

Particle Tracking Velocimetry with Dynamic Aberration Correction for 3D Flow Measurements Through Fluctuating Phase Boundaries

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ABSTRACT

Imaging based flow measurements allow the observation of complex three-dimensional flows with a high temporal resolution. However, at least one optical access with a good imaging quality is needed. In fluids with a dynamic phase boundary, often the only optical access is the dynamic surface (e. g. droplet on opaque surface). In this case, temporally varying aberrations are introduced that can increase the measurement uncertainty significantly. Additionally, many flows in technical systems are three-dimensional and turbulent so that volumetric measurements are desirable. In this contribution, we present the first 3D-3C flow measurement system with dynamic aberration correction and a single optical access. By using a deformable mirror with 69 actuators, a laser guide star and a wavefront sensor, the dynamic aberrations that are introduced by the fluctuating phase boundary can be corrected. By introducing a double-helix point spread function (DH-PSF) with a spatial light modulator (SLM) we achieve three-dimensional flow measurements with only one camera. For demonstration purposes, the flow in a microchannel was measured through an oscillating puddle-like droplet. By applying the adaptive-optics system, the measurement uncertainty could be lowered by 58 % relative to measurements through a static droplet. The technique has the potential to allow three-dimensional flow measurements in droplets on opaque surfaces (e. g. membrane of fuel cell). Thus, new insights about the movement of droplets (e. g. in fuel cells) are made possible.

1. Introduction

Optical flow measurements are widespread because they offer many advantages like high temporal and spatial resolution. However, refractive index changes can severely limit their performance. In the case of imaging based methods (e. g. PIV), temporally varying changes of the refractive index lead to dynamic aberrations which can increase the measurement uncertainty significantly [1].

An example for this is the flow measurement in oscillating droplets or wavy films on an opaque surface (Fig. 1 and 2). Sessile droplets on surfaces are often affected by a gas shear flow, e.g. droplets on surfaces due to rain or condensation or droplets in microchannels of fuel cells. These droplets will oscillate [2] and eventually move [3]. It is still an open question how the inner flow

structure of the droplet and the outer flow interact. Recent investigations give a hint on the coupling of the inner flow structure and a shear layer detachment and the formation of a recirculation region in the droplet wake [4, 5]. However, standard PIV measurements of the inner flow still suffer from an increased uncertainty, since in this case, the only optical access is the oscillating liquid-air interface [6].

The temporal varying refraction of particle light at the surface introduces dynamic distortions to the image that are similar to the Seeing effect in astronomy. As a result, particle images may either move because of dynamic aberrations or because of the actual flow. Usually, this problem is circumvented by matching the refractive index of measurement object and immediate surrounding with custom designed oils. This way, no refraction occurs. However, often this solution makes it necessary to modify the experimental parameters (e. g. different fluid) or even the complete setup. Thus, the measurement object needs to be changed so that it is questionable if this method can still be called contactless. Figure 1 and 2 show such a case.

As a possible solution to this challenge we propose the usage of adaptive optics similar to those applied in astronomy [18, 19, 20].



Fig. 1: Droplet in shear flow on an opaque surface. The only optical access is the oscillating phase boundary.

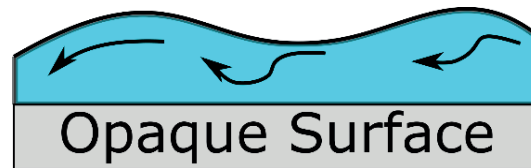


Fig. 2: Film flow on opaque surface. Similarly to Fig. 1, the dynamic surface is the only optical access.

2. Experimental Setup

The optical setup is shown in Fig. 3. It can be separated into two subsystems: The 3D-3C flow measurement system and the dynamic aberration correction.

