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Application of adaptive optics for flexible laser induced ultrasound field generation and uncertainty reduction in measurements

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ABSTRACT

The availability of spatial light modulators as standard turnkey components and their ongoing development makes them attractive for a huge variety of optical measurement systems in industry and research. Here, we outline two examples of how optical measurements can benefit from spatial light modulators.

Ultrasound testing has become an indispensable tool for industrial inspection. Contact-free measurements can be achieved by laser-induced ultrasound. One disadvantage is that due to the highly divergent sound field of the generated shear waves for a point-wise thermoelastic excitation, only a poor spatial selectivity can be achieved. This problem can be solved by creating an ultrasound focus by means of a ring-like laser intensity distribution, but standard fixed-form optical components used for their generation are always optimised to a fixed set of parameters. Here, we demonstrate, how a predefined intensity pattern as e.g. a ring can be created from an arbitrary input laser beam using a phase-retrieval algorithm to shape an ultrasound focus in the sample. By displaying different patterns on the spatial light modulator, the focus can be traversed in all three directions through the object allowing a fast and highly spatially resolving scanning of the sample.

Optical measurements take often place under difficult conditions. They are affected by variations of the refractive index, caused e.g. by phase boundaries between two media of different optical density. This will result in an increased measurement uncertainty or, in the worst case, will cause the measurement to fail. To overcome these limitations, we propose the application of adaptive optics. Optical flow velocity measurements based on image correlation in water that are performed through optical distortions are discussed. We demonstrate how the measurement error induced by refractive index variations can be reduced if a spatial light modulator is used in the measurement setup to compensate for the wavefront distortions.

I. FLEXIBLE LASER-INDUCED ULTRASOUND FIELD GENERATION USING SPATIAL LIGHT MODULATORS

Introduction

Ultrasound testing has become an indispensable tool in the field of industrial inspection, e.g. for the detection of defects in technical components. Conventionally, ultrasound transducers are applied in contact to the specimen, which is not always possible e.g. in the case of curved contact surfaces or if the samples exceed the Curie temperature of common piezo transducers. This problem can be solved with contact-free measurements using laser-induced ultrasound. Here, ultrasound waves are generated by short laser pulses and detected using laser vibrometers [1]. In solid samples, the sound field of the shear waves for a point-wise excitation in the thermoelastic regime is commonly a hollow cone with a large cone angle. This is usually the case for focused lasers with a standard Gaussian intensity profile. Measurements hence suffer from only a poor spatial selectivity and limited measurement depth.

This problem can be overcome if the laser beam used for excitation is formed to a ring. The axial depth of the shear wave focus depends on the diameter of the ring. Shaping a laser beam to a ring-like profile can be performed with diffractive or refractive optical elements, as has been shown e.g. by using axicons [2]. Fixed-form optical components, however, have the disadvantage that they are bound to a given set of parameters, hence allowing only a limited flexibility. First, the incident laser beam must usually have a well-defined and known intensity profile, e.g. a Gaussian profile, to generate the desired output profile. Second, the parameter of the output beam, e.g. the ring diameter, can be varied only within defined limits.

Here, laser-induced ultrasound can benefit from modern spatial light modulators, since they offer a high degree of freedom; common liquid-crystal on silicon (LCoS) spatial light modulators for example can have more than ten Mega-pixels. Recently, a spatial light modulator was used to account for changing light absorption rates in composite materials [3] for a homogeneous excitation of ultrasound in fibers and matrix material, thus avoiding damage to the sample.

Here, we demonstrate how the possibilities of spatial light modulators can be exploited to achieve highly flexible ultrasound focus generation within solid-state samples.

Experimental Setup and Results

We apply a MEMS (Micro Electro Mechanical System) spatial light modulator (Fraunhofer Institute for Photonic Microsystems, Dresden/Germany) as the key component. It is a piston-type, phase-only modulator with an array of 200 x 240 micro-mirrors, which is sufficient for the desired beam shaping application. It was built monolithically from low-temperature sputtered amorphous TiAl with integrated CMOS address circuitry and has a fill factor of about 80 %. In contrast to liquid-crystal spatial light modulators (e.g. LCoS), the MEMS modulator can work independently of the polarization state of the incident light and offers with 250 Hz a much faster frame rate, making the modulator ideal for fast scanning applications. For reasons of strain relaxation, the duty cycle of the modulator is limited to 5 %, which was not of importance here due to the pulsed laser application.

