Doppler Angle Estimation Using the AR Spectrum Model

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Abstract-The transit time spectrum broadening effect has long been explored for Doppler angle estimation. Given acoustic beam geometry, the Doppler angle can be derived based on the mean Doppler frequency and the Doppler bandwidth. Fast Fourier Transform (FFT) based spectral estimators are typically used. One problem with this approach is that a long data acquisition time is required to achieve adequate spectral resolution. In this paper, an autoregressive (AR) model is proposed to obtain the Doppler spectrum using a limited number of flow samples. Since only a small number of samples are used, the data acquisition time is significantly reduced and real-time two-dimensional Doppler angle estimation becomes feasible. Results indicated that the AR method generally provided accurate Doppler bandwidth estimates. It also outperformed the conventional FFT method at small Doppler angles.

I. INTRODUCTION

The Doppler bandwidth has been derived theoretically for a flow moving transverse to the beam axis of a transducer. It was shown that the Doppler bandwidth is inversely proportional to the transit time of a scatterer crossing the ultrasound beam [1]. Thus, the Doppler angle can be found given the beam geometry and the estimated Doppler bandwidth.

FFT is the most commonly used signal processing technique for Doppler bandwidth estimation. One problem with this approach is that a sufficiently long data acquisition time is required to achieve adequate spectral resolution. Thus, the FFT based method is not suitable for real-time two-dimensional Doppler imaging due to the requirement of a long data acquisition time. To overcome the problem, a correlation-based method for Doppler angle estimation was proposed. It has been shown that the correlation-based method can be used for accurate angle estimation using 4 flow samples if proper variance averaging is applied [2].

Another issue for Doppler bandwidth estimation is the interference due to multiple scatterers within a sample volume. The top panel of Fig. 1(a) shows the M-mode image of the envelope of a signal from a single scatterer crossing the sample volume. The middle panel of Fig. 1(a) shows the Doppler signal of the single scatterer with a range gate from 68mm to 70mm. The bottom panel of Fig. 1(a) demonstrates the Doppler spectrum. The three panels of Fig. 1(b) have the same format as Fig. 1(a) except that there are two scatterers. In this case, both the envelope of the Doppler signal and the Doppler bandwidth are affected. The mean Doppler frequency is relatively unchanged.

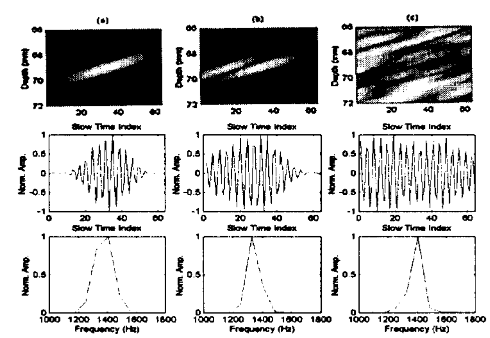

Fig. 1

Fig. 1(c) shows the results in a realistic case where multiple scatterers are present. Both the transit time and Doppler bandwidth are affected. Thus, the estimated Doppler angle may also be incorrect. However, if the Doppler spectrum is obtained by extrapolating a small data set, such interference may be reduced without affecting the spectral resolution. In this paper, we will explore potential of Doppler angle estimation using the AR spectrum model. The proposed approach will estimate the Doppler spectrum using a short data set and will be compared to the FFT-based method.

II. DOPPLER ANGLE ESTIMATION USING THE AR MODEL

Blood flow velocity can be measured by detecting the Doppler frequency shift of echoes backscattered from blood. The Doppler frequency shift f_d is related to the flow velocity by

$$f_d = \frac{2v}{\lambda}\cos\theta, \qquad (1)$$

where v is the flow velocity, λ is the acoustic wavelength and θ is the Doppler angle. The term $v \cdot \cos\theta$ is the axial flow component of the velocity vector.

