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Assessment of sound diffusion in rooms for both time and frequency domain by using a decay-cancelled impulse response

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Summary
A method for measuring the random-incidence scattering coefficient of surfaces has been standardized as ISO 17497-1:2004. However, a method for assessing sound diffusivity in rooms has not been standardized yet. The authors have proposed the “degree of time series fluctuation” as an index for evaluating degree of sound field diffusion by using a decay-cancelled impulse response. In this study, we focused on energy fluctuation not only in time domain but also in frequency domain. First, “degree of frequency domain fluctuation” was newly proposed by using power spectrum of the decay-cancelled impulse response. Additionally two indexes which are simpler in a statistical sense were developed. One is a “time series variation coefficient” in energy of the decay-cancelled impulse response and the other is a “frequency domain variation coefficient” in the power spectrum of the decay-cancelled impulse response. Experiments were conducted using a 1/10 scale model of a rectangular reverberation chamber with various amount of diffusers in order to verify the proposed indexes. As a result, the degree of time series fluctuation and the time series variation coefficient increased when a fluttering echo occurred, and the degree of frequency domain fluctuation and the frequency variation coefficient increased when a low quality reverberation such as a booming occurred. Especially in low frequency range the frequency domain variation coefficient was reasonable for evaluating effects of natural resonance frequencies in a room.

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1. Introduction

Sound diffusion is one of important factors for achieving good acoustics in performance spaces such as concert halls, opera houses and recording studios and so on. Sound diffusion is important not only in such performance spaces but also in testing rooms where sound measurements are conducted. Especially in reverberation chambers high diffusivity is required for achieving reasonable measurement results there.
A method for measuring the random-incidence scattering coefficient of wall surfaces has been standardized as ISO 17497-1:2004. However, a method for assessing sound diffusivity in rooms has not been standardized yet. Several researchers have proposed methods for evaluating sound diffusivity in rooms by using time structure of an impulse response [1-4]. The authors have also proposed the “degree of time series fluctuation” as an index for evaluating degree of sound field diffusion by using a decay-cancelled impulse response [5].
In this study, we focused on energy fluctuation not only in time domain but also in frequency domain. First, “degree of frequency domain fluctuation” was newly proposed by using power spectrum of the decay-cancelled impulse response. Additionally two indexes which are simpler in a statistical sense were developed. One is a “time series variation coefficient” in energy of the decay-cancelled impulse response and the other is a “frequency domain variation coefficient” in the power

spectrum of the decay-cancelled impulse response. Experiments were conducted using a 1/10 scale model of a rectangular reverberation chamber with various amount of diffusers in order to verify the proposed indexes.

2. Decay-cancelled impulse response

Due to reverberation decay, the time-structure of the reflected sounds in a late part of an impulse response is difficult to clarify. Therefore, a method for calculating the decay-cancelled impulse response has been developed [5].

2.1 Basic method for calculating the decay-cancelled impulse response

In this section, the sound field is assumed to have an exponential energy decay with decay rate A. In this sound field, the decay curve is linear. Moreover, the energy decay curve of the reverberation, $E(t)$ is calculated from an impulse response, $p(t)$ as follows:

$$E_S(t)=\int_t^{\infty} p^2(\tau)d\tau \,. \tag{1}$$

Using this energy decay curve, the decay-cancelled impulse response, $g(t)$ is defined as

$$g(t)=\frac{p(t)}{\sqrt{E_S(t)}}. \tag{2}$$

Here, $g^2(t)$ can be interpreted to detect only the time fluctuation of the reflected sound energy by cancelling the energy decay. The squared average of the decay-cancelled impulse response becomes the same as the decay rate A:

$$\overline{g^2(t)} \cong A. \tag{3}$$

Hence, the reverberation time can be obtained using $\overline{g^2(t)}$ as follows:

$$T \cong \frac{13.82}{\overline{g^2(t)}}. \tag{4}$$

Here, the value of 13.82 is derived from the definition of the reverberation time (i.e., $6\ln 10 = 13.82$).

