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A new scattering method that combines roughness and diffraction effects

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Most of today's room acoustics programs make use of scattering coefficients which are used in order to describe surface scattering (roughness of material) and scattering of reflected sound caused by limited surface size (diffraction). A method which combines scattering caused by diffraction due to typical surface dimensions, angle of incidence and incident path length with surface scattering is presented. Each of the two scattering effects is modeled as frequency dependent functions. The benefits are two-fold:

- Separating the user specified surface scattering coefficient from the room geometry makes it easier for the user to make good gestimates of the coefficients that will be in better agreement with the ones that can be measured. In many cases a scattering coefficient of say 5% for all smooth surfaces may be sufficient.
- Scattering due to diffraction is distance and angle dependent and as such it is not known before the source and receiver are defined, and the actual 'ray-tracing' or image source detection takes place. An example on this is that a desktop will provide a strong specular component to its user whereas it will provide scattered sound at remote distances.

1 Introduction

It is commonly accepted that room acoustics prediction programs based on geometrical acoustics must include scattering in order to make reliable predictions of the acoustics condition in rooms such as auditoria and concert halls. In the *First International Round Robin on Room Acoustical Computer Simulations* [1], only simulation programs which included scattering were found to provide reliable results. Most simulation software typically include scattering in terms of scattering coefficients which accounts for scattering caused by surface roughness and limited size of surfaces. The scattering coefficients tell the software how much of the energy should be reflected specularly and how much of the energy should be scattered i.e. reflected in random directions. Lam [2] found that for auditoria, scattering coefficients of 0.1 is suitable for large smooth surfaces and scattering coefficients of 0.7 is suitable for the audience area which provides scattering because of surface roughness. In practice scattering coefficients in the range of 0.2-0.5 are often applied in simulations in order to account for the diffraction introduced by reflector panels and coffered ceilings. The scattering coefficients supplied with the Elmia hall to the participants of the 2nd Round Robin on Room Acoustical Computer Software [3] exemplifies this quite well; although most surfaces, excluding the audience area, are essentially *very* smooth, different scattering coefficients are assigned to different surfaces in order to include scattering due to limited surface size (diffraction) as illustrated in figure 1.

If the part of scattering which relates to surface size could be handled by the simulation program, then we might use the same frequency depending scattering coefficients for all surfaces (e.g. 3 to 5% at 1000 Hz) in order to describe the surface roughness, the only special cases would be:

- Audience area
- Surfaces where details were not included in the model, e.g. coffered ceilings

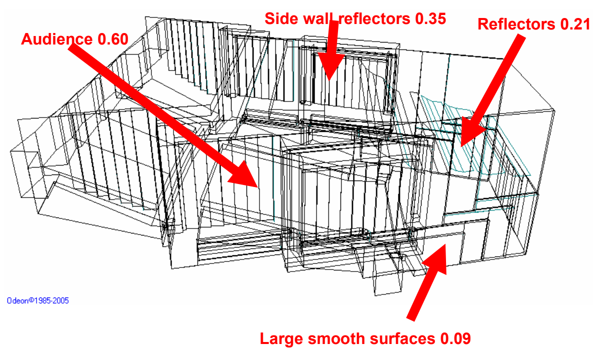

Figure 1: Example on combined scattering coefficients at 1000 Hz used in the Elmia hall, data was provided to participants in the 2nd Round Robin.

2 Geometrical model

Room acoustic programs such as ODEON covered in this paper; make use of some kind of hybrid calculation method combining the Image source method with a Ray-tracing method. The hybrid method applied in ODEON is not the subject of this paper, however for the overview; here is a short description of the principles applied. Point responses from a point source can be calculated by a hybrid method, which combines the image source method and a ray-radiosity method for early reflections below a specified reflection order with a special ray-tracing /radiosity method for late reflections. The optimal reflection order (TO) at which the model makes a transition from the early to the late method depends on the type of room. For a more detailed description please see [4]. Typical values of TO are 1 to 4, but in some cases even a value of 0 may be preferred, in which case only the ray-tracing algorithm is used.

No matter the selected TO, the algorithm includes scattering, so for the simplicity we will in the following assume that TO=0 was chosen; thus only the *RTM* (late ray-tracing) method is described; each time a ray hits /reflects from a surface, a secondary source is generated at the point of incidence. The secondary source has strength and a time delay as calculated from the total reflection path from the original source to the secondary source. Whether the secondary source gives a contribution to the impulse response in a receiver point is determined from a 'visibility' check. Form the above can be derived that a ray which is reflected a 100 times provides 100 secondary sources in the room, so potentially 1000 such rays may contribute as much as 100000 reflections at a receiver depending on visibility.

