Echo suppression effect and coloration of periodic-type diffusers

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Walls and ceilings are often designed to suppress undesirable echoes. For that purpose, walls and ceilings are given absorptive surfaces which absorb sound energy or uneven surfaces which provide wave diffusion. While it is not difficult to predict the degree of echo suppression effects in the case of absorptive surfaces, it is generally difficult to do that in the case of uneven surfaces. In addition, if the surfaces have periodicity, unintended effects called coloration can distort tonal characteristics of the sound field. Thus, many acoustic designers would hesitate to employ this kind of periodic-type diffusers. However, there are some cases where it is necessary to suppress echoes without any energy loss. Periodic-type diffusers have the advantages of easy estimation of diffusion properties, simple method of design, and ready availability. In this study, a subjective experiment with simulated stimuli was carried out to clarify the echo suppression effect of the periodic-type diffusers from the viewpoint of reflected energy level. Although coloration interfered subjective judgments in some cases of the experiment, it is shown that the periodic-type diffusers have echo suppression effect if coloration does not occur. This study is also devoted to discussion about the cause of the coloration.

1 Introduction

An echo is one of the obstacles in halls and theaters. This undesirable echo is caused by reflections with long paths between walls and ceilings. Therefore, for the purpose of suppressing it, walls and ceilings have been often given absorptive surfaces which absorb sound energy or uneven surfaces which provide wave diffusion. In the case of an absorptive surface, the echo suppression effect can be predicted to some extent from its absorption coefficient. However, there are some cases where it is necessary to suppress echoes without any energy loss. In these cases, giving an absorptive surface is not a reasonable alternative. In the case of an uneven surface, it is generally difficult to predict the echo suppression effect. In addition, if the surface has periodicity, unintended effects called coloration can distort tonal characteristics of the sound field. Thus, many acoustic designers would hesitate to employ this kind of periodic-type diffusers [1, 2]. Such types of diffusers, however, have the advantages of easy estimation of diffusion properties, simple method of design, and ready availability [3, 4, 5, 6].

The objective of this study is to clarify the echo suppression effects of periodic-type diffusers. From the viewpoint of sound-pressure-level difference between direct and reflected waves from different types of surfaces, the equivalent level difference of an uneven surface to that of an absorptive surface was investigated by a subjective experiment. Results of this investigation are expected to be helpful for designing walls and ceilings as diffusers. In the experiment, the test stimuli were made from convolution of predicted impulse responses and speeches recorded in an anechoic chamber. Another topic of this study is the unintended coloration, which has been discussed for a long time [7, 8, 9, 10]. During the listening tests, some subjects perceived coloration and got disturbed in their judgments. This coloration is caused by periodicity of diffusers. Discussions on its characteristics and countermeasures against it are also given in this study.

2 Equivalent level difference

Fig.1 shows examples of impulse responses in the cases of an absorptive surface and an uneven surface, where t_d is the delay time of reflected wave. Although the sound-pressure-level difference ΔSPL can be defined clearly in the case of an absorptive surface, it is difficult to determine that in the case of an uneven surface. Thus, the equivalent level difference of an uneven surface is defined here as the level difference of an absorptive surface which is evaluated as the most similar stimulus to that of uneven surface [11, 12, 13]. In this study, the discussion is limited to the case of perpendicular incidence of plane wave.

2.1 Reflection from an uneven surface

The reflected sound from an uneven surface is simulated by using the boundary integral equation method. Fig.2(a) shows the two-dimensional geometrical configuration of an uneven surface, where P is a receiver, p is a point on the boundary, $\mathbf{n}_p$ is the normal vector at the point p, S_1 means a flat part and S_2 means an uneven part of the boundary. The

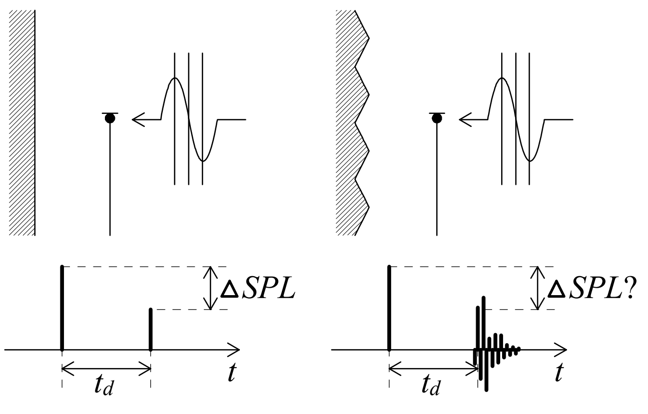

Fig.1 Example of impulse responses.

