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Predicting Acoustics in Class Rooms

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Abstract Typical class rooms have fairly simple geometries, even so room acoustics in this type of room is difficult to predict using today's room acoustics computer modeling software. The reasons why acoustics of class room are harder to predict than acoustics of complicated concert halls might be explained by some typical features of these rooms; parallel walls, low ceiling height (the rooms are flat) and very uneven distribution of absorption.
It is suggested that a part of the explanation to the problem lies in the way scattering is implemented in current models relying on the use of scattering coefficients that are used in order to describe surface scattering (roughness of material) as well scattering of reflected sound caused by limited surface size (diffraction). A method which combines scattering caused by diffraction due to 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.

1. INTRODUCTION

It is commonly accepted that room acoustics prediction program based on geometrical acoustics must include scattering in order to make good 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. This was also the case in the 2nd Round Robin [3] and does seem to give good results when modelling auditoria. That type of room does however have large and proportionate dimensions which limit diffraction and the geometry usually provides some mixing between the three main dimensions of the room because the geometry contains numerous surfaces with odd angles. In fact in concert halls it is quite uncommon to find large parallel walls and if so these will usually have a high surface roughness in order to avoid undesired flutter echoes. In class rooms and offices for that matter the situation is quite different; the dimensions are smaller, in particular ceiling heights are often limited, resulting in diffraction. On the other hand walls are usually parallel resulting in low diffraction, those factors in combination with very uneven distribution of absorption in the room, results in double sloped decays where the late part of the decay may be a flutter echo. Even though boundary surfaces of class rooms may appear large it has been found that scattering coefficients of 0.1 does not lead to correct results. In [4] it was found that scattering coefficients around 0.3 gave better results. If we assume that the difference in optimal scattering coefficients between class rooms and auditoria can be explained by diffraction phenomenon's, then the optimal coefficient may be highly depending on the proportionality of the dimensions of the room as if was also found in [5], resulting in different typical; angles of incidence, path lengths and surface dimensions.

2. GEOMETRICAL MODEL

Room acoustic programs such as ODEON covered in this paper makes use of some kind of hybrid calculation method combing the Image source method with a raytracing method. The hybrid method applied in ODEON is not the subject of this paper, however for the overview here is a short decription 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 [6]. Typical values of TO are 1, 2 or 3, but in some cases even a value of 0 may be preferred, in which case only the ray tracing algorithm is used.

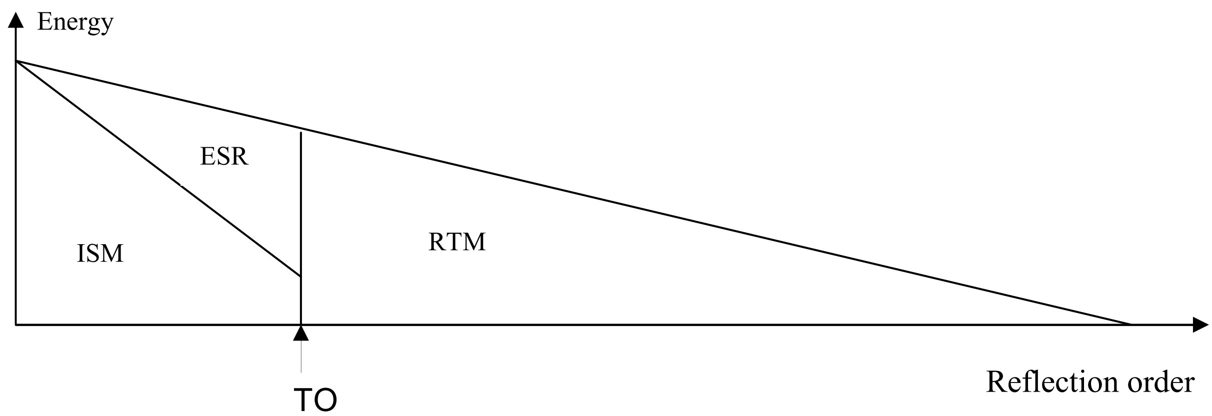

Figure 1:. Summary of the hybrid calculation method as used in ODEON. Early reflections below a selected transition order (TO) are calculated using a combination of the image source method (ISM) and early scattering rays (ESR). Above the TO, reflections are calculated using a ray-tracing method (RTM) 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.

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.

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 [7]) 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 0.02 to 0.20 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.

