Influence of clutters on ultrasonic Doppler blood flow measurements

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Abstract. Ultrasonic Doppler velocimetry, a non-invasive, low-cost and high-penetration technique, is one of the most suitable methods for measuring blood flow velocity at present. Since previous studies often use the simplified models that do not contain the clutter, users have to design high-performance filters to remove clutters that are irrelevant to blood flow. This paper focuses on the influence of clutters on ultrasonic Doppler blood flow measurements. We establish a signal model that contains the clutter and analyse the influence of clutters on correlation algorithms. Simulation results show that clutters caused by static tissues lower velocity estimators and auto-correlation algorithm is more sensitive to clutters than cross-correlation algorithm.

1. Introduction

The detection of blood flow provides information for the diagnosis of cardiovascular diseases [1]. Blood flow indicates the myocardial metabolism and coronary circulation. Its abnormalities are often associated with cardiovascular disorders.

Ultrasonic Doppler velocimetry is one of the most suitable methods for measuring blood flow velocity at present. It is a non-invasive method with advantages of low cost and high penetration. The technique comprises continuous wave Doppler [2], pulsed wave Doppler [3], color Doppler [4]. Pulsed wave Doppler is widely used, because it is easy to extract the information of range and velocity.

Since previous studies often use the simplified models that do not contain the clutter, users have to design high-performance filters to remove clutters that are irrelevant to blood flow. Zobly S M S et al. [5] presented a method for clutter filtering based on the component analysis. The method performed better than FIR and IIR filters in experiments. Song P et al. [6] introduced two methods for clutter filtering based on randomized singular value decomposition (SVD). They focused on accelerating the process with minimal compromise to the performance. Demene C et al. [7] proposed a method for clutter filtering of ultrafast ultrasonic imaging based on spatiotemporal singular value decomposition. The method could provide better contrast to noise ratio than other classical filters. Gao L et al. [8] presented a method for clutter filtering based on multivariate empirical mode decomposition. The method improved the accuracy, because it preserved more slow-blood-flow components. Lee J et al. [9] presented a method for clutter suppression based on time-domain averaging. The method was simple and comparable to projection-initialized IIR filters. Xiao L et al. [10] presented a method for clutter suppression based on dynamic region polynomial regression and singular value decomposition. The
method could dynamically distinguish the range of signal. Kunita M et al. [11] proposed a sinusoidal frequency-modulated technique for continuous wave Doppler. The technique had advantages of low clutter power and high signal-to-noise ratio. Tortoli P et al. [12] compared three methods for peak velocity measurement. The analysis was based on a simplified model. Jensen J A et al. [13] described the parallel simulation method using Field II. Field II is a recognized toolkit for medical ultrasound technology.

This paper focuses on the influence of clutters on ultrasonic Doppler blood flow measurements. There are three main sections in this paper. Firstly, we shall establish a signal model that contains the clutter. Based on that model, we analyze the influence of clutters on correlation algorithms in theory. Finally, we validate the above inferences by simulation.

2. Signal model
To analyse the influence of clutters, it is necessary to establish an accurate signal model of ultrasonic echo signals. The following section starts from the signal model of a single scatterer, and further extends to multiple scatterers. Then, the signal model of pulsed wave Doppler is analysed.

2.1. Signal model of a single scatterer
Assume that there is only one scatterer in the space. Let \( l \) denote its initial distance from the ultrasonic transducer, \( v \) denote its velocity and \( c \) denote the speed of sound. So that the relative speed is \( c - v \). If a pulse is transmitted at the moment of \( \tau \), then it takes the ultrasonic wave \( \Delta \tau = \frac{l}{c-v} + \tau \) to catch up with the scatterer. At the moment of \( \tau + 2\Delta \tau \), the backscattered wave returns to the transducer. In other words, the excitation at the moment of \( \tau \) corresponds to the received signal at the moment of \( \tau + 2\Delta \tau \). Therefore, the received signal of a single scatterer is

\[
s(t) = s(\tau + 2\Delta \tau) = g(\tau) = g\left(\frac{c-v}{c+v}t - \frac{2l}{c+c}\right) \approx g\left(1 - \frac{2v}{c}\right)t - \frac{2l}{c}
\]

where \( g(t) \) is a known function that is related to the excitation and the impulse response.

