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Practical methods to define scattering coefficients in a room acoustics computer model

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Abstract

To predict acoustics of rooms using computer programs based on geometrical assumptions, it is important that scattering is included in the calculations. Therefore scattering is usually included in terms of scattering coefficients which are assigned to each surface telling the software the ratio between the part of the reflected energy which is not being reflected specularily and the total reflected energy. However the effective scattering coefficient of a surface depends not only on the roughness of the surface material indeed diffraction caused by limited dimensions of the surface as well as edge diffraction also causes scattering. For complex rooms it can be difficult to give a reasonable estimate to the magnitudes of scattering coefficients if these should also include diffraction and even if these frequency dependent coefficients could be obtained in the design phase, the processes of obtaining the data becomes quite time consuming thus increasing the cost of design. In this paper, practical methods to define scattering coefficients, which is based on an approach of modeling surface scattering and scattering caused by limited size of surface as well as edge diffraction are presented. The predicted and measured acoustic parameters in real rooms have been compared in order to verify the practical approaches recommended in the paper.

Keywords: Scattering coefficient; Room acoustics; Computer model

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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, concert halls and work rooms as pointed out in Ref. [1–4]. In the *First International Round Robin on Room Acoustical Computer Simulations* [5], only simulation programs including scattering were found to provide reliable results. The investigations carried out by Hodgson [1], Dalenback [2] and Lam [3] have shown that inclusion of scattered reflections not only affect the accuracy of the calculation of acoustical parameters it also influences the quality of auralization. Therefore, room acoustics computer programs based on geometrical acoustics should be able to handle scattering of sound.

Just like the absorption coefficient can be used to describe the absorption of a surface, scattering of a surface can be described by the scattering coefficient. The scattering coefficient is not only dependent on the roughness of the surface material, also the geometry (size and shape) of the geometry is important [6] making it a key issue to obtain realistic scattering coefficients to be used in geometries to be investigated in room acoustic prediction programs. There are two common ways of obtaining the scattering coefficient of a certain surface at present, either through direct measurement [7,8] or based on experience and suggestions such as those found in [9,10]. Although it may be possible, it is impractical to measure all types of surface constructions to be used in a room, therefore till now, in most computer models, scattering coefficients are estimated from experience. This requires that the users must be room acoustics experts, limiting the application of the prediction programs.

Most simulation software typically include scattering in terms of scattering coefficient which accounts for scattering caused by surface roughness, limited size of surfaces and edge diffraction. Farina [11] has taken into account separately the scattering from the edges of finite-size surfaces and the surface scattering coefficient. In his improved beam-tracing algorithm, a scattering coefficient with a "running" value is applied. The value is dependent on the reflection order and the local value of the scattering coefficient of a surface by which the beam axis has hit. For a panel, the local value of scattering coefficient is calculated according to the increase of the scattering coming near to the edges of the panel. Dalenbäck has also considered the edge scattering in the software CATT-Acoustics [12], in which a scattering coefficient dependent on the relation between surface size and wavelength is assigned to the edge; then this part of scattering coefficient will be combined with the normal surface scattering coefficient for the case of reflection order > 1.

In this paper, a novel method considering scattering due to surface roughness and scattering caused by limited size of surface and edge diffraction is described. Comparing with Farina's method, we consider the part of scattered sound from small surfaces not only according to the distance from the hitting point to the center of the surface, but also the source–receiver distance, distance from receiver and source to the surface. Moreover, the following description will show that the part of scattering coefficient is frequency dependent (on the limiting frequency of a surface). Dalenbäck's method also uses a frequency dependent factor and agrees that the maximal value of the edge scattering coefficient is 0.5, but in our method, the scattering coefficient due to edge diffraction is a function of several factors (Eq. (10)), not only the surface size. This is an attempt to include as many of the factors as possible having influence on diffraction from surfaces with limited size.

The method has been applied in two types of rooms: a large multipurpose hall and a small studio namely the Elmia multipurpose hall from the 2nd Round Robin [13] and the PTB Studio from the 3rd Round Robin [14]. The new method described here has been applied in the new version (8.0) of ODEON program. For both room cases, practical methods to define the model and the scattering coefficients when using ODEON program and other similar packages are given. The accuracy of the methods is discussed based on the predicted and measured acoustic parameters in real rooms.

2. Current methods for modeling surface scattering

At present, a number of geometrical acoustics models of scattering have been developed such as randomized diffuse model developed by Hogdson et al. [1], secondary sources model suggested by Dalenbäck [15], diffuse energy model recommended by Kuttruff [16] and splitting coefficient model presented by Embrechts [17]. These models agree that the reflected energy can be divided into two parts at a surface: specular and scattered. Their relation can be denoted by the absorption coefficient α and the scattering coefficient s

$$\underbrace{(1-s)(1-\alpha)}_{\text{Specular}}+\underbrace{\alpha}_{\text{Absorbed}}+\underbrace{s(1-\alpha)}_{\text{Scattered}}=1 \tag{1}$$

The basic idea to consider sound scattering in program ODEON in version 7.0 also obeys the above agreement. It can be briefly described as follows.