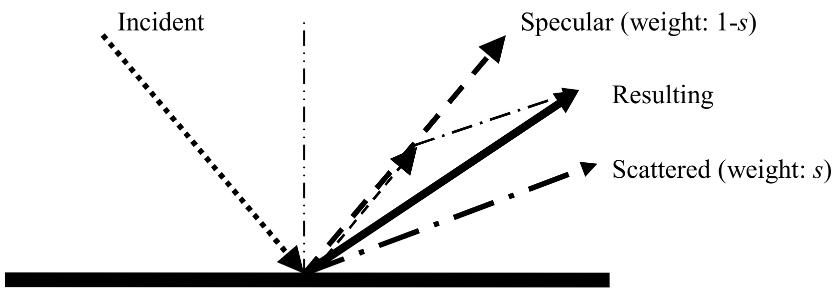

Figure 2: Vector based scattering. Reflecting a ray from a surface with a scattering coefficient of 0.50 results in a reflected direction which is the geometrical average of the specular direction and a random (scattered) direction. Note: The scattering is a 3D phenomena, but here shown in 2D

3. THE REFLECTION BASED SCATTERING COEFFICIENT

In order to better include the diffraction phenomenon's which is assumed to be vital to the acoustics of class rooms, a new method for handling scattering has been developed for the ODEON software [8]. The method takes into account that the amount of scattering caused by diffraction is not fully known before the actual reflections are calculated because angles of incidence, path-lengths etc. are not known before the calculations are carried out. In order to allow such features to be included in predictions, we suggest the *Reflection Based Scattering* coefficient s_r which combines 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:

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

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 $(1-s_d)\cdot(1-s_s)$.

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 3 typical frequency functions are shown. In ODEON 8ß 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.

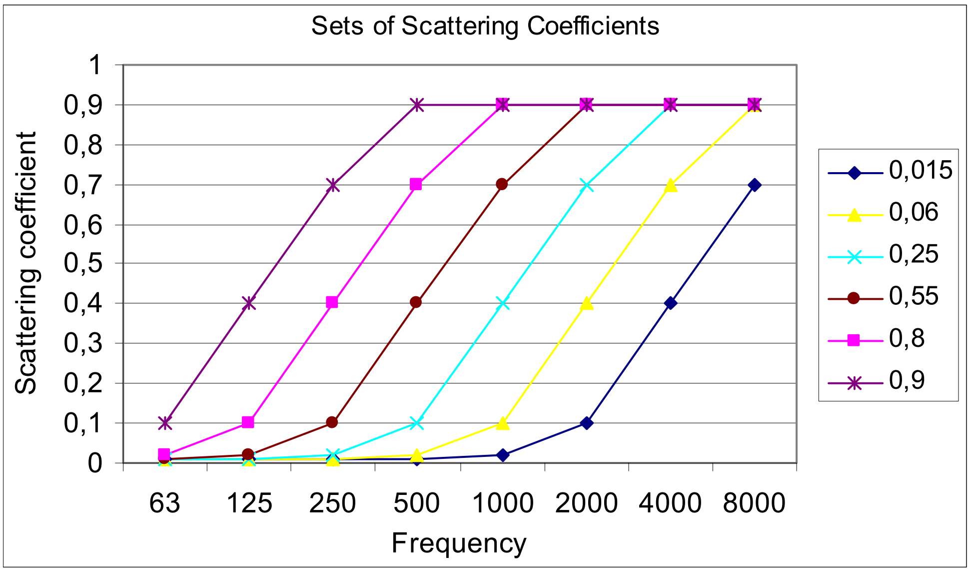

Figure 3: Frequency functions for materials with different surface roughness. The legend of each scattering coefficient curve denotes the scattering coefficient at 707 Hz.

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 [9], the goal in that paper 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 by 3 dB per octave. Below the second limiting frequency f_l (defined by the length of the panel), 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 decrease by 6 dB per octave.

The attenuation factors K_l and K_w are estimates to the fraction of energy which is reflected specularily. These factors take into account the incident and reflected path lengths (for ray tracing we have to assume that reflected path length equals incident path length) and angle of incidence. All information, which is not available before the calculation takes place.

$$K_w = \begin{cases} 1 & for \quad f > f_w \\ \dfrac{f}{f_w} & for \quad f \le f_w \end{cases} \quad , \quad K_l = \begin{cases} 1 & for \quad f > f_l \\ \dfrac{f}{f_l} & for \quad f \le f_l \end{cases} \tag{2}$$

$$f_w = \frac{c \cdot a^*}{2(w \cdot \cos\theta)^2} \quad , \quad f_l = \frac{c \cdot a^*}{2 \cdot l^2} \quad where \quad a^* = \frac{d_{inc} \cdot d_{refl}}{2(d_{inc} + d_{refl})} \tag{3}$$

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

$$s_d = 1 - K_w K_l \tag{4}$$

As can be seen, scattering caused by diffraction is a function of a number of parameters some of which are not known before the actual calculation takes place. An example is that oblique angle of incidence lead to increased scattering whereas parallel walls lead 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 away it only provide scattered sound, $s_d \cong 1$.

