An evaluation on comfortable sound design of unpleasant sounds based on chord-forming with bandlimited sound

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ABSTRACT

The unpleasant noise is one of the important social problems because our quality of life is degraded by it. We have previously proposed the unpleasantness reduction method based on auditory masking to reduce the discomfort feeling of the noise with peak frequency components in a higher frequency. The former proposed method can reduce the discomfort feeling by emitting a control signal to a listener. However, it has the discomfort feeling caused by that the control signal increases the sound energy. To solve this problem, we focus on the reformation of peak frequency components in addition to auditory masking. Here, chords are generally known as typical comfortable sounds in music theory. Chords are felt as comfortable sound, if some peak frequency components are in the specific rules. In this paper, therefore, we propose the comfortable sound design method based on chord-forming with music theory. The proposed method can design the comfortable sound by reforming the spectral structure of the noise to that of comfortable sounds. As a result of evaluation experiments, we confirmed the effectiveness of the proposed method.

Keywords: Comfortable sound design, Chord-forming, Control signal, Band-limited
I-INCE Classification of Subjects Number(s): 01.4

1. INTRODUCTION

The unpleasant noise is one of the huge social problems to be solved because it interferes with our daily livings. The former research has investigated that a discomfort feeling is caused by the noise with peak frequency components in a higher frequency (1). A passive noise control (PNC) and an active noise control (ANC) are generally known as the noise suppression method (2, 3). The PNC absorbs the noise, whereas it has a space restriction. Because, this method is required to put the thick wall without the gap. On the other hand, the ANC reduces the sound pressure level of the noise by emitting an anti-phase sound of that. However, it is difficult to reduce the high frequency noise. Thus, these methods have lower effective to reduce the discomfort feeling of the indoor noise with peak frequency components in the higher frequency.

Accordingly, we have previously proposed an unpleasantness reduction method based on auditory masking to reduce the discomfort feeling of the indoor noise with the peak frequency component in the higher frequency (4). Auditory masking is a phenomenon that one sound is masked another sound by the auditory properties of the human ear. This method can reduce the discomfort feeling of the noise by emitting a masking signal to listeners. However, in principle, this method requires the masking signal with high-power when the noise has high-power. Thus, this method has the risk that it may inflict discomfort feeling.

Here, we focus on chords in music theory because they are generally known as typical comfortable sounds (5). Chords are felt as comfortable sounds when some peak frequency components of them are in the specific rules. For this reason, we can design the comfortable sound by forming the spectral structure of the chord to the peak frequency component of the noise. In this paper, therefore, we propose the comfortable sound design method based on chord-forming to the peak frequency component of the noise. First, the proposed method detects the peak frequency of the noise which is assumed as the nearest musical scale in music theory. Next, the control signal is designed as the components of the chord including the scale. Finally, the comfortable sound is designed by emitting the designed control signal to listeners. However, we consider that the effectiveness of the proposed method is reduced by that the control signal is heard as the beep. To solve

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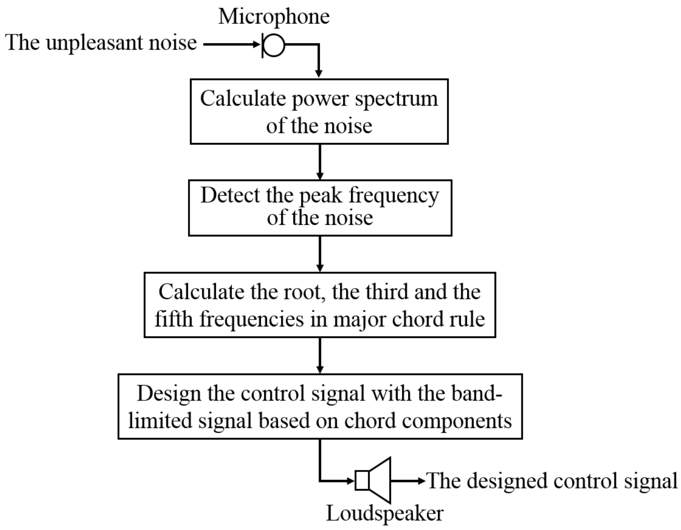


