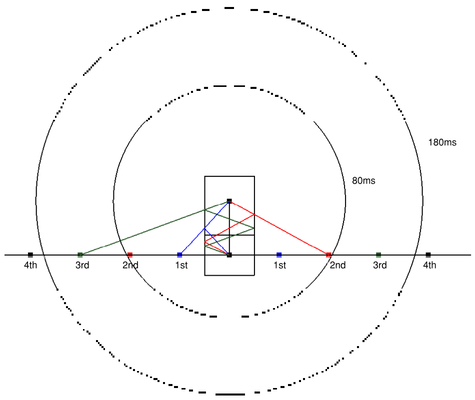

Figure 3. Contribution of image sources to 80ms and 180ms time intervals

For fan-shaped halls, the same geometrical considerations can be made leading to Figures 4 and 5.

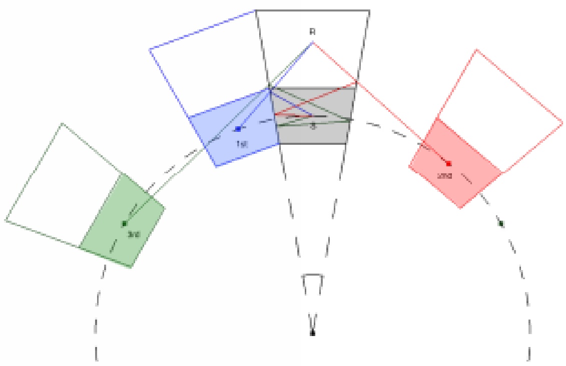

Figure 4. Image sources for fan-shaped halls

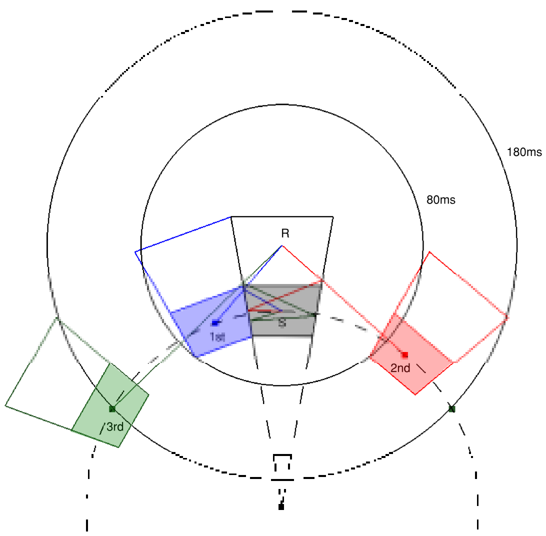

Figure 5. Contribution of image sources to the 80ms and 180ms time intervals – fan shaped halls

It can be seen from Figures 4 and 5 that fan-shaped halls generate image sources that are distributed along a circle the radius of which depends on the angle of splay of the side walls: the wider the fan, the smaller the circle as illustrated in Figure 6 below.

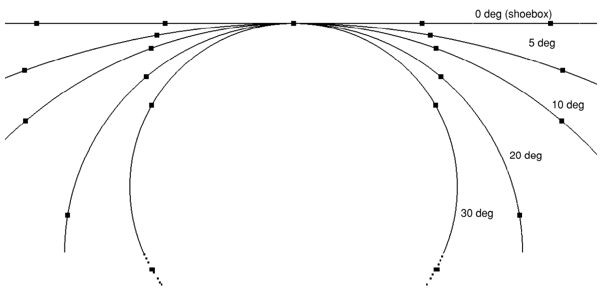

Figure 6. Image source distribution for different angles of splay of the side wall of fan shaped halls

As the angle of splay increases the image sources lie on a smaller circle. The wider splay generates a narrower source impression, and consequently to a lesser sense of envelopment for the audience.

A different situation arises with a greater number of "side walls" as in the Christchurch Town Hall [1]. Similar analysis shows that this wall geometry generates several first order reflections on each side of the receiver, and the distribution brings the image sources forward of the stage, beside and even behind the receiver.

