The Predictive Capacity of Ray Traced Acoustic Models

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Abstract:
This paper examines the potential of acoustic ray tracing as a modelling tool useful to architects and engineers during the design phase. An application has been developed that uses this technique and, whilst the basic algorithms are well understood, some discussion of their implementation is presented. The ability to accurately predict objective acoustic measures is considered, along with the ways in which related information can be displayed in a meaningful form. The authors look at the information relating to spatial behaviour that can be derived from such a model and conclude that the ability to interactively relate sound behaviour and room geometry is of significant benefit.

Introduction

When considering acoustic performance, there would be few architects who do not undertake some form of mental estimation of sound reflection paths before settling on the form of an enclosure. This may even extend to the drawing board for a more comprehensive analysis of some complex geometry. Given the significance of room shape as a factor in overall acoustic performance, such exercises are an essential part of the design process.

Even though the calculation of reflection paths is based on very simple geometric techniques, it is an extremely laborious process and much more suited to a computer application. It is therefore the intent of this paper to investigate the potential of an exhaustive computer ray tracing program as a useful and, more importantly, a meaningful design tool.

Acoustic Ray-Tracing

Computer programs performing acoustic ray traces are certainly not new, going at least as far back as 1972 [1]. Whilst these early programs were restricted to rectangular enclosures, later papers refer to more complex models [2, 3].

It is not the scope of this paper to discuss, in detail, the mechanics of ray tracing as this has been well documented in the literature [4, 5]. It is, however, important to consider some of the assumptions underlying these calculations in order to better understand what exactly is being calculated.

When approaching the problem, it is considered that the transfer of sound energy between two points represents a simple transmission system. Therefore a comparison of input and output will highlight any distortions introduced to the signal by that system. Using a free field reference and neglecting the influence of rapid air movement, enclosing a source and receiver within a bounded space can have only two effects on the transmission of sound energy between them:

- The introduction of indirect energy or reverberation as propagating sound waves reflect off boundary surfaces and
- The introduction of additional quiescent or background noise not originally present in the input signal.

Since neither background noise nor reverberation necessarily distort energy in the frequency domain [6], the analysis of the model is restricted to distortions in the time domain. Additionally, as the level of background noise is assumed to be constant over the short duration of the test period, the reflected portion becomes the main subject of concern.

Acoustic Modelling

One means of modelling this reflected sound is to assume that an infinitely short pulse of intense sound energy is emitted by the source. Sound energy arriving at the receiver may then be considered in two distinct parts; direct energy resulting from a single pulse propagating straight from the source, followed by indirect energy as pulses reflect off boundary surfaces. Thus, by plotting the time delay and intensity of each reflected pulse, relative to the direct pulse, the impulse response and ultimately the sound transmission characteristic between two points within that enclosure, can be uniquely described.

Describing a transmission system in terms of its impulse response is extremely useful, especially in the case of an architectural space. First of all, it allows predictions to be made as to the behaviour of that space to any other input signal using linear systems theory. Second, and more importantly from a formal point of view, it provides a clear indication of the behaviour of early reflections and their relationship to the geometry of the enclosure.

If the position of individual pulses within the impulse response graph can be related to their reflection paths, then tracking down the causes of spurious echoes and spikes becomes the simplest of tasks. Additionally, relating the impulse response to a polar diagram of intensity and azimuth may, for want of an example, enhance the detection of such things as the masking of lateral energy by stronger frontal reflections.

To adequately define an impulse response, the relative delay, direction and intensity of each impulse must be known. Modelling the geometric behaviour of a sound field will yield the relative delay and direction of each pulse whereas the more difficult task of modelling boundary incidence is required to determine intensity.

Modelling Geometric Behaviour

Using the assumptions of geometrical acoustics, a sound ray can be considered to represent the normal to a sound wave propagating away from a source. The path of such a ray can be traced using simple three dimensional geometry, assuming specular reflection upon intersecting a boundary surface. Whilst such an assumption does not hold completely true for boundaries of finite impedance [7], the blurring effects of non-rigid walls are quite complicated yet do not seriously affect the final results under typical conditions [2, 8, 9].

As the primary intention is to yield an impulse response, the method of images is used to derive possible reflection paths. This method replaces the effect of room boundaries with an infinite array of image sources, each corresponding to a particular path of multiple reflection. If each of these images is then taken to emit the same intense pulse as the source, at exactly the same time, then the reverberant sound field can be defined as the sum of the contributions of each image. The delay of a pulse relates to the distance to a particular image from the receiver minus the distance to the source. The direction can then be determined using the relative azimuth and altitude of the image.