Figure 1 – Overview of the proposed method

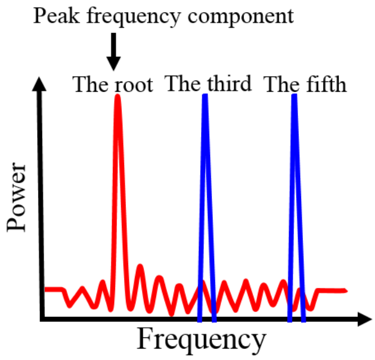


Figure 2 – Chord-forming

this problem, we also propose the control signal with the band-limited signal. Furthermore, we carry out a subject evaluation experiment to confirm the effectiveness of the proposed method.

2. PROPOSED METHOD

We focus on the comfortable chords in music theory because they have some peak frequency components in the specific rules. For this reason, we can design the comfortable sound by forming the spectral structure of the chord to the peak frequency component of the noise. In this paper, therefore, we propose the comfortable sound design method based on chord-forming to the peak frequency component of the noise. In addition, we also propose the control signal with the band-limited signal to reduce the sound which is heard as the beep. Figure 1 shows overview of the proposed method. The below shows the procedure of designing the comfortable sound.

1. Calculate power spectrum of the noise
2. Detect the peak frequency of the noise
3. Assume the peak frequency as the nearest musical scale in music theory
4. Calculate the root, the third and the fifth frequency of the major chord including the musical scale
5. Design the control signal as the root, the third and the fifth components of the major chord with the band-limited signal
6. Emit the designed control signal to listeners

Then, listeners can hear the sound which is reformed to the comfortable chord as shown in Fig. 2.

2.1 Characteristics of chords

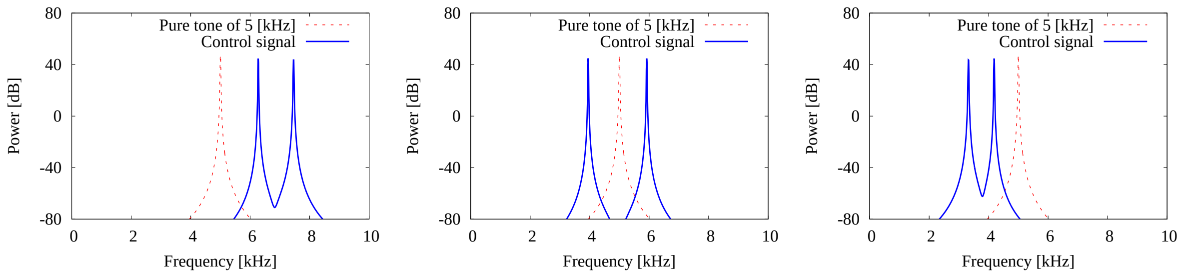
Chords give various psychological impressions to listeners by combining of sounds (5). Chords are felt as the comfortable sound when some components of chords are in the specific rules. We focus on the major chord because it is more consonance and more comfortable sounds (6). The major chord consists of the root, the third and the fifth components. Equation (1) shows the frequency ratio of the major chord in the equal temperament.

$$f_{\text{root}} : f_{\text{third}} : f_{\text{fifth}} = 1 : 2^{\frac{4}{12}} : 2^{\frac{7}{12}} \tag{1}$$

where f_{root}, f_{third} and f_{fifth} are the root, the third and the fifth frequencies of the major chord, respectively.

2.2 Preliminary experiments for chord-forming

As mentioned in the previous chapter, the sound is felt as the comfortable sound when it has the spectral structure of the major chord. For this reason, we can design the comfortable sound by forming the spectral structure of the major chord to the peak frequency component of the noise. Here, we consider that the comfort is varied by the position of the peak frequency component in the major chord. First, we carried out a preliminary experiment to investigate a tendency of chord-forming.