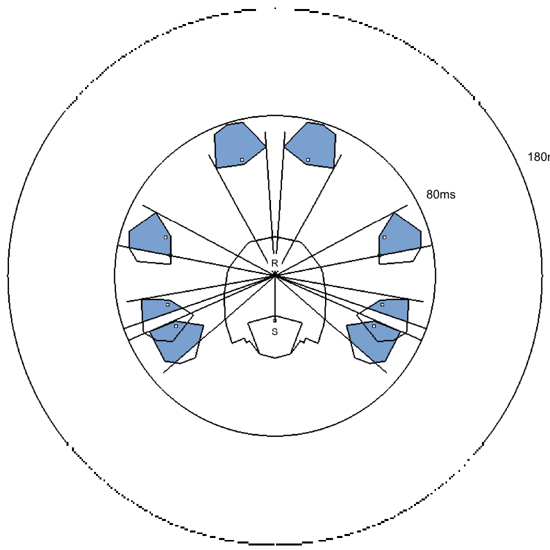

Figure 7. First order image source distribution in Christchurch Town Hall

Figure 7 shows the distribution of first order images surrounding the receiver position. For this receiver position all first order reflections sit within the 80ms time interval to qualify as early reflections. We observe that of the eight first order images of the stage only two are of the complete stage. However it is seen that all stage positions are represented at least four times.

As we consider higher order reflections we find that they similarly surround the receiver. This contributes to increased levels of both early and later listener envelopment beyond that demonstrated in the shoebox or fan shaped hall.

If we move into the three dimensional case we find that the ellipse defining the 80ms time interval is replaced by an ellipsoidal surface. Any suitably orientated surface inside the hall situated within this limit can contribute a first order reflection to the early energy reaching the receiver.

Figure 8 shows source and receiver positions aligned in a model of Christchurch Town Hall, and then with the ellipsoid representing 80ms path difference superimposed. All the interior balcony fronts and oblique ceiling reflectors are included within the ellipsoid.

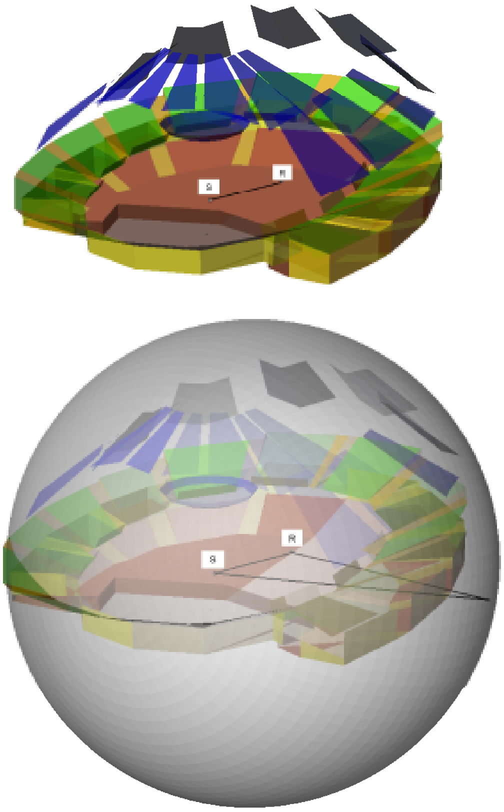

Figure 8. Interior reflectors in Christchurch Town Hall contained within the ellipsoid of 80ms path difference for first order reflections

Similar techniques have been used in the alignment and spacing of the early reflecting surfaces in several recent projects despite very different types of architectural expression being employed.

SUBDIVISION OF SPACE

Recently efforts have been made to relate architectural design to *acoustic efficiency* of room geometries to provide early reflections to the audience [4]. A new criterion and two methods to quantify the early efficiency of the hall were proposed. The criterion (S_{EE}) was designed as the total surface area of all "acoustically efficient surfaces" in the room; that is all surfaces that provide reflections to the audience or back to the musicians.

This concept is used in the Programme Acoustique for the Philharmonie de Paris [5]. The realisation of the early reflection surfaces for the design of this venue is shown in Figure 9.

