NEW METHODS OF SCATTERING COEFFICIENTS COMPUTATION FOR THE PREDICTION OF ROOM ACOUSTIC PARAMETERS

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To include the sound scattering caused by limited size of surfaces in room acoustic computer simulations, some model for scattering must be included in room acoustics computer models. A large concert hall usually contains a variety of small and complex surfaces and it is not practical to obtain accurate scattering coefficients of all these surfaces. Even if these frequency dependent coefficients could be obtained in the design phase, the modeling process would become more time consumed and increase the cost of design. In such a case, the appropriate simplification of the model and the definition of scattering coefficients by experience will become important. But in some other cases, calculation of a detailed model is necessary and possible. For these different cases, practical methods to define or calculate scattering coefficients, which include a new approach of modeling surface scattering and scattering caused by edge diffraction, have been presented. The predicted and measured acoustic parameters have been compared in order to testify the practical approaches recommended in the paper.

1. Introduction

Scattering has been validated to be one of the most important properties of sound in enclosed spaces [1–3]. Scattered reflection can improve the uniformity of a reverberant field and reduce the risk of areas of poor acoustics within a room. Surface scattering has found a role in dispersing reflections which are causing echoes or coloration [4]. The first international round robin test of computer modeling software has clearly indicated that inclusion of scattered reflections is an important factor in achieving good simulation results [5]. The investigations carried out by Hodgson [1], Dalenbäck [2] and Lam [3] have shown that the scattered reflections will not only affect the accuracy of the calculation of acoustical parameters, but also have influence on the quality of auralization.

Scattering coefficient is usually used to describe the scattering property of walls. It has been found that the coefficient is not only dependent on surface material, frequency of sound source, but also dependent on the geometry of the computer model [6]. It is possible for different computer models to get different calculation results on condition that the same scattering coefficients are used. This makes how to obtain the scattering coefficient a key problem. One way is direct measurement [7]. Another is to define it based on experience [8]. It can be found that the direct measurement is not practical for an arbitrary surface. This requests the users to be room acoustics experts, thus will limit the application of the program.

In this paper, rooms are divided into two groups: large and complicated rooms; small and simple rooms. For both cases, a method to consider both scattering due to surface property and scattering caused by edge diffraction has been applied. Practical methods to define the model and the scattering coefficients when using the program ODEON and other similar packages in both room cases have been given.

2. Current Methods for Modeling Surface Scattering

The basic idea to consider sound scattering in program ODEON is 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

$$(1-s)(1-\alpha)+\alpha+s(1-\alpha)=1 \tag{1}$$

The randomized ray propagations and secondary sources have been combined to simulate the scattering. Instead of separating the ray tracing process into two parts, the model uses only a single ray tracing process for each ray. Furthermore, using the secondary sources to model radiation from the surface reflections to the receiver means that it is no longer necessary to check the validity and visibility of the image sources, thus reducing the computation time. However, the image sources in the model may not be the purely specular images. Even when the scattering coefficient is set to be zero, there is still some scattering that has been modeled. And it will reduce the effect of specular sound. To solve the problem, a factor named transition order (TO) has been defined, which can limit the scattering calculation only to those reflections having orders higher than TO. This scattering model has been applied into ODEON from version 2.5 to version7.0, and has been validated to be an efficient model.

The scattering coefficient used in the current model mainly considers the surface scattering due to material property and the TO can take into consideration the shape or structure of the acoustic room [6]. However, it has been found out that sound scattering is also dependent on the distance from the receiver to the edge of some small surfaces where diffraction usually occurs. This means it is not enough to take into account only the scattering due to surface property. Especially at low frequency and in the case where there are many varied small surfaces, the scattering caused by edge diffraction becomes more important and need to be calculated separately.

In the following section, the method to define a scattering coefficient combining both parts of scattering will be described at first. And then practical recommendations to define scattering coefficient for both kinds of rooms will be given.