Because the magnitude of $g^2(t)$ depends on the reverberation time, the time structure cannot be directly compared among different sound fields by the $g^2(t)$. Therefore, the normalized decay-cancelled impulse response $h(t)$ is defined as follows:

$$h(t)=\frac{g(t)}{\sqrt{\overline{g^2(t)}}}=\frac{g(t)}{\sqrt{A}}. \tag{5}$$

In this case, $h^2(t)$ represents the time fluctuation of the relative magnitude of sound energy in the average energy decay curve of the target sound field. If the time fluctuation of the reflected sound energy in an impulse response is small, $h^2(t)$ fluctuates near 1. Using the normalization in equation (5), $\overline{h^2(t)}$ is always equal to 1, and the time fluctuation of the reflected sound energy in an impulse response can be compared between different sound fields.

Eda et al. [4] clarified that the slope ratio proposed by Jeon et al. [2] is equivalent to square of the decay-cancelled impulse response if Δt approaches to zero in the difference equation. To obtain an average decay ratio, Jeon et al. uses the slope of the line between 0 dB and 60 dB on the decay curve. Because this method is influenced by a direct sound level, errors in the average decay ratio may be observed if the direct sound level is large. Hence, we propose the following method to obtain the average decay ratio A:

$$A=\frac{1}{t_2-t_1}\int_{t_1}^{t_2} g^2(t)dt\,, \tag{6}$$

where the integration is taken over the time range t_1 and t_2, which corresponds to -5 dB and -35 dB, respectively, on the decay curve.

When energy decay curve $E_s(t)$ is calculated using equation (1), $E_s(t)$ decays rapidly near the end of the integral range. Thus, the decay-cancelled impulse response calculated by equation (2) diverges near the end of the integral range. Therefore, the time structure of the decay-cancelled impulse response should be evaluated in a time range that is not influenced by divergence.

2.2 Improved method for calculating the decay-cancelled impulse response

If a nonlinear reverberation decay curve occurs, the decay rate A varies with time. Thus, equation (5) can be rewritten as

$$h(t)=\frac{g(t)}{\sqrt{A(t)}}. \tag{7}$$

The instantaneous decay rate $A(t)$ is calculated as follows:

$$A(t)=\frac{1}{\tau_2(t)-\tau_1(t)}\int_{\tau_1(t)}^{\tau_2(t)} g^2(t)dt\,. \tag{8}$$

As shown in Figure 1, $\tau_1(t)$ and $\tau_2(t)$ are defined as the times when the decay levels are +5 dB and -5 dB relative to the decay level at time t. Figure 1 shows an example of the decay ratio calculation for two cases with the same time window setting; one case is for a steep slope while the other is for a shallow slope. In this method, the width of the time window changes automatically depending on the slope of the decay curve. Basically the $A(t)$ is calculated from the time at which the level of the decay curve becomes -5 dB relative to the direct sound level. For the $A(t)$ values before the time at -5 dB, the $A(t)$ at -5 dB is used.

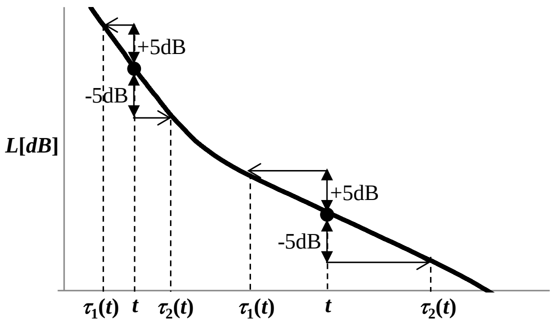

Figure 1. Example of the decay ratio calculation.

Level of the decay curve, $L(t)$, is expressed as follows:

$$L(t) = 10\log_{10} E_s(t) \quad (9)$$

Using equations (1) and (2), the instantaneous slope $L'(t)$ can be expressed as

$$L'(t) = -\frac{10}{\ln 10} \cdot g^2(t) \quad (10)$$

Then, equation (8) can be rewritten using equation (10) as follows:

$$A(t) = -\frac{\ln 10}{10} \cdot \frac{1}{\tau_2(t) - \tau_1(t)} \int_{\tau_1(t)}^{\tau_2(t)} L'(t)dt$$

$$= \frac{\ln 10}{10} \cdot \frac{L[\tau_1(t)] - L[\tau_2(t)]}{\tau_2(t) - \tau_1(t)}. \quad (11)$$