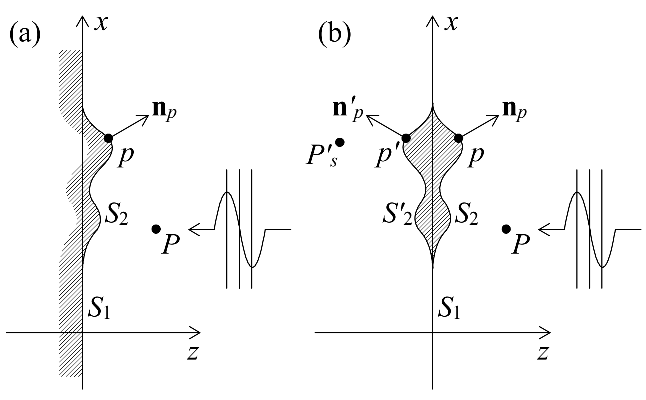

Fig.2 Geometrical configuration of an analytical model.

boundary is assumed to be rigid. Under this situation, the Helmholtz-Kirchhoff Integral formula for the velocity potential φ is written as

$$\varphi(P)=\varphi_D(P)+\int_{S_1+S_2}\varphi(p)\frac{\partial G(P,p)}{\partial \mathbf{n}_p}dS \quad (1)$$

where, $\varphi_D(P)$ is the direct-sound component of a plane wave incidence to the point P and G is the two-dimensional free space Green's function for outgoing waves. Considering that S_1 is flat and rigid, this configuration can be assumed as the same problem which is shown in Fig.2(b). With P'_s, p', S'_2, and $\mathbf{n}'_p$ which are images of P_s, p, S_2, and $\mathbf{n}_p$ with respect to x-axis, Eq.(1) yields

$$\varphi(P)=\varphi_D(P)+\varphi'_D(P) +\int_{S_2}\varphi(p)\frac{\partial G(P,p)}{\partial \mathbf{n}_p}dS+\int_{S'_2}\varphi(p')\frac{\partial G(P,p')}{\partial \mathbf{n}'_p}dS \quad (2)$$

where $\varphi'_D(P)$ is the direct-sound component of an imaginary plane wave incidence to the point P. Allowing for the periodicity of an uneven surface, the velocity potential on the boundary was calculated [14, 15, 16]. After that, Solving Eq.(2) with those potentials, the impulse response at the receiver P was predicted.

2.2 Difference limen of absorptive-surface reflection

In advance of making test stimuli for a subjective experiment on the equivalent Δ*SPL* of a periodic diffuser, difference limen of the reflected sound from an absorptive surface was investigated by the method of limits. Standard stimuli were male and female speeches convolved with the impulse responses for Δ*SPL* of 5 dB and 10 dB, respectively. The time delays considered here are 30 ms, 50 ms, and 80 ms. For example, in the case of the standard stimulus for Δ*SPL* of 5 dB and time delay 50 ms, the comparison stimuli are twenty convolved speeches where the time delay is 50 ms and Δ*SPL* is -5 dB to 15 dB with 1 dB interval. A listening test was conducted and the difference limen is consequently obtained as 3.6 dB to 4.8 dB. Therefore, the interval of test stimuli for a subjective experiment with regards to an equivalent Δ*SPL* of a periodic diffuser was determined as 3 dB.

2.3 Test Stimuli

As for absorptive surfaces, allowing for the discussion in the preceding section, six patterns of impulse responses where Δ*SPL* is -6 dB (A1), -3 dB (A2), 0 dB (A3), 3 dB (A4), 6 dB (A5), and 9 dB (A6) were considered. These responses were convolved with male speeches recorded in an anechoic chamber. Δ*SPL* which is less than 0 dB means that the sound pressure level of the reflected wave is greater than that of the direct wave. The delay time t_d was considered to have three patterns of 30 ms, 50 ms, and 80 ms. Thus, totally, eighteen test stimuli for absorptive surfaces were made.

The diffusers treated here have three types of triangular profile having the same roughness ratio H/L=0.1333 with different period L=0.2 m (D1), 0.6 m (D2), and 1.5 m (D3), where H is the height of the surface with triangular configuration [4, 5]. The total length of the uneven part was assumed to be 9 m and 21 m. The impulse responses predicted by the method discussed in the preceding section were convolved with the speeches.

