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Acoustic characteristics of urban streets in relation to scattering caused by building facades

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Abstract

The relationship between scattering and the acoustic characteristics of urban streets is examined by computer simulation. The simulation method is a combination of the image method for specular reflection and the radiosity method for scattering reflection. The findings are as follows: (1) the effect of scattering on the SPL appears as an increase at short distances and as a decrease at great distances. The range of the increase in SPL is larger in high-facade streets. In low-facade streets, the primary effect of scattering on SPL is a decrease in SPL. (2) In low-facade streets the reverberation time is determined by the sum of absorption coefficient and scattering coefficient. In contrast, in high-facade streets, the reverberation time is determined by the absorption coefficient. (3) The simulated result for the reverberation time shows good agreement with measured value in actual streets. (4) The estimated values for the sum of absorption coefficient and scattering coefficient of facades of actual urban streets range from 0.1 to 0.25.

Keywords: Streets; Scattering; SPL; Reverberation time; Radiosity method

1. Introduction

A number of studies have examined the sound propagation characteristics of streets. By the 1970s, scattering caused by building facades was known to be an important factor in

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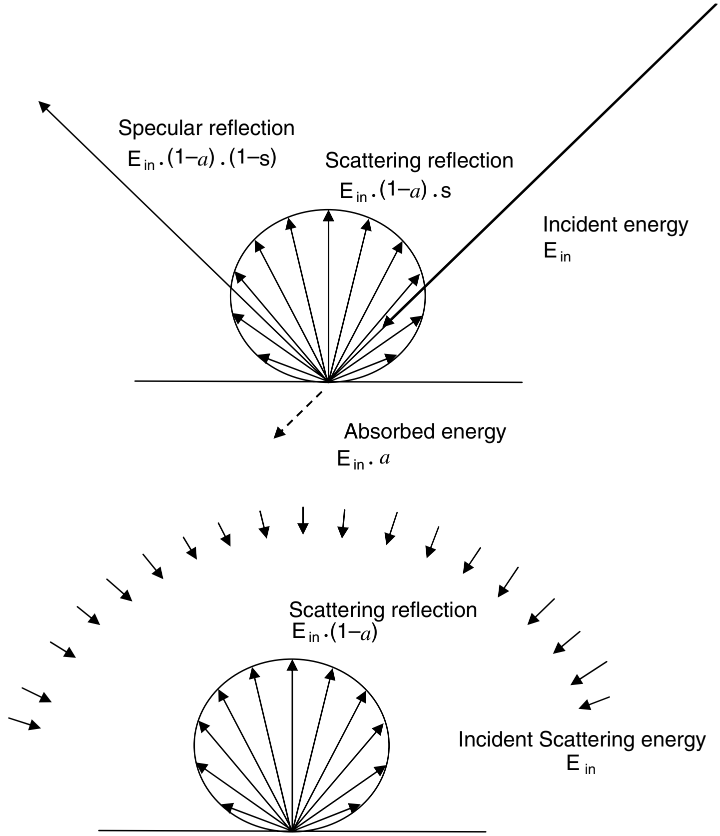

Fig. 1. Specular reflection and scattering reflection.

sound propagation in streets. Lyon [1] cited Delany et al.'s [2] measurement of sound pressure level in an actual street, which indicated a decay of −8 dB/dd at a distance of 20–100 m from the source, as good evidence for scattering reasonably close to the source. Davies [3] calculated the sound pressure level based on a model that considers both geometrical reflection and diffused energy. His results revealed a considerable increase in sound level close to the source due to scattering. Steenackers et al. [4] measured the sound decay curve in actual streets and found that wider streets have a larger apparent absorption coefficient, which includes diffusion. Scattering is included in the apparent absorption coefficient of his model, which therefore cannot show the sound level increase due to scattering. Kang [5] compared the calculation results for two boundaries: diffusely and geometrically reflecting surfaces. Although his study provided useful insight, his calculations were not useful for explaining the actual conditions of a street, in which reflection from building facades is neither completely diffuse nor completely specular.

None of these previous studies systematically examine scattering of various degrees and so cannot provide a useful perspective on the effect of scattering on sound propagation in actual streets. The purpose of this study is to demonstrate the relationship between scattering and the acoustic characteristics of urban streets. The acoustic indices examined in the present study are sound pressure level (SPL) and reverberation time.

2. Calculation method

The simplest model of a street consists of three surfaces: two parallel facades and the ground surface. The upper side and street ends are open and do not cause reflections. The dominant reflection that characterizes the street sound field is the repeatedly reflecting sound between the two parallel facades. In this model, the reflection consists of two components: specular reflection and scattering reflection (see Fig. 1).

The total sound energy density at the receiver in the street is given by the sum of the specular reflection and the scattering reflection:

$$I(t) = I_{\text{spec}}(t) + I_{\text{scatt}}(t), \tag{1}$$

where the direct sound is considered to be included in the specular reflection term.

2.1. Specular reflection

Specular reflection was calculated by the conventional image method (see Fig. 2). The energy density at the receiver caused by an image source (/real source) is calculated by the inverse square law:

$$I_{\text{spec}}(t) = \sum_k \frac{P_{\text{im},k}}{4\pi d_{k,r}^2} \cdot \delta\left(t - \frac{d_{k,r}}{c}\right), \tag{2}$$

where $d_{k,r}$ represents the distance from an image source to the receiver, $P_{\text{im},k}$ is the power of the image source, and subscript k indicates the image source number. The symbol δ represents Dirac's delta function, and $d_{k,r}/c$ indicates the travel time of the specular reflection from image source k, where c denotes the sound velocity.