ODEON 7.0 makes use of a hybrid calculation method which combines 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 Ref. [10]. Typical values of TO are 1–4, 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.

The hybrid method used in ODEON is illustrated in Fig. 1. 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 be zero, the method becomes a ray-tracing model. Note that all the three methods will, most likely, overlap in time.

In the ODEON program, a particular scattering model that is shown in Fig. 2 has been applied. We name it "vector based scattering model" and it is an efficient way to include scattering in a ray-tracing algorithm.

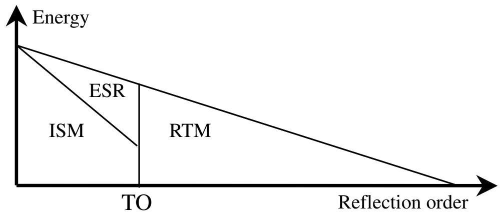

Fig. 1. Summary of the hybrid calculation method as used in ODEON.

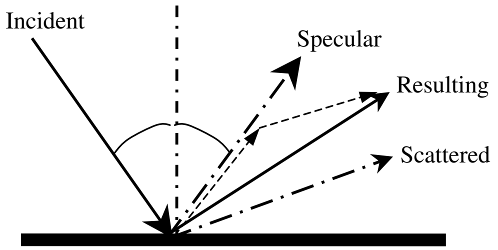

Fig. 2. Vector based scattering.

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 $s = 1$, the reflected ray will propagate in a scattered direction; in ODEON, the scattering model conforms to the Lambert's law, so the reflected ray is deflected to a random direction, with a probability varying with the cosine of the angle with the normal to the surface. If $s = 0$, the reflected ray will propagate in a specular direction which is easily obtained from Snell's law. If s is between 0 and 1, the resulting direction is determined using s as a weighting between the pure specular direction and scattered direction.

3. Practical methods to define scattering coefficient

3.1. A new approach for the calculation of scattering coefficients

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:

3.1.1. 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 ODEON typical measured scattering coefficient frequency functions [18] are used to expand a mid-frequency scattering coefficient input by the user to all frequency bands. This means that only one input value for the scattering coefficients needs to be specified for a surface at the middle frequency around 700 Hz (average of 500–1000 Hz bands), ODEON will expand these coefficients into values for each octave band, using interpolation or extrapolation.

3.1.2. s_d – Scattering due to edge diffraction

As surface edge diffraction also provides scattering, it should be considered in the computer model. Firstly we take a small panel as an example, which is shown in Fig. 3. S, S′ are the original sound source and image source, R is the receiver. It can be derived that the limiting frequency is [19]

$$f_g = \frac{c \cdot d^*}{2A\cos\theta} \tag{2}$$

where c is the speed of sound, A is the area of the small surface and d^* is the characteristic distance, which can be calculated from

$$d^* = \frac{2d_1 \cdot d_2}{d_1 + d_2} \tag{3}$$

Above the limiting frequency, the diffraction losses can be considered negligible, while below the limiting frequency, it is

$$\Delta L = 20\log_{10}\frac{f}{f_g} \tag{4}$$

This means at frequency higher than the limiting frequency, the sound energy can be thought totally specular and below the limiting frequency the scattering energy due to diffraction increases rapidly (6 dB per octave band). This part of scattered energy can be described by s_d, which can be calculated from

$$s_d = 1 - \left(\frac{f}{f_g}\right)^2 = 1 - \left(\frac{2f \cdot A \cdot \cos\theta}{c \cdot d^*}\right)^2 \tag{5}$$

Therefore, the reflection based scattering coefficient s_r can be calculated from

$$s_r = 1 - (1 - s_d)(1 - s_s) \tag{6}$$

where s_d is the fraction of energy scattered due to diffraction (related to path lengths, surface dimensions and distance from edge of surface, etc.) and s_s is the fraction of scattering caused by surface roughness as defined in ISO17497-1 [20].

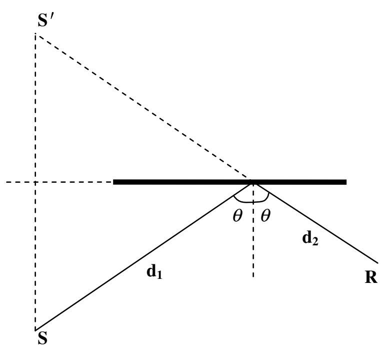

Fig. 3. Sound reflection from a small surface.

For a large 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; 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. It is illustrated in Fig. 4 in which the surface reflects energy specularly at high frequencies, and at low frequencies energy is assumed to be scattered.