Modelling Acoustic behaviour

Calculating the relative intensity of an impulse requires not only the image position but the complete geometric history of each ray. As attenuation is taken to result from the effects of geometric spreading, molecular absorption and incidental absorption, knowledge as to the total distance travelled and the reflection characteristics of each boundary surface intersected is essential.

The effects of geometric spreading and molecular absorption are well known and relatively simple to apply [10, 11]. Incident absorption, however, is more difficult and requires certain assumptions.

The first of these is that boundaries have real impedance and that diffusion, including the diffraction effects of edges, can be neglected. As discussed previously, finite impedance does not invalidate the method, whereas neglecting diffusion and diffraction does ignore a portion of the sound energy arriving at the receiver. As a fraction of total energy, this amount depends upon the geometry of the enclosure and the receivers position within it. The effect of this assumption will be most obvious when considering energy relationships and ratios, however, any such effect is sure to be obscured by a lack of higher order reflections.

The second assumption is that, of the total energy of a sound ray intersecting a boundary, some portion of it will be absorbed, some will pass through and the rest will be reflected back into the enclosure. In practise, the absorption characteristic of a surface is rated by a coefficient indicating the fraction of randomly incident sound energy not reflected. These coefficients often result from tests within reverberation chambers, measuring changes in overall absorption as a result of the presence of a specified surface area of material. For the purposes of this model, the resulting value is taken to be the average amount by which any incident sound ray will be attenuated by that surface. Whilst useful for statistical calculations, these coefficients take no account of incidence angle or the diffusion characteristics of a material.

An ideal model of incident behaviour would be to consider each wall surface as a separate filter through which the impulse signal must pass. The frequency response of a particular reflected pulse could then be determined by taking the Fourier transform of the original input signal and multiplying it by the frequency response of each filter in it's path. The physical shape of the reflected pulse is returned using the inverse Fourier transform of the resulting spectrum. Alternatively, this method may be applied to the test function. An infinitely short sound pulse is referred to as a delta function. The delta function has a flat frequency response with equal energy per cycle (which for the purposes of modelling, is assumed to be unity). Therefore, multiplying only the frequency response of each boundary surface intersected and the effects of molecular absorption would yield an individual transfer function for each possible ray path.

Given the difficulties of obtaining complex absorption functions for all building materials, this work is currently concerned only with discrete frequency bands until this information becomes more readily available.

Another method is to describe each surface as a series of frequency dependant directional coefficients. This may entail measuring the attenuation of an incident sound at a number of angles and frequencies. Thus, based on empirical measurements, such a method inherently includes the diffusion characteristic of the surface, at various angles, as an amount of apparent absorption over and above actual absorption.

For all but phased array gratings, the amount of energy specularly reflected by a totally diffuse surface should be equal to that in all other directions. For a slightly diffuse surface it is much greater, thus it is assumed, for the purposes of this image model, that the reflection in the specular direction is still of greatest significance.

The wisest option would seem to be to include both the single absorption coefficient method as well as the array method based on incidence angle. In this way single coefficients make for both ease and speed of use whilst multiple coefficients allow for a much more detailed model analysis when required and when data is available.

Developing a Design Tool

Taking all of this into consideration, an application is being developed to test these assumptions and determine if such a model can produce reliable predictions. Obviously the image method is not about directly modelling every aspect of a real sound field. However, from an architectural perspective, the geometric and statistical information it can yield is certainly worth pursuing. In addition to calculating the value of particular objective measures, this information can determine not only the best position and orientation of reflectors, but also the most effective absorber location within a wall surface. Thus, whilst statistical calculations can tell how much absorber is required, with this method the architect can work out exactly where to put it and, with a statistical analysis of the incidence angles of each ray on each surface, what type to use.

The application has been termed ‘RayPath’ and was originally developed on a Sun Workstation. It has recently been ported to a DOS environment with another version under MS Windows in the planning stages. The package itself is quite comprehensive but has yet to be extensively field tested, however, initial results, along with the experience of several small jobs, have significantly encouraged the authors.

To target a tool such as this at architects, one needs to carefully consider useability. Obviously it is preferable not to have to invest a great deal of time preparing a model as, generally, the more complex a task, the more likely it is to be undertaken at the very end of the design process.

Therefore the design aims of this package were to:

- Avoid involved modelling methods
- Optimise calculation resources
- Produce meaningful results

It is hoped that by pursuing these aims, if not RayPath then future applications will play less of a role in post-construction problem solving and more of a role in ensuring that spaces perform as intended in the first place.

