3Pa5-16

Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 427-428
8-10 November, 2011

Propagation Velocity of Bone-Conducted Ultrasound in the Human Head

骨導超音波の頭部内伝搬速度

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1. Introduction

An ultrasound with frequency above 20 kHz up to at least 100 kHz, generally exceeding the upper limit of human auditory perception by air-conduction, can be heard via bone-conduction (BC)[1]. This "audible" ultrasound through BC is referred to as the bone-conducted ultrasound (BCU). Various approaches have been applied to clarify the perceptual characteristics of BCU, using psychoacoustical, neurophysiological and physicoacoustical methods. Yet, its mechanism has still been remained unclear.

Propagation velocity would be one of the most important physicoacoustical parameters for characterizing wave propagation of BCU. Although there exists critical difficulties in observing the phenomena taking place inside of the human heads[2-5], BC velocity in the sonic range has been measured directly[6-8] and assessed psychoacoustically[9,10] to be ranged in 50 to 570 m/s, depending on the frequency of the stimulation. However, BC velocity in the ultrasonic range has not been verified.

The present study aimed at clarifying the propagation velocity of BCU, by measuring the accelerations of BCUs bilaterally presented with various signal frequencies and inter-lateral phase differences. BCU velocity was estimated from the acoustical interference pattern by referring to the principle used by Zwislocki in his psychoacoustical study[9]. Further, the obtained BCU velocity was verified by simulation for bilateral interference calculated under a matched condition to the actual measurement.

2. Measurements

2.1 Methods

The experimental setup is shown in **Fig. 1**. Sinusoidal BCUs were presented via vibrators (MA40E7S, Murata Manufacturing) attached to the left and right mastoids. The accelerations were measured with accelerometers (NP3211, Ono Sokki) located inside the left and right ear canals. The stimulus signals were generated digitally on a PC at 192 kHz sampling rate with frequencies from 28 kHz to 32 kHz in 100-Hz steps, and presented bilaterally through a soundboard (Audiofire12, Echo Digital Audio) with inter-lateral phase differences from -2π to 2π in π/8 steps.

The spatial positions of the vibrators and the accelerometers were also obtained using a 3D digitizer (FASTRAK, Polhemus). The obtained xyz coordinates and the distances between the vibrators and the accelerometers are listed in **Table I** and **Table II**, respectively.

2.2 Results

Fig. 2 shows frequency responses of the acceleration at left and right accelerometers for unilateral stimulations, and **Fig. 3** shows inter-lateral attenuations for the unilateral presentations of the left and right vibrators. **Fig. 4** shows distribution of relative acceleration levels at left ear for bilateral stimulation as a function of signal frequency and inter-lateral phase difference to the left-unilateral stimulation measured at left ear.

2.3 Estimation of the propagation velocity

For bilateral presentation of bone-conduction, the average propagation velocity can be determined according to the following equation[9]:

$$\bar{c} = 2\pi S \Big/ \frac{d\varphi}{df},$$

where S is the difference of path length between from vibrators to an accelerometer, φ is the phase difference, and f is the signal frequency.

The differential quotient $d\varphi/df$ is given by the slope of the interference pattern of **Fig. 4**. The average propagation velocity was calculated using these values and estimated as $\bar{c} \approx 269$ m/s, mostly agreed with the results reported by Zwislocki[9].

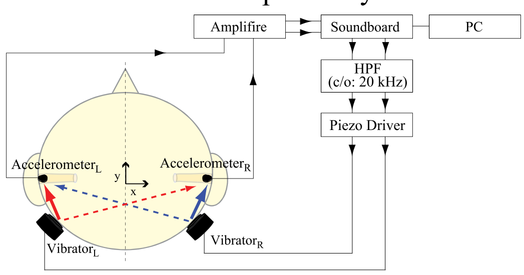

Fig. 1 Experimental setup for the measurements of propagation characteristics of BCU in the head.

3. Simulations

A simple numerical model to examine the effects of cross-talk in bilaterally presented bone-conduction has been proposed by Zurek[11]. The schematic diagram of the model is shown in **Fig. 5**. In order to verify the obtained BCU velocity, acoustical interference in the head was simulated by referring to this model[11] using the same xyz coordinates shown in **Table II** as digitized in the measurement, the inter-lateral attenuation level obtained from **Fig. 3** and the estimated average BCU velocity, i.e., 269 m/s.

