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Multi-frequency phase tracking method for estimation of three-dimensional motion velocity

3 次元移動速度推定のための周波数補償付多周波位相追跡法

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1. Introduction

Recently, ultrasound imaging achieves a high temporal resolution of several thousand Hz by using plane or diverging wave. Under such a high temporal resolution, a displacement of a heart wall between successive frames is often smaller than wavelength. To estimate such a minute displacement, we developed a novel tracking method using phases of ultrasonic echoes at multi-frequencies in the 2D frequency domain.[1)] Since biological tissues are moving in axial, lateral, and elevation directions, the estimation accuracy will degrade easily when such 3-D motion is not considered. Hence, for more accurate motion estimation, it is necessary to estimate tissue motion in 3D space under a high frame rate.

In this report, we propose a multi-frequency 3D phase tracking method with a phased-array probe. The proposed method was validated by computer simulation and also compared with the previous 2D method.

2. Materials and Methods

2.1 Method of computer simulation

Ultrasonic volume data were obtained by Field II simulation [2,3)]. A 3-MHz matrix array probe consisting of 32 × 8 elements (pitch: 0.5 mm in every direction) was simulated. The volume data was obtained by a single plane/diverging wave emitted from 256 elements to achieve a high frame rate of 1000 Hz. Plane and diverging wave were transmitted in the elevation and lateral direction from a virtual source. The source was set at a distance of 30 mm behind the array.

The 256 elements was used for the receive beamforming, and beamformed ultrasonic data was created in the Cartesian coordinate system with the horizontal (lateral and elevation) and vertical sampling intervals of 0.2, 0.2 and 0.02464 mm [4], respectively. The volume data was composed of 201 ×51 scan lines (lateral × elevation). The target consisted of 0.6763 scatterers per square wavelength, as shown in **Fig. 1**. The phantom moved at 10 mm/s in lateral, vertical and elevation directions. The moving velocity was varied from 10 mm/s to 70 mm/s.

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Two-dimensional datasets were also obtained

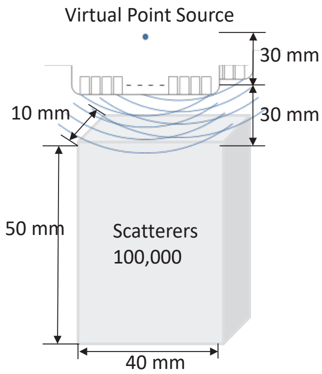

Fig. 1 Simulation model

by simulating the same probe for comparison with the 2D phase tracking method.[1)] The transmit beam was beamformed by acoustic lens in the elevation direction and diverging in the lateral direction. Ultrasonic data was obtained by dynamic parallel receive beamforming.

2.2 3D multi-frequency phase tracking method

The ultrasonic echo datasets consisted of various frequency $(\omega_x, \omega_y, \omega_z)$ components. The 3D frequency spectrum S_n was obtained by FFT and modeled as follows:

$$S_n = A_n \cdot e^{j(\omega_x x + \omega_y y + \omega_z z)}, \quad (1)$$

where A_n was the magnitude of S_n.

When phases of the waves were shifted based on the displacement (u_x, u_y, u_z) between frames, the cross spectrum γ_n was modeled as follows:

$$\gamma_n = A_n \cdot A_{n+1} \cdot e^{-j(\omega_x u_x + \omega_y u_y + \omega_z u_z)}. \quad (2)$$

The displacement was obtained as a least-square solution. The mean squared difference α between the phase of the cross spectrum $\angle\gamma_n$ and its model $\angle\widehat{\gamma_n}$ was defined as follows:

$$\alpha_n = \sum_{f_x, f_y, f_z} w|\angle\gamma_n + \angle\widehat{\gamma_n}|^2, \quad (3)$$

where w was a weight function based on the power spectrum.

