A Fundamental Investigation on Geometrical Acoustic Prediction Method of Sound Fields with Scattering Coefficients for Room Boundary

Kunitaka Nakano[a], Hiroshi Furuya[b*] and Soichiro Kuroki[c]

[a] Graduate School of Environmental Engineering, The University of Kitakyushu, Japan

[b] Department of Architecture, Faculty of Engineering, Kyushu Kyoritsu University, Japan

[c] Department of Architecture, Faculty of Environmental Engineering, The University of Kitakyushu, Japan

* corresponding author: hifuruya@kyukyo-u.ac.jp

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This study deals with the problems of the scattering coefficients that should be assigned to a wall in geometrical acoustic simulations and a fundamental property of the prediction that may be used to model the diffuse reflections. Acoustic simulations in hybrid image/ray tracing model with variable scattering coefficients are performed for two kinds of sound fields: (1) sound field with a reflection from a single wall, which is a plane or a diffusive wall, (2) sound field in auditorium enclosures for three types of floor plan, namely, rectangular, fan-shape and reversed fan-shape. Firstly, the level distributions of reflections from a single wall are investigated in the receiving areas with and without a specular reflection, and the directivity characteristics are also calculated for three incident angles of sound. Secondly, room acoustics parameters are analyzed from impulse responses in auditorium models. In addition, physical scale model experiments are conducted in order to verify the practical approach applying scattering coefficients to geometrical acoustics prediction. As a result, the calculated values in proper assignment of scattering coefficients for the boundaries give close agreement with the measured ones. The difference between them and the behavior of the prediction affected by diffuse reflections are discussed.

Key words: Geometrical acoustics simulation, Surface diffusion, Scattering coefficient, Scale model measurement

1. INTRODUCTION

Sound diffusion on room boundaries can play a key role in determining the sound field within an enclosed space. Commonly used room acoustics prediction methods such as the image source method or the ray-tracing method are usually based on a geometrically specular reflection model, which must be modified to account for scattering phenomenon in order to give realistic results.

The purpose of this study is to investigate the fundamental behavior of geometrical acoustics simulation introducing scattering coefficients[1] for wall diffusion. In this paper, two kinds of sound fields are investigated by means of both acoustics simulation and physical scale model experiment. Firstly, in Study Model 1, the level distribution of reflections from a single wall is fundamentally investigated. Secondly, in Study Model 2, the effects of the variety of scattering coefficients on room acoustics indices are examined using some auditorium models.

2. GEOMETRICAL ACOUSTIC SIMULATION

2.1 Method

The Conical Beam Method[2], the hybrid technique of the image method and the ray-tracing one, is employed. Modeling is performed using 999,999 cones emitted spherically from a point source by applying a ray-tracing algorithm to the axes of them. The maximum order of reflections is set to be nine, and the target range of frequency is from 250 to 2k Hz bands.

2.2 Modeling Conditions

Acoustic simulations with variable scattering coefficients are performed for two kinds of sound fields: (1) single-wall model (Study Model 1), (2) auditorium model (Study Model 2). Impulse responses are calculated when the scattering coefficients s_c of the boundaries are varied in the five steps over a range from 0.0 to 1.0 (s_c = 0.0, 0.1, 0.2, 0.5, 1.0). The coefficient of the audience floor, however, is constant at 0.7[3] in Study Model 2.

Figures 1 and **2** show the conditions in Study Model 1a and 1b using a single wall, respectively. A plane and a diffusive wall, the sizes of which are both 15m×15m, are used. The latter is composed of five isosceles-triangular prisms that have the width of 3m and the base angle of 10°. In Study Model 1a, the observing points are located at 2-meter intervals parallel to the surface of the wall to investigate the distribution of sound pressure levels for specular and non-specular reflections. Two omni-directional point sources are selected with incident angles of 30°(S_A) and 60°(S_B). A geometrical specular reflection from the wall reaches at the points Nos.4-18 for the source S_A, and the points Nos.16-31 for S_B. In Study Model 1b, the observing points are located at 5-degree intervals in a semicircle around the wall to investigate the directivity of reflections. Three sources are selected with incident angles of 0°(S_1), 30°(S_2) and 60°(S_3).

