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Time-Frequency Representation of Ultrasonic Wave Transmitted Through Cancellous Bone: Analysis Method Based on Instantaneous Frequency

海綿骨伝搬超音波の時間周波数表現：瞬時周波数に基づく解析手法の検討

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1. Introduction

Ultrasonic propagation properties of the cancellous bone are strong tools for diagnosis of osteoporosis. Hosokawa and his colleagues have demonstrated the two-wave phenomenon: two distinct longitudinal waves, denoted as fast and slow waves, were observed when a single short pulse was transmitted to a piece of the cancellous bone in water [1,2]. The fast wave is propagated mainly through the cancellous bone, whereas the slow wave is transmitted via water. The wavefront timing and peak amplitude of received fast wave have reported to be strongly correlated with the bone volume fraction of tested specimen [3,4]. Characteristics of multipath propagation in the complex network of trabecular bone may be reflected in deformations of the fast wave [5]. Thus, detailed analyses of time-frequency properties of the fast wave would enable us to obtain more information about the cancellous bone structure.

In the present study, we propose a novel signal processing method based on the instantaneous frequency (IF) to analyze detailed time-frequency properties of the received waves. Here, we tested usefulness and applicability of the proposed method using numerically simulated data.

2. Methods

2.1. Incident signal

A pair of Gaussian-windowed waveforms that have distinct initial phases of 0 and π/2 was used as incident signals:

$$g_R(t) = e^{-t^2/2\sigma_g{}^2} \cdot \cos 2\pi f_g t \quad (1)$$

$$g_I(t) = e^{-t^2/2\sigma_g{}^2} \cdot \sin 2\pi f_g t \quad (2)$$

where, t is time, σ_g is a width of Gaussian window, and f_g indicates signal frequency. In the experiment, we fixed f_g = 1 MHz and σ_g = 0.79 µs.

2.2. Simulation of wave propagation

The finite-difference time-domain (FDTD) simulation of wave propagation was performed in the similar way as described in Nagatani et al. (2009) [5]. The simulated situation was that a piece of bovine cancellous bone with size of 20 × 20 × 9 mm^3 was set between a pair of facing transmitter and receiver in a water filled chamber. The sampling step of simulation was 5 ns. To test an influence of trabecular thickness on IF of the fast wave, we varied thresholds among 112 (thickest), 120, 128, 136 and 144 (thinnest) to binarize 3D-CT data of the bone specimen. A white noise was added to the received signal with a level at -96 dB from an amplitude peak of the received waveform.

2.3. Analysis

Raw IF: Two received signals, $s_R(t)$ and $s_I(t)$ corresponding to two incident signals were regarded as the real and imaginary part of a complex signal $s(t)$. Then, the IF, $f_{ins}(t)$, was obtained as the time derivative of argument of the complex signal:

$$s(t) = s_R(t) + i s_I(t) \quad (3)$$

$$f_{ins}(t) = \frac{1}{2\pi}\frac{d \arg[s(t)]}{dt} \quad (4)$$

Multichannel IF: When the signal has two or more salient spectral components, the raw IF does not accurately represent actual spectral property of the signal because of temporal distortions of the instantaneous phase. Here, we propose a method to improve IF accuracy and to eliminate the distorted intervals using inter-channel variabilities of IFs derived from a multichannel filterbank. Impulse responses of the filters were the Gabor function. The filtering of signal $s(t)$ results in the short-time Fourier transform (STFT), $S(t, f)$. Then, the multichannel IF, $F_{ins}(t, f)$, was obtained as the time derivative of argument of $S(t, f)$:

$$S(t, f) = \int_{-\infty}^{\infty} e^{-(\tau-t)^2/2\sigma^2} s(\tau)\, e^{-i2\pi f\tau} d\tau \quad (5)$$

$$F_{ins}(t, f) = \frac{1}{2\pi}\frac{\partial \arg[S(t,f)]}{\partial t} \quad (6)$$

where, σ is width of Gaussian window, and f indicates center frequency of each filter channel. In this experiment, σ was fixed at 0.25 µs. The F_{ins}

