3Pa5-13

Proceedings of Symposium on Ultrasonic Electronics, Vol. 32 (2011) pp. 421-422
8-10 November, 2011

Frequency dispersion of fast and slow wave velocities in cancellous bone

Katsunori Mizuno[1†], Keisuke Yamashita[1], Mami Matsukawa[1], Takahiko Otani[1], Hiroko Aida[2] and Hirokazu Tsubone[3] ([1]Doshisha Univ.; [2]JRA Equine Research Institute; [3]Univ. Tokyo)

1. Introduction

Recent bone sonometry devices often use speed of sound (SOS) to assess the osteoporosis. However, the porous heterogeneous architecture of cancellous bone, which is often used as an indicator of osteoporosis, makes it difficult to measure SOS. This porous architecture in cancellous bone also induces the characteristic wave propagation of two longitudinal waves, known as fast and slow waves [1]. In addition, it has been reported that the fast wave speed is strongly related to bone structure [2].

Wave velocities are often determined by time-of-flight (TOF) measurements of pulse waves although the group velocity can be affected by the frequency dispersion. There are a few *in vitro* studies on the frequency dependence of two waves because the fast and slow waves are often ovelapped in the time domain, causing the difficulty for the analysis of each wave. If overlapped waves are treated as one wave, negative dispersion of phase velocity often occurs and causes the error of SOS [3]. In this study, we have experimentally succeeded in the measurement of clearly separated two-wave propagation in the cancellous bone and estimated the frequency dispersion of fast and slow wave velocities.

2. Materials and methods

2. 1 Sample preparation

A cross-sectional cancellous bone was obtained from the distal part of the left radius of a racehorse (thoroughbred, 36-month-old, female). The size of the cancellous bone was 76.1×45.2×12.9 mm^3. The specimen was defatted before the measurements by boiling.

2. 2 Measurements

2.2.1 Ultrasonic measurements

Measurements of longitudinal wave were performed using a conventional ultrasonic pulse technique as shown in **Fig. 1**. A PVDF focus transmitter (diameter 20 mm, focal length 40 mm) and a PVDF flat receiver (diameter 10 mm) were used in this experiment. The beam width at the half maximum values of the wave amplitude was approximately 1.5 mm at the focal point. Both PVDF transducers were mounted coaxially with distance of 60 mm in degassed water at about 25°C. One-cycle sinusoidal signal with a center frequency of 1 MHz and amplitude of 50 $V_{p\text{-}p}$ was applied to the transmitter. The longitudinal wave propagated through water, sample and water. The other transducer received the wave, and converted it into the electrical signal. The received signal was amplified by a 40-dB preamplifier and visualized in an oscilloscope. The focal zone of the sound field was set at the surface of the specimen. The trabecular in specimen was well aligned along the direction *y*. The specimen was moved in *x*-*z* plane and the waves were investigated at some measurement points. The bone parameters, such as mean intercept length (MIL) and bone volume fraction (BV/TV) [4] of the specimen were obtained using X-ray micro-CT (SMX100-CT Shimadzu).

2.2.2 Data analysis

The phase velocity is estimated by the following equation,

$$v_{phase}(\omega) = v_{water}\left[1 - \frac{v_{water}}{d}\frac{\Delta\varphi(\omega)}{\omega}\right]^{-1} \quad (1)$$

where v_{water} is the velocity in water, d is the sample thickness, $\Delta\varphi(\omega)$ is the phase difference between the waves which passed sample and only in water, and ω is angular frequency.

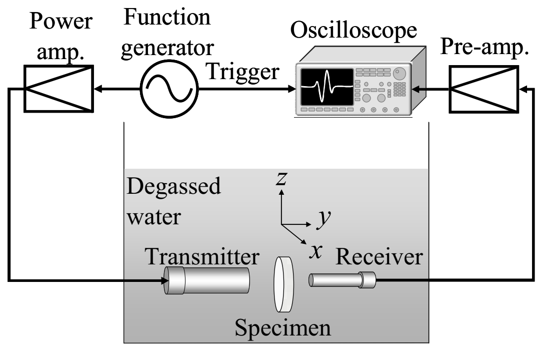


Fig. 1 Measurement system.

mmatsuka@mail.doshisha.ac.jp

3. Results and discussion

3.2 Observed waveforms

Typical observed waveforms are shown in **Fig. 2**. The fast and slow waves were clearly observed at all measurement points without overlapping. We then obtained the fast and slow waves from the original waveforms. The obtained waves of fast and slow waves are represented as dashed lines as shown in Fig. 2.