Figure 3 shows three types of floor plan for auditorium models in Study Model 2: Type(a), reversed fan-shape; Type(b), fan-shape; Type(c), shoe-box. Every type has two kinds of interior geometry, namely, plane and diffusive walls, which are installed along the boundaries except the floor surface. The two sources (S_a, S_b) are located on the platform, and the 24-30 receiving points are selected for calculation all over the seating area. The average absorption coefficients lie in the range of 0.20-0.22. Both the floor area (900m^2) and the ceiling height (18m) are constant in all models.

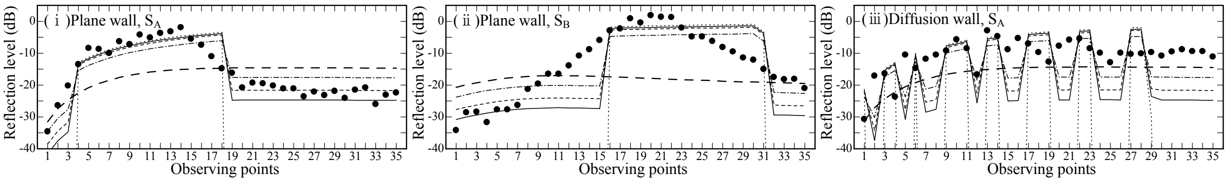
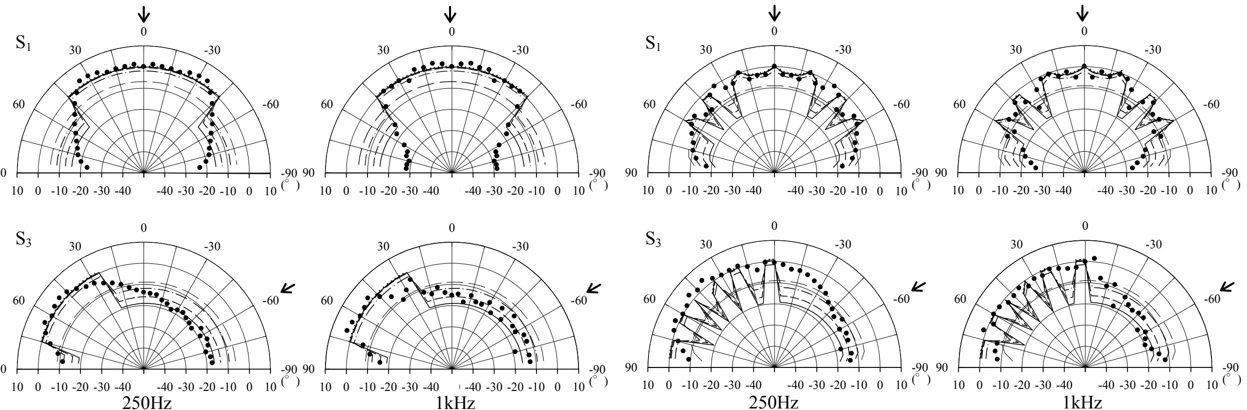


