10.1109/ULTSYM.2012.0642

Ultrasound tissue motion assessment using full correlation analysis

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***Abstract*—Conventional ultrasound cross-correlation technique for tissue motion assessment searches the best match between successive B-mode frames. This strategy neglects the decrease of cross-correlation caused by the time difference between two measurement points utilized for the calculation of cross-correlation. The assumption causes the smaller estimated velocity than the true velocity. In this study, we employ full correlation analysis to compensate for the change of the location where the correlation coefficient is maximum. Simulation study shows that the difference between the true tissue velocity and the expectation of the tissue velocity estimated using the proposed method is 11.3% of that estimated using the conventional cross-correlation technique. These findings indicate the potential of the proposed method to improve the accuracy in tissue motion assessment, including blood flow velocity estimation.**

Keywords-Tissue velocity estimation, ultrasound imaging, cross-correlation, full correlation analysis

I. INTRODUCTION

Doppler ultrasound is one of the most common technique to assess tissue motion, particularly in estimating blood flow velocity. Common color flow mapping technique, known as the auto-correlator, calculates the phase-shift between successive pulse returns to estimate the axial velocity of scatterers [1], [2]. It transmits a narrowband pulse, and measures the phase-shift at the center transmit frequency. Since the technique calculates a single velocity for a received signal of each range gate, it is a 1D approach.

In contrast to the auto-correlator calculating the phase-shift using narrowband signals, many time-domain techniques have been proposed. One of them is the cross-correlation technique, which measure the time-shift to the best match between successive B-mode frames [3]–[5]. Since this technique can measure both the lateral and axial components of flow, it is a 2D approach. However, this technique only considers the noise that does not affect the location where the correlation coefficient is maximum [6]. This means that the technique neglects the decrease of correlation caused by the time difference between two measurement points used for the calculation of cross-correlation.

Another approach is the employment of a broad transmit pulse that acquires a high frame rate. Focusing is performed only in a receive event, and a 2-D vector velocity is acquired by a single or few transmitted pulses [7]–[9]. Since the employment of a broad transmit pulse largely suppresses the signal-to-noise ratio (SNR), temporal coding is used to compensate the suppression of SNR [10]–[12]. However, temporal coding neglects the target motion caused by the arrival-time difference of encoded ultrasound pulses at a measurement point, as shown in Fig. 1. When the difference of pass-lengths $h_2 - h_1$ is 15 mm, the difference of pulse arrival time at a measurement point is 10 μs. The arrival time difference of transmit pulses causes the target motion of 0.03 mm in the case that the target velocity is 3 m/s. Since the wavelength of a 5 MHz ultrasound pulse is 0.3 mm, the target motion of 0.03 mm indicates that the gap of 0.2 λ or less occurs in the delay-and-sum process using coded excitation. This gap not only suppresses SNR but also originates an unexpected blurred image that would cause the error in tissue velocity estimation.

In this study, we examine the effect of the tissue velocity component perpendicular to the measurement plane and the random change in distribution of scatterers on the velocity estimation using a cross-correlation technique. We indicate that the tissue velocity estimated by a conventional cross-correlation technique is smaller than the true velocity. We then propose a method to compensate for the estimation error caused by the conventional cross-correlation technique, and investigate the effectivity of the proposed method in a simulation study.

II. METHODS

For the improvement of the accuracy in tissue velocity assessment we apply full correlation analysis to a cross-correlation technique for tissue motion assessment. Full correlation analysis was applied to atmospheric radar

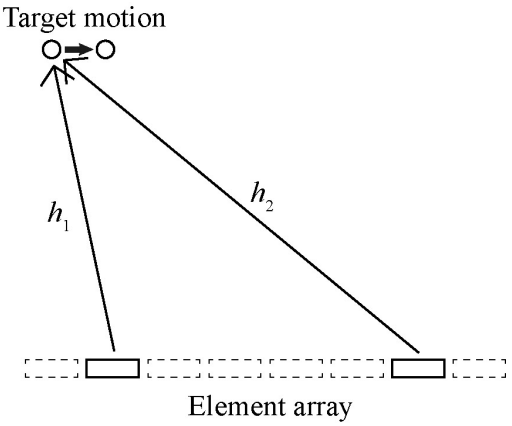

Figure 1. Target motion caused by the arrival-time difference of encoded ultrasound pulses at a measurement point.

observation, and it compensates for the effect of randomly changing pattern on the wind velocity estimation using cross-correlation technique [13] –[15]. In this section, we indicate the error of a conventional cross-correlation technique in tissue velocity estimation, and describe the proposed method to correct the estimation error.

