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Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 561-562
6-8 December, 2010

Linearity of bone-conducted ultrasound transmission in the human head
骨導超音波の頭部伝播の線形性について

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1. Introduction

Ultrasound is inaudible sound that has a frequency above 20 kHz. However, it actually becomes audible through bone conduction (BC).[1)] Interestingly, several studies have reported that bone-conducted ultrasound (BCU) was perceived by some of the profoundly deaf (with not only conductive but also sensorineural hearing loss) as well as normal hearing persons.[2,3)] Therefore, a bone-conducted ultrasonic hearing device is being developed as a novel hearing aid for profoundly deafness.[4)] However, the perception mechanisms remain unclear. The issues of why ultrasound can be heard by BC and how the profoundly deaf people hear it remain unresolved and need to be clarified for the better developments of the new hearing aid system.

The bone-conducted ultrasonic hearing has two interesting features in terms of pitch and loudness perception. One is that an ultrasonic tone in bone conduction produce a sensation of pitch as a pure tone with an audible frequency of about 8 to 16 kHz.[1-5)] The other is that the dynamic range for BCU hearing can be narrower than that for air-conducted audible high frequency sound hearing.[5)] A possible explanation for these phenomena is the effects of nonlinearity of ultrasonic vibration transmission through the human skull bones and soft tissues, or nonlinear properties in the coupling between skin and vibrator.[6)] However, with respect to pitch perception of BCU, Ito and Nakagawa (2010) showed that there was no evidence of the contribution of the nonlinearity in the outer and middle ear, such as the generation of subharmonics or detectable signals at audible high frequencies.[7)] Thus, this suggests that a specific mechanism for the pitch perception may exist in the cochlea or the afferent neural pathway.

On the other hand, with respect to loudness perception, it remains uncertain whether the narrower dynamic range of BCU hearing results from the nonlinearity of the ultrasound transmission. Håkansson *et al*. (1996) investigated the linearity of vibration transmission in the skull and found it linear for normal levels (up to 77 dB HL) and audible frequencies (0.1 – 10 kHz) used for hearing by ordinary bone conduction.[8)]

In the present study, the linearity of bone-conducted ultrasonic vibration transmission in the living human head was investigated using some of the same methods as in Håkansson *et al*.[8)]

2. Methods

2.1 Procedure

For the experiment, five heads of normal hearing subjects were used. The head was excited by stepped sine signals from 10 kHz to 35 kHz in 1-kHz steps with two different excitation force levels through BC. The signals were presented through a vibrator (MA40E7S, Murata Manufacturing Co. Ltd.) that was attached to one of either mastoid portion. Response acceleration was measured with an accelerometer (NP3211, Ono Sokki Co. Ltd.) that was set inside the ear canal on the stimulated side. The excitation force levels were set to levels corresponding to 5 and 10 dB SL (sensation level) at 30 kHz. These levels are loud enough to hear because of the narrow dynamic range of BCU hearing.[5)] All experiments were performed in an anechoic room.

2.2. Estimations of the linearity

Regarding the human head as a system, the input signal to the mastoid portion by BC is the excitation force (F) and the output signal at the ear canal is the response acceleration (A) of the head. Hence, the frequency response function (G), known as accelerance, is given by

$$G(f) = A(f)/F(f),$$

where f is the frequency of the input signal. If the system is linear, the different excitation force levels should yield the same estimate for $G(f)$.[8)]

Another estimation was based on the coherence function that gives a measure of the similarity between two signals. The magnitude squared coherence function of two signals x and y is defined as

$$\gamma_{xy}^2 = \left|\overline{G_{xy}}\right|^2 \Big/ \left(\overline{G_x} \cdot \overline{G_y}\right),$$

where G_{xy} is the cross spectrum of the signals x and y, G_x and G_y are the power spectra of the signals x and y respectively, and the over bar notation "-" denotes its average value. If the system is linear, the coherence function should be close to unity for all frequencies. [8)]

3. Results and Discussion

The two accelerance functions, $G(f)$'s, of the head vibration averaged from all subjects are superimposed in **Fig. 1**. The solid and broken lines indicate the functions for the excitation force levels of 5 and 10 dB SL respectively. The similarities of the $G(f)$'s estimated at different excitation levels are evident from the audible to ultrasonic frequencies.