Let the symbols "a" and "s" denote the absorption and scattering coefficients, respectively. The scattering coefficient indicates the ratio of scattering energy to total reflecting energy. The expression $(1 - a) \cdot s$ denotes the portion of incident energy assumed to be reflected scatteringly, and the expression $(1 - a) \cdot (1 - s)$ denotes the portion of incident

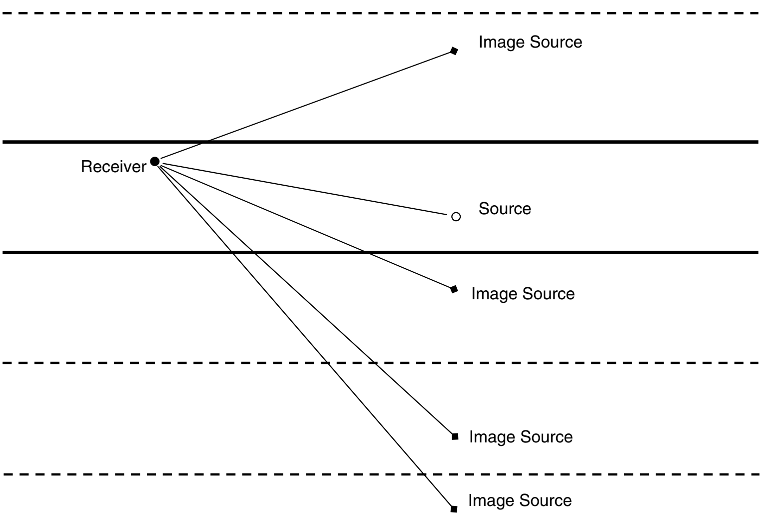

Fig. 2. Contribution from image sources.

energy assumed to be reflected specularly (see Fig. 1). If the reflection order of image source k is n, then the power of the image can be expressed as

$$P_{\mathrm{im},k} = P_{\mathrm{s}} \cdot (1 - a_1) \cdot (1 - s_1) \cdot (1 - a_2) \cdot (1 - s_2) \cdots (1 - a_n) \cdot (1 - s_n), \tag{3}$$

where P_{s} is the power of source and $a_1, \ldots, a_n$ and $s_1, \ldots, s_n$ are the corresponding absorption and scattering coefficients of the facades (/ground), respectively.

2.2. Scattering reflection

Sound energy transmission of scattering reflection is calculated using the radiosity method. For this purpose, the surfaces of the street model are divided into small patches. Although the accuracy of the model increases with the number of patch divisions, the calculation time increases according to the square of the number of patches. Therefore, the patch size of 2 m × 2 m was selected as a compromise.

The first-order scattering reflection radiated from each patch originates from incident specular energy from the source and image sources (see Fig. 3). Incident energy from image k to patch i, $E_{k,i}$, is determined by the power of the image $P_{\mathrm{im},k}$ and the solid angle $g_{k,i}$ of the patch from the image (see Fig. 4):

$$E_{k,i} = \frac{g_{k,i}}{4\pi} P_{\mathrm{im},k}, \tag{4}$$

$$g_{k,i} = \int_{S_i} \frac{\cos\theta_{i,k}}{d_{i,k}^2} \mathrm{d}S_i, \tag{5}$$

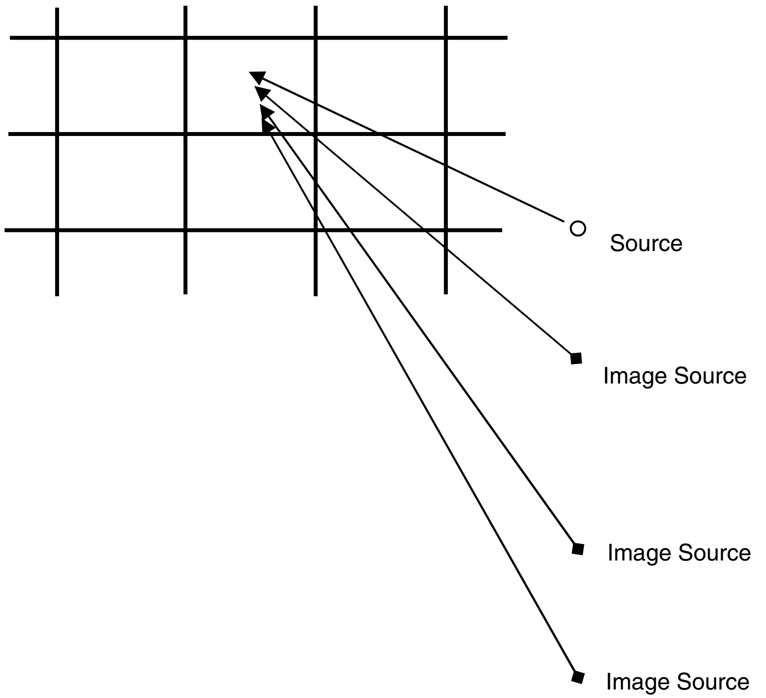

Fig. 3. Incident energy to patch from image sources.

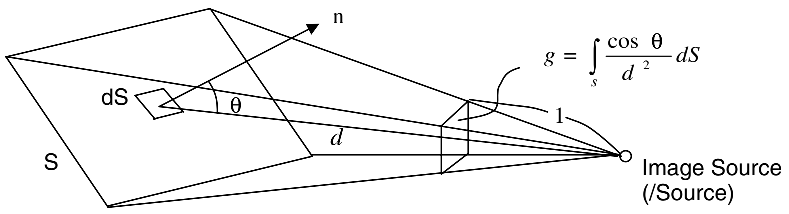

Fig. 4. Solid angle of patch from image source.

where S_i is the area of the patch, $d_{i,k}$ is the distance from the source (/image) to the patch, and $\theta_{i,k}$ is the incident angle of the sound from the source (/image).

When $d_{i,k}$ is large enough compared to S_i, $g_{k,i}$ can be approximated as

$$g_{k,i} = \frac{S_i \cdot \cos\theta_{i,k}}{d_{i,k}^2}. \tag{6}$$

The total incident specular reflection is

$$E_i(t) = \sum_k \left\{ \frac{g_{k,i}}{4\pi} P_{\mathrm{im},k} \cdot \delta\left(t - \frac{d_{i,k}}{c}\right)\right\}. \tag{7}$$

The portion $(1 - a) \cdot s$ of the incident energy of direct sound and specular reflections is reradiated as scattering reflection. Therefore, the first-order scattering reflection power of patch i, $P_{i,1}(t)$, is

$$P_{i,1}(t) = E_i(t) \cdot (1 - a_i) \cdot s_i, \tag{8}$$

where a_i and s_i denote the absorption and scattering coefficients of the patch, respectively. The directional distribution of the scattering energy is assumed to be in accordance with Lambert's cosine law, which means that the energy radiation to the θ direction is proportional to cos θ. The energy density of the first-order scattering reflection at the receiver can be expressed as

$$I_{\mathrm{scatt},1}(t) = \sum_i \frac{P_{i,1}(t - t_i) \cdot \cos\theta_{i,r}}{4\pi d_{i,r}^2}, \tag{9}$$

$$t_i = \frac{d_{i,r}}{c}, \tag{10}$$

where t_i is the travel time of the sound from patch i to the receiver and $\theta_{i,r}$ is the angle between the normal vector of the patch and the direction of the receiver (see Fig. 5).