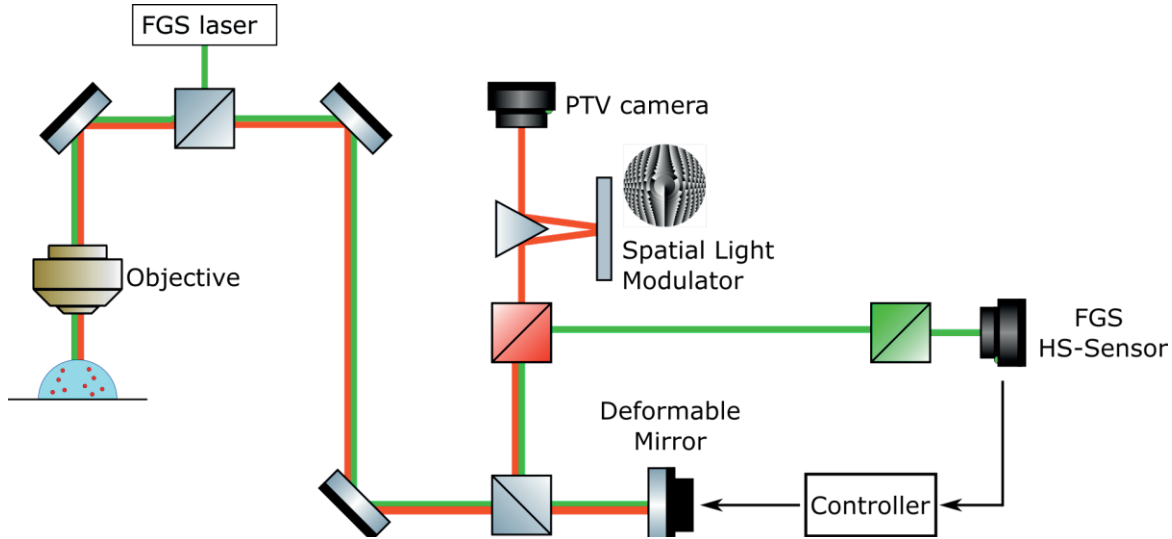


Fig. 3: Simplified optical setup for 3D-3C flow measurements through a fluctuating phase boundary. The deformable mirror, the wavefront sensor and the controller constitute a closed loop. The SLM introduces the DH-PSF.

The former is basically a microscope setup for Particle Tracking Velocimetry (PTV). For measuring all three coordinates of a particle from a single image, a Double-Helix Point Spread Function (DH-PSF) is employed [7, 8, 9]. This point spread function is introduced to the system with a spatial light modulator (SLM) that displays a spiral phase mask [10] (Fig. 4). It is placed in the Fourier plane of the image. The basic concept of 3D microscopy with the DH-PSF can be seen in Fig. 5. Each particle is imaged to two bright spots. Similarly to usual PTV, the center of both points indicates the lateral particle position. The key difference to ordinary PTV is that the depth (axial) coordinate can also be measured from only one image. This is possible because the orientation angle Ψ changes almost linearly with the axial position (Fig. 6).

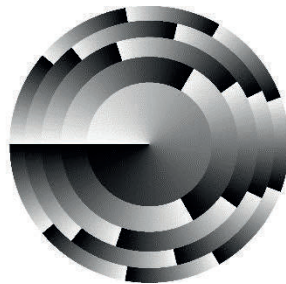


Fig. 4: Spiral phase mask with $N = 5$ azimuthal rings for introducing a DH-PSF to the optical system. White corresponds to a phase shift of 2π and black to 0.

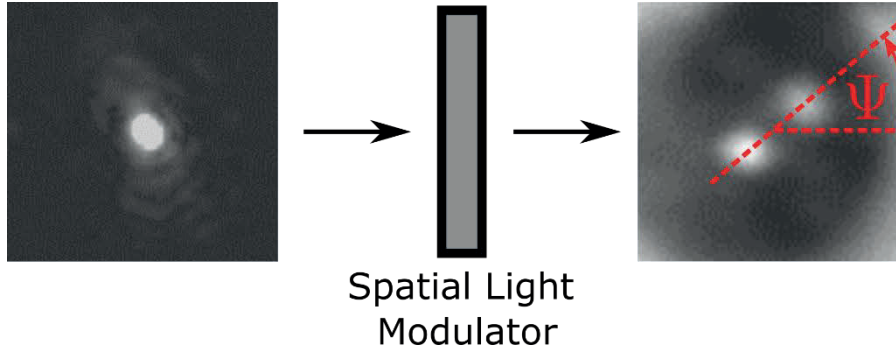


Fig. 5: Basic concept for position measurements with the DH-PSF. Usually a fluorescence particle is seen as a single point in the camera image (left). By introducing the DH-PSF to the system, one particle is imaged to two bright points that are oriented by an angle Ψ . The center of both maximums denotes the lateral position (x, y) of the particle and the angle Ψ encodes its axial position (z).