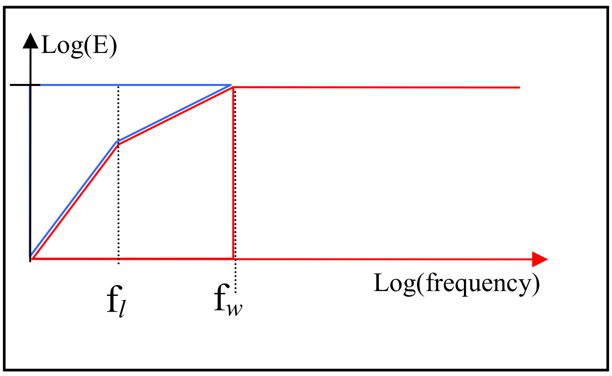

Figure 4: Energy reflected from a free suspended surface given the dimensions $l \cdot w$. At high frequcies the surface reflects energy specularily (red), at low frequencies, energy is assumed to be scattered (blue). f_w is the upper specular cutoff frequency defined by the shortest dimension of the surface, f_l is the lower cutoff frequency which is defined by the length of the surface.

4. OBLIQUE LAMBERT

In the ray-tracing process a number of 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 method used in earlier versions of ODEON, is to assign Lambert directivity patterns, that is the cosine directivity for diffuse radiation. However the result is that the 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 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 *Oblique Lambert* source 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.

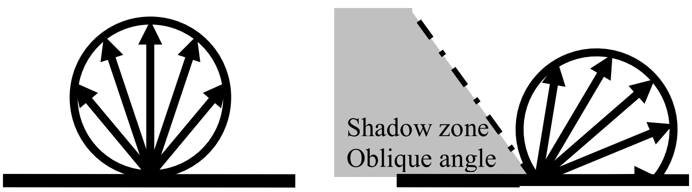

Figure 5: Traditional Lambert directivity to the left and Oblique Lambert to the right. Oblique Lambert produces a shadow zone where no sound is reflected. The shadow zone is small if scattering is high or if the incident direction is nearly perpendicular to the wall. On the other hand if scattering 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.

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.

5. 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 when in fact the reflected sound should be completely scattered. This results in decay curves with numerous spurious spikes – this is no longer 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 higher 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 left side of figure 6 will not be suited for the diffraction algorithms suggested. However an algorithm which can automatically stitch such numerous small surfaces into fewer and larger ones better suited for the diffraction handling has been developed. 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 scattering due to diffraction would have been overestimated.

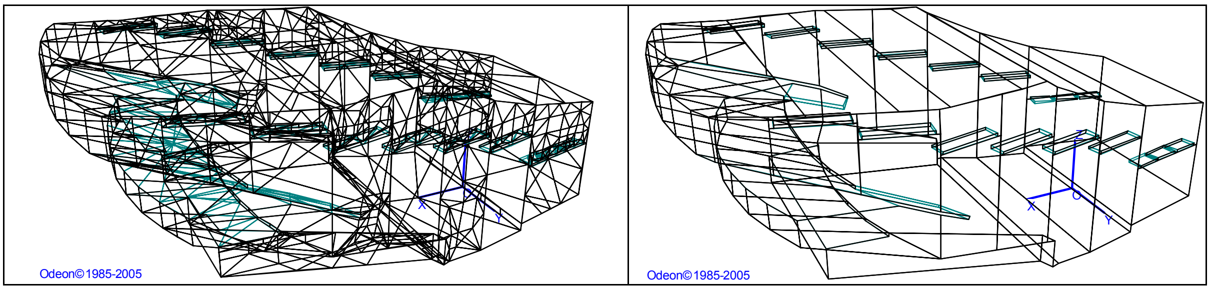

Figure 6: At the left a geometry which was imported from AutoCAD without stitching surfaces, at the right the model which was imported in ODEON using the stitching algorithm (Glue surface option). The number of surfaces was reduced from 1362 to 209 surfaces without any additional user interaction forming a geometry compatible with the Reflection Based Scattering coefficient.

