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Sub-diffusion flow velocimetry with number fluctuation optical coherence tomography

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Abstract: We show number fluctuations dynamic light scattering optical coherence tomography (OCT) for measuring extremely slow, sub-diffusion flows of dilute particle suspensions. Our method removes the minimum measurable velocity limitation of conventional correlation-based or phase-resolved Doppler OCT, set by flowing particles' Brownian motion. Our technique works for any Doppler angle, is applicable to 2D flow imaging with scanning OCT systems and can be used to determine concentration of particles under flow. © 2023 The Author(s)

1. Introduction

Dynamic light scattering optical coherence tomography (DLS-OCT) relies on the measurement of fluctuations of scattered light and coherence gating to obtain simultaneous depth-resolved information about diffusive and translational motion of particles. This information is extracted from the temporal autocorrelation of the OCT signal for every voxel in depth. Initially, DLS-OCT was used for quantitative diffusion imaging [4] and flow measurements of particle suspensions [3,5,9].

For flow measurement DLS-OCT has the advantage over phase resolved Doppler OCT because it is still effective when the Doppler angle is zero, i.e. there is no flow along the beam optical axis. For both methods, the velocity sensitivity is limited by signal-to-noise ratio (SNR) [1] and the Brownian motion of the flowing particles [9, 10]. Hence, it is challenging to measure sub-diffusion flow rates where the Doppler phase shifts and the scattered light intensity fluctuations are small and either buried in the noise or overwhelmed by the Brownian motion. However, in a very dilute regime particle bulk motion gives rise to additional fluctuations in the scatterred intensity at longer time scales compared to particle diffusion [2,6] and enables measurement of a sub-diffusion flow velocity.

In this work we utilize particle number fluctuations of dilute suspensions in DLS-OCT to improve the minimum measurable velocity of omnidirectional flows. We combine and extend the existing theoretical models [1,6–9] for the second-order OCT signal autocovariance and incorporate number fluctuations into them. We show that when using number fluctuations, the minimum measurable velocity of DLS-OCT is freed from the constraint imposed by diffusion. We demonstrate the measurement of lower flow velocities compared to conventional non-dilute DLS-OCT or Doppler OCT.

2. Methods

Flow is generated inside the rectangular flow cell by a syringe pump. As a scattering medium we use the suspension of monodisperse polystyrene particles in water, with particles' volume fraction of 0.005%. Fig. 1 shows the experimental geometry, where θ is the Doppler angle, $w(z)$ is the local beam waist, and v_0 is the total flow velocity with transverse, v_t, and axial, v_z, components. For very dilute systems, the OCT signal magnitude autocovariance $g_2(\tau)$ at larger time delays τ is independent of the particle diffusion but still depends on the flow speed. The number fluctuations correlation analysis was performed by fitting Eq. (1) to the measured OCT signal magnitude autocovariance using $v_0(z)$ and $A(z)$ as free parameters, with

$$g_2(z, \tau > \tau_N) = A(z)\mathrm{e}^{-\frac{v_0(z)^2 \sin^2\theta \tau^2}{w_z^2}} \mathrm{e}^{-\frac{2v_0(z)^2 \cos^2\theta \tau^2}{w(z)^2}}. \quad (1)$$

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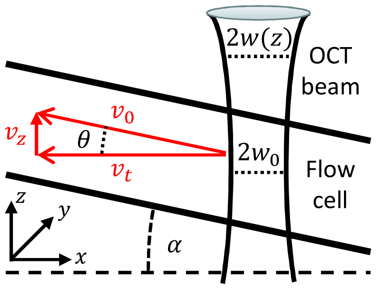

Fig. 1. Geometry of the OCT sample arm and the fluid flow.