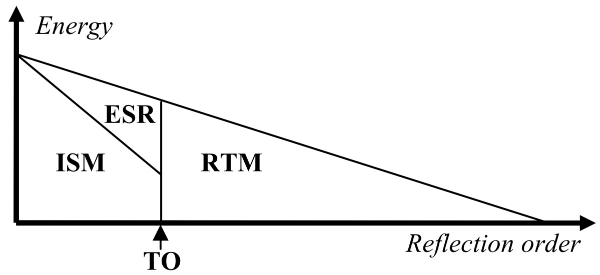

Figure 2: Summary of the hybrid calculation method as used in ODEON. Vector based scattering

The hybrid method used in Odeon is illustrated in figure 2. Early reflections below a selected transition order (TO) are calculated using a combination of the image source method (ISM) and early scattering rays (ESR). Above the TO, reflections are calculated using a ray-tracing method (RTM) which includes scattering. In the special case where the TO is set to zero, the method becomes a ray-tracing model. Note that all three methods will, most likely, overlap in time.

2.1 Vector Based Scattering

Vector based scattering is an efficient way to include scattering in a ray-tracing algorithm. The direction of a reflected ray is calculated by adding the specular vector scaled by a factor (1-s) to a scattered vector (random direction, generated according to the Lambert distribution [2]) which has been scaled by a factor s where s is the scattering coefficient. If s is zero the ray is reflected in the specular direction, if it equals 1 then the ray is reflected in a random direction. Often the resulting scatter coefficient may be in the range of say 5 to 20% and in this case rays will be reflected in directions which differ just slightly from the specular one but this is enough to avoid artifacts due to simple geometrical reflection pattern.

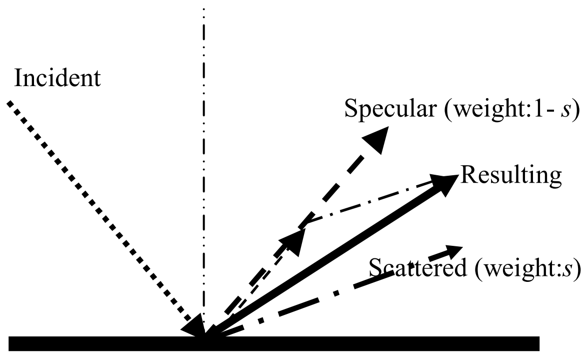

Figure 3: Vector based scattering. Reflecting a ray from a surface with a scattering coefficient of 50% results in a reflected direction which is the geometrical average of the specular direction and a random (scattered) direction. Note: Scattering is a 3D phenomena, but here shown in 2D.

3 The Reflection Based Scattering coefficient

Many of today's room acoustic calculation programs make use of scattering coefficients which accounts for scattering caused by surface roughness and scattering caused by the limited surface size (diffraction). However scattering caused by diffraction is not fully known before the actual reflections are calculated because angles of incidence, path-lengths etc. are not known at that point. In order to allow these features to be included in predictions, we suggest the reflection based scattering coefficient s_r combining the surface roughness scattering coefficient s_s with the scattering coefficient due to diffraction s_d that is calculated individually for each reflection as calculations take place:

$$s_r = 1 - (1 - s_d) \cdot (1 - s_s) \qquad (1)$$

The formula calculates the fraction of energy which is not specular when both diffraction and surface roughness is taken into account. (1-s_d) denotes the energy which is not (edge) diffracted, that is, energy reflected from the surface area either as specular energy or as surface scattered energy, the resulting specular energy fraction from the surface is (1-s_d)·(1-s_s).

3.1 s_s Surface scattering

Surface scattering is in the following assumed to be scattering appearing due to random surface roughness. This type of scattering gives rise to scattering which increase with frequency. In figure 4 typical frequency functions are shown. In ODEON these functions are used in the following way: The user may specify a scattering coefficient for the middle frequency around 700 Hz (average of 500 – 1000 Hz bands), then ODEON expands that coefficient into a value for each octave band, using interpolation or extrapolation.