Since $L[\tau_1(t)] - L[\tau_2(t)] = 10$ (dB), equation (11) can be simplified:

$$A(t) = \frac{\ln 10}{\tau_2(t) - \tau_1(t)}. \quad (12)$$

Additionally, the instantaneous reverberation time can be defined as follows:

$$T(t) = \frac{13.82}{A(t)} = 6[\tau_2(t) - \tau_1(t)]. \quad (13)$$

In this method, the normalized decay-cancelled impulse response $h(t)$ is calculated using

$$h(t) = \frac{g(t)}{\sqrt{A(t)}} = \frac{p(t)}{\sqrt{A(t)}\sqrt{E_s(t)}}. \quad (14)$$

This means that the improved method can detect the time structure $h(t)$ from the impulse response $p(t)$ even when the decay curve is nonlinear. Therefore, with this normalization, $\overline{h^2(t)}$ is always equal to 1. Equation (14) can be transformed as

$$p(t) = h(t)\sqrt{A(t)}\sqrt{E_s(t)}. \quad (15)$$

This means that the improved method can divide the impulse response $p(t)$ into three components of the time structure $h(t)$, the instantaneous decay rate $A(t)$ and the energy decay curve $E_s(t)$.

3. Assessment of sound diffusion in rooms by using the decay-cancelled impulse response

In this chapter, four indexes are proposed for evaluating sound diffusivity in a room for both time domain and frequency domain.

3.1 Assessment in time domain

In this section indexes for assessment in time domain are described.

3.1.1 Degree of time series fluctuation

A squared impulse response $p^2(t)$ means a response in dimension of energy. On the other hand $h^2(t)$ means the time fluctuation of relative magnitude of sound energy to the average energy decay curve of a target sound field. If the time fluctuation of reflected sound energy in an impulse response is small, $h^2(t)$ fluctuate near 1.

Therefore based on this, an analysis method for estimating diffuseness of sound fields is investigated. In evaluation time range, $t1$～$t2$, the total of $h^2(t)$ is defined as R_{total}.

$$R_{total} = \int_{t1}^{t2} h^2(t)dt \quad (16)$$

On the other hand a total of $h^2(t)$ when the value exceeds threshold, k, in the evaluation time range is defined as $R(k)$. And the ratio $z(k)$ is defined as the followings:

$$z(k) = \frac{R(k)}{R_{total}} \quad (17)$$

This ratio $z(k)$ means probability that relative magnitudes of sound energy of the impulse response to the average energy decay curve exceed the threshold k. As shown in Figure 2, the $z(k)$ decreases as the threshold k increases, and $z(k)$ becomes a kind of decay curves. Therefore this $z(k)$ is named as the "fluctuation decay curve". A steeper fluctuation decay curve means that the time fluctuation of the sound energy in the impulse response is small. Therefore diffuseness of sound field might be evaluated by the fluctuation decay curve.

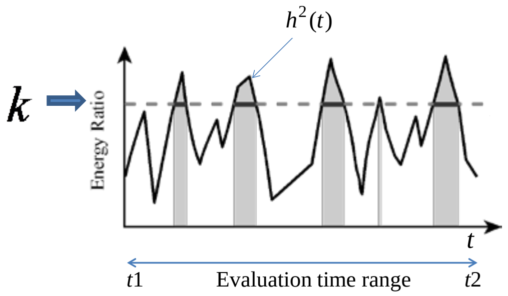

Figure 2. Method for obtaining fluctuation decay curve of reflected sound energy z(k) from h2(t) by using threshold k.

As shown in Figure 3, the threshold k at which fluctuation decay curve $z(k)$ becomes 0.01 is defined as the "degree of time series fluctuation (DTF)" of reflected sound energy. A steeper fluctuation decay curve indicates smaller degree of time series fluctuation. The DTF indicates how large the reflected sound energy where probability of occurrence is 1%. Therefore, smaller DTF means higher degree of diffusion of sound field.