For example, six types of comparison pairs such as D1-A1, D1-A2, D1-A3, D1-A4, D1-A5, and D1-A6 were prepared for D1 type.

2.4 Listening test

Six subjects, all with normal hearing, were presented by a closed-type headphone with a series of comparison pairs and asked to indicate when they detected a difference. From the answers, ratios of difference perception for each pairs were calculated. For each periodic-type diffuser, Δ*SPL* of the absorptive surface which had the least ratio of difference perception was defined as the equivalent Δ*SPL* of the diffuser.

Fig.3 shows experimental results with 95% confidence interval for D2-type diffusers of total length 9 m. In these cases, the equivalent Δ*SPL* are 0 dB to 3 dB. This means that the diffusers can be expected to have echo suppression effects to the same extent as absorptive surfaces which have the same Δ*SPL*. In these cases, no subjects perceived coloration. For D1-type and D3-type diffusers, the equivalent Δ*SPL* were 0 dB to 6 dB and colorations were not perceived.

Fig.4 shows results for D2-type diffusers of total length 21 m. In these cases, the equivalent Δ*SPL* are -3 dB to 0 dB. In other words, any echo suppression effect cannot be expected with these types of diffusers. In the case where many reflected pulses are received within a quite short time interval, subjects would perceive those pulses as one sound and feel it as a large reflection from the viewpoint of sound energy. However, these results may depend on the receiver point. As for these points, it is necessary to do more detailed studies. In addition, some subjects perceived metallic sound, which would be coloration, and got disturbed in their judgments by that. For D1-type and D3-type diffusers, the same results were obtained.

3 Coloration

The following is devoted to a discussion on causes and features of the coloration perceived in the experiment. In addition, the least total length, where the coloration can be detected, is investigated for the diffusers considered here.

3.1 Interference of direct and reflected sound

In order to investigate whether interference of direct and reflected sound is one of the causes of the coloration, only the reflected pulses from the periodic-type diffusers were convolved with male speeches. In a short experiment with these stimuli, subjects perceived coloration again in the cases where the total length of the uneven surface is 21 m. Therefore, it can be said that the interference is not one of the causes of the coloration and they would exist within the reflected sound itself.