The laser-ultrasound setup, as depicted in Fig.1 a), uses a q-switched, frequency-doubled Nd:YAG laser as light source (wavelength 532 nm, pulse width of 5 ns, max. repetition rate of 15 Hz). The original beam of the laser is directed onto the phase modulator and the shaped beam reflected hereof is guided onto the sample (aluminium plate of 3 mm thickness). Polarization optics is used to separate the beam incident on the modulator from the outgoing one. The laser energy was adjusted to 880 μJ per pulse at a repetition rate of 12 Hz, resulting in a radiant fluence ranging from 1.1 MJ/cm^2 to 13 MJ/cm^2 , depending on the ring diameter. The generated sound field is detected on the backside of the sample using a laser vibrometer (Polytec OFV-503,

24 MHz frequency resolution) which is synchronised with the laser and the modulator. For means of beam shaping and observation, a camera is placed at the same distance from the modulator as the sample under investigation.

Beam shaping is performed in two steps: First, the phase and amplitude distribution of the original beam have to be recovered. We do this by using a phase retrieval procedure based on the Gerchberg-Saxton algorithm [4,5], since this offers high spatial resolution while maintaining a simple setup as compared to other phase retrieval techniques like holography. In this procedure, known phase masks are displayed on the modulator and the corresponding intensity distributions on the camera are recorded. Both information are then used to iteratively reconstruct the original wavefront. Knowing the original wavefront, one can use this as input for the generation of a phase mask, which projects the desired intensity distribution onto the sample. For the generation of this phase mask, we are using an input-output-type phase retrieval algorithm as introduced by Fienup [6]. It is easy to implement, offers high diffraction efficiency and converges in a timely fashion. Thus, arbitrary intensity distributions on the sample can be generated from arbitrary input wavefronts. The generation of all phase masks for a single measurement can take several minutes, but is of little consequence for the overall measurement time, since all masks are being calculated prior to the measurement itself.

Fig. 1: Left: Experimental setup for laser-induced ultrasound generation using laser beam shaping. Abbreviations: S: aluminium sample, M: mirror, PBS: polarizing beam splitter, LV: laser vibrometer. The CCD camera is located at the same distance from the beam sampler as the sample in order to monitor the laser intensity profile as it appears on the sample.

Right: Cross-section through the generated, rotationally symmetric sound field for a ring-like intensity distribution. The ultrasound focus can be shifted axially (in depth direction z) by varying the ring diameter $2R$.

Results are displayed in Fig. 2. Fig 2 a) shows two examples of the laser intensity profile after the beam shaping as it appears on the sample. Perfect rings with rectangular cross-sections were obtained. The superimposed speckle noise had no effect on the generated sound field due to its stochastic character.

If a ring-profile is used for ultrasound field excitation, the partial ultrasound waves from each point of the ring will superpose in such a way in the sample that a focus is generated, see Fig. 1 b). The axial depth z of the focus within the sample is given by:

$$z = \frac{R}{\tan \Theta},$$

where Θ is the directivity angle of the main lobe of the sound field, depending on Poisson's ratio and Young's modulus. Obviously, the focus depth can be changed by varying the ring diameter of the excitation beam [7,8]. This is depicted in Fig. 2 b) which shows the amplitude of the sound field at the backside of the aluminum sample for different ring diameters. Results are normalised by the overall beam intensity to account for the intensity dependence of ultrasound generation. As the focus is scanned through the backside of the sample (=measurement plane), the amplitude first increases and decreases again after running through a maximum. The maximum corresponds to the situation at which the focus coincides with the backside. Inserting the sample thickness of 3 mm and the ring diameter of the maximum (4 mm) in the equation above yields an angle of the main ultrasound lobe of 34° , which is in good agreement with common values from literature [1].

