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THE IMPORTANCE OF DIFFUSE REFLECTION IN COMPUTERIZED ROOM ACOUSTIC PREDICTION AND AURALIZATION

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1. INTRODUCTION

It is widely recognized that a fraction of diffusely reflecting surfaces are required to achieve good room acoustics. This holds true for small rooms such as control rooms as well as large rooms such as concert halls.

The concern of this paper is whether proper handling of diffuse reflection is a requirement for successful computerized prediction of room acoustical measures and auralization of spaces [1]. Even today, 14 years after Kuttruff's important paper on the subject [2], several prediction as well as auralization methods exist that assume specular-only reflection. Software exist both in the form of research tools and commercial products. In an ongoing round-robin test for prediction software conducted by Vorlaender in Germany, at least 5 out of 19 participants supplied results based on specular reflection only, and an additional 6 assumed specular-only reflection for prediction of the early to intermediate part of the echogram [3].

Hodgson has published papers about the need to include diffuse reflection in prediction of reverberation time (RT), especially in simply-shaped rooms with uneven absorption distribution [4]. Related to this topic Hodgson has also given guidelines for when estimation of RTs based on the Sabine or Eyring formulas are applicable [5]. By assuming that the number of times a surface is hit is in proportion to its area, these formulas require that all surfaces are visible for all rays at all times which implicates a hall shape without obstructing objects and with diffusely reflecting surfaces.

Ref. [6] presents a general discussion of the properties of diffuse reflection, a discussion of the estimation of diffusion factors and dispersion functions, and a review of computerized methods reported or suggested to handle diffuse reflection.

2. DIFFUSE REFLECTION IN COMPUTERISED PREDICTION

What are the potential problems when room acoustical measures such as RT and Clarity are predicted without taking diffuse reflection into account? Methods concerned here are the Image Source Model, ISM [7], Specular Ray-Tracing, SRT, the Hybrid Method, HM [8], and Cone [9] or Pyramid Tracing, CT, (abbreviations introduced only for convenience). The major problem is a large, possibly very large, over-estimation of the RT especially in simply-shaped rooms with uneven absorption distribution. The clearest example, discussed in [2], is a room with a rectangular floor plan and a highly absorbent floor, see Fig. 1. Energy carried by rays with predominantly vertical direction components will be absorbed quickly while horizontal rays will hold their energy for a longer time and eventually determine the decay rate. With the vertical dimension smaller than the other two the situation worsens since horizontal rays not only loose less energy when reflected but are also reflected less often than vertical ones. The result is a non-exponential decay with a final decay rate much lower than predicted by e.g. the Eyring formula. For this particular case diffuse reflection factors of at least 50 % give a linear decay and reverberation time values close to what is predicted by the Eyring formula. Even with more complex halls, especially when walls are basically parallel, a very strong dependence on diffuse reflection may exist.

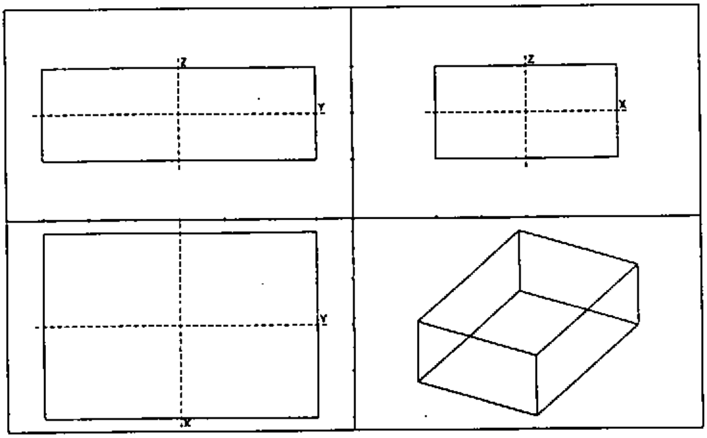

FIGURE 1. Simple hall model. Wall/ceiling absorption 15 %, floor absorption 60 %. The dimensions are 30 by 20 by 10 m giving an Eyring RT of 1.40 s.