Radiated scattering reflection strikes other patches, and the portion $(1 - a_i)$ of the incident scattering energy is again reflected as scattering reflection, and this cycle continues.

The energy exchange of scattering reflection between patches is calculated using the radiosity method, which was originally developed for the study of radiant heat transfer. In order to apply the radiosity method to the sound field problem, the time factor must be considered.

The form factor indicates the radiation energy transfer between two surfaces. The energy transfer from patch i to patch j, $E_{i,j}$, can be expressed using form factor $k_{i,j}$, as

$$E_{i,j} = k_{i,j} \cdot P_i \tag{11}$$

$$k_{i,j} = \int_{S_i}\int_{S_j} \frac{\cos\varphi_{i,j} \cdot \cos\varphi_{j,i}}{\pi d_{i,j}^2} \mathrm{d}S_i \mathrm{d}S_j \tag{12}$$

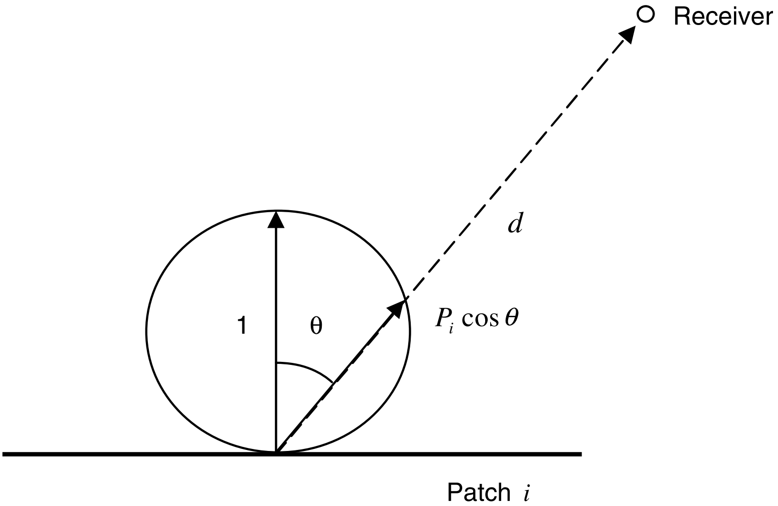

Fig. 5. Contribution of patch to receiver.

where P_i denotes the scattering sound power radiated from patch i and $d_{i,j}$ is the distance between $\mathrm{d}S_i$ and $\mathrm{d}S_j$. The angles $\varphi_{i,j}$ and $\varphi_{j,i}$ are the angles between normal vector of the respective patches and the direction of the objective patch (see Fig. 6). The travel time of the scattering sound from patch i to patch j, $t_{i,j}$, is approximated using the center-to-center distance of both patches, $d_{i,j}$, as

$$t_{i,j} = \frac{d_{i,j}}{c}. \tag{13}$$

The received energy of the Nth-order scattering reflection by patch j can then be expressed as

$$E_{j,N}(t) = \sum_i k_{i,j} \cdot P_{i,N}(t - t_{i,j}). \tag{14}$$

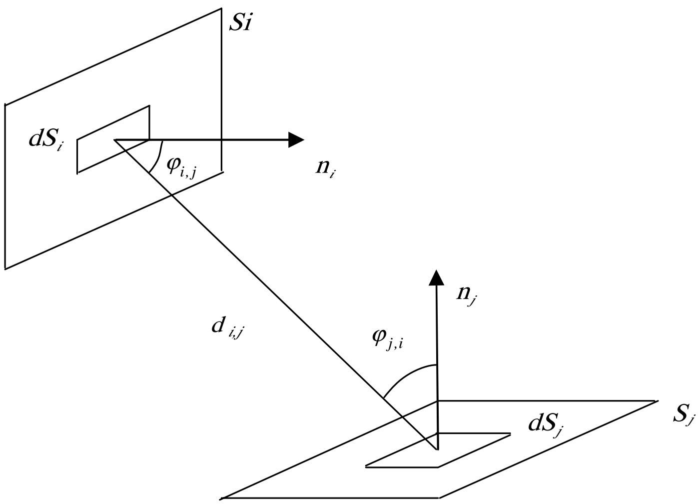

Fig. 6. Form factor.

The portion $(1-a)$ of the received scattering energy is reradiated as the next order scattering reflection:

$$P_{j,N+1}(t) = E_{j,N}(t)\cdot(1-a_j). \tag{15}$$

The calculation is continued until the total power of the Nth-order scattering reflection becomes approximately −60 dB relative to that of first order.

The intensity at the receiver caused by the scattering reflection from patches is calculated by

$$I_{\text{scatt}}(t) = \sum_i \sum_N \frac{P_{i,N}(t-t_{i,r})\cdot\cos\theta_{i,r}}{\pi d_{i,r}^2}. \tag{16}$$

The energy–time function at the receiver point is calculated by summing the specular reflection and scattering reflection:

$$I(t) = I_{\text{spec}}(t) + I_{\text{scatt}}(t). \tag{17}$$

2.3. Street model for calculation

Fig. 7 shows the street model used for calculation. The purpose of the present study is to observe the general acoustic characteristics of urban streets, so the model is simple. Namely, the buildings are continuous and of constant height along the street, and the absorption and scattering coefficients of building facades have the same value for entire surface. The dimensions of the model used for calculation are $l = 120$ m, $w = 20$ m, and $h = 6$, 18, 30 m. The surfaces of the building facades and the ground were divided into 2 m × 2 m patches for the calculation of the radiosity method. The sound source is an omni-directional point source situated at ($x = 30$ m, $y = -4$ m, $z = 1$ m) and the power level is assumed to be 100 dB for the SPL calculation. Receivers are situated along the length of the street at ($x = 31 - 90$ m, $y = -8$ m, $z = 1$ m).

