Reflections At Room Boundaries In Computer Simulation Programs Based On Ray-tracing

M.R. Lautenbach[1], M.L.S. Vercammen[2]

[1] *Peutz bv Zoetermeer, The Netherlands, Email: m.lautenbach@zoetermeer.peutz.nl*
[2] *Peutz bv Mook, The Netherlands, Email: m.vercammen@mook.peutz.nl*

Introduction

Room acoustic modeling based on a geometric approach is used since the 17th century. By discarding interference and diffraction, it is still possible to investigate several aspects of the sound behavior in a room with only energy summation.

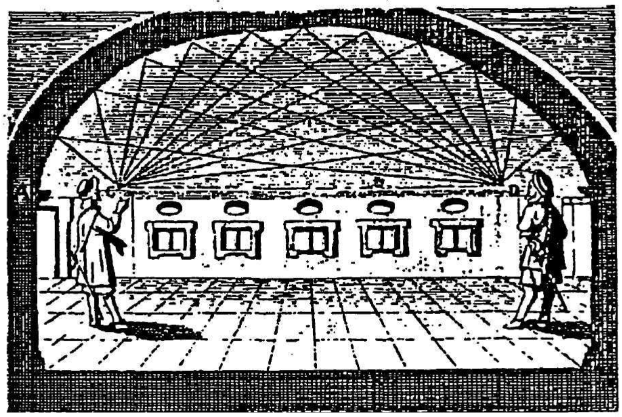

Figure 1: Ray-tracing in the 17th century.

In that case, the propagation of sound can be modeled the same way we can model light, with a ray: a linear displacement of energy which travels with the speed of sound in air in the direction perpendicular to the wave front. The ray itself has no dimensions, it is infinite thin and has only a displacement with a certain direction.

Nowadays there are several computer programs commercially available with which room acoustic parameters can be predicted on the basis of raytracing. One of the most important differences between these computer programs is the way diffuse reflection in a room is modeled and how the scattering coefficient is used. Several methods have been proposed, discussed and implemented [1,2]. For a user it is not easy to find out which methods are implemented in the simulation programs on the given subject and to understand the implications of these methods .

This paper gives an overview of some modelling methods and the way they deal with the scattering coefficient, including an overview of the methods implemented in two of the most used software programs. A comparison between different methods is made to the wave based method for a first order reflection on a flat panel to provide insight in the modelling. It shows that a user should understand the implications the modelling method implemented in the used program and the way the scattering coefficient should be used.

Modelling Scattering

Modelling diffuse reflections in a geometric acoustic approach is necessary for a useful prediction as established by Kuttruff and Hodgson [3,4]. Hargreaves and Cox [5,6] showed that reflections from a flat panel with finite sizes are only really specular in the far field.

When a (continuous) wave front encounters a room boundary or an edge, the wave front will be distorted after a reflection. This can partly be modelled with (discrete) scattering: a redirection of energy propagation. This fits a ray-tracing procedure, with the scattering coefficient (s) to indicate how much of the energy is not to reflect specular. There are several ways to implement the modelleing of scattering into ray-tracing procedures and several distribution functions for the scattering [1 to 10]. Absorption is left out in this overview:

1. Stochastic redirection of each single ray.

1.1. At a reflection a random number is generated, if this number is smaller than the scattering coefficient, the ray will be redirected taking into account the distribution function. Otherwise the ray will continue in the specular direction.

1.2. A derivative of 1.1 is the vector-based scattering: the direction of the reflected ray is calculated from the vector sum of (1-s)*specular direction and s*redirection. The redirection is according to the distribution function chosen.

2. Ray-splitting (not implemented in mentioned programs)

2.1. At a reflection the ray will be split up in two: one for the specular direction and one for the redirected direction, with the energy ratio according to the scattering coefficient.

2.2. Many rays for the redirected part, according to the distribution function chosen as described e.g. in [7].

3. Secondary source (I)

When a reflection takes place at a room boundary, a (temporary) secondary source is created at the reflection point. If this secondary source is visible from a receiver, a contribution (taking into account the history of the ray, the distance from reflection point to receiver and the distribution function) is made to the echogram. The ray itself will not hit a receiver, the (temporary) secondary source takes no energy from the ray.

