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Transverse flowmetry of carbon particles based on photoacoustic Doppler standard deviation using an auto-correlation method*

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In order to measure the flow velocity of carbon particle suspension perpendicular to the receiving axis of ultrasound transducer, the standard deviation of photoacoustic Doppler frequency spectrum is used to estimate the bandwidth broadening, and the spectrum standard deviation is calculated by an auto-correlation method. A 532 nm pulsed laser with the repetition rate of 20 Hz is used as a pumping source to generate photoacoustic signal. The photoacoustic signals are detected using a focused PZT ultrasound transducer with the central frequency of 10 MHz. The suspension of carbon particles is driven by a syringe pump. The complex photoacoustic signal is calculated by Hilbert transformation from time domain signal before auto-correlation. The standard deviation of the Doppler bandwidth broadening is calculated by averaging the auto-correlation results of several individual A scans. The feasibility of the proposed method is demonstrated by measuring the spectrum standard deviation of the transversal carbon particle flow from 5.0 mm/s to 8.4 mm/s. The experimental results show that the auto-correlation result is approximately linearly distributed within the measuring range.

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The photoacoustic Doppler (PAD)[1] signal has many advantages over conventional Doppler ultrasound signal[2]. The studies of PAD flow measurement include axial and transverse flow detections. In axial flow detection using a continuous-wave modulation and lock-in detection, the PAD shift and the axial flow velocity were calculated by short time fast Fourier transform[3,4]. In axial flow detection using dual pulsed lasers, the time shift of successive photoacoustic signal and the axial velocity were calculated by time domain cross-correlation[5]. In PAD flowmetry of velocity vector or raster scan imaging, the transverse component of flow velocity is sometimes critical. When the Doppler angle approaches 90°, the PAD frequency shift will be about zero. Previous studies in the fields of ultrasound and optical Doppler tomography (ODT) have demonstrated the feasibility of using Doppler bandwidth broadening to measure transverse flow component[6-8]. The spectrum broadening can be estimated by the standard deviation of Doppler spectrum[7,8]. The previous study of PAD effect has demonstrated the feasibility of using cross-correlation to calculate standard deviation of PAD spectrum in transversal flow measurement[9-12]. In those studies, the pulsed laser with the repetition rate of several kilohertz was used to avoid the uncorrelation or signal aliasing between sequential A-scans[9,10]. However, it is difficult for a single high power pulsed laser to reach the repetition rate of several kilohertzs, and the measuring range is also limited by the time interval between sequential scans.

To overcome the limitations of scanning speed in cross-correlation, we introduce the auto-correlation method of individual A scans into PAD flow measurement[13]. The standard deviation of the PAD spectrum is averaged by several individual A scans. The time delay of PAD signal in auto-correlation is defined by users[13]. In this experiment, a 532 nm pulsed laser with the repetition rate of 20 Hz is used as a pumping source to generate photoacoustic signal. The photoacoustic signals are detected using a focused PZT ultrasound transducer with the central frequency of 10 MHz. The feasibility of the proposed method is verified.

As is known in ultrasound Doppler and laser Doppler velocimetry, there are a number of sources, including velocity gradient, turbulence, Brownian motion, speckle and transit time of a scatter crossing the probe beam, to contribute to the broadening of the Doppler spectrum[7,13]. When the flow velocity is low, the Brownian motion

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dominates the spectrum broadening. When the flow velocity is high, the transit time broadening is dominant[7]. In PAD, the bandwidth broadening caused by illumination angle can be neglected. The Doppler bandwidth is mainly determined by the transit time of the moving optical absorbers across the focal point of the transducer, when the flow velocity is not too low[9,10]. The 3-dB Doppler bandwidth B_d is given by[7,9,13]

$$B_{\mathrm{d}} = \frac{4v\sin\theta NA_{\mathrm{eff}}}{\lambda} + b \approx f_0 \frac{v}{c}\frac{W}{F}\sin\theta \,, \tag{1}$$

where v is the flow velocity, NA_{eff} is the effective numerical aperture of the focused ultrasound transducer, θ is the Doppler angle, f_0 is the central frequency of the transducer, W and F are the element diameter and the focal length of the transducer, c is the ultrasound speed, and b is the fundamental bandwidth of the spectrum owing to Brownian motion, velocity gradient and other sources independent of flow velocity[7,13].

