Photoacoustic Doppler flowmetry of carbon particles flow using an autocorrelation method*

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In order to measure the axial flowing velocity of carbon particle suspension with particle diameter of tens of micrometers, the photoacoustic Doppler (PAD) frequency shift is calculated based on a series of individual A scans using an autocorrelation method. A 532 nm pulsed laser with repetition rate of 20 Hz is used as a pumping source to generate photoacoustic signal. The photoacoustic signals are detected using a focused piezoelectric (PZT) ultrasound transducer with central frequency of 5 MHz. The suspension of carbon particles is driven by a syringe pump. The complex photoacoustic signal is calculated by the Hilbert transformation from time-domain photoacoustic signal, and then it is autocorrelated to calculate the Doppler frequency shift. The photoacoustic Doppler frequency shift is calculated by averaging the autocorrelation results of some individual A scans. The advantage of the autocorrelation method is that the time delay in autocorrelation can be defined by user, and the requirement of high pulse repetition rate is avoided. The feasibility of the proposed autocorrelation method is preliminarily demonstrated by quantifying the motion of a carbon particle suspension with flow velocity from 5 mm/s to 60 mm/s. The experimental results show that there is an approximately linear relation between the autocorrelation result and the setting velocity.

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Photoacoustic tomography (PAT) combines the merits of pure optical imaging and ultrasound imaging together. It can give high contrast and high resolution pictures inside biological tissue. The principle of PAT is that the heterogeneous biological structures can generate acoustic wave under the irradiation of short laser pulse[1]. As the optical absorption coefficient of red blood cells at certain wavelength is about 100 times higher than that of the surrounding vascular tissues, PAT can be used for the imaging of micro-blood vessels inside soft tissues with high spatial resolution and contrast. The feasibility of using photoacoustic Doppler (PAD) effect in flowmetry was demonstrated in previous research. The photoacoustic Doppler shift was generated by a continuous wave (CW) excitation of infrared laser diode, and the fast Fourier transform was used to calculate axial velocity[2]. The photoacoustic Doppler signal was generated by a 523 nm pulsed laser with repetition rate of 1 724 Hz, and the bandwidth broadening was obtained by cross-correlation algorithm in frequency domain to calculate transverse velocity[3,4]. The time-shift of successive photoacoustic signals excited by dual pulsed lasers was obtained, and the axial velocity was calculated by time-domain cross-correlation[5]. In those studies, the power of the CW laser diode was about 150 mW, the lower optical power was more applicable in clinical field but the generation efficiency of photoacoustic signal was lower than that using the pulsed laser[2]. In the photoacoustic Doppler system using pulsed laser, cross-correlation algorithm of sequential A scans was used to calculate time shift or frequency shift. The time interval between sequential A scans must be less than millisecond to avoid sequential signals uncorrelated or aliasing[3-5]. It is difficult to get a pulsed laser with repetition rate of several kilohertzs, and the correlation between sequential A scans is also limited by the repetition rate.

As was known, the autocorrelation has been used in clinical pulsed-echo Doppler ultrasound and ODT system to calculate signal phase shift[6]. In this paper, we introduce the autocorrelation method of individual A scans for the calculation of photoacoustic Doppler frequency shift. Different from the cross-correlation method, the limitation of scanning speed can be overcome by the defined time delay ΔT. The aliasing can be avoided when ΔT is chosen as much less than the time interval T between sequential A scans. The lower limit of ΔT is the sampling interval t_s[7]. In our experiment, a 532 nm pulsed laser with repetition rate of 20 Hz is used. The carbon particle suspension liquid is used as blood mimicking phantom. The feasibility of the proposed autocor-

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relation method is preliminarily demonstrated by quantifying the motion of a carbon particles suspension with flow velocity from 5 mm/s to 60 mm/s. The experimental results show that there is an approximately linear relation between the autocorrelation result and the setting velocity.

