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Wavefront shaping for flow-field measurements through varying phase boundaries

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ABSTRACT

We propose the usage of wavefront shaping approaches for image correlation based flow-field measurements. 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 widely used in fluid mechanics, as they enable fast, non-invasive data acquisition. However, distortions present 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, correction of time varying optical distortion is elaborate. Although software-based correction may be adequate in some applications, generally it is preferable to compensate for the influence of time varying distortions with hardware based approaches, using wavefront shaping.

Adaptive optics (AO) originally known from astronomy [1], has the great potential to clear up information-containing-light of any distorting effect. The wavefront manipulation is commonly performed using e.g. deformable mirrors (DM) or liquid crystal modulators (SLM).

The biggest challenge for AO-correction is finding an appropriate phase mask that compensates for the distortions. The approach to this task is strongly depending on the desired application and the nature, i.e. the spatial frequency content and the amplitude, of the distortion. For example, the transmission matrix approach [2, 3] is not well applicable for the correction of time-varying aberrations but it is just suitable for static ones. Iterative optimization [4, 5] is a sensor-less AO technique that requires an iteration rate clearly higher than the measurement rate. Hence, for iterative AO mainly deformable mirrors are used, as these enable adequate high refresh rates. But, DMs commonly just have a small number of pixels, with a relatively large pixel size, which limits the correctable spatial frequency content of the aberration.

Sensor-based AO systems usually consist of a sensor for measuring the wave front distortions, the adaptive optical element 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. Digital optical phase conjugation (DOPC) is a prominent sensor-based AO technique [6, 7]. For DOPC commonly a guide-star is used that interacts with the aberration and allows measuring its phase-fingerprint. A correction is enabled by displaying the conjugate phase on a spatial light modulator.

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However, 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 the wavefront sensing techniques (e.g. Hartman-Shack sensors, phase retrieval or digital holography) strongly depend, however, on both the principle of the measurement system as well as the nature and the characteristics of the optical 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.

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

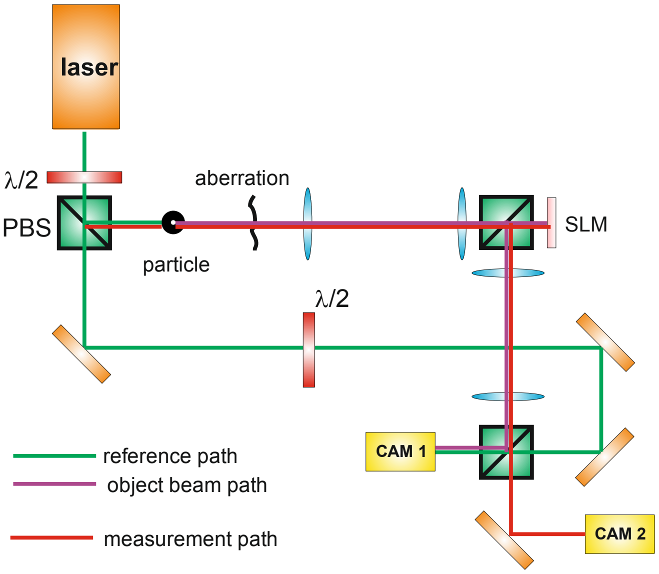

Figure 1: Sketch of the sensor-based adaptive optics setup. SLM: spatial light modulator, CAM1: Digital camera used for holography, CAM2: Camera for the measurement.

For the first experiments, the setup depicted in Figure 1 is used. This setup enables mimicking a particle measurement (in this example an iris diaphragm) using CAM2. The source is a 532 nm Nd:YAG laser that illuminates a polarizing beam splitter. The half-wave plate is applied to set the intensity ratio of object and reference paths. A plan convex lens is placed into the setup as an aberration, introducing mainly tilt and defocus. A digital camera (CAM1) is used to record off-axis digital holograms and the angular spectrum approach is applied to extract the phase information [14]. A reference hologram measured without the iris in the beam path is used as a guide-star. 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 guide-star phase has to be conjugated to correct for the aberration, when displayed on the SLM. These first exemplary tests are performed in a time-multiplex scheme.