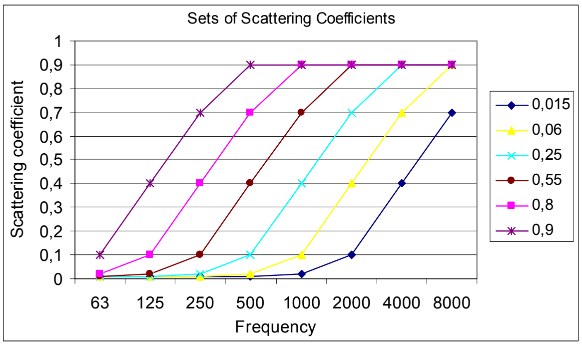

Figure 4: Frequency functions for materials with different surface roughness. The legend of each scattering coefficient curve denotes the scattering coefficient at 707 Hz.

At present it has not been investigated in depth which scattering coefficient (at the mid-frequency 707 Hz) should be used for various materials. However initial investigations indicate that the following magnitudes may be sound.

Table 1. Suggested scattering coefficients to use for various materials. The given values are for the middle frequency at around 700 Hz to be assigned to surfaces in ODEON. Suggestions may be subject to changes as more knowledge on the subject is obtained.

Material	**Mid-frequency scattering coefficient, $s_{s,m}$**
Smooth painted concrete	0.01 – 0.03
Brickwork, filled joints but not plastered	0.05 – 0.1
Brickwork with open joints,	0.1 – 0.2
Bookshelf, with some books	0.3
Audience area	0.6 – 0.7

3.2 s_d Scattering due to diffraction

In order to estimate scattering due to diffraction, reflector theory is applied. The main theory is presented in [5,6], the goal in these papers was to estimate the specular contribution of a reflector with a limited area; given the basic dimensions of the surface, angle of incidence, incident and reflected path-lengths. Given the fraction of the energy which is reflected specularly we can however also describe the fraction s_d which has been scattered due to diffraction. A short summary of the method is as follows: For a panel with the dimensions $l \cdot w$; above the upper limiting frequency f_w (defined by the short dimension of the panel) the frequency response can be simplified to be flat, i.e. that of an infinitely large panel, below f_w the response will fall off with by 3 dB per octave. Below the second limiting frequency f_l, an additional 3 dB per octave is added resulting in a fall off by 6 dB per octave. In the special case of a quadratic surface there will only be one limiting frequency below which the specular component will fall off by 6 dB per octave. The attenuation factors K_l and K_w are estimates to the fraction of energy which is reflected specularly. These factors takes into account the incident and reflected path lengths (for ray-tracing we have to assume that reflected equals incident path length), angle of incidence and distance for reflection point to the closest edge on the surface all information which is not available before the calculation takes place.

$$K_w = \begin{cases} 1 & for \quad f > f_w \\ \dfrac{f}{f_w} & for \quad f <= f_w \end{cases} \tag{2}$$

$$K_l = \begin{cases} 1 & for \quad f > f_l \\ \dfrac{f}{f_l} & for \quad f <= f_l \end{cases} \tag{3}$$

$$f_w = \frac{c \cdot a^*}{2(w \cdot \cos\theta)^2} \quad , \quad f_l = \frac{c \cdot a^*}{2 \cdot l^2}$$

$$where \quad a^* = \frac{d_{inc} \cdot d_{refl}}{2(d_{inc} + d_{refl})} \tag{4}$$

If we assume energy conservation, then we must also assume that the energy which is not reflected specularly has been diffracted - scattered due to diffraction. This leads to the following formulae for our scattering coefficient due to diffraction:

$$s_d = 1 - K_w K_l \tag{5}$$

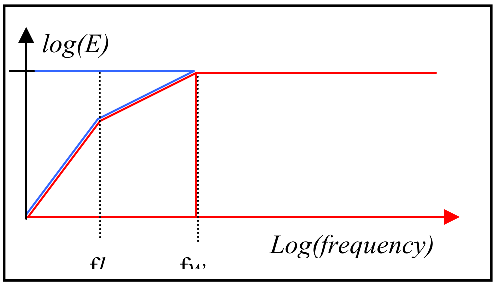

Figure 5: Energy reflected from a free suspended surface given the dimensions *l·w*. At high frequencies the surface reflects energy specularly (red), at low frequencies, energy is assumed to be scattered (blue). f_w is the upper specular cut off frequency defined by the shortest dimension of the surface, f_l is the lower cutoff frequency which is defined by the length of the surface.

