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Study on suppression effect of air-conducted sound by bone-conducted sound

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ABSTRACT

This paper proposes a method for suppressing air-conducted (AC) sound by presenting bone-conducted (BC) sound. First, the amplitude and phase of BC tones at six frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz) were examined by using a method of limits to suppress AC tones presented via earphones. On the basis of the results of the first experiment, finite-impulse-response (FIR) filters, dependent upon participants, were then designed as "a compensation filter" to cancel out AC sound by presenting BC sound. Next, whether or not AC complex tones presented via earphones could be suppressed by simultaneously presenting BC complex tones compensated for by FIR filtering was investigated. Finally, whether or not this method could be applied to suppress stationary noise was also investigated. From these investigations, the proposed method was found to adequately suppress AC complex tones, and the average amounts of suppression for the AC and AC complex tones were approximately 5 and 1 dB, respectively. In addition, it was also shown that the proposed method can be used to suppress AC stationary noise but not greatly.

1. INTRODUCTION

There are various environmental noises in our daily life. Exposure to sounds with an A-weighted sound pressure level of 85 dB for more than 8 hours per day greatly increases the risk of noise-induced hearing loss [1, 2]. Therefore, it is necessary to protect our ears by suppressing heavy noise from the viewpoint of hearing protection.

At present, there are means of hearing protection such as earplugs and earmuffs that act as physical noise suppression. In addition, there are techniques for active noise control (ANC) that act

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as noise suppression for specific sounds [3, 4]. However, since these methods are based on the premise that the ears are blocked physically to suppress external noise, they suppress not only noise but also target sounds not to be missed, such as speech and alert signals. Therefore, there is demand for an alternative method of suppressing external noise without physically blocking the ears.

The ultimate goal of this study is to realize a noise suppression technique using bone conduction devices, enabling us to perceive sound without physically blocking the ears. The purpose of this paper is to clarify whether or not air-conducted (AC) sound is successfully suppressed by bone-conducted (BC) sound as a basic study on noise suppression methods using bone conduction devices.

2. SUPPRESSING AIR-CONDUCTED SOUND BY BONE-CONDUCTED SOUND

Stenfelt conducted an experiment to clarify whether or not BC sound was perceptually canceled out by AC sound presentation by modifying the amplitude and phase of each sound [5, 6]. As a result, both AC and BC sounds were found to be canceled out, indicating that there is a linear relationship between the transmission pathways of AC and BC sound. Ito and Sakamoto conducted another experiment based on this finding and the principle of ANC to investigate whether or not noise is suppressed by presenting BC sound after adjusting the amplitude of the anti-phase component of environmental noise [7]. As a result, the noise was found to be suppressed by BC sound presentation, but the amount of noise suppression obtained in this experiment was not sufficient. The reason for the poor amount of suppression is assumed to be the complete difference in phase characteristics between the transmission pathways of AC and BC sound [5, 6].

Focusing on this point, the authors preliminarily investigated whether pure tones presented through air-conduction are suppressed by presenting BC pure tones with the amplitude and phase manipulated. As a result, an average suppression of 4.49 dB was achieved. However, since an adjustment method was used, there was a remaining issue in that the participants may have had a subjective influence.

In this study, by adopting a method of limits, which can minimize the subjective influence of participants in an experiment, we aim to clarify the amplitude and phase for BC tones that effectively suppress AC tones. In addition, we aim to clarify the amplitude and phase of BC tones when mixed sound comprising AC and BC tones has the minimum loudness.

Therefore, the method of limits is used to determine the amplitude and phase of BC tones for suppression after determining the amplitude and phase of a standard stimulus by using the method of adjustment.

Figure 1(a) shows a schematic diagram of the experimental principle. Figure 1(b) shows an example of an answer expected in the experiment. As shown in Fig. 1(b), the loudness of the mixed sound is expected to decrease once and then increase again due to changes in amplitude and phase. In other words, it is expected that there are two discrimination thresholds for the standard stimulus. The amplitude and phase of BC tones that completely suppress AC tones are obtained by finding the median of these two thresholds. This is conducted in the first three experiments described in Sect. 3.

