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Scanning dynamic light scattering optical coherence tomography for measurement of high omnidirectional flow velocities

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ABSTRACT

We show scanning dynamic light scattering optical coherence tomography (OCT) omnidirectional flow measurements. Our method improves the velocity measurement limit over conventional correlation-based or phase-resolved Doppler OCT by more than a factor of 2. Our technique is applicable without a-priori knowledge of the flow geometry as our method works both for non-zero Doppler angle and non-ideal scan alignment. In addition, the method improves the particle diffusion coefficient estimation for particles under flow.

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 particle sizing[3] where the particle size is determined from the estimated diffusion coefficient using the Stokes-Einstein relation.

Flow measurements with OCT have been performed using phase-resolved Doppler OCT, lateral resonant Doppler OCT,[7] and M-scan correlation-based DLS-OCT.[2,4,8] The axial velocity of Doppler OCT is limited by phase wrapping. In the correlation-based measurements, the maximum transverse velocity is limited by the decorrelation rate, which depends on the spatial resolution of the system.[5] The axial velocity range is limited by interference fringe washout[1] and the coherence length of the source. When measuring the diffusion of particles under flow, the decorrelation in the flow causes uncertainty in the estimated diffusion coefficient,[9] which, in case of high flows, cannot be measured at all.

In this work we apply beam scanning in DLS-OCT to improve the maximum measurable velocity limit for omnidirectional flows. We extend the existing theoretical models[6,8] for the OCT signal autocorrelation and incorporate the motion of the beam into it. We show that when scanning the OCT beam in the direction of the flow, the dynamic velocity range is significantly increased. We demonstrate that the B-scan correlation-based DLS-OCT method is capable of measuring a far higher range of velocities than standard Doppler OCT, lateral resonant Doppler OCT[7] or conventional correlation analysis (M-scan) with stationary beam.

2. METHODS

Flow is generated inside the rectangular flow cell by a syringe pump. We use Intralipid with dilution 1:40 as scattering medium. For scanning the beam along any arbitrary flow direction, lateral and axial scanning schemes are implemented. Fig. 1 shows the experimental geometry with the flow and OCT beam motion. Lateral beam scanning, perpendicular to the beam direction with speed v_b, is executed by moving galvo mirrors. The axial scanning with speed v_z is performed numerically using voxel-shifting or phase multiplication techniques. Since DLS-OCT provides simultaneous information for all depths, it is possible to numerically align the beam scanning vector along any arbitrary direction in 3D.

Scanning DLS-OCT correlation analysis was performed by fitting the autocovariance function,

$$g_2(z,\tau) = A_2(z)\mathrm{e}^{-2Dq^2\tau}\mathrm{e}^{-\frac{(v_0(z)-v_s)^2\sin^2\theta\,\tau^2}{w_z^2}}\mathrm{e}^{-\frac{2(v_0(z)-v_s)^2\cos^2\theta\,\tau^2}{w_0^2}}, \quad (1)$$

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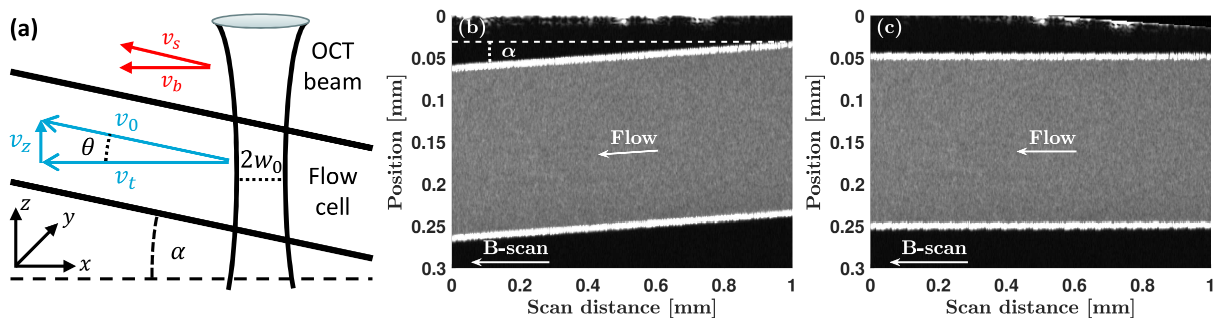

Figure 1. Scanning OCT setup and alignment. (a) Flow cell and OCT beam geometry. (b) Original depth-resolved B-scan image. (c) B-scan alignment in spatial domain.

to the depth-resolved OCT signal amplitude using $v_0(z)$ and $A_2(z)$ as free parameters. Here D is the particle diffusion coefficient, τ is the correlation time lag, w_z is the coherence waist function, w_0 is the beam waist in focus, θ is the Doppler angle and v_s is the beam scan speed. For omnidirectional measurements without a-priori knowledge of flow orientation parameters, B-scans at different speeds are performed and least-squares method is used to solve for velocity profiles.

3. RESULTS

We performed experiments at different flow cell tilt angles and pump discharge rates. Fig. 2 shows the comparison of results obtained using the conventional and our method for the Doppler angle of 0.39 degrees. Parabolic dashed curves represent the theoretical velocity profiles based on the pump discharge rate. Results that significantly deviate from the expected values are omitted in the plot. Horizontal dashed lines show the maximum velocities that can be measured using every method. Only the suggested B-scan correlation analysis method is capable of correctly measuring depth-resolved velocities up to 250 mm/s. Clearly, with the B-scan method demonstrated here we can measure much higher flows. We obtain similar results for other tilting indicating that there is no explicit dependence of the method accuracy on the Doppler angle. Furthermore, we found that when performing multiple scans at different speeds, then no calibration measurement, a-priori flow knowledge or perfect scan alignment is required. This is demonstrated by scanning the beam at an in-plane angle with respect to the flow direction at several different speeds and obtaining the velocity profile.