In Eq. (1) τ_N is the time scale at which the diffusional decorrelation has already occurred and w_z is the coherence function waist. In 1D depth-resolved measurements, the OCT signal was obtained at the center width of the flow cell as a function of time from which the velocity profile was determined. The number of particles in the scattering volume, $\langle N\rangle$, was calculated using

$$\langle N\rangle = \frac{|g_1(z,\tau=0)|^2}{2^{3/2}g_2(z,\tau=0)_{\langle N\rangle}} - 2^{-3/2}\,, \tag{2}$$

where $g_2(z,\tau=0)_{\langle N\rangle}$ is the extrapolation of the fit of Eq. (1) at $\tau=0$, and $g_1(z,\tau=0)$ is an extrapolation of the fit to the first-order normalized autocovariance function at $\tau=0$.

2D flow measurements with number fluctuation DLS-OCT were performed by laterally scanning the OCT beam along the flow cell, perpendicular to the flow direction. For resolving the transverse flow profile the scanning location was chosen near the flow cell edge. Data processing steps were the same in 1D. However, instead of correlating the field magnitude fluctuations at a single position, the temporal autocovariance at each B-scan location was performed. This reduced the effective sampling rate from 5.5 kHz to approximately 45 Hz in 2D.

3. Results

We performed experiments at different Doppler angles θ and pump discharge rates Q. Fig. 2(a-b) shows the comparison of results for $\theta = 0.34^\circ$ obtained using the conventional Doppler OCT and the number fluctuations DLS-OCT developed by us. The Doppler OCT sensitivity is very low, making it impossible to accurately measure flow velocities for these low axial speeds. This is clearly indicated by the spread of measurements in Fig. 2(c). The number fluctuations DLS-OCT method, on the other hand, can accurately determine flow velocities for all considered flow speeds. These flow profiles also cannot be measured using the standard, non-dilute DLS-OCT, as the profile velocities are well below the limit set by diffusion, which is approximately 3.3 mm/s for our setup.

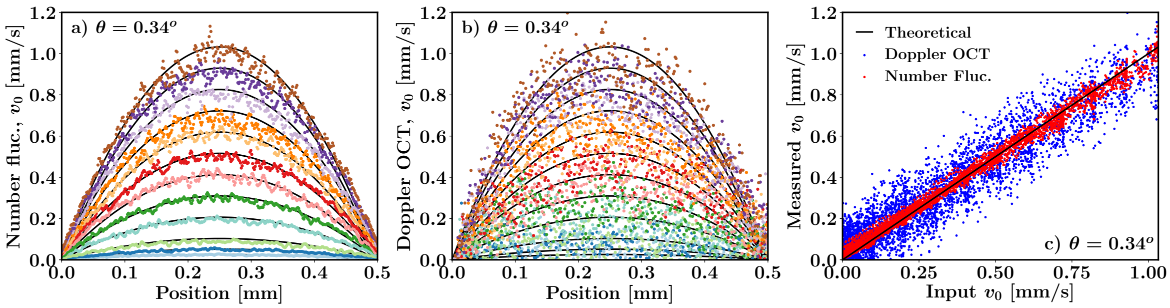

Fig. 2. 1D depth-resolved measurements: flow profiles measured using (a) number fluctuation DLS-OCT and (b) Doppler OCT. (c) Measured versus input velocities for both methods.

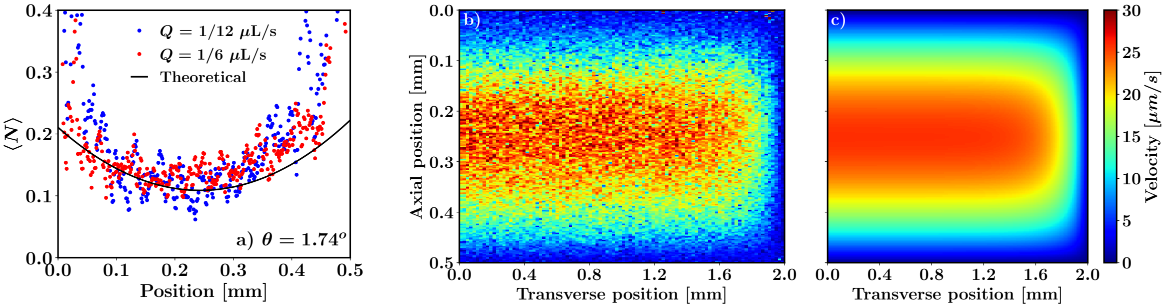

Fig. 3. (a) Measured number of particles in scattering volume for two different discharge rates, (b-c) measured and theoretical 2D velocity profiles for $Q = 1/12$ µL/s.