A. Error Source of Cross-correlation Technique in Tissue Motion Assessment

Fig. 2 shows the system model used in this study. In this model, a layer with scatterers moves horizontally, i.e. the tissue motion has the *x* and *y* components, and the ultrasound beam is scanned in the *x* direction. We consider the random change in the distribution of scatterers in the layer. The two factors, the *y* component of the tissue motion and random change in the distribution of scatterers, decrease the cross-correlation with the passage of time. This effect not only decreases the maximum of the cross-correlation coefficient between successive two frames, but also puts the location where the correlation coefficient is maximum forward, as shown in Fig. 3. We explain this effect using a simple model given by:

$$C(d,\tau) = \exp(-\alpha_0 d^2)\exp(-\beta_0 \tau^2), \quad (1)$$

$$d^2 = (\xi - v_x\tau)^2 + (v_y\tau)^2, \quad (2)$$

where d is the distance between the center of the beam spot $(\xi,0)$ and the tissue location at the posterior measurement, τ is the time difference between two measurement points, α_0 and β_0 are positive numbers, and v_x and v_y are the x and y components of the tissue velocity, respectively. The expectation of the correlation coefficient in Eq. (1) is rewritten as the following equation.

$$C(\xi,\tau) = \exp\{-\alpha_0(\xi - v_x\tau)^2\}\exp\{-(\alpha_0 v_y{}^2 + \beta_0)\tau^2\}. \quad (3)$$

Eq. (3) indicates the important fact; the location where the correlation coefficient is maximum is put forward by the two factors, the random change in the distribution of scatterers and the velocity component perpendicular to the measurement direction. The x component of the tissue velocity estimated by a conventional cross-correlation technique is expressed as follows.

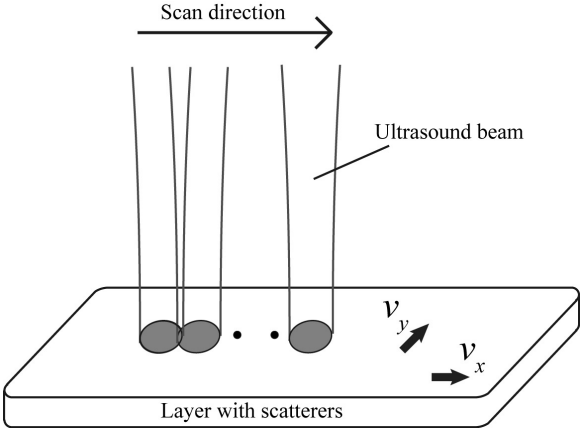

Figure 2. Simulation model used in this study. v_x and v_y are the x and y components of the tissue velocity, respectively. Ultrasound beam is scanned in the x direction.

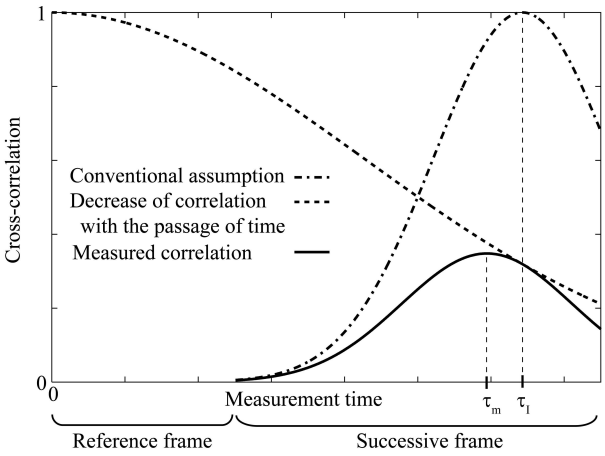

Figure 3. Correlation coefficient considering the two factors, the random change in the distribution of scatterers and the velocity component perpendicular to the measurement direction. The two factors decrease the correlation with the passage of time, putting the location where the correlation coefficient is maximum forward.

$$v_x' = (1 - NT_{PR}/\tau_m)I_{sl}/T_{PR}, \quad (4)$$

where N is the number of scan lines in a frame, T_{PR} is the pulse repetition time, τ_m is the time when the correlation coefficient is maximum, and I_{sl} is the scan line interval. Since τ_m is smaller than τ_l, the time of maximum correlation when $v_y = 0$ and no random change exists in scatterer distribution, the conventional technique estimates the tissue velocity smaller than the true velocity. This estimation error usually occurs in the employment of the conventional technique because the two factors generally suppress the cross-correlation.