6. CASE STUDY

The following example illustrates the problems which occur when predicting acoustics in a class room and similar rooms where the ceiling height is low and distribution of absorption is very uneven. The room chosen for the case study is the lecture room at Acoustic Technology, Ørsted-DTU. It is a box shaped room with the dimensions 9.46 x 6.69 x 3.00 metres, measured average reverberation time was 0.44 seconds at 1000 Hz. The surfaces are: Walls of painted brickwork, windows, wooden floor, blackboards, a wooden door, a suspended ceiling with high absorption and furniture of wood. Virtually the whole range of absorption coefficients is in use at mid-frequencies.

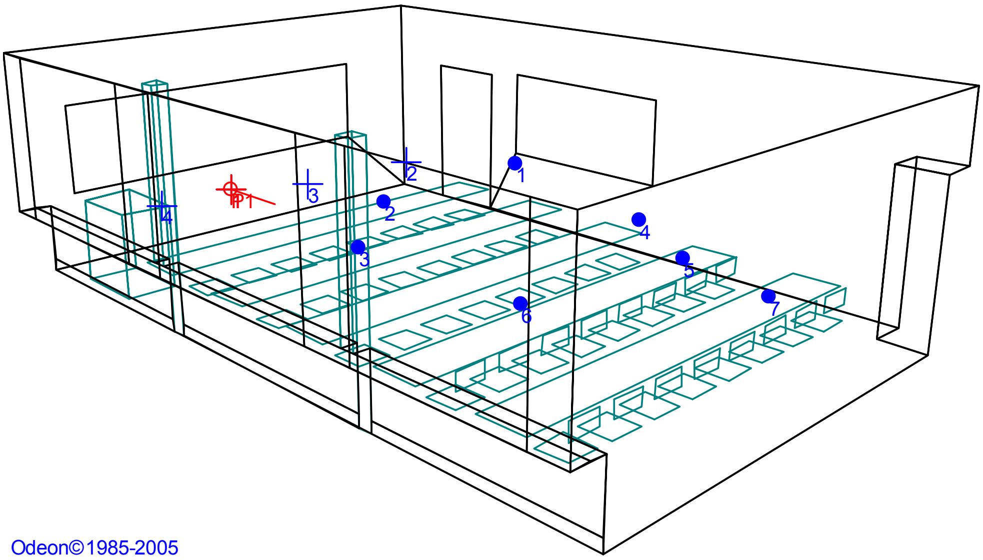

Figure 7: Model of the lecture room at Acoustic Technology, Ørsted-DTU. The room is a box shaped room with the dimensions 9.46 x 6.69 x 3.00 metres, measured average reverberation time was 0.44 seconds at 1000 Hz.

Initial calculations were carried out with one source and seven receiver positions. The materials were not fitted rather they were chosen from a library of 'standard materials' therefore may not reflect accurately the properties of the real materials; however the data have sufficient accuracy in order to illustrate the problem. To limit the data presented in the following, only reverberation time T_{30} at the 1000 Hz octave band is presented. Other parameters may also be relevant, indeed one reason to use a prediction program such as ODEON may be to predict parameters such as C_{80}, D_{50} or STI or to be able to auralize the acoustics of a room. However T_{30} illustrates the problem quite well.

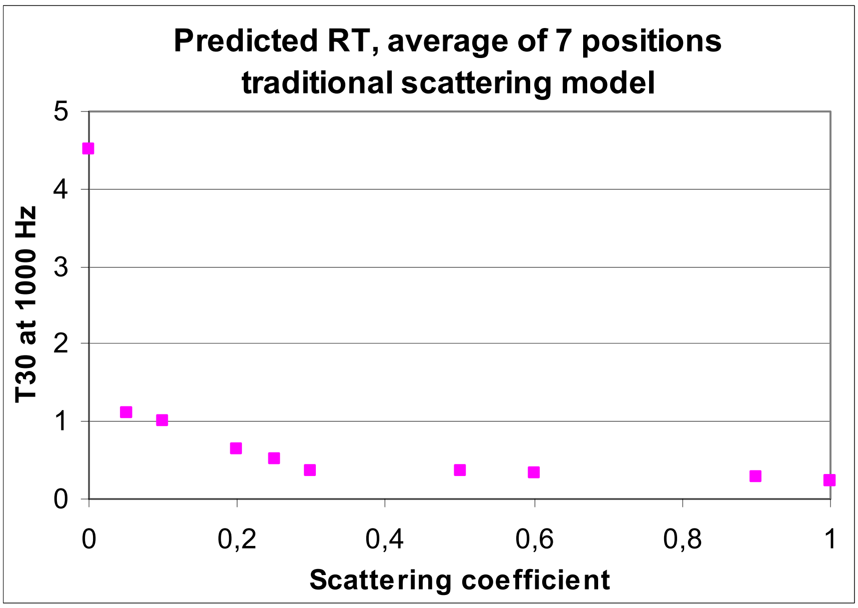

Figure 8: Predicted reverberation time at 1000 Hz as function of scattering coefficient when a traditional scattering model is used. For comparison the average of the measured reverberation time was 0.44 seconds and the reverberation time predicted with the Sabine formula was 0.37 seconds