Figure 3(a) shows the measured particle density in different flow conditions. The obtained number of particles in the focal area, $\langle N \rangle$, matches well with the expected distribution at positions close to beam waist. Deviations increase towards the flow cell edges where the SNR is lower and the local beam waist is larger. As expected, $\langle N \rangle$ is minimum near the beam waist and maximum near the channel edges.

2D measurements were performed at the flow cell edge for $\theta = 1.84^\circ$ and the pump discharge rate of $1/12$ µL/s. Fig. 3(b-c) show transverse and axial velocity profiles obtained using number fluctuation DLS-OCT as well as theoretical flow profiles. Due to particle diffusion limitations such profiles can be obtained neither by Doppler OCT nor by non-dilute DLS-OCT. The obtained velocity distributions are in agreement with the expected values and both the transverse and the axial flow profiles are clearly visible.

4. Conclusion

We have implemented the number fluctuation DLS-OCT method for measuring sub-diffusion, low-speed flows in dilute particle suspensions. Our method extends the minimum measurable velocity limit compared to the standard non-dilute DLS-OCT or Doppler OCT techniques and completely removes the limitation on the minimum measurable flow due to particles' diffusive motion. We have shown that our method is independent of the Doppler angle, is applicable to 2D flow velocimetry with scanning OCT setup and can be used to determine particle concentration in flowing dilute suspensions.

References

1. M. A. Choma, A. K. Ellerbee, S. Yardanfar, and J. A. Izatt. Doppler flow imaging of cytoplasmic streaming using spectral domain phase microscopy. *Journal of Biomedical Optics*, 11(2):024014, 2006.
2. D. P. Chowdhury, C. M. Sorensen, T. W. Taylor, J. F. Merklin, and T. W. Lester. Application of photon correlation spectroscopy to flowing brownian motion systems. *Applied Optics*, 23(22):4149–4154, 1984.
3. B. K. Huang and M. A. Choma. Resolving directional ambiguity in dynamic light scattering-based transverse motion velocimetry in optical coherence tomography. *Optics Letters*, 39(3):521—524, 2014.
4. J. Kalkman, R. Sprik, and T. G. van Leeuwen. Path-length-resolved diffusive particle dynamics in spectral-domain optical coherence tomography. *Physical Review Letters*, 105(198302), 2010.
5. J. Lee, W. Wu, J. Y. Jiang, B. Zhu, and D. A. Boas. Dynamic light scattering optical coherence tomography. *Optics Express*, 20(20):22262–22277, 2012.
6. T. W. Taylor and C. M. Sorensen. Gaussian beam effects on the photon correlation spectrum from a flowing Brownian motion system. *Applied Optics*, 25(14):2421–2426, 1986.
7. N. Uribe-Patarroyo, A. L. Post, S. Ruiz-Lopera, D. J. Faber, and B. E. Bouma. Noise and bias in optical coherence tomography intensity signal decorrelation. *OSA Continuum*, 3(4):709–741, 2020.
8. N. Uribe-Patarroyo, M. Villiger, and B. E. Bouma. Quantitative technique for robust and noise-tolerant speed measurements based on speckle decorrelation in optical coherence tomography. *Optics Express*, 22(20):24411–24429, 2014.
9. N. Weiss, T. G. van Leeuwen, and J. Kalkman. Localized measurement of longitudinal and transverse flow velocities in colloidal suspensions using optical coherence tomography. *Physical Review E*, 88(042312), 2013.
10. S. Yazdanfar, C. Yang, M. V. Sarunic, and J. A. Izatt. Frequency estimation precision in Doppler optical coherence tomography using the Cramer-Rao lower bound. *Optics Express*, 13(2):410–416, 2005.