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Subjective effects of sound fields due to periodic-type diffusers

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1. Introduction

To provide diffuse reflections, walls and ceilings with periodic unevenness have been often designed. As for the shape and the size of this unevenness, discussions have been given exclusively in relation to the wavelength of the incident wave, and the use of this type of diffusers has been done in an empirical manner. Regarding this matter, an objective measure named *DNSD* was introduced by Takahashi,[1,2] which can express the degree of diffusion of a reflector with periodic profile. With the help of this measure, it is possible to evaluate diffusion of the surface, and to design effective diffuse-type reflectors.

In addition to this property of diffusion, reflection of the surface should not have particular characteristics of the response that may have a serious effect on our subjective experience. A well-known problem is "coloration" caused by interference between the direct and the reflected waves, which might seriously appear in this case due to periodicity of the surface.

From this point, we conducted hearing tests for the differential sensitivity to diffusion for the purpose of studying subjective properties of diffuse reflection. In relation to this experiment, we measured also physical properties of diffuse reflection for three types of diffuser used in the subjective experiments. This letter briefly reports the results and findings of this research.

2. Experimental setup and procedures

Reflectors treated here are three types (D1, D2, D3) having the same roughness ratio ($H/L=0.1333$) with different roughness size, which are shown in Fig. 1. Type D3 was designed as a reflector with the highest diffusion in the frequency range 250 Hz to 2 kHz under a normal incidence. We prepared also an ordinary plane surface as a reflector for reference, which is here, designated "P".

All experiments were carried out using 1/3-scale models of these reflectors set in an anechoic chamber. Each reflector made from plywood had the same size (1.8×3.0 m), and had no surface treatment. The distance between a loudspeaker and each reflector was 5 m (15 m in full scale). A receiver was located at 0.3 m (0.9 m in full scale) away from the neutral plane of each reflector along the line normal to the plane through the surface top. The neutral plane is assumed to be lying at a mid-position between the surface top and the surface bottom for the corrugated case, and the surface itself for the plane case.

2.1 Measurement of physical properties

The outline of the measurements is shown in Fig. 1. The reflected sound field was evaluated in terms of both sound pressure level (SPL) characteristics and the impulse response, which were obtained by deconvolution of a source and a FFT technique.[3] Impulsive source recorded in DAT was used for this purpose.

2.2 Hearing tests

Three kinds of band-limited pink noise were used as the source signals, which are wide band-noise (200 Hz-24 kHz), band-noise at low frequencies (200 Hz-6 kHz), and band-noise at high frequencies (6-24 kHz). These signals were fed into a loudspeaker through a graphic equalizer to get a uniform spectrum. The reflected sound fields caused by 1/3-scale model of each reflector were recorded in DAT. These were transferred to a PC to convert the data into those corresponding to the real frequency range. Then the frequencies in full scale are 67 Hz-8 kHz, 67 Hz-2 kHz, and 2-8 kHz, respectively. Each piece of test signals lasted for 5 seconds was arranged to obtain a series of comparison pair, such as P-P, P-D1, D1-P, P-D2, and so on, including 10 sets of each same pair (20 sets for the case P-P).

Paired comparison tests were conducted in an anechoic chamber with these stimuli emitted from a loudspeaker monophonically. Five subjects, all had normal hearing, were presented with a series of comparison pair and asked to indicate when they detected the difference.

3. Results and discussion

3.1 Physical properties

The experimental results of impulse (low-pass filtered at 2 kHz) and frequency responses of each reflected sound field represented in full scale, in comparison with the theory, are shown in Fig. 2. The results and findings are almost the same as those obtained in Ref. 3), which are summarized as follows:

There are some particular features due to periodic roughness of the reflector such as irregular peaks and dips at frequencies above the critical frequency f_{min}, and scattered pulses of reflection in the impulse response. The critical frequency f_{min} shown in each graph is the lowest frequency that causes scattering, which depends on both the surface period and angles of incidence, and can be easily estimated from the wave scattering theory.[3] At frequencies below this critical frequency, a surface with any corrugation behaves just like a rigid plane, as shown in the SPL characteristics of each graph. In all cases, theoretical results are in good agreement with experimental data. This means that conducting hearing tests by a convolution technique using the response estimated from the theory may be possible. The details regarding this matter are now under investigation.

3.2 Subjective experiments

In order to clarify whether any difference between specular reflection and diffuse reflection due to periodic roughness can be perceived or not, the data obtained from a percentage of the judgements that detected the difference were statistically analyzed. The results of 95% confidence interval for perception of the difference are shown in Fig. 3, in which a circle symbol represents the mean value. From these graphs, it is seen that in the case P-D2 and P-D3, more than 50% of the judgements detected the difference for all sound sources. The ratio of difference perception increases as the degree of roughness size of the surface corrugation increases.

It can be seen also that in the case P-P, although which is an identical pair, some differential judgements are made. Then one-way analysis of variance was used to explain their subjective significance. The results are shown in Table 1. In all cases of the frequency range, the values of F-statistic are well over the value of F at the 5% significance level ($F_{3,6}(0.05)=3.239$). This means that the differential perception among them is statistically significant.