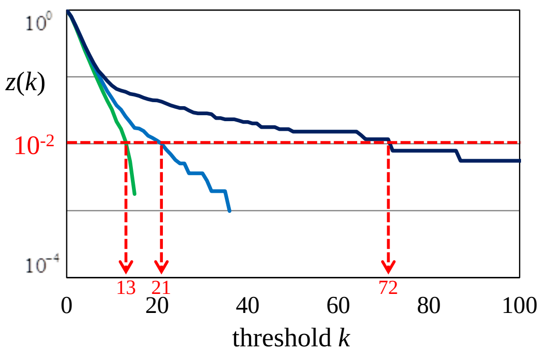

Figure 3. Examples of fluctuation decay curves of three different sound fields and degrees of time series fluctuation of them

3.1.2 Time series variation coefficient

Time series variation coefficient (TVC) is defined as a variation coefficient of $h^2(t)$. The TVC means relative magnitude of fluctuation of square of the decay-cancelled impulse response. The TVC can be calculated as Equation (18).

$$TVC = \frac{\sqrt{\frac{1}{t2-t1}\int_{t1}^{t2}\left[\left\{h^2(t)\right\}-\overline{h^2(t)}\right]^2 dt}}{\overline{h^2(t)}} \tag{18}$$

An average of $h^2(t)$ becomes always 1 due to its definition. Therefore a calculation of the TVC can be simplified as Equation (19).

$$TVC = \sqrt{\frac{1}{t2-t1}\int_{t1}^{t2}\left[\left\{h^2(t)\right\}-1\right]^2 dt} \tag{19}$$

This index is simple in a statistical sense and can be obtained without calculation of the fluctuation decay curve.

3.2 Assessment in frequency domain

Sound diffusivity in a room must influence frequency response of the room. Therefore in this section indexes for assessment in frequency domain are described.

3.2.1 Degree of frequency domain fluctuation

First a power spectrum, $P(f)$, is calculated by FFT of the decay-cancelled impulse response, $g(t)$. Here f represents frequency. Next a normalized power spectrum, $P_n(f)$, is calculated as Equations (20) and (21).

$$P_n(f) = \frac{P(f)}{\overline{P(f)}} \tag{20}$$

$$\overline{P(f)} = \frac{1}{f2-f1}\int_{f1}^{f2} P(f)\,df \tag{21}$$

Based on $P_n(f)$ an analysis method for estimating diffuseness of sound fields is investigated as same as the DTF. In evaluation frequency range, $f1$～$f2$, the total of $P_n(f)$ is defined as R_{f_total}.

$$R_{f\_total} = \int_{f1}^{f2} P_n(f)\,df \tag{22}$$

A total of $P_n(f)$ when the value exceeds threshold, k, in the evaluation frequency range is defined as $R_f(k)$. And the ratio $z_f(k)$ is defined as the followings:

$$Z_f\left(k\right)=\frac{R_f\left(k\right)}{R_{f\_total}} \qquad (23)$$

The threshold k at which fluctuation decay curve $z_f(k)$ becomes 0.01 is defined as the "degree of frequency domain fluctuation (*DFF*)". A steeper fluctuation decay curve indicates smaller *DFF*. The *DFF* indicates how large the power spectrum where probability of occurrence is 1%. Therefore, smaller *DFF* means higher degree of diffusion of sound field.

3.2.2 Frequency domain variation coefficient

Frequency domain variation coefficient (*FVC*) is defined as a variation coefficient of the power spectrum $P_n(f)$. The *FVC* means relative magnitude of fluctuation of the power spectrum. The *FVC* can be calculated as Equation (24).

$$FVC=\frac{\sqrt{\frac{1}{f2-f1}\int_{f1}^{f2}\left[\left\{P_n\left(f\right)\right\}-\overline{P_n\left(f\right)}\right]^2 df}}{\overline{P_n\left(f\right)}} \qquad (24)$$

An average of $P_n(f)$ becomes always 1 due to its definition. Therefore a calculation of the *FVC* can be simplified as Equation (25).

$$FVC=\sqrt{\frac{1}{f2-f1}\int_{f1}^{f2}\left[\left\{P_n\left(f\right)\right\}-1\right]^2 df} \qquad (25)$$

4. Verification of proposed indexes

In this chapter, the proposed indexes were verified by a 1/10 scale model experiment.