The attenuation factors K_l and K_w are estimates to the fraction of energy which is reflected specularly. These factors take into account the incident and reflected path lengths, see (3), and angle of incidence.

$$K_w = \begin{cases} 1 & \text{for} \quad f > f_w \\ \frac{f}{f_w} & \text{for} \quad f \leqslant f_w \end{cases}, \quad K_l = \begin{cases} 1 & \text{for} \quad f > f_l \\ \frac{f}{f_l} & \text{for} \quad f \leqslant f_l \end{cases} \tag{7}$$

$$f_w = \frac{c \cdot d^*}{2(w \cdot \cos\theta)^2}, \quad f_l = \frac{c \cdot d^*}{2 \cdot l^2} \tag{8}$$

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 formula for the scattering coefficient due to diffraction:

$$s_d = 1 - K_w \cdot K_l \cdot (1 - s_e) \tag{9}$$

In order to compensate for the extra diffraction which occurs when a reflection appears close to an edge of a free surface, the specular component is reduced by a factor $1 - s_e$. The edge scattering coefficient is defined to be 0.5 if the reflection happens at the edge of a surface saying that half of the energy is scattered by the edge and the other half is reflected from the surface area. If the reflection point is far from the edge, then the edge scattering becomes zero; initial investigations suggests that edge scattering can be assumed to be zero when the distance to the edge is greater than approximately one wave length, therefore we define:

$$s_e = \begin{cases} 0 & \text{for} \quad d_{\text{edge}} \cdot \cos\theta \geqslant \frac{c}{f} \\ 0.5\left(1 - \frac{d_{\text{edge}} \cdot f \cdot \cos\theta}{c}\right) & \text{for} \quad d_{\text{edge}} \cdot \cos\theta < \frac{c}{f} \end{cases} \tag{10}$$

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 d_*. If source or receiver is close to a surface, this surface may provide a specular reflection even if it is small; on the other hand if far from away it will only provide scattered sound, $s_d \approx 1$.

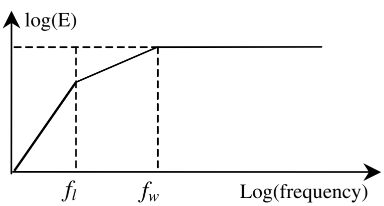

Fig. 4. Energy reflected from a free suspended surface.

As long as surfaces are truly freely suspended surfaces, they will act as effective diffusers down to infinitely low frequencies. For surfaces which are elements in the boundary of the room, such as windows, doors, paintings and blackboards, one should however not expect these elements to provide effective scattering down to infinitely low frequencies. From diffuser theory [21,22] it is found that typical behavior is that the effectiveness of a diffuser decreases rapidly below a cut-off frequency which can roughly be defined from the depth of the diffuser (wall construction) being less than half a wave length. Two octave bands below the cut-off frequency the diffuser is no longer effective. At the lowest frequencies however, the dimensions of the room will provide some diffraction, therefore at the lowest frequencies the dimensions of the reflecting panel as used in the formulae for f_l and f_w are substituted with the approximate dimensions of appropriate cross-section of the room and a combination of surface and room dimensions are used for frequencies in-between high and low frequencies.

It is worth noticing that it is not only the depth of the wall construction which enables the elements of the wall construction to provide diffraction, also angles between the surfaces, offsets, e.g., the window being mounted in a window hole or the surfaces being made of different materials provides the phase shifts which results in diffraction. Therefore it may be reasonable to assume that the boundary walls have a 'minimum depth' which accounts for such phase shifts, e.g., 10 cm. As an example let us assume that we have a window mounted in a wall in a window hole of say 10 cm; let the projection of the area be $A\cos\theta = 0.5\ \mathrm{m}^2$ and the characteristic distance $d^* = 5.0$ m; when the frequency is above $344/(2 \times 0.10) = 1720$ Hz, the window area can be looked as a separate surface and can be calculated according to the above scattering algorithms; when the frequency is below 1720 Hz, then reflection due to the area of the window is not fully efficient and at a fourth of that frequency the window is not providing reflection at all due to its limited size. However at such low frequencies there will still be some diffraction because the window is ultimately a part of the boundary of the room which has a limited area itself.

The above algorithm combines scattering due to edge diffraction and scattering due to surface roughness, therefore it reduces the influence of the user specified scattering coefficient which should only include scattering due to surface roughness, thus requiring less experience from the user.

3.2. Methods to define scattering coefficients for different rooms

For different room complexity, the cost of model design and the accuracy of parameter prediction may be different. To obtain a balance between cost and accuracy, we suggest two different ways to deal with small surfaces in large concert halls and small rooms.

3.2.1. Small and simple rooms

For such kind of rooms, the number of main walls is usually small and diffusing surfaces may be distributed on a few walls to achieve special acoustics effect. For instance, a studio room may need better acoustic behaviors at low frequency bands. It is required that some walls have to be equipped with special diffusers to counterbalance the weak scattering due to the simple structure of the room.

