1P5-4

Accuracy evaluation of 3D velocity estimation by multi-frequency phase tracking method with matrix array probe
マトリックスアレイプローブを用いた 3 次元位相差追跡法の精度評価

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1. Introduction

Ultrasonic imaging is widely used in clinical situations to measure detailed dynamics of rapidly moving heart wall. Recently, ultrasound imaging achieves a high frame rate of several thousand Hz[1]. Under such a high temporal resolution, a displacement of a heart wall between successive frames is often smaller than a spatial sampling interval. To estimate such a minute displacement, we developed a novel tracking method using phase information of RF echo signals at multi-frequencies in the 2D frequency domain[2]. As biological tissues move three dimensionally, the estimation accuracy degrades easily when such 3-D motion is not considered using a 1D probe. Hence, for more accurate motion estimation, it is necessary to estimate tissue motion in 3D space.

In this report, we propose a multi-frequency 3D phase tracking method with a matrix array probe. The proposed method was validated by performing 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[3,4]. Three 3-MHz matrix array probes consisting of 32×8 (lateral × elevation), 32×16 and 32 × 32 elements (pitch: 0.5 mm in every direction) were used in the simulation experiments. The volume data was obtained by a single plane/diverging (lateral/elevation directions) wave emitted from all elements to achieve a high frame rate of 1000 Hz. The plane and diverging wave were transmitted in the elevation and lateral direction from a virtual source. The virtual source was set at a distance of 30 mm behind the array as shown in **Fig. 1(a)**. RF signals received by the all elements were used for the receive beamforming, and the 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[1], respectively. The volume data was composed of 201×101 scan lines (lateral × elevation). The phantom consisted of 31.62 scatterers per cubic wavelength as shown in **Fig. 1**. The moving velocities were varied from 10 mm/s to 70 mm/s in elevation and fixed at 10 mm/s in lateral and vertical directions.

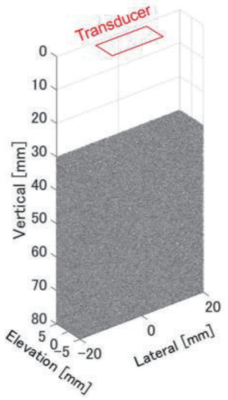

Fig. 1 Simulation model.

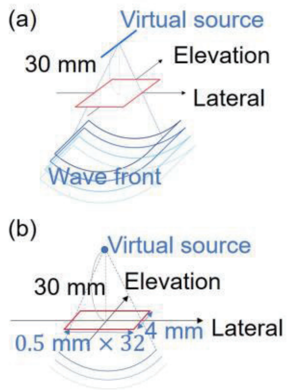

Fig. 2 Transmitted wave.
(a) For 3D datasets.
(b) For 2D datasets.

Two-dimensional datasets were also obtained by simulating a probe consisting of 32 elements (width: 0.5 mm, height: 4 mm) for comparison with the previous 2D phase tracking method[2]. The transmit beam was focused by acoustic lens in the elevation direction and diverged in the lateral direction as shown in **Fig. 2(b)**. The data was obtained by dynamic parallel receive beamforming.

2.2 3D multi-frequency phase tracking method

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

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

where A_n is the magnitude of S_n.

When phases of the signals were shifted based on the displacement (u_x, u_y, u_z) between frames, the 3D frequency spectrum S_{n+1} was modeled as follows:

$$S_{n+1} = A_{n+1} \cdot e^{j\{\omega_x(x-u_x)+\omega_y(y-u_y)+\omega_z(z-u_z)\}}. \qquad (2)$$

The cross spectrum γ_n of S_n and S_{n+1} was modeled as follows:

$$\gamma_n = A_n \cdot A_{n+1} \cdot e^{-j(\omega_x u_x + \omega_y u_y + \omega_z u_z)}. \qquad (3)$$