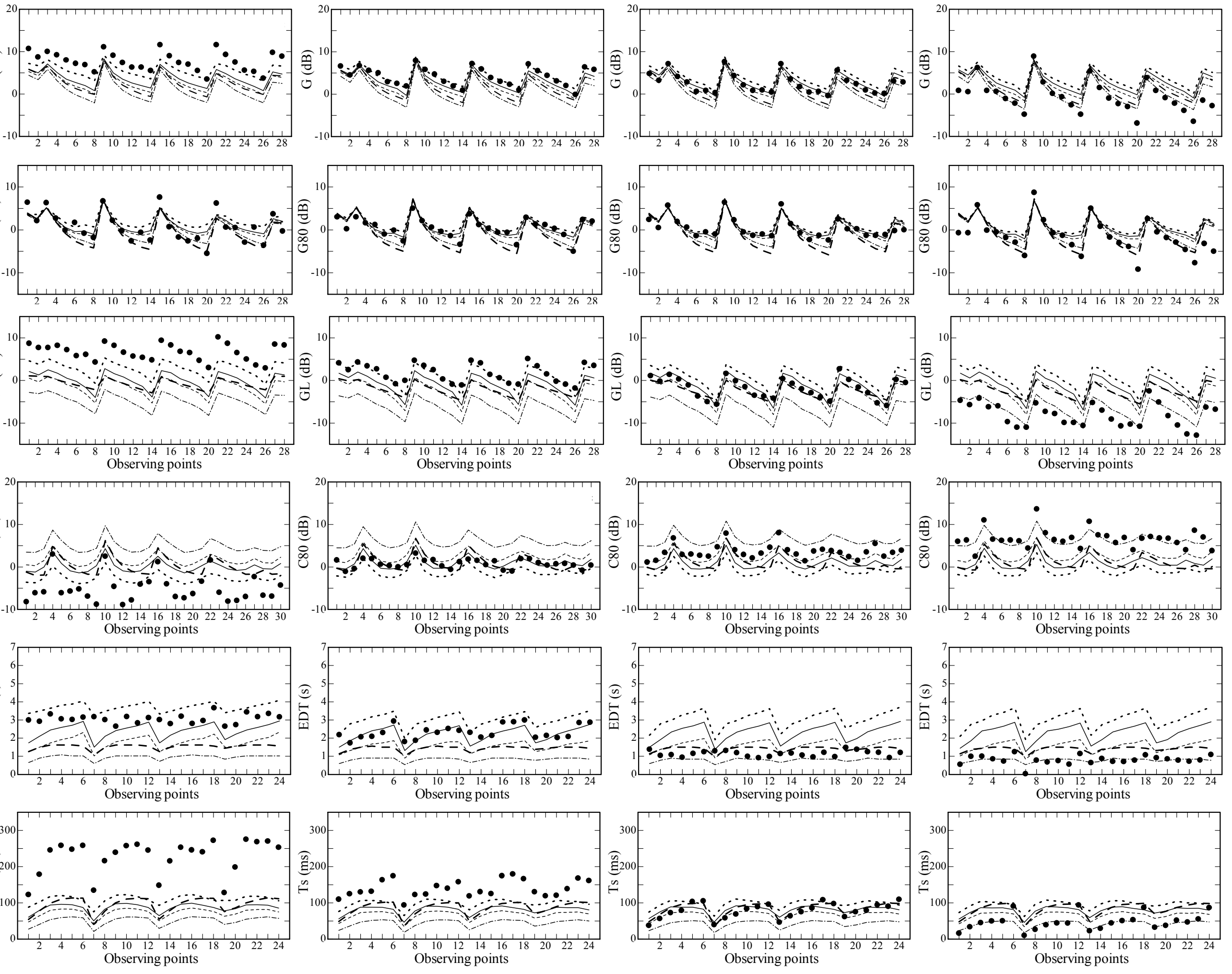
Fig. 4 Reflection levels for the plane and diffusion walls (500Hz); 0dB = direct sound energy at each observing point; calculated values: dotted line, (a) without scattering; solid line, (b) s_c= 0.10; broken line, (c) s_c= 0.20; dot-dash line, (d) s_c= 0.50; long broken line, (e) s_c= 1.00; ●, measured values.



250Hz 1kHz 250Hz 1kHz

(i)Plane wall (ii)Diffusion wall

Fig. 5 Directional distribution of reflections; calculated values: dotted line, (a) without scattering; solid line, (b) s_c= 0.10; broken line, (c) s_c= 0.20; dot-dash line, (d) s_c= 0.50; long broken line, (e) s_c= 1.00; ●, measured values; the arrow indicates the incident direction of sound.



250Hz 500Hz 1kHz 2kHz

Fig.6 Comparison between calculated and measured acoustical parameters auditorium models; G, G80 and GL in the floor type (a), C80 and D50 in type (b), EDT and Ts in type (c) ; calculated values: dotted line, (i) without scattering; solid line, (ii) s_θ= 0.10; broken line, (iii) s_θ= 0.20; dot-dash line, (iv) s_θ= 0.50; long broken line, (v) s_θ= 1.00; ●, measured values.

2.3 Acoustic Quantities

In Study Model 1, a direct sound energy and reflected sound energy including specular and scattering components from the wall are analyzed. In Study Model 2, seven room acoustic parameters, namely Strength G, G80, GL, C80, D50, EDT and TS, are calculated from the impulse responses.

