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A Study of a Comfortable Sound Design for Higher-Frequency Noise based on Auditory Masking

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ABSTRACT

Higher-frequency noises based on the wind noises or air-conditioning noises were generated, and “artificial source” for masking them was designed automatically on the basis of “auditory masking”. The higher-frequency noises consist of three kinds of frequency band and seven kinds of centre frequency ranging from 2 to 6 MHz. The artificial sources are designed by calculating the frequency band and the power level that can mask the higher-frequency noises according to the theory of auditory masking. A “comfortable” sound is then created by adding the artificial source to the target noise. Two evaluation experiments using the higher-frequency noises with added artificial source were carried out. One is a relative evaluation to evaluate whether an unpleasant feeling is reduced by addition of artificial source. In this evaluation, the subjects compared higher-frequency noises before and after the artificial source addition. The other experiment is an absolute evaluation to evaluate each sound source according to a rating scale of five grades. The results of the two evaluation experiments, confirm that the narrower the higher-frequency noise band becomes, the more the unpleasant feeling of the higher-frequency noises could be reduced without reducing sound pressure level regardless of the centre frequency of the higher-frequency noises.

INTRODUCTION

Methods for noise suppression based on noise-power reduction are generally employed to overcome noise problems the world over. It is essential to reduce loud noises such as that cased by traffic, construction sites, and so on. However, people may often perceive unpleasant feelings in quiet surroundings even though the noises are low-power ones. One the other hand, it has also been reported that quiet surroundings without a noise of certain power cause an unpleasant and anxious feeling. It is considered that such low-power noise problems cannot be solved only by reducing the sound-pressure level of the noise. Our research thus focuses on reducing unpleasant feelings without reducing noise power by adding “artificial sources” on the basis of “auditory masking.” The auditory masking is phenomenon that one sound is drowned out by another sound and has been utilized in various methods [1] [2]. In the present study, we studied a method for designing artificial sources, which can be used to mask unpleasant noises and design a comfortable sound according to the theory of auditory masking. We tried to automatically design artificial sources for masking unpleasant noises. The purpose of this study is to reduce unpleasant feelings by adding the designed artificial sources to the noise. Firstly, we analyzed the spectrum of the noise. Secondly, we calculated the frequency band and power level suitable for masking the higher-frequency noises. We then designed the artificial sources according to the calculated values. We added the designed artificial sources to the noise, and experimentally evaluated the effect of these sound sources. We generated white noise limited by band pass filter as the intended higher-frequency noise. This higher-frequency noise has power in a particular frequency band found to be related to unpleasant feelings in a conventional study [3]. We also designed artificial sources from pink noise processed by band pass filter. The spectrum power of pink noise is in inverse proportion to the frequency, thus pink noise is called 1/f noise. Sound that has this 1/f feature, for example, the sound of flowing water, and ocean waves, is felt pleasant. We therefore, designed the artificial sources based on pink noise in order to reduce the unpleasant feelings. Moreover, we experimentally evaluated the level of unpleasantness of the higher-frequency noises before and after the addition of the artificial sources. The experimental results validated the utility of the proposed method based on auditory masking.

A STUDY OF AUDITORY MASKING

Auditory masking is phenomenon that one sound is drowned out by another sound. This phenomenon is defined as the threshold of hearing one sound being increasing by the other sound. In this study we used the theory and equation based on auditory masking.

Critical band

The certain frequency band that can influence the threshold of hearing one sound masked by another sound is called the “critical band”. The critical band is uniquely determined by the frequency of the masked sound and given by the following approximation [4].

$$CB = 25 + 75(1 + 1.4(\frac{f}{1000})^2)^{0.69}. \tag{1}$$

Here, CB stands for critical band, and f is the frequency of masked sound. For example, the threshold of hearing a sound with a frequency of 1000 Hz can only be increased by a noise with a bandwidth of about 162 Hz and centred on 1000 Hz. If the power level except for the critical band increases, the threshold of hearing the masked sound remains constant. This phenomenon is referred to as an auditory filter. A recent study is on an accurate estimation of an auditory filter [5], and has showed that an auditory filter has asymmetric and nonlinear properties. However in the present study we used Eq. (1) to simply calculate the critical band and design the artificial sources.