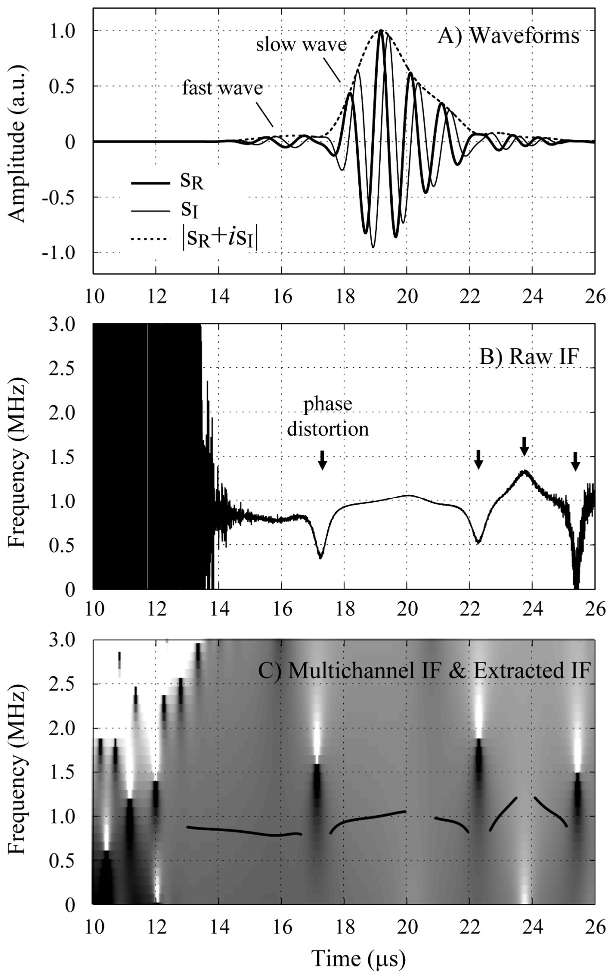

Fig. 1. Examples of received waveforms and amplitude envelope (A), raw IF (B) and extracted stable IF superimposed on multichannel IF map (C).

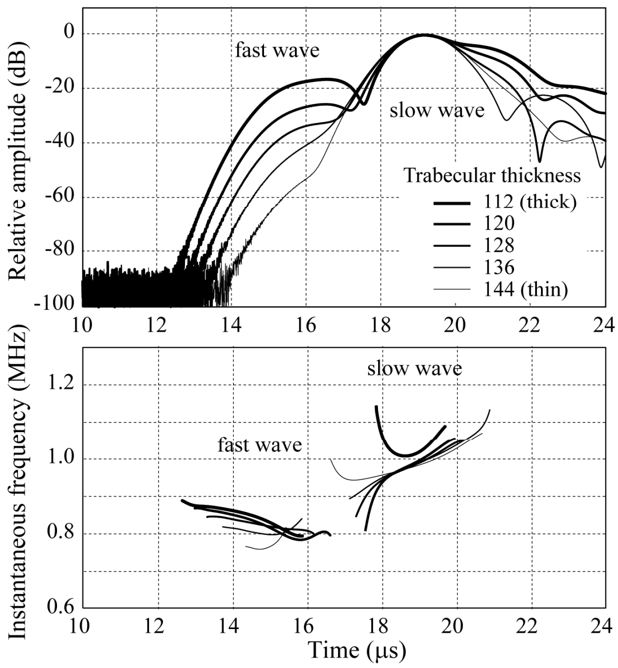

Fig. 2. Influence of trabecular thickness on the amplitude envelope (upper panel) and the extracted IF (lower panel).

agrees with the filter center frequency at a spectral peak of the input signal, and has a plateau around the peak on the frequency axis, called as 'fixed point' [6]. Then, we extracted IFs corresponding to the filter center frequency within spectrally stable areas where F_{ins} slope was between 0 and 0.5 Hz/Hz and its curvature was between -0.003 and 0.003 Hz/Hz^2 on the frequency axis.

3. Result & Discussion

The fast and slow waves were observed in the FDTD-simulated waveforms (**Fig.1A**). The raw IF showed rapid fluctuations at time points where two waves appeared to be overlapped, and was quite noisy if the signal level was very low (**Fig.1B**). The multichannel method successfully eliminated the irregularly fluctuated interval of the raw IF, with differentiating the fast wave and other waves (**Fig.1C**). The extracted IF represented a precise tracking of spectral peak of the signal. It was also found that IF of the fast wave was lower than that of the slow wave (**Fig.2B**), consistent with previous studies indicating low-pass like spectral characteristics of the cancellous bone [1,7]. Moreover, IF of the fast wave appeared to tend to descend gradually irrespective of trabecular thickness (Fig.2B). This tendency may be attributed to the nature of multipath propagation in the trabecular network that the low-pass effect should depend on total length of propagation path, suggesting a possibility that the descending IF of the fast wave predicts a richness of the trabecular network in the cancellous bone.

4. Conclusion

The present study proposed a novel method based on the IF to analyze detailed time-frequency properties of ultrasonic waves transmitted through the cancellous bone. As result of the analysis on FDTD-simulated data, our method displayed the IF trajectory of the fast and slow waves, and suggested a descending tendency of IF of the fast wave.

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