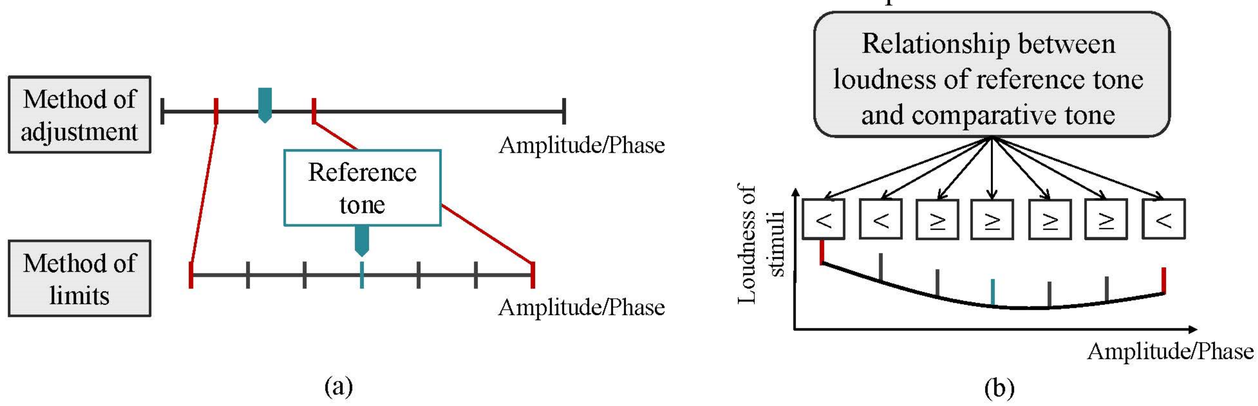

Figure 1: (a) Schematic diagram of experimental principle and (b) example of expected answer

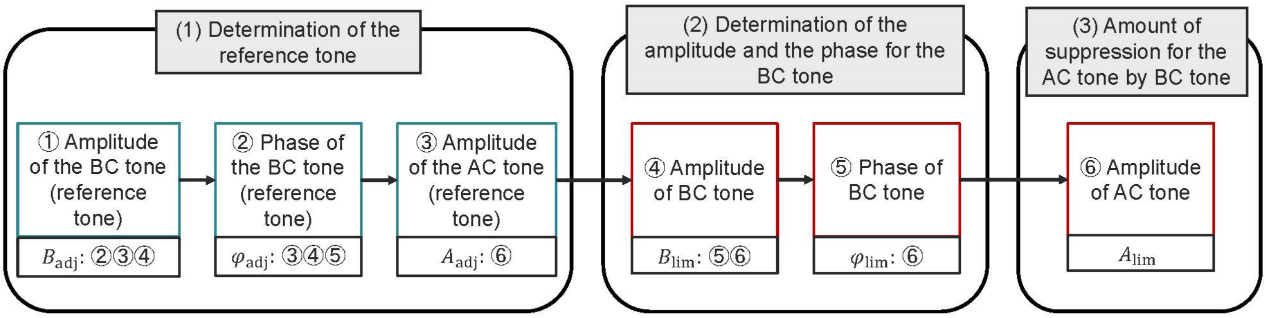

Figure 2: Outline of experimental procedure

In this study, general AC noise suppression by BC sound presentation is investigated to discuss the applicability of the basis of AC sound suppression by BC sound presentation. Compensation filters for cancelling out AC sound by BC sound presentation are designed from the results of the first three experiments. Those filters are then applied to two types of noise stimuli, complex tone and stationary noise (band-limited white noise). This is conducted in the second experiment described in Sect. 4.

3. EXPERIMENTS FOR PURE TONE SUPPRESSION

Three experiments were conducted to determine the amplitude and phase of BC tones for suppressing AC tones as a basic study of noise suppression.

3.1. Participants

Ten native Japanese speakers (one female and nine males) aged 22 to 25 participated in the experiments. The absolute threshold of all participants measured through a standard audiometric tone test with a RION AA-72B audiometer was a hearing level of 12 dB or less for both ears at octave frequencies between 125 and 8,000 Hz (i.e., all had normal hearing). They are graduate school students.

3.2. Apparatus

The experiments were conducted in a soundproof room. The sound pressure level of the background noise was lower than 26 dB. The experimental stimuli were simultaneously presented to both ears through a BC headphone (TEAC HP-F200) with an amplifier (Audio-Technica AT-HA5000) and an earphone (Etymotic ER3 SE) with another amplifier (the same type as mentioned above). A PC screen and keyboard were placed in front of the participants. The presentation of the stimuli was controlled using MATLAB 2021b on a PC (Windows 10) and routed through an A/D converter (Roland Rubix 44). The sampling frequency was 44,100 Hz, and the number of quantizing bits was 16.

3.3. Stimuli

Six pure tones were used as stimuli. The signal frequencies of the six tones were 250, 500, 1000, 2000, 4000, and 8000 Hz. All stimuli were binaurally presented to the participants.

3.4. Procedure

Figure 2 shows an outline of the procedure used in the experiments. The three experiments were conducted in sequence. First, Experiment I was conducted to determine the standard stimulus. Next, Experiment II was conducted to investigate the amplitude and phase of the bone-conducted sound that maximized the suppression of the AC sound. Finally, Experiment III was conducted to investigate the amount of suppression of the AC sound when the BC sound was presented under the obtained amplitude and phase conditions. The detailed procedures of the three experiments are described below.