Method for calculating power level of artificial sources

It is important to calculate lowest level for masking a noise because the artificial sources should be designed to have the lowest power possible so as to comfortable surroundings. Equations (2) and (3) describe the case that white noise masks pure sound [6].

$$M = \beta_m - \beta_0, \tag{2}$$

$$10^{\beta_m/10} = 10^{(B_N+\kappa)/10} + 10^{\beta_0/10}. \tag{3}$$

Here, M is masking level, β_m is the threshold of hearing a masked pure sound, β_0 is the threshold of hearing unmasked pure sound, B_N is the power level of white noise with frequency of 1 Hz, and κ is a unique value depends on the frequency of pure sound. According to Eq. (3),

$$10^{(\beta_m-\beta_0)/10} = 10^{(B_N+\kappa-\beta_0)/10} + 1, \tag{4}$$

then $B_N + \kappa - \beta_0$ is defined as Z

$$10^{M/10} = 10^{Z/10} + 1. \tag{5}$$

It is therefore possible to approximately equate M with Z. Moreover, κ for f Hz is expressed as follows,

$$\kappa = 10\log_{10}\Delta f, \tag{6}$$

Where Δf is the critical band for f Hz. According to $M = Z$,

$$\begin{aligned} \beta_m - \beta_0 &= B_N + \kappa - \beta_0, \\ \beta_m &= B_N + \kappa, \\ &= B_N + 10\log_{10}\Delta f, \end{aligned} \tag{9}$$

$$B_N = \beta_m - 10\log_{10}\Delta f. \tag{10}$$

Thus, if the power level of the noise to be masked is x dB, the noise can be masked subject to $x < \beta_m$. For the purpose of designing a comfortable sound, the artificial source should have a lower power level. B_N (the power level of an artificial sorce with a frequency of 1 Hz for masking a noise of x dB) can therefore be calculated by Eq. (11) as follows.

$$B_N = x - 10\log_{10}\Delta f. \tag{11}$$

PROPOSED METHOD FOR DESIGNING ARTIFICIAL SOURCES

The higher-frequency noises

Higher-frequency noises were generated from white noise limited by a band pass filter. The higher-frequency noises consist of three kinds of frequency band, which is 100, 200, and 350 Hz. These frequency bands were generated, respectively, by changing the order of the band pass filter with N of 128, 256, and 512. The higher-frequency noises also consist of seven kinds of centre frequency, which is 2000, 3000, 3500, 4000, 4500, 5000, and 6000 Hz. A total of 21 higher-frequency noises were generated. Figure 1 shows the three higher-frequency noises, whose centre frequency is 3500 Hz.

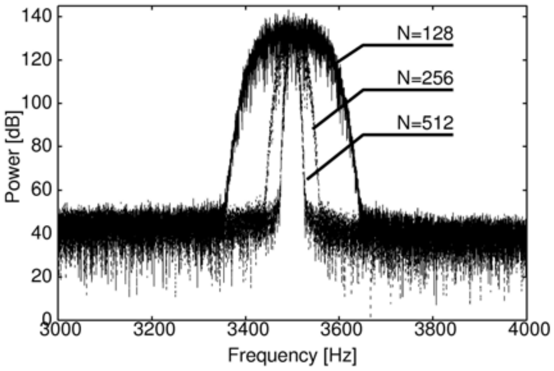

Figure 1. Higher-frequency noises with centre frequency of 3500 Hz

Artificial sources

Artificial sources based on the spectrum of the higher-frequency noises were designed by calculating the frequency band and power level at which the higher-frequency noises are masked. The power spectrum of the higher-frequency noise is plotted in Figure 2 as line (A), and values calculated from Eqs. (1) and (11) is plotted as dotted line (B). The dot plot makes it possible to calculate the frequency band and the power level that can mask the higher-frequency noises.

