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The cross-correlation in spectral domain based Doppler optical coherence tomography

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A B S T R A C T S

We propose a cross-correlation method which is based on the cross-correlation of two adjacent A-scans of interferogram fringe for imaging the velocities of the blood flowing in vessels. The method was tested by measurements of the velocities of flowing particles within a glass capillary with known mean velocities. Mean standard deviations of flow velocities of the particles determined through the proposed method were compared to those by the conventional phase resolved method. *In vivo* imaging of a mouse ear was performed and the Doppler flow velocity maps were reconstructed by both methods. The experimental results demonstrated that the proposed method can significantly suppress the phase noises caused by phase instabilities and improve the signal to noise ratio of blood flow map.

1. Introduction

Spectral domain optical coherence tomography (SDOCT) [1,2] is a non-invasive imaging technology, capable of providing high resolution, depth resolved cross-sectional images of highly scattering sample, such as biological, with high speed. In order to obtain additional biological information of tissue, many functional SDOCTs have been developed. Thanks to the advantages of the improved imaging speed and sensitivity in SDOCT, a functional extension of SDOCT, spectral domain phase resolved Doppler OCT (PRDOCT) [3,4], which relies on the phase difference between successive A-lines at the same depth, was developed to extract velocity information of blood flow in functional vessels within the scanned tissue beds. To optimize the performance of PRDOCT, Ren et al. proposed a moving-scatterer- sensitivity optical Doppler tomography (MSS-ODT) technique to improve sensitivity for imaging blood flow *in vivo* [5], and Wang and An also proposed a Doppler optical micro-angiography (DOMAG) method to remove the characteristic texture pattern noise caused by the heterogeneous property of sample [6]. A modified phase-resolved method has also been reported to reduce the underestimation of the velocity by an extended averaging before calculating the phase difference [7]. Other approaches have also been tried to eliminate the deterioration by evaluation of the flow velocity from fluctuations [8,9] or variance [10] of intensity instead of phase shift. However, two main factors, low signal-to-noise ratio (SNR) [11,12] and motion artifacts causing severe phase instabilities [13], deteriorate and even preclude accurate determination of velocity using the conventional phase resolved method. The SNR of phase difference is influenced by the overlap degree of light spots on the sample and time interval between adjacent A-lines [14]. As the time interval decreases, SNRs of both phase difference and intensity signal detected by CCD decrease.

In this manuscript, we propose a cross-correlation method which is based on the cross-correlation of two adjacent A-scans of interferogram fringes for imaging of velocity information in a SDOCT system. The proposed method can significantly decrease the influence of noise caused by phase instabilities on the images of velocity information without need of increasing the overlap degree of light spots and time interval between adjacent A-lines.

2. Theorem of the proposed method

Fig. 1 is a block diagram for computing structural and Doppler flow images from the spectral fringe intensity profiles $I_j(\lambda)$ using cross-correlation method, where j is the index for A-scans and λ is wavelength. First, the spectral fringe intensity profiles are converted from wavelength domain to wavenumber domain ($I_j^{'}(k)$) by a standard spline interpolation algorithm to keep the axial resolution at different depth the same, where k represents wavenumber. The results $I_j^{'}(k)$ for the jth axial scan are correlated with the high frequency component $I_{j+1}^{''}(k)$ for the $(j+1)$th axial scan which is extracted by a high pass filter to yield a new spectral fringe intensity profiles $F_j(k)$. with a double number of pixels. Here,

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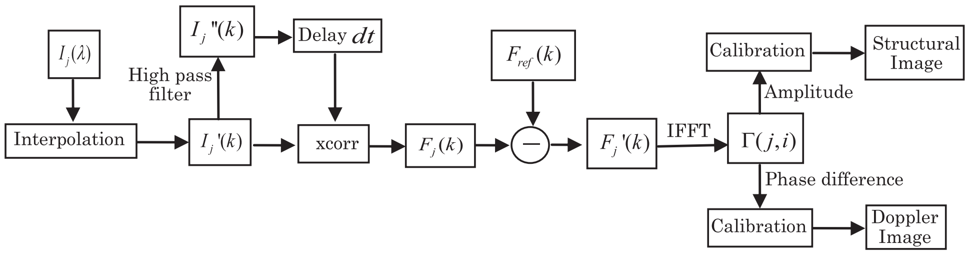

Fig. 1. Block diagram of signal processing for cross-correlation method.

the high pass filter is used to remove the influence of DC component in the correlation progress. In this work, the cut off frequency of high pass filter is the frequency of spectral fringes corresponding to the depth of 2 μm, which means that the spectral fringes corresponding to the depth > 2 μm can be remained. It should be noted that the maximum of the cut off frequency is the frequency of spectral fringes corresponding to the depth of sample surface. Then the DC component $F_{ref}(k)$ of new spectral fringe profiles obtained by calculating the median of all new A-lines is subtracted from each new A-line profiles $F_j(k)$. The (z) depth-dependent complex analytic signal $\tilde{\Gamma}(j, i)$ for the jth axial scan was obtained by taking the inverse Fourier transform of $F_j'(k)$ and then removing the redundant mirror signal for $z < 0$, where i is the index for axial pixels. A structural image can be produced by taking the magnitude of $\tilde{\Gamma}(j, i)$ with a procedure of calibration for all A-lines within a frame. The calibration procedure is to combine two adjacent pixels as one point through averaging, which makes the number of pixels in axial direction as same as that of the conventional phase resolved method. The Doppler frequency shift $f_D(p, q)$ at any given pixel (p, q) is then calculated from $\tilde{\Gamma}(j, i)$ by [7]

