

Proceedings of the Institute of Acoustics

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

R Essert

Arup Acoustics, Boston House, 36-38 Fitzroy Square, London, W1P 5LL, UK.

1. INTRODUCTION

Over the last quarter century progress has accelerated in our understanding of the effects that spatial distribution of sound have on our perception. We can consider the sound propagation in a room as the change in spatial attributes of the sound field over time, or as the change in time/frequency response for a given input and output over space. The room response is a function of space and time, and can be "sliced" in many different ways for our understanding of the process. This paper will focus mostly on the impulse response - the response at an output from a given input. It is an essential part of analysis in modelling, measurement and control.

I call the room response for a single point source and point receiver the 3D impulse response (3DIR). This includes the effects of source and receiver directivities. It can encompass several channels of data, which together provide complete information on amplitude as a function of time and direction. The binaural room impulse response (BRIR) is sufficient to describe the inputs to our two ears, which is enough to render perceptual models, but it doesn't explicitly relate to direction. The 3DIR includes directional information, and therefore relationships with the room geometry, the architecture of the space.

What are a sufficient number of degrees of freedom? If we rely totally on perception based models and measurement of binaural room impulse responses, we may know how a room sounds, but may not be able to link the sound specifically to the architecture. As room acoustics consultants and designers we need both the perceptual and the spatial models, to relate the sound field to the architecture and to perception.

Much of the recent work focused on the spatial aspects of sound fields is relevant to, indeed driven by, the analysis and design of auditoria. In this paper we will review some aspects of spatial hearing, spatial measurements, modelling and auralisation. We will also look at what spatial sound fields are preferred for different events and how geometrical form can influence them.

Auditorium designs have responded to the growing understanding of spatial sound, but not enough. By understanding the links between architecture and acoustics we can make greater progress in translating acoustical goals into room shape. We need to be more proactive in design, but we also need to understand which goals are appropriate for which rooms and which uses.

2. PERCEPTION

Our understanding of sound perception has come a long way since W.C. Sabine measured reverberation times by ear in Sanders Theatre. The suggestions by Marshall and Barron and the Gittingen and Berlin groups that room geometry is important to our sense of acoustical space was a watershed. Their deduction that lateral energy has something to do with it has been accepted ever since. Just how much and through what means remain the subject of debate. Blauert's work on spatial hearing has illuminated a great deal about the mechanisms and reasons behind our perception of space and timbre. Our ears, head

Proceedings of the Institute of Acoustics

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

and torso filter the sound before it gets to the auditory nerve, creating binaural dissimilarity that varies with frequency. The same mechanism creates a dependence of perceived timbre (and loudness) on direction of arrival of sound. An ensemble of reflected waves arriving from different directions is processed by the brain as an ensemble according to a complex set of rules.

Is our sense of envelopment due to amplitude differences between the ears, or to phase differences, or both? Ando and others are focused on Interaural Correlation Coefficient (IACC) as a better indicator of the perception of envelopment. Griesinger has related "Room Impression" to fluctuations in amplitude and timing differences between the two ears.

Our perception of acoustical space seems to be multidimensional. Among the distinct perceptions for music in concert halls are what we currently call (a) source broadening (b) envelopment. These have been linked to (a) lower frequency, earlier sound and (b) higher frequency, later sound, respectively. Can we control them independently with architecture? With electronics? Do we want to? It has been clear since the work of Khl that some spatial effects are dependent on overall sound level, or in effect, the absolute measure of lateral energy. There is little argument that these spaciousness (envelopment, etc.) are important in music acoustics, but little agreement on what is enough. Is there an optimum? If so, it would seem to be dependent on the type of performance or repertoire of music.

In researching how we hear and what we like, we keep in mind the practical analysis and modelling applications. What is sufficient accuracy? If we try to model all the physics and hearing/psychological processes to the highest possible accuracy, we may be overdetermining the result if we can't hear all the dimensions or all the accuracy.

3. MEASUREMENT

Sabine used his ears and a stopwatch to measure sound decays. Since then, the vast majority of auditorium acoustics measurement was, and still is, done with a single omnidirectional microphone. In the 60's and 70's we began to record and analyse impulse responses, looking at various energy ratios. These still involved single channel data, for the most part. Directional information was sometimes investigated with directional microphones and parabolic reflectors.

With the recognition that lateral sound and binaural dissimilarity are important in concert hall acoustics, Barron and others began to measure lateral fraction and Ando pushed forward with Interaural Cross Correlation and the binaural impulse response. The Lateral Energy Fraction at a point has been measured in halls for some years now, though Bradley, Beranek and others have evidence that it is not well correlated with perception.

For concert hall and theatre designers information on the spatial aspects of the sound field is helpful in relating the sound to the architecture, to help us understand which surfaces ultimately reflect the sound to the listener. Moreover, we need to study the directional attributes of sound fields in halls and correlate them with perceptual attributes.