(a) The position of the peak frequency is the root of the major chord

(b) The position of the peak frequency is the third of the major chord

(c) The position of the peak frequency is the fifth of the major chord

Figure 3 – Power spectrum of pure tone of 5 [kHz] and control signal

2.2.1 Conditions of preliminary experiments for chord-forming

We carried out the preliminary experiment in the soundproof room with background noise of less than $L_A = 20$ [dB]. In the preliminary experiment, we use pure tones of 3, 4 and 5 [kHz] as the unpleasant noise. In designing the control signal, the position of the peak frequency is the root, the third, or the fifth of the major chord. Figures 3(a), 3(b) and 3(c) show the power spectrum of pure tone of 5 [kHz] and the control signal which is designed when the positions of the peak frequency are the root, the third or the fifth of the major chord, respectively. We control the energy ratio of the noise and the control signal to 0 [dB]. In the preliminary experiment, each noise is evaluated by six subjects (three females and three males) in their twenties. The subject compares the comfort of the noise and the sound which is added the control signal, and selects the more comfortable sound. The number of the presentation is six times for each combination. The presentation is randomly ordered.

2.2.2 Results of preliminary experiments for chord-forming

Figure 4 shows the result of the preliminary experiment. In Fig. 4, the horizontal axis represents types of the noise, and the vertical axis represents the average ratio of selecting the sound including the control signal S_{ave} derived from Eq. (2).

$$S_{\mathrm{ave}} = \frac{1}{I}\sum_{i=1}^{I} S_i, \tag{2}$$

$$S_i = \frac{n_i}{N}, \tag{3}$$

where i is index of subject, I is the number of subjects, S_i is the ratio of selecting the sound including the control signal to the number of the presentations, n_i is the number of selecting the more comfort sounds including the control signal as the more comfortable sound by comparing whether or not including the control signal, and N is the number of presenting the combinations of the only unpleasant noise and the sound including the control signal, in each condition. Each graph represents selectivity of chord-forming to the noise when the position of the peak frequency is the root, the third and the fifth of the major chord. As the result of the preliminary experiment, we confirmed that the chord-forming is highly effective when the position of the peak frequency is the fifth of the major chord. However, the selectivity does not achieve 100 % at all noise signals of pure tone. Because, the control signal is heard as the beep by being designed with the pure tone. To solve this problem, we propose the method which designs the control signal with the band-limited signal.

2.3 Comfortable sound design based on chord-forming with the band-limited signal

As the result of the preliminary experiment, the proposed method can design the comfortable sound by chord-forming when the position of the peak frequency is the fifth of the major chord. Figure 5 shows the conceptual diagram of chord-forming with the band-limited signal. Furthermore, we consider that the effectiveness of the proposed method can be better by adding the band-limited component to the fifth of the major chord, and Fig. 6 shows the conceptual diagram of it. In this paper, the band-limited signal is designed by band-pass filtering with a white noise.

The below shows the procedure of designing the control signal with the band-limited signal. The root