$$f_D(p, q) = \tan^{-1}\left[\frac{\mathrm{Im}\left(\sum_{j=p}^{p+N}\sum_{i=q}^{q+M}\left(\tilde{\Gamma}_{j,i}\bullet\tilde{\Gamma}_{j+1,i}{}^{*}\right)\right)}{\mathrm{Re}\left(\sum_{j=p}^{p+N}\sum_{i=q}^{q+M}\left(\tilde{\Gamma}_{j,i}\bullet\tilde{\Gamma}_{j+1,i}{}^{*}\right)\right)}\right]\Big/(2\pi\cdot dt)\quad N = 1, 2, \ldots, \tag{1}$$

where N is the horizontal window size (determined by the sampling frequency of A-lines in the transverse direction), M is the axial window size, $\tilde{\Gamma}_{j+1,i}{}^{*}$ is the conjugate of $\tilde{\Gamma}_{j+1,i}$, and dt is the time interval of two adjacent A-lines.

The two adjacent A-scans of spectral interference fringe can be approximately regarded as from the same lateral position because the movement between two adjacent A-scans is much smaller than the lateral resolution. In the cross-correlation method, the new A-lines are obtained by cross correlation of two adjacent A-scans of spectral interference fringes, which has two advantages: first the random noise in the spectral fringe induced in the signal detection process can be effectively suppressed; second, the pixel number of new A-lines is doubled without changing the frequency of spectral fringe intensity profiles, leading to doubling the axial size of window (M) over that in conventional phase resolved method and keeping the smallest distance between two adjacent blood vessels unchanged. Because the number of phase difference vectors used in calculating Doppler frequency shift $(f_D(p, q))$ with Eq. (1) is doubled, the cross-correlation method can further suppress the noise caused by phase instabilities and improve the SNR of Doppler frequency shift maps.

In SDOCT system, it is clear that the depth interval (Δh) between two adjacent pixels has to be smaller than axial resolution (Δz). The intensity of M pixels in the range of Δz can then be approximated to represent the information of sample at the same depth. Due to the maximum frequency of spectral fringes detected by SDOCT system is determined by CCD, according to Nyquist sampling theorem, the depth (z_{max}) corresponding to maximum frequency of spectral fringes can be expressed by

$$z_{max} = \frac{L\pi}{2\Delta k'} \tag{2}$$

where L is the pixel number of CCD, $\Delta k'$ is the range of wavenumber from first pixel to last pixel of CCD. Then the depth interval (Δh) between two adjacent pixels can be expressed by

$$\Delta h = \frac{z_{max}}{L/2} \tag{3}$$

Because the wavenumber $\Delta k'$ can be expressed as $\Delta k' = \frac{2\pi}{\lambda_{min}} - \frac{2\pi}{\lambda_{max}} \approx \frac{2\pi\cdot\Delta\lambda'}{\lambda_0^2}$, where $\Delta\lambda'$ is the wavelength range received by the CCD from first pixel to last pixel, λ_0 is the central wavelength of light source. The depth resolution can be expressed as $\Delta z = \frac{2\ln 2}{\pi}\frac{\lambda_0^2}{\Delta\lambda}$, where $\Delta\lambda$ is the full width at half maximum (FWHM) of light source. So the value of Mcan be determined by the following equation:

$$M = \left\langle \frac{\Delta z}{\Delta h} + 1 \right\rangle = \left\langle \frac{0.88\Delta\lambda'}{\Delta\lambda} + 1 \right\rangle \tag{4}$$

where $\langle\,\rangle$ represents an operation which returns the nearest bigger integer.

As pointed out in Ref. [7], the distribution of phase difference between adjacent A-lines can be expressed as a constant phasor plus a random phasor, and the probability density function can be expressed as a Gaussian function. As the mean velocity $(\bar{v})$ of the moving particles increases, the phase difference $(\Delta\varphi)$ distribution moves closer to the maximum $-\pi$ or π, the probability of phase wrap increases, which decreases the accuracy of velocity measurement and increase the measuring error (standard deviation, STD). The growing progress of STD can be described by the accumulated probabilities integral of Gaussian distribution, which can be expressed as Gauss error function, so the STD of calculated Doppler frequency shift *versus* mean velocity $(\bar{v})$ can be given by

$$STD = \frac{1}{2} + \frac{1}{\sqrt{\pi}}\cdot\sum_{m=0}^{\infty}(-1)^m\frac{(\bar{v} - v_{max})^{2m+1}}{m!(2m+1)}, (0 \le \bar{v} \le v_{max}) \tag{5}$$

where v_{max} is the maximum velocity that can be measured by SDOCT which is determined by the time interval of two adjacent A-scans, m is an integer.

3. Experimental results and discussions

3.1. System setup

The schematic of the fiber optics based SDOCT system used in our study is shown in Fig. 2. The broadband light source is a super luminescent diode (SLD) with a center wavelength of 830 nm and