2.2. Signal model of multiple scatterers
The previous subsection described the signal model of a single scatterer. In this subsection, we will extend to multiple scatterers.

Group the scatterers by distance. Note that near erythrocytes have approximately the same speed. We can group them by distance and assume that erythrocytes within the same group have the same speed. The group is also called sample volume.

Besides the scattering of erythrocytes, the received signal contains a lot of clutters and noises. The ultrasonic wave will reflect at the region where the acoustic impedance is not uniform. Since the reflections mainly result from static tissues, they contain little information about blood flow. They are disturbances of no interest, termed clutters. In consideration of the time delay \( t_{\text{delay}} \) caused by electronic circuits, the received signal from a particular sample volume could be written as

\[
x(t) = s(t) + e(t) = \beta g\left(t - t_{\text{delay}} - \frac{2L}{c}\right) + \alpha g\left(1 - \frac{2v}{c}\right)(t - t_{\text{delay}} - \frac{2l}{c}) + e(t),
\]

where \( \beta \) is the synthetical intensity of clutters; \( L \) is the distance between the transducer and the clutter source; \( \alpha \) is the synthetical scattering intensity of erythrocytes; \( l \) is the distance between the sample volume and the transducer; \( e(t) \) is observation noise. Take \( \beta \) and \( \alpha \) as unknown deterministic parameters, because the synthetical intensity should be close to a deterministic value according to the law of large numbers.
2.3. Signal model of pulsed wave Doppler

For a practical pulsed wave Doppler instrument, the excitation is periodic pulses in general. Then, \( g(t) \) could be expressed by

\[
g(t) = \sum_p u(t - pT_{\text{prf}}),
\]

where \( T_{\text{prf}} \) is pulse repetition period, pulse repetition frequency is \( f_{\text{prf}} = \left( \frac{T_{\text{prf}}}{T} \right)^3 \); \( u(t) \) is a known function defined on \([0, t_0)\) where \( t_0 \) is the pulse duration. In order to avoid the difficulty caused by overlapped echoes, assume that \( t_0 \ll T_{\text{prf}} \). Let \( f_s \) denote the sampling frequency, then the sampling interval is \( T_s = f_s^{-1} \). For a given time \( t \), define the \( n_s \)-th signal starting from \( t \) in the \( n_{\text{prf}} \)-th period as \( s[n_s, n_{\text{prf}}] \). Similarly, define the sampling value and random noise at that moment as \( x[n_s, n_{\text{prf}}] \) and \( \epsilon[n_s, n_{\text{prf}}] \), respectively. Thus,

\[
s[n_s, n_{\text{prf}}] = s(t_s + n_s \tau_s + n_{\text{prf}} T_{\text{prf}}) \\
\approx \beta u\left(T_s n_s + t_s - t_{\text{delay}} - \frac{2L}{c}\right) + \alpha u\left(T_s n_s - \frac{2vT_{\text{prf}}}{c} n_{\text{prf}} + t_s - t_{\text{delay}} - \frac{2l}{c}\right).
\]

The sinusoidal ultrasonic excitation could be written as \( u(t) = A_0 \sin(2\pi f_0 t), 0 \leq t < t_0 \). Letting \( \varphi_k = t_s - t_{\text{delay}} - \frac{2L}{c} \) and \( \varphi_l = t_s - t_{\text{delay}} - \frac{2l}{c} \), we have

\[
s[n_s, n_{\text{prf}}] \approx \beta A_0 \sin\left(2\pi f_0 T_s n_s + 2\pi f_0 \varphi_k\right) + \alpha A_0 \sin\left(2\pi f_0 T_s n_s - \frac{4\pi f_0 T_{\text{prf}} v}{c} n_{\text{prf}} + 2\pi f_0 \varphi_k\right).
\]

In summary, if the excitation is periodic sinusoidal pulses, then the \( n_s \)-th sampling value in the \( n_{\text{prf}} \)-th period could be expressed by

\[
x[n_s, n_{\text{prf}}] = s[n_s, n_{\text{prf}}] + \epsilon[n_s, n_{\text{prf}}] \\
\approx \beta A_0 \sin\left(2\pi f_0 T_s n_s + 2\pi f_0 \varphi_k\right) + \alpha A_0 \sin\left(2\pi f_0 T_s n_s - \frac{4\pi f_0 T_{\text{prf}} v}{c} n_{\text{prf}} + 2\pi f_0 \varphi_k\right) + \epsilon[n_s, n_{\text{prf}}].
\]

We established a signal model of pulsed wave Doppler. In this model, clutters were regarded as fixed frequency disturbances whose amplitude and phase were unknown.