First set of calculations were carried out using a traditional scattering model where the user-specified scattering coefficients should be large enough to account for scattering due to limited surfaces size as well as scattering due to surface roughness. Calculations were carried out using different scattering coefficients in order to find the magnitude of influence from the choice of coefficient as well as to find the best choice. In order to keep things simple, the same scattering coefficient was applied to all surfaces although it could be argued that larger coefficients should be used for the smaller surfaces such as chairs and tables.

As can be seen the results are dramatically influenced by the scattering coefficient chosen, when the scattering coefficient is set to zero, that is completely smooth walls, which are considered infinitely large, the predicted reverberation time is very far away from the measured $T_{avr} = 0.44$ seconds. Scattering coefficients in the range of 0.25 to 0.5 seems to provide predictions which correspond better with measured reverberation. These scattering coefficients are in agreement with the findings in [4] where 0.3 was suggested, however the scattering coefficient of 0.1 found by Lam [2] for large smooth surfaces in concert halls leads to dramatic over estimation of the reverberation time.

In the second set of calculations the *Reflection Based Scattering* method was applied. In this case no extreme results are found. It seems that best results are obtained when a scattering coefficient between 0.05 and 0.10 is used. It should be recalled, that frequency dependent scattering is actually applied, but only the mid-frequency value need to be specified. The walls in the room consist of painted brickwork with filled joints a fairly but not completely smooth material, Lab. measurement according to ISO/FDIS 17497-1 [10] of smooth materials indicates that s_s lies around 0.02-0.03 for the mid-frequencies [11] so this seems to be a realistic choice. The predicted results where lower and higher scattering coefficients were applied do not seem unrealistic.

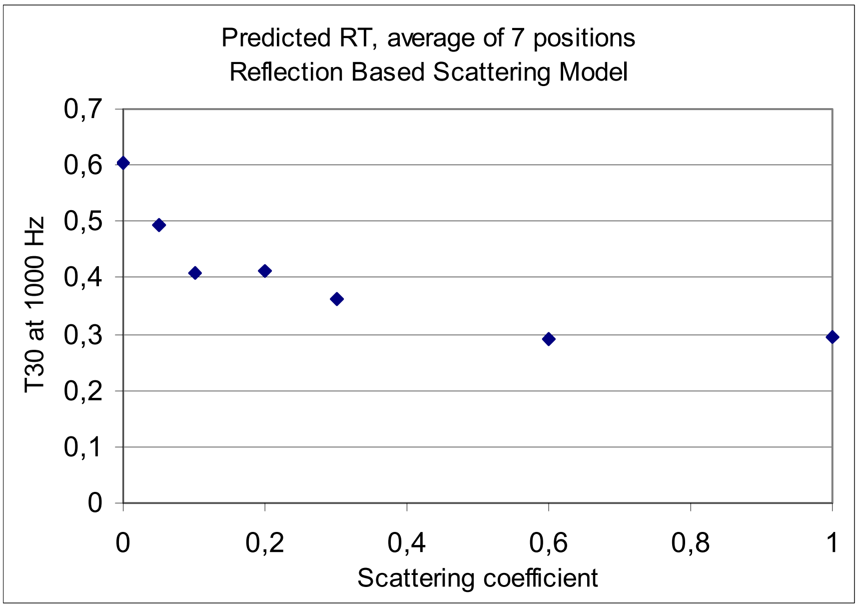

Figure 9: Predicted reverberation time at 1000 Hz as function of scattering coefficient when the Reflection Based Scattering model is used. The measured reverberation time of 0.44 seconds indicates that a scattering coefficient between 0.05 and 0.10 is optimum.

7. CONCLUSIONS

A novel method for modelling of scattering which combines the separate components of frequency depending scattering due to surface roughness and diffraction was developed. Initial evaluations do indicate that the scattering coefficients to be used with this method are compatible with those obtained through measurements according to ISO/DIS 17497-1. Some of the benefits are; less guesswork for the user of the prediction software, improved predictions and less sensitivity to small surfaces, e.g. better compatibility with architects CAD models.

8. REFERENCES

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