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SOUND FIELDS AND SUBJECTIVE EFFECTS OF SCATTERING BY PERIODIC-TYPE DIFFUSERS

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Walls and ceilings with quasi-periodic unevenness have often been designed to provide diffuse reflections. As for the shape and the size of this unevenness, with the help of some statistical treatment, it is possible to design effective diffusers with an intended directional pattern; this has great merit in sound fields with respect to spatial aspects. In addition to this spatial property of diffusion, reflection from the surface should not have particular response characteristics that may have a serious effect on our subjective experience. A well-known problem is "colouration" caused by interference between direct and reflected waves, which might create an odd tonal distortion in the case of a surface with periodic unevenness. This may be the reason that creating a periodic series of reflections at the receiver is generally avoided. Two issues need to be addressed: (1) is a periodic structure of reflection a major obstacle in practical use? and (2) to what degree is structural repetition acceptable? Clarification of these matters is necessary in order to design effective diffusers for practical applications. This study examines the physical properties of, and the subjective effects of tonal response to, sound fields caused by scattering from periodic-type diffusers.
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1. INTRODUCTION

Uneven reflecting surfaces are widely used as walls and ceilings in halls and theatres to provide diffuse reflections. For spatial aspects of diffuse reflections, the author introduced an objective measure, named doubly normalized standard deviatation (*DNSD*), which can express the degree of diffusion of a reflecting surface with a periodic profile [1, 2]. With the help of this measure or others [3], quantitative evaluation of diffusion is possible and the design of effective diffuse surfaces can be attained. In addition to this property of diffusion, surface reflection should not have particular characteristics of response that may have a serious effect on the human subjective experience.

Sounds composed of a direct sound followed by a succession of reflections invariably cause a change of spectrum. When this change of timbre is perceived, the tonal effect is referred to as "colouration." Such tonal effect problems have been observed and studied since the time of Huygens, who observed a tonal effect caused by periodic reflections from steps of a staircase [4]. Subsequently, it became clear that only a single reflection caused a serious change of timbre. In 1951, Haas [5] studied the effect of a single reflection on speech intelligibility. Since then, colouration problems have been widely investigated in the field of architectural acoustics as well as psychological acoustics.

Most studies concerned with this topic have been performed by means of artificial sound fields in an anechoic chamber, with loudspeakers fed by direct sound signals and

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reflections with time delay and level differences. These additional loudspeakers were assumed to be image sources owing to reflections from large plane surfaces, i.e., specular reflection has been assumed; in real sound fields, reflectors with uneven surfaces have been widely used to provide diffusion. Barron [6] implicitly suggests use of diffuse reflections for a ceiling reflector to obtain efficient levels of bass sound and to avoid tonal colouration. However, if the reflector has unevenness with any periodic behaviour, most acoustic designers would hesitate to employ this kind of structure [7, 8]. Periodic or quasi-periodic structures have the advantages of easy estimation of diffuse properties, simple method of design, and ready availability. Thus, for problems of diffuse reflections from uneven surfaces with a periodic profile, tentative countermeasures have been proposed including possibilities of both improving the sound fields and the risk of sound quality deterioration. The present study clarifies the following points: (i) does a periodic structure cause different kinds of colouration? and (ii) to what degree is the structural repetition acceptable?

Regarding a similar problem regarding the effect of diffuse reflections on the listener's hearing experience, Cox *et al.* [9], conducted some tests to determine whether diffuse reflections were perceived differently from specular reflections with respect to both tonal and spatial effects. They used simple artificial systems and found reduced effects of diffusion. Torres *et al.* [10] conducted listening tests using source signals convolved with binaural impulse responses computed for a real hall, which includes the first order diffuse reflection approximated by Lambert's law. In their investigation, they addressed both tonal effects and spaciousness and reported audible differences owing to a change in diffusion.

