MOTION ARTIFACT ELIMINATION ALGORITHM WITH EIGEN-BASED CLUTTER FILTER FOR COLOR DOPPLER PROCESSING

Zih-Ling Liu, Yu-Hao Chen, Cheng-Zhou Zhan, and An-Yeu (Andy) Wu

Graduate Institute of Electronics Engineering, and Department of Electrical Engineering,
National Taiwan University, Taipei, 106, Taiwan, R.O.C.
lindaliu@access.ee.ntu.edu.tw

ABSTRACT

Color Doppler imaging is used to visualize the distribution of blood flow in the region of interest. Slight relative motion may cause severe image corruption and incorrect blood velocity estimation. In this work, we propose a velocity bias cancellation algorithm based on the autocorrelation technique widely used in color Doppler and eigen-based clutter filter to eliminate the motion artifact. The proposed algorithm assists clutter filter to suppress tissue noises effectively and compensates the biased blood velocity. It has more than 3-9 dB better performance and the error of blood velocity estimation can be reduced by more than 69%.

Index Terms— Ultrasound, Color Doppler, Motion artifact

1. INTRODUCTION

As shown in Fig. 1(b), slight motion between the probe and subjects caused by tissue motion, respiration, body and probe movements causes severe image corruption and incorrect blood velocity estimation in color Doppler imaging. The image corruption originates from the failure of the suppression of the clutter noises originating from the reverberation of tissue which is originally stationary and slow-moving without motion artifact. And the incorrect blood velocity is biased by the velocity of motion. Therefore, patients are asked to hold their breath to reduce the relative motion. However, requesting children and unconscious patients to suspend their breathing is difficult. Furthermore, motion cannot be avoided in the emergency situation, such as in an ambulance and in battlefield.

To suppress the clutter noises with motion artifact, eigen-based clutter filter has been proposed [1][2] to adapt the passband and stopband with the moving tissue. In order to address the clutter signal accurately, [2] views the mean frequency of dominant eigen-component as the center frequency of clutter noise. Nevertheless, this method is unsuitable when clutter-to-blood ratio (CBR) of eigen-component distribution is low, which may eliminate the blood information instead of clutter noise. In addition to the clutter noise issue, little research takes the biased blood velocity into consideration. It leads to severe inaccuracy of blood velocity estimation when the motion artifact is large.

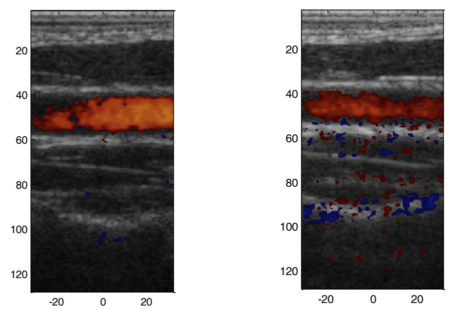


Fig. 1. (a) Normal image and (b) motion-corrupted image.

In this work, we propose a velocity bias cancellation algorithm based on eigen-based clutter filter. It possesses a biased velocity estimation mechanism utilizing autocorrelation technique [4] of color Doppler to raise the correctness of motion estimation. Besides, the proposed algorithm can effectively suppress clutter noise with more than 3-9 dB better performance and compensate the biased velocity which reduces the velocity error by more than 69%.

This paper is organized as follows. The eigen-based clutter filters are described in Section 2, and the proposed velocity bias cancellation algorithm is shown in Section 3. The simulation results and comparisons are presented in Section 4, and the paper is concluded in Section 5.

2. EIGEN-BASED CLUTTER FILTER

The general filter model can be represented by the matrix-vector multiplication as:

$$\mathbf{y} = \mathbf{A}\mathbf{x}, \tag{1}$$

where $\mathbf{x}$ is the input signal vector, $\mathbf{A}$ is the clutter filter matrix, and $\mathbf{y}$ is the filtered signal vector. The eigen-based clutter filter can adapt to the clutter signal characteristics as a regression filter which can be written as

$$\mathbf{A} = \mathbf{I} - \sum_{u=1}^{K} \mathbf{e}_i \mathbf{e}_i^H, \tag{2}$$

where $\mathbf{e}_i$ is an orthonormal basis for the clutter signal space, K is the clutter space order, and $(\cdot)^H$ indicates the Hermitian operation. By subtracting the signal component contained in the clutter space, the filtered matrix $\mathbf{A}$ can project the input signal vector $\mathbf{x}$ into the orthogonal component out of the clutter space.

