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Determining Fast and Slow Ultrasound Waves in Cancellous Bone Using Frequency Domain Interferometry : Application to Simulation Data

周波数領域干渉計法を用いた骨伝導超音波の二波分離:シミュレーションデータへの適用

Hirofumi Taki[1], Yoshiki Nagatani [2,3], Mami Matsukawa [4] and Toru Sato[1]
([1]Kyoto Univ.; [2]Kobe City Coll. Tech.; [3]CNRS / Univ. Paris-Est Créteil; [4]Doshisha Univ.)
瀧宏文 [1]，長谷 芳樹 [2,3]，松川 真美 [4]，佐藤亨 [1]
([1] 京都大学, [2] 神戸市立工業高等専門学校, [3]CNRS・パリ東大学クレテイユ, [4] 同志社大学)

1. Introduction

Osteoporosis is a disease that causes the increased possibility for the bone fracture risk. Quantitative ultrasound (QUS) has the potential to diagnose osteoporosis [1]-[3]. It is known that the received signal of QUS in cancellous bone consists of the fast and slow longitudinal waves [4]-[6]. The decomposition of fast and slow waves provides the information of cancellous bone that is supposed to be a good indicator of bone change caused by osteoporosis in an early stage. Therefore, the fast and accurate characterization of the fast and slow waves is desirable for the screening of osteoporosis.

For the purpose of high-range-resolution ultrasound imaging we have employed frequency domain interferometry (FDI) [7][8]. This method suppresses the contribution of undesired signals subject to a constant response to a desired signal. In this study, we employ the FDI imaging method to extract the two waves from the received signal.

2. Materials and Methods

The FDI imaging method extracts signals from received data, where the signals have the same waveform as a desired signal. Therefore, the extraction of fast and slow waves requires proper selection of desired signals that have the same waveforms as the fast and slow waves. In this study, we prepare various candidates for fast and slow waves, where the candidates are constructed by using the transfer function that satisfies the Kramer-Kronig relations for media exhibiting linear-with-frequency attenuation coefficients [9][10].

The FDI imaging method outputs the estimated intensity profile for each desired signal. The frequency components of a received signal are normalized by those of each desired signal. A frequency component of a received signal is expressed by the following formula:

$$X_{\mathrm{H}l} = X_l X_{\mathrm{R}l}^{\ *} \Big/ \left(\left| X_{\mathrm{R}l} \right|^2 + \eta \right), \tag{1}$$

where X_l, $X_{\mathrm{H}l}$ and $X_{\mathrm{R}l}$ are respectively the l-th frequency component of the received signal, that of the received signal after normalization, and that of the desired signal, $[]^*$ denotes the complex conjugate, and η is a constant term for stabilization. The estimated intensity profile calculated by the FDI imaging method is expressed by the following formula:

$$P_{\mathrm{CAP}}(r) = \frac{1}{\mathbf{C}^{\mathrm{T}*} \left(\mathbf{R} + \eta' \mathbf{E} \right)^{-1} \mathbf{C}}, \tag{2}$$

$$\mathbf{C} = \left[\mathrm{e}^{\mathrm{j}k_1 r} \quad \mathrm{e}^{\mathrm{j}k_2 r} \quad \cdots \quad \mathrm{e}^{\mathrm{j}k_N r} \right]^{\mathrm{T}}, \tag{3}$$

where $\mathbf{R}$ is the covariance matrix of a received signal after frequency averaging, $[]^{\mathrm{T}}$ denotes the transpose, $\eta'\mathbf{E}$ is a diagonal loading for stabilization, $r/2$ is the measurement depth, and k_l is the wavenumber of the l-th frequency component.

The proposed method chooses the candidates for the fast and slow waves by using the FDI intensity profile. We use a linear least squares method to select the fast and slow waves from the candidates. The extraction of the fast and slow waves from a received data requires less than 10 s using a Desktop PC with a single CPU.