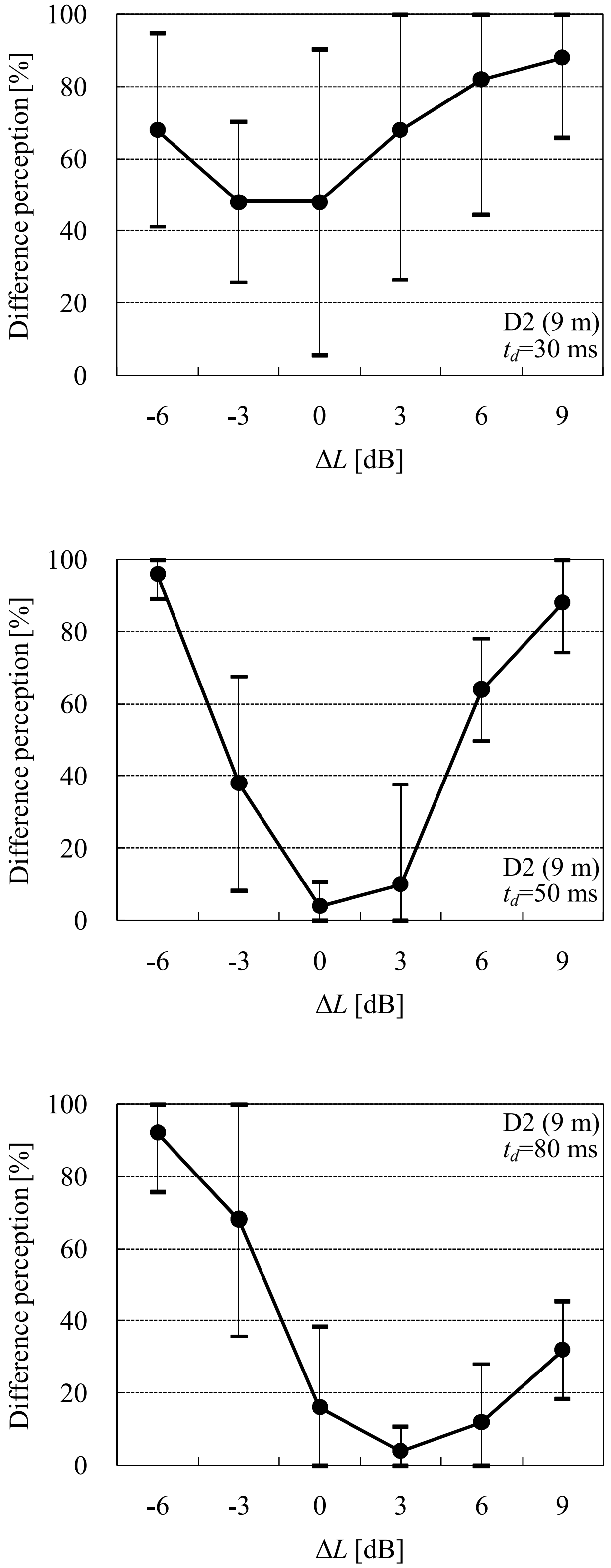

Fig.3 Experimental results for D2-type diffusers of 9 m.

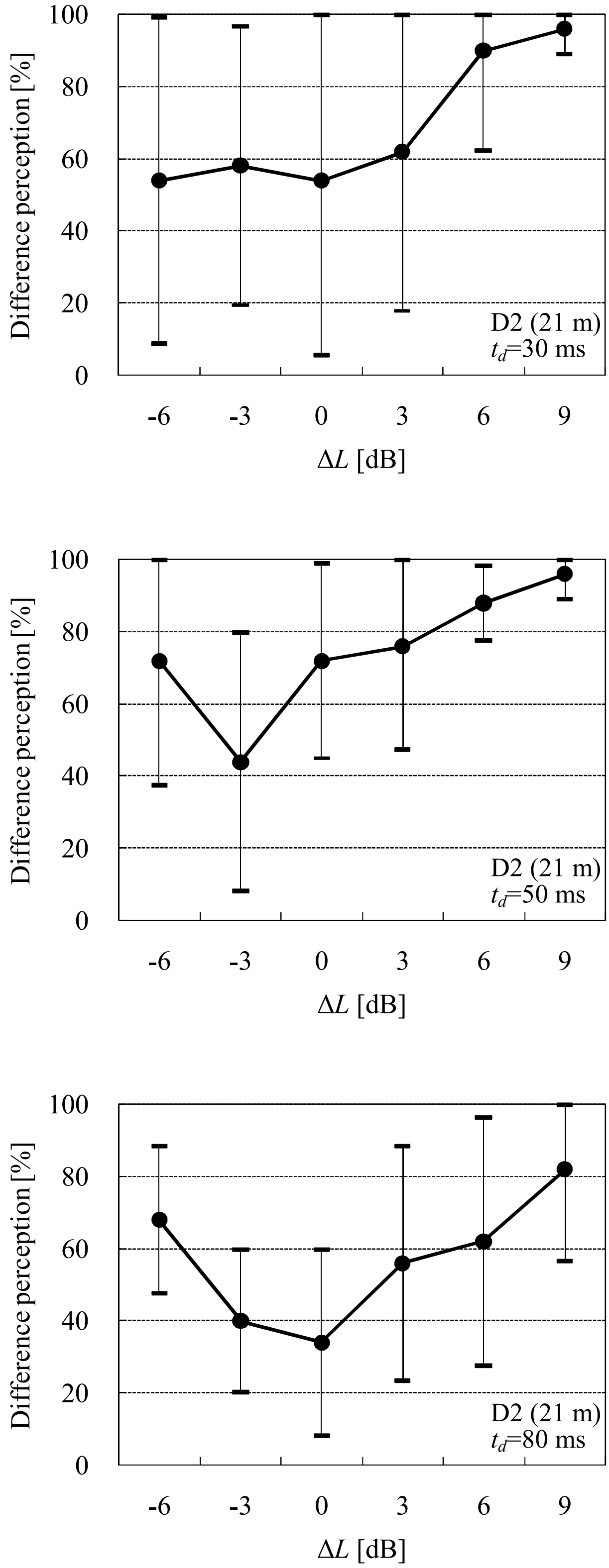

Fig.4 Experimental results for D2-type diffusers of 21 m.

3.2 Sound spectrogram

Fig.5 shows the sound spectrogram of the impulse response with which coloration was perceived. Considering the spectrogram of the reflected wave, its characteristics can be divided into two parts of time intervals. In the early part of the reflected wave, a kind of sweep sound can be seen. This sweep is considered to be formed by a set of first reflections from vertices of each triangle on the surface. In the later part, sharp peaks at a regular interval can be seen and they last for several milli seconds. It is interesting that these peak frequencies are equal to multiples of the lowest frequency $f_{min}=c_0/L$ for scattering, where c_0 is the speed of sound [4]. These peak values tend to increase as the total length of uneven surface becomes longer and the delay time becomes larger.

