Lens inspection using Multiple Aperture Shear Interferometry: Comparison to Wave Front Sensing Methods

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We present a new method for lens inspection, called Multiple Aperture Shear Interferometry (MArS) using the spatial coherence function of light as a primary measurand. MArS allows the use of several independent light sources (illumination apertures) at the same time. In this paper, we however only employ a single light source in order to enable a direct comparision to wave front sensing.

1 Introduction

For lens inspection many interferometric methods are used that post high demands on the spatial and temporal coherence of light which imposes strong restrictions on the measurement system, because the light that is reflected by the specimen has to travel through an often small entrance pupil of the imaging system. These limitations can be overcome by using the mutual intensity function as a primary measurand [1]. The main advantages are that this method allows the use of multiple independent light sources at the same time and that LEDs can be used.

Although the light of multiple independent lightsources generally can not be described by a time-independent wave field or wave front $U(\vec{r})$, one can always find a time-independent description of the mutual intensity G for a time-dependent wave field $U(\vec{r},t)$, which is just the sum of the n independent wave fields $U_n(\vec{r},t)$.

G is a statistical property of light that describes the spatial covariance of the time-dependent complex amplitude $U(\vec{r},t)$ at two positions $\vec{r}_1$ and $\vec{r}_2$

$$G(\vec{r}_1,\vec{r}_2) = \langle U^*(\vec{r}_1,t)U(\vec{r}_2,t)\rangle_T \qquad (1)$$

G can be measured using a shear interferometer which overlays a complex amplitude $U(\vec{r},t)$ with a copy of itself $U(\vec{r}+\vec{s},t)$ that is shifted by a shear $\vec{s}$. In this case the mutual intensity can be written as $G(\vec{r},\vec{r}+\vec{s})$. For multiple measurements of G at a fixed position $\vec{r}_0$ with different shears $\vec{s}$ we can reformulate the mutual intensity as a function of $\vec{s}$. Furthermore due to the light of independent lightsources being mutually incoherent, when inserting the sum $\sum_n U_n$ into Eq. 1 all terms except those of light from a lightsource interfering with itself are 0. Thus G can be formulated as [1]

$$G_{\vec{r}_0}(\vec{s}) = \sum_n U^*(\vec{r}_0)U(\vec{r}_0+\vec{s}) \qquad (2)$$

$G_{\vec{r}_0}$ now is a sum of wave fields $U_n(\vec{r}_0+\vec{s})$ around $\vec{r}_0$ which contains the correlation coefficient of every point $\vec{r}_0$ with its corresponding neighbouring points, multiplied with a constant term $U_n^*(\vec{r}_0)$. For a sufficiently small area around $\vec{r}_0$, $U_n(\vec{r}_0+\vec{s})$ can be approximated as plane waves which allows for a frequency analysis using a Fourier-transform and thus determining the dominant wave vectors $\vec{k}_{\vec{r}_0,\vec{s}}$ of the plane waves that stand orthogonally on the wave front. Decomposing $G_{\mathbf{r0}}$ into its summands is non-trivial due to the non-linear dependencies of the plane waves on the frequencies [2].

For one single light source a wave front W can be calculated through integrating the wave vectors $\vec{k}_{\vec{r}_0,\vec{s}}$ by Fourier expansion [3] using a transfer function $T(\vec{v}) = i\vec{v}$ with a Tikhonov regularisation α,

$$W(\vec{r}) = \mathcal{F}^{-1}\left\{\mathcal{F}\left(\vec{k}_{\vec{r}_0,\vec{s}}\right)\cdot\frac{T(\vec{v})}{|T(\vec{v})|^2+\alpha}\right\} \qquad (3)$$

The surface profile can be recovered using W as a starting point of a least-squares-optimization with the gradients of the measured wave front. For more than one light source the wave front may be recovered using an inverse raytracer.