In this case, all the surfaces including the small ones of the diffusers will be considered in a detailed computer model. And one scattering coefficient due to the surface roughness s_s can be assigned to all these small surfaces. The recommended value lies in the range of 0.01

and 0.05. The scattering coefficient due to surface roughness is then combined with the part representing the scattering caused by surface edge diffraction.

In offices or classrooms, there is furniture such as tables and shelves. If a table plate is close to a source or receiver point, it is likely to produce a strong reflection at the receiver, so it also should be included in the model.

3.2.2. Large and complicated rooms

For a large room such as concert and opera halls, the shape and its interior of the room is usually complicated. It is likely to contain many small surfaces and modeling these rooms with a high level of detail is likely to be a waste of time at its best. It is recommended to simplify the real building when turning it into a visible computer model. This implies that, e.g., some details of the walls may be left out. But for such kind of walls the comparatively bigger scattering coefficients should be defined. The value is usually in the range of 0.3–0.8.

Some practical guidelines for the simplification:

(1) *Curved surfaces*. Curved surfaces have to be approximated by dividing them into plane sections. Kuttruff [23] has analyzed the errors of such approximation and has pointed out that how fine subdivisions should be depends on the wavelength. Experientially we can subdivide depending on the type of curved surface and how important the surface is. Convex curves naturally disperse sound energy, so if the surface is in an exposed position (e.g., the end of a balcony near the stage), one should avoid simply replacing a quarter circle with a single plane, which might then act like a reflector. Concave curves naturally focus sound energy, and we must try to arrange that this effect is preserved. Except at focal regions, these errors can be minimized by improving the degree of approximation [23]. However this does not mean that a large number of subdivisions are the solution. Using many surfaces in the model will make the model visually complex, and increase the probability of errors in the model, typically small leaks may become a problem. Subdivisions about every 10–30° will probably be adequate to reproduce focusing trends, without excessive numbers of surfaces.

(2) *Audience area*. Modeling each step between the rows in an audience area is not recommended. The audience area can be simplified a lot without compromising the quality of the results. This guideline also applies to podium on stage.

(3) If 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.

(4) *Other special cases*. Some geometries generated in CAD programs such as AutoCAD may be subdivided into extremely many small surfaces which have no relevance for diffraction calculations. The geometry in the left of Fig. 5 will not be suited for the diffraction algorithm suggested. Thus an algorithm has been created 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 a 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,

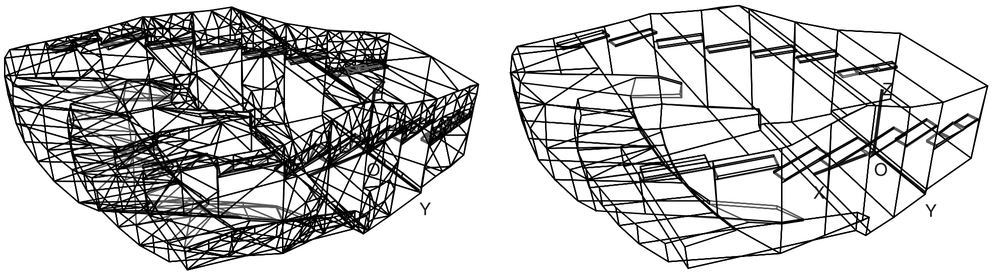

Fig. 5. Model imported from AutoCAD (left) and imported in ODEON using the stitching algorithm (right).

avoiding specular reflections from far away small objects. In Fig. 5, the left geometry was imported from AutoCAD without stitching surfaces; the right model was imported in ODEON using the stitching algorithm (Glue surfaces option).

4. Prediction of various rooms

The basic idea of the algorithm for simple test cases involving single and arrays of reflecting surfaces in free air has been studied in previous publications [19,21,22] and will not be repeated here. The testing here will be based on full size rooms and two different real rooms will be studied.

4.1. Modeling a studio room

The PTB studio (in the open curtain configuration), which was used to test different computer models in the 3rd International round robin [14] has been chosen as an example in this paper. The two geometrical models of the studio which was also used in the Round Robin, named "simple" and "detailed" respectively were used in the test, see Fig. 6.

There are 70 surfaces in the simple model and the total surface area is 421 m^2. For the detailed model, there are 268 surfaces and the total surface area is 450 m^2. In the simple model the small diffusers on the ceiling and one wall have been neglected. The omni-directional point source is located at $(x, y, z) = (1.5, 3.5, 1.5)$ and three receivers are: R1(−2.00, 3.00, 1.20), R2(2.00, 6.00, 1.20), R3(0.00, 7.50, 1.20). The total ray number is 10,000 and the transition order is 0. The scattering coefficients of various surfaces are listed in Table 1. The measurement results are the mean value of 18 participants, which can be downloaded from the PTB website [24].