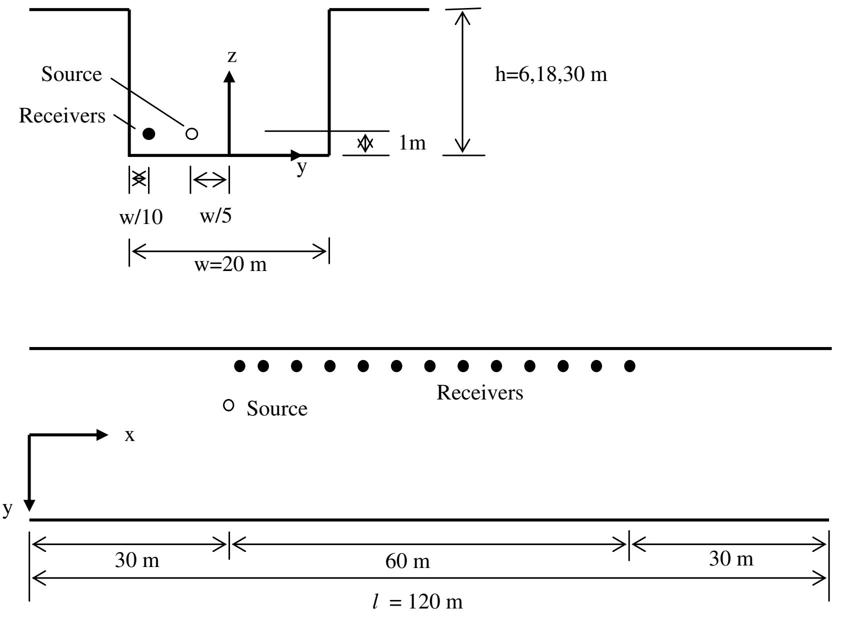

Fig. 7. Plan and cross-section of an idealized street showing the source and receiver positions used in calculation.

Calculations were performed for the facade for scattering coefficients from 0 to 1 and absorption coefficients from 0 to 0.5. Since the ground surface of the street is usually fairly flat and paved by a hard material, the scattering and absorption coefficients of the ground surface of the street were restricted to a maximum of 0.1 in order to simulate the actual street conditions. In order to examine the completely scattered condition, a scattering coefficient of 1 was applied to both the facades and the ground surface (Table 1). Calculations were performed for various combinations of scattering and absorption coefficients.

Table 1
Scattering and absorption coefficients used in calculation

Scattering coefficient									
Facade	0	0.05	0.1	0.15	0.2	0.3	0.4	0.7	1
Ground	0	0.05	0.1	0.1	0.1	0.1	0.1	0.1	1
Absorption coefficient									
Facade	0	0.05	0.1	0.15	0.2	0.3	0.5		
Ground	0	0.05	0.1	0.1	0.1	0.1	0.1		

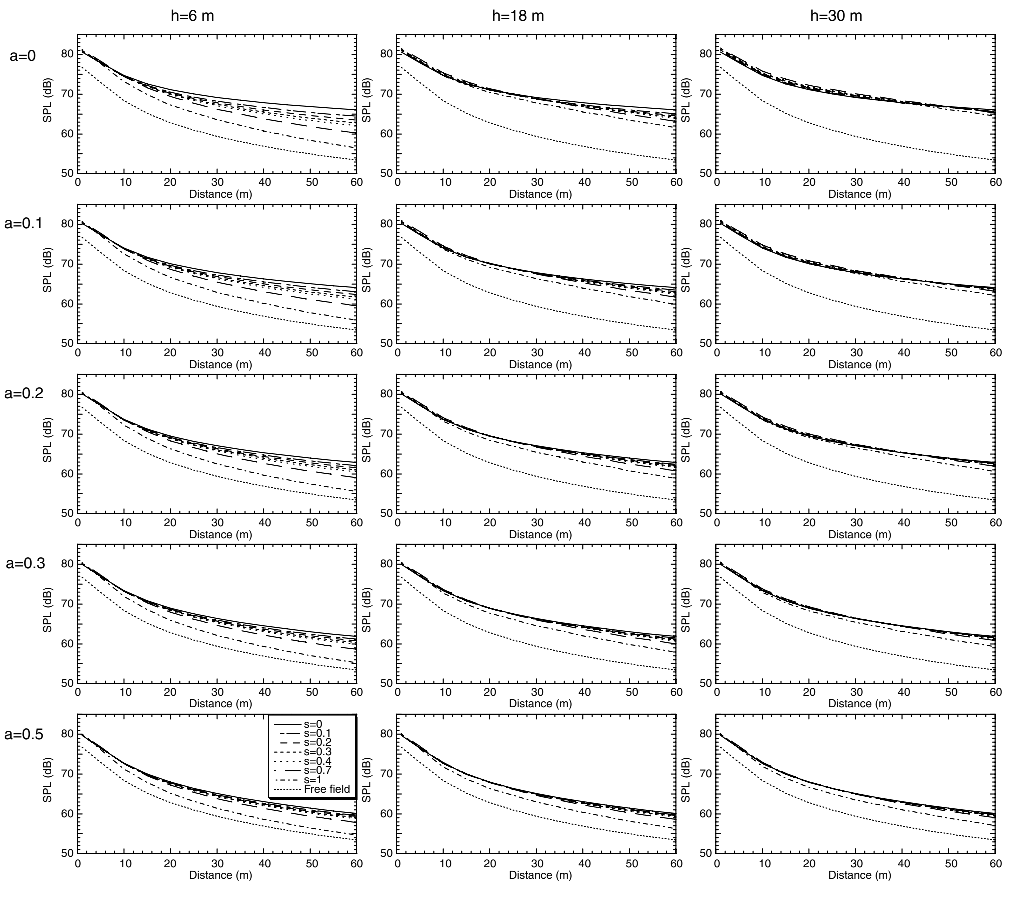

Fig. 8. Sound pressure level as a function of source–receiver distance.