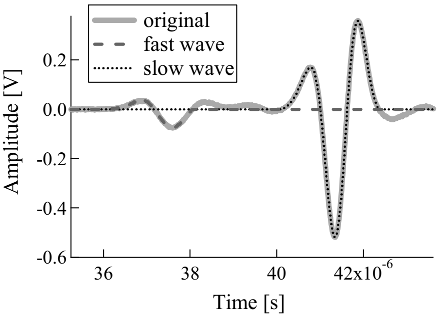


Fig. 2 Experimentally observed waveforms (solid line: original waveform, dashed line: fast wave, dotted line: slow wave).

3.2 Phase velocities of fast and slow waves

Figure 3 shows the amplitude spectra of observed waves. As a reference, the amplitude spectrum of the original wave with both fast and slow waves is shown. The center frequency of the fast wave was 480 kHz and that of slow wave was 750 kHz. The typical phase velocities of the fast and slow waves are shown in **Figs. 4(a) and 4(b)**. The frequency dependence around the center frequency was investigated. The frequency dispersion of the fast wave velocity was about 40 m/s in the range of 400-600 kHz. On the other hand, the frequency dispersion of the slow wave velocity was not observed in the range of 600-900 kHz. The overlap often occurs but sometimes we cannot find out the existence of overlapping in time domain. In this case, the process of overlapping wave results in the wrong information of wave properties. Especially, the dispersion of fast wave velocity may affect on the group velocity of overlapped wave. Then, we should pay special attention on the SOS.

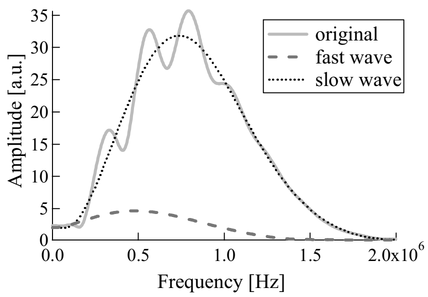
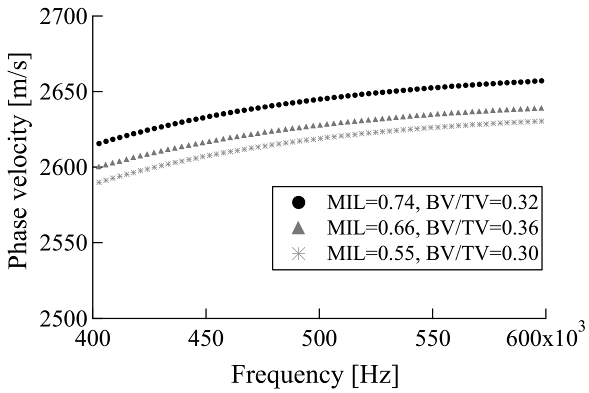
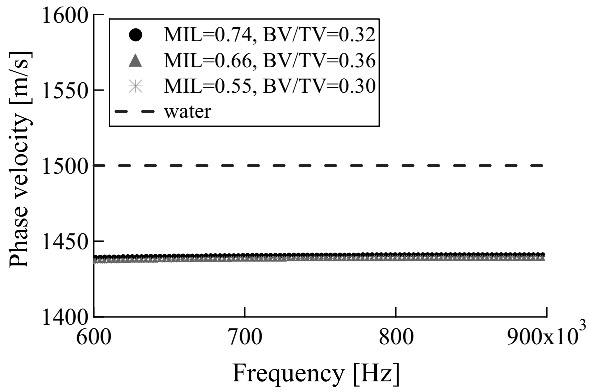


Fig. 3 Spectra of observed waves (solid line: original wave, dashed line: fast wave, dotted line: slow wave).



(a) Fast wave



(b) Slow wave

Fig. 4 Phase velocities of the (a) fast and (b) slow waves at three different points.

4. Conclusion

Ultrasonic wave propagation in the cancellous bone of a racehorse was investigated. The clear separation of fast and slow waves was observed at all measurement points. The center frequencies of the observed fast and slow waves were 480 kHz and 750 kHz, which were lower than that of input signal (=1 MHz). The small frequency dispersion of the fast wave velocity was found, whereas the slow wave velocity did not show dispersion. In addition, the velocity of fast wave varied with MIL and BV/TV which was not found in the slow wave velocity. This information may improve the frequency dependent error of SOS of present QUS system and possibly provide additional parameters for bone assessment.

References

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