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Smart adaptive photonic sensor systems

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Abstract:

Adaptive optics is a rapidly developing field. Predominantly adaptive optics is known from astronomy, where it has led to a renaissance of large earth-bound telescopes. Optical distortions of the light path through the atmosphere are corrected by controlled adaptive elements such as optical Micro-Electro-Mechanical Systems (MEMS). Currently adaptive optics for a variety of applications is used. They allow in ophthalmology a fine resolution of the retina. Intriguing is the possibility to resolve retinal cells by adaptive optics, which enables an early detection of the risk for diseases such as heart and brain stroke. Adaptive optics is also found as electrically controllable focusing elements of digital CCD/CMOS cameras in cell phones.

We have harnessed the power of various programmable photonics devices for the interferometric measurement and sensor techniques. This invited plenary talk will describe research conducted to demonstrate distortion-free laser measurements through a dynamic interface by a closed-loop optoelectronic system. We are employing electrically tunable optofluidics membrane lenses and MEMS micro mirrors to correct low-order wavefront distortions effectively. Our work represents a paradigm shift in measurement and sensor techniques from using static to dynamic adaptive optical elements.

Key words: Smart sensor systems, control engineering, CMOS/CCD cameras, spatial light modulators, MEMS, biomedicine, process techniques, flow measurements.

Introduction

Laser interferometers have become a well-established and indispensable tool for precision measurements in a huge variety of scientific and industrial applications. Using a frequency evaluation, two-beam interferometers are used to measure velocities, e.g. surface velocities or seeding particles carried in flows (Laser Doppler Velocimetry). Measurement uncertainties can be in the range of 0.01 %. However, such precision can be achieved only under ideal conditions. It is well known that refractive index effects [Birch 1993], caused e.g. by temperature, pressure and concentration variations or fluctuating interfaces between two media of different optical density, can result in severe distortions of the optical wavefront and systematic measurement errors [Opt Expr]. Especially on the field of flow measurement a lot of applications with refractive index variations exist [J Optomech].

The principles of adaptive optics can be used to overcome this metrological problem, as it is e.g. commonly used in modern earth-bound telescopes [Beckers 1993, Hardy 1998]. An AO system in general comprises a wavefront sensor to measure the distortion of the wavefronts, an electric control circuit which derives the actuator displacement and a deformable optical element (Deformable Membrane Mirrors, Micro-electro-mechanic mirror arrays, liquid-crystal spatial light modulators, scanning mirrors, electrically

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tunable lenses, etc.) which correct the distortions.

The problem of measuring the optical distortion is solved by observing a single star (NGS: natural guide star), considered a point source, nearby the object to be investigated. If no NGS is available, researchers can switch to artificial guide stars [Fugate 1991], e.g. laser-based excitation of sodium atoms in the mesosphere (LGS: laser guide star). In biomedicine, where light is distorted by the transmission of biological, scattering tissue, several other ways of realizing a guide star have been demonstrated, e.g. using ultrasound-encoded light [Xu 2011], fluorescence [Bertoletti2012,Tao2012] or two-photon absorption [Katz 2014].

In our former works we have presented an adaptive optics Mach-Zehnder interferometer which enables flow velocity measurements through a fluctuating air-water interface [Opt Exp, J Optomech]. The interferometer was equipped with a wavefront sensor and adaptive optical elements to compensate for wavefront distortions caused by capillary waves. The wavefront aberrations were measured with a Hartmann-Shack camera behind the disturbing interface, i.e. in transmission which demanded a second optical access. For practical applications a measurement through only one optical access is required in almost all cases. As an example, a water jet emitted in air owns no undisturbed optical access to inner flow field. We have solved this problem by using a new type of guide star, the Fresnel guide star. Here, the Fresnel reflex from the gas-liquid interface is used instead of the transmitted beam to measure the aberrations and to enable a closed-loop beam aberration correction.

Flow velocity measurements

A Mach-Zehnder interferometer for measuring the flow velocity in fluids is considered (Laser Doppler Velocimeter). The velocity is gained as the product of the measured Doppler frequency f and the fringe spacing d in the interferometer, with as the interference fringe spacing, □□ as the laser wavelength and □ as the crossing half angle of the interfering beams. The beams are directed through an open water surface with stochastically excited capillary waves as the optical distortion. The fluctuating interface can deteriorate the measurement properties as follows [Opt Exp, J Optomech]:

i) A parasitic phase shift is introduced due to different optical path lengths in the interferometer.

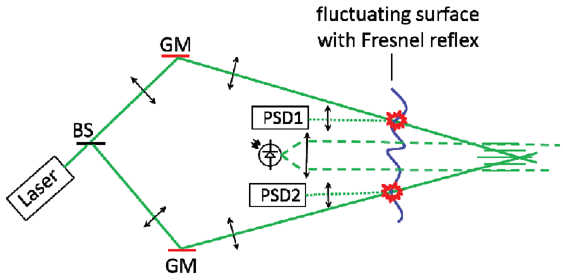

Fig. 1. Mach-Zehnder interferometer for velocity measurements (Laser Doppler Velocimetry) with implemented dual adaptive optic system based on two-axis galvanometer mirrors (GM) and Position Sensitive Detectors (PSD) for evaluating the Fresnel reflex. The adaptive optics system compensates the tip/tilt error caused by the fluctuating gas/liquid interface.