Figure 2 gives a new view of the phenomenon by showing the *power weighted mean free path, l_p*, as a function of time. The l_p is derived by weighing each path by the current power of the ray. In Fig. 2 diffuse reflection factors range from 0 to 100%. With a high degree of diffuse reflection l_p quickly stabilizes close to the traditional $4V/S$ value but with predominantly specular reflection it gradually gets longer and stabilizes at a much higher value. The reason that the final value of l_p does not stabilize exactly at $4V/S$ even with high diffusion factors is probably to be found in the statistical distribution of individual ray powers in each time segment. In all cases, however, the mean free path and mean absorption factor as estimated by the rays are the same regardless of diffusion factor. Corresponding decay curves are shown in Fig. 3. Since without diffuse reflection the initial decay rate is much higher than the final, early-to-late measures such as Clarity may be over-estimated in spite of a predicted too long late RT. The curves in Figs. 2 and 3 are produced with a ray-tracing procedure where diffuse reflection is handled by randomizing the direction of rays reflected off diffusing surfaces. This is the most common method to handle diffuse reflection in room acoustics.

Pure HM and CT methods, as they are currently implemented, also display another problem. As the cones get wider and since actually only the centre ray of each cone is traced, an increasing amount of valid specular reflection paths remain undetected as the rays extend. This loss of reflections to some extent compensates for the too long late RT at the expense of a too low level in the reverberation tail. More accurately CT should have been named *approximate* cone- or pyramid-tracing. A further problem associated with approximate CT is that receivers located close to surfaces suffer loss of reflections.

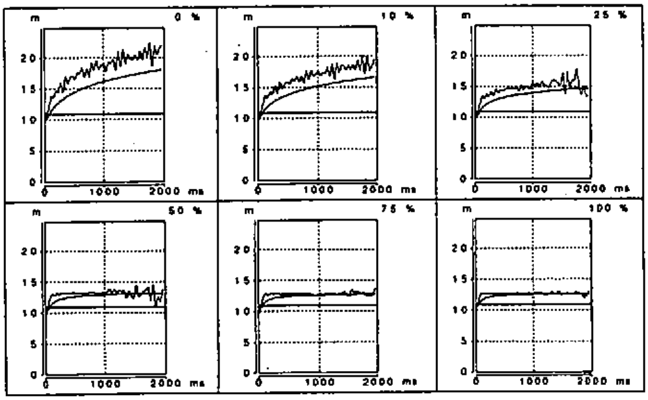

FIGURE 2. Power weighted mean free path, l_p, as a function of time for the model in Fig. 1. From upper left to lower right diffusion factors are 0, 10, 25, 50, 75, and 100 %. The horizontal line is the classical $4V/S$, the smooth line is accumulated l_p. Time segments are 7 ms wide.

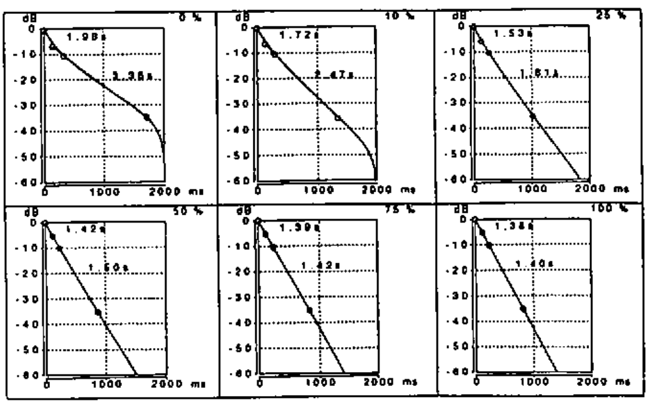

FIGURE 3. Decay curves corresponding to Fig. 2. Early Decay Time and T-30 are indicated.