Generating a Model

One of the first major hurdles to be overcome by any ray-tracer is how to input the geometry of a model. Exactly the same problems face visual ray tracing programs, in which the solution is most often to provide an entity description language. Whilst used mainly to construct the model from simple geometric primitives, many of these languages provide quite sophisticated features such as constructive solid geometry and the creation of parametric solids. To use these, the user creates a text file describing the model which is then read by the program during execution.

RayPath provides such a language, however, the concerns of an acoustic ray tracer are slightly different as models are not easily created using simple closed primitives. Consider, for example the model shown in Fig 1.1, consisting of three intersecting rectangular prisms. The visual ray tracer is most often concerned only with external form in which case the model is very simple to create. The acoustic ray tracer, however, is concerned with the internal volume so the exact points of intersection of all prisms must be determined in order to ensure that the volume is continuous through all of the appropriate planes.

In its current state of development, RayPath describes its models as a series of planes composed of connecting vertices. This allows a degree of pre-processing to be undertaken prior to the main calculation and has proved most adequate for the majority of enclosures. Problems arise, however, in the modelling of curved surfaces. To accurately model a curve requires a large number of planes. The image method algorithm is rather sensitive to the number of planes in a model as well as to the depth of reflection: an approximate equation for the number of possible images being;

$$planes + (planes - 1)\ depth$$

It is therefore of significant benefit to have only one element represent the whole curved surface. As a result, two additional primitives have been solved for inclusion in the model, hemispheres and cylinders. Obviously more primitive will follow as a result of further use of the package.

One of the problems of a text based approach is that the user has very limited visual feedback whilst constructing the model and may only effect modification by re-editing and re-loading the file. What is far more desirable is a visual interface in which the user can interactively create and manipulate the model in 3 dimensions. Rather than attempt to produce what would have to be a rather complex CAD program, it was considered more appropriate to utilise an existing package.

As a result, RayPath can directly import DXF files produced by such programs as AutoCAD and Microstation. Of course, only 3 dimensional elements are recognised, however, these include all of the new AME solids of AutoCAD Release 11 (cf: Fig 1.2). As the DXF format itself is rather dated and difficult to edit, models may then be saved in RayPath's own text format to allow further rotation, translation or scaling. *[Note: A comprehensive 3D modelling system has since been implemented]*

Performing Calculations

Once a model has been created, it is a simply matter to commence a ray trace. Obviously a particular source/receiver combination must be selected as multiple positions can be specified as part of the model. Beyond a certain reflection depth the basic image method becomes very time consuming, given the shear number of calculations involved. To allow for time restrictions, a maximum reflection depth can also be specified by the user.

Lengthy calculation times are a problem common to all types of ray tracing. Whilst the algorithms are quite well known, they remain computationally intensive. However, there are still improvements in efficiency to be found, specifically Point-in-Polygon routines in which the calculation spends most of its time [12].

Using the method of images, the source position is recursively reflected about each boundary object to yield image positions lying outside of the enclosure. Basic three dimensional geometry is used to calculate these positions and to determine if they are real or imaginary. A real image is one accessed by a ray in which no intersection point occurs outside the bounds of an intersected object and no ray segment passes through any other object. The exact points and angles of intersection with each boundary object are returned for each real ray in order to allow further analysis.

This method is exhaustive, calculating and testing all possible images for their validity. It also returns all of the information required to determine the impulse response. However, each increase in reflection depth leads to an exponential increase in calculation time. What was considered quite important was a means of running a quick test of the enclosure that didn't take as long as the image method, yet provided some of the same information. To this end an additional algorithm proposed by Vorlander [13] has been implemented.

This new algorithm combines the image method with random ray generation. Using this method, the point receiver is replaced by a sphere of finite radius. A specified number of random rays are then generated to a depth set by the user. Each segment of a ray is then tested to see if it intersects the sphere. If so, there is a significant chance that there exists another ray, reflecting off the same sequence of boundary objects, but passing exactly through the centre of the sphere (cf: Fig 1.3). As both the current image position and reflection sequence is known, it is a simple matter to trace the new ray from the centre of the intersected sphere to the image point, testing to see if it is a true ray of not.

The benefits of this method are quite significant. Rays can be generated with as great a reflection depth as required without the corresponding exponential increase in calculation time. Once a ray has been generated, it can be tested against as many spherical receivers as can be specified within the enclosure (cf: Fig 1.4). Thus the time spent calculating one ray may yield any number of true rays for any number of receiver points at any depth.

Unlike the method of images, this algorithm samples only from the set of real rays within the enclosure and is by no means exhaustive. Therefore a number of algorithms for the generation of sampled rays have been developed. This means that rays can be selected at random, based on a fixed interval, restricted to a given range of angles or only off a specified plane. As a result it is necessary to keep in mind the bias that any of these choices place on the acoustic measures derived from a particular set of rays.