3. Influence of clutters on correlation algorithms

3.1. Auto-correlation algorithm

The velocity estimator of auto-correlation algorithm is

\[
\hat{v} = \frac{c}{4\pi f_0 T_{\text{prf}}} \arctan \left( \frac{\sum (I[n]Q[n+1] - I[n+1]Q[n])}{\sum (I[n]Q[n+1] + Q[n]Q[n+1])} \right),
\]

where \( c \) is the speed of sound, \( f_0 \) is the centre frequency of the ultrasonic excitation \( u(t) \), \( T_{\text{prf}} \) is the pulse repetition period, and
Substituting equation (6) into equation (7), we have

\[ \hat{v} = \frac{c}{4\pi f_0 T_{prf}} \arctan \frac{\sin(4\pi f_0 T_{prf} v / c)}{\beta^2 / \alpha^2 + \cos(4\pi f_0 T_{prf} v / c)}. \]  

In general, \( \beta \) is bigger than \( \alpha \) because the reflections of static tissues are greater than the scattering of erythrocytes. Then,

\[ \hat{v} < \frac{c}{4\pi f_0 T_{prf}} \cdot \frac{4\pi f_0 T_{prf} v}{c} = v. \]  

Clutters tend to lower the estimator, especially when the signal-to-clutter ratio is low. The influence should be considered and could be revised as system error. Noting that even excellent filters cannot remove clutters completely, the influence is inevitable. Therefore, a high-performance filter is necessary to improve the signal-to-clutter ratio. In other words, auto-correlation algorithm relays on the performance of filters. The schematic diagram of auto-correlation algorithm is shown in figure 1.

**Figure 1.** Auto-correlation algorithm.

### 3.2. Cross-correlation algorithm

The velocity estimator of cross-correlation algorithm is

\[ \hat{v} = \frac{cT_s}{2T_{prf} \Delta n_{prf}} \arg \max_k \sum_{n_{prf}} R[k, n_{prf}], \]  

where \( c \) is the speed of sound, \( T_s \) is the sampling interval, \( T_{prf} \) is the pulse repetition period, \( \Delta n_{prf} \) is the difference of two period indexes used for correlation calculation, and

\[ R[k, n_{prf}] = \frac{1}{N_x - k} \sum_{n_{prf} = 0}^{N_x - k - 1} \left( x[n_{prf} + k, n_{prf} + \Delta n_{prf}] \right). \]  

Substituting equation (6) into equation (12), we have

\[ \hat{v} = \frac{cT_s}{2T_{prf} \Delta n_{prf}} \arg \max_k \left[ \frac{\beta^2}{\alpha^2} \cos(2\pi f_0 T_s k) + \cos \left( 2\pi f_0 T_{prf} k - \frac{4\pi f_0 T_{prf} \Delta n_{prf} v}{c} \right) \right]. \]
The influence of clutters is largely dependent on $\beta^2 / \alpha^2$ that represents the signal-to-clutter ratio. Noting that $k$ is an integer, the velocity estimator of cross-correlation algorithm takes discrete values. When the signal-to-clutter ratio is high, clutters have slight influence on the velocity estimator. The slight change makes no difference. However, clutters produce an assignable influence on the velocity estimator when the signal-to-clutter ratio is low. Therefore, a high-pass filter is essential in a noisy environment. From equation (14), clutters caused by static tissues tend to lower the estimator. The schematic diagram of cross-correlation algorithm is shown in figure 2.

![Figure 2. Cross-correlation algorithm.](image)

Compared with auto-correlation algorithm, cross-correlation algorithm is easier to design. Auto-correlation algorithm attenuates high-frequency noise with an orthogonal low-pass filter and removes clutters with a high-pass filter. By contrast, cross-correlation algorithm requires only a high-pass filter that is optional when clutters are weak.