4. Many secondary sources (II)

This method is usually combined with the Image Source Method for the first reflection(s). With ISM the modelling of scattering is possible if the energy at a reflection point is divided between the image source and a procedure that handles the modelling of scattering, see figure 2.

Two different methods are described for secondary sources:

a) A surface with a scattering coefficient > 0 is divided in a number of sub-surfaces. The size of those sub-surfaces is governed by s(1 - α) giving hard diffusing surfaces the highest density. Vectors from the main source to the centre of the sub-surfaces to the receiver are calculated with Lambert reflection weighting. The reflection strength detected is added to the echogram, creating a „smear" of low energy contributions.

b) When a "reflection" is detected at a room boundary, secondary sources are created distributed over the surface. From these secondary sources a ray-tracing is started. For the receivers visible to the secondary sources, several low energy contributions are made to the echogram, smeared in time.

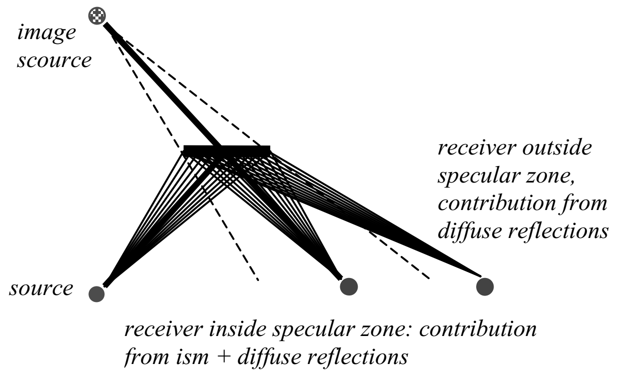

Figure 2. General idea of secondary sources with ISM

Several distribution functions are:

1. Lambert cosine law, the intensity in a certain direction only depends on the cosine of the angle of reflection, not on the angle of incidence.

2. Oblique Lambert, a derivation of the foregoing, taking into account the direction of the angle of incidence by the vector sum of the specular and scattered reflection.

3. Uniform.

User Input: the Scattering Coefficient

The input of the scattering coefficient is handled differently in different programs. The possibilities range from a mid-frequency one-number input which is expanded to other octave bands by the program to an octave band user input in the same way as with the absorption coefficient and in agreement with the measurement method. Diffraction may be separately taken into account for either free suspended elements or for finite surface sizes in general. In the first case, diffraction is modeled by scattering if the distance from the reflection to the edge is smaller than 0.25 times the wave length. The latter is a method in which the scattering coefficient increases with frequency, angle of incidence and distance/time, and decreases with surface size. These different methods leave the user with the question whether diffraction should be included in the scattering coefficient or not. A real sound wave will not notice the difference between surface roughness or diffraction due to finite surface size at room boundaries. Basically it's the same physical aspect, but for a different bandwidth of frequencies. Although a user has to assign a scattering coefficient with a certain surface, which agrees with the approach of surface roughness, optionally taking diffusing effect of diffraction into account by increasing the scattering coefficient for low frequencies might be justifiable, unless it is taken into account for in another way in the program.

With the introduction of the scattering coefficient and the measurement method of ISO 17497-1 2004 it was expected that the available measurement data would increase, or that measurement results could lead to better guidelines for some typical cases. So far, that doesn't seem to be the case. There is a list of data published [6], derived from calculated polar responses. In this conversion from polar response to scattering coefficient, a comparison is made to the scattering of a flat panel. Because the low frequency scattering of a flat panel with finite size is relative high, the final correlation scattering coefficient at low frequencies is always low, even lower than the diffusion coefficient. For higher frequencies derived with the same method, the correlation scattering coefficient for a certain surface shape is usually higher than the diffusion coefficient. It would be interesting to do some comparison on that point.

Implemented methods in CATT-Acoustic and Odeon

This paragraph gives a short overview of the implemented scattering modelling methods the programs CATT-Acoustic and Odeon. There are more programs available, so the intention is not give a complete overview. Also these programs are in continuous in development, therefore this overview may only be partly up to date.

CATT-A v. 8.0f [7,8]: Many secondary sources (as described in 4a) for the first reflection. Stochastic redirection with randomized cone-tracing for the higher order reflections. User input of scattering coefficient per octave band. Optional inclusion of the diffusing effect of diffraction for free suspended or finite elements. Distribution function Lambert.