B. Full Correlation Analysis Applied to Correlation Technique for Ultrasound Tissue Motion Assessment

Full correlation analysis does not employ the simple model given by Eq. (1). It only assumes that the contour of equal correlation coefficients between couples of measurement points traces an ellipse with the center at the origin.

$$\alpha d^2 + \beta\tau^2 = \gamma(C), \quad (5)$$

where α and β are positive numbers, C is a value of correlation coefficient, $\gamma(1) = 0$ and $\gamma(C) > 0$ when $0 < C < 1$. Eq. (5) is rewritten by:

$$\alpha(\xi - v_x\tau)^2 + (\alpha v_y{}^2 + \beta)\tau^2 = \gamma(C). \quad (6)$$

The solid curve in Fig. 4 shows a contour of equal correlation coefficients. Since a common ultrasound imager scans an ultrasound beam in a measurement plane, the measurement time varies even in an identical frame. Therefore, the correlation coefficients calculated by measurement points locate along the line segments on the correlation map shown in Fig. 4, where the slope of the segments is T_{PR}/I_{sl}

The location where the correlation coefficient is maximum is at the point of tangency between the correlation line segment of the successive frame, l_1, and a correlation ellipse, i.e. the point P in Fig. 4. Since the estimation of the true tissue velocity

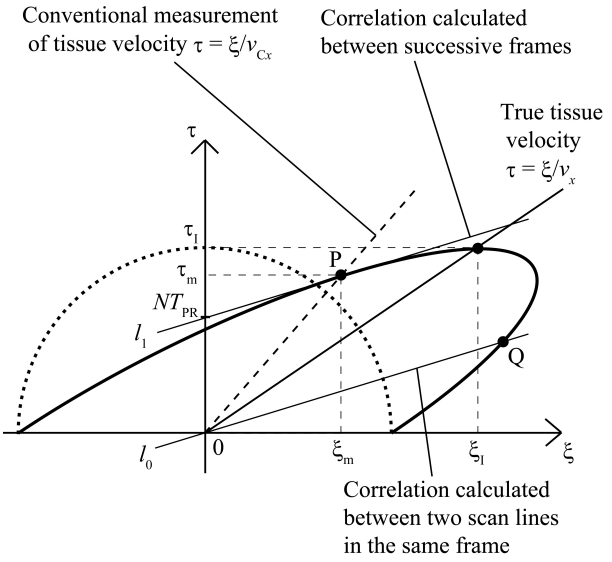

Figure 4. Contour of equal correlation coefficients between couples of measurement points. ξ and τ denotes the distance and time difference between two measurement points, respectively. v_x and v_{Cx} are the true tissue velocity and tissue velocity estimated by the conventional cross-correlation technique, respectively. v_x is equal to ξ_I/τ_I , and v_{Cx} is equal to ξ_m/τ_m. P indicates the location of the maximum cross-correlation between the successive B-mode frames. Broken curve is the contour of equal correlation coefficient when v_x = 0.

needs the acquisition of the function of the ellipse in the ξ-τ plane, another point is necessary to estimate the tissue velocity. We thus calculate the correlation between scan lines that exist in the same frame, in other words we calculate the correlation coefficients on the line segment l_0 in Fig. 4. We search the location where the correlation coefficient is equal to that of P, i.e. the point Q in Fig. 4. The acquisition of the locations of P and Q can estimate the *x* component of the true tissue velocity v_x. We call this technique as modified full correlation analysis.

C. Simulation setup

In the simulation study, we employed an ultrasound pulse $s_T(t)$, where the center frequency is 5 MHz, –3 dB fractional bandwidth is 60%, and the sampling frequency is 30 MHz. The density of point scatterers in a tissue layer is 100 units per cube millimeter. The pulse repetition frequency is 7.5 kHz. A B-mode image frame consists of 5 scan lines, i.e. N = 5, and the scan line interval is 1.2 mm. The –6 dB width of an ultrasound beam at the depth of 8 cm is 2.4 mm, and the received signal is calculated as follows.

$$s(t) = \sum_k f_B(x_B - x_{Sk}, y_B - y_{Sk}) s_T(t - 2z_{Sk}/c) \qquad (7)$$

$$f_B(x,y) = \begin{cases} \exp\{-\delta(x^2+y^2)\} & : x^2+y^2 \le 16 \ (\mathrm{mm}^2) \\ 0 & : x^2+y^2 > 16 \ (\mathrm{mm}^2) \end{cases} \qquad (8)$$

where (x_B, y_B) is the center location of a beam spot, and (x_{Sk}, y_{Sk}, z_{Sk}) is the location of the *k*-th scatterer in the layer, and δ is a positive number which depends on the beam width. The sound velocity in the medium c is equal to 1500 m/s. In this study, we calculate cross-correlation coefficients between two measurement points by the following equation.

$$C_S(\xi,\tau) = \frac{\int s_R(t)s(t)dt}{\sqrt{\int |s_R(t)|^2 dt \int |s(t)|^2 dt}} \qquad (9)$$

where $s_R(t)$ is the reference signal, and the reference scan line is at the center in the anterior frame. We set the correlation window width as 1 mm, i.e. 1.33 μs. We utilize the average of 10 cross-correlation coefficients for the tissue velocity assessment using the conventional and proposed methods.