If the hall geometry is 'mixing enough' correct estimates may be produced even without handling diffuse reflection. As far as this author knows no method has been developed that can determine in advance if a shape is mixing enough to allow for a specular-only method. With a method that handles diffuse reflection it may be very useful to test a hall design also assuming all diffusion factors to be zero. If the results differ dramatically one may suspect that the design is 'dangerous'. Diffusion factors are difficult to estimate and if the design is very sensitive to a change in these factors the actual RT may be too far from the predicted one and possibly detrimental phenomena such as flutter echoes may occur.

3. DIFFUSE REFLECTION IN AURALIZATION

In addition to the potential problems discussed in the previous section, problems are associated with the subsequent use of predicted specular echograms for auralization. Let us assume for a moment that a particular hall shape is mixing enough so that room acoustic measures and RT are predicted reasonably well even without diffuse reflection included. How would a Binaural Room Impulse Response, BRIR, sound when synthesized from thus predicted octave-band echograms using methods such as the HM or the CT capable of creating echograms long enough for auralization? An example of a concert hall echogram created using cone-tracing is shown in Fig. 4. Note the jagged late part. When synthesising BRIRs from echograms such as in Fig. 4 echoes are clearly heard if the BRIR is convolved with transient program material. By direct listening to the BRIR (similar to listening to a pistol shot in a hall) the unnatural character of the response is even clearer. If the BRIR is replayed with a decreased sample rate it sounds like dropping a set of steel balls on a marble floor.

Since prediction is based on geometrical acoustics we may allow us to make an illustrative analogy with optics. If a person is seated in a concert hall where all walls are optical mirrors (possibly tinted analogous to frequency selective absorption). What the person sees when looking around in the hall are numerous fragmented mirror copies of objects in the hall. Even after many orders of reflection he will be able to recognize bits and pieces of, for example, the orchestra especially if some mirrors are large. These pieces of objects correspond to the echoes heard in a BRIR synthesized from specular-only reflections. If, however, several of the walls are given a dull finish and thereby reflecting light in a diffuse manner, only the very first reflections are recognisable in detail and high-order reflections become blurred. For room acoustics, this corresponds to the first strong specular reflections in a concert hall and the subsequent increasingly noise-like reverberation tail.

Many existing prediction/auralization systems are based on a detailed estimation of the early part of the echogram and a late part estimated from simplified or statistical methods. Ideally, an auralization method should not only create a convincing decay but also preserve the spatial characteristics of a specific location in the audience. Positions under a balcony, for example, ought not to have the same type of reverberation tail as positions on the main floor. There is some evidence that trained listeners can detect also small differences in the late part of the decay [10]. Since a more correct late part echogram, including diffuse reflection, tends to require rather heavy computations, for some time most commercially available methods will probably stay with an early-late part division.

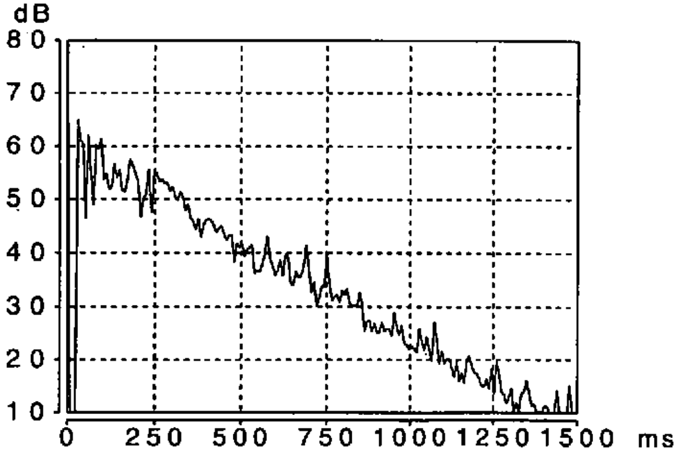

FIGURE 4. A concert hall echogram from cone-tracing summed in 10 ms time intervals.