The influence of clutters on correlation algorithms can be summarized in three aspects. (1) Clutters tend to lower the velocity estimator. (2) Auto-correlation algorithm is more sensitive to clutters. (3) Cross-correlation algorithm is easier to implement.

4. Simulation results and discussion
The previous section analysed the influence of clutters on correlation algorithms in theory. In this section, we will validate the above inferences by simulation. Firstly, generate ultrasonic echo signals using Field II. Then, compute velocity estimators using correlation algorithms. Finally, compare the estimators with the theoretical velocity. The schematic diagram is shown in figure 3.

![Figure 3. Echo signal simulation and algorithm analysis.](image)

Set simulation parameters. Assume that $c=1540\,\text{m/s}$, $f_0=5\,\text{MHz}$, $f_s=40\,\text{MHz}$, $f_{prf}=10\,\text{kHz}$, $N_{prf}=32$, the angle between the ultrasonic beam and blood flow is $45^\circ$, the radius of a blood vessel is 4mm and the given velocity $v$ has a parabolic distribution whose maximum value is 0.8m/s. The scattering intensity ratio of erythrocytes to static tissues is 0.1.

![Figure 4. Ultrasonic echo signal.](image)
The generated echo signal in one period is shown in figure 4. The horizontal coordinate is the sampling time that corresponds to the depth. The vertical coordinate is the normalized amplitude of the signal.

From figure 4, the amplitude on two sides is bigger than that in the middle. The signal on two sides mainly results from clutters, while the signal in the middle mainly contains the scattering of erythrocytes. It is identical to the simulation condition that the scattering intensity of static tissues is greater than erythrocytes.

Compute velocity estimators using correlation algorithms. The results are shown in figure 5. The horizontal coordinate is the radial distance from the centre of the blood vessel. $v$ represents the theoretical velocity; $\hat{v}$ represents the velocity estimator.

![Figure 5](image_url)

**Figure 5.** Velocity estimators of (a) auto-correlation and (b) cross-correlation.

From figure 5, velocity estimators are considerably close to the theoretical velocity. It indicates that both algorithms could perform well when the signal-to-clutter ratio is high. Compared with the theoretical value, velocity estimators tend to be small, mainly in the following two reasons. (1) Since there are scatterers of different velocities in the same sample volume, the overall average velocity is always smaller than the maximum theoretical value 0.8m/s. (2) The residual clutter lowers the estimators.

To validate the influence of clutters on measurements, reduce the signal intensity and simulate again. The results are shown in figure 6. The scattering intensity ratio of erythrocytes to static tissues is 0.01.

![Figure 6](image_url)

**Figure 6.** Velocity estimators of (a) auto-correlation and (b) cross-correlation.

From figure 6, the velocity estimator in the left subgraph is obviously away from the theoretical velocity $v$, while the velocity estimator in the right subgraph is still close to $v$ when $v$ is small.
Comparison of figure 5 and figure 6 indicates that auto-correlation algorithm is more easily affected when the signal-to-clutter ratio is low.

5. Conclusions
To analyse the influence of clutters on ultrasonic Doppler blood flow measurements, we established a signal model of pulsed wave Doppler. In this model, clutters were regarded as fixed frequency disturbances whose amplitude and phase were unknown. The influence of clutters on correlation algorithms largely depends on the signal-to-clutter ratio. The influence can be summarized in three aspects. (1) Since the filter cannot remove clutters completely, the residual clutters tend to lower the velocity estimators. The estimators are always smaller than the maximum theoretical value 0.8m/s, because there are scatterers of different velocities in the same sample volume. (2) Auto-correlation algorithm is more sensitive to clutters than cross-correlation algorithm. The estimator of auto-correlation algorithm is obviously away from the theoretical value, when the signal-to-clutter ratio is in a low level. (3) Cross-correlation algorithm is easier to implement. Auto-correlation algorithm requires an orthogonal low-pass filter to attenuate high-frequency noise and a high-pass filter to remove low-frequency clutters. By contrast, cross-correlation algorithm needs only a high-pass filter.

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