3.4.1 Experiment I: Determining standard stimulus

The purpose of Experiment I was to obtain the amplitude and phase of the standard stimulus. In step ①, the amplitude of the BC sound of the standard stimulus was determined by loudness matching of the BC tones on the basis of the AC tones by using the method of adjustment. A pure tone, $A_{50}\sin(2\pi ft)$, was presented to the participants by air-conduction, followed by the presentation of a BC tone, $B\sin(2\pi ft)$. Here, the amplitude A_{50} denotes the amplitude of the AC tone when the A-weighted sound pressure level is 50 dB. The amplitude $B = B_{\mathrm{adj}}$ was determined by instructing the participants to adjust the amplitude B to where the loudness of the AC tone equaled that of the BC tone using a slide bar.

In step ②, the phase of the BC tone that maximizes the suppression of the AC tone was determined by using the method of adjustment, and the phase of the standard stimulus was then determined. A mixed sound comprising AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{adj}}\sin(2\pi ft + \varphi)$ was presented to the participants. The phase $\varphi = \varphi_{\mathrm{adj}}$ was determined by instructing the participants to adjust the phase φ that minimizes the loudness of the mixed sound using the slide bar.

In step ③, the amount of suppression of the AC tone was determined by using the method of adjustment, and the amplitude of the AC tone used as the standard stimulus was determined. A mixed sound comprising AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{adj}}\sin\left(2\pi ft + \varphi_{\mathrm{adj}}\right)$ was presented to the participants, followed by AC tone $A\sin(2\pi ft)$. The amplitude $A = A_{\mathrm{adj}}$ was determined by instructing the participants to adjust the amplitude A to where the loudness of the mixed sound equaled that of the AC tone $A\sin(2\pi ft)$ using the slide bar.

3.4.2 Experiment II: Determining amplitude and phase for BC sound

The purpose of Experiment II was to clarify the amplitude and phase conditions of the BC tone maximizing the suppression of the AC tone.

In step ④, the amplitude of the BC tone that maximizes the suppression of the AC tone was determined by using the limit method. As a standard stimulus, a mixed sound comprising AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{adj}}\sin\left(2\pi ft + \varphi_{\mathrm{adj}}\right)$ was presented as the standard stimulus, and in sequence, a mixed sound comprising AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{com}}\sin\left(2\pi ft + \varphi_{\mathrm{adj}}\right)$ was presented as the comparative stimulus. Here, B_{com} denotes the amplitude of the BC tone obtained by controlling B_{adj}, and it was set to change in 1-dB steps. The participants were asked to answer whether or not the loudness of the comparative stimulus was "louder" or "not louder" than that of the standard stimulus. We determined the median amplitude $B = B_{\mathrm{lim}}$ at which the response from the participants changed from "louder" to "not louder" and at which the response from them changed from "not louder" to "louder."

In step ⑤, the phase of the BC tone that maximizes the suppression of the AC tone was determined by using the limit method. A mixture of AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{lim}}\sin\left(2\pi ft + \varphi_{\mathrm{adj}}\right)$ was presented as the standard stimulus, and in sequence, a mixture of AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{lim}}\sin(2\pi ft + \varphi_{\mathrm{com}})$ was presented as the comparative stimulus. Here, φ_{com} denotes the phase of the BC tone obtained by controlling φ_{adj}, and it was set to change in 5-deg steps. The participants were asked to answer whether or not the loudness of the comparative stimulus was "louder" or "not louder" than that of the standard stimulus. We determined the median phase $\varphi = \varphi_{\mathrm{lim}}$ at which the response from the participants changed from "louder" to "not louder" and changed from "not louder" to "louder."

3.4.2 Experiment III: Determining amount of suppression for AC sound by BC sound presentation

The purpose of Experiment III was to clarify the amount of suppression of the AC tone when the BC tone was presented under the conditions for the amplitude and phase of the BC tone obtained in Experiment II.

