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Adaptive flow-field measurements using digital holography

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ABSTRACT

Variations of the optical detection path-length in image correlation based flow-field measurements result in strong errors in position allocation and thus lead to a strong enhancement of the measurement uncertainty of the velocity. In this contribution we use digital holography to measure the wavefront distortion induced by fluctuating phase boundary, employing spatially extended guide stars. The measured phase information is used to correct the influence of the phase boundary in the detection path employing a spatial light modulator. We analyze the potential of guide stars that are reflected by the phase boundary, i.e. the Fresnel reflex, and transmitted. Our results show, that the usage of wavefront shaping enables to strongly reduce the measurement uncertainty and to strongly improve the quality of image correlation based flow-field measurements. The approaches presented here are not limited to application in flow measurement, but could be useful for a variety of applications.

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 [2, 3] approach 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 optical phase conjugation (OPC) [6, 7] may also be limited by the aberration or the task.

For OPC 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, 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. Hence, in this paper we introduce spatially extended guide star techniques and show first results of adaptive corrections used for image correlation based flow-field measurements.

2. EXPERIMENTS

2.1 Transmission geometry

We use the micro particle image velocimetry (μ PIV) setup sketched in Figure 1. The sample under test is a 500 μm square micro channel. We use a 532 nm high-power LED for illumination of the particle field 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, which means that the flow-velocity is maximal. Polystyrol particles of 3 μm diameter suspended in de-ionized water are used as tracer particles. A Nemesys syringe pump drives a constant flow of 0.01 $\mu\text{l/s}$. Light from the depth of interest (DOI) within the micro channel is collected using a microscope objective (20x, NA=0.4). The depth of correlation of this setup is approximately 30 μm , while laterally the whole micro channel is imaged. The sample light is imaged on the PIV camera. After a reference measurement, a distortion is located between the micro channel and the SLM. Now the sample light transmits through the distortion. A laser beam with a wavelength of 532 nm is used as a guide-star to probe the distortion, which is sketched by the green beam path in transmission. This beam acts as an object beam and the purple 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 guide star and the sample light share a widely common path; therefore they have to be separated, before they reach the wavefront sensing and the measurement camera. As the first experiments are used for proof of concept experiments we use static distortions, hence the measurement and the correction steps can be performed successively. For real applications at fluctuating distortions wavelength multiplexing could be an appropriate approach for separating the light.

Figure 1: Sketch of the sensor-based adaptive optics setup.

As a first step a measurement without distortion is performed for reference. Secondly, a distortion is introduced and the measurement is repeated. In this example the distortion is a translucent foil. The microscope objective is kept aligned in image axially the middle of the micro channel throughout the experiment. However, the introduction of the distortion in the detection path leads to a change of the optical path-length, which consequently results in a detuning of the setup [15]. The translucent foil additionally leads to a strong drop of contrast and signal-to-noise ratio, resulting in blurred particle images shown in Figure 2. Now the guide star is used to measure the fingerprint of the distortion. As the guide star passes the aberration in transmission like the sample light does, the recorded phase has just to be conjugated and then displayed on the SLM. After this correction step, the measurement is repeated resulting in the corrected image on the right of Fig. 2. As can clearly be seen, the contrast and the signal-to-noise ratio are strongly improved compared to the distorted measurement.

Figure 2: Zoom into the background subtracted images of particles in the micro channel for the reference, the distorted and the corrected case.

The corresponding flow velocity profiles are depicted in Figure 3. As can be seen, the foil induces a reduction of the flow velocity, a slight deformation and a change of the smooth parabolic reference (black line) profile to a wavy distorted profile (red line). It is remarkable that the correlation based nature of evaluation is still capable to obtain such results, despite the strong degradation of the image quality. The velocity error, i.e. the deviation to the reference, is in the range of 25 %. After correction, the velocity error is reduced to about 1 % (green line). The residual error can be

explained by the non-ideal phase correction and by differences in the interaction angle between the guide star or the sample light and the aberration.

Figure 3: Exemplary flow velocity profiles for the reference, distorted and corrected particle flows in the micro channel. The correction is performed using the transmission guide star.

These results show that the general approach of a transmitting guide star has the potential to improve flow velocity measurements through phase boundaries. However, as the sample light and the guide star travel the same path the guide star light has to pass the measurement volume. This restricts the applicability to flows with rather low particle concentrations.