4.1 Measurement method

Figure 4 shows the block diagram of the 1/10 scale model experiment. Two walls are absorptive and one wall is diffusive. The scale model is a cube 0.7m on a side (7m in real scale). The model is made of acrylic board with thickness of 15mm. Needle felt is used as a material of absorptive walls. The acrylic board and the needle felt can be considered as almost perfect reflective and absorptive materials respectively in 1/10 scale model experiment.

Five 1/4 inch microphones are located at receiving positions from R1 to R5. A small dodecahedron loudspeaker is used as a point sound source which is located at a corner of the room. Time stretched pulse signal is radiated from the loudspeaker for obtaining impulse responses at the receiving positions. A sampling frequency and a quantization bit rate are 192 Hz and 24 bit respectively.

A square pyramid shown in Figure 5 is used as a diffuser. Two sizes of the diffuser, square pyramid (L) and square pyramid (S) are used as indicated in Table 1. Diffusers are made of styrene board 5mm thick. Area ratio of total area of the diffusers to area of a wall is set to five steps at 10, 20, 30, 40, 50%. The diffusers are attached on the wall, randomly and uniformly.

4.2 Analysis method

First, 1/3 octave band filtered impulse responses are calculated using an impulse response at each receiving position. A range of 1/3 octave center frequency is from 20 Hz to 10 kHz. Next, band filtered decay-cancelled impulse responses are calculated from the band filtered impulse responses. Finally four kinds of the indexes proposed above are calculated at each 1/3 octave band by using each band filtered decay-cancelled impulse response.

S/N ratios of filtered impulse responses are different each other. Therefore evaluation time ranges, $t1$～$t2$, are different depending on each S/N ratio of filtered impulse responses. The $t1$ is set at 100 ms from an arrival time of a direct sound and the $t2$ is set at a time where an energy decay level becomes +10 dB to a noise floor of the decay curve. As for the evaluation frequency range, a lower and upper limit frequencies $f1$ and $f2$, are the same as those of each 1/3 octave band.

The indexes at every 1/3 octave band are obtained by averaging over all of the receiving positions. Finally, frequency characteristics of the indexes can be obtained.

4.3 Results and discussion

Results of *DTF*, *TVC*, *DFF* and *FVC* in various conditions of diffusers are shown in Figures 6, 7, 8 and 9 respectively. On the whole, all index values tend to decrease basically as the number of diffusers increases. Because smaller index value means higher degree of diffusion of sound field, it can be said that attached diffusers improved diffusivity of the sound field. Focusing on the difference in the size of the diffuser, the larger diffusers affect the index value in the lower frequency range than the smaller diffusers. Indexes of time domain, *DTF* and *TVC* changed in above 500 Hz. Although indexes of frequency domain, *DFF* and *FVC* changed from lower frequency 200 Hz, these did not change in above 4 kHz.

Figure 10 shows the square of the normalized decay-cancelled impulse responses in the 6300 Hz 1/3 octave band where only the indices *DTF* and *TVC* have changed, comparing the conditions without the diffuser and with 50% diffusers. Comparing these results, it can be seen that the diffusers reduced flutter echo. As shown by this result, it has been shown that the *DTF* and *TVC* can evaluate the magnitude of the variation of reflected sound energy such as flutter echo in the time domain especially in high frequency range. Comparing *DTF* and *TVC*, although the change of *DTF* was slightly large, almost the same trend was shown.

Figure 11 shows the power spectrum of the decay-cancelled impulse responses at R3, comparing the conditions without the diffuser and with 50% diffusers. Sharp spectrum peaks are observed especially in the low-mid frequency range. These peaks are natural frequencies of the room, which may cause acoustic problems such as the booming sound. In the condition with 50 % of squre pyramids (S), it can be seen that the peaks in above 600 Hz are suppressed by the diffusers. As shown by this result, it has been shown that the DFF and FVC can evaluate the magnitude of the variation of frequency spectrum. Especially *DFF* and *FVC* change in lower frequency range than the *DTF* and *TVC*. Comparing *DFF* and *FVC*, especially in very low frequency range from 20 to 100 Hz, the *FVC* was reasonable because only the *FVC* can evaluate effects of natural resonance frequencies in a room.

