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Adaptive wavefront shaping for flow-field measurements

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ABSTRACT

In this contribution we use wavefront shaping approaches for image correlation based flow-field measurements for the first time. Aberrations introduced by a single phase boundary in the detection beam path were explored. Variations of the optical path-length result in strong errors in position allocation and thus to an enhancement of the measurement uncertainty of the velocity. Our results show that the usage of wavefront shaping enables to reduce these errors and to strongly improve the quality of image correlation based flow-field measurements. First experimental and simulated results underline the importance of these approaches.

Keywords: Adaptive optics, digital holography, flow-field measurements

1. INTRODUCTION

Optical flow measurements are to date the key to basic and applied investigations in fluid mechanics. Distortions in the optical paths can lead to unpredictable effects on the measurement technique which results in measurement errors. While the influence of static distortions can easily be taken into account via calibration measurements, there are a lot of cases where the optical distortion varies with time which makes its compensation elaborate. Although software-based correction may be valid in some applications, generally it is preferable to compensate for the influence of time varying distortions with hardware based approaches.

The principle of wavefront correction by means of adaptive optics (AO), originally known from astronomy [1], has the general potential to correct for the distortions mentioned above. Such wavefront correction systems consist usually of a sensor for measuring the wave front distortions, an adaptive optical element, e.g. a deformable mirror (DM) or liquid crystal modulator (SLM), and a control unit that reads the wavefront data and calculates the control parameters for the adaptive element. Hence, the AO system represents a closed-loop feed-forward control for the optical measurement system. The choice of the AO element and the wavefront sensing technique strongly depends on the spatial frequency content and the amplitude of the distortion. Hence, the approach for e.g. a single smooth phase boundary occurring at gas-liquid interfaces at film flows, levitated droplets or at water channels is different, then for distortions that have a refractive index distribution throughout an extended volume. Some examples are listed as follows,

- temperature gradients, e.g., in combustions or in experiments with thermal convection
- pressure gradients, e.g., compression and expansion fronts or shock waves in compressible fluids
- concentration gradients, e.g., in mixtures of gases or in electrolysis cells.
- multiphase-media, e.g. biological tissue.

The biggest challenge for AO correction is finding an appropriate phase mask that compensates for the distortions.

Several ways have been proposed for this task, but their applicability strongly depends on the application and the nature

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of the aberration. For example, the transmission matrix approach [2, 3] is not well applicable for the correction of time-varying aberrations but requires static ones. The usage of other approaches like iterative optimization [4, 5] or digital optical phase conjugation (DOPC) [6, 7] may also be limited by the aberration or the task.

For DOPC commonly a guide-star is used that interacts with the aberration and hence allows measuring a phase fingerprint of the aberration. A correction is enabled by displaying the conjugate phase on a spatial light modulator. The implementation of a guide-star into the measurement system may be a hurdle. Often invasive insertion of reference beacons is required [8, 9], or very complex approaches based on ultrasound guide stars [7] are used. The choice of the adaptive optical approach and used methods strongly depends, however, on both the principle of the measurement system as well as the nature and the characteristics of the optical distortion. A wavefront shaping system and guide-star technique hence has to be considered specifically for each measurement system and measurement task

In our previous work we demonstrated that the principle of wavefront correction based on adaptive optics can be implemented to fluid-flow measurement techniques in order to measure through unsteady optical distortions [10, 11, 12]. A laser Doppler velocimeter (LDV), realized by a two-beam interferometer, was equipped with either a deformable membrane mirror or a combination of 2D tip/tilt mirrors and tunable fluid-membrane lenses [13]. The measurements were performed through a fluctuating air-water interface with capillary waves. As applications in flow-measurements require non-invasive guide stars preferably used with one optical access, we introduced the Fresnel guide star, which gains the information about the distortion (control parameters) from the fraction of light reflected from the water surface (Fresnel reflex) [12]. It was shown that the number of burst signals can be increased significantly when the wavefront control was activated and that the statistic measurement error is reduced concurrently.

Besides LDV, Particle Image Velocimetry (PIV) represents nowadays one of the most often applied flow measurement techniques [12]. It is based on the correlation of two subsequently taken camera images of a seeded flow. Whereas a LDV represents a two-beam interferometer with two single beams to be corrected, PIV is based on imaging and hence the extended optical path transferring the image has to be corrected. In this paper we show first results of adaptive corrections used for image correlation based flow-field measurements.