Moreover, the mean frequency was obtained by shifting the FFT window in every direction, respectively by spatial sampling intervals $(\delta_x, \delta_y, \delta_z)$ and the phase difference of the cross spectrum φ_n was written as follows:

$$\varphi_n = \omega_x \cdot i\delta_x + \omega_y \cdot j\delta_y + \omega_z \cdot k\delta_z, \quad (4)$$

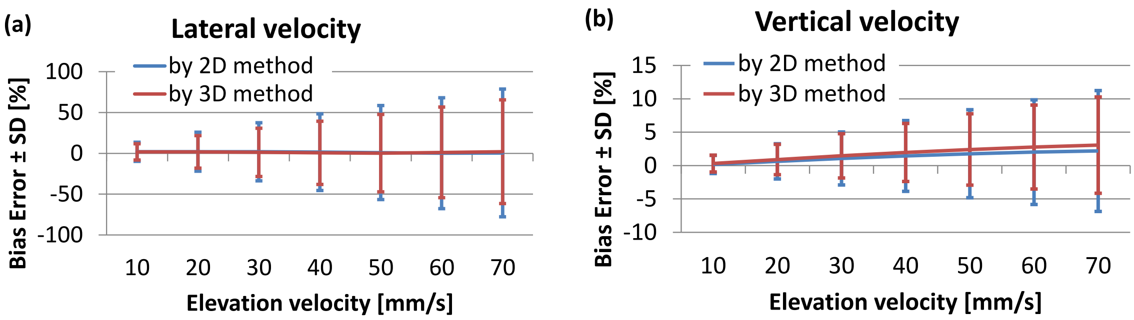

Fig. 2 Bias errors and SDs of velocity in (a) lateral and (b) vertical directions estimated by 2D and 3D multi-frequency phase tracking method when elevation velocity was varied.

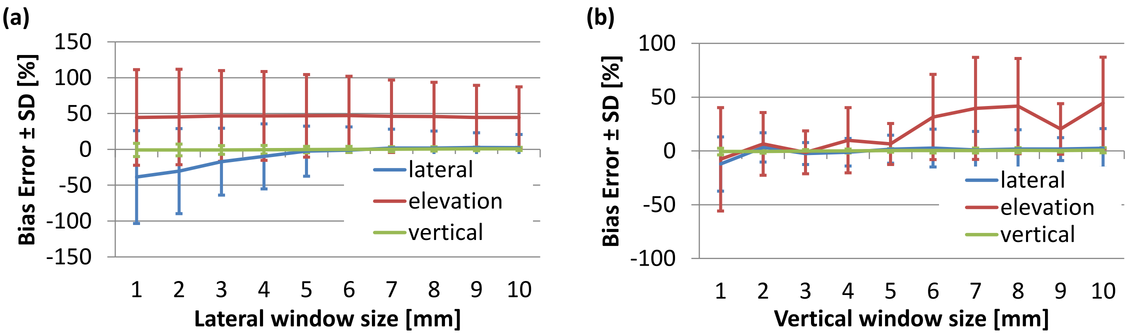

Fig. 3 Bias errors and SDs of velocity estimated by 3D method multi-frequency phase tracking method when FFT window sizes in (a) lateral and (b) vertical directions were respectively varied.

where i, j and k were integers indicating the shifted direction. One of those values was set at 1 and the others were set at 0.

In this study, two kinds of simulation experiments were conducted to evaluate the accuracy of the proposed 3D estimator. First, the phantom was moved at 10 mm/s in lateral and vertical directions and 10-70 mm/s in elevation direction. The FFT window sizes were 10 mm in lateral and vertical directions and 9.8 mm in elevation direction. Then, FFT window sizes in lateral and vertical directions were varied from 1 mm to 10 mm, respectively. In this case, the scatterers moved at 10 mm/s in every direction.

3. Simulation Experimental Results

3.1 Effect of movement in elevation direction

Figure 2 shows bias errors between the true and estimated velocities in every direction and its standard deviations (SDs) by 2D and 3D multi-frequency phase tracking method. The results show that the SDs in both directions increase with increases of the elevation velocity. However, the SD calculated by the 3D method was less than 2D motion estimator.

3.2 Effects of FFT window size on accuracy

Figure 3 shows that bias errors and SDs of velocities estimated with different FFT window sizes. These results show that a FFT window size of about 10 mm in every direction was required to obtain good velocity estimates. A window size of 10 mm was similar to a typical kernel size in the speckle tracking method (STM). However, in STM, a similarity function, such as cross correlation function, needed to be calculated with different lags in every direction to estimate a 3D displacement. Therefore, the STM requires larger volume data.

4. Conclusion

We proposed the multi-frequency 3D phase tracking method with phased-array probe. In this paper, the simulation was performed to compare the proposed method with the previous 2D method. SD was suppressed 29.1 % in lateral and 3.7 % in vertical at elevational velocity of 70 mm/s. With the maximum FFT window size, bias errors and SDs were 2.4±18.3 % in lateral and 0.7±2.7 % in vertical directions.

References

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