# An active unpleasantness control system for indoor noise based on auditory masking


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***Abstract*—Noise reduction methods have been proposed for various large noises. However, we often perceive unpleasant feeling even if the small noise arises in quiet indoor environments. To overcome this problem, we focus on auditory masking which is phenomenon that human can't hear a target noise by composite sound. In this paper, we propose the unpleasantness reduction method based on auditory masking for indoor noise. In the proposed method, we discuss how to design the artificial sound for noise control. Furthermore, we develop an active unpleasantness reduction system based on the proposed method. As a result of evaluation experiments, we could confirm the effectiveness of the development system.**


## I. Introduction

Unpleasant noise which often interferes with our lives is a huge social problem. Therefore, various methods have recently been studied to overcome noise problems [1]. Methods for noise suppression based on noise power reduction are generally used to overcome noise problems all over the world [2]. It is essential to reduce loud noises such as those caused by traffic, construction sites, and so on. Methods for noise suppression have been proposed in recent studies, and many products that intend to reduce noise power are in the marketplace. However, in quiet surroundings, we often perceive noise as unpleasant even if the noise is low-power. In particular, in the case of an indoor noise including high frequency noise such as that from air-conditioning units, this tendency is remarkable [3]. It is considered that such low-power noise problems cannot be solved by only reducing the sound pressure level of noise. Our research is thus focused on reducing sound that causes unpleasant feelings not by reducing the noise power but by adding artificial sources to noise on the basis of auditory masking. Auditory masking is one of the auditory properties of the human ear, and it is the phenomenon that one sound is drowned out by another sound. It has been studied with various methods [4][5]. For this paper, we designed the artificial sources for indoor noise with small-power recorded in real environments on the basis of auditory masking. This indoor noise had a peak frequency in the frequency band related to unpleasantness [3]. First, the spectrum of the noise was analyzed, and the peak frequency of the noise was detected in order to design the artificial source. Second, the critical band was calculated in order to mask the peak frequency of the indoor noise. The artificial source was designed on the basis of comfortable sound and the calculated critical band. For this paper, we used pink noise, the sound of running water, and the sound of running water sound weighted on the basis of 1/f as the comfortable sound. Finally, the designed artificial source was emitted to a noisy area in order to reduce the unpleasantness of that noise with auditory masking. Then, an evaluation experiment was carried out to confirm the effectiveness of the designed artificial source. Moreover, we developed an active unpleasantness reduction system based on the proposed method.

## II. Auditory Masking

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

### A. Critical Band

The specific 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 Eq. (1) [6].

$$\mathrm{CB} \;=\; 25 + 75\left(1 + 1.4\left(\frac{f}{1000}\right)^2\right)^{0.69}, \tag{1}$$

where CB stands for critical band, and $f$ is the frequency of the masked sound. For example, the threshold of hearing a sound with a frequency of 1000 [Hz] can only be increased only by a noise with a bandwidth of about 162 [Hz] that centers on 1000 [Hz]. Even if the sound pressure of the band except for the critical bandwidth increases, the threshold of hearing the sound with a frequency of 1000 [Hz] remains constant. This phenomenon is referred to as the auditory filter. A recent study, on the accurate estimation of auditory filters has asymmetric and nonlinear properties [7]. In this study, we needed to simply and rapidly calculate the critical band and design the artificial sources. We therefore used Eq.(1) to calculate the critical band.