To validate the scattering method presented in the paper, it has been compared with the old method applied in the ODEON 7.0. Three cases have been studied: (1) simple model, old scattering method; (2) simple model, new scattering method; (3) detailed model, new scattering method. The acoustic parameters C_{80}, T_{30}, Ts, EDT, LF_{80}, D_{50} and G have been predicted and compared with the measured results. Fig. 7 has shown some of the results at the receiving position R2.

4.2. Modeling a concert hall

The Swedish concert hall Elmia has been studied. Two different models were used in ODEON. One simplified and another is with a high level in detail. See Fig. 8.

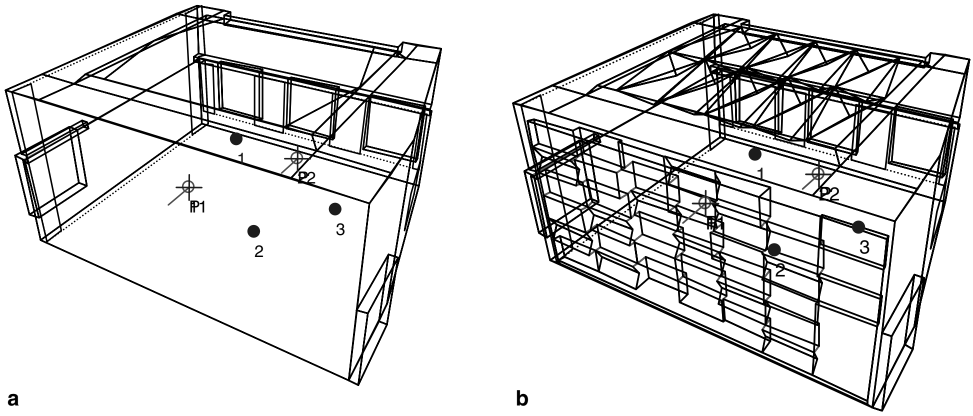

Fig. 6. PTB studio (a) simple model (b) detailed model.

Table 1
Scattering coefficients for PTB studio model

Case	Surface	Scattering coefficient
Simple model old method	Parquet	0.20
	Wilhelmi	0.30
	Curtain (open)	0.48
	Studio wall	0.20
	Window glass	0.10
	Wood absorber	0.95
	Ceiling	0.95
Simple model new method	Ceiling	0.85
	Wood absorber	0.85
	Other surfaces	0.02
Detailed model new method	All surfaces	0.02

There are 94 surfaces in the simple model and the total surface area is 4409 m^2. For the detailed model, there are 470 surfaces and the total surface area is 4932 m^2. In the simple model the small diffusers on the side faces have been simplified. The omni-directional point source is located at $(x, y, z) = (8.5, 0.0, 25.5)$ and six receivers are: R1(13.8, 0.0, 24.9), R2(12.9, 10.5, 28.7), R3(19.9, 5.1, 26.1), R4(25.5, −4.9, 27.5), R5(24.8, 11.9, 29.1), R6(37.80, 6.40, 131.85). 10,000 rays have been used to calculate the acoustics parameters C_{80}, T_{30}, Ts, EDT, LF_{80}, D_{50} and G. The transition order is set to be 4 and the scattering coefficients of various surfaces are listed in Table 2.

The predicted acoustic parameters have been compared with those of measurements. Some of the results at position R6 are shown by Fig. 9.

4.3. Discussion

4.3.1. Accuracy of different scattering models

For the PTB studio, the mean errors of the three cases at 6 frequency bands have been calculated and listed in Table 3. For Elmia concert hall, the mean errors of the two cases at six frequency bands are listed in Table 4.