In step ⑥, a mixed sound comprising AC tone $A_{50}\sin(2\pi ft)$ and BC tone $B_{\mathrm{lim}}\sin(2\pi ft + \varphi_{\mathrm{lim}})$ was presented as the standard stimulus, and in sequence, AC tone $A_{\mathrm{com}}\sin(2\pi ft)$ was presented as the comparative stimulus. Here, A_{com} denotes the amplitude of the AC tone obtained by controlling A_{adj}, and it was set to change in 0.5-dB steps. The participants were asked to answer whether or not the loudness of the comparative stimulus was "louder" or "not louder" than that of the standard stimulus. For the ascending series, the amplitude $A = A_{\text{lim}}$ was determined at which the response from the participants changed from "not louder" to "louder." For the descending series, the amplitude $A = A_{\text{lim}}$ was also determined at which the answer from the participants changed from "louder" to "not louder." The amount of suppression level, L_{sup} in dB, is defined as the following equation and used for comparative evaluation.

$$L_{\text{sup}} = 20 \log_{10} \frac{A_{50}}{A_{\text{lim}}} \tag{1}$$

3.4. Results and discussion

From Experiment I, the amplitude B_{adj}, phase φ_{lim}, and amplitude A_{adj} of the standard stimulus were stable. However, the amplitude B_{adj} of the standard stimulus was found to vary greatly among individuals.

Figure 3 shows the amplitude and phase of the BC tone that suppresses the AC tone most at each frequency, obtained from Experiment II. Figure 3(a) shows the amplitude of the BC tone at each frequency obtained in step ④. Figure 3(b) shows the phase of the BC tone at each frequency obtained in step ⑤. From Fig. 3, the amplitude and phase of the BC tone that suppressed the AC tone most effectively were clarified by using the limit method. There were large differences in amplitude among individuals, and no common trend was observed. It was found that even if the amplitude of the BC tone was large at a specific frequency, it was not necessarily the case that the amplitude was large at other frequencies, as in the case of participant #10. On the other hand, it was found that the phase of the BC sound, excluding outliers, was within the range of 132 deg even in the case of maximum variation. This suggests that there is a certain condition for suppressing the AC tone common to all participants regarding the phase of the BC tone.

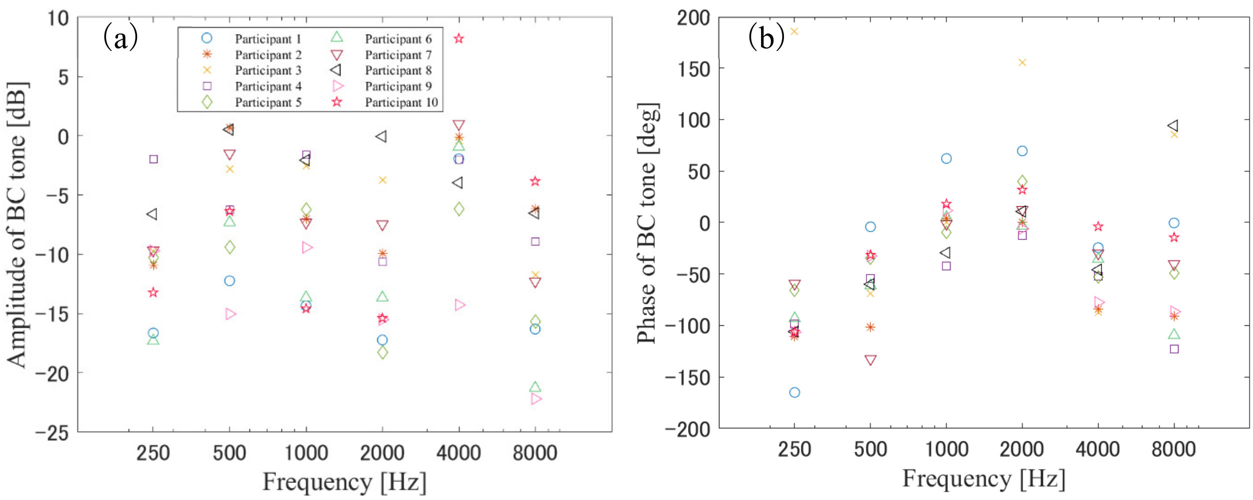

Figure 3: (a) Amplitude and (b) phase of BC tones suppressing AC tones most at six frequencies.

Figure 4 shows the amount of suppression of the AC sound at each frequency when the BC tone was presented with the amplitude and phase that suppressed the AC tone most, obtained in Experiment III. Similarly to the result of Experiment II, large individual differences were observed, but it was found that suppression effects were observed at all frequencies. The average amount of suppression was 4.95 dB, which exceeded the amount of suppression obtained by the authors using only the adjustment method (4.49 dB) [6]. From the results of Experiment III using the limit method, it was clarified that a pure tone presented through air-conduction can be suppressed by controlling the amplitude and phase of the BC tone.

The effect of binaural hearing was assumed to be a factor in individual differences in these experiments. Loudness has an additive effect for the left and right ears [8]. Considering this, it is conceivable that a suppression effect may not be observed in both ears even if suppression is achieved in one ear. There was, for example, a participant who had a 15-dB difference in minimum audibility level in both ears, in which hearing levels are in the range of normal hearing. This suggested that the loudness of the AC sound was different among both ears. In addition, this suggested that the loudness of the BC tone was different among both ears, depending on how the bone conduction headphones were attached. The influence of where bone conduction headphones are attached is considered to be a factor for a negative amount of suppression. The time required for the experiment at each frequency exceeded 1 hour, including a break time. It is assumed that the attachment position shifted during experiments, so the phase condition of the BC tone that suppresses the AC tone changed.