It is known that the Doppler bandwidth bw is inversely proportional to the transit time of an acoustic scatterer crossing the sample volume. The relation is given by

$$bw = \kappa \frac{v \cdot \sin\theta}{w}, \qquad (2)$$

where κ is a scaling factor and w is the beam width. Given a Doppler spectrum and acoustic beam geometry, the Doppler angle θ can be found by [1]

$$\theta = \tan^{-1}\left(\frac{w \cdot bw}{\kappa \cdot v \cdot \cos\theta}\right). \qquad (3)$$

Alternatively, the Doppler angle can also be found by [3]

$$\theta = \tan^{-1}\left(\frac{f_{max} - f_p}{f_p} \cdot \frac{2F}{W}\right), \qquad (4)$$

where f_p is the peak frequency of the Doppler spectrum, F is the transducer focal length and W is the transducer width. The latter approach has the advantage when aspect ratio of the sample volume is not sufficiently large.

The AR model assumes that the value of a signal $y(n)$ can be described by a linear combination of previous values of the same signal and a white noise input [4]. For an 8-th order AR model, we have

$$y(n)=e(n)-a_1y(n-1)-a_2y(n-2)-\cdots-a_8y(n-8), (5)$$

where $e(n)$ is the white noise input. Variance of $e(n)$ and a_i s can be estimated by solving Yule-Walker equations.

Assuming an 8-th order AR model, the 8 flow samples are qualified for Doppler angle estimation if the following two conditions are simultaneously satisfied. First, one of the flow samples must correspond to a maximum in the fast time direction (i.e., range direction). Second, signal intensity of the flow samples increases and reaches a peak before it starts to decrease along the slow time direction (i.e., firing sequence). The criteria must be met to ensure proper selection of the Doppler signal. It is graphically demonstrated in Fig. 2. In panel (a), the circle corresponds to a maximum along the depth indicating an adequate SNR. Panel (b) shows the Doppler signal intensity at the depth defined in (a). In this case, a peak is found in the first few samples indicating that a group of scatterers are passing through the sample volume and hence the flow samples can be used. Panel (c) corresponds to the original Doppler signal. The extrapolated Doppler signal using the first 8 samples are shown in panel (d).

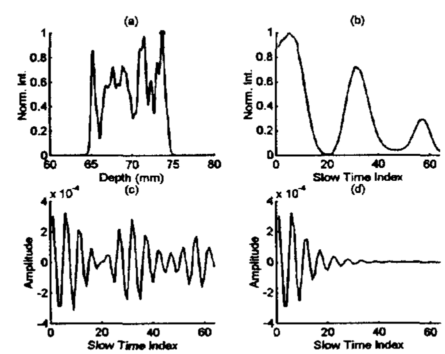

Fig. 2

III. SIMULATION RESULTS

Simulations were performed to test the proposed approach. The simulation model developed by A. T. Kerr and J. W. Hunt was adopted [5]. In the simulations, the transducer had a center frequency of 5MHz and a 19mm aperture size. The focal point was 70mm away from the transducer and the pulse repetition interval (PRI) was 100μ sec. For the AR method, 64 samples were obtained by extrapolating 8 original flow samples. The resulting 64 samples were then Fourier transformed to obtain the Doppler spectrum. The spectrum was also compared to the spectrum obtained by Fourier transforming 64 original flow samples.

The estimated Doppler frequency shift and the Doppler bandwidth with Doppler angles between 35 and 75 degrees are shown in Fig. 3. The theoretical values were obtained based on (1) and (2). Fig. 3 shows that both the AR method and the FFT method had reasonable agreement with the theoretical values.

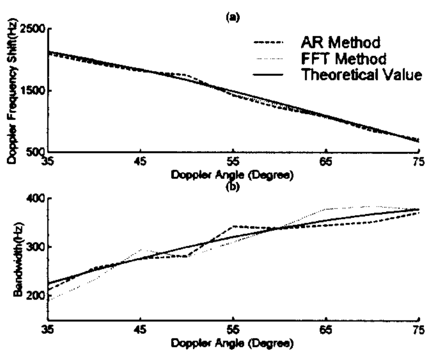

Fig. 3

The FFT method requires that the observation time must be longer than the transit time. Therefore, the following condition must be satisfied

$$\theta \geq \sin^{-1}\left(\frac{w}{v(N-1)PRI}\right) \equiv \theta_c, \quad (6)$$

where N is the number of flow samples, PRI is the pulse repetition interval and θ_c is defined as the critical angle. For the AR method, only 8 flow samples were used in this paper. The remaining flow samples were obtained by extrapolation. Thus, (6) is no longer required. Effects of the critical angle with the AR method are shown in Fig. 4. The flow velocity was a constant at 40cm/sec and the critical angle was 24^o according to (6). Results indicate that at small angles the FFT-based method (dotted) was less accurate than the AR method (dashed).