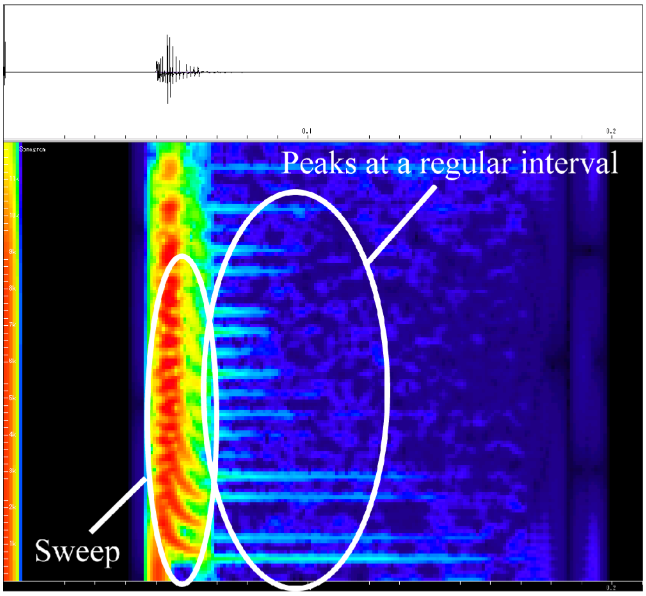

Fig.5 Spectrogram of the impulse response with coloration.

In order to investigate which part of the reflection is the most effective on the coloration, both early and later parts of the reflected sound was divided more in detail into some arbitrary short intervals and the divided parts were convolved with male speeches respectively. In a short experiment with these stimuli, subjects perceived coloration only in the cases of convoluted sound with later parts of the reflected sound. Thus, it can be said that the coloration of periodic-type diffusers is caused by the sharp peaks at a regular interval in the frequency domain. In addition, whether the coloration can be perceived or not is determined by both the total length of the uneven surface and the time delay. In addition, the tonal characteristics of the coloration depend on the period of the diffuser.

3.3 Length threshold of coloration

In order to investigate the least total length, where the coloration can be detected for the diffusers considered here, a subjective experiment was carried out. Impulse responses with delay time 30 ms, 50 ms, and 80 ms were predicted for the cases of total length configurations as shown in Table 1. Test stimuli were made from convolution of these responses and male speeches recorded in an anechoic chamber. In methods of limits, standard stimuli were stimuli for the cases of S1-type diffusers. For example, ten types of comparison pairs such as S1-S1, S1-S2, S1-S3, S1-S4, S1-S5, S1-S6, S1-S7, S1-S8, S1-S9, and S1-S10 were prepared for D1 type with each time delay.

Experimental results of ascending series and descending series for each time delay are shown in Fig.6. As discussed in the preceding section, it is generally easier to perceive coloration as the total length becomes longer. As for the cases of delay time 30 ms, the average threshold tends to be shorter as the period L becomes longer. The threshold lengths were 16.44 m for D1 type, 8.62 m for D2 type, and 9.48 m for D3 type. It is true that these results also depend on characteristics of the speeches which were used in the convolution. However, it should be noted that coloration could be detected if a length is longer than these values. As for the cases of time delay 50 ms, D2-type diffusers showed the least total length threshold. The least total lengths were

	D1 (L=0.2 m)	D2 (L=0.6 m)	D3 (L=1.5 m)
S1	9.0 m	9.0 m	7.5 m
S2	12.2 m	12.6 m	10.5 m
S3	15.0 m	15.0 m	13.5 m
S4	18.2 m	18.6 m	16.5 m
S5	21.0 m	21.0 m	19.5 m
S6	24.2 m	24.6 m	22.5 m
S7	27.0 m	27.0 m	25.5 m
S8	30.2 m	30.6 m	28.5 m
S9	33.0 m	33.0 m	31.5 m
S10	36.2 m	36.6 m	34.5 m