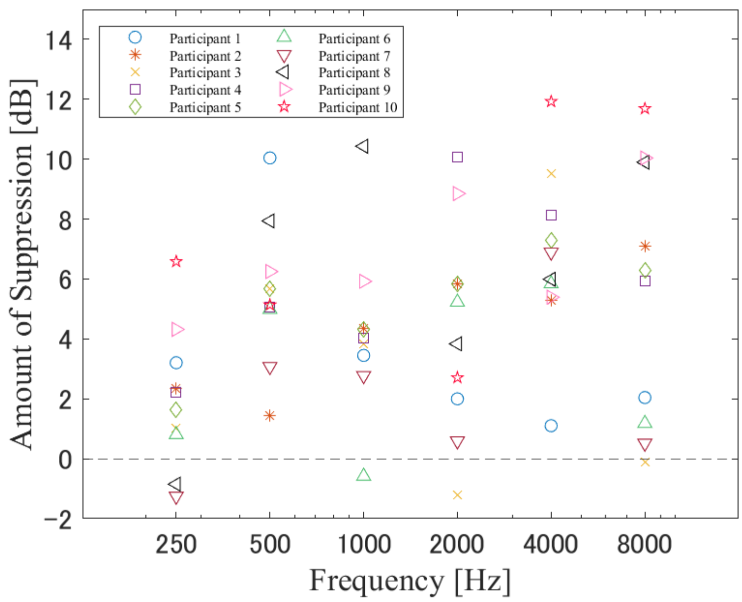

Figure 4: Amount of suppression level L_{sup} of air-conducted tone at each frequency when bone-conducted tone was presented with amplitude and phase that suppress air-conducted tone most.

4. EXPERIMENTS FOR APPLICABILITY

In this study, two experiments were conducted in sequence to investigate the amount of suppression of the AC sound when the BC sound was presented on the basis of the results of the above experiments as shown in Fig. 4.

4.1. Design of compensation filter

The amplitudes and phases of BC tones suppressing AC tones most at the six frequencies were found to be dependent upon the participants. Thus, specific compensation for AC sound suppression at various frequencies was assumed to be necessary for specific participants.

Compensation filters were designed as finite impulse response (FIR) filters. For the filter design, we interpolated eight data points of the amplitude and phase of the BC tone from 0 Hz to 10,000 Hz including the six tone frequencies from 250 Hz to 8,000 Hz where the edges (0 and 10,000 Hz) were predicted from six data points of them by using spline interpolation. The eight data points are plotted in Figs. 5 and 6 with black-filled circles, while the interpolated curves are plotted by solid curves with an asterisk. The compensation filter was then derived as an FIR filter from these data points of the amplitude and phase by using the program “arbmagnphase” in the filter-design toolbox (arbitrary response magnitude and phase filter specification object). Here, the order of the FIR filter was set to 150, and all frequency specifications were supplied at a normalized frequency where the sampling frequency was 20,000 Hz.

Figures 5 and 6 show the frequency characteristics of the FIR filter derived from the results of Experiment III. Figure 5 shows the filter characteristics of participant #4 (the best case), where the root-mean-squared errors (RMSEs) of the amplitude and phase characteristics were 2.00 dB and 0.84 deg. Figure 6 shows the filter characteristics of participant #3 (the worst case), where the RMSEs of the amplitude and phase characteristics were 7.98 dB and 3.93 deg. For the other eight participants, we derived the FIR filters that depended upon the eight participants, but we omitted a plot of the frequency characteristics of these filters. The mean (standard deviation) for the RMSEs of the amplitude and phase characteristics of the ten filters were 5.41 dB (2.37) and 1.26 deg. (0.96).

It was very difficult to derive the FIR filter to completely fit the amplitude and phase characteristics with very low RMSEs simultaneously. We also tried to derive an infinite impulse response (IIR) filter from the interpolated characteristics with the eight data positions by using a recursive digital filter design tool ("yulewakl"); however, the derived IIR filter could not satisfy stability since a few poles were outside of the unit circle.

In this paper, two experiments were conducted to investigate the amount of the suppression of the AC sound when the BC sound was presented by using the participant-dependent FIR filter used as a compensation filter derived from the results of the experiments as shown in Fig. 4.

