3P5-1

Numerical simulation for determining minimum beam steering angle for estimation of blood flow velocity vectors

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1. Introduction

High-frame-rate ultrasound imaging achieved an extremely high imaging frame rate of several thousand frames per second. It is excellent for visualization of blood flow dynamics. Also, the flow velocity vectors can be estimated independently of the beam-to-flow angle by applying the vector Doppler method to the visualized echo signals from blood cells [1,2]. However, the echo signals from blood cells are weak, resulting in a low signal-to-noise ratio. To obtain stronger scattered waves from blood cells, the transmission frequency should be increased. This is because the intensities of the echo signals from blood cells are proportional to the fourth power of the frequency due to Rayleigh scattering when the blood cell size is sufficiently smaller than the wavelength of the transmitted wave. In order to receive the echo signal with high sensitivity, it is desirable to activate transducers at a center frequency close to its resonant frequency.

In this study, we used the vector Doppler method with plane wave imaging and the repeated transmit sequence [3]. Plane waves were transmitted in three directions, and axial velocities in the respective directions were measured. When applying the vector Doppler method, a larger beam steering angle during transmission is advantageous for estimating the flow velocity vectors. However, at higher transmission frequencies, a smaller beam steering angle is preferable. This is because grating lobe artifacts adversely affect velocity estimation. In numerical simulations, we evaluated the accuracy of estimating the flow velocity vectors when the beam steering angle is small.

2. Method

2.1 Transmit-receive sequence

In this study, the vector Doppler method was implemented in plane wave imaging with the coherent plane wave compound (CPWC) technique and repeated transmit sequence[3]. **Fig. 1** shows the method of axial velocity estimation in the repeated transmit sequence**.** Plane waves are used for transmission with two transmissions at each steering angle of $-\theta$, 0, and θ. This is done to keep the pulse repetition interval (PRI) as short as possible at each transmission angle and to improve the maximum detection speed. Reception delay-and-sum (DAS) beamforming was performed on the complex radio frequency (RF) signals received by the individual transducer elements to obtain complex beamformed RF signals at each plane wave steering angle.

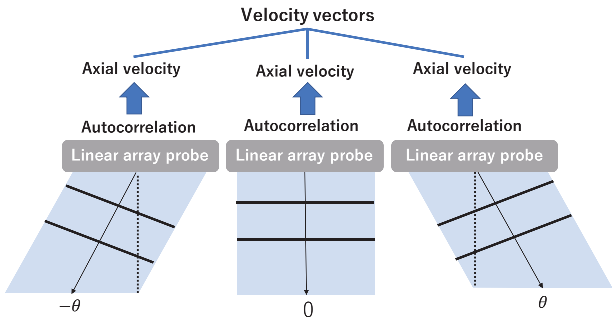

Fig. 1 Illustration of axial velocity estimation in CPWC and repeated transmit sequence.

2.2 Estimation of velocity vectors

To estimate the velocity vectors, a receiving beam was created for each receiving focus. The autocorrelation method[4] was applied to the beamformed RF signals at receive steering angles of $-\theta$, 0, and θ to obtain the wavenumbers in the lateral and vertical directions. From those two-dimensional wavenumbers, the center frequency and beam steering angle were estimated, and the axial velocity was obtained. The autocorrelation kernel size was set at (lateral, vertical) = (1.05 mm, 0.925 mm). Velocity vectors were estimated from the axial velocities obtained at different steering angles in reception using the vector Doppler method.

2.3 Simulation

In this study, Field II [5,6] was used to simulate echo signals received by individual elements when plane waves were transmitted using a linear array probe. The center frequencies were 4.8 and 6.94 MHz. The probe consisted of 192 elements with a pitch of 0.2 mm. Ultrasonic point scatterers were randomly placed in a straight tube with a diameter of 5 mm. These scatterers were moved along the tube axis at maximum velocities of 100, 250, 500, 750, and 1000 mm/s. A parabolic flow was assumed, and the velocity at the interface between the flow and the tube wall was set to zero.