Odeon v. 9.1 [9,10]: Many secondary sources (as described in 4b) for reflections up to transition order (user input from 0 to 10). A combination of vector-based ray-tracing with secondary source contribution at reflection points for the higher reflection orders. User input of scattering coefficient one number for mid-frequency, expanded to other frequency bands by Odeon. Diffraction modelling for finite surface sizes. Distribution function oblique Lambert.

Influence of modelling method on results

In order to get a reasonable insight in the influence of the different modelling methods an extensive comparison between calculations and measurements in existing rooms would be necessary. Instead, to get an idea of the influence of the results, a look into Round Robin III is made, and a comparison is given to a first order reflection of the wave based calculation (Kirchhoff). Some remarks up front are in place though:

- The accuracy of a calculation can never be higher than the accuracy of measurements.
- The accuracy of a calculation can never be higher than the accuracy of the input parameters.
- The expected accuracy of the prediction methods seem to grow far beyond that level.

Round Robin III 2005 by Bork [11] has some interesting aspects related to the subject of this paper. A studio with a high degree of sound diffusive surfaces was the subject of this investigation. Measurements were made in the studio as well as in the laboratory for the absorption and scattering. 21 participants got all the data to make their prediction of room acoustic parameters. This was split up in phase 2, scattering modeled by the use of the scattering coefficient, and phase 3, scattering mainly modeled by room geometry, but with an additional scattering coefficient of 0.2.

Unfortunately, the survey was blind, so no information is acquired on the different modelling methods for scattering, and the distribution of calculation results is significant in both cases. With 6 extreme predictions removed, it can be derived that in general the use of scattering coefficients instead of geometric modelling gives a better and little bit more accurate prediction when compared to the measurement results, espacially at low frequencies.

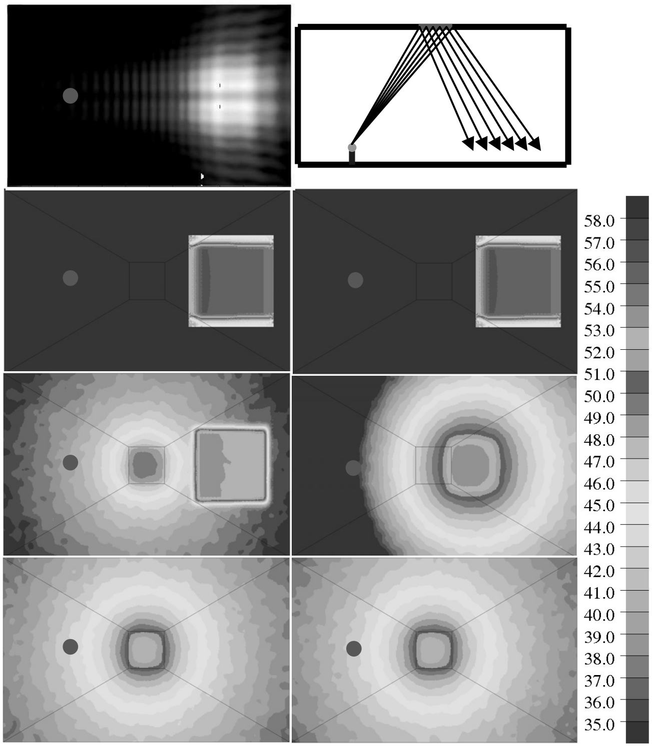

Figure 3. Comparison of calculated reflection from 5x5m square from a point source (pink) at 20 m below and 11,5 m to the left, angle of incidence 30º, 1kHz (as seen on top right)
On top left: wave based method
Below from top to bottom 0%, 50% and 100% scattering
Below left: randomized ray-tracing
Below right: vector-based ray-tracing

Additionally, a comparison is made to the first order reflection calculated with the Kirchhoff expression (1) for the sound pressure at a point in a volume V bounded by a surface S, derived from Green's theorem and the Helmholtz equation, with a monopole source:

$$P = \frac{\hat{p}}{4\pi}\int_S \left(\frac{1+jkr}{r}\cos\alpha + \frac{1+jkD}{D}\cos\varphi\right)\frac{e^{-jk(D+r)}}{Dr}dS \quad (1)$$

Therefore an acoustically hard surface of 5 * 5 m is placed in a completely absorptive environment (figure 3 top right). A source position is located at 20 m below the middle of the reflecting panel with incident angle of 30º, see figure 3 on top right. For 1 kHz, the results in sound pressure levels for three modelling methods with different scattering coefficients a comparison is given. In all cases the direct sound is excluded.