In order to check fundamental aspects of diffuse reflection, listening tests were first conducted to determine differential sensitivity to tonal effect of sound fields caused by periodic-type diffusers. Considering the goals of this research, a case where tonal distortion was estimated to be high was assumed. From this point, diffusers were chosen with a roughness size giving highest diffusion at frequencies above f_{min} under normal incidence of sound. The critical frequency f_{min} is the lowest frequency where the reflector causes scattering. This depends on both the surface period and angle of incidence; it can be estimated easily from the wave scattering theory. Second, judgements of paired comparison tests between specular and diffuse reflections with parameters of both the number of structural repetitions and listening position were analyzed using a statistical procedure. The experiments used a computer simulation technique from the wave scattering theory for reflectors with periodic or quasi-periodic corrugations to make source signals for test stimuli. Validity of this method is also discussed.

2. SUBJECTIVE EXPERIMENTS USING SCALE MODELS AND THEORETICAL PREDICTIONS

2.1. WAVE SCATTERING FROM A PERIODIC SURFACE

A periodic boundary surface with the period L, having an arbitrary profile with grooves parallel to the y-axis is lying in the $x-y$ plane is shown in Figure 1. The incident plane wave with unit amplitude expressed as the velocity potential is described by $\psi_i(x, y, z) = \mathrm{e}^{\mathrm{i}(\alpha_0 x+\beta_0 y-\gamma_0 z)}$. Owing to the periodicity of the surface, in the region above the highest point of the surface, the reflected waves can be expressed as [11, 12]

$$\psi_r(x, y, z) = \mathrm{e}^{\mathrm{i}\beta_0 y} \sum_{n=-\infty}^{\infty} \Psi_n \mathrm{e}^{\mathrm{i}(\alpha_n x+\gamma_n z)}, \tag{1}$$

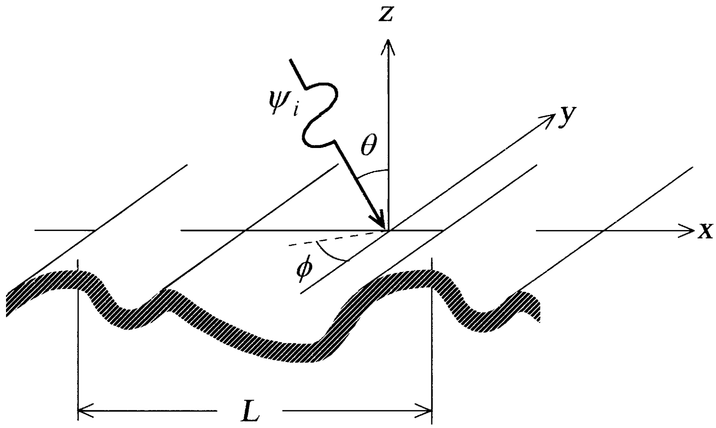

Figure 1. Geometrical configuration and co-ordinate system of a wave scattering model.

where

$$\alpha_n = \alpha_n + 2n\pi/L,$$
$$\gamma_n = [(k^2 - \beta_0^2) - \alpha_0^2]^{1/2}, \quad (2)$$

with $\mathrm{Re}\{\gamma_n\} \geqslant 0$ and $\mathrm{Im}\{\gamma_n\} \geqslant 0$ corresponding to the time factor $e^{-i\omega t}$, and where $\alpha_0 = k \sin\phi \sin\theta, \beta_0 = k\cos\phi\sin\theta$, $\gamma_0 = k\cos\theta$ with and k as the wave number.

The unknown factor Ψ_n can be obtained by solving the boundary integral equation with a fundamental solution for the problem of wave scattering from a periodic boundary surface under an appropriate boundary condition. Owing to the property of a complex quantity, when γ_n is imaginary in equation (1) it does not contribute to the reflected energy, i.e., the reflected waves in the far field can be expressed as

$$\psi_r(x, y, z) = e^{i\beta_0 y} \sum^{N} \Psi_n e^{i(\alpha_n x + \gamma_n z)}, \quad (3)$$

in which N is the number of n when γ_n is real. This expression shows that the reflected sound field can be obtained by a superposition of its component plane waves propagating in the direction determined by two angular factors α_n and γ_n.