3. SCALE MODEL EXPERIMENTS

The 1/20-scale model experiments are also conducted in order to verify the practical approach applying scattering coefficients to geometrical prediction. Impulse responses are acquired with a discharged spark-pulse source by means of synchronous addition of 128 times at a sampling frequency of 128 kHz in a semi-anechoic room. The interior of models is constructed of lacquer-finished plywood of 5mm thick for reflective walls and 4mm-thick felt sheets for absorptive ones in Study Model 2.

4. RESULTS AND DISCUSSIONS

4.1 Study Model 1: A Single Wall Model

4.1.1 Level distribution of reflections

The calculated results of reflection levels corresponding to five values of scattering coefficients are shown with the measured ones in **Fig.4**. As for a plane wall, the level variation of calculated values shows the same tendency with the measured ones, and the correlation coefficients *r* between them are high from 0.69 to 0.92 for the source S_A and from 0.69 to 0.80 for S_B, except in s_c=1.0. For the source S_B, however, larger differences between them are recognized at both ends of specular reflection area. It is thought that this is because diffraction waves originating from the edges of the wall affect strongly the results. Since the difference for S_A(30°) is much smaller than that for S_B(60°), this means that the degree of the diffraction effect is dependent on the incident angle of sound on the wall. As for a diffusive wall, the result indicates a similar tendency, and many edges cause disagreements between the calculated and measured values in the non-specular reflection area.

4.1.2 Directional distribution of reflections

The reflection directivities corresponding to five values of scattering coefficients are shown in **Fig.5**.

Firstly, as for a plane wall, the calculated directivity patterns, except in s_c=1.0, give close agreement with the measured ones in any source (*r*=0.82-0.95). However, as the frequency becomes lower and the incident angle increases, the difference between them becomes larger in the border between the areas with and without a specular reflection. To be more specific, at the receiving points of 15°-30° for the source S_3 the calculated values at 1k Hz give closer agreement with the measured, but those at 250 Hz do not. These results are also caused by the diffraction waves from the edges of the wall like the results in the preceding section.

Secondly, as for a diffusive wall, the result indicates a similar tendency. For instance, at 1k Hz for the source S_1 the calculated results generally agree with the measured ones according to peaks and dips of level, while both at 250 Hz and for the source S_3 there are larger differences between them in the non-specular reflection area. In other words, it is found that *r* is the highest for the source S_1 (*r*=0.55-0.75), and becomes higher with the increase of frequency. Furthermore, regarding the effect of scattering coefficients, *r* is the highest in s_c=0.5 for the source S_1, in s_c=0.1-0.2 for the source S_2 and in s_c=0.1 for the source S_3. These results suggest that the scattering coefficient is dependent on the incident angle of sound.

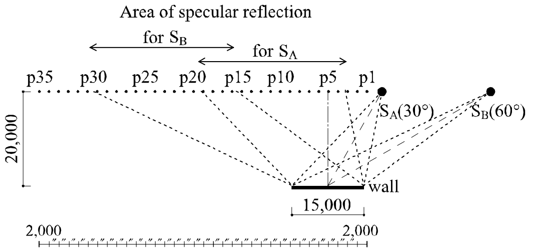


Fig. 1 Illustration of the condition in study model 1a for the sound field with a single reflection.

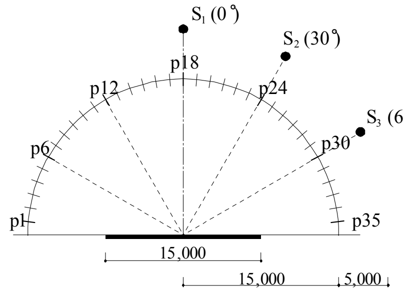


Fig. 2 Illustration of the condition in study model 1b for the directivity of reflections.

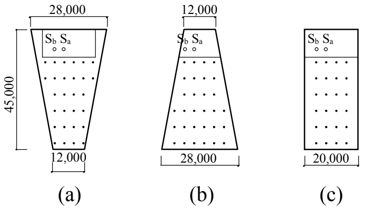


Fig. 3 Three kinds of floor plan for auditorium models in study model 2 ; Type(a), reversed fan-shape; Type(b), fan-shape; Type(c), shoe-box.

4.2 Study Model 2: Auditorium Model

4.2.1 Results of room acoustic parameters

Figure 6 shows the calculated results of room acoustic parameters with the measured ones. The correlation coefficients between them in floor Type (b) are shown in **Table 1**.