4. A CONE SPLIT-UP ALGORITHM

A very general algorithm for handling the interaction between specular and diffuse reflection is now in the final stage of research. The method is based on approximate cone-tracing where two of its inherent problems, described above, have been compensated for and where diffuse reflection is handled by a split-up of cones/rays incident on diffusing surfaces [11], [12]. For the model in Fig. 1 the algorithm gives the same result as the simpler ray-tracing procedure. The method is specifically tailored for use with auralization and generates tens of millions of weak diffuse reflections in addition to the purely specular ones. The algorithm reveals that in typical concert halls specular reflections very rapidly transfer their energy into diffuse and a very smooth and natural-sounding late reverberation is created. Figure 5 shows a sample echogram corresponding to that in Fig. 4 but where diffuse reflection is fully taken into account using the cone spit-up algorithm.

The algorithm is not based on an early-late part division, although the attention to detail is relaxed for late specular as well as diffuse reflection. Two versions of the algorithm are implemented: a simple version for fast prediction of RT and room acoustical measures but whose echograms cannot be used as a basis for auralization, and a complex version well suited for auralization. The complex version is computationally heavy but still gives reasonable calculation times on a modern PC. Prediction of the concert hall echogram in Fig. 5 using a 90 MHz Pentium lasted 38 minutes (the model consisted of 156 surfaces) A total of 40 million reflections were generated, of these 14000 were purely specular.

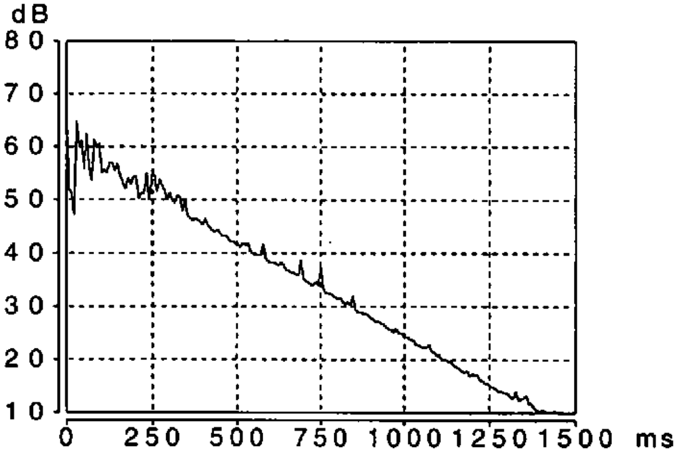

FIGURE 5. A concert hall echogram corresponding to Fig. 4 but with diffuse reflection included using a cone split-up algorithm.

5. ESTIMATION OF DIFFUSION FACTORS

Even if methods exist that can take the interaction between diffuse and specular reflection into account, there is little information available on the dispersion from various diffusing surfaces in room acoustics. With commercially available dedicated diffusors, some kind of measurement data can often be obtained from the manufacturer. This data is not necessarily in a form that adapts well to the use in a prediction program. A work-group on standards in the Audio Engineering Society, AES, (SC-4-1) is currently developing general measurement as well as numerical procedures to assess dispersion data from surfaces [13].

Currently the majority of programs that handle diffuse reflection assign diffusion factors to surfaces and apply Lambert's law [14]. The most common way to estimate diffusion factors for use in prediction is to set values in relation to wavelength/roughness ratio. As is discussed above the choice of diffusion factors may have a very high influence on the estimation of reverberation time. Also the estimation of absorption factors may sometimes be difficult. In that case, however, vast resources of measured data can be used as guidelines. Unfortunately, the choice of geometry approximation and diffusion factors may have a strong influence since they both affect the direction and distribution of rays, whereas absorption factors merely alter the level of individual reflections a few decibels up and down. If absorption factors are reasonably correct on average an unsatisfactory comparison with measured data can very seldom be attributed to errors in absorption factors

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6. CONCLUSIONS

For computerized prediction in general and auralization in particular, methods should handle diffuse reflection. Without diffuse reflection severe overestimation of reverberation time values may result. With auralization, the lack of diffuse reflection may create binaural room impulse responses with unnatural decay characteristics with echoes that are clearly heard with transient program material or by direct listening to the binaural room impulse response. Even for algorithms with proper handling of diffuse reflection, such as the cone split-up procedure mentioned in this paper, the required input data in the form of diffusion factors or dispersion functions of diffusing surfaces is still lacking.

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