An objective measure *DNSD* is defined for evaluating the performance of a diffuser [1], which takes the form

$$DNSD = \frac{\sigma}{\sigma_{max}}, \quad (4)$$

where σ is the standard deviation of the normalized sound intensity I_n of each component wave defined as $I_n = |\Psi_n|^2 / \sum^N |\Psi_n|^2$ and σ_{max} is the maximum value of σ. Thus the value of *DNSD* varies in the range 0–1·0 corresponding to the amount of scatter; $DNSD = 0$ for a uniform diffusion, and $DNSD = 1$ for a specular reflection. In the case of optimum diffusers with intended directional patterns, a similar procedure can be applied, in which the calculation of *DNSD* is performed for the quantity I_n that is weighted for the angles corresponding to the intensity directions emphasized [2].

As can be seen in equation (3), an elemental plane wave of order n propagates towards the direction depending on the factor γ_n with the condition that γ_n is real. Reflection from a surface with diffusion properties means that the value of N is greater than 2. From equation (2), a reflection corresponding to the condition $n = 0$ always occurs, which is the

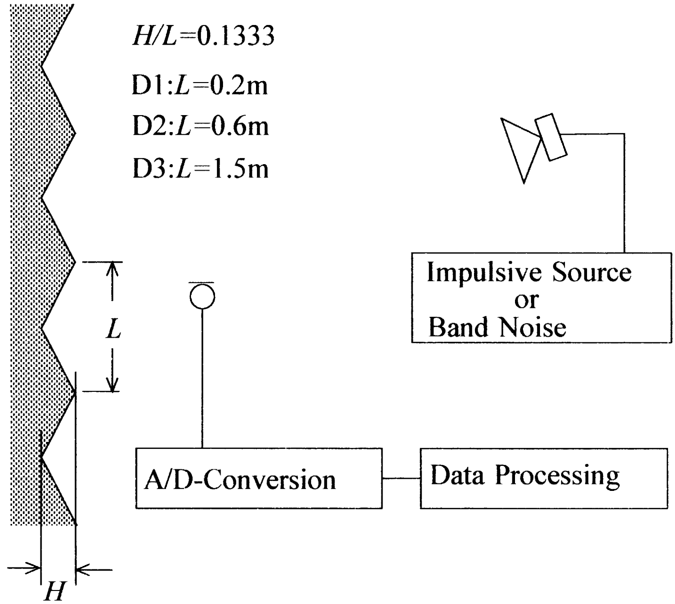

Figure 2. Configuration of the diffuser and the experimental set-up.

specular element. A state of $n = \pm 1$, in which at least one scattering element exists, yields the condition for the lowest frequency, where the reflector causes scattering, which is

$$f_{min} = \frac{c}{L(|\sin\phi|\sin\theta + \sqrt{1 - \cos^2\phi\sin^2\theta})}, \tag{5}$$

where c is the speed of sound.

2.2. EXPERIMENTAL SETUP AND PROCEDURES

The reflectors treated here have three types of triangular profile (D1, D2, D3) having the same roughness ratio ($H/L = 0{\cdot}1333$) with different roughness size; they are shown in Figure 2. These are designed as reflectors of the highest diffusion in the frequency range above f_{min} under normal incidence. Values of f_{min} calculated from equation (5) are 1700, 567, and 227 Hz for diffuser types D1, D2, and D3 respectively. The *DNSD* characteristics, frequency parameter of normalized wave number kL and the frequency corresponding to the surface period of each type, are shown in Figure 3. An ordinary plane surface was also prepared as a reference reflector, designated here as "P".

