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A Preliminary Study of Pitch Matching between 40-kHz Air-conducted Ultrasonic Wave and Air-conducted Audible Sound

40 kHz 気導超音波と気導可聴音のピッチマッチングの試み

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1. Introduction

It has generally been believed that humans can not perceive high-frequency soundwave higher than about 20 kHz as a normal auditory sound. However, it is reported that some of the younger group whose age was between 18 and 33 could hear 24-kHz pure tone at more than 88 dB sound pressure level (SPL) [2]. In case of bone conduction, clear perception of the ultrasound up to 100 kHz is also reported [2,3]. A measurement of the hearing threshold of air-conducted 40 kHz ultrasound is also reported: the mean threshold was around 133.3 dB SPL [4]. In addition, several investigations pointed that the perveived bone-conducted ultrasound derived a high-frequency pitch, which was approximately from 8 kHz to 16 kHz [5-7].

These findings implies that the human inner ear has certain sensitivity to ultrasound. However, the perveived pitch of the air-conducted ultrasound has not been investigated. In this study, therefore, we performed a pitch-matching experiment between the normal audible sound and the 40-kHz air-conducted ultrasound which is widely used in our daily lives.

2. Method

In this study, pitch-matching was performed with an adjusting method in order to reduce the experiment time. However, since a preliminary experiment suggested that the matched frequency might be more than 10 kHz, the loudness change of the audible sound could be a problem. If the sound is presented at a same sound pressure level, the loudness of the sound at such high frequency drastically changes according to a slight change of frequency, which may deteriorate the performance of the pitch-matching. Therefore, we tried to keep the loudness of the air-conducted audible sound even when the presented frequency is changed.

Although ISO226:2003 already shows the equal-loudness-level contour of human hearing, its upper limit remains at 12.5 kHz, which is not enough to our experiment [8]. Therefore, we utilized the data of high-frequency hearing threshold reported by Herbertz [9]. The amplitude gradient at high-frequency range was calculated by linearly fitting the curve on logarithmic scale between 12.5 kHz and 16.0 kHz. As a result, the derived slope was about 120 dB/oct. The presentation software was designed to automatically apply this slope only to the normal audible sound at more than 12.5 kHz. The designed frequency response is shown in Fig. 1.

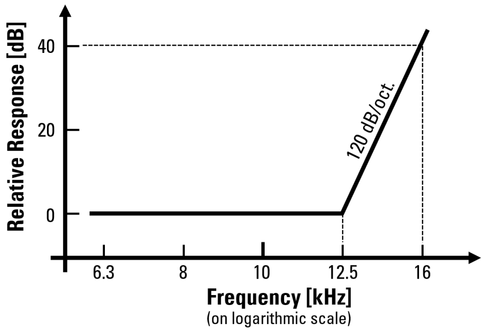

Fig. 1 Designed frequency characteristics of the air-conducted audible sound.

In addition, since it was known that the hearing threshold of ultrasound [4] and the equal-loudness-level contour of audible sound [10] varies a lot depending on each participant, the loudness of the 12.5-kHz audible sound was roughly matched to the loudness of the 40-kHz ultrasound by each participant prior to the experiment. For the participants who could not perceive 12.5-kHz sound, the initial frequency was lowered before the loudness matching so that they could clearly perceive the audible sound.

Moreover, since the pitch-matching operation was performed with an adjusting method as described above, the results may be affected by the initial frequency of the presented sound. In order to cancel the effect, the initial frequency was selected alternatingly: the odd-numbered trials will be started at lower frequency compared to the previous trial and the even-numbered trials will be started at higher frequency. The absolute difference compared to the previous trial was randomly selected between

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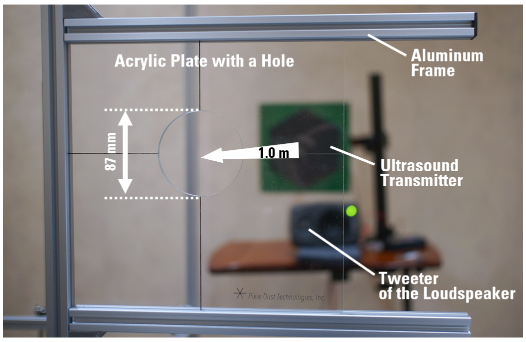

Fig. 2 Alignment of the acrylic panel and the transmitters of ultrasound and audible sound.

0.5 kHz and 1.0 kHz at each trial.

The 40-kHz air-conducted ultrasound was transmitted via an ultrasound array speaker (custom-fabricated by Pixie Dust Technologies including 271 elements of T4010B4 by Nippon Ceramic) whose transducers are driven in-phase. Since the area where the sound pressure is almost homogeneous was quite narrow even all elements are driven in-phase, the participants are requested to hear the sound via a small hole on a acrylic plate aligned at a distance of 1.0 m right in front of the speakers so that the participants can hear the stimuli stably. The diameter of the hole was 87 mm which was decided by considering the distribution of the size of auricle of young Japanese [11]. The participants were requested to lightly lean against the plate to keep their posture easily.

The audible sound was presented via a loud speaker with amplifier (8010A, GENELEC). Since the two speakers could not be installed at exactly same position, the ultrasound speaker, which has much shorter wavelength, was positioned exactly in front of the hole of the plate. Then, the audible-sound speaker was positioned at the bottom part of the ultrasound speaker. The alignment of the plate and the speakers is shown in Fig. 2.

The presented level of the ultrasound was set to 140 dB SPL, which satisfies two requirements: expected to be larger enough than the hearing threshold at 133.3 dB [4] and safe enough [12]. The sound pressure level was measured at the center of the hole of the plate using a microphone (B&K, Type 4939 with protection grid).

The duration of the stimuli of both ultrasound and audible sound was 550 ms including 50-ms tapers applied both to the rising and falling area. The presentation frequency was 1.0 Hz and the ultrasound and the audible sound was played alternatingly. The participants were requested to adjust the frequency of the audible sound by using a mouse connected to a PC until they feel the pitches are almost same. The pitch-matching trials are repeated six times by each participants and the mean frequency was calculated.

Ten participants with normal hearing (mean ±SD = 24.3±2.8 years old, 6 male and 4 female), who agreed to the consent in writing, were participated in the experiment. The participants who could not stably hear the air-conducted ultrasound are excluded from the number. The objects which the participants directly touch were cleaned using alcohol at each time.

3. Result and Discussion

As a result, the mean and the standard deviation of matched-frequency of 40-kHz air-conducted ultrasound among ten participants was 11.85 ± 1.01 kHz.

First, it should be pointed that all participants who heard the ultrasound were able to perform the pitch-matching task between ultrasound and audible sound. It will help us to understand the perception mechanism of air-conducted ultrasound. Next, the matched frequency value of the air-conducted ultrasound was similar to those of the bone-conducted ultrasound in literatures [5-7]. We should carefully check the similarities and differences between these two different stimuli in the future work. In addition, we should mention that the data was derived only from the young people. By performing the measurement for older people, more precise knowledge about the perception mechanism is expected to be unveiled in the future.

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