When the successive laser pulses irradiate the surface of the tissue phantom, the deposited optical energy inside tissue can cause the optical absorbing particle, such as red blood cell, to generate photoacoustic signal. Such a signal generated by moving optical absorbing particle is also called as photoacoustic Doppler signal. By denoting the complex autocorrelation function with $R(\tau)$, the phase shift $\Delta\phi$ is[6-10]

$$\Delta\phi = \tan^{-1}\frac{R_y(\tau)}{R_x(\tau)}, \quad (1)$$

where $R_y(\tau)$ and $R_x(\tau)$ are the imaginary part and real part of the complex autocorrelation function $R(\tau)$, respectively. The Doppler frequency shift is[6-10]

$$\Delta\omega = \frac{\Delta\phi}{\tau}. \quad (2)$$

The complex autocorrelation function with $R(\tau)$ is given as[6]:

$$R(\tau) = \sum_{j=1}^{n} \tilde{p}_j(t)\tilde{p}_j^{*}(t-\tau) = R_x(\tau) + \mathrm{i}R_y(\tau), \quad (3)$$

where $\tilde{p}_j(t)$ is the complex signal of time domain signal $p_j(t)$ of the jth scan, and $\tau=\Delta T$ is the temporal lag of autocorrelation. In cross-correlation method, $\tau=T$, where T is the time interval between sequential scans, but it needs high scanning speed to obtain smaller T to avoid signal aliasing. In autocorrelation method, $\tau=\Delta T$ can be defined, and the aliasing can be avoided when τ is chosen as much less than the time interval T between sequential A scans[9]. The complex signal $\tilde{p}_j(t)$ is calculated by the Hilbert transformation of time domain signal $p_j(t)$. Because the photoacoustic signal induced by pulsed laser is in wideband, the digitized photoacoustic signal $p_j(t)$ firstly passes through a ramp filter to increase the signal-to-noise ratio (SNR) before Hilbert transformation. The ramp filter is given by[11]

$$W(\omega) = \left[1+\cos(\frac{\pi\omega}{\omega_c})\Big/2\right], \quad (4)$$

where ω_c is the cutoff frequency. The frequency response of the ramp filter is shown in Fig.1, where the filter functions with different cutoff frequencies and the filter functions of linear/nonlinear filter are given.

The experimental setup is shown in Fig.2. A 532 nm Nd:YAG laser with repetition rate of 20 Hz (Quanta-Ray INDI, Spectrum Physics) is used as the pumping source. An ultrasound transducer with central frequency of 5 MHz (Olympus IR-0508-S-SU) followed by a low-noise preamplifier (Olympus 5676) is used to collect photoacoustic signal. And then the photoacoustic signal is collected using the segmented memory feature of the oscilloscope (Agilent 90404A). The focal length and the diameter of the focal region of the transducer are 4.6 cm and 0.95 mm, respectively. The flow sample is a carbon particle suspension with the volume fraction about 10% in distilled water. The diameters of carbon particles (activated charcoal C3345, Sigma-Aldrich) are less than 75 μm. The solution for suspending the particles is made by dissolving an appropriate amount of solid sodium polytungstatef (71913, Sigma-Aldrich) into distilled water. The fluid flow is generated by a syringe pump (LSP01-1A, Longerpump, China) with a 10 mL syringe and a tygon tube (inner diameter of 0.95 mm, Saint-Gobain performance plastics).

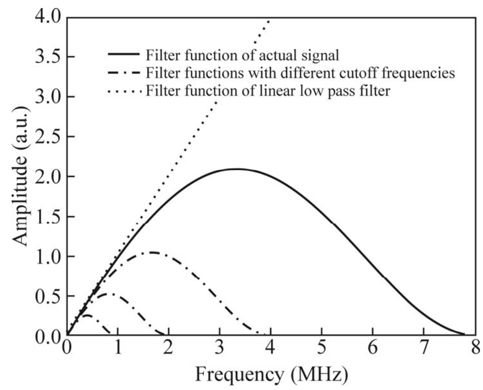

Fig.1 Frequency responses of ramp filter

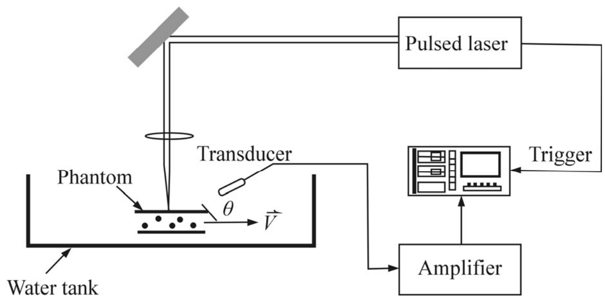

Fig.2 Schematic diagram of the experimental setup

The original detected photoacoustic signal of carbon particles suspension is shown in Fig.3(a), and the low pass filtered photoacoustic signal of carbon particle suspension in time domain before autocorrelation is shown in Fig.3(b). The signal is detected by a 5 MHz spherical focus transducer with focal spot size of 0.97 mm, and the upper cutoff frequency of ramp filter is set as 7.5 MHz. Photoacoustic Doppler shift calculated by autocorrelation at flow speed from 5 mm/s to 60 mm/s is shown in Fig.4, and the line is the linear fitting of the data points. In Fig.4, the data points are the autocorrelation results of the experimental data, and each data point is calculated by averaging the autocorrelation results of ten scans. The distribution of data results shows that the autocorrelation result has an approximately linear relation with the pre-setting velocity. In cross-correlation, the time lag T is the time interval between sequential A scans and depends on the system scanning speed. The maximum frequency shift and the correlation between sequential A scans are limited by