2.2 Reflection geometry: Fresnel guide star

Many real life applications just offer one optical access to the region of interest. Hence, the transmission guide star approach described in section 2.1 is not usable. The only solution is to use the Fresnel reflection at the distortion as a guide star to get the information for the correcting phase mask. In contrast to the transmission guide star, the Fresnel guide star just propagates in a medium with refractive index n_1 . Hence, the refractive index of n_2 has to be known to compensate for the phase distortion of the sample light travelling from medium with refractive index n_2 to the medium with n_1 , correctly.

Figure 4: The Fresnel guide star (FGS) at a phase boundary.

Additionally, in contrast to the transmission guide star it is not the phase conjugate that has to be displayed on the SLM, but the measured phase weighted by the phase factor c_ϕ . Additionally, the double-passing of the path, due to reflection geometry has to be taken into account. We obtain equation (1):

$$\varphi_{SLM,FGS} = c_\phi \Delta \varphi_{FGS} \quad (1)$$

with $c_\phi = \frac{1}{2} \frac{n_2 - n_1}{n_1}$. As a proof of principle, we use the convex part of a plano-convex lens with $f=500$ mm as distortion.

The modified setup using the Fresnel guide star (FGS) is sketched in Fig. 5. The difference to the setup of Fig. 2 is that now a half-wave plate combined with a polarizing beam-splitter (PBS) is used to split the beams. The PBS directs the light towards the distortion, where it is reflected. Due to the commonly reduced reflectivity of transparent or translucent media, the polarizing optics is required to split the intensities in the object and reference arms as required. Another half-wave plate is used to adjust the polarization in the reference path.

Figure 5: Sketch of the micro PIV setup using the Fresnel guide star (FGS) approach

The procedure for the measurements is the same as before. At first, a reference measurement is conducted without distortion. Afterwards the distortion is introduced and a distorted and a corrected measurement are performed. In our example we use a BK-7 lens from Thorlabs, which has a refractive index of $n_{lens}=1.5195$. The phase factor can be

calculated as $c_\phi = \frac{1}{2} \frac{n_{lens} - n_{air}}{n_{air}} = 0.2595$. In other words: the FGS measures approximately the fourfold curvature

compared to the acting distortion that distorts the sample light. As the spatial frequency content of the off-axis holograms prohibited adequate spectral separation we chose phase-shifting digital holography in in-line geometry for phase reconstruction [16] as it uses the whole spatial bandwidth of the camera.

The SLM was used to shift the phase of the object beam to acquire four phase shifted holograms. The resulting wrapped phase is unwrapped, weighted by the phase factor and interpolated to the SLM pixel size. The flow in this measurement was set at $0.025 \mu\text{l/s}$. The lens is placed into the beam path slightly tilted, to obtain a spatial separation of the Fresnel reflex on the convex boundary and the flat backside. The distorted flow profile plotted in Fig.6 (red line) shows the expected behaviour. The introduction of the defocus aberration into the setup leads to a detuning of the setup. An additional tilt can be observed due to the tilted lens. The resulting velocity error reaches up to 90 %. Using the FGS enables reducing the error down to 3-4 %.

However, there is still a deformation of the corrected flow profile visible that results in slightly increased velocity errors near the micro channel walls. These errors are due to the imperfect phase correction, resulting due to the angle

differences between the FGS beam and the sample light. But the correction works sufficiently good and enabled the correction with one optical access.

Fig. 6: Exemplary flow velocity profiles for the reference, distorted and corrected particle flows in the micro channel. The correction is performed using the Fresnel guide star.

3. SUMMARY AND OUTLOOK

Imaging-based flow measurement techniques require accurate position assignment of the tracer particles. However, fluctuating distortions located between the depth of interest and the camera lead to increased positioning and consequently to velocity errors. We show that wavefront shaping techniques based on spatially distributed guide stars have the potential to reduce these errors. Both transmission and Fresnel guide stars proved to be adequate to compensate the distortion effect, enabling measurements through translucent media or disturbing phase boundaries.

The applicability of these approaches is strongly limited by the pixel size, pixel number or achievable frame rates of spatial light modulators. However, the expected technological progress will boost the achievable performances of digital optoelectronic devices, overcoming current limitations in the future. Hence, adaptive optical techniques will revolutionise the capabilities of optical flow measurement and may even open up new applications that are currently limited by too strong distortions.

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