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Anti-aliasing method for 2D phase-sensitive motion estimator in ultrasound measurement

超音波計測における 2 次元位相追跡法のアンチエイリアシング法

Michiya Mozumi[1], Ryo Nagaoka[1], Magnus Cinthio[2], and Hideyuki Hasegawa[1]
([1] University of Toyama, Toyama, Japan; [2] Lund University, Lund, Sweden)
茂澄倫也 [1]，長岡　亮 [1]，シンチオ　マグナス [2]，長谷川英之 [1]　([1] 富山大院，[2] ルンド大学)

1. Introduction

In ultrasound imaging, the motion estimation method was employed in some applications, such as the elastography[1-3] and pulse wave imaging[4,5]. The block matching-based method is one of the common methods to track the tissue motion in the ultrasound imaging[6,7]. The block matching method is independent on the ultrasound beam angle and able to acquire the 2D or 3D motion vector. The block matching method, however, requires a spatial interpolation method[7,8] because the spatial resolution of the block matching was limited to the spatial sampling interval.

Meanwhile, phase-sensitive method estimates the tissue motion using phase information of echo signals and estimates the velocity based on the phase difference on complex ultrasound signals between successive frames. In the phase-sensitive method, a computational cost becomes low because a spatial interpolation method is not required. Meanwhile, the phase-sensitive method has an issue on the aliasing effect and cannot obtain an accurate motion estimate when the displacement speed is larger than the aliasing limit. The high-frame rate ultrasound imaging gains attention as an emerging imaging technique, and this technique can increase the aliasing limit. However, even such a case, it is not enough to capture a fast-moving object such as the blood flow in the stenotic artery. Hence, the anti-aliasing method is needed for this reason.

In this study, we proposed the anti-aliasing method for the 2D phase-sensitive motion estimator proposed by our group[9]. The performance of the proposed method is evaluated by simulation experiments.

2. Materials and Methods

2.1 2D phase-sensitive motion estimator [9]

Let us define n-th frame beamformed signals $s(x,z,n)$, where (x,z) is a specific spatial point in a B-mode image. Also, let us define the cross spectrum $\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n) = S(\omega_x,\omega_z,n+\Delta N_\mathrm{F}) \cdot S^*(\omega_x,\omega_z,n)$, where ΔN_F is a frame interval for a motion estimation, and $S(\omega_x,\omega_z,n)$ is a 2D frequency spectrum obtained by applying 2D Fourier transform to the 2D beamformed signals. The signals are extracted from $s(x,z,n)$ around the tracking point by a 2D gaussian window. Based on the model in Ref. 9, the cross spectrum $\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)$ can be expressed as

$$\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n) = a(\omega_x,\omega_z,n) \cdot e^{-j(u_x\omega_x+u_z\omega_z)}, \quad (1)$$

where u_x and u_z denotes displacement component in the lateral and depth direction. $a(\omega_x,\omega_z,n)$ is the amplitude of the cross spectrum. Based on the 2D weighted least squares method, u_x and u_z can be determined to minimize the difference between the phase of observation $\angle\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)$ and model $-(u_x\omega_x+u_z\omega_z)$ in the half plane of (ω_x,ω_z). In this study, the amplitude spectrum $a(\omega_x,\omega_z,n)$ was used as the weighting function. The velocity v_x and v_z was calculated as $v_x = \mathrm{FR}\cdot u_x/\Delta N_\mathrm{F}$ and $v_z = \mathrm{FR}\cdot u_z/\Delta N_\mathrm{F}$, where FR is the frame rate of the system.

2.2 Anti-aliasing method for the 2D phase-sensitive method

The motion estimator described in Sec. 2.1 employs the slope of the phase of the cross spectrum. Therefore, the aliasing effect occurs when the displacement is larger than a half wavelength. In such a case, the phase spectrum $\angle\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)$ was wrapped and velocity cannot be estimated accurately. In this section, we propose an additional signal processing to compensate the aliasing effect in the phase spectrum. The phase-compensated cross spectrum is expressed as

$$\gamma'_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n) = \frac{\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)\cdot\gamma^*_{\Delta N_\mathrm{F}}(\omega'_x,\omega'_z,n)}{\left|\gamma_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)\cdot\gamma^*_{\Delta N_\mathrm{F}}(\omega'_x,\omega'_z,n)\right|}, \quad (2)$$