Figure 3 shows that randomized ray-tracing separates the "image" of the reflection from the scattered energy (Lambert). Vector-based ray-tracing leaves the scattered energy around the "image" of reflection, but the "image" is not in place anymore. Both methods are by default not used for the first reflection in the mentioned programs, but sometimes can be chosen. 0% and 100% scattering result in the expected too sharp edges and Lambert distribution respectively.

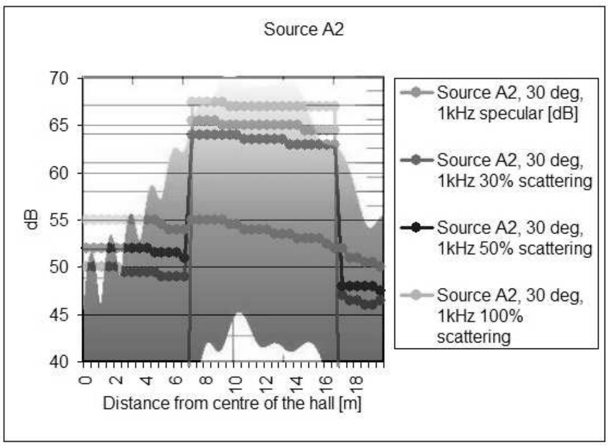

Figure 4. Comparison of the first order(s) secondary sources to the wave based method for the same configuration as in figure 3

Figure 4 shows that the „many secondary sources" method as described in 4 gives good results, the "image" of the reflection is in the right position, and with 30% scattering for a flat panel the comparison with the sound pressure amplitude is also quite good.

Conclusion

There are several methods to model scattering with ray-tracing procedures. The secondary sources method as described has basically a good energy distribution for a single order reflection from a flat panel if some scattering is applied (in this case 0.3). Other methods as shown in figure 3 are less accurate for the prediction of a one order reflection from a specific surface. Due to their non-expanding number of rays, they are suitable for the „reverberation tail“ of an echogram.

Because of the different methods for first / early reflections and „late“ reflections, users of raytracing programs should be aware of the methods implemented to understand the implications and accuracy of different methods.

The input of the scattering coefficient is handled basically different in the mentioned programs. The development of this input parameter seems to go different ways, and the user should therefore inform him/herself about the way the scattering coefficient is used in the specific program and how this is related to the gathered data that is used as input.

Acknoledgements

The authors want to thank the people behind the described software programs because of their long time effort in the developement of these programs and the kindness and stimulating way of answering our questions on the given subject.

We are very grateful to our collegue Paul Mees of Daidalos Peutz for assisting in the calcutions.

References

[1] A macroscopic view of diffuse reflection, B. Dalenbäck, M. Kleiner, P. Svensson, J. Audio Eng. Soc. Vol 42, 1994

[2] Auralization, M. Vorländer, Springer, 2008

[3] A simple iteration scheme for the computation of decay constants in enclosures with diffusely reflecting surfaces, H. Kuttruff, J. Acoust. Soc. Am. 98, 1995

[4] Evidence of diffuse reflections in rooms, M. Hodgson, J. Acoust. Soc. Am. 89, 1991

[5] Surface diffusion coefficients for room acoustics: Free-field measurements, T. Hargreaves, T. Cox, Y. Lam, J. Acoust. Soc. Am. 108, 2000

[6] Acoustic absorbers and diffusers, T. Cox, P. D'Antonio, Spon Press, 2004

[7] Room acoustic prediction based on a unified treatment of diffuse and specular reflection, B. Dalenbäck, J. Acoust. Soc. Am. 100, 1996

[8] Catt-A v. 8.0f Manual

[9] A new scattering method that combines roughness and diffraction effects, C. Christensen, J. Rindel, Forum Acusticum, 2005

[10] Odeon v. 9.1 Manual

[11] Report on the 3rd Round Robin on Room Acoustical Computer Simulation – Part I and II, I. Bork, , Acta Acustica united with Acustica vol. 91, 2005