Directional synthetic aperture flow imaging using a dual stage beamformer approach

Li, Ye; Jensen, Jørgen Arendt

Published in: Proceedings of 2011 IEEE International Ultrasonics Symposium

Link to article, DOI: 10.1109/ULTSYM.2011.0309

Publication date: 2011

Document Version
Early version, also known as pre-print

Citation (APA):
Directional Synthetic Aperture Flow Imaging Using a Dual Stage Beamformer Approach

Ye Li and Jørgen Arendt Jensen

Center for Fast Ultrasound Imaging,
Biomedical Engineering group, Department of Electrical Engineering, Bldg. 349,
Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

Directional Synthetic Aperture Flow Imaging Using a Dual Stage Beamformer Approach

Ye Li and Jørgen Arendt Jensen
Center for Fast Ultrasound Imaging, Department of Electrical Engineering, Build. 349
Technical University of Denmark, 2800, Kgs. Lyngby, Denmark

Abstract—A new method for directional synthetic aperture flow imaging using a dual stage beamformer approach is presented. The velocity estimation is angle independent and the amount of calculations is reduced compared to full synthetic aperture, but still maintains all the advantages at the same time. The new method has been studied using the Field II simulations and experimental flow rig measurements. A linear array transducer with 7 MHz center frequency is used, and 64 elements are active to transmit and receive signals. The data is processed in two stages. The first stage has a fixed focus point. In the second stage, focal points are considered as virtual sources and data is beamformed along the flow direction. Then the velocities are estimated by finding the spatial shift between two signals.

In the experimental measurements the angle between the transmit beam and flow vessel was 70° and a laminar flow with a parabolic profile was generated by a flow rig. The flow with a peak velocity of 0.1 m/s was sampled at a pulse repetition frequency of 4 kHz. The signals were transmitted and received by the experimental scanner SARUS (Synthetic Aperture Real-time Ultrasound System). A relative standard deviation of 2.3% and bias of 6.4% at 65° were achieved in the simulations, and 4.3% and 4.2% for the experimental measurements. A color flow map image was made in 48 emissions corresponding to a frame rate of 83 frames/s.

I. INTRODUCTION

The angle dependency of velocity estimates is a major limitation for flow estimation in current ultrasound systems. The data are beamformed along the transmitted ultrasound beam, so only the velocity projected onto the beam direction can be estimated. However, many blood vessels lie along the skin surface that is nearly perpendicular to the transducer surface, which is a major challenge in the clinic.

Many authors have proposed different methods for solving the angle dependency problem. Fox [1] developed a method using multiple crossed-beams to measure the flow velocity and the angle. Trahey and coworkers [2] developed a method for flow imaging based on tracking the motion of the speckle pattern on the B-mode images. Jensen and Munk [3] developed a method that produces a transverse oscillation in the field. Once the lateral modulation is generated in the field, the velocity component in that direction can be estimated. Newhouse and coworkers [4] estimate the multi-dimensional velocity using the spectral broadening phenomenon. The amplitude of echo signals are modulated by the lateral and elevation beam patterns.

The Synthetic Aperture (SA) technique is a solution to this problem. The major advantage of SA is, that the data is available continuously and can be focused dynamically both in transmit and receive [5], [6]. Using recursive imaging, the flow motion can be tracked from the instantaneous high resolution image so the whole color flow map can be created quickly [7]. So the SA technique can be applied to fast flow imaging. Furthermore, the data can be beamformed in any direction with the SA technique, so the vector flow can be obtained by finding the directional signal along the flow direction, and this can be done for any direction. Jensen and Nikolov [8] have investigated this method through simulations, experiments and in vivo measurements. The relative standard deviation can be 0.36% compared to the peak velocity.

However, full SA requires a large amount of calculations, which gives a high demand on data transfer and storage in the system. Although SA has many advantages against conventional methods, currently it is hard to implement in a scanner. SA dual stage beamforming approach is an alternative method to implement the SA technique. SA using a dual stage beamformer approach is developed for reducing the amount of calculations, but still maintains the advantages of SA [9]. With this method, the angle should be known before the estimation. The angle can be determined based on finding the angle of maximum normalized cross-correlation function [10], so a fully autonomous velocity estimation system can be made. In this paper, results from both simulations and experimental measurements are presented, and a color flow map image is shown. The frame rate is 10 times higher than the conventional method and the amount of calculations is reduced compared to full SA.

II. DUAL STAGE BEAMFORMER AND DIRECTIONAL BEAMFORMING

The received signals are processed in two separate beamformers. In the first beamformer, a fixed delay profile is applied on the received data to beamform image lines. In the second stage, the time-of-flight (TOF) is calculated as the distance from the transmit element to the image point via the transmit focus point and back to the receive element via the receive focus point. The data are aligned in phase based on selecting the same TOF and the output data from the first stage is focused dynamically in receive [9]. The beamformed data in the first stage represents the information within the focused ultrasound beam, which is defined by an opening angle $\alpha$ [9], [11]

$$\alpha = 2 \arctan \frac{1}{2F^2},$$  \hspace{1cm} (1)

$$\alpha = 2 \arctan \frac{1}{2F^2},$$  \hspace{1cm} (1)

In the experimental measurements, the relative standard deviation is 36% compared to the peak velocity.
where \( F \) is the ratio of the focal point depth to the length of the active sub-aperture.