As for the parameters of sound pressure level (G, G80, GL), the calculated values give close agreement with the measured ones. Although there is a somewhat difference in GL at 250 Hz, *r* is high of 0.80 or more for any s_c. Therefore it can be said that the calculated results satisfactorily describe the measured distributions of sound pressure level.

As for C80, D50 and TS, the calculated values generally correlate well with measured ones. Like in GL, however, there is also a significant difference at 250 Hz for any parameter (3dB in C80, 13% in D50, 123 ms in TS). That is, at lower frequency the calculated values of C80 and D50 are larger than the measured, and conversely TS values smaller. These results are consistent with the above-mentioned results in GL that the late sound energy is underestimated at 250 Hz in the simulation. In addition, the difference at lower frequency between the calculated and measured values

Table 1 Correlation coefficients of acoustical parameters between calculated and measured in study model 2 (floor type (b), sound source S_a).

Parameter	s_θ	Flat-surface model				Diffusion model			
		Frequency(Hz)				Frequency(Hz)			
		250	500	1k	2k	250	500	1k	2k
G	0.0	0.92	0.96	0.94	0.92	0.95	0.92	0.92	0.93
	0.1	0.95	0.95	0.95	0.92	0.96	0.91	0.92	0.93
	0.2	0.95	0.95	0.95	0.92	0.96	0.92	0.92	0.93
	0.5	0.95	0.95	0.96	0.91	0.97	0.92	0.93	0.93
	1.0	0.95	0.94	0.95	0.91	0.97	0.93	0.93	0.93
G80	0.0	0.88	0.91	0.95	0.85	0.89	0.86	0.88	0.86
	0.1	0.89	0.92	0.95	0.87	0.91	0.88	0.90	0.88
	0.2	0.89	0.93	0.95	0.88	0.91	0.89	0.91	0.89
	0.5	0.87	0.95	0.96	0.90	0.91	0.92	0.92	0.91
	1.0	0.86	0.96	0.95	0.90	0.92	0.93	0.93	0.92
GL	0.0	0.83	0.92	0.92	0.90	0.87	0.87	0.91	0.89
	0.1	0.85	0.93	0.92	0.90	0.87	0.88	0.91	0.89
	0.2	0.85	0.94	0.92	0.90	0.88	0.87	0.92	0.90
	0.5	0.85	0.94	0.90	0.89	0.88	0.88	0.92	0.90
	1.0	0.78	0.90	0.83	0.83	0.82	0.86	0.89	0.86
C80	0.0	0.82	0.60	0.89	0.58	0.77	0.70	0.79	0.71
	0.1	0.85	0.60	0.89	0.59	0.82	0.70	0.80	0.70
	0.2	0.84	0.62	0.89	0.58	0.83	0.70	0.80	0.69
	0.5	0.81	0.71	0.86	0.69	0.86	0.75	0.83	0.71
	1.0	0.70	0.78	0.64	0.84	0.80	0.89	0.87	0.86
D50	0.0	0.92	0.73	0.88	0.63	0.84	0.89	0.87	0.79
	0.1	0.93	0.73	0.89	0.64	0.87	0.90	0.87	0.78
	0.2	0.92	0.75	0.89	0.64	0.87	0.90	0.88	0.77
	0.5	0.89	0.81	0.87	0.71	0.87	0.90	0.88	0.76
	1.0	0.83	0.88	0.75	0.86	0.89	0.93	0.87	0.86
EDT	0.0	-0.03	0.10	-0.36	0.30	0.16	0.83	0.44	-0.03
	0.1	-0.06	0.11	-0.37	0.34	0.34	0.82	0.40	0.02
	0.2	-0.06	0.23	-0.25	0.45	0.30	0.74	0.33	0.05
	0.5	-0.19	0.36	0.18	0.57	0.35	0.56	0.35	-0.10
	1.0	-0.26	0.31	-0.05	0.59	0.44	0.60	0.49	-0.10
Ts	0.0	0.57	0.32	0.63	0.07	0.56	0.36	0.56	0.39
	0.1	0.77	0.53	0.76	0.28	0.81	0.57	0.71	0.54
	0.2	0.79	0.67	0.84	0.47	0.86	0.68	0.80	0.63
	0.5	0.68	0.87	0.83	0.78	0.88	0.83	0.90	0.77
	1.0	0.62	0.85	0.74	0.87	0.89	0.90	0.91	0.87