Fig. 2: a) Generated intensity distributions: rings with 2 mm (top) and 4 mm (bottom) diameter and 250 μm thickness; scales are in millimeters.

b) Measured surface displacement of the backside of the sample for different ring diameters at the front side. As the ring diameter is increased, the focus is shifted axially through the backplane. A maximum occurs when the focus coincides with the backside.

Changing the ring diameter allows for a depth scan of the focus (z axis, “A-scan”). To realise a scan in the two transverse directions (x and y axes, “C-scan”), the phase mask can be computed in such a way that the outgoing beam leaves the modulator under a desired deflection angle. Hence, every x -, y -, z -position is represented by a different phase mask. As a consequence, a fast 3D scan of the ultrasound focus can be accomplished without mechanically moved parts by displaying the corresponding phase masks on the spatial light modulator, where the scanning speed is just limited by the maximum frame rate of the modulator.

II. UNCERTAINTY REDUCTION IN MEASUREMENTS USING ADAPTIVE OPTICS

Introduction

Optical measurements often have to be performed under difficult conditions. They are affected by variations of the refractive index, caused e.g. by temperature, concentration or pressure gradients. This will give rise to an increased measurement uncertainty [9–11] or cause the measurement to fail. To overcome these limitations, we propose the employment of adaptive optics [9–11]. Correction of distorted images by means of adaptive optics is widely known from astronomy with earth-bound telescopes to compensate for distortions induced by the turbulent atmosphere of the earth [12–14]. Such adaptive optical system usually consist of a wavefront sensor for measuring the distortion, a spatial light modulator (SLM) to compensate for the distortions and a control algorithm, which calculates the settings of the individual SLM elements [15]. We have shown that this idea can be beneficially adapted to flow measurements as well [9–11]. As an example, optic flow velocity measurements based on image correlation in water that are performed through a fluctuating air-water-interface are discussed in the following. Measurement errors of several ten percent can occur. We demonstrate how this error can be reduced by using a deformable mirror in a measurement setup for distortion compensation without an extra wavefront sensor.

This method can pave the way for the employment of measurement techniques at applications which could previously not be covered due to refractive index effects.

Experimental Setup and Investigations

Fig. 3: Twin Particle Image Velocimetry (PIV) setup comprising a distorted measurement path (upper camera) and a synchronised reference measurement path (lower camera) without distortion. Abbreviations: MO: long-distance microscope objectives, CCD: charge-coupled device cameras, PC: personal computer. Both cameras are aligned to the same field of view of the flow. By comparing the results of both PIV systems, the measurement error induced by the distortion can be estimated.

Particle Image Velocimetry is an imaging-based flow velocity measurement technique, which is based on the correlation of two images of a particle-laden flow taken subsequently in a distinct time interval Δt [16]. Particle images are subdivided into interrogation windows and for each interrogation window a velocity vector is calculated from the particle shift which is obtained by a cross-correlation. The aim of our experiments was to investigate the effects of optical distortions on the velocity measurements and to demonstrate the possibility of error correction using adaptive optics.

The test flow was a laminar water flow in a rectangular channel, which was illuminated with a horizontal laser light sheet. The light sheet was observed with two cameras, one from the top and one through the bottom of the channel. Both cameras were synchronized by an external trigger and operated at a frame rate of 100 Hz. The cameras were calibrated such that they captured the same field of view. In the upper (measurement) path, the optical distortions were introduced. It contained also a deformable membrane mirror (DMM), co. ALPAO/France, type DM 69, with 69 elements to correct for the introduced distortion. The influence of the free water/air interface was neglected since the flow was sufficiently slow. Open-source software PIVlab [17] was used for PIV image processing.

A lens with $f = 140$ mm focal length, acting as a defocus aberration, was inserted into the measurement path as an example and the flow was measured while the deformable mirror was set plane. In Fig. 4, the distorted measured velocity field (upper camera) is opposed to the measured velocity field without distortion (lower camera). It gets obvious that the velocity measurement with the distortion suffers from strong systematic deviation; the mean velocity of the entire field is seemingly increased from 2.25 m/s to 3.12 m/s, corresponding to a relative increase of 39 %. At the same time, the statistical error is increased, here from 6.9 % to 11.2 %. This is due to the fact that the particle images become blurred from the distortion and hence the cross-correlation peak, which is the basis for the calculation of the velocity, is broadened.