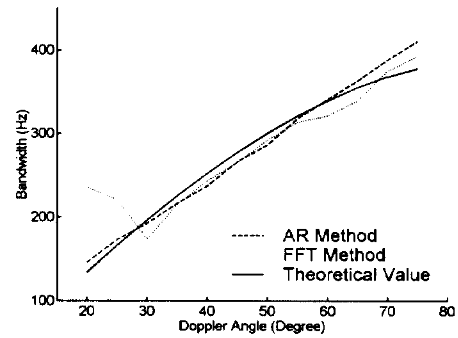

Fig. 4

Simulations of laminar flows were also performed. For a laminar flow, the velocity V_s can be expressed by

$$V_s = V_{\max}\left[1 - \left(\frac{r_i}{r}\right)^2\right], \quad (7)$$

where r is the vessel radius, $V_{\max}$ is the maximum flow velocity and r_i is radial distance relative to the center of vessel. The maximum flow velocity $V_{\max}$ was 40cm/sec. The critical angle in this case was again 24^o. The Doppler angle was estimated using (4). Results were shown in Fig. 5.

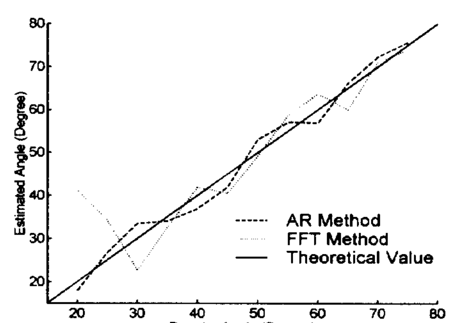

Fig. 5

IV. EXPERIMENTAL RESULTS

Experiments were conducted to investigate performance of the AR method. A block diagram of the experiment system is shown in Fig. 6. Data analysis and graphic display were done on a PC using MATLAB.

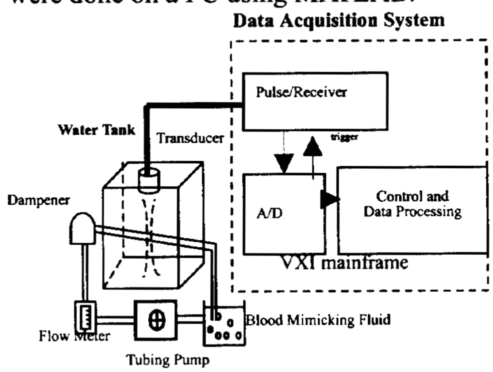

Fig. 6

The Doppler angles used in this paper were 33^o, 45^o, 54^o, 60^o and 72^o. At each angle, five Doppler data sets were used. Results were shown in Fig. 7. The upper panel shows that estimated Doppler angles using the AR method. The AR method had an average estimation error of 3.6^o and standard deviation ranged from 4.6^o to 7.6^o. The average was denoted by "x" and the standard deviation was denoted by the error bar. The FFT method shown in the lower panel using 64 flow samples had an average error of 4.7^o and standard deviation ranged from 3.0^o to 5.2^o degrees. The experimental results indicate that no significant differences in Doppler angle estimation between the AR method and the FFT method were found at these Doppler angles.

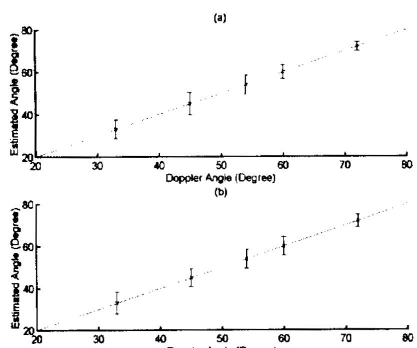

Fig. 7

V. CONCLUSIONS

In this paper, a new approach using a limited number of flow samples for Doppler angle estimation was proposed. An 8-th order AR model was used to extrapolate the original 8 flow samples to 64 flow samples for spectrum estimation. Based on simulations and experimental results, the AR method not only accurately estimated the Doppler bandwidth, it also outperformed the conventional FFT method at small Doppler angles. Since only a limited number of flow samples were used, real-time two-dimensional Doppler angle estimation is possible.

VI. REFERENCES

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