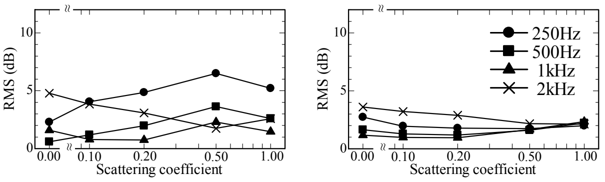
becomes smaller with the decrease of s_c, and at higher frequency with the increase of s_c. As for EDT, there is not much difference between them, but they correlate poorly with each other. The results in three floor-type models show the same tendency.

4.2.2 Effects of scattering coefficients

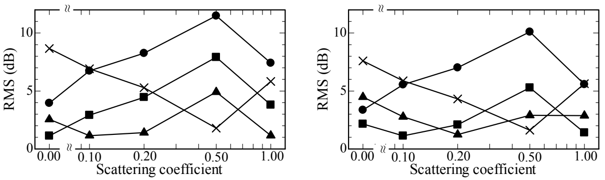
In order to investigate the influence of setting values of scattering coefficients s_c on the calculations of room acoustic parameters, the root-mean-square deviations RMS between the calculated and measured values are obtained. **Figure 7** shows the relation between s_c and RMS.

As for the early reflection level G80, the changes in RMS corresponding to the variation from 0.0 to 1.0 in s_c are very small of around 1dB at any frequency. On the other hand, for the late reflection level GL, the changes in RMS are significantly large, that is, 7.5 dB at 250 Hz, 6.8 dB at 500 Hz, 3.8 dB at 1 kHz and 6.9 dB at 2 kHz. Furthermore, the RMS at each frequency band has a minimum value in s_c=0.0(at 500 Hz or less), in s_c=0.1(at 1 kHz), and in s_c=0.5(at 2 kHz), respectively. The minimum RMSs are approximately from 1 to 2 dB. Likewise, as for C80 the values of s_c strongly affect the RMS at any frequency, because this parameter is also dependent on late sound energy by definition. Similar results are found in other acoustic parameters.

Consequently, the scattering coefficients s_m that can minimize the RMS value at each frequency band are derived from above results. The frequency characteristics of s_m are shown in **Fig.8**. It can be seen that the s_m value becomes higher with the increase of frequency for any acoustic parameter. These results give a suggestion on the practical treatment of scattering coefficients in geometrical acoustic prediction.



(i) G (type(a)) (ii) G80 (type(a))



(iii) GL (type(a)) (iv) C80 (type(b))

Fig.7 Root-mean-square deviations between calculated and measured acoustical parameters versus scattering coefficients (sound source S_a).

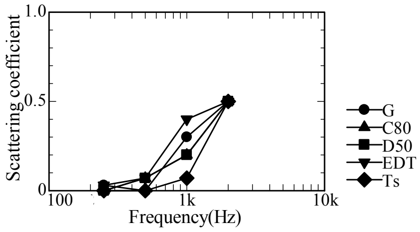


Fig.8 Frequency characteristics of scattering coefficients s_m that minimize the root-mean-square deviations between calculated and measured acoustical parameters.

5. CONCLUSIONS

Geometrical acoustic simulations with variable scattering coefficients were performed for two kinds of sound fields, and the calculated results were compared with the measured ones by scale model experiments.

Firstly, in the single-wall models, the calculated distributions of reflected levels generally agreed with the measured ones, except in s_c=1.0. However, as the frequency became lower and the incident angle of sound increased, the difference between them became larger near the border between the receiving areas with and without a specular reflection. These results indicate the strong effect of diffraction waves originating from the edges of the wall.

Secondly, in the auditorium models, the calculated results of room acoustic parameters gave close agreement with the measured ones by choosing a proper s_c. In the parameters related to late reflections such as GL and C80, however, there was a significant difference between them at lower frequency, because the late energy was underestimated in the simulation. Regarding the effect of scattering coefficients, it was clearly found that the estimation of late energy is strongly influenced by the setting coefficients.

Further research on the way of assignment of scattering coefficients on the edge area of walls is needed in order to obtain the best possible estimate of sound fields in geometrical acoustic simulations.

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