Axial Kasai Autocorrelation Estimation of High Flow Velocity without Aliasing using Time-Domain Doppler Optical Coherence Tomography

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In this paper, we demonstrate flow velocity estimation using the Kasai autocorrelation in the axial direction, along the beam path, with better frequency resolution than the short time fast Fourier transform (STFFT). Using a time-domain Doppler OCT system based on an 8 kHz rapid-scanning optical delay line, axial data of hardware demodulated in-phase and quadrature signals of flowing Intralipid in a 0.5mm inner diameter vessel were processed using the axial Kasai autocorrelation algorithm. At high flow rates, the phase changed linearly with flow velocity. M-mode images of parabolic flow profiles where estimated peak velocities greater than 10 cm/sec were obtained without aliasing or phase unwrapping techniques. The STFFT of the same data lacked adequate resolution for velocity estimation. When used in conjunction with Kasai autocorrelation in the lateral direction, which yields better velocity sensitivity to low flow velocities yet suffers from aliasing, the combined 2-dimensional Kasai techniques can provide flow detection for both the high and low flow ranges. Discussion of the mid-flow region, which bridges these two ranges, will be made.

Optical Coherence Tomography (OCT) is a method for non-invasively acquiring high resolution images of subsurface tissue structure. Resolutions of 1-10\textmu m have been reported\textsuperscript{4}. The short-time fast Fourier transform (STFFT) has been applied to detect the Doppler shift due to blood flow but the computational complexity and the need for adequate velocity resolution typically result in slow imaging frame rate\textsuperscript{1,6,9}. Through the use of autocorrelation methods, such as the Kasai velocity estimator, Doppler frequency shifts can be estimated\textsuperscript{3} in phase sensitive Doppler OCT systems (DOCT) in real-time, where phase changes in the transverse direction occur due to moving scatters. Aliasing limits the maximum detectable velocity to a few mm/s before phase-unwrapping techniques are applied, which then extends the velocity detection dynamic range\textsuperscript{1,3,4,5,7,10}. However, at high flow rates, the separation between aliasing rings can be smaller than the spatial resolution of the imaging system, making phase-unwrapping unreliable. Although the mm/s range is acceptable for microcirculatory imaging, there are applications that have higher velocity requirements, for example in the coronary vasculature.

\begin{equation}
\phi = \tan^{-1} \left( \frac{\sum_{m=0}^{M-1} \sum_{n=0}^{N-2} [I(m,n)Q(m+1,n)+Q(m,n)I(m+1,n)]}{\sum_{m=0}^{M-1} \sum_{n=0}^{N-2} [Q(m,n)I(m+1,n)+I(m,n)Q(m+1,n)]} \right)
\end{equation}

\begin{equation}
\Delta f = \frac{f_s}{2\pi} \phi
\end{equation}

where \(f_s\) is the sampling frequency, \(M\) and \(N\) are the computation window sizes in the axial and transverse direction, \(I\) and \(Q\) are hardware demodulated in-phase and quadrature components of the backscattered signal, and \(m\) and \(n\) refer to the axial and transverse indices. The flow velocity is related to the frequency change by

\begin{equation}
v = \frac{\lambda_o \Delta f}{2n_i \cos \theta}
\end{equation}

where \(v\) is the velocity at a specific point, \(\lambda_o\) is the centre wavelength of the light, \(n_i\) is the refractive index of the sample and \(\theta\) is the Doppler angle.
A flow phantom experiment was set up using a gravity pump with 1% Intralipid fluid flowing in a glass capillary of 0.5 mm inner diameter. Images were acquired using a time-domain DOCT system containing a 5 mW broadband light source centred at 1.3 μm with a 63 nm bandwidth. The system captured 512 axial points per axial scan and the axial scanning rate was \( f_a = 8 \) kHz through a rapid-scanning optical delay (RSOD) line in the reference arm, which also contained a phase modulator for producing a carrier frequency of 4.3 MHz. The OCT signal was then demodulated and digitized at 10 MHz. The hardware demodulated I and Q signals were processed using the Kasai autocorrelation in the axial direction for different window sizes of \( N = 2 \) to \( 32 \) and \( M = 16 \) to \( 32 \). Misalignments in the RSOD, wavelength dependent scattering and absorption, and non-linearity’s in the demodulation process contributed to a background axial phase change, even on stationary samples, which was subtracted for flow visualization.

Flow velocity was estimated by measured volumetric flow rate and assumed parabolic profile. As the entrance length was minimal and the Reynolds number was 22, laminar flow was assumed.

Using the axial Kasai algorithm, M-mode images were created as seen in figure 2A using \( N = 32 \) and \( M = 32 \). As compared to the M-mode image generated by calculating the centroid through use of STFFT at a moving window length of 32 in the axial direction (Figure 2B), the axial Kasai clearly shows a flow pattern through the tube while the STFFT is dominated by noise.

In order to compensate for the background axial phase change, the stationary background signal was estimated by imaging stationary Intralipid solution and subtracted. Equation (1.2) was applied to data calculated with equation (1.1) using \( N = 2 \) and \( M = 32 \) and the background signal was subtracted. Results were averaged over 20 consecutive A-scans and plotted in Figure 3. It can be seen that there is a parabolic profile.

Using a fixed flow rate, the experiment was performed at Doppler angles of 24° and 40°. The corresponding velocity vs. depth profile was plotted in Figure 4, showing consistent estimation of the flow velocity.

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plotted in Figure 5 as the axial Kasai estimated frequency shift versus the flow rate setting.

![Graph](image)

Figure 5 – The axial Kasai estimate of the maximum Doppler frequency in the centre of the tube averaged over 1000 A-scans, for a range of flow rates. Red line is a linear fit.

In summary, the axial Kasai autocorrelation method demonstrates a parabolic profile at high flow velocities in the capillary tube. We are currently working on modifications to the experimental set-up to improve the signal to noise characteristics of the system. The STFFT method, when compared with the axial Kasai given similar window sizes, lacks the resolution to resolve details of the flow pattern and is more computationally expensive.

We are currently exploring phase-unwrapping techniques to extend our previous lateral Kasai algorithm's maximum detectable velocity such that it can be bridged to the minimum detectable velocity in the axial direction. Detailed analysis of the background axial phase change also suggests that the scatterer’s size and its wavelength dependent scattering cross-section are contributing factors. The centroid frequency change can therefore be detected by the axial Kasai algorithm and is being incorporated into a spectroscopic OCT system where the endogenous and exogenous scatterer's optical properties may be probed.

References