First, pink noise is generated. Figure 2 shows that the artificial sources require noise about 120 dB to mask the higher-frequency noise. However, after the frequency band is determined, the artificial source that can mask the higher-frequency noise can be obtained by adjusting the power level of the pink noise. Second, the highest and lowest frequency at which the power level is more than a certain level is calculated from the dot plots. In this way, according to the calculated frequency, pink noise that is processed by the band pass filter can be designed. The power level adjusted for the pink noise can thus defined as that of the artificial source to mask the higher-frequency noise. The power spectrum of the artificial noise obtained from Fig. 2 is plotted as line (C).

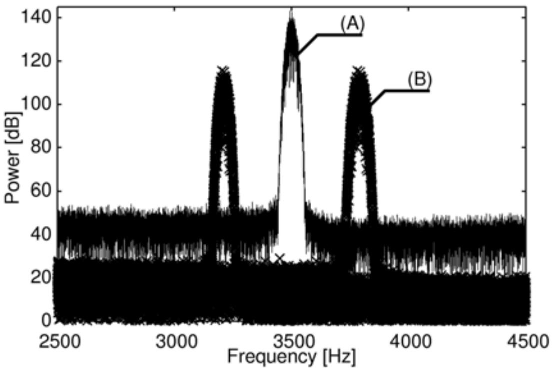

Figure 2. Power spectrum of higher-frequency noise (A) and plotted as dotted line (B)

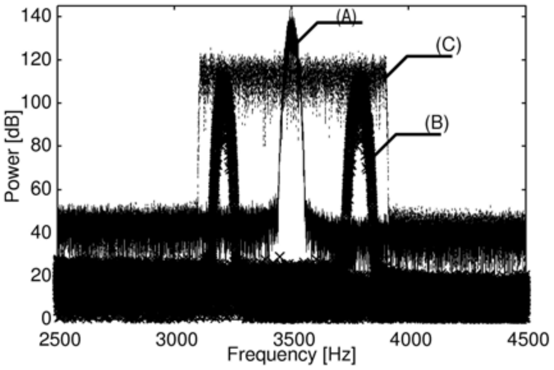

Figure 3. Artificial source obtained from Fig. 2

Finally the characteristic of a comfortable sound is obtained by adding the artificial sources to the higher-frequency noises. Accordingly, the following equation holds,

$$z(t) = x(t) + \alpha(h(t) * y(t)), \tag{12}$$

where t is time, $x(t)$ is the higher-frequency noise, $z(t)$ is the noise after adding the artificial noise, $h(t)$ is a parameter of the band pass filter, $y(t)$ is pink noise for the artificial sources, and α is a parameter for adjusting the power level of the pink noise processed by the band pass filter. The asterisk stands for convolution.

EVALUATION EXPERIMENTS

The effectiveness of the sound-source masking by using x(t) and z(t) was evaluated in two experiments in a soundproof room with background noise of less than 30 dB. One experiment is evaluated relatively whether an unpleasant feeling was reduced, and the other experiment evaluated the absolute value for the unpleasantness of each sound source.

Subjects

Ten students (5 females and 5 males) participated in the experiments. No subjects had any hearing problems.

Relative-evaluation experiment

Subjects compare higher-frequency noises before and after the artificial source addition (described in terms of parameters x(t) and z(t) above) and evaluate these sound sources according to the following three choices.

1. Unpleasantness of the first source is less than that of the second source.

2. Unpleasantness of both sources is the same.

3. Unpleasantness of the second sources is less than that of the first source.

We presented 42 sources (21 × 2) as a set of two sources before and after the artificial source addition. The order of the two sources was unknown to the subjects. The subjects can freely try to listen to the sources repeatedly.