3. Results and discussion

3.1. Sound pressure level (SPL)

Fig. 8 shows the calculated SPL, in which the abscissa represents the x-directional distance. The effect of scattering on the SPL appears as an increase at short distances and as a decrease at great distances. The range of the increase in SPL is larger in high-facade streets. However, the level change due to scattering is not large. The largest increase in SPL at a short distance, just over 1 dB, is observed for the case of high facades ($h = 30$ m) and an absorption coefficient $a = 0$. In every other case, the increase in SPL is less than 1 dB. In low-facade streets, increases in SPL are rare and the primary effect of scattering on SPL is a decrease in SPL.

If we represent streets as rectangular rooms, one of the distinguishing acoustic characteristics of urban streets is that the ceiling (open sky) is completely absorbent. The incident

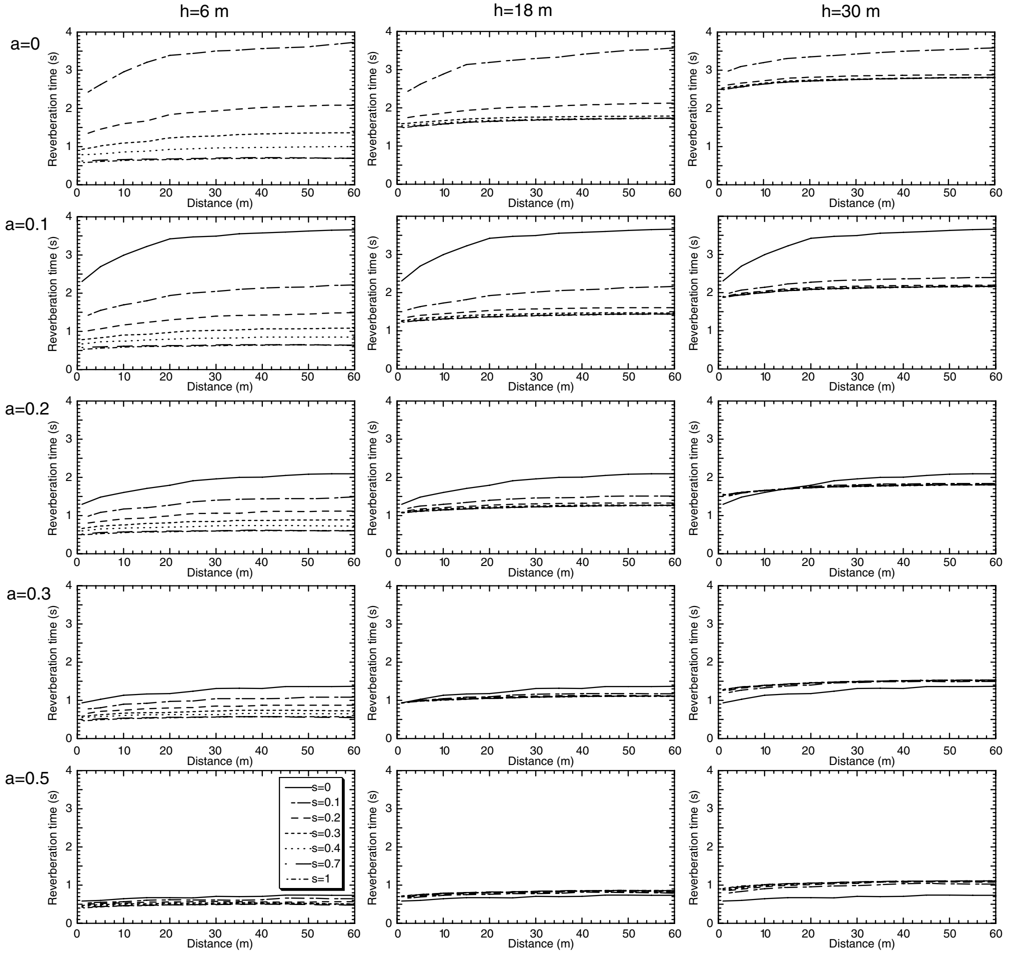

Fig. 9. Reverberation time as a function of source–receiver distance.

sound energy to the street "ceiling" is completely absorbed, and the ceiling generates no reflection. In the case of low-facade streets, namely streets with a low height to width ratio, the ratio of the open ceiling area to entire surface is large and the ratio of scattering energy disappearing into the sky is relatively large. In other words, the scattering sound quickly disappears into the open sky and remains in the street for only a short time. Thus, the dominant reflection in low-facade street is specular reflection (see Fig. 10). On the other hand, since the specularly reflected portion is indicated by $(1 - a) \cdot (1 - s)$, scattering is equally as effective as absorption in reducing specular reflection. As a result, the increase in scattering causes the decrease in the dominant reflection energy, which results in the decrease in the total sound energy.

In contrast, in the case of high building facades, namely large height to width ratios, the ratio of the open ceiling area to the area of the entire surface is low and the ratio of scattering energy that disappears into the sky is also relatively small. Therefore, the increase in the scattering coefficient results only in the scattering energy being maintained in the street, and the increase in the scattering energy is sufficient in order to compensate for the decrease in specular energy. Thus, the increase in the scattering coefficient hardly affects the SPL in high-facade streets.