Finally, it was confirmed by hearing that the flutter echo occurred when the DTF and TVC were large, and that a low-quality reverberation such as a booming sound was generated when the DFF and FVC were large.

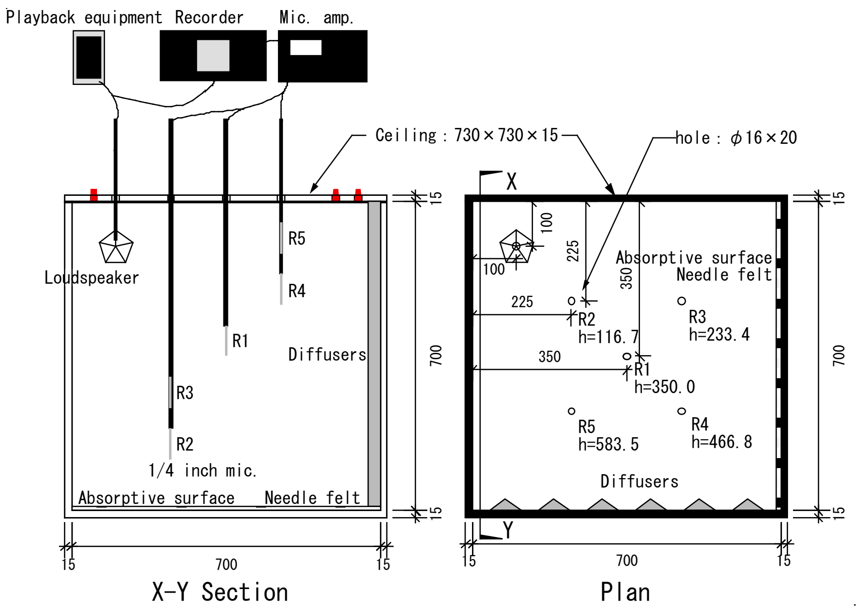

Figure 4. Block diagram of 1/10 scale model experiment, and arrangement of a sound source and receiving positions R1 – R5.

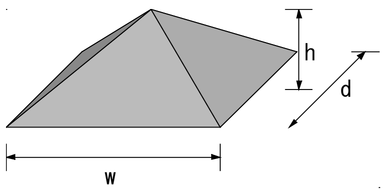

Table I. Sizes of two types of diffuser.

Diffuser type	Size w*d*h(mm)
Square pyramid (L)	80*80*30
Square pyramid (S)	40*40*15

Figure 5. Configuration of a diffuser used in the experiment.

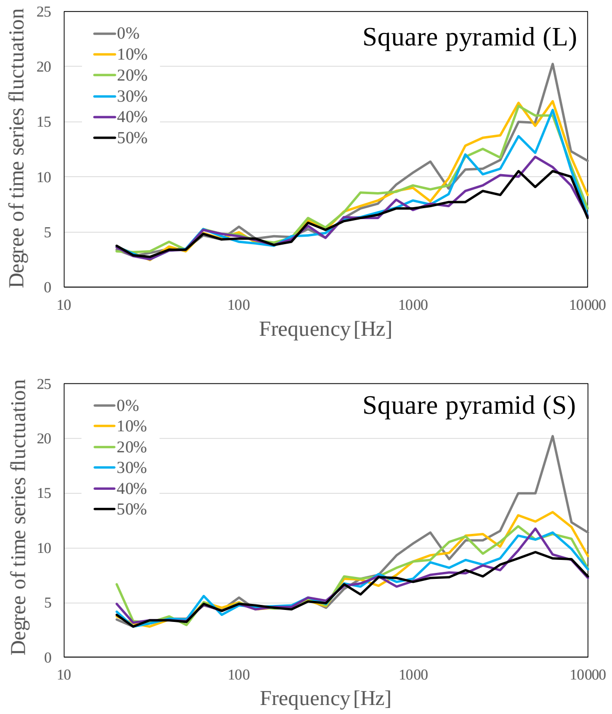

Figure 6. Results of the degree of time series fluctuation.