To attenuate the clutter noise successfully by the regression filter, it is important to determine the clutter space order. Since tissue movement is generally slow compared to blood flow, [2] determines the clutter space Φ_c as eigenvectors with low frequency parts by comparing the mean frequency of the eigenvector with a fixed frequency threshold f_{th}, which is called *fixed frequency thresholding* in this work:

$$\Phi_c = \left\{ \mathbf{e}_i \,\middle|\, |f_i| < f_{th} \right\}, i = 1, \ldots, N, \tag{3}$$

where the mean frequency f_i of each eigenvector $\mathbf{e}_i$ can be calculated by lag-one autocorrelator [4]:

$$f_i = \frac{1}{2\pi T} \angle \left[\sum_{n=0}^{N-2} \mathbf{e}_i^*(n) \mathbf{e}_i(n+1) \right], \tag{4}$$

where T is the pulse repetition interval and * denotes the complex conjugate. To handle clutter signals with center frequency f_c, (3) can be revised as a *dynamic frequency thresholding* form:

$$\Phi_c = \left\{ \mathbf{e}_i \,\middle|\, |f_i - f_c| < f_{th} \right\}, i = 1, \ldots, N, \tag{5}$$

when the clutter-to-blood ratio (CBR) of eigen-component distribution is high, f_c can be calculated as the mean frequency of the eigen-component with largest eigenvalue.

3. PROPOSED VELOCITY BIAS CANCELLATION ALGORITHM

In this section, we propose a velocity bias cancellation algorithm based on eigen-based clutter filter. In this work, we assume the relative motion is in the same direction in a region. The proposed algorithm includes three steps in three different blocks shown in Fig. 2. First, velocity bias caused by motion artifact is calculated in the biased velocity estimation. Second, the frequency threshold in eigen-based clutter is adjusted with the velocity bias and the variance of the estimated velocity. Finally, the biased blood velocity is compensated by the velocity bias to get the correct velocity in flow parameter estimation. The proposed velocity bias cancellation algorithm can effectively assist eigen-based clutter filter to eliminate moving tissue and compensate the biased blood velocity.

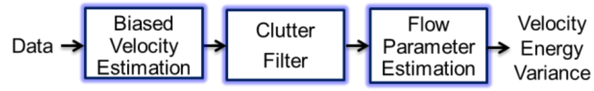


Fig. 2. Block diagram of color Doppler imaging system with proposed velocity bias cancellation. algorithm.

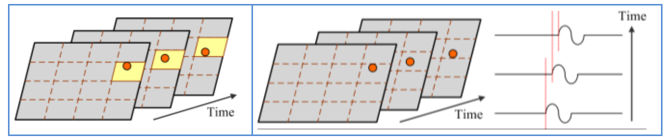


Fig. 3. (a) Use cross-correlation to find the displacement between frames, (b) use autocorrelation technique to compute the phase difference and velocity.

3.1. Biased Velocity Estimation

Several motion compensation algorithms [5][6] utilizing cross-correlation of pixels to estimate displacement of motion artifact, which is called velocity bias in this work. However, cross-correlation is not suitable for color Doppler because of the decimation of RF data. The input data of Doppler processing are baseband signals whose sampling rate is much lower. Therefore, the length each pixel representing increases. As shown in Fig. 3(a), when cross-correlation technique is utilized, the displacement of two frames is likely to be computed incorrectly since the displacement is less than the length that a pixel represents.

In order to raise the correctness of biased velocity estimation, we propose the weighted autocorrelation method. Autocorrelation technique [4] is widely used in color Doppler to calculate the flow parameter, such as velocity, and energy. Since autocorrelation technique computes the phase difference between frames, it is not affected by the length that each pixel represents. The autocorrelation and frequency of slow-time signal X in pixel (m,n) can be represented respectively as follows:

$$\hat{R}_{m,n}(T) = \frac{1}{N-1} \sum_{i=1}^{N-1} X((i+1)\cdot T) X^*(i \cdot T), \tag{6}$$

$$\overline{f_{m,n}} = \frac{\angle \hat{R}_{m,n}(T)}{2\pi T}, \tag{7}$$

where T is the pulse repetition interval. Moreover, in order to avoid the influence of the blood velocity, we use energy as weight to calculate the average frequency bias because the energy of tissue signal is typically 40-80dB stronger than the one of blood signal. And the center frequency f_c of tissue in (5), which will be called frequency bias f_b in this work, is revised and represented as following:

