Form profiler based on imaging with spatially partially coherent light

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We present a fast and robust method for shape measurements of technical objects. It is based on a 4f-imaging system with a modulator placed in the Fourier plane, and using light of limited spatial coherence. The modulator is used to enable fast depth scanning while the limited spatial coherence enables depth discrimination. The method is demonstrated by measuring the shape of a tilted metal plate.

1 Introduction

For the application of Optical metrology in an industrial environment, it is not only important to precisely measure the geometry of a product [1], but also to provide a low measurement time and robustness against mechanical distortions [2]. For the investigation of microscopic objects, the measurement technique should additionally offer an extended depth of focus.

Here, we present a new method based on a common-path imaging system under spatially partially coherent illumination. In contrast to other interferometric configurations, common-path approaches are robust against mechanical vibrations. Depth scanning is achieved at a rate of approx. 500 Hz by means of a tunable lens, in analogy to spatial light modulator (SLM) based phase retrieval [3, 4]. Since the method is based on spatially partially coherent light, we can use light sources such as light bulbs or LEDs for illumination, thus increasing the eye-safety of the measuring system. In the following, we verify the proposed approach by measuring the 3D shape of a tilted plate with an optically rough surface.

2 Experimental Setup

Figure 1 shows the proposed $4f$-based arrangement. It consists of a $4f$-imaging system with two identical lenses having the same focal length of $f = 150$ mm, an electrically tunable lens, and a band limiting aperture with adjustable diameter D integrated in the common Fourier plane. The first lens performs a forward Fourier transform of the input field. The tunable lens across the Fourier domain enables dynamic phase manipulations by electrically adjusting its focal length F_L [5]. Hereafter, the second lens performs a second forward Fourier transform, thereby imaging the modulated input field onto the camera sensor. Thus the image of the test object is rotated by 180° and $\vec{y} = -\vec{x}$ holds. The high speed camera (VKT Fastcam Nini UX 100) at the image plane has a resolution of 1020×1024 pixels and a pixel pitch of $10\,\mu$m. The camera can capture up to 4200 fps at full resolution. The electrically tunable lens (EL-10-30-C-VIS-LD-MV, Optotune) with a switching time of < 3 ms is used as modulator.

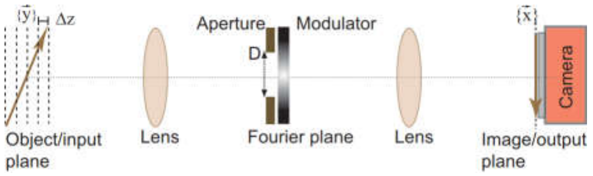

Fig. 1 *Scheme of the proposed measurement setup based on a $4f$-imaging system under spatially partially coherent illumination. A tunable lens located in the Fourier domain enables the modulation of light at the input plane with different chirp functions. Various out-of-focus propagated representations of the input light can be generated at the image plane, without the requirement for mechanically moving parts. Δz denotes the distance between two successive planes. The aperture with diameter D in the Fourier plane enables the adjustment of the speckle size suitable to the camera.*

As a test object, we investigate an optically rough tilted plate. For illumination, a fiber coupled LED supplies light with mean wavelength of $\lambda = 630$ nm and a half maximum bandwidth of 18 nm resulting in an illumination with a temporal coherence length of $l_c = 10\,\mu$m. The fiber diameter is $r_s = 400\,\mu$m. At the fiber tip, a lens collimator with a focal length of $f_c = 6.17$ mm is located. The tilted plate is placed at the object plane of a microscope objective of $10\times$ magnification (M) at the image plane. Hence, the propagation distance at the object plane Δz and at the image plane z are related by $z = M^2 \Delta z$. For depth discrimination, light with limited spatial coherence is required. According to the Van Cittert-Zernike theorem, the spatial coherence length of light emitted

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from a circular source is given by [6]

$$l_{coh} = 1.22\frac{\lambda f_c}{r_s}\,, \tag{1}$$

where f_c is the focal length of the fiber collimator. Utilizing the design parameters of the setup, the spatial coherence length at the object plane is found to be $11\,\mu$m. To discriminate between out-of-focus planes, the contrast of the intensities at these planes is calculated. We found, that the depth discrimination requires that the radius (r_p) of the point spread function (PSF) of the imaging system needs to be larger than the spatial coherence length

$$r_p > l_{coh}\,. \tag{2}$$

Here, the PSF radius is given by $r_p = \Delta z \cdot D/2f$. Utilizing the parameters of the setup's design and for $\Delta z = 25\,\mu$m, the radius of the PSF is $r_p = 13\,\mu$m. Since Eq.(2) is true, an intensity distribution with high contrast is ensured only for object points located across the input plane of the imaging system. Due to intensity averaging effects, the contrast decreases and eventually drops to zero for out-of-focus objects points [7] as will be experimentally demonstrated in the following section.

3 Experimental results and discussion

Figure 2 shows two examples of the captured speckle fields generated at the image plane for two different focal lengths of $F_L = 725$ and 295 mm. For form determination, a set of 21 intensity images in < 100 ms is captured with an axial step of $25\,\mu$m.

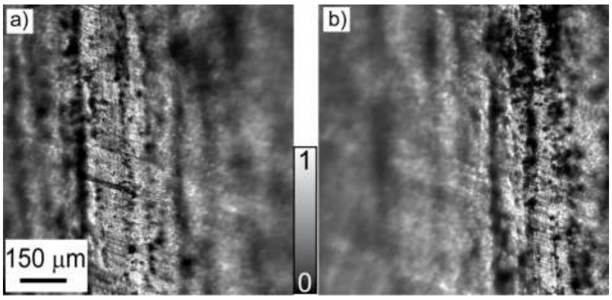

Fig. 2 *Two examples of intensity images captured for a) $F_L = 725$ mm and b) $F_L = 295$ mm.*

We use the Michelson contrast to perform depth discrimination. The 3D form and an extended depth of focus image of the tilted plate are reconstructed and shown in Fig.(3). To achieve this result, a sliding window for comparing the contrast of all captured images is utilized. The measurement is compared with a geometrical model of the tilted plate. We found that both measurements agree well with each other and have a height deviation of $7\,\mu$m.

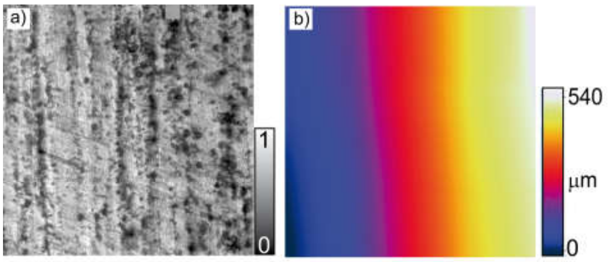

Fig. 3 *Results from speckle contrast variation: a) An extended depth of focus image calculated from the set of all captured images, and b) the reconstructed height map.*

4 Conclusions

We have shown that spatially partially coherent light, emitted from an LED can be used in $4f$-based imaging systems to investigate technical objects. The approach currently provides shape measurement with measurement uncertainty of $< 10\,\mu$m and offers an extended depth of focus of a few millimeters. The measurement time is in the range of 0.1 s. Additional benefits are a low sensitivity towards vibration, and low demands regarding eye safety.

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