2 Experimental results

We did a measurement of a cylindrical lens in reflection mode with MArS using only a single lightsource as well as a comparison measurement using a wave front sensing method (Computational Shear Interferometry, abbreviated CoSI [4]) on the same setup. The setup is a 4*f* configuration with an electronically configurable birefringend liquid crystal spatial light modulator (SLM) as the shearing element in the Fourier domain. We polarize the incident light between the birefringend axes so that half the light is modulated by a blazed grating while the other half reflects at the back of the SLM. So we have two shifted and orthogonally polarized images that in

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turn are brought to interfere, using a polarizer in front of the camera. The specimen was illuminated using parallel light. The light source was an LED with a central wavelength of λ = 636.4 nm and a coherence length of around l_c = 10 µm. The camera is an AVT Pike with 2452x2056 pixels with a pixel pitch of Δp = 3.45 µm. The magnification of the setup was 1:2.35 and we measured 15 mm times 8 mm areas of the specimen. The whole cylindrical lens is 55 mm by 8 mm and was measured in four parts with an overlap of 3 mm. There were 121 phase shifted measurements on a quadratic 11x11 grid of shears ranging from 10 to 20 Pixels on the camera which corresponds to 81 µm to 162 µm in the object plane. As a reference a mirror with λ/10 precision was used. A schematic image of this setup is given in Fig. 1.

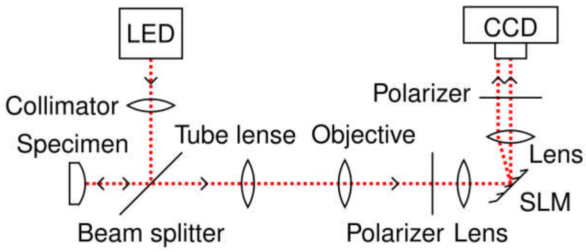

Fig. 1 *Schematic image of the shear interferometer used for our experiments.*

Using the wave front sensing method which we use as a reference point for MArS we recovered the residual with peak-to-valley values of PV_{CoSI} = 140 nm. Using our new MArS method we find peak-to-valley values of PV_{MArS} = 500 nm. In Fig. 2 we see the residual of the reconstructed lens profile subtracted by a fitted paraboloid.

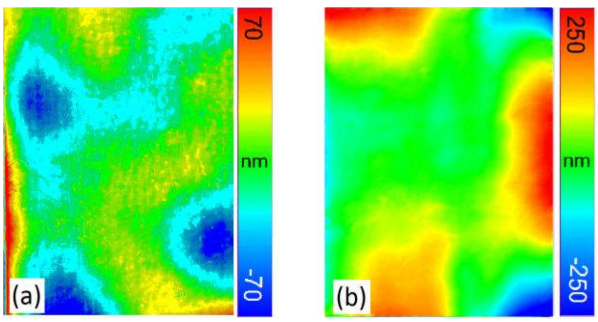

Fig. 2 (a)*: Residual of the lens reconstruction using CoSI.* ***(b)****: Residual using MArS.*

As of now MArS is still less exact than wave front sensing, though when looking at different sections of the cylindrical lens, there is a periodic signal-dependent deviation. If we subtract a mean residual of multiple sections of the specimen the remaining residual of the whole lens we find that the deviation drops to about $PV_{MArS,mean}$ = 160 nm, a similar range as in wave front sensing. In Fig. 3 we see the stitched wave front of the lens, the residual after subtracting the fitted paraboloid, as well as the remaining residual after subtracting the mean residual.

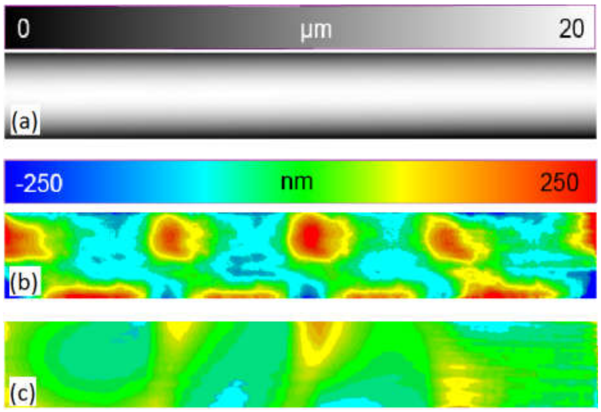

Fig. 3 (a)*: Stitched reconstruction of the whole lens made up out of four single MArS-measurements.* ***(b)****: Residual of the lens profile after subtracting a fitted paraboloid.* ***(c)****: Residual after subtracting a mean residual.*

The periodic signal-dependent deviation may be caused by a parasitic reflex of some surface along the setup. Such a reflex would effect the direction of the calculated wave vector since it might broaden the peak in the frequency domain of the mutual intensity. In conclusion the physical limit is still not reached. Nevertheless, apart from systematical deviations, MArS appears to be in a similar range of precision as wave front sensing methods.

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