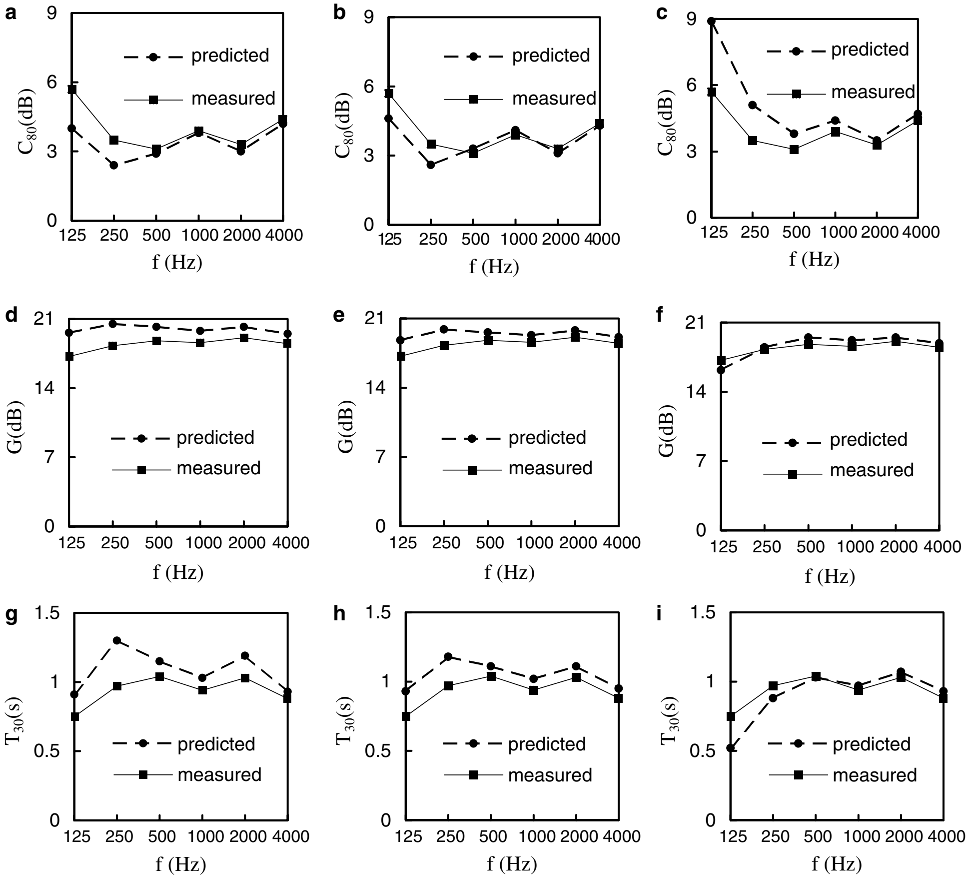

Fig. 7. Comparison of predicted and measured parameters in PTB studio: (a) C_{80}-simple model-old method; (b) C_{80}-simple model-new method; (c) C_{80}-detailed model-new method; (d) G-simple model-old method; (e) G-simple model-new method; (f) G-detailed model-new method; (g) T_{30}-simple model-old method; (h) T_{30}-simple model-new method; (i) T_{30}-detailed model-new method.

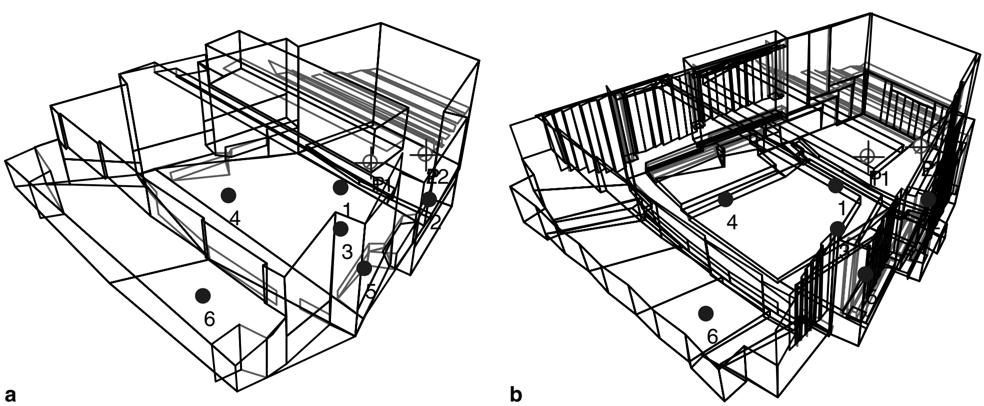

Fig. 8. Elmia concert hall: (a) simplified model, (b) detailed model.

Table 2
Scattering coefficients for Elmia model

	Surface	Scattering coefficient
Simplified model	Audience area	0.60
	Simplified surfaces	0.30
	Other surfaces	0.02
Detailed model	Audience area	0.60
	Side reflectors	0.35
	Ceiling	0.30
	Other surfaces	0.02