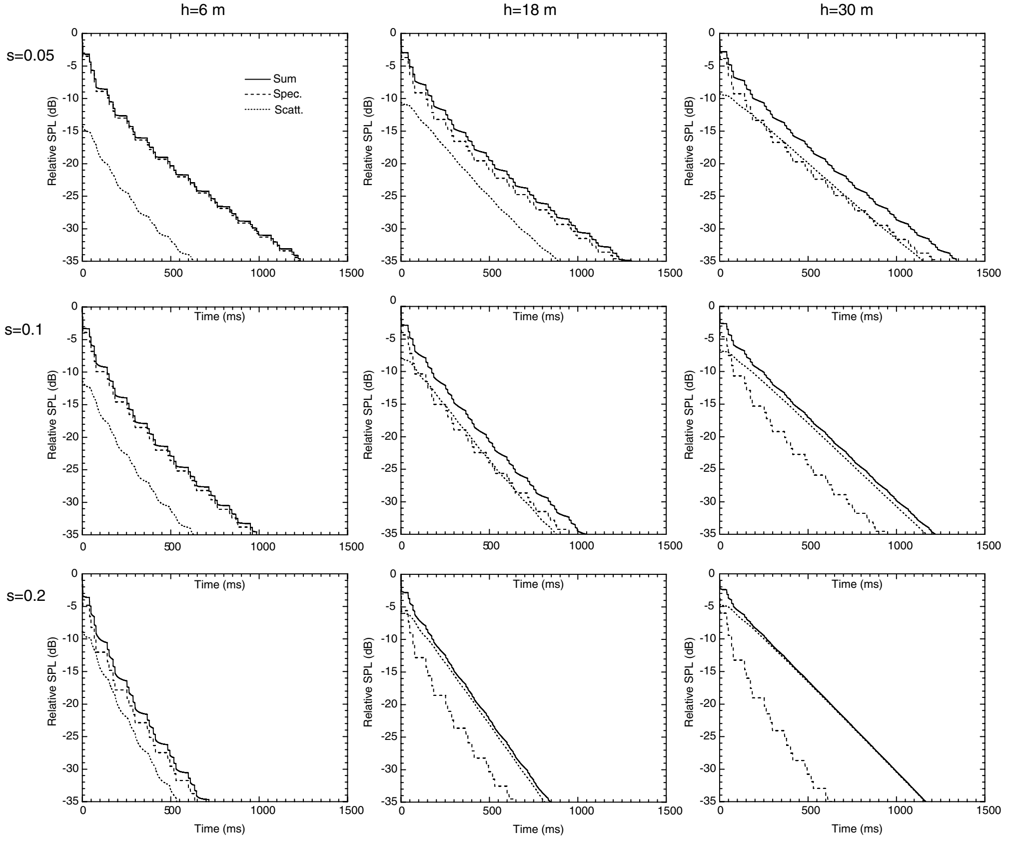

Fig. 10. Energy time decay curves of specular and scattering reflection.

3.2. Reverberation time

The reverberation time is calculated from the time decay curve, which is deduced from the energy–time function through inverse integration. Fig. 9 shows the calculated results for reverberation time. The parameter is the scattering coefficient. We show that increased scattering appears as a decrease in the reverberation time in a low-facade street. Here also,

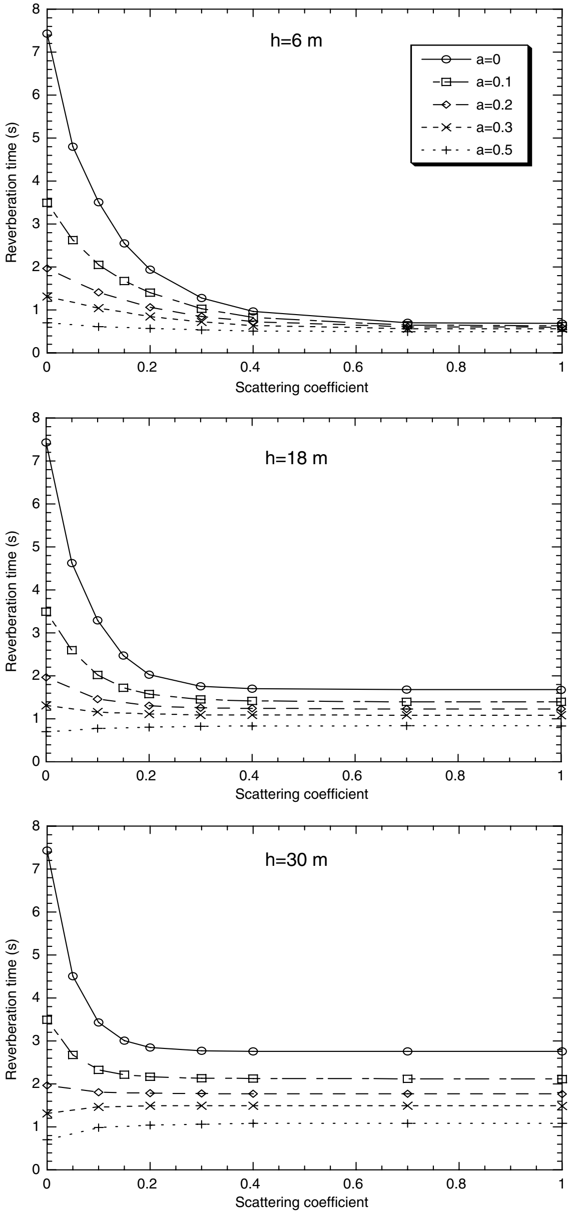

Fig. 11. Reverberation time as a function of scattering coefficient.

scattering has the same effect as absorption. However, scattering has little effect on the reverberation time in high-facade streets. The effect of scattering on reverberation time becomes smaller in streets having higher facades.

Fig. 10 shows a number of time decay curve examples. The condition of absorption coefficient is fixed at $a = 0.1$. Each diagram shows three curves: one representing the scattering energy (dotted line), one representing the specular energy (dashed line), and one representing the total energy (solid line). In high-facade streets, scattering reflection becomes dominant, even though for a small scattering coefficient (0.1). In contrast, specular reflection remains dominant up to $s = 0.2$ in low-facade streets.

Reverberation time is determined by the dominant late reflection, which is generally specular reflection in low-facade streets and scattering reflection in high-facade streets. The decay rate of specular reflection is equally affected by the absorption and scattering coefficients. This is why an increase in the scattering coefficient decreases the reverberation time in low-facade streets.

On the other hand, the decay rate of scattering reflection is affected only by the mean absorption coefficient. Therefore, an increase in the scattering coefficient does not affect the reverberation time in high-facade streets.

Fig. 11 shows the reverberation time at a distance of 30 m from the source. The horizontal axis indicates the scattering coefficient. The parameter is the absorption coefficient.