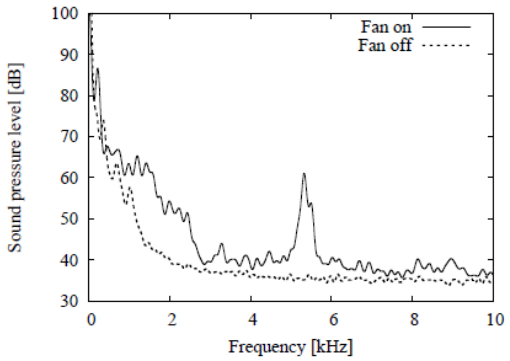



Fig. 1. Spectral envelopes of indoor noise in bedroom with and without ventilatory equipment

TABLE I
CONDITIONS FOR SUBJECTIVE EVALUATION EXPERIMENT

| Experiment conditions | |
|---|---|
| Environment | Soundproof room (19.0 dBA) |
| Loudspeaker | DIATONE DS-7 |
| Subjects | 6 subjects (Two females and four males) |
| **Sound sources** | |
| Number of evaluated sources | 6 |
| Sampling rate | 48000 Hz |
| Quantization bits | 16 bit |

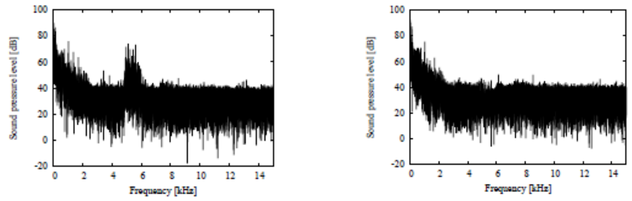
## III. UNPLEASANT FREQUENCY BAND OF INDOOR NOISE

### *A. Preliminary Experiment for Examining Unpleasant Frequency*

In this paper, we used ventilatory equipment noise in a bedroom as the indoor noise in a quiet environment. Figure 1 shows the spectral envelopes of indoor noise in the bedroom with and without ventilatory equipment. In this figure, the horizontal axis represents the frequency, and the vertical axis represents the power level. As shown in Fig. 1, when the ventilatory equipments was operated, an intensive increase of power was confirmed at a frequency of around 5 kHz. Therefore, we presumed that this frequency with a peak frequency around 5 kHz was an unpleasant frequency for indoor noise. We then carried out a preliminary experiment in order to examine whether this peak frequency was unpleasant. In the preliminary experiment, we evaluated the discomfort level of evaluation sounds. Table I shows the preliminary experimental conditions. We evaluated two sounds extracted from original indoor noise as evaluation sounds. Moreover, we also evaluated the evaluation sounds that were designed by emphasizing and suppressing the sound pressure level of an original indoor noise at 4.5 $\sim$ 5.5 kHz. The power spectra of each evaluation sound are shown in Fig. 2. Subjects were asked to rate the discomfort level of the indoor noise with and without peak frequency on the basis of Table II after one minute of listening.

TABLE II
RATING SCALE FOR PRELIMINARY EXPERIMENT

| | |
|---|---|
| 5 | Very annoyed |
| 4 | Quite annoyed |
| 3 | Moderately annoyed |
| 2 | A little annoyed |
| 1 | Not at all annoyed |




(a) Emphasized at 4.5 $\sim$ 5.5 kHz (b) Suppressed at 4.5 $\sim$ 5.5 kHz

Fig. 2. Power spectra of indoor noise that were emphasized and suppressed at a power on 4.5 $\sim$ 5.5 kHz

### *B. Preliminary Experimental Results*

Figure 3 shows the results of the preliminary experiment. In this figure, the horizontal axis represents each evaluation sound, and the vertical axis represents the unpleasantness based on the mean opinion score (MOS) [8]. As a result, indoor noises that were emphasized at a power of 4.5 $\sim$ 5.5 kHz caused much discomfort. In comparison, indoor noises that were suppressed at a power of 4.5 $\sim$ 5.5 kHz caused less discomfort. In this paper, the peak frequency of indoor noise is therefore defined as the unpleasant frequency. For this reason, we studied an artificial source for masking the peak frequency.

## IV. PROPOSED METHOD FOR DESIGNING ARTIFICIAL SOURCES

We proposed the method for designing the masking sound to reduce the unpleasantness of the indoor noise. In our proposed method, first, indoor noise is analyzed, and a peak frequency is dependently detected on the power spectrum of the noise. Second, the proposed method calculates the bandwidth that can mask the detected peak frequency, and then artificial sources are generated on the basis of the calculated frequency bandwidth.