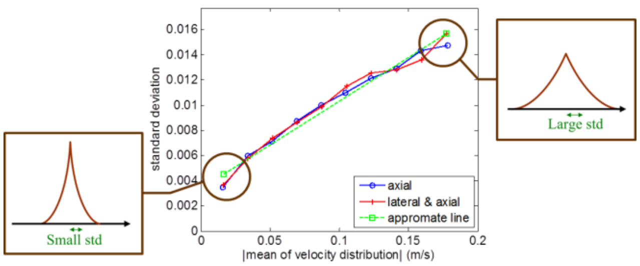


Fig. 4. Relationship between the mean and the standard deviation of velocity distribution in tissue.

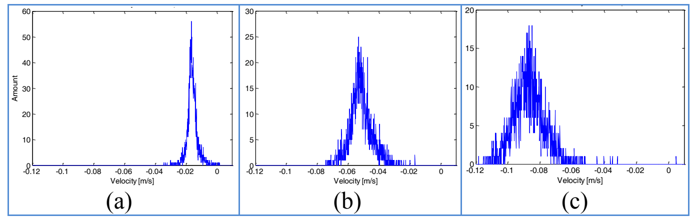


Fig. 5. Estimated velocity distributions in tissue calculated by autocorrelation technique under (a) probe velocities = 0.02m/s↑, (b) probe velocities = 0.06m/s↑, (c) probe velocities = 0.1m/s↑.

$$f_b = \frac{1}{\sum_{m=1}^{M}\sum_{n=1}^{N} E_{m,n}} \sum_{m=1}^{M}\sum_{n=1}^{N} E_{m,n} \cdot \overline{f_{m,n}}, \tag{8}$$

where $E_{m,n}$ is the energy of slow-time signal X in pixel (m,n), which is written as

$$E_{m,n} = \frac{1}{N}\sum_{i=1}^{N} X(i \cdot T) X^*(i \cdot T). \tag{9}$$

And the velocity bias V_b can be calculated from the frequency bias, which is written as

$$V_b = \frac{c}{2f_0} f_b. \tag{10}$$

3.2. Frequency-threshold Adjusting in Clutter Filter

In this step, the frequency threshold in (5) will be adjusted by frequency bias calculated in biased velocity estimation. To observe the distribution of estimated velocities of moving tissue, we use the Field II [7] program to generate synthetic data with different probe velocities. The direction of motion is divided into axial and lateral motion. Axial motion is the motion that the probe moves toward or away from the subject, and the lateral motion is in the direction perpendicular to the axial motion.

With different probe velocities, the means and standard deviations of velocities estimated by autocorrelation technique for tissue part are computed. As shown in Fig. 4, the blue line is from the data with only axial probe motion from 0.02 m/s to 0.2 m/s upward, while the red line is from the data with axial probe motion from 0.02 m/s to 0.2 m/s upward and lateral probe motion from 0.01 m/s to 0.1 m/s rightward, which is half the value of corresponding axial motion. We find that the standard deviation increases mainly with the mean of estimated velocity of axial motion. Besides, an approximate linear relationship exists between the mean and the standard deviation of estimated velocity. In other words, a linear function of the green line shown in Fig. 4 could be utilized to describe their relationship. This means that when the mean velocity is obtained, its approximate standard deviation can be calculated.

Moreover, we observe their velocity distribution under different axial probe velocities as shown in Fig. 5. Their velocity distributions can be mapped into symmetrical exponential distributions. For exponential distribution, more than 95% of values are within 3 standard deviations. That is, the frequency threshold in eigen-based clutter filter can be adjusted with the mean and standard deviation of the estimated velocity bias to eliminate the clutter noise caused by moving tissue. Thus, (5) can be revised and rewritten as

$$\Phi_c = \left\{ e_k \left| \left| f_k - f_b \right| < \left(f_{th} + 3\sigma_f \right) \right. \right\}, \tag{11}$$

where σ_f is the frequency of standard deviation of velocity distribution, which can be transformed from velocity as the relationship between velocity and frequency depicted in (10).