Table 1 Total lengths for the subjective experiment

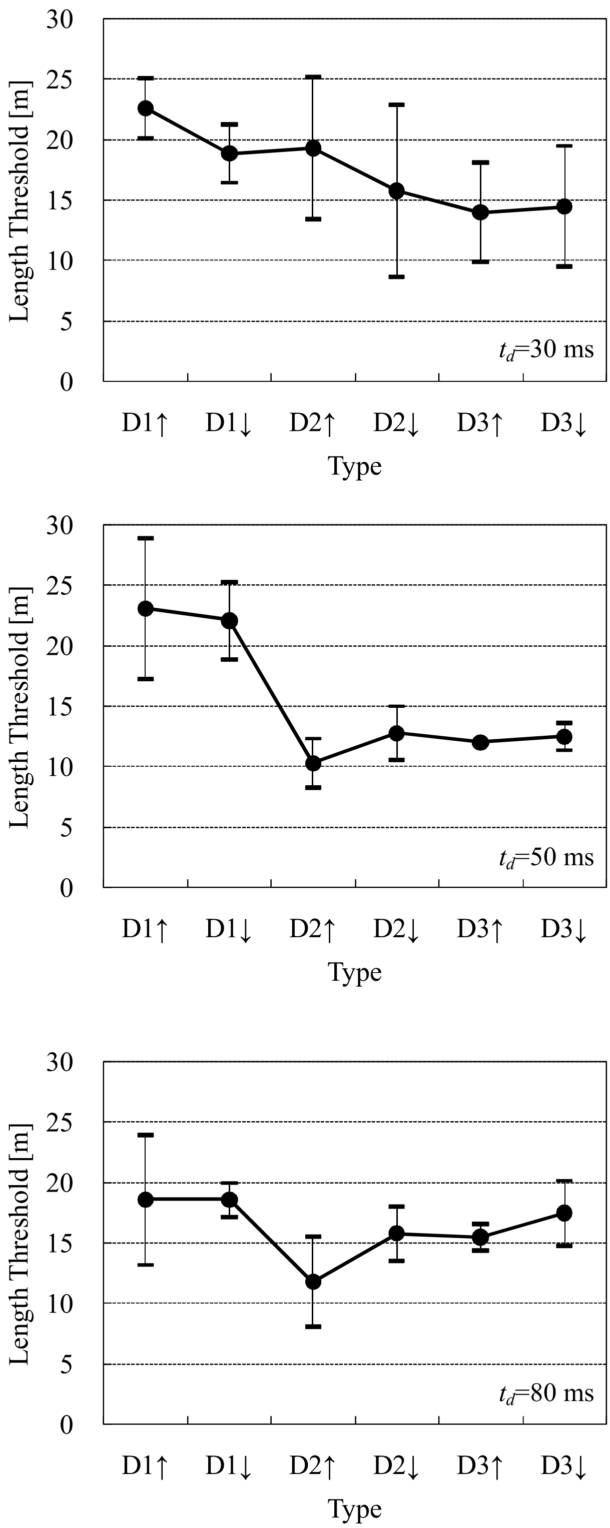

Fig.6 Experimental results of the length threshold.

17.25 m for D1 type, 8.24 m for D2 type, and 11.38 m for D3 type. For the cases of delay time 80 ms, D2-type diffusers showed the least threshold of 8.06 m. The other thresholds were 13.21 m for D1 type and 14.38 m for D3 type.

4 Conclusion

In this study, from the viewpoint of sound-pressure-level difference between direct and reflected waves, an equivalent level difference for a periodic-type diffuser is defined and investigated by some subjective experiments. The equivalent level difference was 0 dB to 3dB in the case where the total length of the diffuser is 9 m and -3 dB to 0 dB in the case where the total length is 21 m. If the length of the diffuser is short, the diffuser can be expected to have echo suppression effects to the same extent as absorptive surfaces which have the same ΔSPL. However, for the case of the total length 21 m, some subjects perceived metallic sound, which would be coloration, and got disturbed in their judgments by that. Thus, in those cases, the equivalent level difference may not be determined exactly.

The coloration can be detected due to later parts of the reflected sound, where sharp peaks at a regular interval can be seen in the frequency domain. These peak frequencies are equal to multiples of the lowest frequency $f_{min}=c_0/L$ for scattering. These peak values tend to increase as the total length of uneven surface becomes longer and the delay time becomes larger. It is true that these results would depend on the receiver point and speeches which was convolved with impulse responses. However, as for the periodic-type diffusers considered in this study, it should be noted that there is a possibility of coloration if the total length is longer than 8 m.

From these results, when periodic-type diffusers are considered to be installed as walls or ceilings and you would like to stand on the safety side, it is necessary to change the pattern such as direction of their periodicity within a certain total length. In the case where coloration cannot be detected, the periodic-type diffusers would be expected to have echo suppression effects to the same extent as the absorptive surface which has a difference level of 0 dB to 6 dB.

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