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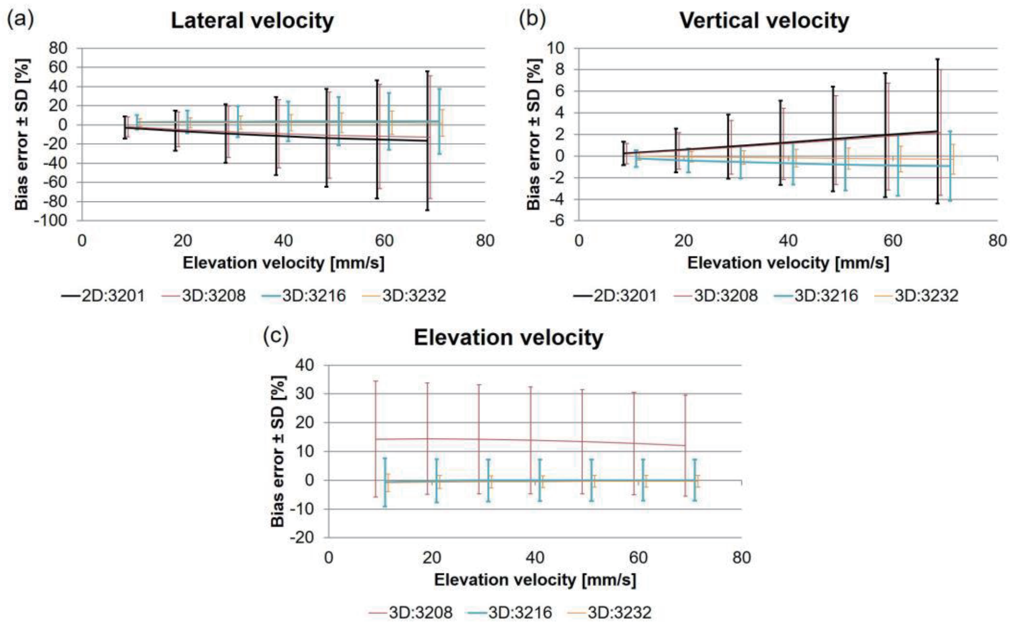

Fig. 3 Bias errors and SDs of velocity in (a) lateral, (b) vertical, and (c) elevation directions estimated by 2D and 3D multi-frequency phase tracking method when elevation velocity was varied.

The model of the phase angle of γ_n was also modeled with the estimated displacement $(\widehat{u_x}, \widehat{u_y}, \widehat{u_z})$ as follows:

$$\angle\widehat{\gamma_n} = -\omega_x \widehat{u_x} - \omega_y \widehat{u_y} - \omega_z \widehat{u_z}. \quad (4)$$

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:

$$\alpha_n = \sum_{f_x,f_y,f_z} w|\angle\gamma_n - \angle\widehat{\gamma_n}|^2, \quad (5)$$

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

Moreover, the mean frequency for the least-square solution was obtained by shifting the FFT window within the same frame. When the FFT window was shifted based on spatial sampling intervals $(\delta_x, \delta_y, \delta_z)$, the displacement in Eq. (2) were replaced by them. The phase difference of the cross spectrum φ_n was written as follows:

$$\varphi_n = \omega_x \cdot i\delta_x + \omega_y \cdot j\delta_y + \omega_z \cdot k\delta_z, \quad (6)$$

where and 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, the simulation experiments were performed to evaluate the accuracy of the proposed 3D estimator with three types of matrix probes. 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 every direction.

3. Simulation Experimental Results

Figure 3 shows bias errors between the true and estimated velocities in every direction and its standard deviations (SDs) by the 2D and 3D multi-frequency phase tracking method.

The result shows both the bias errors and SDs obtained by the 3D method are smaller than those by the 2D estimator in the lateral velocity estimation. Bias errors and SDs decreased following to increase the number of elements in the elevation direction. The bias errors were suppressed using the probe with more than 16 elements. The results show that the SDs in both directions increase with increases of the elevation velocity.

4. Conclusion

We proposed the multi-frequency 3D phase tracking method with a matrix array probe. In this paper, the simulation was performed to compare the proposed method with the previous 2D method. The SD was suppressed by 8.4 % in lateral and 0.9 % in vertical at elevational velocity of 70 mm/s. In the case when a matrix array probe had more elements than 16 in the elevation direction, the bias error by the proposed method could be reduced to less than 10%.

References

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