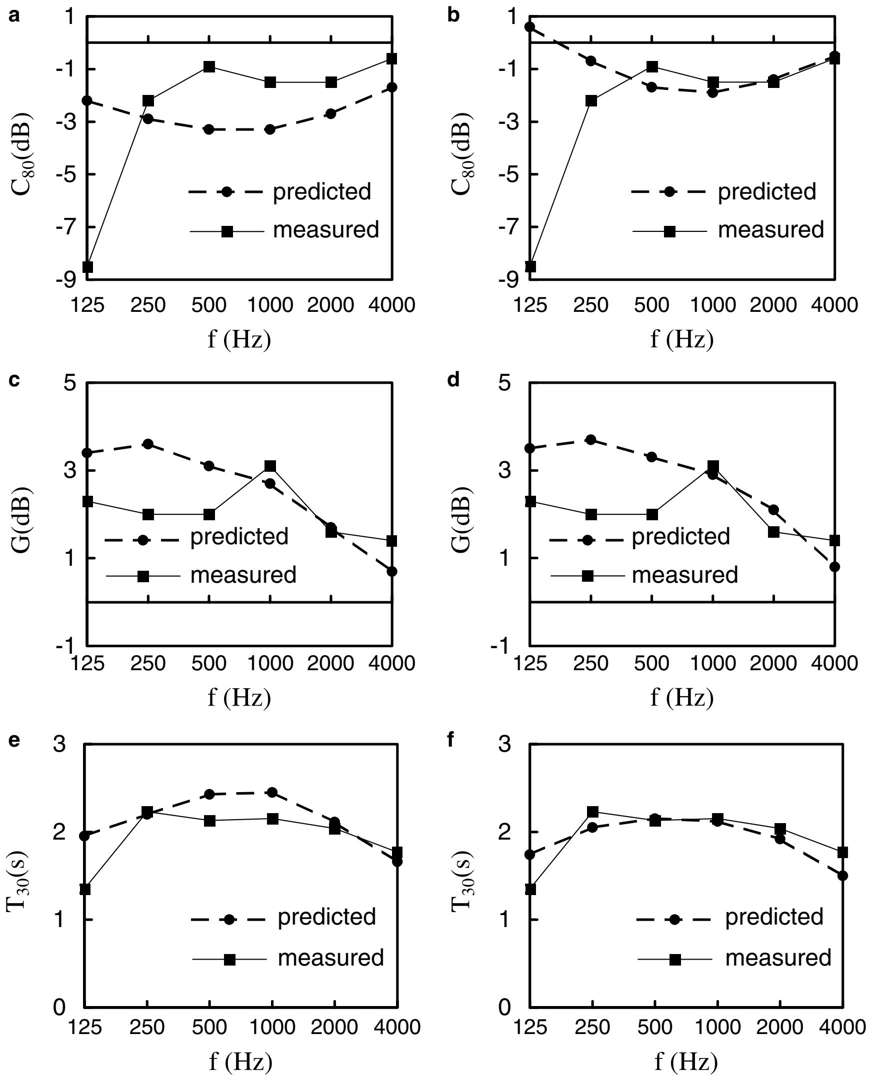

Fig. 9. Comparison of predicted and measured parameters in Elmia concert hall: (a) C_{80}-simple model; (b) C_{80}-detailed model; (c) G-simple model; (d) G-detailed model; (e) T_{30}-simple model; (f) T_{30}-detailed model.

Table 3
Average errors of three receiving positions in PTB studio

Model	Parameter	Frequency (Hz)					
		125	250	500	1000	2000	4000
Simple model-old method	C_{80} (dB)	1.8	1.1	0.2	0.1	0.2	0.1
	G (dB)	2.5	2.2	1.5	1.3	1.3	1.0
	T_{30} (s)	0.17	0.27	0.13	0.06	0.12	0.06
Simple model-new method	C_{80} (dB)	1.17	0.4	0.4	0.97	0.7	1.1
	G (dB)	1.8	1.6	1.0	0.9	0.9	0.3
	T_{30} (s)	0.17	0.21	0.08	0.08	0.1	0.07
Detailed model-new method	C_{80} (dB)	4.8	1.7	0.7	0.5	0.3	0.4
	G (dB)	1.2	0.2	0.7	0.7	0.6	0.3
	T_{30} (s)	0.14	0.11	0.01	0.03	0.04	0.04

Table 4
Average errors of six receiving positions in Elmia concert hall

Model	Parameter	Frequency band (Hz)					
		125	250	500	1000	2000	4000
Simple model-new method	C_{80} (dB)	4.0	1.3	1.5	1.2	1.5	1.7
	G (dB)	1.1	2.0	1.0	0.7	0.7	0.8
	T_{30} (s)	0.12	0.02	0.2	0.23	0.04	0.18
Detailed model-new method	C_{80} (dB)	4.7	1.5	0.9	1.0	0.9	1.2
	G (dB)	1.8	1.6	0.9	0.5	0.3	1.0
	T_{30} (s)	0.30	0.21	0.05	0.01	0.14	0.28

From Fig. 7 and Table 3, it can be found when using the new method for the simple model, the results are better than those of the old method for the same model. And when using the new method for the detailed model, the results are the best except for C_{80}. The predicted C_{80} is bigger than the measured ones and the difference is much bigger at low frequency bands when using the new method for the detailed model. This may indicate that more early sound energy is collected because of the reflection and diffraction from those small surfaces that have not been considered in the simple model. The calculation results of other parameters have also clearly shown that the new method is better than the old one for such kind of rooms.

From Fig. 9 and Table 4, it is difficult to decide which one is better, the simplified model or the detailed one, because for all the three parameters C_{80}, G and T_{30}, in some frequency bands, the detailed model can obtain better results, but in other frequency bands the simplified model can obtain more accurate results. In other words, the accuracy of the two models is comparable. According to the results of some other parameters like LF_{80}, Ts and D_{50}, it can also be concluded that the accuracy of these two models is approximately the same. However, if the complexity of designing the model is discriminating, the simplified model will be a more practical choice for the prediction of such kind of rooms.