Figure 3 shows the obtained normalized diffusion coefficients for the particles in the solution under flow for $\theta = 0.39^{\circ}$ at discharge rates of 1/30 mL/s and 1/15 mL/s. The black curves correspond to static diffusion measurements (no flow), blue curves correspond to the conventional M-scan diffusion measurements under flow,

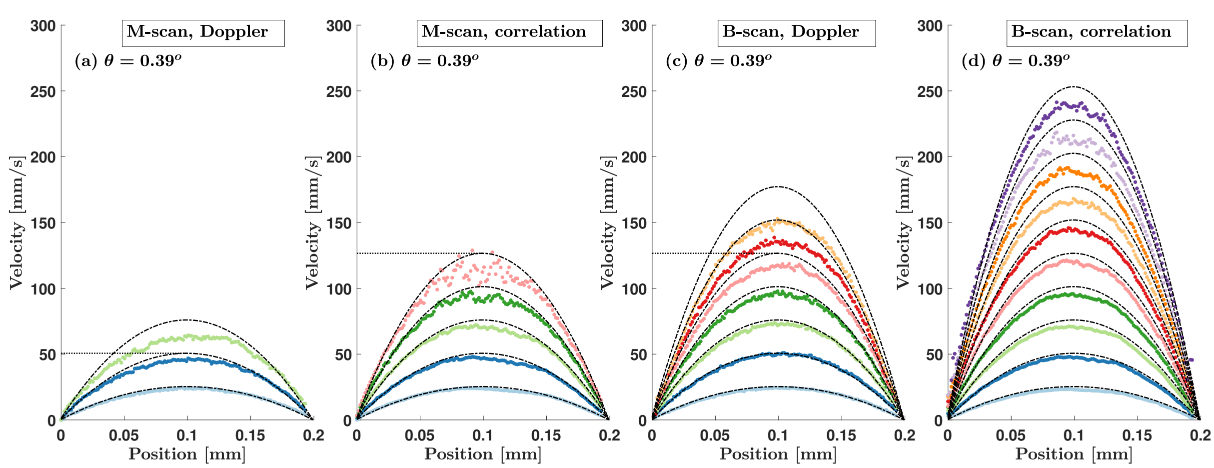

Figure 2. Flow profiles measured using different methods for the Doppler angle $\theta = 0.39^{\circ}$. (a) Doppler OCT. (b) M-scan correlation analysis. (c) B-scan (resonant) Doppler OCT. (d) B-scan correlation analysis

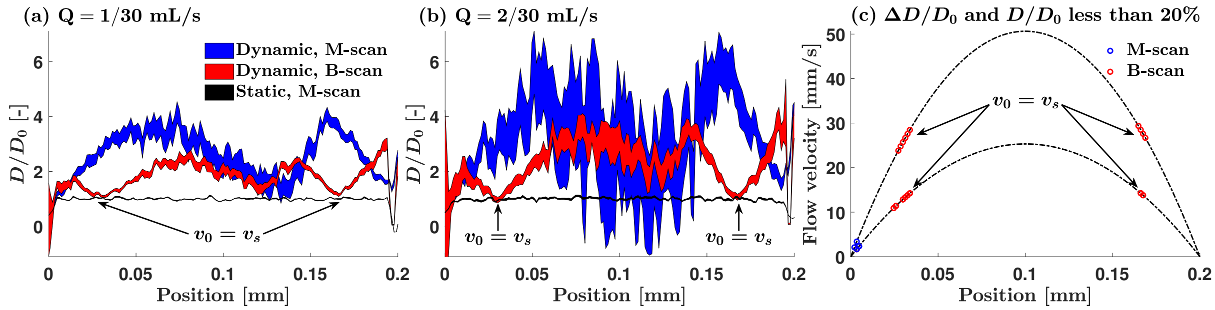

Figure 3. Diffusion estimation under static and flow conditions with or without scanning. (a) Normalized diffusion coefficient for 1/30 mL/s discharge rate. (b) Normalized diffusion coefficient for 1/15 mL/s discharge rate. The areas in the curve represent 95% confidence intervals. The locations where the effective scan speed equals the flow speed are indicated. (c) Locations in the flow profile where the relative error of the diffusion coefficient is less than 20%.

and red curves correspond to B-scan diffusion measurements under flow. For M-scan diffusion measurement the obtained diffusion coefficients become less reliable as the flow velocity increases. With the B-scan measurements, D can be estimated accurately inside the channel further away from its walls indicated by the arrows and with a higher accuracy at more depth voxels than in the M-scan mode.

4. CONCLUSION

We have implemented the B-scan correlation-based DLS-OCT method for measuring omnidirectional flows. Our method extends the maximum measurable velocity limit by at least a factor of 2 compared to the standard M-scan DLS-OCT or Doppler OCT techniques. We have shown that our method can be applied to flow geometries where a proper scan alignment is not possible. In addition, we have demonstrated that the suggested method can be used to estimate a diffusion coefficient more accurately under flow conditions.

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