Subjective experiments were carried out using two methods: using 1/3-scale models of these reflectors set in an anechoic chamber [13] and using simulation models based on a theory of wave scattering from a periodically corrugated surface. In the scale models, each reflector made from plywood had the same size ($1{\cdot}8\,\text{m} \times 3{\cdot}0\,\text{m}$), and had no surface treatment. A receiver was located at 0·9 m (full scale) from the neutral plane of each reflector along the line normal to the plane through the upper edge of the surface. The neutral plane is assumed to be lying at a mid-position between the upper edge of the surface and lower edge of the surface for the corrugated case, and the surface itself for the plane case. In this investigation, the case of normal incidence of a plane wave is assumed; the response at the receiver point includes direct sound. In the scale model experiments in

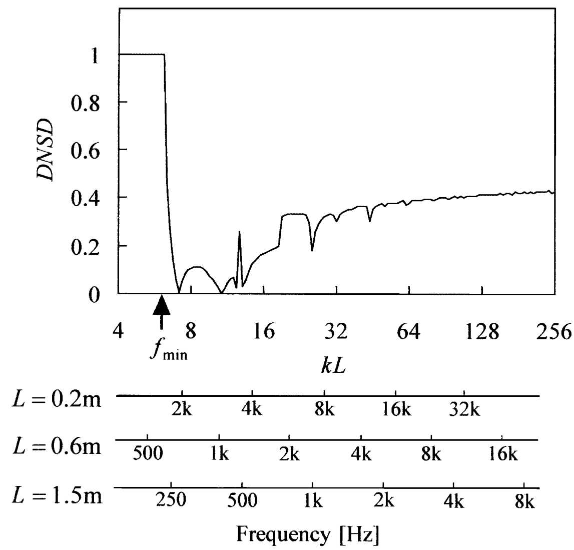

Figure 3. *DNSD* characteristics of the diffuser with a normalized wave numbver *kL*, and the frequency corresponding to each surface period.

order to approximate to plane wave incidence conditions, the loudspeaker was set as far as possible from the reflector.

Physical properties were measured by the procedure outlined in Figure 2. The reflected sound field was evaluated both in terms of sound pressure level (SPL) characteristics comprising reflections including the direct sound, and its impulse response, which were obtained by deconvolution of a source and a FFT technique [14]. Impulsive source recorded on a DAT recorder was used for this purpose.

2.3. LISTENING TESTS

For fundamental problems here, a case must be assumed where subjective measurements are highly sensitive to tonal change. Therefore, three kinds of band-limited pink noise were used as source signals: wide band-noise, band-noise at low and mid-frequencies, and band-noise at high frequencies. In the experiments using scale models, these signals were fed into a loudspeaker (FOSTEX S100: 10 cm cone type, full range) through a graphic equalizer to yield a uniform spectrum. The reflected sound fields caused by the 1/3-scale model of each reflector were recorded on a DAT recorder. These were transferred to a PC to convert the data into those corresponding to the real frequency range. Frequencies in full scale were 67 Hz–8 kHz, 67 Hz–2 kHz, and 2–8 kHz, respectively.

Each test signal segment, lasting about 5 s, was arranged to obtain a series of comparison pairs, such as P–P, P–D1, D1–P, P–D2, and so on, including 10 sets of identical pairs (20 sets for the case P–P). Paired comparison tests using scale models were conducted in an anechoic chamber with these stimuli emitted from a loudspeaker (DIATONE DS-500: two-way type) monophonically. Five subjects, all with normal hearing, were presented with a series of comparison pairs and asked to indicate when they detected a difference. An audiometer (RION AA-56) was used to check normal hearing.