By combining PTV with this 3D microscopy technique, 3D-3C flow measurements are possible with only one camera. Fig. 7 and 8 show an example measurement in a 3.5- μl droplet that was placed in a shear flow of air. The air flow was measured as 4.35 m/s with a hot-wire anemometer. The droplet was placed on acrylic glass so that the inner flow could be measured through the transparent surface. A double vortex emerges (Fig. 7), which corresponds well to previous findings [4]. By applying the DH-PSF-PTV technique, for the first time this flow is measured three-dimensionally. This way, a tilt of both vortices relative to the horizontal plane is observed for the first time (Fig. 8). In contrast to other defocus-based 3D-3C measurement techniques [11, 12, 13, 14], the Double-Helix Point Spread Function is more flexible regarding the measurement range. The simplest way to increase or decrease the measurement range is to change the parameters of the phase mask on the SLM. Furthermore, theoretical investigations showed that the Cramer-Rao lower bound of the DH-PSF from [16] is up to 30 % lower for a sufficient Signal-to-Background Ratio (SBR) [17].

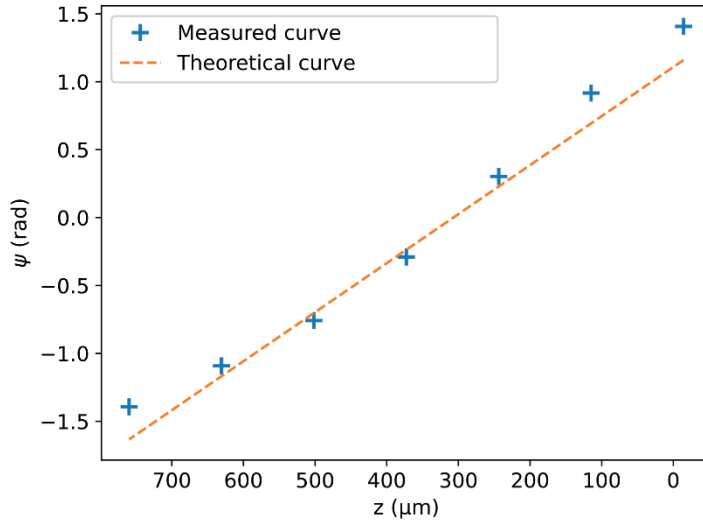


Fig. 6: Ψ - z calibration curve for 3D microscopy with the DH-PSF. Ψ denotes the orientation angle of the DH-PSF and z the axial position. Optical aberrations stemming from the optical system are the main reason for the difference between measured and theoretical curve.

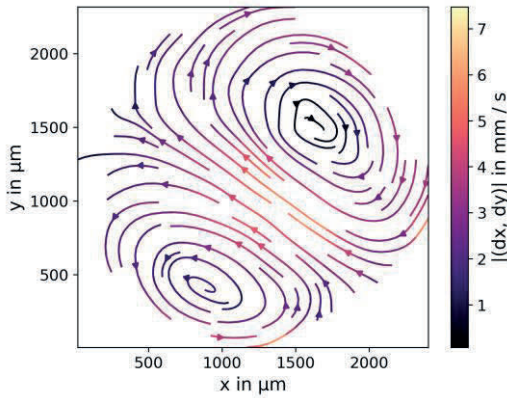


Fig. 7: Double vortex in 3,5- μ l droplet for frontal air flow from the top. Water and air flow are parallel in the center of the droplet.