Proceedings of the Institute of Acoustics

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

Our goals for 3D measurements include the following:

- Development of a library of 3D measurements made in many facilities
- Diagnostic tool to help understand the directional behaviour of the sound field in time
- Full 3D spatial impulse response, including pressure as a function of time, direction
- Ability to slice data across time and space
- Motivate / develop new approaches to visualisation / animation
- Auralisation - independent of specific ears used in recording

Large arrays for high directional resolution have been developed by several teams. However, we can recognise that four channels of information is sufficient in principle to fully describe the 3D spatial sound field, though at a price of lower spatial resolution. The four channels are three orthogonal directional vectors and a total pressure.

Recently, several groups have developed room acoustics measurement systems based on 4 omnidirectional pressure microphones in a tetrahedral array:

- Yamasaki and Itow
- Sekiguchi, Kimura & Hanyu
- Korenaga

and a 3D Intensity Method:

- Abdou and Guy

The Soundfield microphone, pioneered by Michael Gerzon and Duane Cooper in the 70's, is a very closely spaced tetrahedral array of cardioid microphones, time aligned to measure the sound at a point at the centre of the array. The four signals can be combined in a certain way to give pressure gradient (fig-8) response in X, Y, Z directions and the pressure response W; this set of outputs has been called "B-format".

I had been using an omni/fig-8 microphone pair for lateral energy fraction measurements, and along the way, developed an approach to show the instantaneous lateral or frontal fraction. The process is a cross correlation of the pressure and gradient channels, normalized by the autocorrelation of the pressure channel, for a short time window that, ideally, would be chosen according to perceptual relevance.

Since the Soundfield microphone B-format outputs are equivalent to the cosine directivity pressure gradient microphone, we can use the same formula to derive the fractions for each direction X, Y, Z with the common W pressure response.

The x, y, z fractions constitute the amplitude shading in each direction according to the cosine weighting of the microphone. We can therefore consider the three directional fractions to be "directional cosines" to establish the general resultant direction of sound at a particular instant with respect to the receiver (listener).

Proceedings of the Institute of Acoustics

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

4. MODELLING AND AURALISATION (SOUND RENDERING)

Acoustical modelling and auralisation techniques have helped us to understand spatial aspects of sound by visualising explicitly 3D sound paths in the model and by listening to modelled phenomena. They have challenged us to think explicitly about some of the more detailed aspects of the behaviour of sound in halls and of sound sources, as well as of perception.

Mainstream acoustical modelling in architectural projects is based fundamentally on geometrical acoustics, with ad hoc extensions for non-trivial phenomena such as edge diffraction, diffusion, and oblique angle absorption coefficients.

The directivity of instruments and voices has an influence on our perception of the timbre of the instruments and their loudness (and therefore balance with others in the ensemble). The behaviour of violin sound radiation is complex, the quality of sound different in various directions. How many directions are sufficient for modelling? Loudspeaker manufacturers are publishing the directivities of their horns at 10 degrees, but that may be overkill. Auralisation will help us find what is the appropriate amount of detail.

One of the great needs is anechoic source music and speech measured at a number of directions. Instruments and voices are not isotropic sources, and an orchestra is not a point source. In modelling we use an approximation of a number of point sources, but we don't have source material recorded separately at each instrument of the orchestra.

We are controlling the rendering of sound in space, a tremendously complex undertaking. Technology for auralisation is being driven in part from the military and aerospace industry. In spatial auditory display of warnings to airplane pilots Begault and Wenzel at NASA Ames have located audio signals and communication channels in virtual audio space to enhance the ability of pilots to separate streams of information. Related work in auditory display of non-audio data includes the use of data to control a sound generator ("sonification"), and the translation of data waveforms into the audible domain for purposes of monitoring ("audification").

5. DESIGN EVOLUTION

Design of concert rooms has followed, roughly in parallel, the state of the knowledge in concert hall acoustics. Certain basic shapes evolved for each performance/event type. This was not driven by knowledge of any deterministic connection between room shape and sound, but rather by the way people gather naturally, for proximity and sightlines, for structural capacity and for social reasons.

At first, distance, clear sightlines and shielding from noise were the principle factors considered. The plan shape and steep rake of open Greek and Roman amphitheatres brought people as close as possible to the performers, and the steep rake allowed the first-order floor reflection to benefit the listeners and also served as a barrier from the street activity. Without a roof, this was essentially 2-dimensional space, with 2 parameters - distance and seating slope.

As George Izenour reminds us, the Greeks and Romans also built roofed theatres that behaved as contained 3-dimensional spaces. Whether the ancients, including Vitruvius, knew the reasons for the acoustical differences between roofed and open spaces is an open question. Did the higher level of reverberance under the roof influence the composition or performance of the odes and oratories of the day?

Proceedings of the Institute of Acoustics

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

Through much of the Middle Ages and the Renaissance, churches and cathedrals became more and more reverberant as buildings were designed taller. The sound absorption in those buildings is concentrated at the floor plane, and the upper reaches of the spaces are mostly vertical, hard, and rectilinear (except for domes). The hard "top hat" volume sustains reverberation stronger and longer in the upper part of the room than in the lower portion near the audience. This is a loosely coupled volume system. We are all familiar with the sense in tall churches that the reverberance moves upward with time.

