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SCANNING DLS-OCT FLOW IMAGING

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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..

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 [1] 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 [2], and M-scan correlation-based DLS-OCT [3,4,5]. 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 [6]. The axial velocity range is limited by interference fringe washout [7] 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 [8], 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 [3,9] 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 then standard Doppler OCT, lateral resonant Doppler OCT [2] or conventional correlation analysis (M-scan) with stationary beam.

2 Methods

Flow was generated inside the rectangular flow cell by a syringe pump. We used Intralipid with dilution 1:40 as scattering medium. The experiments were performed using a Thorlabs GANYMEDE II HR series spectral domain OCT System, with a bandwidth centered around 900 nm with an axial resolution of 3 µm in air. The OCT system was operated both in M-scan and B-scan modes. For scanning the beam along any arbitrary flow direction, lateral and axial scanning schemes were implemented. Fig. (1) shows the experimental geometry with the flow and OCT beam motion. Lateral beam scanning (B-scan), perpendicular to the beam direction, is executed by moving galvo mirrors. Axial scanning is performed numerically. Since DLS-OCT provides simultaneous information for all depths, it is possible to numerically align the beam scan vector along any arbitrary direction in 3D using a spatial shift of the OCT signal in the depth domain obtained after the inverse Fourier transformation of the spectrum, or, equivalently, by using a phase multiplication in the frequency domain before the inverse Fourier transform. Fig. (2) shows a typical B-scan flow cell image at a nonzero tilt angle before and after the numerical alignment.

3 Results

We performed experiments at three different flow cell tilt angles and at ten different pump discharge rates. Fig. (3-4) show the comparison of results obtained using the conventional and our method for a tilt angle of 0.94 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 tilt angles, 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 a non-zero in-plane angle with respect to the flow direction at five several different scan speeds, performing the numerical alignment, and obtaining the velocity profiles.

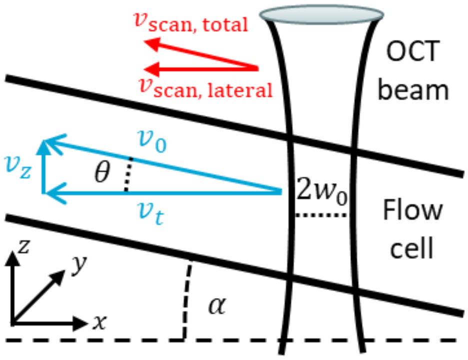

***Figure 1** – Flow geometry and OCT setup*

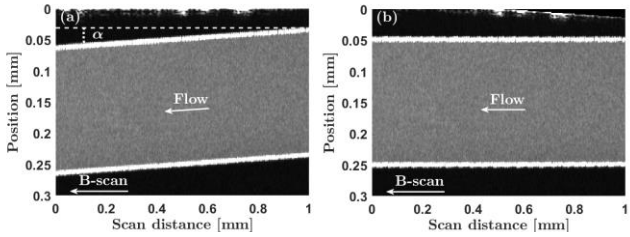

***Figure 2** – Original depth-resolved B-scan image (a) and numerically aligned OCT image (b)*

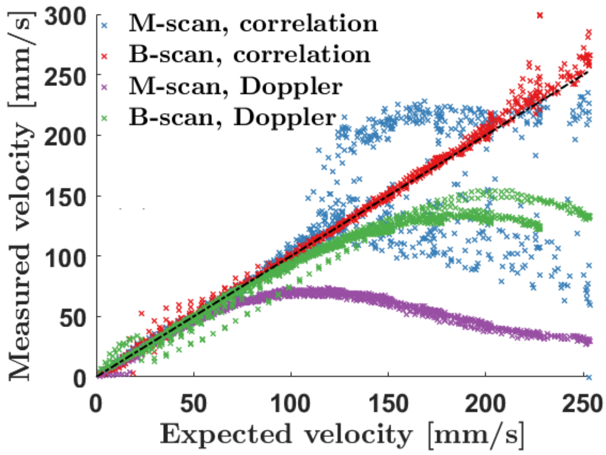

***Figure 3** – Measured versus expected flow velocities for all methods with tilt angle 0.94 degrees*

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.

5 References

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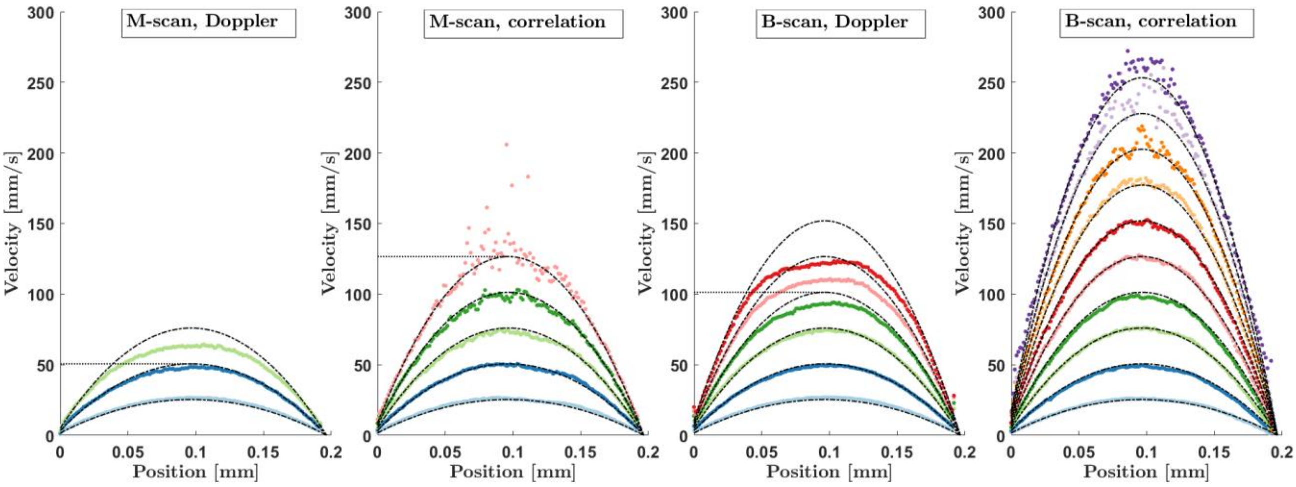

Figure 4 *– Flow profiles obtained using different OCT methods with tilt angle 0.94 degrees*