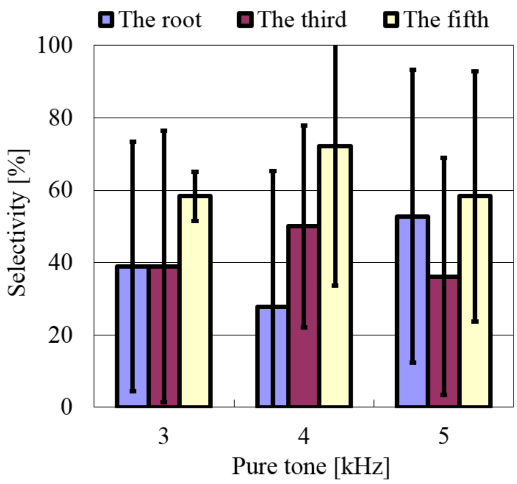


Figure 4 – Results of preliminary experiment

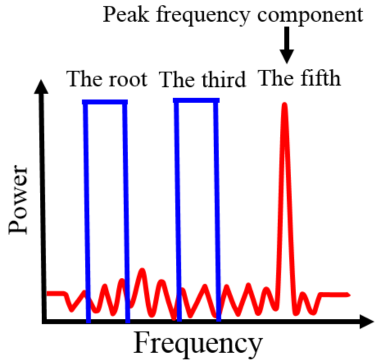


Figure 5 – Chord-forming with the band-limited signal

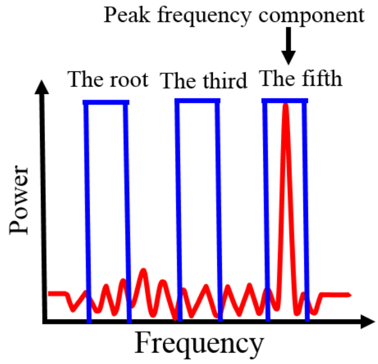


Figure 6 – Chord-forming with the band-limited signal and adding the band-limited component to the fifth

frequency f_{root} and the third frequency f_{third} of the major chord are derived from Eqs. (4) and (5).

$$f_{\text{root}} = f_{\text{fifth}} \cdot 2^{-\frac{7}{12}}, \tag{4}$$

$$f_{\text{third}} = f_{\text{fifth}} \cdot 2^{-\frac{3}{12}}, \tag{5}$$

where f_{fifth} is the detected peak frequency of the noise. Then, the control signal $y(t)$ is derived from Eq. (6).

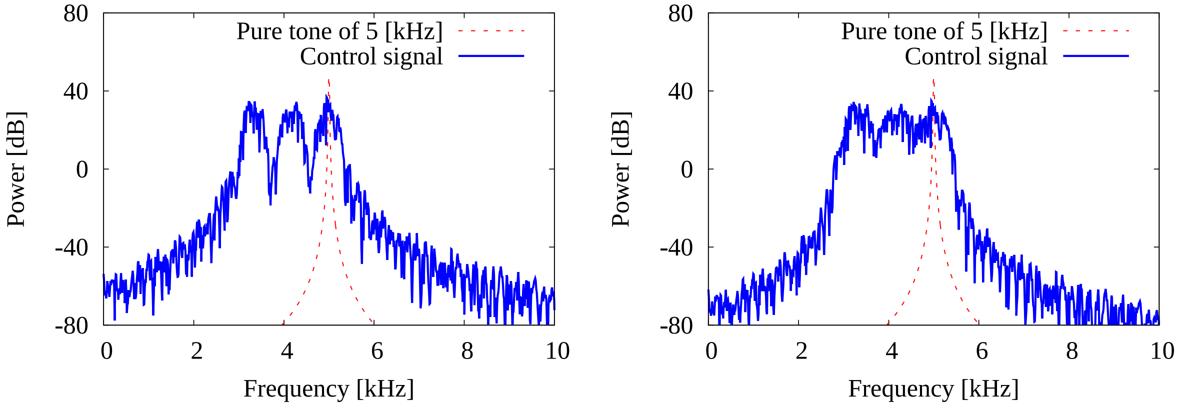
$$y(t) = y_{\text{root}}(t) + y_{\text{third}}(t) + y_{\text{fifth}}(t), \tag{6}$$

$$\begin{aligned} y_{\text{root}}(t) &= w(t) * h_{\text{root}}(t), \\ &= \int_{f_{\text{root}}-\frac{\alpha}{2}}^{f_{\text{root}}+\frac{\alpha}{2}} W(f) \cdot e^{j2\pi ft} df, \end{aligned} \tag{7}$$

$$\begin{aligned} y_{\text{third}}(t) &= w(t) * h_{\text{third}}(t), \\ &= \int_{f_{\text{third}}-\frac{\alpha}{2}}^{f_{\text{third}}+\frac{\alpha}{2}} W(f) \cdot e^{j2\pi ft} df, \end{aligned} \tag{8}$$

$$\begin{aligned} y_{\text{fifth}}(t) &= w(t) * h_{\text{fifth}}(t), \\ &= \int_{f_{\text{fifth}}-\frac{\alpha}{2}}^{f_{\text{fifth}}+\frac{\alpha}{2}} W(f) \cdot e^{j2\pi ft} df, \end{aligned} \tag{9}$$

where t is time index, f is frequency index, $y_{\text{root}}(t)$ is the root component, $y_{\text{third}}(t)$ is the third component, $y_{\text{fifth}}(t)$ is the fifth component, $w(t)$ is a white noise, $h_{\text{root}}(t)$, $h_{\text{third}}(t)$ and $h_{\text{fifth}}(t)$ are band-pass filters for each chord component, $W(f)$ is a white noise in the frequency domain and α is the bandwidth. The symbol $*$ stands for convolution.



