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Fast Decomposition Method Based on Adaptive Beamforming Technique with a Phase Rotation Parameter for the Analysis of Two Wave Phenomenon in Cancellous Bone

適応型ビームフォーミングを用いた高速分析法による海綿骨中の超音波 2 波伝搬現象解析

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1. Introduction

Quantitative ultrasound (QUS) is the modality that estimates the bone quality using the ultrasound signals passing through bone [1]-[3]. The ultrasound signal passing through cancellous bone is supposed to consist of two longitudinal waves, that is fast and slow waves [4]-[6]. Because the analysis of two wave phenomenon should reveal the bone quality, it is very important to decompose two waves accurately for the bone quality assessment.

We have proposed a fast decomposition method that uses adaptive beamforming technique [7],[8]. A previous work shows that the waveform of the ultrasound signal that passes through cancellous bone changes not only the specimen thickness but also transducer size [9]. In the present study, we apply this method to ultrasound signals received by various transducer sizes in a simulation study.

2. Materials and Methods

2.1 Simulation settings

We used the elastic FDTD simulation to acquire the ultrasound signal that passes through cancellous bone [10]. The three-dimensional bone model was created using X-ray micro-focus computed tomography (CT) images (SMX-100CT, Shimadzu, Kyoto, Japan) of a bovine cancellous bone sample. The bone model dimensions were 15×15×6 mm^3 and the simulation field dimensions were 16×16×13 mm^3. A single sinusoidal ultrasound wave of a 1 MHz center frequency was radiated from a flat transmitter. The ultrasound signal passing through cancellous bone was received by a receiver placed opposite the transmitter. We used square transducers with side lengths of 6.4, 9.7, 12.9 and 16 mm.

2.2 Wave transfer function

Several studies assume that two waves are propagating through cancellous bone that exhibits linear-with-frequency attenuation. This model neglects the effect that there will be multiple paths with various path lengths during ultrasound propagation through cancellous bone. Because the ultrasound wave is typically received by a flat transducer, the uneven wavefront should change the waveform of the received signal. We approximated this effect using the following equations:

$$S_{\mathrm{R}}(f) = S_{\mathrm{I}}(f)\left[F_{\mathrm{T1}}(f)H_1(f) + F_{\mathrm{T2}}(f)H_2(f)\right], \quad (1)$$

where $S_{\mathrm{R}}(f)$ is a frequency component of the received signal passing through a bone specimen in water at frequency f, $S_{\mathrm{I}}(f)$ is the same component passing through a water-only path, $F_{\mathrm{T1}}(f)$ and $F_{\mathrm{T2}}(f)$ are the frequency components of the effect that originate from the multiple paths, and $H_1(f)$ and $H_2(f)$ are the transfer functions for the fast and slow waves, respectively.

We approximate that the effect of the uneven wavefront caused by multiple paths in the main frequency band is expressed by the following formula:

$$F_{\mathrm{T}i}(f) \cong A_{\mathrm{T}i} \exp\left[-\gamma_i f + \mathrm{j}(\delta_i f + \theta_i)\right], \quad (2)$$

where $A_{\mathrm{T}i}$, γ_i, δ_i and θ_i are real constants. $\gamma_i f$ and $\mathrm{j}\delta_i f$ denote the attenuation and the time shift caused by the arrival time distribution at the receive element, respectively. We call θ_i the phase rotation parameter which is independent of f. The transfer function with the rotation parameter is expressed by the following formulae [8]:

$$H_i'(f) = F_{\mathrm{T}i}(f)H_i(f)$$
$$= A_i' \exp\left[-\beta_i' fd + \mathrm{j}\left\{\frac{2\pi fd}{c_i(f)} - \frac{2\pi fd}{c_{\mathrm{W}}}\right\} + \mathrm{j}\delta_i f + \mathrm{j}\theta_i\right], \quad (3)$$

$$A_i' = A_i A_{\mathrm{T}i}, \quad (4)$$

$$\beta_i' = \beta_i + \frac{\gamma_i}{d}, \quad (5)$$

A_i is the signal amplitude parameter that is independent of f, β_i is the attenuation coefficient in the conventional model, d is the bone specimen thickness, $c_i(f)$ is the phase velocity, and c_W is the sound velocity in water.

