Proceedings of Symposium on Ultrasonic Electronics, Vol. 36 (2015)
5-7 November, 2015

Propagation Characteristics of the Bone-conducted Ultrasound in the Living Human Head: Estimation of the Propagation Delay by Gabor Wavelet Analysis

骨導超音波の頭部内伝搬特性 -ガボールウェーブレット解析による伝搬遅延特性の推定

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1. Introduction

An ultrasound with frequency above 20 kHz (up to about 100 kHz) can be heard via bone-conduction (BC)[1)]. This “audible” ultrasound through BC is referred to as the bone-conducted ultrasound (BCU). The perception mechanisms of BCU, however, have still unclear. For the better understanding of the perception mechanisms of BCU, various approach have been made: estimation of the propagation process of BCU in the head by using computer simulations or actual measurements is one of these approaches. In the previous studies, we estimated the propagation velocity of BCU in a living human head as approximately 300 m/s by using the pattern of acoustic interference of simultaneous bilateral excitation[2)]. Further, we estimated the characteristics of the propagation delay of ultrasonic sinusoidal pulse by using across-frequency phase disturbance of the acceleration responses[3)]. In this method, however, it was difficult to detect the precise delay of paths if there are frequency dispersion in the transmission pathways. On the other hand, the existence of frequency dispersion of the propagation delay can be useful information for identification of the pathway and the mode.

Overall characteristics of the propagation delay of a transmission system is generally obtained by calculating the impulse responses. Meanwhile, propagation delay characteristics at a particular frequency can be roughly obtained by measuring responses to a short term sinusoidal wave or calculating the spectrogram of the impulse response. However, when dealing with relatively low frequency transmission with using these methods, there is a problem concerning time resolution since the resolution of the delay depends on the wavelength of the signal or the length of the time window the of short-time FFT.

In order to detect the precise propagation delay at a particular frequency, we had focused on a phase interference caused at the time of arrival of the delayed components in the responses for a sinusoidal input signal in a multipath propagation environment.

Previously, authors have attempted to detect the propagation delay of BCU in the head with utilizing the fact that the instantaneous frequency of sinusoidal wave responses varies greatly during the phase interference caused by the delayed components[4)]. However, there were problems related to isolate the signal with artifacts since the variation of the instantaneous frequency is easily caused not only by the phase interference with delayed components but also by artifacts such as noise.

To detect the phase interference caused by the delayed components of the sinusoidal wave responses, this study focused on the detectability of discontinuous parts of signal with the wavelet analysis[5)]. In particular, considering ease of designing filter shape in the case of using a complex Gabor filter as a base wavelet, this study attempted to obtain the frequency-specific delay characteristics of the BCU in the human head by using Gabor wavelet analysis.

2. Measurements

2.1 Methods

In the measurement, the impulse responses were measured for the living human head. Sinusoidal wave responses of the BCU were obtained by convolution of the measured impulse response and the sinusoidal waves. Gabor wavelet analysis was applied to these pseudo-sinusoidal wave responses and the delay characteristics were extracted from the analysis output.

2.2 Impulse Response Measurements

The measurement setup is shown in **Fig.1**. Vibrators (Murata Manufacturing MA40E7S) were attached onto the subjects’ mastoid processes and accelerometers (Ono Sokki NP3211) were placed at the left and right ear canal entrances.

A time-stretched pulse (TSP) signal with 2^{17} samples was used as an excitation signal. The excitation signals were presented unilaterally and the acceleration responses at ipsi- and contra-lateral ears were recorded. In order to improve the SN ratio of the response signals, 500 times averaging was

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performed for each measurement. Impulse responses were calculated by convolving the inverse filter of the original TSP signal with the responses.

The excitation signals were synthesized digitally with a sampling frequency of 800 kHz, generated through a 16-bit AD/DA converter (National Instruments, PXI-6120). The analog signals from the accelerometers were converted to digital signals by the AD/DA converter with a 16-bit and 800-kHz sampling and stored in a PC.