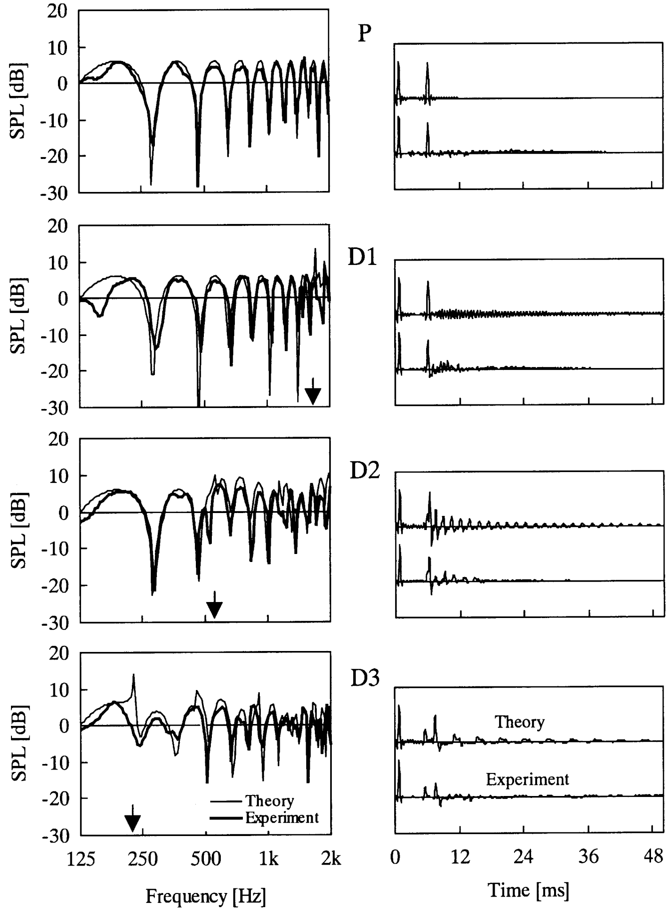

Figure 4. SPL characteristics and the impulse response of the reflected sound fields generated by each type of the diffuser. Critical frequency f_{min} is represented by a symbol ↓.

In experiments using theoretical (computer simulation) models, stimuli were made from convolution of the calculated impulse response and noise signals of the same bands and presented (two-ear monophonically) by a headphone (SONY MDR-Z900: closed type). In all subjective experiments, the sound level of paired stimuli was adjusted to the same level.

2.4. RESULTS AND DISCUSSION

Figure 4 shows 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. Results and findings are almost identical to those obtained in reference [14], which are summarized as follows. There are some particular features due to periodic reflector roughness, 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 estimated from equation (5), where the reflector causes scattering. At frequencies below this critical frequency, a surface

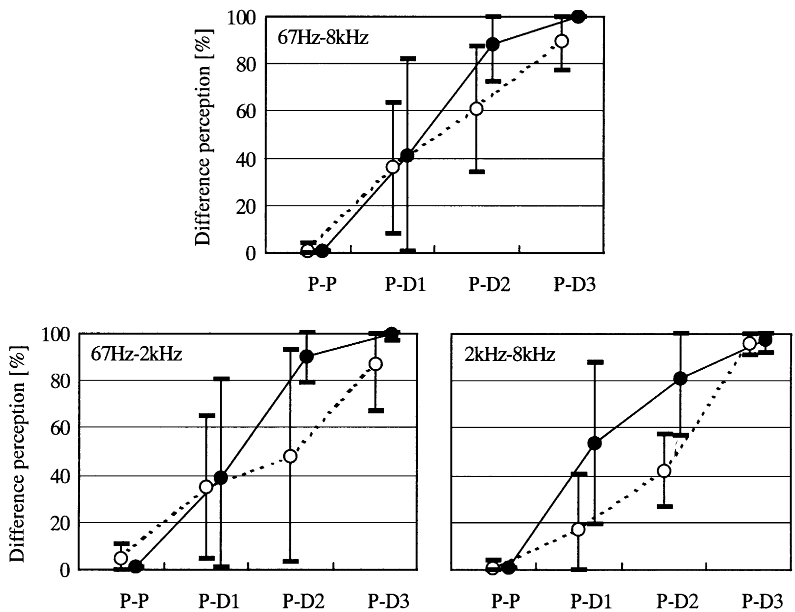

Figure 5. Difference perception for tonal effects of scattering: –○–, using scale models; –●–, theoretical models.

with any corrugation behaves just like a rigid plane as shown in SPL characteristics of each graph.