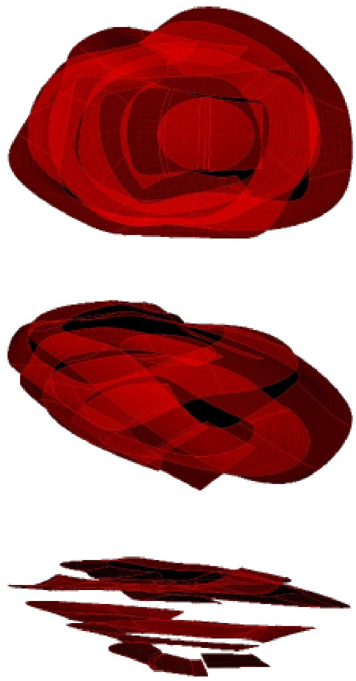

Figure 9. View of seating and early reflection surfaces for the Philharmonie de Paris

A second criterion (Ω_{EE}) is more refined and quantifies the same criteria in terms of solid-angles. This takes into consideration the orientation of the surfaces with respect to the source. More details are available in reference [4].

This encouraging approach not only provides a quick and efficient way of determining the potential of a specific room geometry for sufficient early energy, but provides an easy way for the architect to understand the criterion.

However, the surfaces that meet the above requirements are numerous, and can include surfaces within 15m from the audience that provide weak high order reflections. This may lead to an over-estimation of the early efficiency of the geometry. Indeed, a geometry can achieve a specified value of S_{EE} or Ω_{EE}, yet the design will not provide sufficient early energy, or adequate balance between early/late energy or between frontal/lateral reflections.

It is consequently proposed to refine the selection criteria for the efficient surfaces and limit the criterion estimation to the surfaces that provide 1st order and very close 2nd order reflections to the audience. This will result in an estimation of surfaces that are not only near the audience or source but also appropriately directed and oriented in the space. The inclusion of the close 2nd order reflections is justified by the evidence provided in the first part of this paper: narrow shoebox halls provide many useful 2nd order reflections that meet the criterion and contribute significantly to source broadening.

In addition to the above comment, reflection efficiency of a room can also be expressed in terms of distribution to the audience. The criterion proposed in reference [4] can be achieved and yet result in a disparity of its intended effect over the whole audience area. It is therefore important to consider the various audience areas and therefore define Ω_{EE} within all spatial domains of the room, each one being associated with a specific audience area.

The cross-section in Figure 10 illustrates how this can be achieved in a typical room comprising of a stall audience and three balconies.

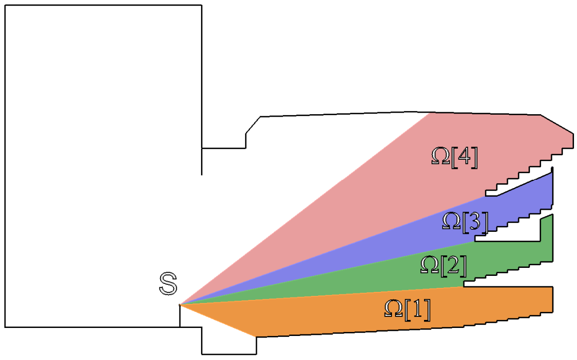

Figure 10. A solid angle domain for each audience area

The above 2D illustration shows how the 'vertical' sub-division of the space can, combined with the planar sub-division discussed in the first part of the paper, lead to an identification of the most useful surfaces to direct early reflections to a specific audience area.

One can go further and define, for each audience area, a solid angle where reflective surfaces are most efficient at directing early reflections of the entire stage/orchestra.

However, Figure 10 only includes the surfaces that are appropriately located to provide 1st order or close 2nd order reflections and are 'naturally' located in the space. This does not mean that only the energy within these solid angles is useful and sufficient. Indeed surfaces outside these solid angles can be oriented to direct reflections respective seating areas and thus increase the *early efficiency* of the room behond what the general shape of the room provides. This was successfully implemented in Segerstrom Hall at the Orange County Performing Arts Centre by Marshall and Hyde, and more recently at the Beijing Television Studio, as illustrated in Figures 11 and 12.