3. Results

We investigated the performance of the proposed method in a simulation study by using a 3D elastic finite-difference time-domain (FDTD) technique [11]. We used X-ray CT images of actual cancellous bone specimens to construct bone specimens of various thicknesses used in the simulation study. Fig. 1 shows the candidates for a fast wave constructed by using the transfer function based on the Kramer-Kronig relations. The employment of multiple candidates with different specimen thickness enables to prepare candidates of

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E-mail address: htaki@i.kyoto-u.ac.jp

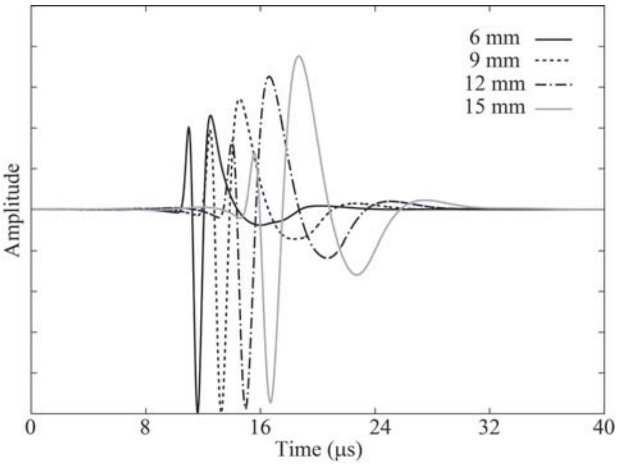

Fig. 1 Waveform of the candidates for a fast wave constructed by using the transfer function based on the Kramer-Kronig relations

various waveforms. Therefore, the proposed method may satisfy the condition that each of the fast and slow waves is similar to at least one of the candidates in waveform, without a priori information about the specimen thickness and accurate attenuation coefficients.

Fig. 2 shows the waveforms of the fast and slow waves estimated by the proposed method for the simulation data of 9 and 12 mm bone specimens. This result indicates that the proposed method has high accuracy in extracting fast and slow waves from a received signal acquired by QUS. The residual intensities of 9 and 12 mm bone specimens were −28.5 and −25.6 dB lower than the intensities of the received signals, respectively.

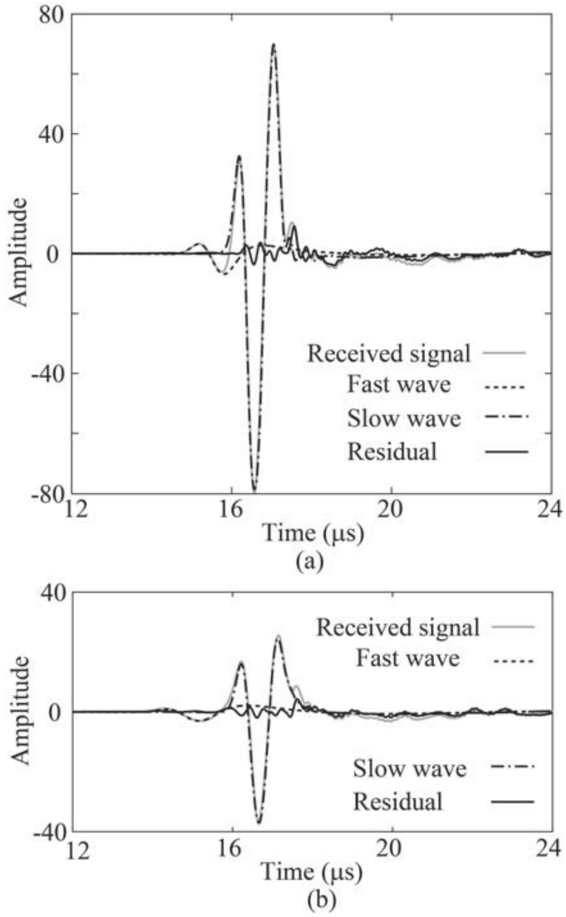

Fig. 2 Waveforms of the fast and slow waves estimated by the proposed method for the simulation data of (a) 9 and (b) 12 mm bone specimens.

4. Conclusion

In the present study, we proposed a decomposition method of two waves in cancellous bone based on FDI imaging method. The proposed method requires less than 10 s for the accurate extraction of two waves from a received signal.

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