Reverberation time converges to the value at $s = 1$ as scattering increases. The convergence is faster in high-facade streets, and the reverberation time shows an almost constant value in the range of scattering coefficients from 0.2 to 1. The condition in which the scattering coefficient is $s = 1$ is considered to be a diffuse field. With respect to reverberation time, the sound field in high-facade streets becomes diffuse at a relatively small scattering coefficient. The reverberation time of this range is in accord with the value calculated using the theory for a diffuse field. Fig. 12 shows the comparison between simulated and

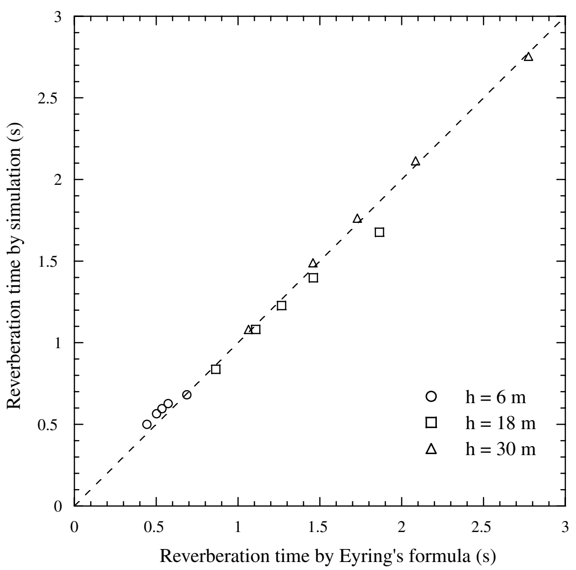

Fig. 12. Comparison between simulated and calculated reverberation time.

calculated reverberation time. The calculation was made using Eyring's formula considering the street model as a rectangular room of size (l, w and h) with entirely absorptive surfaces, upper side and street ends. The simulated reverberation times are the values for the condition of scattering coefficient of $s = 1.0$.

The attenuation of specular reflection is determined by $(1 - a) \cdot (1 - s)$, so that the value $(a + s)$ can be considered to be the apparent absorption coefficient for specular

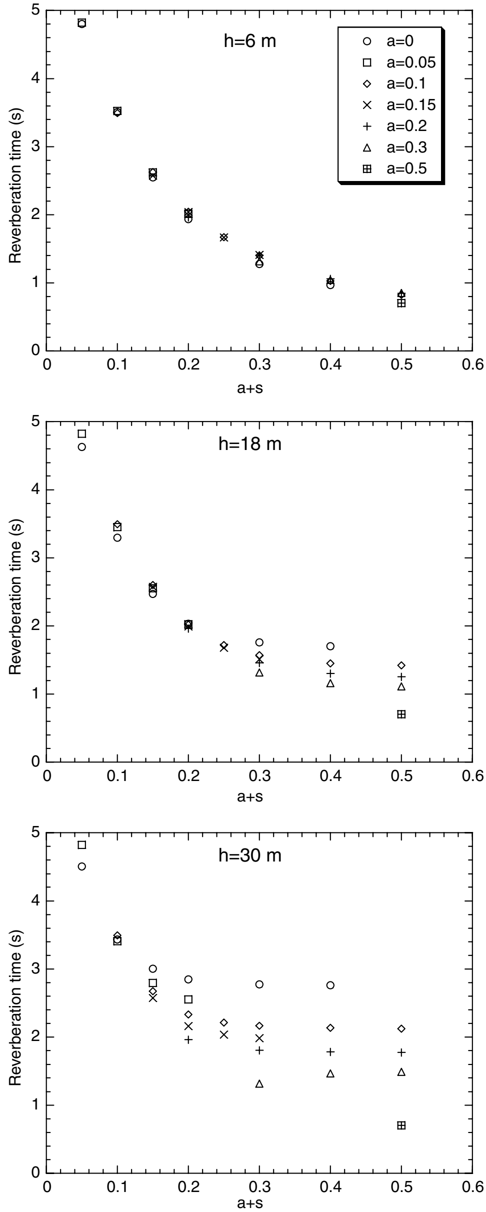

Fig. 13. Reverberation time as a function of $(a + s)$ (the sum of absorption and scattering coefficients).

reflection, as long as a and s are relatively small. If specular reflection is dominant over scattering reflection then the reverberation time is mainly related to the decay rate of specular reflection, which is determined by the value $(a + s)$ and the width of the street, w.

Fig. 13 shows the reverberation time as a function of the value $(a + s)$. In low-facade streets, in which $h = 6$ or $h/w = 0.3$, the reverberation time is uniquely determined by $(a + s)$ in the range up to $(a + s) = 0.5$. In the case of $h = 18$ or $h/w = 0.9$, the upper limit of this range is 0.25. The reverberation time is determined by $(a + s)$ within a limited range of $(a + s)$, and the range is larger for streets having a low h/w ratio. More specifically, the reverberation time is a function of the value $(a + s)$ if $h/w < 0.9$ and $(a + s) < 0.25$.

Since the condition that reverberation time is determined by $(a + s)$ is a sound field in which specular reflection is dominant, another determining factor for the reverberation time in such field is the width of the street. Generally, the determining factors for the reverberation time of small h/w ratio streets are the value $(a + s)$ and the width of the street.

3.3. Comparison between simulated and measured reverberation times

It is desirable to show the validity of the simulation by comparison with the value measured in actual streets. However, since reliable data on the absorption and scattering coefficients of the facades of actual streets are usually not available, we cannot compare the absolute value of the reverberation time, but rather the tendency of the change thereof as a function of distance from the sound source. A detailed measurement in an actual street, which is appropriate for this purpose, has been reported by Picaut and Simon [6]. For the sake of comparison, the simulation was carried out using a model of this street ($l = 100$ m, $w = 12$ m, $h = 8$ m). The sound source is situated at the point ($x = 16$ m, $y = 0$ m, $z = 1$ m), and receivers are situated along the street length ($x = 17$–96 m, $y = 0$ m, $z = 1$ m).

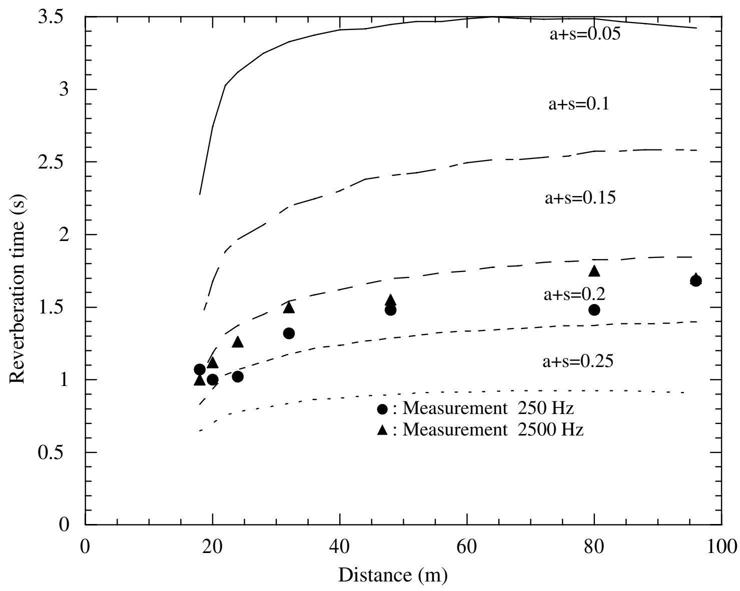

Fig. 14. Simulated and measured reverberation times.