The purposes of this research focuses on deviation of diffuse characteristics from regular comb-filter characteristics. From such a viewpoint, theoretical results seem to agree well with experimental data. This means that a convolution technique using the response estimated from theory is potentially useful for conducting listening tests. However, some differences between theory and experiment result from two differences between infinite and finite conditions. One is the difference in dimension, i.e., an infinite dimension is assumed in theory, while the dimension is necessarily finite ($1{\cdot}8\,\mathrm{m} \times 3{\cdot}0\,\mathrm{m}$) in the experiment. This influence creates a general tendency towards increased error as frequency decreases. Another difference is that of periodic condition. In theory, true periodicity (infinite repetitions of the period) is assumed, but quasi-periodicity is absolutely necessary in the experiment. Such an insufficient periodic condition in the experiment would be a main cause for the absence of a sharp in the SPL characteristics. From these points, it is necessary to check the effect of difference on auditory sense.

To check this and to clarify whether any difference can be perceived as a tonal effect between specular and diffuse reflections due to periodic roughness, data obtained from judgement percentages of those who detected the difference were statistically analyzed. Results with a 95% confidence interval for difference perception are shown in Figure 5; a circle symbol represents the mean value. In tests using scale model measurements, the only difference in the type of reflector in each pair is that due to the corrugation profile. Other factors are negligible. However, a slight effect due to difference in edge-diffraction effect may exist. For tests using theoretical calculations, differences of perception in comparing two types of each pair are caused solely by different reflector types.

These graphs show that, in the case P–D2 and P–D3 for the theoretical models, subjects detected a difference for more than 80% of judgements for all sound sources. The ratio of difference perception increases as the degree of surface corrugation roughness increases.

Experiments using theoretical models can further clarify the difference over scale model experiments.

Also, in the case of P–P, although it is an identical pair, some differential judgements are made. For them, one-way analysis of variance was used to explain their subjective significance. Results (not shown here) showed that in all frequency ranges, F-statistic values are well over the value of F at the 5% significance level. Differential perception among them is statistically significant.

We also want to determine the relation among all pairs, and more specifically, which pairs are different. The Tukey multiple-comparison method was used for this purpose. Results (not shown here) showed that subjective experiences for the reflected sound fields D2 and D3 clearly differ from those of a plane surface. It was also found that the tendency of differential sensitivity to tonal change associated with the degree of diffusion shown in Figure 5 is statistically significant.

3. THE EFFECT OF FINITE CORRUGATION OF THE SURFACE

Some particular features of the sound field caused by a diffuser with periodic roughness are specified as follows [14]:

(a) deviations from regularity of frequency response, i.e., irregular peaks and dips with irregular interval in frequency characteristics;

(b) scattered pulses of reflection in impulse response at around an arrival time estimated from the geometrical path length and temporal structure disorder which follows them;

(c) sharp peaks appearing in frequency characteristics which correspond to a series of attenuating pulses with a regular interval in the impulse response.

Features (a) and (b) are closely related to the reflector period and roughness. Even a few repetitions of corrugation (quasi-periodic roughness) can cause these effects. Feature (c) can be interpreted as a similar phenomenon to that which occurred in the case of a source–receiver system in parallel walls. This phenomenon may be caused by an infinite repetition of corrugation (true-periodic roughness) of the diffuser. To confirm these findings, the sound field caused by a triangular-type corrugation of finite repetition with $L = 0{\cdot}6$ m (D2-type) set on a rigid plane of infinite extent was calculated by a method based on the Helmholtz–Kirchhoff integral formula. Figure 6 shows results for a case with 11 repetitions and a receiving point 1 m away from the neutral plane of the surface in comparison with the infinite repetition (true-periodic) case. Other cases (3, 7, and 11 repetitions) are shown in Figure 7, in which the receiver distance is 3 m. In this case, the effect of edge diffraction at corrugated borders generally becomes efficient as frequency