A problem not touched on by Vorlander is the number of duplicated rays generated as a result of the radius of each sphere. It is quite possible that two random rays, travelling in slightly different directions, reflect off of the same set of planes, intersect the same sphere and result in the same true ray. To guard against this by testing each new ray against all previously true rays, for all receiver points, would consume far too much memory and greatly increase calculation time.

The solution in RayPath is to store all true rays in a large temporary file. At the completion of the calculation, this file is sorted by delay time and boundary intersections. This makes checking a simple matter of comparing consecutive rays in the temporary file and filtering out any duplications. Problems arise with this method when sorting on machines with limited core memory as some temporary files can be in the order of several megabytes. *[Note: Application now tests each new ray against all previously stored rays instead of using a temprary file]*

Experience with this algorithm has shown it to be a remarkably fast and effective means of overviewing the behaviour of an enclosure. Using a single calculation of perhaps 1000 rays to a depth of 32 reflections may take up to an hour, but will yield a sample impulse response for as many points of interest as are required.

As a quantitative tool, however, there can be no measure of the fraction of real images actually represented, even at the lowest orders of reflection. Whilst this can be overcome, to a degree, by increasing the radius of each sphere relative to the room volume, this creates far more duplications, and thus a much larger temporary file.

Communicating Results

Both types of calculation produce a diverse range of information, the majority of which is graphical in nature. An analysis of this information can be used to derive some of the objective measures used to predict sound field behaviour as well as some useful statistics. Given this diversity, it was decided to group results into three categories: spatial, graphical and numerical.

Spatial Information

As discussed previously, the main spatial information returned by ray tracing calculations are image positions and reflection paths. In RayPath, both images and rays can be viewed individually or as a group in orthographic, perspective or axonometric projection (cf: Fig 1.5).

Viewing rays in this manner quickly provides an idea of the effectiveness of a reflector, for example. This is of significant use to the architect as a visual appreciation can not only measure, but also suggest modifications to position and orientation. Similarly, the spatial distribution of images can be used to appreciate the spatial impression perceived at a particular receiver point as well as highlighting any voids.

Of particular use in the control of echoes is the ability to appreciate the distribution of intersection points over individual elements or the model as a whole. Whilst in Fig 1.5 it is difficult to interpret the relative influence of intersection clusters in a plane, in RayPath itself shades of blue are used to represent the depth of each point in the reflection tree. Thus it is quite obvious when a strong cluster of dark blue points appear. *[Note: not implemented in the Windows version]*

Graphical Information

Graphical information refers to data such as the impulse response which can be graphed against two axis. An example of such a graph is shown in Fig 1.6 where the level of each impulse is shown against its delay. Displayed in this manner, each impulse can be compared to the general rate of decay over time. Thus it is possible to detect particular impulses or groups of impulses that may be discerned as echoes rather than as part of the reverberant sound.

Schroeder [14] has shown that performing a reverse integration of this impulse response produces a smooth decay curve equivalent to the ensemble average of many such decays. It is therefore possible to display this integrated decay curve and to calculate the line-of-best-fit for use in the estimation of reverberation time (cf: Fig 1.6). Using such a graph also enables an estimation of just how exponential the decay within an enclosure actually is.

In order to more accurately display the distribution and contribution of images, a polar diagram can also be produced. As the relative direction and level of each image is known, the ratio of lateral and frontal reflections can be appreciated.

Finally, the intersection points previously calculated can be used to analyse the range of incidence angles over which an individual model element is hit by calculated rays. Displayed in five degree intervals against the total number of intersections with a particular plane, the effectiveness of specific acoustic materials can be estimated. Fig 1.7 compares two floor planes, the first being the audience plane, the second the stage. From this spread of angles, it can be seen that the audience plane experiences a relatively large number of near-normal rays (0-15 degrees) striking it’s surface relative to those near grazing incidence (75-90 degrees). The stage, on the other hand, never experiences near-normal intersections. This is obviously due to the parallel ceiling immediately above, any rays striking the stage at near-normal incidence simply reflect back and forth between the two, never reaching the receiver position.

Knowing the characteristics of acoustic materials at various angles of incidence, such graphs can assist in the most effective choice of surface treatment when required.

Numerical Information

Numerical information refers to both single figure measures and tabulated data. This obviously includes all of the objective measures derived directly from the model as well as intersection statistics. Such information is output to either the system console or a line printer. Such measures can be grouped into related categories.