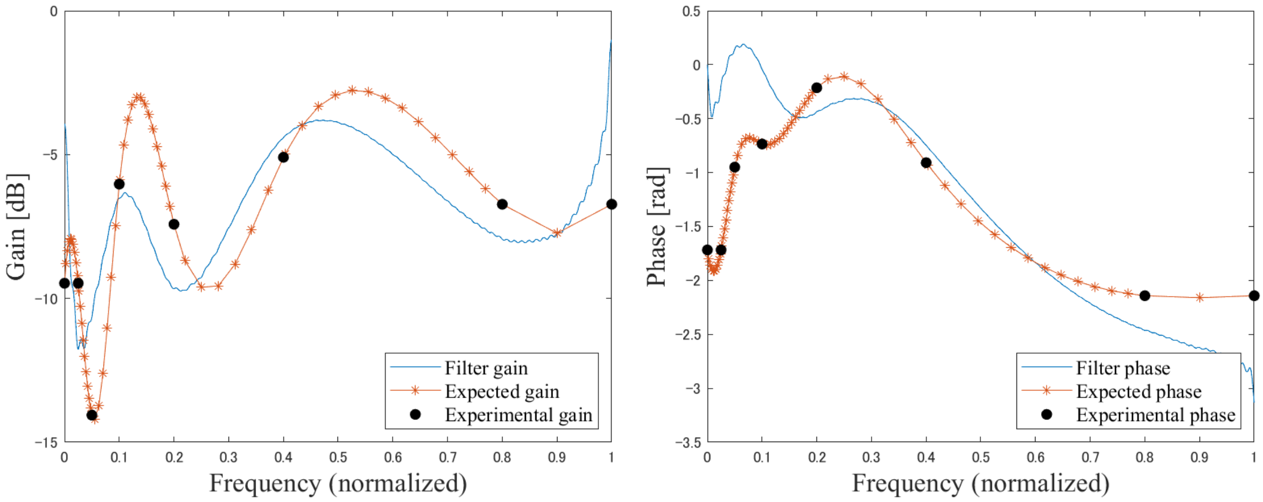

Figure 5: Frequency characteristics of FIR filter derived from results of Experiment III for participant #4: (a) filter gain and (b) phase.

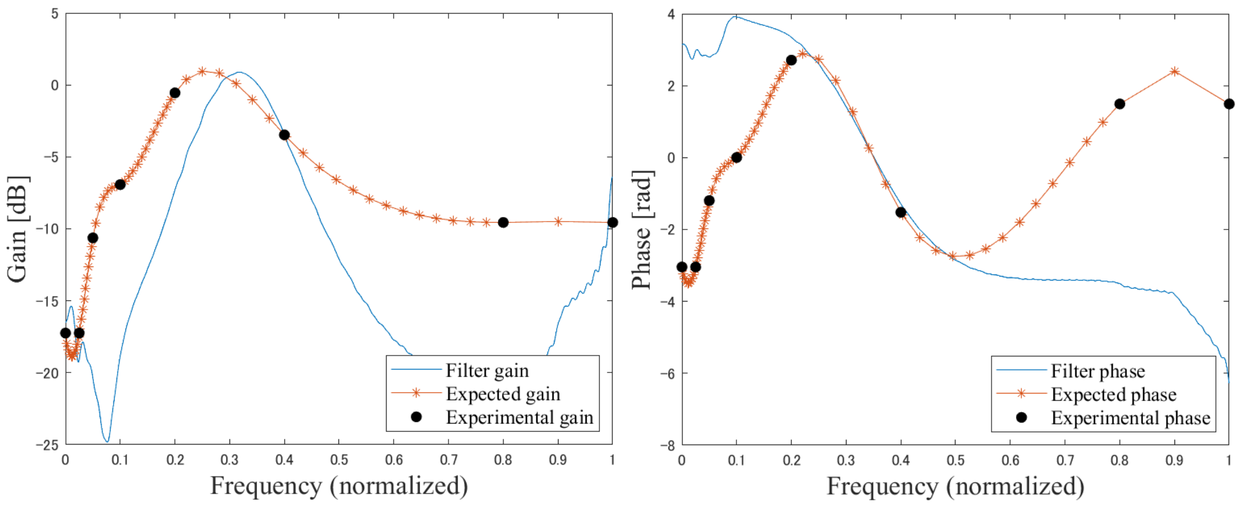

Figure 6: Frequency characteristics of FIR filter derived from results of Experiment III for participant #3: (a) filter gain and (b) phase.

4.2. Subjective evaluation for proposed method for complex tone

The purpose of this experiment was to clarify whether an AC complex tone can be suppressed using a bone conduction device.

4.2.1 Participants

Four native Japanese speakers (one female and three males) aged 23 to 25 participated in this experiment. They were four of the ten participants in the experiments described in Sect. 3. Two of them were participants whose derived FIR filters had the top-two best characteristics in Sec. 4.1, and the other two were participants whose derived FIR filters had the bottom-two best characteristics (worst two characteristics) in Sec. 4.1.