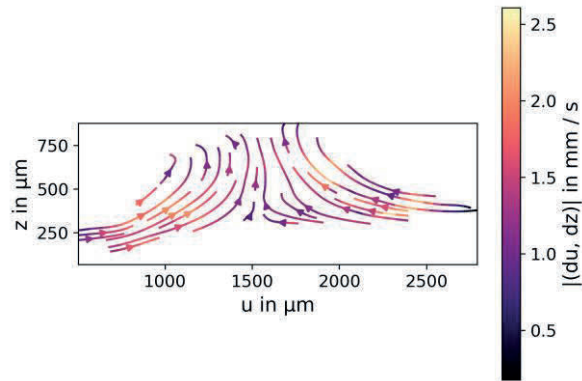


Fig. 8: Double vortex in 3,5- μ l droplet from the side. The normal vector of the projection plane points in the direction of air flow. It can be seen that both vortices are tilted towards the horizontal plane. Here, the intersection angle between rotational axis and the y -axis is about 25° for the left vortex and 20° for the right vortex.

The aberration correction system is the second subsystem of the complete setup. The basic idea of it is to measure the surface perturbations of the phase boundary and to correct for them with a

deformable mirror (Alpao DM-69) in real-time. For achieving the former, a laser beam illuminates the measurement volume from the top. Its reflection at the surface is imaged to a deformable mirror and after that to a Hartmann-Shack sensor. Because of its similarity to the laser guide stars in astronomy, we called this concept that is based on the Fresnel reflex of the interface Fresnel Guide Star (FGS).

The Hartmann-Shack sensor evaluates the wavefront of the incoming light. Because the wavefront is related to the local phase boundary displacement, it is possible to calculate a mirror shape that corrects the optical aberrations. This process is implemented as a closed-loop so that the optical disturbance of the particle images is corrected perpetually.

The advantage of using a reflecting laser beam (Fresnel Guide Star) for disturbance measurement is that one optical access - that introduces dynamic aberrations - is sufficient. In contrast, the application of a transmitting laser guide star requires at least two optical accesses and one of them must not introduce dynamic optical disturbances. Thus, it becomes possible, inter alia, to apply adaptive optics correction to droplets on opaque surfaces. It should be noted, that in the current development stage we still used a transmitting laser beam to calibrate the setup and to acquire reference data. However, this restriction is not given by physical constraints. In our future works on droplets on an opaque substrate we will apply the reflective configuration only.

Because the surface of the droplet can oscillate with several hundred Hertz, the digital controller must have a high control cycle rate. Therefore, the signal processing of the wavefront sensor as well as the control algorithm for the deformable mirror are implemented on an in-house developed electronic platform, that is based on a FPGSoC chip (Zynq-7100) [15]. This way, 2100 to 3600 control cycles per second can be achieved (depending on algorithm parameters).

3. Results

For characterisation of the system, several experiments were conducted. The average position uncertainty of the 3D-PTV system was determined with a three-axis linear actuator stage. For that purpose, an isolated fluorescence particle was moved on a three-dimensional grid. For every point in that grid, ten pictures were recorded and evaluated for retrieving the random position uncertainty. By comparing the reference position of the actuator and the measured position, the systematic uncertainty can be obtained. For a measurement volume size of $1127.8 \mu\text{m} \times 1127.8 \mu\text{m} \times 800 \mu\text{m}$, a total position uncertainty of $1.642 \mu\text{m}$ for the lateral position and $12.32 \mu\text{m}$ for the axial position is achieved according to GUM. These values include random as well as systematic measurement uncertainties.

For characterising the performance of combined aberration correction and 3D particle tracking, the flow in a microchannel (Ibidi 800 μm Uncoated) was measured through an oscillating puddle-like 3-ml droplet (Fig. 9). The oscillation was induced with a grazing air flow. The flow in the microchannel is well-suited as a reference because it is stationary and its flow profile can be calculated analytically. The surface of the droplet introduces unknown dynamic aberrations to the particle images which results in an increased flow uncertainty. The mean spectrum of the aberrations at the droplet surface is plotted in Fig. 10. It can be seen that the aberrations to be corrected oscillate with up to 300 Hz. Table 1 denotes the parameters of the experiment.

Measure- ment time	Distance of measurement position to inflow	Fluorescence particles	Liquid inside microchan- nel	Volume flow rate	Frames per second	Measurement volume size
76 s	7.5 mm	PS-FluoRot- Fi317 (microparticles GmbH)	Salt water with 1.05 g / cm^3	7 $\mu\text{l/s}$	60.6 Hz	1 mm x0.75 mm x800 μm

Figure 11 shows the flow profiles for four cases: Measurement without phase boundary, through a static phase boundary and through an oscillating phase boundary with and without activated aberration correction. It can be seen, that the measurement uncertainty increases significantly if the phase boundary oscillates (Fig 11.c, Fig. 12) and no correction is applied. However, by enabling the adaptive-optics correction the random uncertainty can be lowered by 58 % (Fig 11.d, Fig. 12).