Fig. 14 compares the simulated and measured reverberation times. The tendency of reverberation time as a function of distance shows good agreement, which indicates the validity of the proposed model. The value of the apparent absorption coefficient ($a + s$) of this street is between 0.15 and 0.2.

As mentioned in the previous chapter, the determining factors of the reverberation time of small h/w ratio streets are apparent absorption coefficient ($a + s$) and street width. Therefore, we can determine the value of ($a + s$) of actual streets from the measured reverberation times and the width of the streets. Schröder [7] measured the reverberation time in 53 streets in Düsseldorf. For the sake of comparison, the simulation was performed for the model according to the measurement conditions. Most of the streets measured by Schröder have a height to width ratio of from 0.3 to 1.0, which is the condition in which the reverberation time is determined by ($a + s$) and w, as long as ($a + s$) is smaller than 0.25. Schröder showed two types of reverberation time because some of the recorded decay

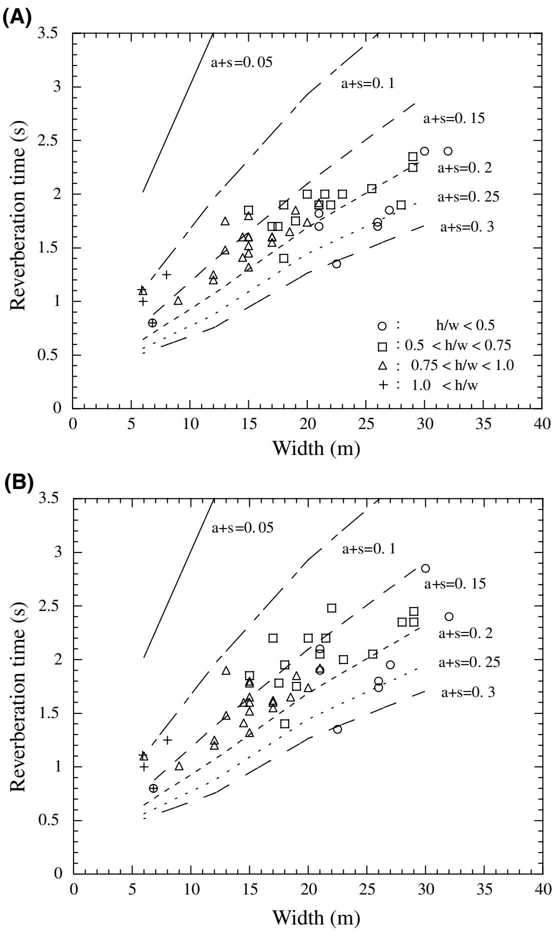

Fig. 15. Relationship between measured reverberation time and ($a + s$) (the sum of absorption and scattering coefficients): (A) reverberation time derived from the entire decay curve; (B) reverberation time derived from the late part of the decay curve.

curves were observed to bend. One of the reverberation times is derived from the entire decay curve, and the other is derived from the late part of the decay curve.

Fig. 15 shows the measured reverberation time as a function of street width. The lines in the figure show the simulated reverberation time for corresponding $(a + s)$ values. The majority of the measured reverberation times lie between the curve $(a + s) = 0.1$ and the curve $(a + s) = 0.25$, and two thirds of the measured reverberation times lie between $(a + s) = 0.15$ and $(a + s) = 0.2$. The plots are distributed along the $(a + s)$ curves, and the distribution tendencies of the h/w groups show no significant differences. For the streets measured by Schröder, the typical value of the apparent absorption coefficient of the facades of urban streets was estimated to be approximately 0.15–0.2.

4. Conclusions

The acoustic characteristics of urban streets are examined using computer simulation in relation to scattering caused by building facades. The simulation method is a combination of the image method for specular reflection and the radiosity method for scattering reflection. The findings of the present study are as follows:

1. The effect of scattering on the SPL appears as an increase at short distances and as a decrease at great distances. The range of the increase in SPL is larger in high-facade streets. However, the level change due to scattering is not large. In low-facade streets, the primary effect of scattering on SPL is a decrease in SPL.
2. In low-facade streets, the dominant energy of late reflection is specular reflection. Since the scattering coefficient is equally as effective as the absorption coefficient in attenuating specular reflection, the reverberation time is determined by the sum of absorption coefficient and scattering coefficient. In contrast, in high-facade streets, scattering reflection is dominant and the reverberation time is determined by the absorption coefficient as a diffuse field.
3. The simulated result for the reverberation time shows good agreement with measured value in actual streets, indicating the validity of the proposed method.
4. The estimated values for the sum of the absorption coefficient and the scattering coefficient of facades of actual urban streets range from 0.1 to 0.25.

References

[1] Lyon RH. Role of multiple reflections and reverberation in urban noise propagation. J Acoust Soc Am 1974;55:493–503.
[2] Delany ME, Copeland WE, Payne RC. Propagation of traffic noise in typical urban situations. Nat Phys Lab Rep 1971;Ac54.
[3] Davies HG. Multiple-reflection diffuse-scattering model for noise propagation in streets. J Acoust Soc Am 1978;64:517–21.
[4] Steenackers P, Myncke H, Cops A. Reverberation in town streets. Acustica 1978;40:115–9.
[5] Kang J. Sound propagation in street canyons: comparison between diffusely and geometrically reflecting boundaries. J Acoust Soc Am 2000;107(3):1394–404.
[6] Picaut J, Simon L. A scale model experiment for the study of sound propagation in urban areas. Appl Acoust 2001;62(3):327–40.
[7] Schröder E. Nachhall in geschlossen bebauten Straßen. Lärmbekämpfung 1973;17:11–5.