where (ω'_x,ω'_z) is the spatial frequencies at which $\gamma_{\Delta N_\mathrm{F}}(\omega'_x,\omega'_z,n)$ has the maximum amplitude. Based on the 2D weighted least squares method, u_x and u_z was determined to minimize the difference between the phase of observation $\angle\gamma'_{\Delta N_\mathrm{F}}(\omega_x,\omega_z,n)$ and model $-(u_x\omega_x+u_z\omega_z+q)$ in the half plane

hasegawa@eng.u-toyama.ac.jp

of (ω_x, ω_z), where q is an intercept. In this study, the amplitude spectrum $|\gamma_{\Delta N_F}(\omega_x, \omega_z, n)|$ was used as the weighting function.

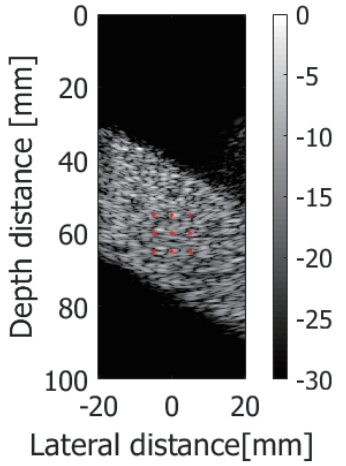

Fig. 1 B-mode image of steady flow simulation phantom. Red dots represent tracking points.

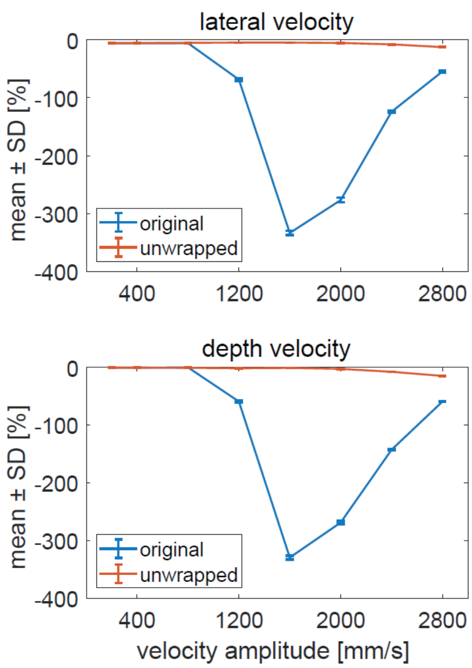

Fig. 2 Bias error and standard deviation of the measured velocity. (top) Lateral velocity component. (bottom) Depth velocity component.

2.3 Simulation phantom experiment

Received ultrasound echoes were simulated using Field II simulation program[10,11]. The steady flow phantom was mimicked by distributing point scatterers. Moving velocities of point scatterers were set to be 200 mm/s. Point scatterers moved at an angle of 60°. The transmit–receive sequence of ultrasound is described in Ref. 12. In such a sequence, beamformed signals were obtained at a frame rate of 6250 Hz. Finally, the phase-sensitive method was applied to obtained beamformed signals. **Figure 1** shows the B-mode image obtained in this study. In **Fig. 1**, red dots are tracking points. Also, the frames were decimated to simulate higher velocity.

To evaluate the estimation accuracy of the proposed method, bias errors and standard deviations of estimated velocity were calculated. In this study, bias error b was calculated as

$$b = \frac{1}{N} \sum_{x,z,n} \frac{u(x,z,n) - u_{\mathrm{true}}(x,z,n)}{u_{\mathrm{true}}(x,z,n)}, \quad (3)$$

where u_{true} is true velocity and N is the total number of observations.

3. Results

Figure 2 shows the simulation results. In blue line depicted in **Fig. 2**, the aliasing effect occurs when the velocity amplitude is more than 1200 mm/s. On the other hand, in orange lines, significant bias errors were not observed by compensating the discontinuity in the phase spectrum.

4. Conclusion

In this study, we proposed the anti-aliasing method for the 2D phase-sensitive motion estimator. The simulation results show that the proposed method could compensate the discontinuity in the phase spectrum and the velocity could be estimated accurately without the aliasing.

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