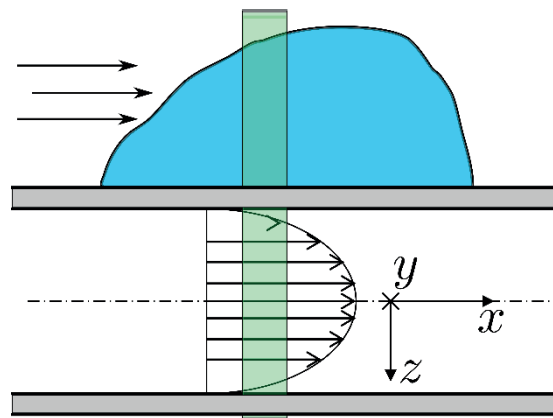


Fig. 9: For characterisation of the system, the flow in a microchannel (Ibidi 800 μm Uncoated) was measured through a puddle-like droplet (from the top).

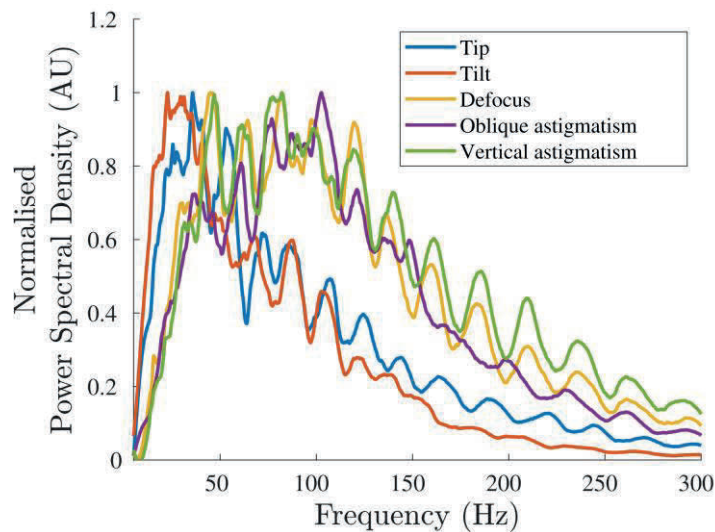
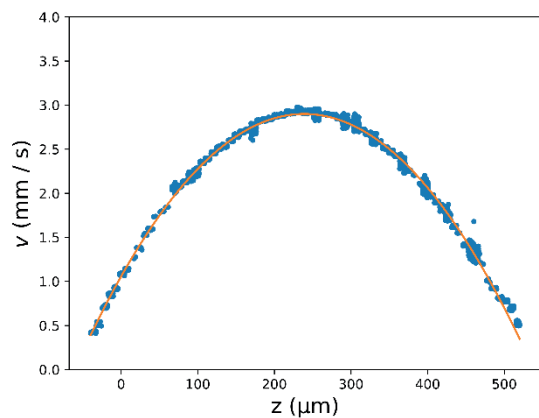
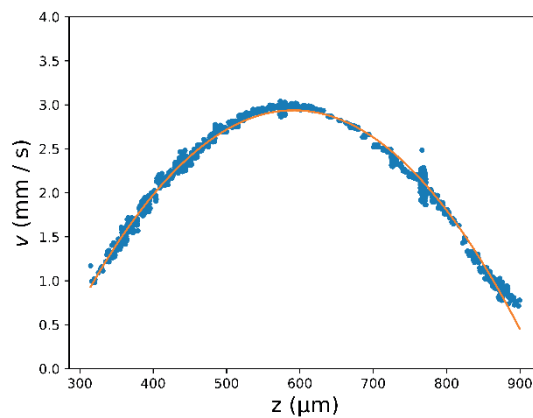