4.2.2 Apparatus

The experiments were conducted in the same soundproof room that we used in Sect. 3. The experimental stimuli were simultaneously presented to both ears through a BC headphone (TEAC HP-F200) with an amplifier (Audio-Technica AT-HA5000) and earphones (Etymotic ER3 SE) with an amplifier (Audio-Technica AT-HA5000). A PC screen and keyboard were placed in front of the participants. The presentation of the stimuli was controlled using MATLAB 2021b on a PC (Windows 10) and routed through an A/D converter (Roland Rubix 44). The sampling frequency was 44,100 Hz, and the number of quantizing bits was 16.

4.2.3 Stimuli

A complex tone consisting of six pure tones was used as stimuli. These stimuli were created using MATLAB 2021b. All stimuli were binaurally presented to the participants. Here, AC and BC complex tones were defined as $\sum A_{50,i} \sin(2\pi f_i t)$ and $\sum B_{\mathrm{lim},i} \sin\left(2\pi f_i t + \varphi_{\mathrm{lim},i}\right)$, where $i = 1, 2, \ldots, 6$ and $f_i = 250, 500, 1000, 2000, 4000,$ and 8000 Hz.

4.2.4 Procedure

The amount of suppression of the AC complex tone was determined by using the method of adjustment. A mixture of AC complex tone $\sum A_{50,i} \sin(2\pi f_i t)$ and BC complex tone $\sum B_{\mathrm{lim},i} \sin\left(2\pi f_i t + \varphi_{\mathrm{lim},i}\right)$ was presented as a standard stimulus. Here, $B_{\mathrm{lim},i}$ and $\varphi_{\mathrm{lim},i}$ were determined by the amplitude and phase characteristics of the FIR filter acting as a compensation filter dependent on the participant. Then, AC complex tone $\sum A_i \sin(2\pi f_i t)$ was presented as a comparative stimulus. The amplitude $A_i = A_{\mathrm{sup},i}$ was determined by instructing the participants to adjust the amplitude A to where the loudness of the mixed sound was equal to that of AC complex tone $\sum A_i \sin(2\pi f_i t)$ using the slide bar. The amount of suppression level, L_{sup} in dB, is defined as

$$L_{\mathrm{sup}} = \sum 20 \log_{10} \frac{A_{50,i}}{A_{\mathrm{sup},i}}. \tag{2}$$

4.2.5 Results and discussion

Figure 7 shows the amount of suppression of the AC complex tone when the BC complex tone was presented to the four participants by using the participant-dependent FIR filter. All four results indicated a positive suppression level. The average amount of suppression was 0.95 dB, which did not exceed the amount of suppression (4.95 dB) obtained by the authors using the method of limits in Experiment III.

We compared the amount of suppression for the pure tones at six frequencies with the amount of suppression for the complex tones. It was found that the difference between the amount of suppression for the pure tones and the amount of suppression for the complex tones was high when the amplitude and phase characteristics of the FIR filter at the tone frequency did not match the corresponding data points in Figs. 5 and 6. Therefore, one reason sufficient suppression was not achieved could be that this was highly caused by approximation errors of the compensation filter. Another reason may be the deviation due to the mounting position of the bone conduction device.

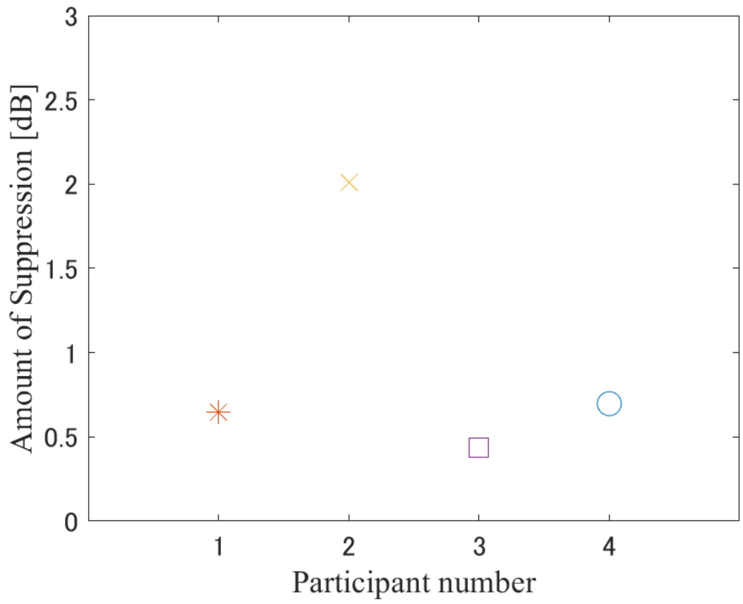

Figure 7: Amount of suppression level, L_{sup}, of AC complex-tone when presenting BC complex-tone.