2.3 Gabor Wavelet Analysis

A complex Gabor filter is defined as the product of a Gaussian kernel times a complex sinusoid, i.e.

$$g(t) = ke^{i\theta}w(at)s(t) \tag{1}$$

Where,

$$w(t) = e^{-\pi t^2}, \tag{2}$$

$$s(t) = e^{j(2\pi f_0 t)}. \tag{3}$$

Here k, θ, a, and f_0 are filter parameters: the peak filter response is at f_0, and the half-magnitude bandwidth is approximately equal to a.

In the Gabor wavelet analysis, the filters which denoted in **Eq.1** were applied to the pseudo-sinusoidal responses generated from the measured impulse responses convolved with a 30-kHz continuous sinusoid for frequency channels with the center-frequencies f_0 logarithmically spaced 100 points from 10 to 400 kHz. Parameters of the filter were set as follows: k=1, θ=0, and a=0.35.

3. Results and discussion

Figs.2 and **3** show the results of Gabor wavelet analysis for ipsi- and contra-lateral transmission, respectively. In each figure, the upper panels show the pseudo-sinusoidal wave responses and the lower panels show the decibel notation of the absolute value of the complex output of the wavelet analysis.

In the Gabor wavelet analysis, generally a wedge-like pattern of amplitude with wide at low center frequencies and narrow at high center frequencies occurs at the discontinuous portion of the signal$^{5)}$. In the lower panels of **Figs.2** and **3**, in addition to the increasing amplitude corresponding to the frequency of the sinusoidal wave, wedge-like amplitude increasing portions occurred in corresponding to the delay time of the first arrival component and subsequent parts.

However, in the contralateral response, the wedge-like portion also occurred even when the signal was not yet reached while the amplitude was relatively small. Isolating the wedge which was derived from the delay characteristics from these across-channel portion which might be derived from noise is a future challenge.

If these information concerning the delay in the outputs of Gabor wavelet analysis for sinusoidal wave responses can be abstracted effectively for various frequencies, it is thought to become possible to obtain across-frequency delay characteristics of BCU transmission in the head.

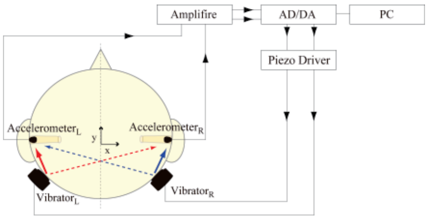

Fig. 1. Experimental set-up for the impulse response measurement of BCU in a human head.

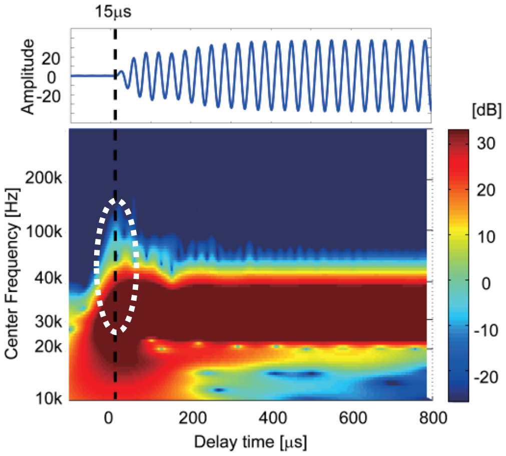

Fig. 2. Wavelet analysis for ipsi-lateral transmission of right-side excitation.

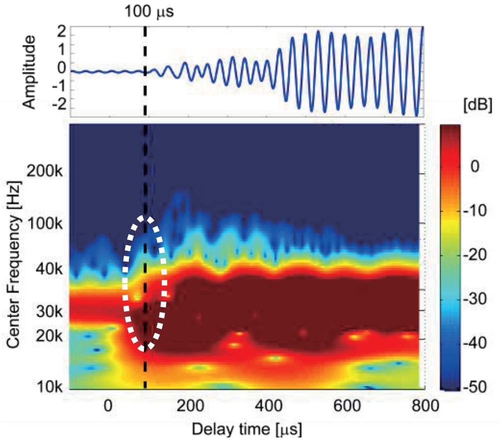

Fig. 3. Wavelet analysis for contra-lateral transmission of right-side excitation.

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