3. Practical Methods to Define Scattering Coefficient

3.1. *A new method for the calculation of scattering coefficient*

To consider surface edge diffraction, we take a small panel as an example, which is shown in Fig.1. S,S′ are the original sound source and image source, R is the receiver. It can be derived that the limiting frequency is [9]

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

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

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

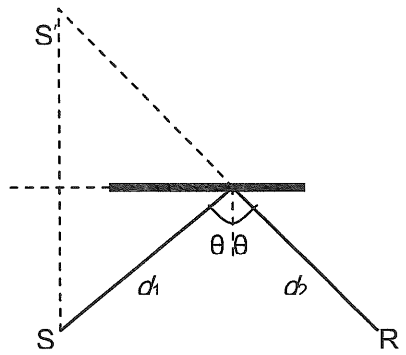


Figure 1. Sound reflection from a small surface.

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 (6dB per octave band). This part of scattered energy can be represented by a factor s_D, which can be calculated from

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

Therefore, the total scattering coefficient s can be calculated from

$$s = 1-(1-s_D)(1-s_S) \tag{6}$$

Where s_D is the factor related with distance from receiver to the edge of a surface and s_S is the scattering coefficient due to the surface property (defined in ISO/ FDIS17497-1).

Then the new direction of a reflected ray can be determined according to the value of s. If s=1, the reflected ray will propagate in a scattered way which can be calculated according to Lambert's law; if s=0,the reflected ray will propagate in a specular direction and can be easily obtained from Snell's law; if s is between 0 and 1, a new reflected direction can be determined by using s as a weighting between the pure specular direction and scattered direction [10].

The above algorithm has combined the scattering due to edge diffraction and scattering due to surface property, therefore, it can reduce the influence of the scattering coefficient due to surface, which usually has to be defined according to the subjective experience of users.

3.2. *Methods to define scattering coefficients for different rooms*

For the case there are a variety of small and complex surfaces the computation will become more time consuming and it is also impossible to obtain the frequency dependent scattering coefficients due to surface property for all the surfaces. But in other cases, especially when the low frequency sound is more important, the detailed room model has to be considered. Therefore, we suggest two different ways to deal with small surfaces in large concert halls and small rooms.

A. *Small and simple rooms*

For such kind of rooms, the number of main walls is usually small and the diffuser arrays may distribute in 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. On the other hand, as the sources or receivers are close to the reflector, which will produce strong reflections, considering the detailed structure of the model is necessary.

In this case, one scattering coefficient due to surface s_S can be assigned to all these small surfaces. The recommended value is between 0.01 and 0.05. The scattering coefficient due to surface then will be 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 likely to produce a strong reflection at the receiver, so it also should be included in the model.

B. *Large and complicated rooms*

For a large artistic room, the shape and its interior structure are usually complicated. It is likely to contain too many small surfaces and to establish a model with such a degree of detail is likely to be a waste of time. It is recommended to simplify the real room when turning it into a visible computer model. That means some detailed parts of the walls may be deleted. But for such kind of walls the comparatively bigger scattering coefficients should be defined. The value is usually defined bigger than 0.3 and smaller than 0.8.

There are some guidelines for the simplification:

(1) Curved surface. Curved surfaces have to be approximated by dividing them into plane sections. How finely to subdivide depends on the type of curved surface and how important the surface is. Using many surfaces in the model will make the model visually complex, and increase the probability of errors in the model, typically small leaks becomes a problem. Subdivisions about every 10° to 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. However, this rule does not apply to open-air theatres.

(3) Podium on stage. The guideline is the same as that for the audience area. Rather than modeling each step of the podium, the podium can be simplified into a few sloped surfaces.