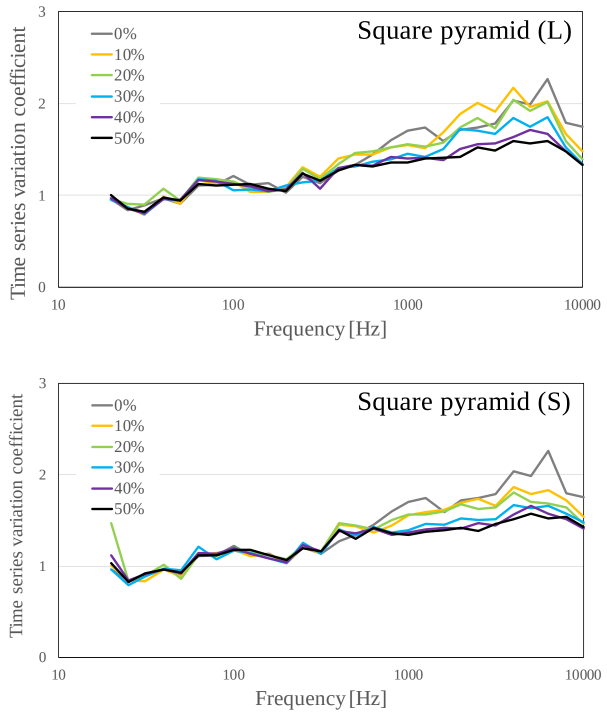

Figure 7. Results of the time series variation coefficient.

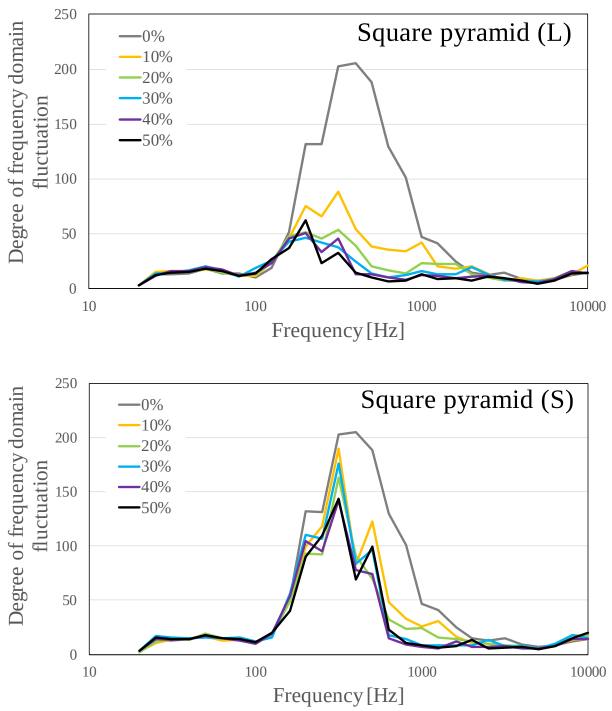

Figure 8. Results of the degree of frequency domain fluctuation.

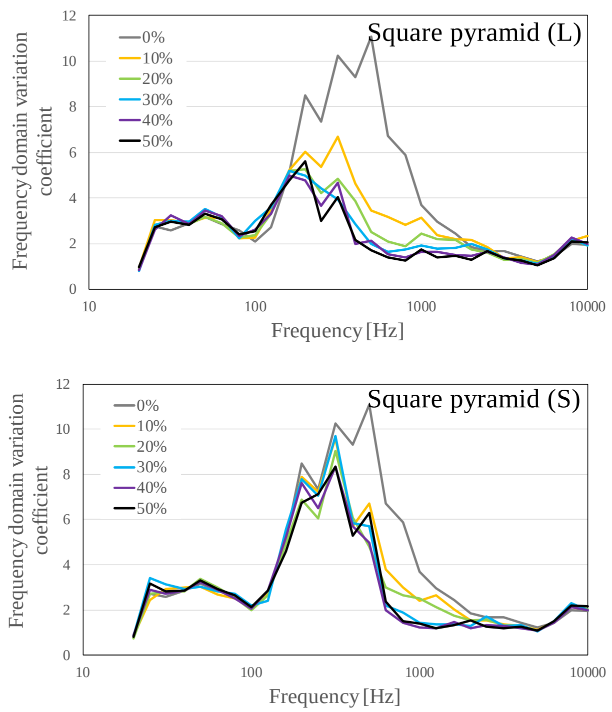

Figure 9. Results of the frequency domain variation coefficient.