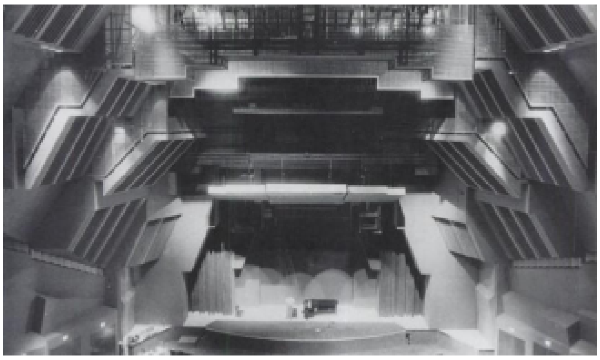

Figure 11. Side wall reflectors in Orange County Performing Arts Centre to control distribution of early and late reflections

Figure 12. Side wall reflectors in Beijing Television Studio angled to create controlled distribution of early and later sound

The concept has also been used in the Guangzhou Opera House and the Philharmonie de Paris which incorporate very different architectural forms. This demonstates the degree of flexibility in the realisation of this approach.

Figure 13. Curved side walls used to generate early reflections in the Guangzhou Opera House

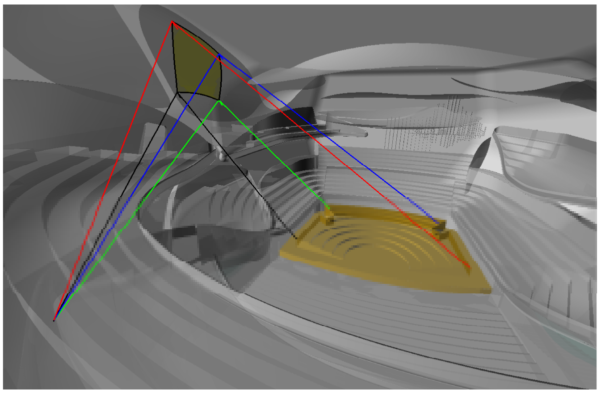

Figure 14. Whole stage image generated by interior reflectors in the Philharmonie de Paris model

SUBDIVISION OF TIME

The second comment that can be made on the proposed criterion is that, although the criterion implies a division of space (surfaces location) and time (distance to source and receiver thus delay) it does not address explicitly the question of early to late energy balance.

Indeed achieving a certain value of early efficiency (either S_{EE} or Ω_{EE}) defined in a project brief, and therefore before a room geometry is proposed, does not guarantee an appropriate balance between early (source presence) to late response (room presence). Extending the criterion to the subsequent time intervals of the room response may provide further guidance to the designers or a more complete description of the acoustics of the room.

It is evident that the solid angle expression of the early efficiency of a space is the most meaningful to acousticians. The proposed time intervals over which the solid angle efficiency of the room can be defined are the following:

- Early directed field (0 to 80ms) comprising of a criterion for all early reflections and one for the *lateral early reflections*
- Late field (80 to 180ms) for all early reflections
- Diffuse field (> 180ms) for the surfaces that directly "feed" the reverberant field
- Stage field for the surface oriented to provide reflections back to the musicians.

Values for these various parameters are not proposed here as they depend highly on the expected use and repertoire for each project. However, we note that a good balance between the early directed and late fields is important, and this can potentially be adjusted without compromising the diffuse and stage fields.

CONCLUSION

The present paper has presented an approach for the design of concert halls that is based on the proposed architectural criterion proposed by Jurkiewicz & Kahle.

It was shown that interpreting the criterion in the context of space and time sub-division can lead to a thorough and systematic method to ensure that all seating areas in a room benefit from early reflections of the entire stage.

Further developments of the criterion are proposed to both refine its relevance and describe more completely the acoustic response of a room and in particular, the control of lateral and frontal energy, and the balance between early and late response of the room.

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