4.3.2. Influence of TO on prediction accuracy

As in the ODEON model, the value of TO is also a factor which can affect the scattering modeling, we have calculated the normalized total errors in the cases of different TO and ray number. The error has included all sources, receivers, frequency bands and all acoustic parameters we have computed, which can be described by

$$\text{Error} = \frac{\sum_{n=1}^{\text{AP}} \sum_{n=1}^{\text{Freq}} \sum_{n=1}^{\text{Pos}} \frac{|\text{AP}_{\text{measured}} - \text{AP}_{\text{simulated}}|}{\text{SL}}}{N_{\text{AP}} \cdot N_{\text{Freq}} \cdot N_{\text{Pos}}} \tag{11}$$

where $\text{AP}_{\text{measured}}$ is the measured value of the current acoustic parameter; $\text{AP}_{\text{simulated}}$ the simulated value of the current acoustic parameter; SL the subjective limen for the current acoustic parameter (5% for RT and EDT; 1.0 dB for SPL; 1.0 dB for C; 10 ms for Ts; 0.05 for LF); N_{AP} the number of acoustic parameters; N_{Freq} the number of frequency bands and N_{Pos} is the number of measuring positions.

Figs. 10 and 11 have shown the relationship among the total error, TO and total ray number. From Fig. 10 it can be found that for the PTB room in all ray number cases, the optimal value of TO is between 0 and 2. From Fig. 11 it also can be concluded that for the Elmia hall, the TO = 2, 3, 4 can yield best results in all ray number cases. Both figures have also shown that the total ray number should be large enough. It seems that the larger the ray number, the smoother the error–TO curve will be.

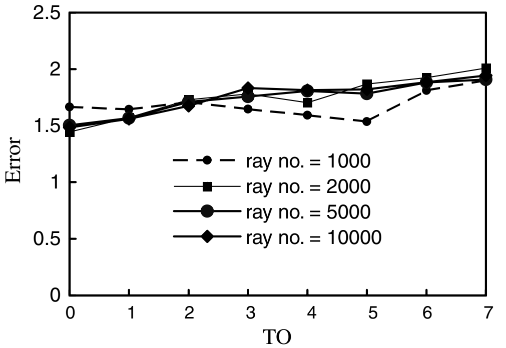

Fig. 10. Errors when using various TO and number of rays for detailed PTB model.

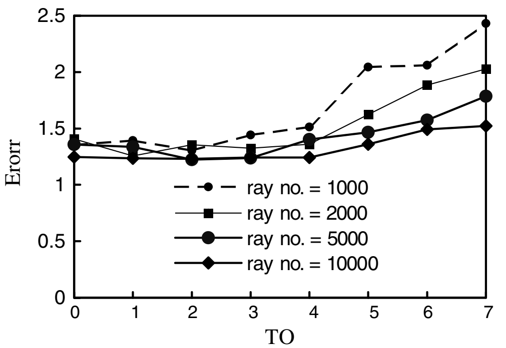

Fig. 11. Errors when using various TO and number of rays for simplified Elmia model.

Table 5
Recommended surface scattering coefficients

Material	Scattering coefficient at mid-frequency
Audience area	0.6–0.7
Rough building structures, 0.3–0.5 m deep	0.4–0.5
Bookshelf, with some books	0.3
Brickwork with open joints	0.1–0.2
Brickwork, filled joints but not plastered	0.05–0.1
Smooth surfaces, general	0.02–0.05
Smooth painted concrete	0.005–0.02

5. Concluding remarks

A novel scattering model for the room acoustics computer model ODEON and practical methods for the consideration of surface scattering has been presented. It is found that the new method is an improvement compared to the conventional method which only considers the scattering coefficient due to predefined scattering coefficients estimated by the user. At least, the new method can reduce guesswork about scattering coefficients even if we cannot obtain better prediction results.

For acoustic consultants or other users of room acoustics computer models, it is also an important problem to realize the balance between the accuracy and level of detail in modeling. The general guideline is that with the new scattering method the inclusion of details in the model tends to improve the accuracy of the acoustical predictions; this is most pronounced in the small room example, whereas the influence of the level of detail is less pronounced in the large complicated room.

As described in Section 2, the scattering coefficient in the new scattering model has been divided into two parts, in which the first part (s_d, scattering due to edge diffraction) can be calculated by the program automatically and only the second part (s_s, surface scattering) should be inputted by the users. Here we give some recommendations on defining the second part of scattering coefficients. If the geometry of a model has been simplified, the coefficient of the substituted surface is usually between 0.3 and 0.8. If all major details of a room have been modeled, then most surfaces can be thought of as smooth and consequently the same scattering coefficient can be used for all these surfaces, e.g., a value in the range from 0.02 to 0.05. Table 5 has shown the recommended values in some common cases.

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