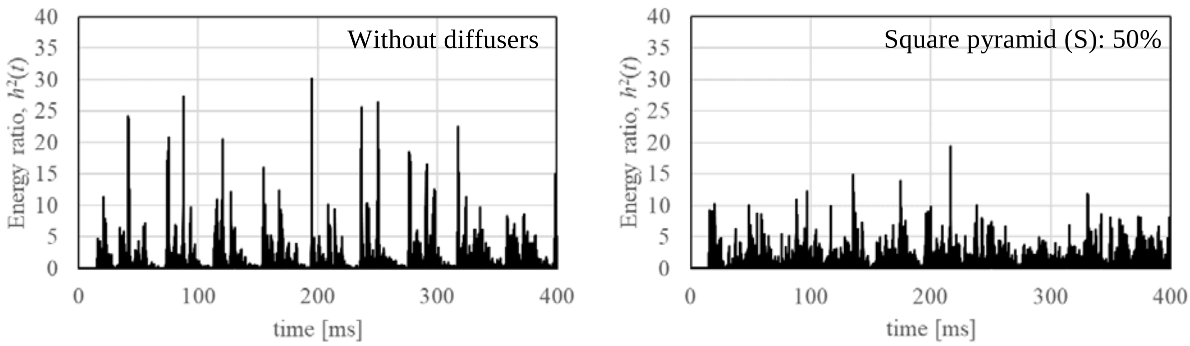

Figure 10. Square of normalised decay-cancelled impulse responses at R3 in the conditions with/without diffusers (6300Hz 1/3 oct. band).

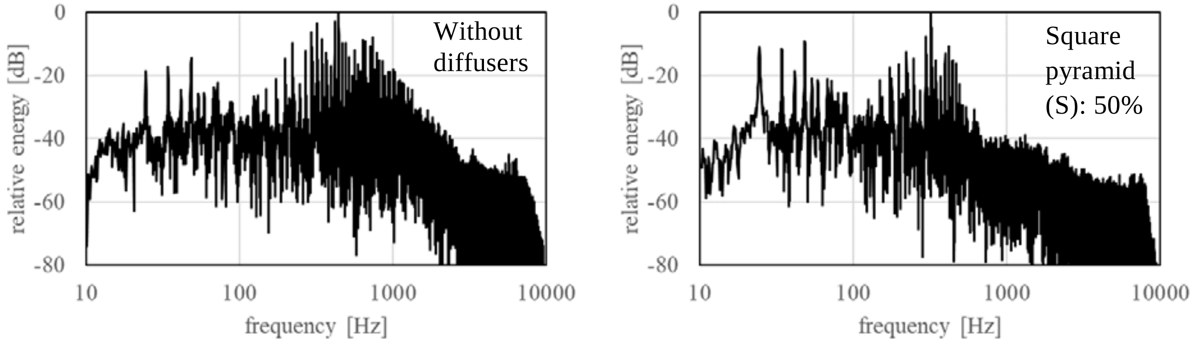

Figure 11. Power spectrums at R3 in the conditions with/without diffusers.

5. Conclusions

In this study, we focused on energy fluctuation not only in time domain but also in frequency domain. The degree of frequency domain fluctuation, the time series variation coefficient and the frequency domain variation coefficient are newly proposed by using the decay-cancelled impulse response. The 1/10 scale model experiments were conducted in order to verify the proposed indexes.

As a result, the degree of time series fluctuation and the time series variation coefficient increased when a fluttering echo occurred, and the degree of frequency domain fluctuation and the frequency variation coefficient increased when a low quality reverberation such as a booming sound occurred. Especially in very low frequency range the frequency domain variation coefficient was reasonable for evaluating effects of natural resonance frequencies in a room.

Because isotropy of sound energy is also important for assessment of the sound field diffusion, we also have been studying to evaluate the isotropy [6].

Acknowledgement

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