4.3. Subjective evaluation for proposed method for stationary noise

The purpose of this experiment was to clarify whether or not AC stationary noise can be suppressed using a bone conduction device.

4.3.1 Participants and apparatus

The same four native Japanese speakers in Sect. 4.2 participated in this experiment. The equipment we used in previous experiments was also used in this experiment.

4.3.2 Stimuli

The stationary noise used in this experiment was band-limited white noise. This noise was created from white noise by bandpass filtering where the cut-off frequencies were 250 Hz and 8,000 Hz. The noise duration was 1.5 seconds. Ten band-limited noise signals were used as the stimulus in this experiment.

4.2.3 Procedure

A mixture of AC stationary noise and BC stationary noise was presented as a standard stimulus. Here, BC stationary noise was processed by using the participant-dependent FIR filter to compensate for the amplitude and phase characteristics. Then, AC stationary noise was in sequence presented as a comparative stimulus to the participants. We determined the sound pressure level in dB at which the loudness of the mixed sound was equal to that of the AC stationary noise by using a loudness matching technique. The amount of the suppression level, L_{sup} in dB, was calculated by subtracting this sound pressure level during loudness matching from the sound pressure level of the AC sound.

4.2.4 Results and discussion

Figure 8 shows the amount of suppression of the AC stationary noise when the BC stationary noise was presented to the four participants by using the participant-dependent FIR filter. All ten points for the four participants were plotted widely among positive and negative suppression levels. The average amounts of suppression for each participant were 0.4 dB, 0.1 dB, 0.0 dB, and -0.1 dB, and the total average amount of suppression was almost zero. From these results, it was shown that BC sound presentation using a compensation filter can be used to suppress AC stationary noise but not greatly.

A possible reason for the insufficient suppression effect in this case was that the amplitude and phase characteristics could not be reproduced with good accuracy due to the design of the FIR filter used as a compensation filter. Another possible reason sufficient suppression was not achieved may be the deviation due to the mounting position of the bone conduction device.

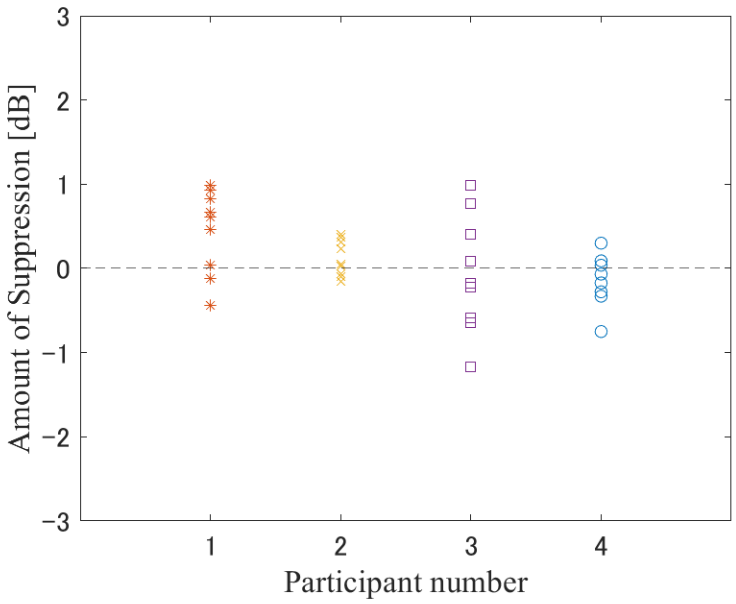

Figure 8: Amount of suppression level of AC stationary noise by presenting BC stationary noise.

5. CONCLUSION

We investigated whether or not air-conducted (AC) sound presented by using earphones can be suppressed by sound presented by a bone conduction (BC) device using listening experiments with a method of limits. First, we examined the amplitude and phase of BC tones at six frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz) by using the method of limits to suppress AC tones presented via earphones. Next, we investigated whether or not AC complex tones presented via earphones could be suppressed by simultaneously presenting BC complex tones compensated for by FIR filtering. Finally, we investigated whether or not this method can be used to suppress stationary noise. From this study, the amplitude and phase of the BC sound when suppressing the AC sound at each frequency to the maximum were clarified. It was found that BC sound presentation with an FIR filter can adequately suppress AC tones as well as AC complex tones, and the average amounts of suppression for AC and AC complex tones were about 5 and 1 dB, respectively. In addition, it was also shown that the proposed method can be used to suppress AC stationary noise but not greatly.

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