Absolute-evaluation experiment

The subjects evaluate each sound source according to rating scale with the following five grades.

1. Not at all bothered or annoyed

2. A little bothered or annoyed

3. Moderately bothered or annoyed

4. Quite a lot bothered or annoyed

5. Very much bothered or annoyed

We presented the sound sources from the set of 42 sound sources. The sound sources were randomly reproduced. The subjects listen to all the sound sources randomly five seconds, followed by a silent pause of three seconds. They then evaluate each sound sources individually. This experiment is different from the relative-evaluation experiment in that the subjects are not able to listen to the sound sources repeatedly. This experiment was carried out twice for each subject to compensate time variability.

Result and discussion

Relative-evaluation experiment

Tables 1 to 3 list the results of relative-evaluation experiment. The frequency band of the higher-frequency noise is 350 Hz for table 1, 200 Hz for Table 2, and 100 Hz for Table 3. In these tables, values 1 to 3 represent the choices of the relative evaluation experiment.

Value 1. Unpleasantness of source before the artificial source addition is less than that after the artificial source addition.

Value 2. Unpleasantness of both sources is the same.

Value 3. Unpleasantness of source after the artificial source addition is less than that before the artificial source addition.

The frequency in the left columns is the centre frequency of the higher-frequency noise. The number in each column means the number of subjects who made that choice.

According to the results of the relative-evaluation experiment, in the case that the subjects compared with the higher-frequency noises before and after the artificial sources addition, the narrower the higher-frequency noise band becomes, the more unpleasant feeling can be reduced.

According to Tables 1 to 3, the narrower the higher-frequency noise band becomes, the more the subjects chose value 3. In addition, since the number of subjects who choice value 2 decreased, the narrower higher-frequency noise band becomes, and the more the clearly subject felt the difference between before and after the artificial source addition. However we can't confirm the significant difference by the centre frequency of higher-frequency noises.

Table 1. Results of relative-evaluation experiment with higher-frequency noise band of 350 Hz.

Centre frequency	Value 1	Value 2	Value 3
2000Hz	4	2	4
3000Hz	3	3	4
3500Hz	2	3	5
4000Hz	3	2	5
4500Hz	4	3	3
5000Hz	3	2	5
6000Hz	2	6	2

Table 2. Results of relative-evaluation experiment with higher-frequency noise band of 200 Hz.

Centre frequency	Value 1	Value 2	Value 3
2000Hz	4	0	6
3000Hz	3	2	5
3500Hz	4	0	6
4000Hz	2	3	5
4500Hz	1	2	7
5000Hz	1	2	7
6000Hz	3	3	4

Table 3. Results of relative-evaluation experiment with higher-frequency noise band of 100 Hz.

Centre frequency	Value 1	Value 2	Value 3
2000Hz	3	0	7
3000Hz	2	0	8
3500Hz	1	2	7
4000Hz	3	0	7
4500Hz	2	2	6
5000Hz	2	0	8
6000Hz	2	1	7

Absolute-evaluation experiment

Figures 4 to 6 show the results of the absolute-evaluation experiment. Figure 4 represents the case that the frequency band of the higher-frequency noise is 350 Hz, Fig. 5, 200 Hz, and Fig. 6, 100 Hz. In these figures, the horizontal axis plots the centre frequency of the higher-frequency noises, and the vertical axis plots the unpleasantness based on a "mean opinion score (MOS)". In this study, the lower the MOS value, the lower the feeling of unpleasantness. The solid line represents the average and variance of the evaluated noise before addition of the artificial source. The dashed line is those values after addition of the artificial sources. The numbers in rectangles are the difference the MOS values between before and after the artificial source addition.

According to the results of the absolute-evaluation experiment, since the MOS decrease in each centre frequency, the unpleasant feeling can be reduced. In addition, the narrower the higher-frequency band is, the wider the difference between unpleasantness before and after the artificial source addition. However we can't confirm the significant difference by the centre frequency of higher-frequency noises.