Later we notice an effort to provide specific surfaces to assist with clarity by provide supporting sound reflections. One common example is a lid above the pulpit.

Eighteenth and nineteenth century music rooms were still limited in width by the clear span of timber trusses. Into the mid 19th century the shaping was still mostly empirical, and the "shoebox" form was popular. Music of the time was composed with the performance rooms in mind, and these rooms provided a strong, laterally biased reverberation.

Opera grew up in drier spaces, with audience stacked on the side walls up to the ceiling. Still, complete absence of reflections is not what was desired or designed. Beauty of tone and some sense of room sound is important for both the audiences and the performers.

Chinese opera, typical of many Asian performing arts, evolved outdoors. Here there's no sense of indoor space, not much in the way of reflecting surfaces. The piercing vocal techniques, the percussive orchestrations and the small audience sizes have been influenced accordingly.

5.1 The 20th Century

Sabine found a simple relation between volume, area and decay time. We know this as RT or $T60$, a one-dimensional parameter depending on volume and area.

After considering volume and area, the next level of detail includes specific reflections. Certain first-order reflectors arrive at the listener from overhead. A low ceiling tends to promote low reverberance, lack of envelopment and generally inadequate increase in loudness as it directs sound into the absorbing audience.

In the early 60's Leo Beranek postulated the importance of Initial Time delay Gap, and this often led to arrays of small reflectors suspended below the ceiling. This allowed the ceiling to be higher to sustain reverberance, but the reverberation was still addressed as simply a function of volume and area or number of seats, and the twin assumptions that (a) a diffuse field is perceptually desirable and (b) the late sound field in large, perceptually "reverberant" halls is diffuse.

Wide fan shaped and oval halls with overhead reflectors were not received well. The halls of the early 1980's in Toronto, San Francisco and Melbourne come to mind. The analysis of what these halls are missing has led us to look at the importance of running liveness, loudness of reverberation, and to take more seriously the notion that envelopment is related to loudness of lateral sound, both early and early and late lateral sound.

DEVELOPING AWARENESS AND CONTROL OF SPATIAL SOUND

The importance of lateral reflections was advanced by Barron and Marshall. At first this spawned "first-order designs" with wall elements or applied wall panels tilted down and in to direct strong first order reflections to the centre of the audience. Examples include halls in Christchurch, Wellington, Nottingham, Colorado Springs and Glasgow. One attribute of this sort of hall is a faster decay and greater clarity, as the tilted reflectors send the sound into the audience. This fact has been used to advantage in multipurpose halls such as Colorado Springs, Basingstoke, among others. The development of reverberance in the auditorium is strong and lateral, but dies away fairly quickly, which is good for opera and musical theatre, where intelligibility is important.

In realising that the reverberant level was important, we looked for ways to achieve strong lateralisation of the sound and strong reverberant level, or reverberation efficiency. The next step was 1st & 2nd order lateral reflections. We can learn from the old halls that narrow, tall shoebox spaces provide 1st order side wall and ceiling reflections, and sustain reverberance horizontally above the audience plane. This can result in a muddy sound if there is not enough early energy. Adding a 2nd and perhaps 3rd side tier soffit returns more energy immediately to the lower levels. With appropriate dimensions, this geometry adds 2nd order strong lateral reflections. But it also retains the vertical opposed surfaces that sustain reverberance. This is reverberation efficiency. Some halls, such as Carnegie Hall, have the audience densely stacked at the rear, and sparsely arranged on the side tiers. This supports lateral energy and not much higher order front-back energy flow. In halls where there are few people on either the side or rear walls at high level, reverberance is developed between the side walls and between the front and rear walls, but there is a different time constant, or group delay, between the two. Boston Symphony Hall is a classic case where the length is great enough and the rear wall tall enough that one hears the return of a broad bundle of energy, a "push" from the rear wall.

Listeners want to feel surrounded by reverberance in symphony, organ chorus concerts. In balance with an appropriate measure of directional fidelity. In amplified events, the clarity, intelligibility and directional fidelity are considered more important. Variable sound absorption systems affect the spatial qualities as well as the time response.

Coupled volumes have been used to provide extended reverberance. In multipurpose halls, coupled spaces have been developed from "found space", such as stage fly space, to greater and lesser effect. In concert halls coupled volumes have surrounded the top of the room. New designs will bring the chamber down lower around the performers and audience.

This is leading toward an ability to tailor the acoustical spaciousness of a room, much as we have been tailoring the decay rate. Just as our control of time response has moved from a period of architectural development, and then into electronics, so our control of spatial aspects is moving through a stage of mechanical/architectural control systems and into electronic mimicry of the architectural solutions. This will evolve into the extension of the electronic control into areas that are not or cannot be dealt with architecturally: from sound effects to virtual rooms, to variable spaciousness, to direct performer control of spatial sound.