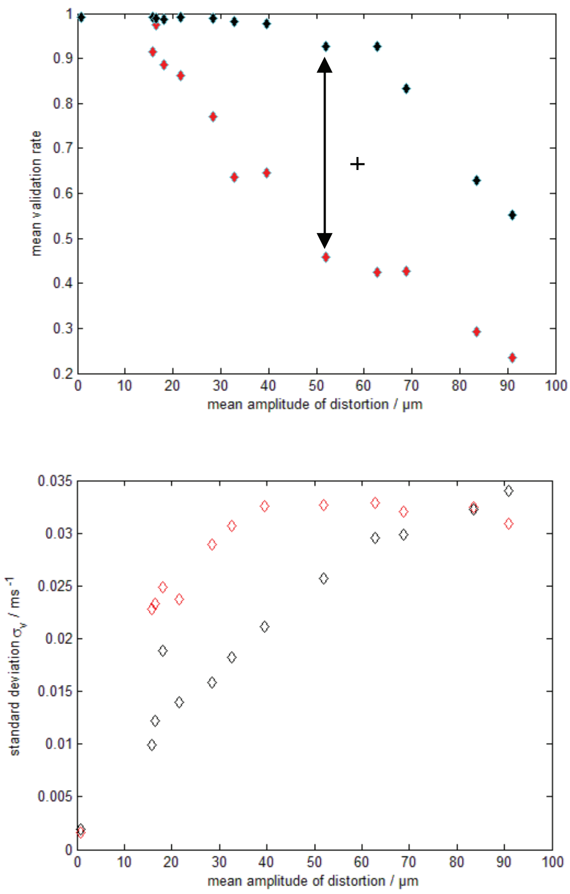

Fig. 2: Mean validation (top) and mean standard deviation (bottom) in dependence of the amplitude of the distortion (capillary wave).

ii) A dislocation of the measurement position can occur due to variations of the height and the inclination of the interface.

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iii) An increase of the measurement uncertainty can occur due a variation of the calibration constant d at an inclined interface.
iv) The measurement uncertainty can be increased also due to the curvature of the interface (lens effect).
v) The interference visibility can be reduced due a loss of beam overlap in the case of an inclined interface.

These distortions can be corrected using an adaptive optics system. A detailed experimental analysis revealed that only that only low-order Zernike polynomials (piston, tip/tilt, defocus) dominate the wavefront distortions [Opt Exp, J Optomech]. Distortions of higher orders, i.e. with higher spatial frequency, can be neglected. Hence, we employed a combination of adjustable fluid-membrane lenses with two-axis galvanometric mirrors as adaptive elements. A Hartmann-Shack (HS) sensor was used to measure the wavefront distortions and a standard PC to calculate the actuating variables.
In our former work, the HS sensor was placed underneath the basin with the consequence that the parameters of the measured=transmitted beam are stabilized. A difficulty arises when the reflected beam is to be used for beam stabilization since it shows a different behavior because Snell's law of refraction. We solved this problem by implementing Snell´s law into the control loop. In Fig. 1 the experimental setup is shown for a correction of the beam tip/tilt by using the Fresnel reflex.
Whereas in astronomy the Strehl ratio is used for imaging systems to characterize the quality of the aberration correction of the AO system, for the non-imaging case considered here the rate of valid signals is used instead. The validation rate is given by the number of valid measurement signals with respect to the number of all acquired signals and depends mainly on the interference visibility.
In Figs. 2a,b the mean validation rate and the mean velocity standard deviation are displayed in dependence of the mean amplitude of the distortion, e.g. the mean amplitude of the capillary waves. Data were obtained from a characterization experiment which used a velocity reference to generate defined signals (for this demonstration experiment, only one beam was corrected for now). It is obvious that the wavefront correction by the adaptive optics system results in a significant increase of the validation rate and a reduction of the measurement uncertainty.

Summary

Refractive index variations, caused by fluctuating refractive index fields or interfaces, can deteriorate the properties of laser-optic distance and velocity measurements, based e.g. on interferometers. A lower rate of valid signals and an increased uncertainty can be the consequences.

To overcome these limitations, the principle of wavefront correction by means of adaptive optics, which is commonly known from astronomy and ophthalmology, can be applied to laser measurement techniques as well.

In this contribution, a Mach-Zehnder interferometer for fluid flow velocity measurements was presented, that was equipped with a dual adaptive optics system to corrected wavefront distortions caused by a fluctuating air-water interface.
Using the wavefront correction, the the number of valid signals is improved significantly whereas the measurement uncertainty is reduced concurrently. Measurements in the presence of optical distortions can be performed in a shorter time and with a higher statistical reliability.

As a new technique for we have introduced the Fresnel reflex as a new realization of a laser guide star. It enables measurements with backward scattering through media with discrete changes of the refractive index, i.e. optical interfaces, with only one optical access. Such measurements through disturbing fluid interfaces with only a single-sided optical access play an important role at several fields of fluid mechanics.

At convection research an improved understanding of heat transfer by turbulence can be achieved by measurements at liquid jets in gaseous atmosphere. Another example is the investigation of the energy efficiency of film cooling devices, where liquid film with film thicknesses below 1 mm on a structured, opaque substrate are employed.

As a result, adaptive optics offers new perspectives for metrology at applications that were hardly accessible by laser measurement techniques so far.

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Brief biography of the first author:

Prof. Jürgen Czarske studied physics and electrical engineering at the Leibniz University of Hannover, where he also received his Ph. D. degree in 1995 and his venia legendi (Dr.-Ing. habil.) in 2003. In 1995 Prof. Czarske has joined the Laser Zentrum Hannover e.V., a private research institute. Since 2004 he is full professor at TU Dresden, School of Engineering. Prof. Czarske has published over 500 papers and talks. Among other honors he has been awarded by the AHMT measurement technique prize in 1996, an international Berthold Leibinger innovation prize in 2008 and 2014 by a Reinhart Koselleck award of German Research Foundation (DFG).

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