Fig. 6 shows the results of the simulation for the interference pattern at the left ear, with the estimated propagation velocity. The simulated interference pattern mostly agreed with the measured results shown in **Fig. 4**.

4. Conclusions

The present study investigated the propagation velocity of BCU, by measuring at the left and right ear canals the accelerations of BCUs presented unilaterally and bilaterally. The propagation velocity calculated from the acoustical interference pattern induced by the bilateral presentation was estimated to be 269 m/s. The estimated velocity was further verified by a simple simulation for bilateral presentation of bone-conduction. The simulated acoustical interference pattern mostly agreed with the results of the actual measurements, supporting the validity of the estimated propagation velocity of BCU.

Acknowledgment

This research was supported by the Funding Program for Next-Generation World-Leading Researchers provided by the Cabinet Office, Government of Japan.

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Table I. Positions of the vibrators and the accelerometers.

Position	Coordinate (mm) x	y	z
$Vib._L$	-72.2	-19.5	-15.8
$Vib._R$	66.9	-24.4	-14.8
$Acc._L$	-59.7	-0.3	-4.9
$Acc._R$	55.0	0.1	7.5

Table II. Distances between the vibrator and the accelerometer.

Pathway	Distance (mm)
$\overrightarrow{Vib._L Acc_L}$	30.9
$\overrightarrow{Vib._L Acc_R}$	130.8
$\overrightarrow{Vib._R Acc_L}$	130.4
$\overrightarrow{Vib._R Acc_R}$	35.2

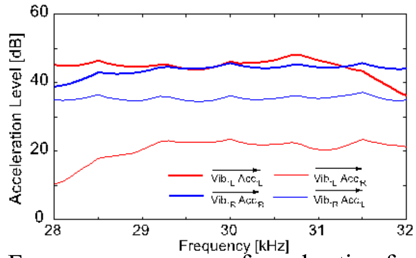

Fig. 2 Frequency responses of acceleration for unilateral stimulations with the left (red) and the right (blue) vibrators.

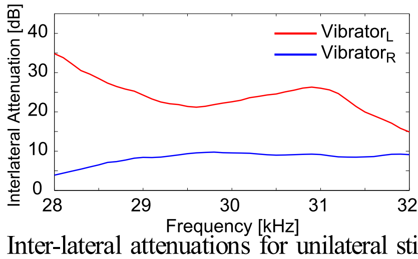

Fig. 3 Inter-lateral attenuations for unilateral stimulations with the left (red) and the right (blue) vibrators.

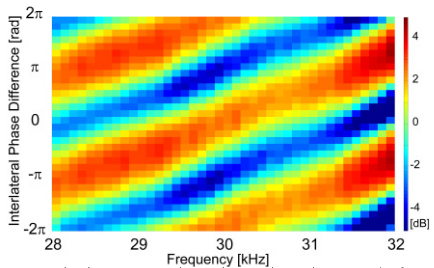

Fig. 4 Relative acceleration levels at left ear for bilateral stimulation to the left-unilateral stimulation measured at left ear.

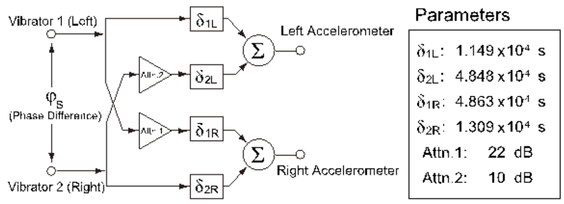

Fig. 5 Schematic diagram of numeric cross-talk model.

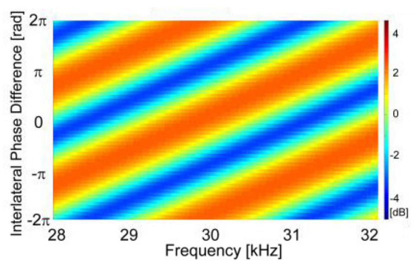

Fig. 6 Simulated acoustical interference level at left ear for bilateral stimulation under similar conditions of the actual measurement.