### *A. Detection of Peak Frequency*

In our research, we aim at masking the peak frequency of the indoor noise in order to reduce unpleasantness. An overview of the proposed method is shown in Fig. 4. The peak frequency $Peak_i^F$ is calculated by using a spectral envelope of the indoor noise in Eq. (2).

$$Peak_i^F = P_i - \mu_i^F, \tag{2}$$

where $P_i$ stands for the power spectrum of $i$ [Hz], and $\mu_i^F$ is the median of the power in $F$ [Hz] that centers on $i$ [Hz]. This value represents how the power of $i$ [Hz] has exerted value in the frequency band around $i$ [Hz]. Figure 5 shows the power spectrum of the indoor noise and $Peak_i^F$ calculated for the

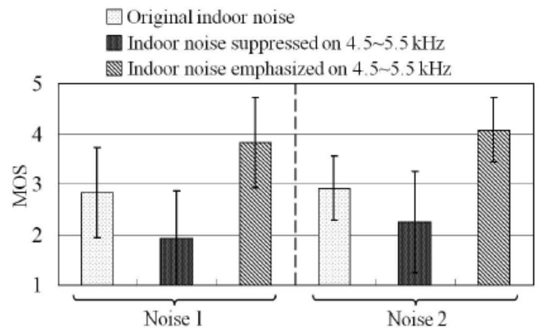



Fig. 3. Results of pre-experiment by MOS

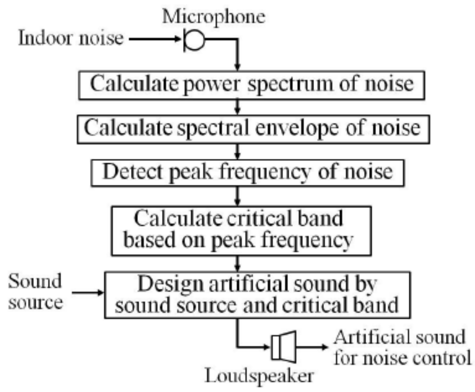



Fig. 4. Overview of proposed method

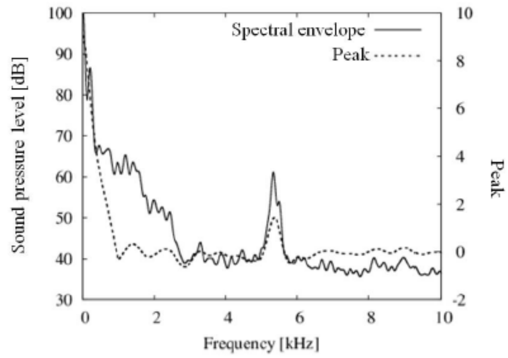



Fig. 5. Power spectrum of noise and value peak

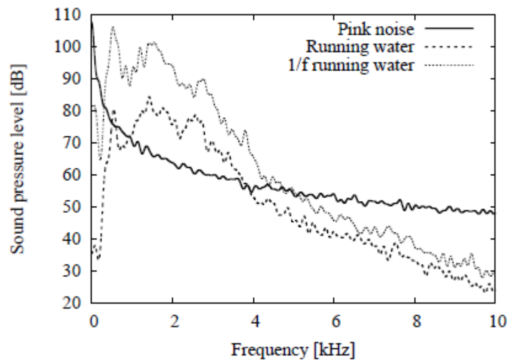



Fig. 6. Spectral envelopes of pink noise and sounds of running water sound, and 1/f running water

case in which $F$ [Hz] is experimentally 2000 [Hz]. In this paper, because the purpose of this study is to reduce high frequency noise that causes unpleasantness, we estimated $i$ [Hz] as the peak frequency for the case in which $Peak_i^F$ has the highest value in $i > 2000$.