The relationship between the standard deviation σ and the Doppler bandwidth (full width at 1/e of the maximum spectrum amplitude) is[7]

$$B_{1/\mathrm{e}} = 4\sigma \,. \tag{2}$$

Then the standard deviation σ is given by auto-correlation as[13]

$$\sigma^2 = \frac{2}{(\Delta T)^2}\left[1 - \frac{\left|\sum_{j=1}^{n} \tilde{\Gamma}_j \tilde{\Gamma}_j^*(\Delta T)\right|}{\sum_{j=1}^{n} \tilde{\Gamma}_j \tilde{\Gamma}_j^*}\right], \tag{3}$$

where ΔT is the temporal lag in auto-correlation. Other than cross-correlation[9,10], ΔT can be user defined, and aliasing is readily avoided if ΔT is chosen to be much less than the interval between sequential A scans. The lower limit of ΔT is the data sampling interval[13]. Here, ΔT is chosen to be 0.5 μs in the experiment.

The complex signal $\tilde{\Gamma}_j$ is calculated by Hilbert transformation of the time domain signal $\Gamma_j(t)$, and j denotes the jth scan. Five A-scans are auto-correlated in experiment. As the irradiation laser is short pulse, $\Gamma_j(t)$ has wide band, and firstly passes through a ramp filter to increase the signal-to-noise ratio (SNR) before Hilbert transformation. The ramp filter is given by[14]

$$W(\omega) = 1 + \cos\left(\frac{\pi\omega}{\omega_{\mathrm{c}}}\right) \Big/ 2 \,, \tag{4}$$

where ω_c is the cutoff frequency of 10 MHz.

The experimental setup based on pulsed laser has been described in previous work[15]. The photoacoustic signal detection scheme is shown in Fig.1. 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 10 MHz (Olympus IR-1008-S-SU) followed by a low-noise preamplifier (Olympus 5676) is used to collect photoacoustic signal. The focal length of the transducer is 19 mm, and the beam diameter at the focal point is 0.23 mm. The photoacoustic signal is collected using the segmented memory feature of the oscilloscope (Agilent 90404A). Five A-scans are used in the calculation of σ by auto-correlation. The flow sample is a carbon particle suspension with the volume fraction about 10% in distilled water. The diameter of carbon particles (activated charcoal C3345, Sigma-Aldrich) is less than 75 μm. The solution for suspending the particles was made by dissolving an appropriate amount of solid sodium polytungstate (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 with inner diameter of 0.95 mm (Saint-Gobain Performance Plastics). In Fig.1, θ=90° is the Doppler angle.

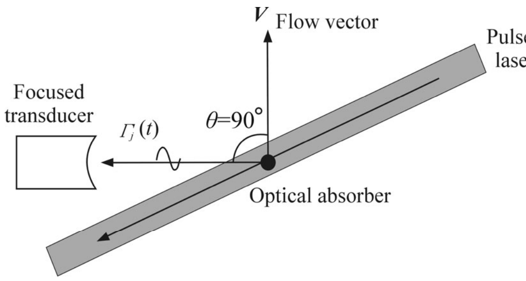

Fig.1 Schematic diagram of experimental setup for photoacoustic signal detection

Five sequential A scans of photoacoustic signals are shown in Fig.2, where T is the interval between successive laser pulses.