Thus, by these two observed phenomena, which might be caused by the estimation error of autocorrelation technique, we can suppress most of the moving tissue by adjusting the frequency threshold.

3.3. Velocity Compensation

Since the blood velocity is biased by the motion artifact, it should be compensated with the velocity bias in the flow parameter estimation block to get the correct estimated velocity. The correct estimated velocity $V_{correct}$ can be obtained by compensated the original estimated velocity V_{origin} with V_b as follow,

$$V_{correct} = V_{origin} - V_b. \tag{12}$$

4. SIMULATION RESULTS AND COMPARISONS

Since the general medical ultrasound images we get are hard to know the velocity bias and the accurate blood velocity they should be, conventional metrics can't be used to measure the quality after filtering implementation. Therefore, we use the Field II [7] program to generate synthetic data to

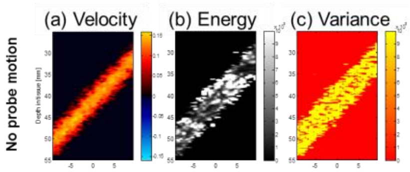


Fig. 6. Color Doppler images without probe motion (a) velocity, (b) energy, (c) variance.

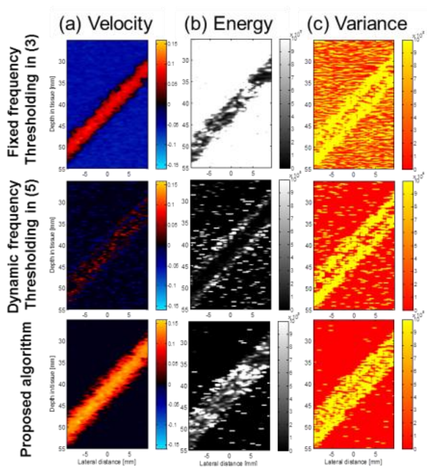
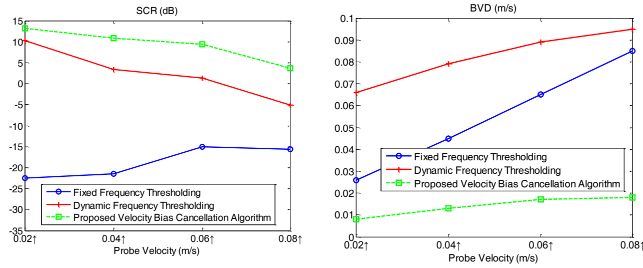


Fig. 7. Color Doppler images with probe velocity 0.06 m/s upward (a) velocity, (b) energy, (c) variance.

evaluate the performance. The color Doppler imaging without motion artifact is taken to be the golden pattern, which is shown in Fig.6. For quantitative evaluation, two parameters are utilized. One is the signal-to-clutter ratio (SCR) [8], which is used to evaluate the effectiveness of clutter rejection. And the other is the blood velocity difference (BVD), which is used to evaluate the accuracy of velocity compensation; the smaller the BVD is, the better accuracy of blood velocity is achieved. Its definition is depicted as

$$BVD = \frac{\sum_{m,n} \left| V_{NoMotion} - V_{Compensate} \right|}{M \cdot N}, \qquad (13)$$

The simulation results are shown in Fig. 7 and Fig. 8. As depicted in Fig. 7, the clutter filter fails to suppress the clutter noise with fixed frequency thresholding. Most of the tissue signals are regarded as blood signals with velocity around -0.06 m/s due to the probe velocity. Although dynamic frequency thresholding eliminates more clutter noise, it reduces huge blood information as well. However, by applying the proposed method, most of the tissue signals can be eliminated effectively and the blood velocity estimation is similar with the one without motion artifact in Fig. 6. Besides, as shown in Fig. 8, compared with the reference works, the SCR increases about 3-9 dB and the error of blood velocity estimation can be reduced by more than 69% by applying the proposed algorithm.



(a) (b)

Fig. 8. (a) SCR , (b) BVD of different algorithms used in joint-decision algorithm under different axial probe velocities.

5. CONCLUSION

In this work, we propose a velocity bias cancellation algorithm based on the autocorrelation technique and eigen-based clutter filter to eliminate the motion artifact effectively. Compared with the reference works, the proposed algorithm has 3-9 dB better performance and the error of blood velocity estimation can be reduced by more than 69%.

6. ACKNOWLEDGMENT

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