As can be seen, scattering caused by diffraction is a function of a number of parameters of which some of them are not known before the actual calculation takes place. An example is that oblique angles of incidence leads to increased scattering whereas parallel walls leads to low scattering and sometimes flutter echoes. Another example is indicated by the characteristic distance a^*, if source or receiver is close to a surface, this surface may provide a specular reflection even if its small, on the other hand if far from away it will only provide scattered sound, $s_d \approx 1$.

3.3 Oblique Lambert

In the ray-tracing process, a number if secondary sources are generated at the collision points between walls and the rays traced. It has not been covered yet which directivity to assign to these sources. A straight away solution which is the one we have been using up till now is to assign Lambert directivity patterns, that is, the cosine directivity which is a model for diffuse area radiation. However the result would be that the last reflection from the secondary sources to the actual receiver point is handled with 100% scattering, no matter actual scattering properties for the reflection. This is not the optimum solution, in fact when it comes to the last reflection path from wall to receiver we know not only the incident path length to the wall also the path length from the wall to the receiver is available, allowing a better estimate of the characteristic distance a^* than was the case in the ray-tracing process where d_{refl} was assumed to be equal to d_{inc}. So which directivity to assign to the secondary sources? We propose a directivity pattern which we will call *Oblique Lambert*. Reusing the concept of *Vector based scattering*, an orientation of our Lambert sources can be obtained taking the *Reflection Based Scattering* coefficient into account. If scattering is zero then the orientation of the *Oblique Lambert* source is found by Snell's Law, if the scattering coefficient is one then the orientation is that of the traditional Lambert source and finally for all cases in-between the orientation is determined by the vector found using the *Vector Based Scattering* method.

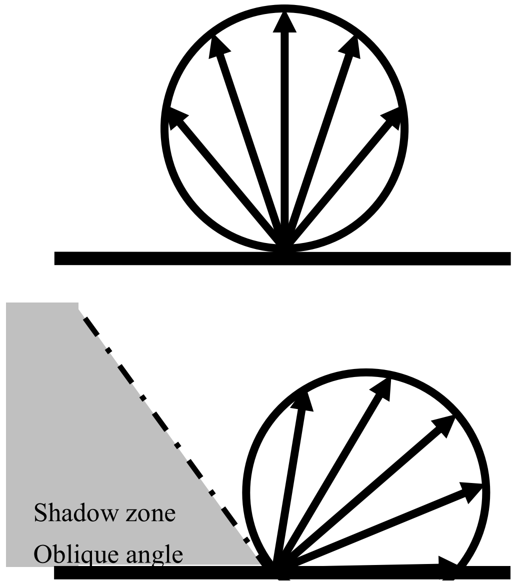

Figure 6: Traditional Lambert directivity at the top and Oblique Lambert at the bottom. Oblique Lambert produces a shadow zone where no sound is reflected. The shadow zone is small if scattering is high or if the incident direction is perpendicular to the wall. On the other hand if scattering is low and the incident direction is oblique then the shadow zone becomes large.

If *Oblique Lambert* was implemented as described without any further steps, this would lead to an energy loss because part of the Lambert balloon is radiating energy out of the room. In order to compensate for this, the directivity pattern has to be scaled with a factor which accounts for the lost energy. If the angle is zero the factor is one and if the angle is 90° the factor becomes its maximum of two because half of the balloon is outside the room. Factors for angles between 0° and 90° have been found using numerical integration.

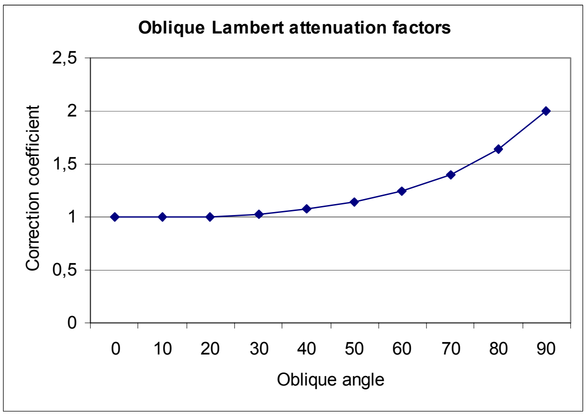

Figure 7: Correction factor for *Oblique Lambert*. When the oblique angle is zero, *Oblique Lambert* corresponds to traditional Lambert and the correction coefficient is one. When the oblique angle is 90° corresponding to grazing incidence on a smooth surface, the correction factor reaches its maximum of two.