3. Results and Discussion

Fig. 1 shows the fast and slow waves estimated by the proposed decomposition method for a specimen thickness of 6 mm in the simulation study, where the transducer size was 6.4 mm. Fig. 2 shows the residual intensity normalized with respect to the received signal intensity over the fitting region, where the transducer size ranged from 6.4 to 16 mm. These results demonstrate the high performance of the proposed method in accurate decomposition of two waves.

Fig. 3 shows the phase rotation parameters for fast and slow waves, where the transducer size ranged from 6.4 to 16 mm. The phase rotation variation of slow wave caused by the change in the transducer size was smaller than that of fast wave.

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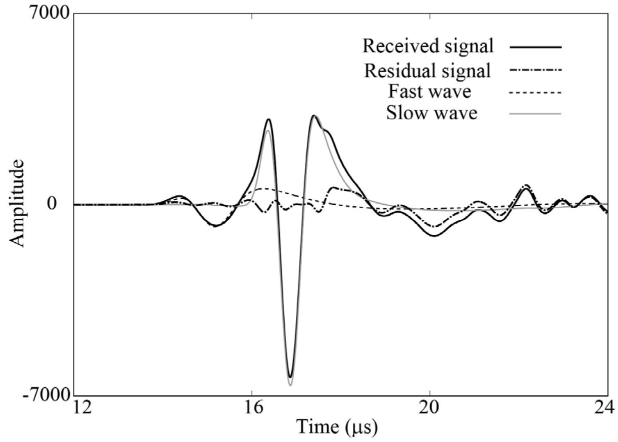

Fig. 1 Fast and slow waves estimated by the proposed decomposition method in the simulation study, where the specimen thickness was 6 mm and the transducer size was 6.4 mm.

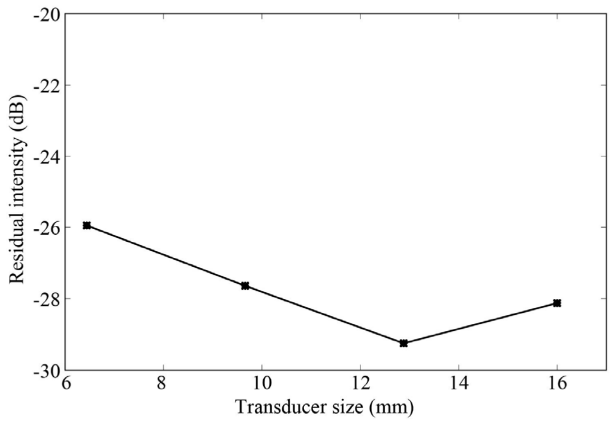

Fig. 2 Residual intensity normalized with respect to the received signal intensity over the fitting region for specimen thickness of 6 mm, where the transducer size ranged from 6.4 to 16 mm.

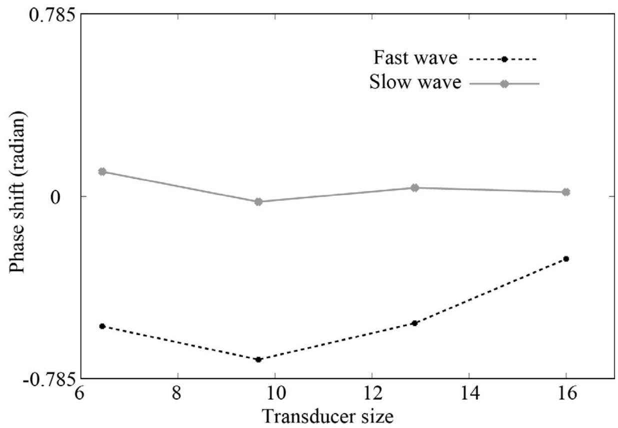

Fig. 3 Phase rotation parameters for fast and slow waves for specimen thickness of 6 mm, where the transducer size ranged from 6.4 to 16 mm.