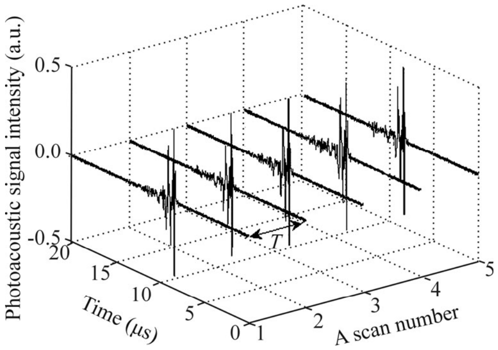

Fig.2 A-scans of photoacoustic signals in time domain used in auto-correlation

The auto-correlation results of the sequential A scans and the linear fitting of the auto-correlation results are shown in Fig.3. It can be seen from Fig.3 that the relationship between auto-correlation result and the preset velocity is approximately linear in the velocity range from 5.0 mm/s to 8.4 mm/s with increment of 0.2 mm/s. In cross-correlation, the time lag ΔT is determined by the laser repetition rate. The pulsed laser with high repetition rate is needed to make the sequential A scans correlated.

In auto-correlation, the time lag ΔT of the individual A-scan can be user defined, and aliasing or uncorrelation can be avoided if ΔT is chosen to be much less than the interval T between sequential A scans, within a certain measurable velocity range determined by the spatial resolution of the transducer. The lower limit of ΔT is the sampling interval t_s in auto-correlation. In our experiment, the time lag ΔT is chosen to be 0.5 μs which is greater than the data sampling interval.

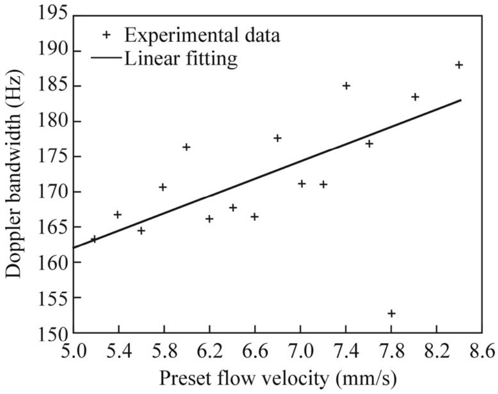

Fig.3 Standard deviation of bandwidth calculated by auto-correlation

However, when the preset flow velocity is below 5 mm/s, the auto-correlation results distribute randomly in our experiment. The reason can be considered as the Brownian motion, the velocity gradient and the turbulence dominating the broadening of the Doppler spectrum which is independent of flow velocity. The velocity gradient and the turbulence can be minimized if the focal spot of transducer is small enough. In other group's previous studies using cross-correlation with high repetition rate pulsed laser[9], a 75 MHz transducer with focal spot size of 27 μm was used and the measurable transverse flow range was below 4.4 mm/s[10]. On the other hand, the maximum measurable flow velocity is also limited if the focal spot size of the transducer is too small under a certain laser repletion rate because of the loss of correlation. In our experiment, a 10 MHz transducer with the focal spot size of 0.23 mm is used. The minimum measurable transverse flow velocity is about 5 mm/s because of the larger focal region of the transducer. The linearity can be improved if the transducer's focal spot size is smaller and the laser repetition rate is higher.

The feasibility of using auto-correlation method and spectrum standard deviation in the PAD measurement of transversal flow is preliminarily studied. Other than cross-correlation method, the time lag in auto-correlation method can be user defined, and the need of high repetition rate pulsed laser is avoided. In auto-correlation, the measurable range is not limited by the laser repetition rate and the spatial resolution of the transducer theoretically. A suspension of carbon particles with scale of tens of micrometers is used as the fluid phantom. The motion velocity of the carbon particle suspension flow is preset to be from 5.0 mm/s to 8.4 mm/s with increment of 0.2 mm/s. The experimental results show that the auto-correlation results approximately distribute with the preset velocity linearly in the measurement range. The linearity can be improved if the transducer's focal spot size is smaller and the laser repetition rate is higher.

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