2. EXPERIMENTS

We use the Micro particle image velocimetry (µPIV) setup sketched in Figure 1. In order to introduce aberrations in a controlled way, the SLM is used to mimic a distorting phase boundary. The sample under test is a 500 µm square micro channel. We use a 532 nm high-power LED for illumination in transmission geometry. The red arrows in the Figure 1 depict the flow-field measurement-path. The setup is aligned in a way that the measurement takes place at an axial position located in the middle of the micro-channel, in which the local flow-velocity is maximal. The depth of correlation is approximately 30 µm, while laterally the whole micro channel is imaged. In this test experiment we use a time-multiplex with one SLM. The procedure is as follows:

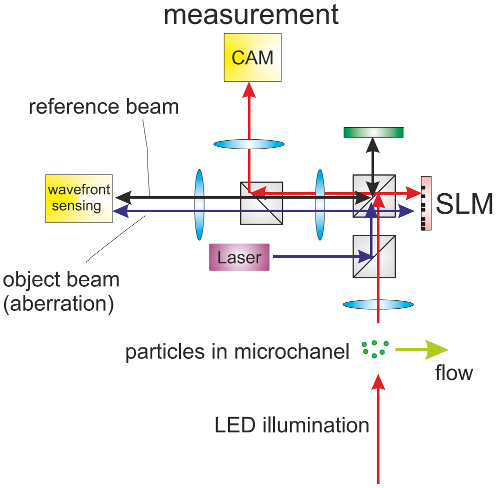

Figure 1: Sketch of the sensor-based adaptive optics setup. SLM: spatial light modulator, CAM: digital camera.

As a first step, the SLM displays a homogeneous phase. We measure the undisturbed flow-field as a reference. Secondly, the SLM displays aberrations that lead to distortion of the flow-field measurement.

A laser beam with a wavelength of 532 nm is used as a guide-star to probe the aberration, which is sketched by the purple beam path. This beam acts as an object beam and the black path as a reference beam of an off-axis digital holographic setup. A hologram of the aberration is recorded and the phase information is reconstructed using the angular spectrum method [14]. The aberration introduces a change of the optical path-length, which has to be compensated. The guide-star passes the aberration like the sample light does. Hence, the recorded phase has to be conjugated and then displayed on the SLM. The calculated conjugate phase information is added on the displayed aberration and the corrected PIV measurement is recorded.

In the following example, the aberration displayed on the SLM was a simple defocus aberration (lens effect). As an example flow-velocity plots are shown in Fig. 2. The velocity profile of the aberrated measurement shows strongly decreased values compared to the reference. This can be easily explained: the detection was still aligned to measure the central plane of the micro-channel, where the flow-velocity is highest. But the imitated lens leads to defocus, which means that the measurement is performed in a different depth, where the velocity values are surely decreased.

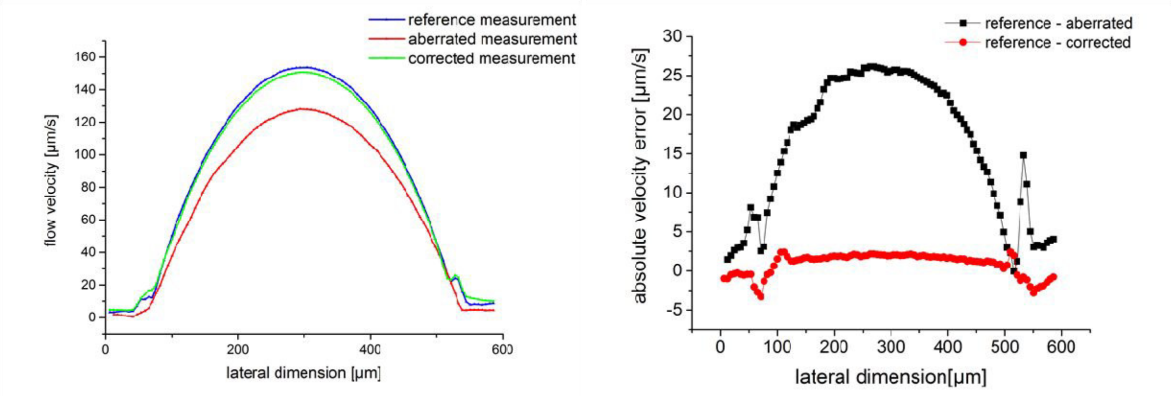

Figure 2: Exemplary results for the adaptive correction of the PIV measurements. Flow velocity profiles (left) and velocity error (right).