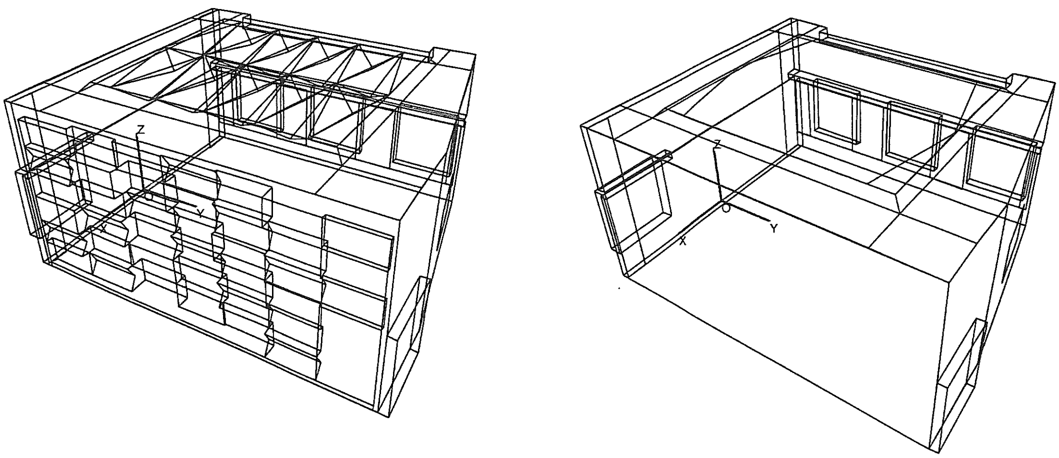
4. Prediction of Various Models

4.1. *Conditions of experiments*

A. PTB studio

The PTB studio, which was used to test different computer models in international round robin, has been chosen as an example in this paper. Two computer models for the studio have been designed for ODEON, named "simple" and "detailed" respectively, see Fig.2.

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 10000 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.



(a) (b)

Figure 2. PTB studio (a) simple model (b) detailed model.

To validate the scattering method presented in the paper, it has been compared with the old method applied in the ODEON ver7.0. 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 modeled and compared with the measured results.

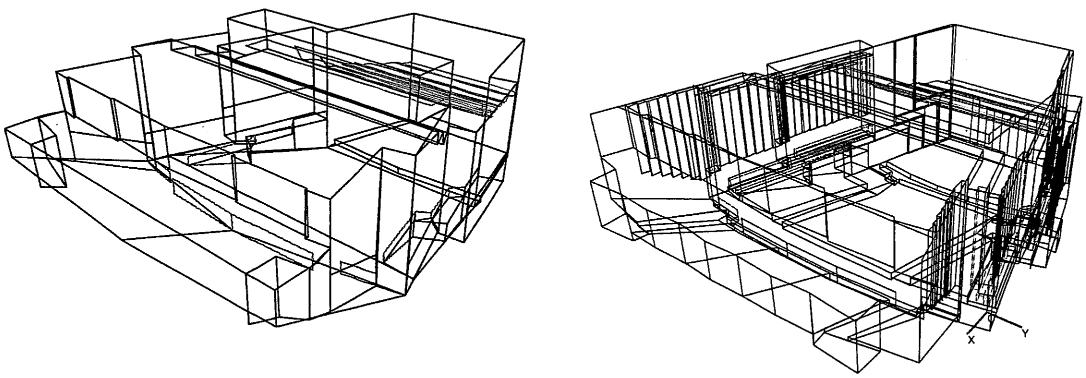
Table 1. Scattering coefficients for PTB studio model.

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 other surfaces	0.02

B. Elmia concert hall

Two kinds of models of the Swedish concert hall Elmia were set up in ODEON. One is simplified and another is in detail. See Fig. 3.

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). 10000 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.



(a) (b)

Figure 3. Elmia concert hall (a) simplified model (b) detailed model.

Table 2. Scattering coefficients for Elmia model.

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

4.2. *Results and discussion*

A. Accuracy of different scattering models

For the PTB studio, the mean errors of the three cases at 6 frequency bands are listed in table 3. For the Elmia concert hall, the mean errors of the two cases at 6 frequency bands are listed in table 4.

Table 3. Average errors of at three receiving positions in PTB studio.

	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)	1.6	1.1	0.1	0.2	0.1	0.1
	G(dB)	2.0	1.8	1.1	0.8	0.8	0.8
	Ts(s)	0.16	0.20	0.09	0.04	0.06	0.12
Detailed model-new method	C_{80}(dB)	3.0	1.2	0.4	0.4	0.3	0.4
	G(dB)	0.1	0.7	1.0	0.7	0.6	0.7
	T_{30}(s)	0.16	0.09	0.03	0.07	0.04	0.03

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

	Parameter	Frequency band(Hz)					
		125	250	500	1000	2000	4000
Simple model-new method	C_{80}(dB)	2.9	0.8	1.4	1.2	1.3	1.7
	G(dB)	1.0	2.2	1.1	0.8	0.7	1.3
	T_{30}(s)	0.32	0.13	0.18	0.09	0.15	0.23
Detailed model-new method	C_{80}(dB)	3.7	1.3	0.8	0.9	0.9	0.8
	G(dB)	1.6	1.8	0.9	0.4	0.6	1.8
	T_{30}(s)	0.42	0.33	0.23	0.20	0.27	0.28

Table 3 shows that when using the new method for the simple model, the results are better than those of the old method. 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 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.