### B. Design of Artificial Source

The critical band is calculated on the basis of the detected peak frequency with Eq. (1). Then, the band-pass filter that passes the band in the critical band that centers on the peak frequency is designed for the artificial source. The artificial source $y(t)$ is designed from Eq. (3).

$$y(t) \quad = \quad x(t) * h(t), \tag{3}$$

where, $t$ is the time index, $x(t)$ is the sound source, and $h(t)$ is the band-pass filter. The symbol * stands for the convolution. In this paper, we used pink noise, the sound of running water, and the sound of running water weighted on the basis of 1/f as the sound source for the artificial source. The spectral envelopes of each sound source are shown in Fig. 6. Furthermore, we also studied the use of the utilizing the bandwidths that are expanded 0, 1, and 2 [kHz] to a frequency lower than the calculated frequency bandwidth.

## V. Subjective Evaluation Experiment

### A. Conditions of Subjective Evaluation Experiment

The effectiveness of the proposed method was evaluated in a soundproof room with background noise of less than 20 dBA. In the experiments, the unpleasantness of each sound source was evaluated by ten subjects (five females and five males) by using a rating scale method. No subjects had any hearing problems. The evaluated sound sources consisted of only indoor noise and nine artificial sources (three kinds of sound source and three kinds of frequency bandwidth) added to noise. Table III shows the conditions for the subjective evaluation experiment. The subjects evaluated each sound source in accordance with the rating scale with the five grades shown in Tab. IV. Figure 7 shows the experimental environment in the soundproof room. We presented the indoor noise by using Loudspeaker 1, which creates a indoor noise environment in soundproof room. Sound pressure level (SPL) of the emitted indoor noise was about 40 dB at a position of the subject. The indoor noise was recorded with a microphone and analyzed in order to design artificial sources. The designed artificial sources were also presented by Loudspeaker 2 in the soundproof room. In this experiment, SPL of the emitted designed artificial sources was about 45 dB including SPL of the indoor noise at a position of the subject. Subjects

TABLE III
CONDITIONS FOR SUBJECTIVE EVALUATION EXPERIMENT

| Experimental conditions | |
|---|---|
| Environment | Soundproof room (19.0 dBA) |
| Loudspeaker | DIATONE DS-7 |
| Subjects | 10 subjects (Five females and five males) |
| **Sound sources** | |
| Number of evaluated sources | 10 |
| Sampling rate | 48000 Hz |
| Quantization bits | 16 bit |

TABLE IV
RATING SCALE FOR SUBJECTIVE EVALUATION

| | |
|---|---|
| 5 | Very annoyed |
| 4 | Quite annoyed |
| 3 | Moderately annoyed |
| 2 | A little annoyed |
| 1 | Not at all annoyed |

individually evaluated each sound source. This experiment was carried out twice for each subject to compensate for time variability.

### B. Results of Subjective Evaluation Experiment

Figure 8 shows the result of the subjective evaluation experiment. In this figure, the horizontal axis represents the evaluated sound source, and the vertical axis represents the unpleasantness based on MOS. In this study, the lower the MOS value, the lower the feeling of unpleasantness. As shown in Fig. 8, for the case in which artificial sources were made from pink noise, the unpleasantness increased in comparison with only indoor noise. In comparison, for the case in which the artificial sources were made from the sound of running water, artificial sources whose expansion of the frequency band was 0 [kHz] had approximately the same unpleasantness as did only indoor noise, and artificial sources whose expansion of the frequency band was 1 [kHz] and 2 [kHz] had less unpleasantness than did only indoor noise. Also, artificial sources that had a wider frequency bandwidth had less unpleasantness. For the artificial sources made from the sound of running water weighted on the basis of 1/f, the same tendencies were confirmed as with the sound of running water.