A last remark on *Oblique Lambert* is that it can include *frequency depending scattering* at virtually no computational cost. This part of the algorithm does not involve any ray-tracing which tends to be the heavy computational part in room acoustics prediction, only the orientation of the *Oblique Lambert* source has to be recalculated for each frequency of interest in order to model scattering as a function of frequency.

4 Optimal size of surface and level of detail

Common questions with prediction programs based on geometrical assumptions are how small surfaces should be included in models, which details should be included and which should be omitted etc. Without a diffraction algorithm such as the one described above, risks are that far away objects contribute with strong specular reflections where in fact the reflected sound should be completely scattered resulting in decay curves with numerous spurious spikes – this should not be a problem with this novel algorithm. So which recommendations should be given? The straight forward answer is that surfaces which look big from any relevant source or receiver position should be modeled. If on the other hand the surfaces are far away from sources and receivers then many small surfaces may be substituted with fewer large ones, in this case, one should however remember to compensate for details not modeled by assigning appropriate scatting coefficients. Some geometries generated in CAD programs such as AutoCAD may be subdivided into many small surfaces which are not relevant for diffraction calculations. The geometry in the top of figure 8 will not be suited for the diffraction algorithms suggested. Thus we have made an algorithm which can automatically stitch such numerous small surfaces into fewer and larger surfaces better suited for the diffraction handling. At the same time the stitched geometry is far easier to handle when it comes to assigning surface properties and much better suited for visualization and printouts. If the original model had been used, then the scattering due to diffraction would have been overestimated. Even when using the stitched geometry there may still be small objects which are not relevant to the acoustic predictions, however the diffraction algorithm will scatter sound from such objects, avoiding specular reflections from far away small objects.

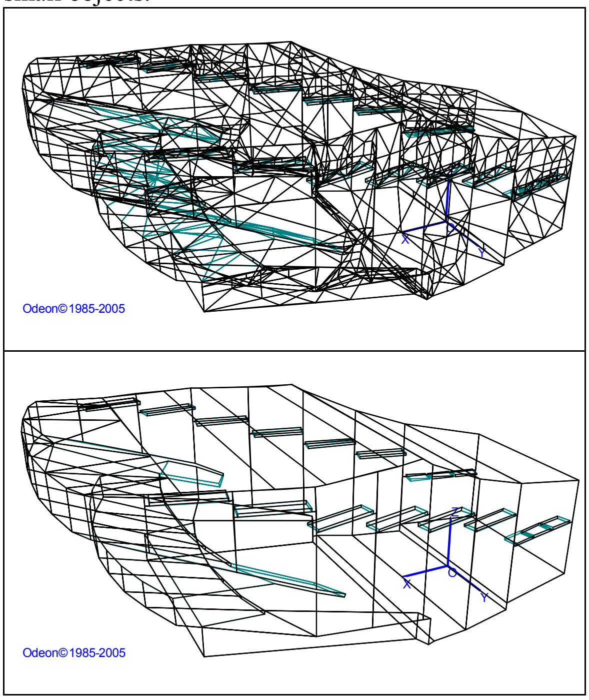

Figure 8: At the top a geometry which was imported from AutoCAD without stitching surfaces, at the bottom the model which was imported in ODEON using the stitching algorithm (Glue surfaces option). The number of surfaces was reduced from 869 to 115 surfaces without any additional user interaction forming a geometry compatible with the Reflection Based Scattering coefficient.

5 Conclusion

A new method for modeling of scattering which combines the separate components of scattering due to surface roughness and diffraction was developed, allowing the software user to use the scattering coefficients which can be obtained from measurements according to ISO-17497-1 [7].

The benefits are less guesswork and less work, improved prediction – not investigated in depth at this point and less sensitivity to small surfaces, e.g. better compatibility with architects CAD models.

6 References

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[2] Lam Y.W., "On the modelling of diffuse reflections in room acoustics prediction", Refereed Invited Paper, Proc. BEPAC & EPSRC Conference on Sustainable Building, p.106-113, 1997.

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[5] J.H. Rindel: Attenuation of Sound Reflections due to Diffraction. NAM-86, Aalborg 1986. Proceedings p. 257-260.

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[7] ISO 17497-1: Acoustics - Measurement of sound scattering properties of surfaces – Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room. 2004.