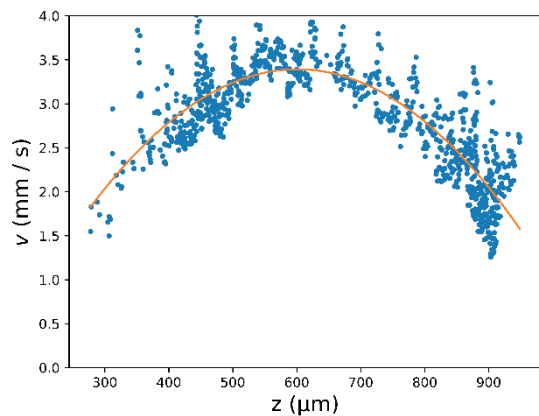
Fig. 10: Measured PSD of the first five Zernike polynomials for an oscillating puddle-like 3-ml droplet on a microchannel (averaged over 10 droplets).



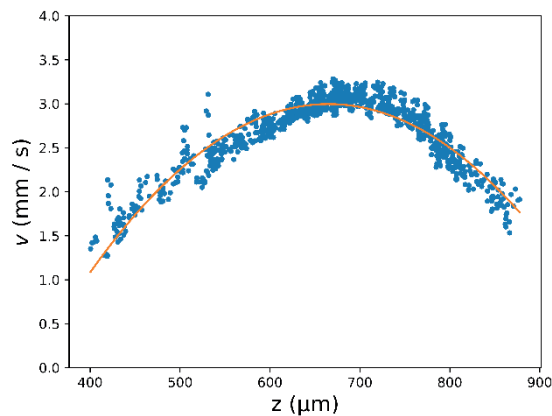
a) No Droplet



b) Static Droplet



c) Oscillating droplet, no correction



d) Oscillating droplet, with correction

Fig. 11: Measured flow profiles for different cases. Measurement points with a larger deviation than 2σ to the average value were eliminated with an outlier test.

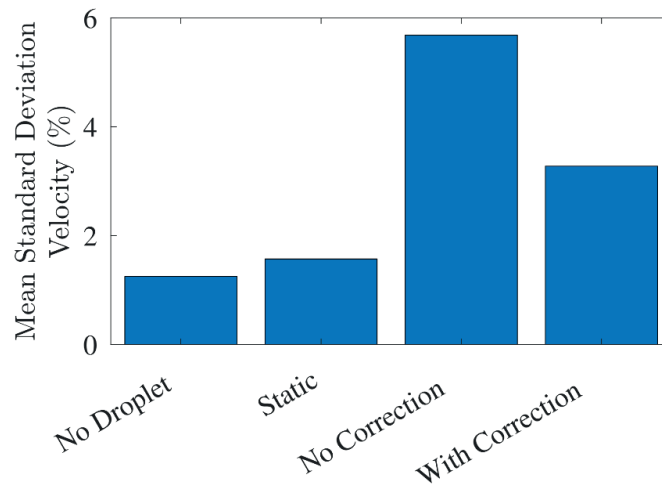


Fig. 12: Mean relative deviation of measurement points from average.

4. Summary

In this contribution, we present the first 3D-3C flow measurement system with a dynamic aberration correction using a deformable mirror. The usage of a Fresnel Guide Star (FGS) makes it possible to correct the aberrations that are introduced by a fluctuating phase boundary with a single optical access. This way, the measurement uncertainty stemming from this dynamic boundary surface can be lowered. For achieving three-dimensional measurements, a Double-Helix Point Spread Function (DH-PSF) is introduced to the optical system with a Spatial Light Modulator (SLM). This technique allows three-dimensional position measurements of particles from only one image and with a single camera. For characterisation of the complete system, the well-known flow in a microchannel was measured through an oscillating puddle-like droplet that introduces unknown aberrations. In comparison to the flow measurement through a static droplet, the uncertainty could be lowered by 58 %. The combination of 3D-3C measurements and dynamic aberration correction has the potential to allow flow measurements directly in technical systems without the necessity to modify the experimental setup (e. g. the installation of transparent walls). An example for this is the flow measurement in droplets on porous, opaque surfaces (like the membrane in PEM fuel cells). A better understanding of this flow could facilitate the optimization of fuel cells, which is a key aspect in the transformation to a sustainable economy.

A better understanding of this flow could facilitate the optimization of fuel cells leading to significant progress in the transformation to a sustainable economy.

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