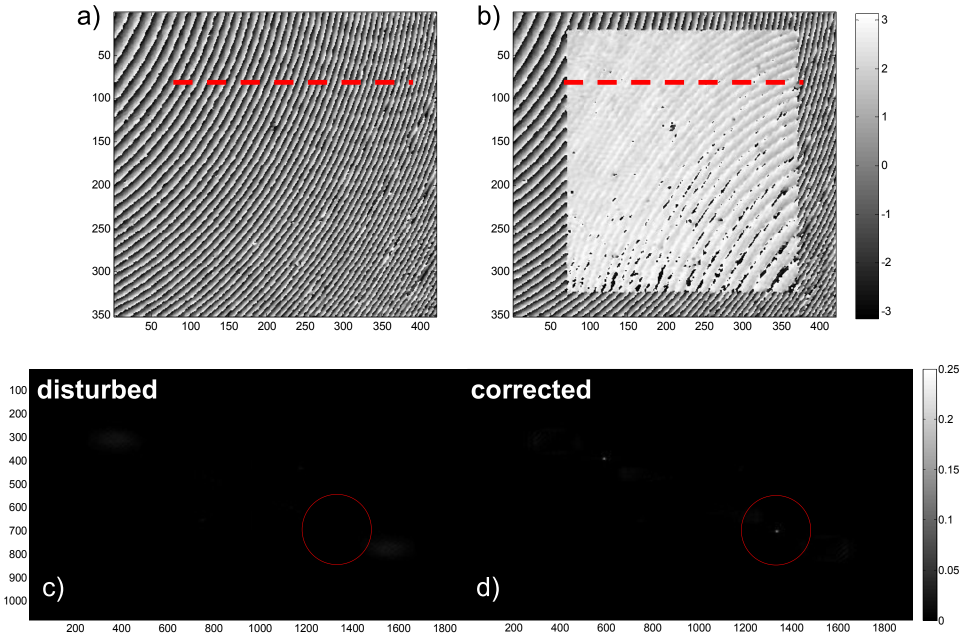

Figure 2: a) Disturbed phase information and b) corrected phase information. The red dotted lines mark the position of the line-plots shown in Figure 4. Corresponding disturbed (c) and corrected (d) angular spectra.

The reference hologram is recorded without aberration in the beam-path. The aberrating lens is placed in the object beam path and disturbs the measurement. The reconstructed phase aberration is shown in Figure 2a. The corresponding angular spectrum (Figure 2c) has an increased diameter in comparison to the reference measurement and is spatially shifted, as the lens is not located on the optical axis.

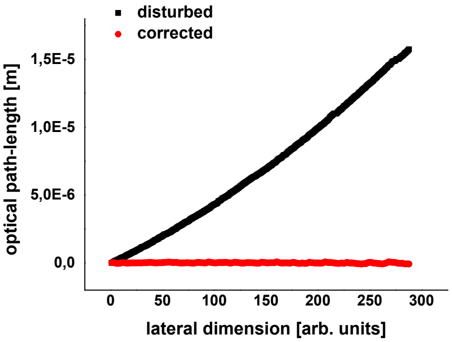

Figure 3: Line plot, across the unwrapped red lines in Figures 2a) and 2b).

The original position of the spectrum is the centre of the red circle marked in Figure 2c. The measurement is performed with CAM 2. As shown in Figure 4 the measured position of the mimicked particle is shifted with respect to the undistorted measurement.After displaying the conjugate phase on the SLM another hologram is recorded to test the correction. Figure 2b shows the reconstructed phase of the hologram, recorded with the SLM displaying the phase conjugate. Figure 3 shows the unwrapped line-plot across the red line in Figures 2a) and 2b). As expected, the phase in the used correction-window is constant, proving, that the correction was successful. Furthermore the corrected angular spectrum is shifted to the reference position, and the spectral bandwidth is strongly reduced (Figure 2d). The mimicked particle shown in Figure 4 on the right is also shifted to the original position showing that the influence of the lens is diminished.

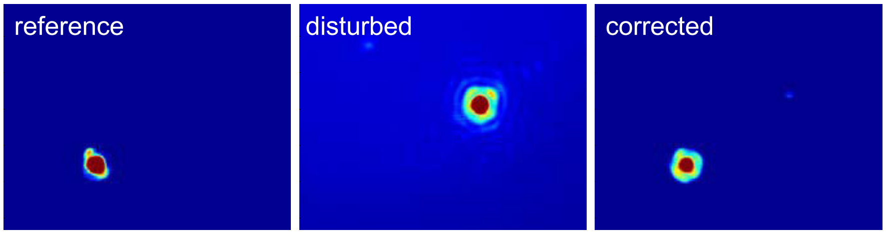

Figure 4: Reference Line plot, across the unwrapped red lines in Figures 2a) and 2b).