## VI. ACTIVE UNPLEASANTNESS REDUCTION SYSTEM

In a real environment, the peak frequency of the indoor noise often changes with time. Therefore, the proposed method should automatically design suitable artificial sources with time. For this reason, we developed an active unpleasantness reduction system based on the proposed method. Figure 9 shows the unit of the developed system. Figure 10 shows the calculation board for automatically calculating and designing the artificial source. First, this system records indoor noise with a microphone located on the top of the unit. Next, it detects the peak frequency and designs the artificial source. Finally, it emits the designed artificial source to all over the area with loudspeakers. Table V shows the operating conditions of the developed system. However, this system sometimes fails to detect the peak frequency because it records the indoor noise with the emitted artificial source. Furthermore, it need to manually operate the emission energy of the designed artificial source by the noise level. Therefore, as future work, we will implement an echo canceller and calibration function of the emission energy in this system.

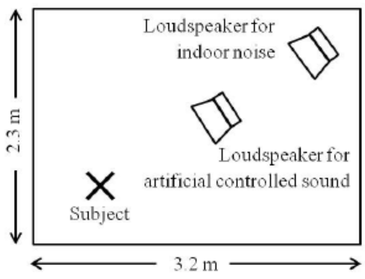


Fig. 7. Experimental environment

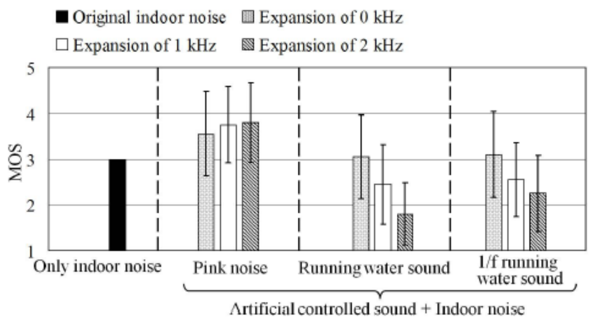


Fig. 8. Result of subjective evaluation

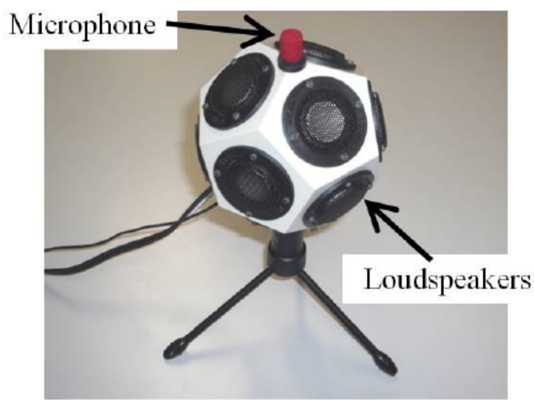


Fig. 9. Unit of developed system

Fig. 10. Calculation board for the developed system (Beagleboard-Xm)

TABLE V
OPERATING CONDITIONS OF THE DEVELOPED SYSTEM

| | |
|---|---|
| Sampling rate | 48000 Hz |
| Quantization bits | 16 bits |
| Frame length | 256 samples |
| Frame shift length | 128 samples |
| FFT point | 1024 samples |
| Detection range of peak frequency | 1000 $\sim$ 10000 Hz |

## VII. CONCLUSIONS

We proposed a method for designing artificial sources on the basis of auditory masking in order to reduce unpleasant feelings without noise power reduction. The theory and the equation of auditory masking were used in order to calculate the frequency band that can mask indoor small-power noise in real environments and to design the artificial sources. The purpose of this study was to reduce unpleasant feelings of noise not by reducing noise power but by adding artificial sources to noise. To validate the effectiveness of the proposed method, a subjective evaluation experiment was carried out. As a result, we confirmed that the artificial sources made from natural sources such as the sound of running water effectively reduced the unpleasantness of indoor noise. Moreover, we developed the active unpleasantness reduction system based on the proposed method. In future work, we will try to design a more comfortable masking sound.


## ACKNOWLEDGMENTS

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