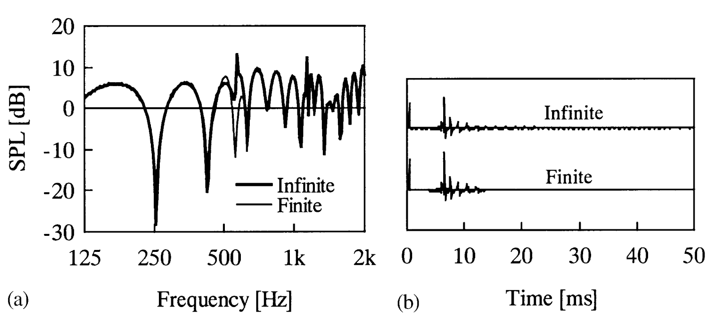

Figure 6. Comparison between infinite and finite case of the diffuser. SPL characteristics (a) and the impulse response (b).

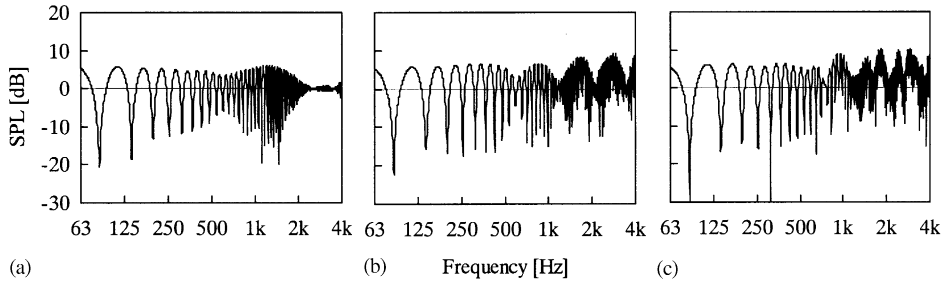

Figure 7. Variation of SPL characteristics with the number of repetitions of the corrugation: 3-repetitions (a); 5-repetitions (b); 11-repetitions (c).

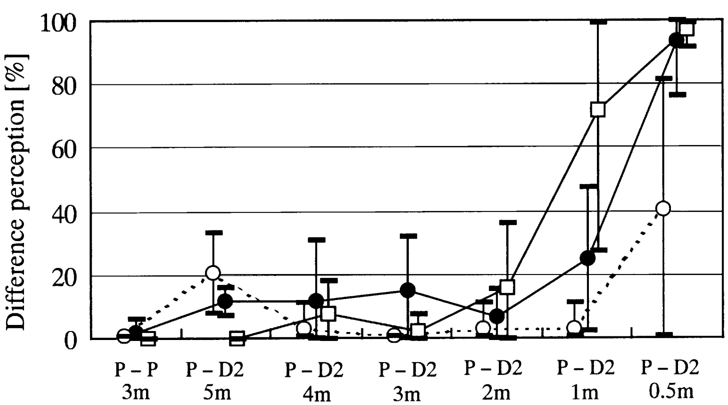

Figure 8. Difference perception for tonal effects of scattering obtained by paired comparison tests for D2-type diffusers in comparison with the specular reflection *P*. The source signals of the stimuli are band-limited pink noise: –○–, 63–500 Hz;–●–, 500 Hz–2 kHz; –□–, 2–6·3 kHz.

decreases; it becomes less efficient as the number of repetitions increases. Then, from results, irregularities occurring at frequencies above 500 Hz in SPL characteristics seem to be little affected by edge diffraction.