The described result can be interpreted as follows: in flow-measurements commonly particles are used to track the flow. The used optics creates a measurement volume where the particles are detected. If now an aberration changes the optical path-length in the detection path, the assignment to the particle position is erroneous. This strongly increases the measurement uncertainty, as the measurement takes place at a position, which does not accord to the measurement volume settings. Wavefront-shaping enables to correct for these errors and to react on disturbing path-length changes.

Exemplary flow-velocity plots are shown in Figure 5. Here the SLM was used to introduce a lens-aberration into the detection-path of a micro-particle image velocimetry setup (µPIV). The sample under test is a 500 µm square micro channel. A 532 nm high-power LED is used for illumination in transmission geometry and a guide-star is used to probe the aberration, in this case: the SLM. 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. 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.

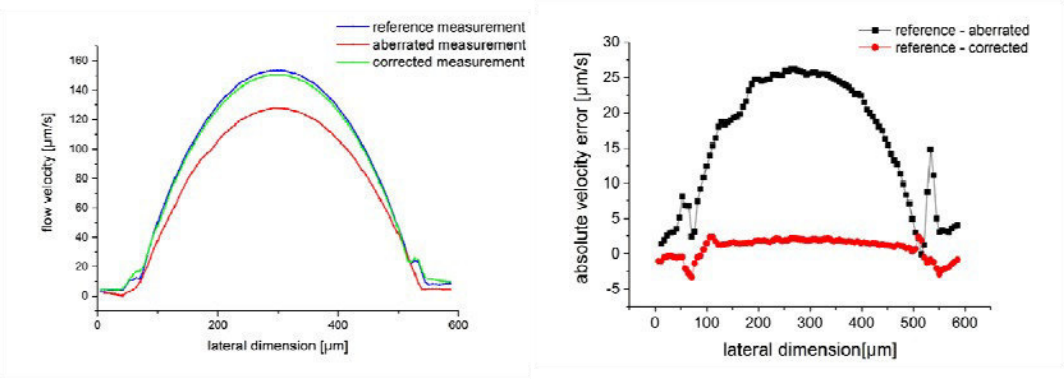

Figure 5: Exemplary results for the adaptive correction of the PIV measurements. Flow velocity profiles (left) and velocity error (right).

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.

In another example, diffuse phase masks were used for aberrations leading to strong influence on the PIV measurement, as can be seen in the middle-part of Figure 6. Here, the particles can not be distinguished from the diffuse background. After correction, the particles are visible. Surprisingly, here the flow-velocity error was relatively small, in the magnitude of 5 %.

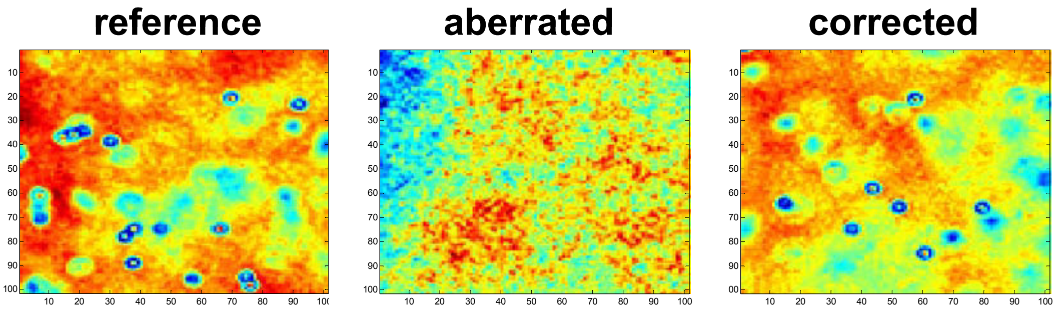

Figure 6: Exemplary, magnified part of the micro-channel measurement through a speckled phase boundary. After correction with a guide-star approach, the particles can be resolved.

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 or other MEMS modulators [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.

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 through scattering tissue. The technological progress will boost the achievable performances and will enable to measure flows that were not measureable before.

4. ACKNOWLEDGEMENTS

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