T. Instead, in autocorrelation, the time lag ΔT can be chosen manually much less than the interval T between sequential A scans, and the lower limit of ΔT is the sampling interval t_s in axial direction. As the data sampling frequency f_s is 250 MHz, ΔT can be chosen as lower as $1/f_s$=0.004 μs. In our experiment, because the maximum flow speed is not so high, ΔT in autocorrelation is 0.01 μs.

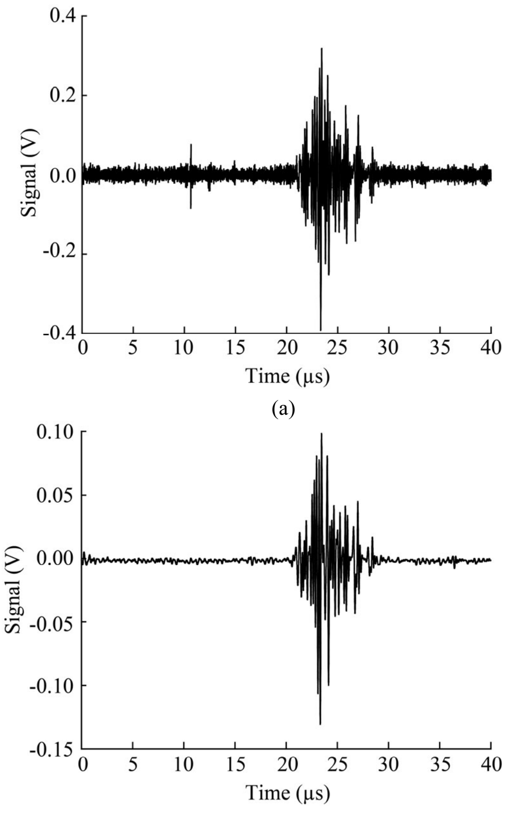

Fig.3 (a) The original detected photoacoustic signal of carbon particles suspension and (b) the filtered photoacoustic signal by the ramp filter

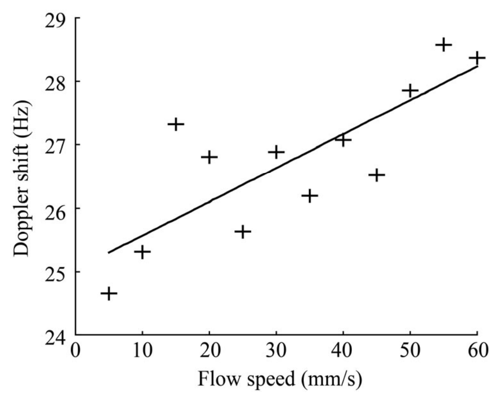

Fig.4 Photoacoustic Doppler shift calculated by autocorrelation at flow speed from 5 mm/s to 60 mm/s

It also can be seen from Fig.4 that the linearity of the data points is not high. The main reason is considered as the limitation of the spatial resolution. The focal spot size of the used 5 MHz transducer is about 0.97 mm. The contribution of velocity gradient and turbulence may be the main reason of the nonlinearity of the data points. It can be minimized when the spatial resolution is high enough. In previous cross-correlation method[4], a 75 MHz transducer is used and the focal spot size is 27 μm. So the linearity can be improved if the transducer with smaller focal spot size is used in autocorrelation.

The feasibility of using autocorrelation method and pulsed laser in photoacoustic Doppler flowmetry is preliminarily studied. Unlike previous cross-correlation method which needs high sequential scanning rate to avoid uncorrelation between signal pair, the advantage of autocorrelation method is that the time lag can be defined. The maximum frequency shift is not limited to the time interval between sequential A scans in autocorrelation. A carbon particle suspension is used as the fluid phantom, in which the diameters of particles are tens of micrometers. The motion of the carbon particle suspension with flow velocity from 5 mm/s to 60 mm/s is measured. The experimental results show that the autocorrelation result has an approximately linear relation with the setting velocity. The linearity of the autocorrelation results can be improved by increasing the spatial resolution using the transducer with high central frequency.

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