The directional beamforming is applied in the second stage. Instead of beamforming the data along the ultrasound beam, it is focused along the flow direction. SA can obtain high resolution images (HRIs) continuously, and the data can be focused in any direction. The new coordinate for directional beamforming is shown in Fig. 1

The directional beamforming is applied in the second stage. Instead of beamforming the data along the ultrasound beam, it is focused along the flow direction. SA can obtain high resolution images (HRIs) continuously, and the data can be focused in any direction. The new coordinate for directional beamforming is shown in Fig. 1

\[
\begin{align*}
\vec{r}_{ip}(k) &= [k\Delta x' \sin(\theta), 0, k\Delta z' \cos(\theta) + z_{ves}], \\
\end{align*}
\]

where \( x', y', z' \) represent the new coordinates, \( z_{ves} \) is the depth of the vessel, while \( x, y, z \) are the original ones. \( \theta \) is defined as the angle between the ultrasound beam and the flow direction. Therefore, the focusing points \( \vec{r}_{ip}(k) \) can be expressed as

\[
\begin{align*}
H^{(n)}(\vec{r}_{ip}(k)) = H^{(n-N)}(\vec{r}_{ip}(k) - \vec{v}T_{ref}N), \\
\end{align*}
\]

where \( \vec{v} \) is the velocity of the scatterers and \( T_{ref} \) is the pulse repetition time. The shift term in (5) indicates the speed of the movement over a number of emissions. The cross-correlation technique is used to estimate this shift. As the received signal is sampled at discrete space, the form is

\[
H_d(k) = H(\vec{r}_{ip}(k))
\]

Then the cross-correlation function can be calculated in discrete form. Since the cross-correlation function is estimated from two signals at the same depth in the \( z' \) coordinate, the cross-correlation can be expressed in one dimension. The discrete version is

\[
R_{n-N,n}(l) = \frac{1}{N_k+1} \sum_{k=-N_k/2}^{N_k/2} H_d^{(n-N)}(k)H_d^{(n)}(k+l)
\]

where \( N_k+1 \) is the number of samples in the high resolution signal, \( k_s \) is the delay lag indicating the peak value in the cross-correlation function. Therefore, the spatial shift can be represented as a delay lag in the cross-correlation function, thus, the speed along the flow direction can be

\[
|\vec{v}| = \frac{k_s\Delta z}{N_kT_{ref}},
\]

where \( k_s \) is the delay lag in the cross correlation function, \( \Delta z \) is the spatial sampling interval, and \( N \) is the number of emissions in one sequence.

**IV. RESULTS**

The method was simulated using Field II [12, 13] and verified through experimental measurements. Table I shows the parameters used in both simulations and measurement.

In the simulation, the blood flow is mimicked by numerous moving scatterers with a random uniform distribution and they have random Gaussian distributed amplitudes. 200,000 scatterers are confined in the simulated blood vessel, which is 30 mm long. Laminar flow with a parabolic profile moves in the vessel, and the peak velocity is 0.1 m/s.

In the experiment, the flow is generated by a circulating flow rig system as illustrated in Fig. 2. A gear pump drive (Cole-Parmer, Model: 75211-15) controls the volume flow in the tube. The air-trap device is used to remove air bubbles from the closed circuit and a commercial flow meter Danfoss MAGFLO (Type MAG 3000) is used as the reference for the volume

![Image of a setup of an ultrasound imaging system with directional beamformer](attachment:image-url)
The advantage of this new method is that the amount of calculations are reduced compared to full SA imaging. Full SA needs all the channel data to be used in beamforming one image, which requires a lot of data access and transfer. Current ultrasound systems are not capable of fulfilling these requirements. However, the dual stage beamformer simplify the whole beamforming. The first stage is simple, since a fixed
delay profile is used. The second stage requires almost the same amount of calculations as dynamic receive focusing in conventional ultrasound system. This reduces both the memory demands and number of calculations to perform.

VI. DISCUSSION AND CONCLUSION

The new method for making directional SA flow imaging using a dual stage beamformer approach is presented. The high resolution directional image lines can be achieved continuously due to the continuous available data. The high frame rate of 83 Hz can be obtained in the presented approach, since HRIs are available at every emissions. The low variance velocity estimates can be achieved, because any number of cross-correlation functions can be averaged to improve the performance. Although the simple mean subtraction echo canceling is applied in this paper, there is no limits to use other more advanced clutter filters, since data is available continuously. The simulations and experiments substantiate that it can be used for directional flow estimation and the amount of calculations for the new method compared to full SA is reduced.

REFERENCES