We also want to know which pairs are different, or more generally, the relation among all pairs. For this purpose, the Tukey multiple-comparison method was

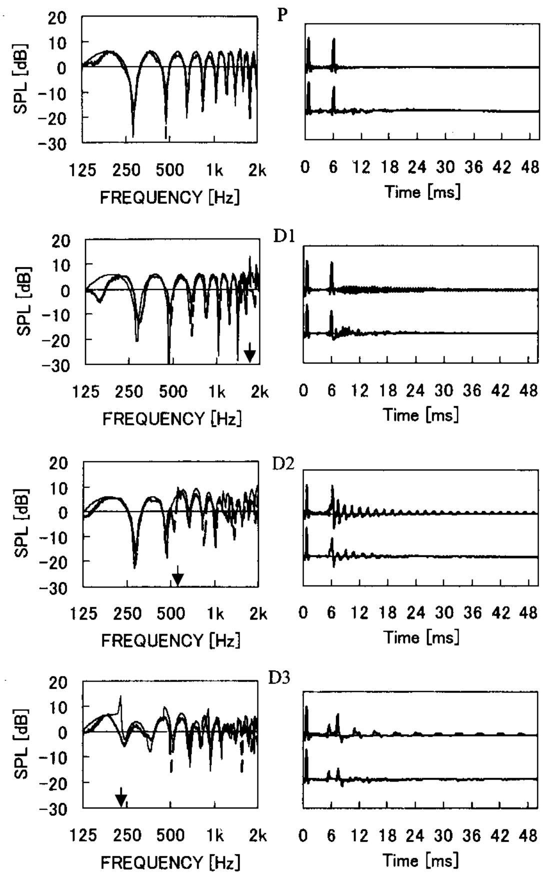

Fig. 2 SPL characteristics and impulse response of the reflected sound fields. ——, Theory; ------, experiment in SPL characteristics, and theory(upper), experiment (low) in impulse responses. Critical frequency f_{min} is represented by a symbol ↓.

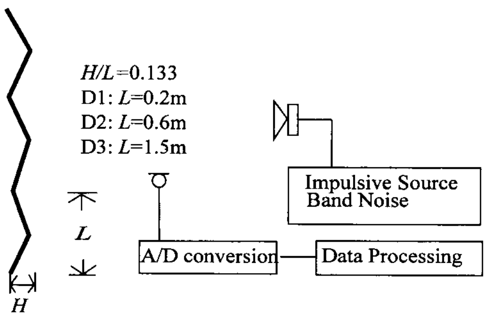

Fig. 1 Experimental setup.

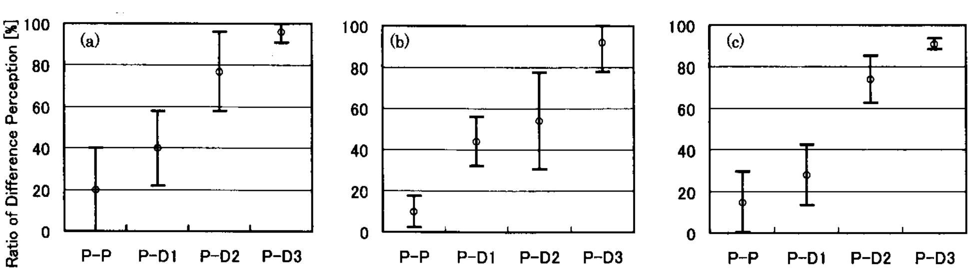

Fig. 3 Confidence interval of 95% for the case (a) 67 Hz-8 kHz, (b) 67 Hz-2 kHz, and (c) 2-8 kHz.

Table 1 Probability of significance.

Frequency range	*F*-statistic	Sig. level
67 Hz–8 kHz	32.853	0.000
67 Hz–2 kHz	36.880	0.000
2 kHz–8 kHz	74.178	0.000

Table 2 Significance level in multiple comparison.

	P-D1	P-D2	P-D3
P-P	0.128	0.000*	0.000*
	0.003*	0.000*	0.000*
	0.171	0.000*	0.000*
P-D1	—	0.003*	0.000*
	—	0.592	0.000*
	—	0.000*	0.000*
P-D2	—	—	0.157
	—	—	0.001*
	—	—	0.051

* The difference is significant at the 5% level.
Upper row: 67 Hz–8 kHz
Middle row: 67 Hz–2 kHz
Bottom row: 2 kHz–8 kHz.

Table 3 Sound level [dBA] at the listening position.

Frequency range	P	D1	D2	D3
67 Hz–8 kHz	62.2	62.6	62.0	61.2
67 Hz–2 kHz	59.7	59.8	61.2	59.7
2 kHz–8 kHz	69.9	70.0	70.0	69.0

used. As can be seen in the results (Table 2), it became clear that our subjective experiences in the reflected sound fields of D2 and D3 clearly differ from those of plane surface. It was also found that the tendency of the differential sensitivity to the degree of diffusion shown in Fig. 2 is statistically significant.

Up to now, we have discussed the differential sensitivity as the total effect of the sound fields including changes in the intensity. There is also a possibility that the change in the intensity may affect the results. To confirm this matter, we measured the sound level [dBA] of each test piece at the listening position, which are shown in Table 3. For the case of noise, it is known that at about 60 dB (sensation level) the relative differential threshold is about 0.4 dB.[4] From this fact, the difference in the intensity of the present case cannot be disregarded. However, from the regression analysis, we could not find any significant relation between the percentage of judgments and the sound-level difference.

4. Conclusions

For the purpose of studying the subjective effects of sound fields caused by periodic-type diffusers, we conducted both measurements of the physical properties and subjective experiments for three kinds of diffusers and an ordinary plane reflector. The fact that the theoretical results are in good agreement with experimental data will enable us to conduct subjective tests based on computer simulation techniques.

For the subjective experiments, a comparison technique was employed, in which subjects were tested in terms of perception of the difference between specular and diffuse reflections. It was shown, from the results of statistical analysis, that as the effective frequency range of diffusion increases, the ratio of differential perception increases. However, there still remains a possibility of dependence on changes in the intensity of sound stimuli in each pair. To get more accurate information, further investigation will be required for this subject, as well as the use of more realistic sound sources, and the use of more sophisticated technique.

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