(a) Bandwidth 100 [Hz] (b) Bandwidth 500 [Hz]

Figure 7 – Power spectrum of pure tone of 5 [kHz] and control signal

Table 1 – Rating scale for subjective evaluation experiment

5	Very comfortable
4	Quite comfortable
3	Same level as unpleasant noise
2	A little comfortable
1	Not at all comfortable

3. SUBJECTIVE EVALUATION EXPERIMENT

We carried out a subjective evaluation experiment to confirm the effectiveness of the proposed method. Furthermore, we investigated the change of the comfort in various bandwidth of the control signal.

3.1 Conditions of subjective evaluation experiment

We carried out the subjective evaluation experiment in the soundproof room with background noise of less than $L_A = 19.3$ [dB]. In the subjective evaluation experiment, we use pure tones of 3, 4 and 5 [kHz] as the unpleasant noise. In designing the control signal, the bandwidth of the control signal is 0, 100, 300 or 500 [Hz]. Figures 7(a) and 7(b) show the power spectrum of pure tone of 5 [kHz] and the control signals designed when the bandwidth is 100 [Hz] and 500 [Hz]. We control the energy ratio of the noise and the control signal to 0 [dB]. In the subjective experiment, each noise is evaluated by ten subjects (three females and seven males) in their twenties. The evaluation method is comparing the comfort of the original sound and the sound including the control signal, in the five grade evaluation as shown in Table 1. The number of the presentation is two times for each combination. The presentation is randomly ordered.

3.2 Results of subjective evaluation experiment

Figure 8 shows the result of the subjective evaluation experiment. In Fig. 8, the horizontal axis represents the bandwidth of the control signal, and the vertical axis represents the score. In this paper, the higher score means the higher comfort and the lower score means the lower comfort. As shown in Fig. 8, the result with the bandwidth 100 [Hz] is more comfortable in comparison to that with the bandwidth 0 [Hz]. The discomfort feeling increases in the bandwidth 0 [Hz] because the control signal might be heard as the beep. The control signal with a band-limited signal can achieve the comfortable sound design. However, from the results with bandwidths 100 [Hz], 300 [Hz] and 500 [Hz], the comfort feeling tends to decrease by excessively expanding the bandwidth. The consonance of the chord is degraded because the control signal is similar to the white noise (7). The same tendencies were confirmed at all noise signals of pure tone. As a result of the subjective evaluation experiment, we confirmed the effectiveness of the proposed method with bandwidth 100 [Hz].

4. CONCLUSIONS

In this paper, we proposed the comfortable sound design method based on chord-forming to the peak frequency of the noise. As the result of subjective evaluation experiments using five grade evaluation, we confirmed the effectiveness of the proposed method. Furthermore, we confirmed the further effectiveness of

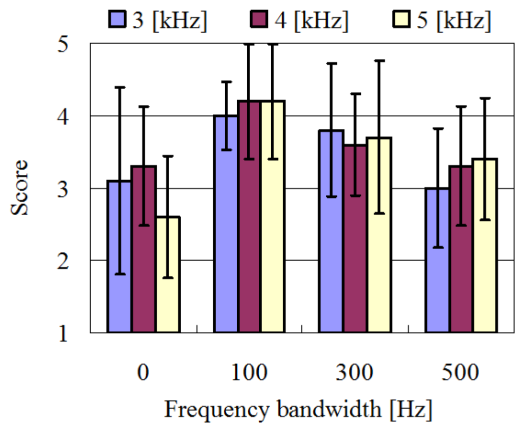


Figure 8 – Results of subjective evaluation experiment

the proposed method by designing the control signal with the band-limited signal. In future work, we intend to extend the proposed method to the noise in the real environment.

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