The correction compensates for the defocus error and shifts the detection back to the middle of the channel. This simple example shows, that without adaptive correction, the defocus leads to velocity errors up to 15 %, while after the correction the error is just about 1 %. The residual error can be explained by angle-errors between the aberration probing with the guide-star and the aberration of the sample-light. But these errors can in some cases be accounted for by prior calibration.

To verify, we also performed simulations that underlined the strong increase of uncertainty in such examples. The simulations also proved the power of adaptive optics, to compensate for path-length errors in the detection and to keep the measurement at a constant position. Note that it is also possible to correct the illumination path in order to keep the illumination at a constant position. In the experiments shown here, we just concentrated on the influences on the detection path.

Up to now the aberration was a smooth phase boundary. Displaying a speckled phase pattern mimics a rough phase-boundary. The procedure is performed as described above. An example is plotted in Figure 3. The left part of the image shows the aberrated measurement. Though no single particle can be resolved, the image correlation based analysis of the data still allows obtaining good flow profiles with small errors in the magnitude of 5 %.

Note that these are exemplary data and more severe influences can be obtained with an increase in amplitude and spatial frequencies of the speckled phase. After the correction single particles can clearly be resolved and the error is reduced to about 1 % as in the other example.

Though the presented experiments apply two optical accesses, a correction approach using a Fresnel guide-star enables fast correction of fluctuating single phase boundaries with just one optical access. Also there are approaches to correct more complex aberrations consisting of multiple phase boundaries.

Adaptive correction is limited by the choice of the spatial light-modulator. Depending on the desired performance a compromise has to be found between rates, pixel-sizes and pixel numbers. The LCoS spatial light modulator used here has a strong polarization influence. This can be a limiting factor for some applications, as polarizers have to be used to filter the appropriate polarization. Deformable mirrors are polarization insensitive and potentially very fast, but have just a small number of relatively big pixels, which limits their applicability. The gap between these two types of modulators is filled by Piston-type Micro Mirror Arrays [16] that may be an adequate substitute. For sure the technological progress will open up further possibilities and will increase the power of adaptive optics.

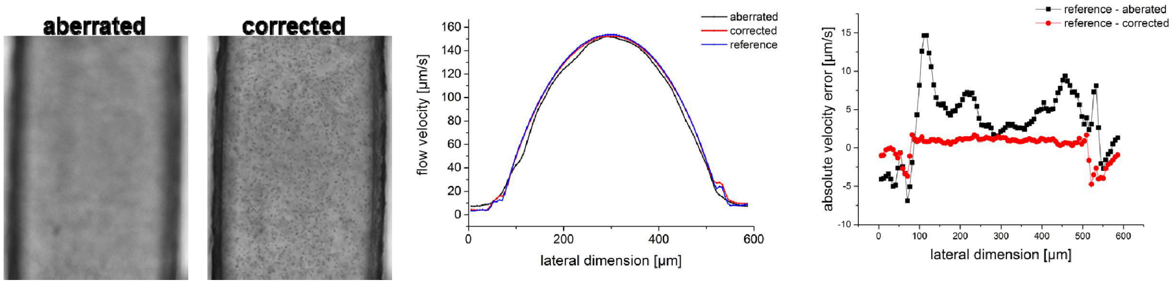

Figure 3: Exemplary results for PIV measurements through a speckled phase boundary. Aberrated and corrected PIV images (left), flow velocity profiles (middle) and velocity error (right).

3. SUMMARY AND OUTLOOK

We show that wave front shaping approaches have the potential to strongly improve image correlation based flow-field measurements and to decrease the measurement uncertainty. In general Adaptive optics has the power to open up new applications for image correlation based flow measurements, e.g. in micro- and nanofluidics and in life sciences, e.g. for blood-flow measurements in biological tissue. The technological progress will boost the achievable performances and will enable to measure flows that were not measureable before.

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