In this system 8 transmit and receive events are needed for the tissue motion assessment; three events for the anterior frame including the reference signal acquisition, and 5 events for the posterior frame. We suppose that the tissue velocity is constant during the tissue motion estimation of 1.07 ms. We investigate the performance of the proposed method in the estimation of the *x* component of the tissue velocity v_x, where v_x = 2 m/s and v_y is from 0 to 5 m/s. In the simulation study, we neglect the randomly changing distribution of scatterers in the layer, i.e. $\beta = 0$.

III. Results

Fig. 5 shows the *x* component of the tissue velocity estimated by a conventional cross-correlation technique and the proposed modified full correlation analysis, where the true *x* component is 2 m/s. When the *y* component of the tissue velocity is 0 to 5 m/s the average tissue velocities in the *x* direction estimated by the conventional and proposed methods are 1.03 and 1.89 m/s, respectively. Therefore, the difference between the true velocity and the average velocity estimated using the proposed method is 11.3% of that estimated using the conventional method. Tissue velocity estimated by the conventional technique tends to decrease in response to the increase of the velocity in the *y* direction. Since the large tissue velocity in the *y* direction severely decreases correlation with the passage of time, the finding supports the theoretical investigation shown in Section II A.

The difference of the proposed method is 0.05 m/s and less when the *y* component of the tissue velocity is from 0 to 3.5 m/s, where the maximum estimation error of the conventional

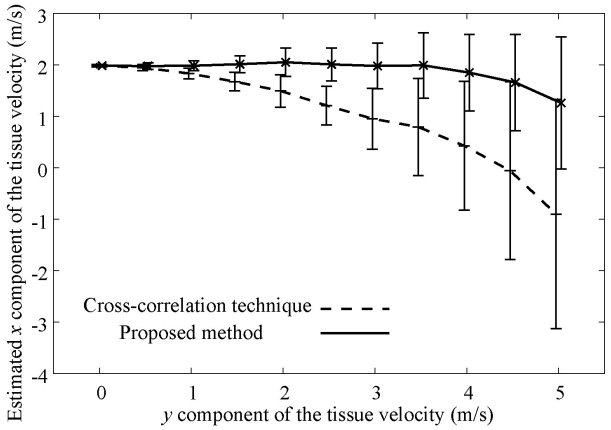

Figure 5. *x* component of the tissue velocity estimated by a conventional cross-correlation technique and the proposed method, where the true *x* component is 2 m/s. *y* component of the tissue velocity is 0 to 5 m/s. Each error bar shows the standard deviation.

method is 1.2 m/s. In the case that the *y* component of the tissue velocity is 4.5 and 5 m/s, the conventional technique even failed to judge the tissue motion direction; however, the proposed method succeeded to estimate the direction of the tissue motion, and the estimation error using the proposed method is 16.6 and 25.5% of that estimated using the conventional technique, respectively. These results indicate that the proposed method has the potential to compensate for the decrease of the estimated tissue velocity caused by the two factors; the random change in the distribution of scatterers and the velocity component perpendicular to the measurement direction.

IV. CONCLUSIONS

In this study, we indicate that the two factors, the randomly changing distribution of scatterers and the tissue velocity in the direction perpendicular to the measurement direction, decrease the tissue velocity estimated by a conventional cross-correlation technique. We proposed a method to compensate for the estimation error caused by the conventional technique, and investigate the effectivity of the proposed method in a simulation study. In the simulation study, the expectation of the estimated tissue velocity using the proposed method is close to the true velocity, and the difference between and the true velocity and the expectation of the estimated velocity using the proposed method is 11.3% of that estimated using the conventional cross-correlation technique. The error in tissue velocity estimated by the proposed method is 0.05 m/s and less when the tissue velocity perpendicular to the measurement direction is from 0 to 3.5 m/s, where the maximum error estimated by the conventional method is 1.2 m/s.

These findings indicate the potential of the modified full correlation analysis proposed in this study to improve the accuracy in tissue motion assessment; particularly in the condition that the random change in the distribution of scatterers and the velocity component perpendicular to the measurement direction are dominant.

ACKNOWLEDGMENT

This work is partly supported by the Research and Development Committee Grants of the Japan Society of Ultrasonics in Medicine, Japan and the Innovative Techno-Hub for Integrated Medical Bio-imaging Project of the Special Coordination Funds for Promoting Science and Technology, from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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