As a result, the presence of optical distortions in the optical measurement path leads to an increase of both the systematic and the statistic measurement error.

Fig. 4: Influence of an optical distortion (defocus aberration) on the measured velocity field of a laminar flow. Left: Velocity field measured with the upper camera and introduced distortion. Right: Velocity field measured with the lower camera (undistorted case). The strong systematic deviation is obvious.

Image correction using adaptive optics

Adaptive optical systems for wavefront correction usually consist of a wavefront sensor, a control algorithm, and a spatial light modulator in closed-loop operation. On the other hand, the setup can be simplified if the wavefront sensor is omitted and the wavefront is estimated indirectly, which is possible under some circumstances, e.g. at imaging techniques. To this end, a quality metric has to be introduced [18] that is derived from the image and that is maximised iteratively. Here we used the maximum gradient of the PIV particle image as a sharpness metric. The optimisation started with the 4th order Zernike polynomial (defocus) using Noll's sequential notation to be displayed at the DMM. Lower order Zernike polynomials result only in a transverse shift of the particle image, which does not affect the velocity measurement. A genetic algorithm was employed to find the optimum amplitude for the given polynomial. This procedure was repeated for all other Zernike polynomials until the 15th Zernike mode. This was the maximum order that can be displayed on the DMM and hence be corrected.

Results

An example of the results of the optimisation process is displayed in Fig. 5. Figs. 5 a)-c) show the images of the particles from the flow. With present distortion, particle images appear blurred (b) compared to the undistorted case (a). The image optimisation increases the sharpness (c) and the particle image appear almost as sharp as in the undistorted case. Figs. 5 d)-f) show the difference of the velocity fields from the upper and lower camera, i.e. from the distorted to the undistorted case. In the ideal, undistorted case (d) this would be zero since both cameras measure the same flow field (finite difference values are caused by camera noise and remaining alignment error). With a distortion introduced (e), a significant difference occurs revealing a systematic measurement deviation, which is almost vanishing to zero again (f) after the optimisation process. Furthermore, introducing the distortion is accompanied by an increase of the standard deviation by a factor of two (not shown), which is reduced by the same factor after optimisation.

Fig. 5: Improvement of a distorted PIV measurement achieved by adaptive-optical image correction. a)-c): Particle images taken for a) the undistorted, b) the distorted and c) the corrected case. Particle images appear blurred in the presence of a distortion (b), resulting in an increased systematic error for the measured velocity field (e). d)-f): Resulting deviation of the measured velocity fields from the upper path (with distortion) with respect to the reference path (without distortion) for d) the undistorted, e) the distorted and f) the corrected case. After applying the adaptive optics image correction, the difference is reduced to almost zero, meaning that the measured velocity field is close to the actual field.

III. CONCLUSION

Measurement and testing systems can benefit from the possibilities of commonly available spatial light modulators.

These devices can transform the laser intensity profile into any desired profile wherever the standard Gaussian beam profile emitted from most lasers is not suited for the application. Here we addressed laser-induced ultrasound generation, where laser beam shaping allows not only for a quantitative, but also for a qualitative improvement. Shaping the profile of the excitation beam to a ring allows for the generation of a focus of the ultrasound beam within the sample, which is not possible with a standard Gaussian beam. In contrast to standard fixed-form refractive or diffractive beam shaping elements, spatial light modulators offer a high flexibility for the application: First, the desired intensity profile, here the ring, can be generated independently of the profile of the incident laser beam, what we achieved by applying an iterative, fast-converging phase retrieval algorithm. Second, the ultrasound focus can be traversed in all three directions in space without mechanically moved parts by displaying different phase masks on the modulator. Changing the ring diameter will shift the focus in the axial direction while a computed beam deflection will traverse the focus in the lateral directions. The scanning speed is mainly limited by the frame rate of the modulator.