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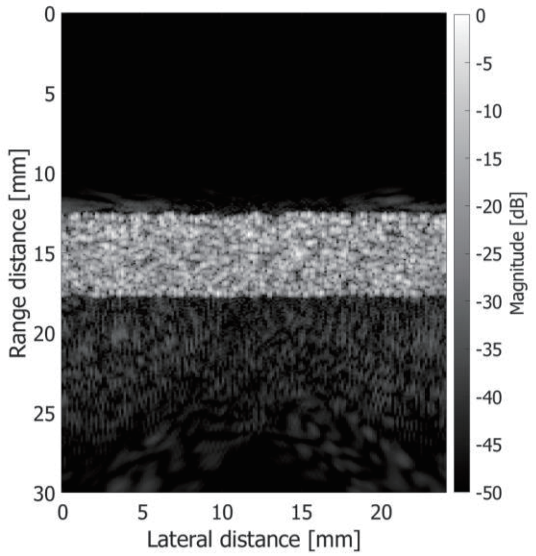

Fig. 2 B-mode image of simulation phantom.

3. Results

Fig. 2 shows a B-mode image of the simulated phantom. Root mean squared error (RMSE) in the estimated velocity vectors were evaluated as

$$\mathrm{RMSE} = \sqrt{\frac{E_{R_f}[|\hat{\mathrm{v}} - \mathrm{v}_{\mathrm{tru}}|^2]}{E_{R_f}[|\mathrm{v}_{\mathrm{tru}}|^2]}}, \quad (1)$$

where $\mathrm{v}_{\mathrm{tru}}$ is the true velocity vector and R_f is the region where the flow phantom exists. **Fig. 3** shows a color map of RMSE values per maximum flow velocity and steering angle at 6.94 MHz. The angle of the grating lobe is about 6.2° at 6.94 MHz and about 37° at 4.8 MHz. In case of 6.94 MHz, RMSE is the minimum of about 8% at steering angles of 10° and 12.5°. Although grating lobes occur, it can be seen that larger angles are more advantageous. **Fig. 4** shows a comparison of the RMSE values of 15° at 4.8 MHz and 10° at 6.94 MHz. Such a comparison was done to determine which is more advantageous between increasing the angle and increasing the frequency. The results show that 6.94 MHz provides a better estimation accuracy for all investigated flow velocities. Therefore, it is shown that the vector Doppler method is more effective even with smaller steering angles at a higher ultrasonic frequency.

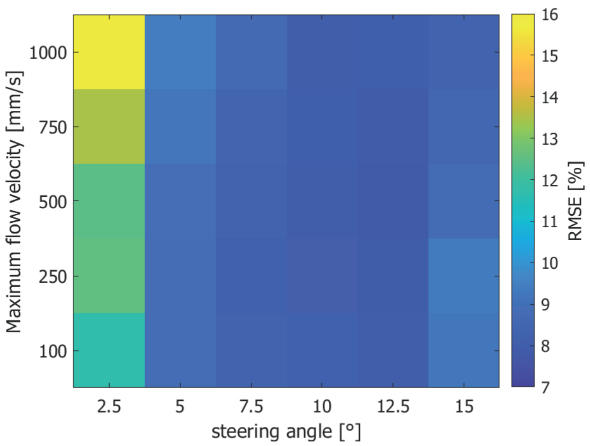

Fig. 3 RMSEs in estimated velocities per maximum flow velocity and steering angle at 6.94 MHz.

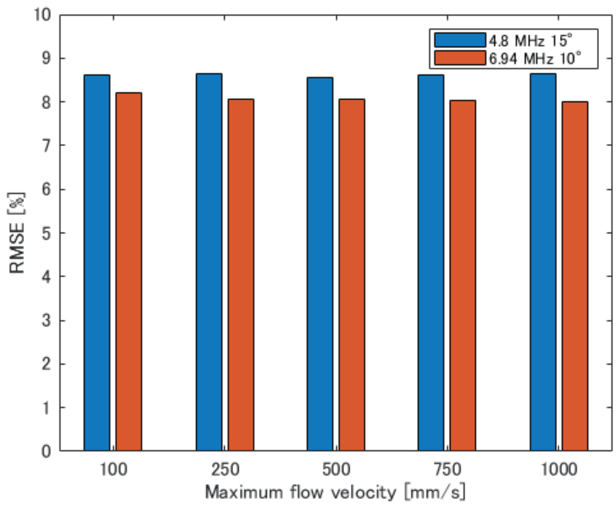

Fig. 4 RMSEs in estimated velocities at different center frequency and steering angle.

4. Conclusion

In this study, simulations were used to evaluate the accuracy of estimating velocity vectors in plane wave imaging using CPWC and repeated transmit sequence when the vector Doppler method is used. The results showed that the estimation accuracy was higher at 6.94 MHz with a small beam steering angle than at 4.8 MHz with a large beam steering angle. This indicates that it is beneficial to use the vector Doppler method with a higher frequency for blood flow imaging.

References

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