Three different types of coherence functions are plotted in **Fig. 2**. The blue and green lines indicate the coherence functions between the input $F(f)$ and output $G(f)$ with the excitation levels of 5 and 10 dB SL respectively. Here, the input function $F(f)$ represents the frequency response of the vibrator MA40E7S used in this study. The results show that both coherence functions have high ratios ranging between 0.8 and 0.95 at the ultrasonic frequencies above 20 kHz, whereas the functions both fluctuate at the audible high frequencies and have lowest ratios at 10 kHz. This suggests that the sound transmission of the head includes more nonlinear components or noise in the audible frequency range than in the ultrasonic range.

On the other hand, the red line in **Fig. 2** indicates the coherence function between the two outputs $G(f)$'s with different excitation force levels. The function shows very high ratios close to unity at all frequencies. The results suggest that the ultrasound transmission of the head behaves almost linearly in this frequency range and for these excitation force levels used by the BCU hearing aid system. Consequently, the narrow dynamic range of BCU hearing, i.e., the greater growth rate of loudness with increasing excitation force level for ultrasonic frequencies than for audible frequencies, is likely not to be due to the nonlinearity of the ultrasound transmission in the human head but to the perception mechanisms in the inner ear or the afferent neural pathway.

Acknowledgment
A part of this work was supported by the Grants-in-Aid for Scientific Research of Japan Society for the Promotion of Science,(22680038).

References

1. R. Pumphrey: Nature. **166** (1950) pp. 571.
2. M.L.Lenhardt, R. Skellett, P. Wang, A.M. Clarke: Science, **253** (1991) pp.82-85.
3. H.Hosoi, S.Imaizumi, T.Sakaguchi, M.Tonoike, K. Murata: The Lancet, **351** (1998) pp. 496-497.
4. S. Nakagawa, Y. Okamoto, Y. Fujisaka: Trans. Jpn.Soc.Med.Bio.Eng.,**44**(1) (2006) pp.184-189.
5. T. Nishimura, S. Nakagawa, T. Sakaguchi, H. Hosoi: Hear. Res., **175** (2003) pp. 171-177.
6. S. M. Khanna, J. Tonndorf, J. E. Queller: J. Acoust. Soc. Am. **60**(1) (1976) pp. 139-154.
7. K. Ito, S. Nakagawa: Jpn. J. Appl. Phys., 49 (2010) pp. 07HF31 1-7.
8. B. Håkansson, P. Carlsson, A. Brandt, S. Stenfelt: J. Acoust. Soc. Am. **99**(4) (1996) pp. 2239-2243.

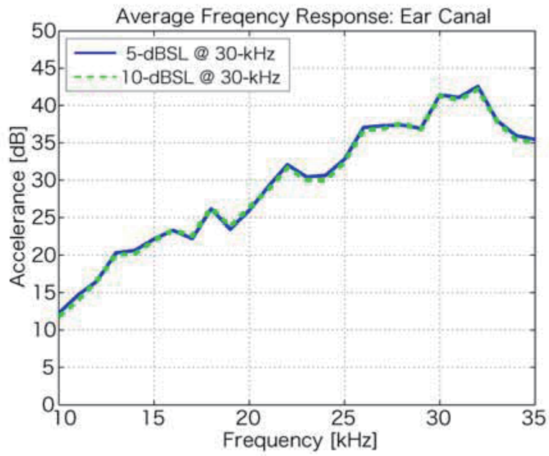

Fig. 1 Accelerances of the head vibration from an audible to ultrasonic range. The solid and broken lines indicate different excitation force levels.

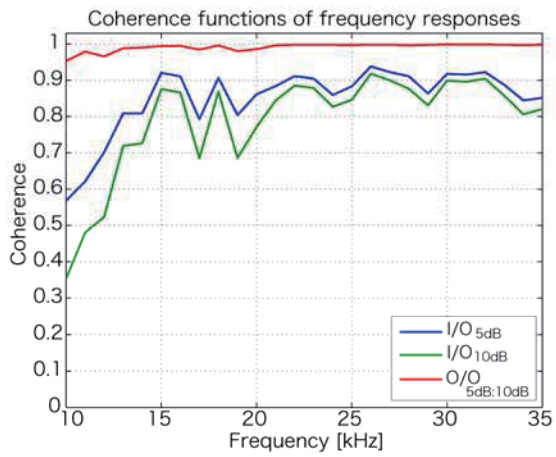

Fig. 2 Coherence functions. The blue and green lines indicate relations between input and output with different excitation levels. The red line indicates a relation between the two outputs with different excitation force levels.