Moreover, spatial light modulators can help to reduce measurement errors in optical measurement systems. Such errors can be introduced by variations of the refractive index, either by refractive index fields like temperature or concentration gradients or by phase boundaries between two media of different optical density. We presented a PIV flow measurement system that was equipped with a 69-element deformable membrane mirror. The AO wavefront correction system is based on a sensor-free configuration which optimises the particle images iteratively by means of a quality metric. It was demonstrated that in the presence of an optical distortion measurement errors arise and that these can be reduced significantly by the adaptive-optical image correction.

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References

- [1] S.J. Davies, C. Edwards, G.S. Taylor, and S.B. Palmer, "Laser-generated ultrasound: its properties, mechanisms and multifarious applications," *J. Phys. D: Appl Phys* 26, 329–348, 1993
- [2] P. Cielo, F. Nadeau, and M. Lamontagne, "Laser generation of convergent acoustic waves for materials inspection," *Ultrasonics* 23, 55–62, 1985
- [3] M. Kalms, S. Hellmers, P. Huke, and R. B. Bergmann, "Beam shaping using liquid crystal-on-silicon spatial light modulators for laser ultrasound generation," *Opt. Eng.* 53(4), 044110, 2014
- [4] R.W. Gerchberg, W.O. Saxton, "A Practical Algorithm for the Determination of Phase from Image and Diffraction Plane Pictures," *Optik* 35, 237 (1972).
- [5] F. Zhang and G. Pedrini and W. Osten, "Phase retrieval of arbitrary complex-valued fields through aperture-planemodulation," *Phys. Rev. A* 75, 043805 (2007).
- [6] J. Fienup, "Phase retrieval algorithms: a comparison," *Appl. Opt.* 21(15), 2758–2769, 1982
- [7] F. Schmieder, L. Büttner, J. Czarske, "Adaptive laser-induced ultrasound generation using a micro-mirror array spatial light modulator", *Optics Express* 24(20), 22536–22543, 2016
- [8] F. Schmieder, L. Büttner, J. Czarske, „Adaptive focusing of ultrasound shear waves using laser beam shaping”, 5th International Symposium on Laser Ultrasonics and Advanced Sensing, 3a.2, 04.–08.07.2016, Linz/Austria
- [9] L. Büttner, C. Leithold, J. Czarske, "Interferometric Velocity Measurements through a fluctuating Gas-Liquid Interface employing Adaptive Optics", *Optics Express* 21(25), 30653–30663, 2013
- [10] H. Radner, L. Büttner, J. Czarske, "Interferometric velocity measurements through a fluctuating phase boundary using two Fresnel guide stars", *Optics Letters* 40(16), 3766–3769, 2015
- [11] N. Koukourakis, B. Fregin, J. König, L. Büttner, J. Czarske, "Wavefront shaping for imaging based flow field measurements through distortions using a Fresnel guide star", *Optics Express* 24(19), 22074–22087, 2016
- [12] J.M. Beckers, "Adaptive Optics for Astronomy: Principles, Performance, and Applications", *Annual Review of Astronomy and Astrophysics* 31(1), 13–62, 1993
- [13] John W. Hardy, "Adaptive Optics for Astronomical Telescopes", Oxford University Press, New York, 1998, ISBN: 019509019-5.
- [14] A. Glindemann, S. Hippler, T. Berkefeld, W. Hackenberg, "Adaptive Optics on Large Telescopes", *Experimental Astronomy* 10, 2000
- [15] R. Tyson, "Principles of Adaptive Optics", Third Edition; CRC Press: Boca Raton/USA, 2010.
- [16] M. Raffel, C.E. Willert, S. Wereley, J. Kompenhans, „Particle Image Velocimetry: A Practical Guide", Springer, 2nd ed. 2007
- [17] W. Thielicke and E. J. Stamhuis, "PIVlab - Towards User-friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB," *J. Open Res. Softw.* 2(1), e30, 2014
- [18] M.J. Booth, "Wavefront sensorless adaptive optics for large aberrations", *Optics Letters* 32(1), 5–7, 2007