1. *Energy Ratios:*

Having calculated an integrated decay curve, it is possible to derive early-to-late energy ratios for different times. Such ratios are given by:

where x represents the initial period, in milliseconds, over which energy is considered early. As briefly discussed earlier, such ratios can be highly inaccurate. The reason for this is that no single impulse response can ever represent the contribution of every possible image. The method of images itself imposes a limit on the order of reflections calculated, thereby ignoring a great number of distant images. Using the combined method, some of these distant images may be represented, however, the more distant the images, the less significant the sampled fraction is compared to the total number.

In addition, whilst diffracted and diffuse energy is ignored over both the early and late periods, their durations are certainly not equal. Both of these factors will therefore tend to greatly over-emphasise the significance of early energy, leading to grossly inflated ratios. The effect of this is to increase the overall rate of energy decay.

Further research is therefore required in order to understand and compensate for these effects. In the interim, RayPath calculates three of these ratios, 80ms (C[80]), 50ms (C[50]) and 35ms (C[35]), as suggested by Gimenez & Marin [15], as a means of simple quantification.

2. *Reverberation Time:*

The rate of energy decay is also used to estimate both Reverberation and Early Decay Times. The Early Decay Time, calculated over the first 10dB, is mostly unaffected by these factors in all but the lowest order calculations. Reverberation time, when measured over the full 60dB, is greatly affected. Therefore, RayPath allows the user to specify a range over which the reverberation time will be calculated and then extrapolated out to 60dB. In test models used to date, it is usually possible to represent the first 30 dB with some degree of accuracy, however the user, at this stage, must still be aware of a tendency toward underestimated times.

3. *Spatial Impression:*

This measure refers to the subjective feeling of envelopment within a sound field and results from the influence of side or lateral reflections. To quantify this effect, the Lateral Energy Fraction is used [16]. This is given by:

As the Lateral Energy Fraction is concerned primarily with the first 80ms of decay, reasonably accurate values are possible given a reasonable reflection depth. In this case, distant images are not considered in the calculation and the influence of diffusion and diffraction, to a degree, will cancel as a result of the division. The real effects of diffusion, if anything, will further serve to actually enhance spatial impression.

4. *Speech Intelligibility:*

There are a number of methods for the calculation of speech intelligibility from an impulse response. The most commonly used are those derived from Useful/Detrimental energy ratios [17] and the

Speech Transmission Index [6]. As the first of these is based on energy relationships, it is also an unreliable measure. The Speech Transmission Index, however, is based on the modulation transfer function which, in turn, is given by the vectorial sum of the calculated transmission paths divided by their absolute sum. Thus, given a reasonably representative sample of the impulse response, this measure can be most useful.

All of the numerical measures so far described can be viewed in their relative positions within the model itself. This has the benefit of allowing spatial patterns within these values to be discerned. Figure 1.8 illustrates this feature, clearly showing the difference between estimated Early Decay and Reverberation Times.

5. *Intersection Statistics:*

In addition to being able to display the distribution of intersection points over the whole model, a table of intersection statistics can also be generated. This table indicates surface area along with the percentage of total intersections within each individual plane. This allows the most statistically significant planes to be determined, aided by an index value (cf: Fig 1.9). *[Note: Not implemented in the Windows Version]*

Discussion

Obviously, the accurate prediction of energy relationships is not yet the strongest aspect of acoustic ray tracing. However, the information it provides in terms of the spatial behaviour of sound is of great importance.

The most significant aspect of RayPath, which has yet to be touched on in this paper, is the level of interaction available to the user. As can be seen from Figure 1.2, two graphics canvases are provided on the screen. The upper canvas is used to display the model and its associated spatial information. The lower canvas is used for the display of graphs. At any stage and in any view, both canvases can be interrelated.

For example, clicking the mouse button in the impulse response graph highlights the closest impulse. If displaying the model, the upper canvas will then show the exact geometric path of the corresponding ray else the corresponding image is highlighted within the polar diagram. Similarly, clicking in the model canvas will select the closest ray or image at the same time highlighting the corresponding impulse. All views allow some form of user selection and interaction.

Another aspect of this is the ability to modify either the material or absorption coefficient of any plane and immediately see its effect on the impulse response. As the geometry remains the same, it is a simple matter to recalculate the relative intensity for all of the existing rays whenever some attenuation factor changes. The new impulse response appears in place of the original so the effect can be fully appreciated by toggling between two values and observing any changes. Using this feature, the model can be finely tuned to the desired performance and then used to guide the actual design.

Whilst other means may allow a more accurate prediction of some objective measures, it is this potential as an interactive design tool that is considered the primary asset of a computer ray tracing model.

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