In other words, absolute-evaluation experiment confirmed the same tendency as that found in the relative-evaluation experiment. It is concluded that the unpleasant feeling can be reduced by adding artificial source to the higher-frequency noise without reducing the sound pressure level regardless of centre frequency of the higher-frequency noises.

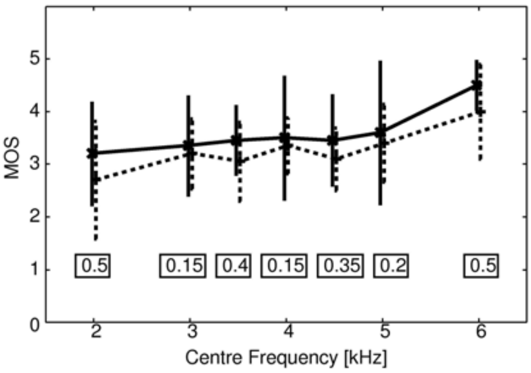

Figure 4. Results of absolute-evaluation experiment with higher-frequency noises band of 350 Hz

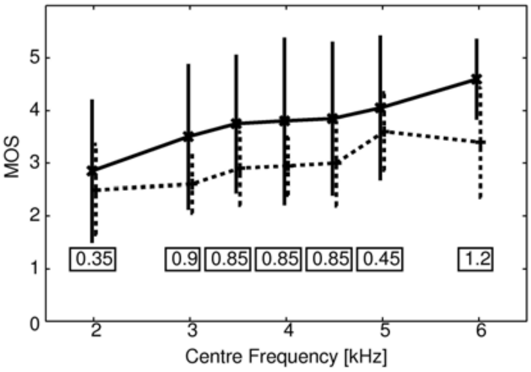

Figure 5. Results of absolute-evaluation experiment with higher-frequency noises band of 200 Hz

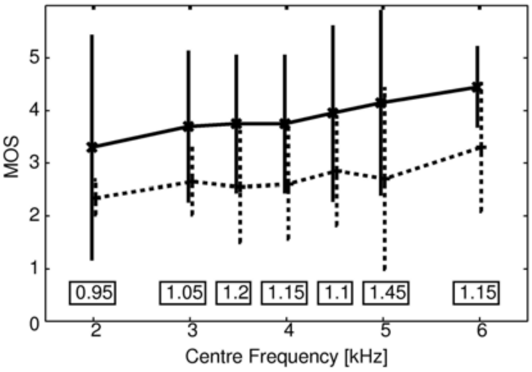

Figure 6. Results of absolute-evaluation experiment with higher-frequency noises band of 100 Hz

CONCLUSIONS

We proposed the method to design the artificial sources on the basis of auditory masking for reducing unpleasant feelings without reducing sound pressure level. The theory and equation of auditory masking was used to calculate the frequency band and the power level that can mask higher-frequency noises and to design the artificial sources. The purpose of this study was reducing unpleasant feeling by adding the artificial sources to the higher-frequency noises. In order to validate the effectiveness of the proposed method, two evaluation experiments were carried out. One is the relative evaluation experiment, and the other is the absolute evaluation experiment. As the result of relative evaluation experiment, we confirmed that the narrower the higher-frequency noise band becomes, the stronger the effect of the proposed method. This tendency was also confirmed by the absolute-evaluation experiment not only by the relative-evaluation experiment. These results indicate that the unpleasant feelings of the higher-frequency noises can be reduced without reducing the sound pressure level regardless of the centre frequency of the higher-frequency noises. In particular, it was confirmed that the higher-frequency noise with a narrower band effectively reduces the unpleasant feelings. In our future work, we will try to extend the proposed method and additionally study it. In this study, we only validated that it is possible to reduce unpleasant feelings without reducing sound pressure level. Accordingly, we should continue studying ways to further reduce unpleasant feelings, for example, by studying the way to design the artificial source.

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