Table 4 has shown that the prediction accuracy of C_{80} and G of the two models is comparable. Both of them can get acceptable results at different frequency bands. But for the parameter T_{30}, the simple model can obtain better results at all frequency bands. This means the simplified model can also achieve satisfied results. According to the results of some other parameters like LF_{80}, Ts and D_{50}, it also can be concluded that the accuracy of these two models is approximate.

B. Influence of TO on the prediction accuracy

As in the ODEON model, the value of TO is also a important factor which can affect the scattering modeling, different TO cases have also been calculated. C_{80} and EDT are investigated in this paper. Table 5 and 6 have given the results.

It can be found that when the TO is set to be zero or 1 for the PTB studio model, the accuracy is better. From TO=2 to TO=5, the average error of the six frequency bands will exceed 1dB. From table 6, it can be found that when TO=4 or TO=5, the mean errors at all frequency bands are smaller. These results may indicate that for the typical concert hall the TO should be higher than 3, while for approximately proportionate rooms zero or 1 are the best choice for TO.

Table 5. TO and predicted C_{80}(dB) in PTB detailed model.

f(Hz)	125	250	500	1000	2000	4000
TO=0	8.7	4.6	3.4	4.3	3.5	4.7
TO=1	8.8	4.8	3.8	4.6	3.7	4.8
TO=2	9.1	5.4	4.3	4.9	4.1	4.9
TO=3	9.5	6.0	4.8	5.2	4.2	4.8
TO=4	9.3	6.3	5.1	5.3	4.3	4.7
TO=5	8.8	6.1	5.0	5.1	4.2	4.6
Measured	5.7	3.5	3.1	3.9	3.3	4.4

Table 6. TO and predicted EDT(s) in Elmia simple model.

f(Hz)	125	250	500	1000	2000	4000
TO=0	1.47	1.86	1.92	1.89	1.76	1.50
TO=1	1.86	1.66	1.70	1.70	1.74	1.14
TO=2	1.88	1.88	1.98	1.84	1.90	1.40
TO=3	2.06	2.09	1.98	1.75	1.72	1.58
TO=4	1.91	2.34	2.15	2.44	2.25	1.86
TO=5	2.02	2.23	2.08	2.10	1.93	1.96
Measured	2.10	2.33	2.19	2.22	2.04	1.70

C. Computation time and model complexity

From table 7, it can be found that with the same number of rays, the computation time of the detailed and the simple PTB studio model is very close. But as concluded in section "A", there is an obvious increase of accuracy. It means the new method for the detailed model is more practical than that for the simple model. For the Elmia concert hall this is more obvious. The computation time has increased to 525% if the detailed model is used, but the accuracy has almost no increase.

Table 7. Comparison of different models.

	PTB simple	PTB detailed	Elmia simple	Elmia detailed
Total surfaces	70	268	94	470
Total area(m^2)	421	450	4409	4932
Total rays	20000	20000	20000	20000
Source number	1	1	1	1
Receiver number	3	3	6	6
Computation time(s)	34	33	40	211

*the CPU frequency of the computer is 2.0GHz.

5. Concluding Remarks

A scattering model has been presented and practical methods for the consideration of surface scattering when using room acoustics computer model ODEON. These methods are better than the conventional methods that only consider the scattering coefficient due to surface property.

For acoustic consultants or computer model users, it is also an important problem to realize the balance between the accuracy and design difficulty. Two different ways have been given for the two groups of rooms, and some rules have been recommended on the inclusion or simplification of small surfaces in rooms. The discussion of the paper has indicated that for large complicated rooms, it is practical to simplify model geometry, while for small rooms, it will be benefited from the calculation of detailed models.

The recommendation of scattering coefficient definition in various cases is as follows. If the geometry of a model has been simplified, the coefficient of the substituted surface should be a bit smaller than that determined by experience and usually between 0.3 and 0.8. If all the detail of a room is considered, each surface can be thought as smooth except for some special ones, therefore, the same scattering coefficient (s_S) for all of these smooth surfaces can be set to be a low value from 0.01 to 0.05.

As for transition order, in a general way, it should be smaller than 3 in small and simple shaped rooms and in large concert hall, it is better to set the transition order around 4.

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