These results indicate that no sharp peaks occur in the finite-repetition case; a prediction theory for critical frequency of scattering derived from the infinite theory can also be applied to the practical finite-repetition case. Problems concerning features (a) and (b) remain in the finite-repetition case. To investigate effects of these features on human hearing, some subjective experiments were conducted by means of a convolution technique using theoretical models. First of all, listening tests were conducted for a D2-type diffuser ($L = 0{\cdot}6$ m, $f_{min} = 567$ Hz) for 3 repetitions with a receiver distance parameter (0·5, 1,. . .,5 m) from the surface along the normal line through the surface top in the centre of corrugation. In the case of a P–P pair, the receiver distance was 3 m away from the surface. Figure 8 shows results of paired comparison tests for 95% confidence intervals for perception of difference between specular and diffuse reflection. Source signals are three types of band-limited pink noise; the frequencies are low (63–500 Hz), middle (500 Hz–2 kHz), and high (2–6·3 kHz). As the observer approaches the reflector, he can detect difference more easily. As predicted from the critical frequency of scattering, at frequencies below this value, the difference becomes imperceptible. At a receiver point more than 3 m away from the surface, the effect on our auditory sense at high frequencies

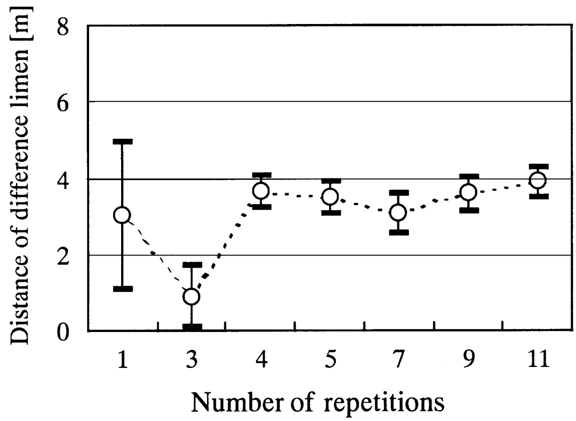

Figure 9. Distance of difference limen versus the number of repetitions of the corrugation, in the case of normal incidence.

decreases. Based on these findings, to find the receiver distance where subjects detect a difference for more than 50% of judgements between specular and diffuse reflections, the same tests were conducted with the stimuli of pink noise at mid-frequencies for various numbers of corrugation repetitions. Such a maximum distance is defined here as "distance of difference limen". Percentages of judgements obtained by paired comparison tests were analyzed using best-fit cumulative normal distribution [15]. From results shown in Figure 9, where a receiver is located more than 4 m away from the reflector in the case of normal incidence, it is hard for the observer to perceive tonal difference between specular and diffuse reflections.

4. CONCLUSIONS

For studying tonal effects of sound fields caused by periodic-type diffusers on our hearing sense, experiments based on scattering theory for a corrugated surface of infinite and finite extent were conducted together with scale model experiments. Discussion of physical properties of the sound field and results of subjective experiments yielded the following conclusions:

- Fundamental response of the sound field caused by periodic-type (quasi-periodic) diffusers can be predicted by an ordinary theory of scattering from a surface with periodic corrugation.
- As the range of effective diffusivity in frequency scale increases, the ratio of perception of difference between specular and diffuse reflections increases.
- As the listening position gets closer to the diffuser, subjective tonal effects of response increase.
- For periodic-type diffusers having a roughness size that gives highest diffusion at frequencies above 567 Hz under a normal sound incidence, the distance of difference limen is about 4 m within the range up to 11 corrugation repetitions.

The receiver distance of 4 m for barely audible difference implies that reflection delay is about 24 ms, which is lower than the perception threshold of colouration for a single specular reflection [16]. This may be a key to identify the special effect of colouration due to the periodic structure of the reflection. Future study will be necessary to examine this matter in relation to the effect of oblique incidence and the effect of many more repetitions reaching almost true periodicity, to clarify safety conditions for using periodic structures of reflection, and to identify spatial effects of diffuse reflections.

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