Testing aspheric lenses: some new approaches with increased flexibility

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Abstract

Optical metrology delivers a unique approach for the measurement of surfaces, both technical and optical, over a wide measurement range from macro to nano. Meanwhile a broad spectrum of methods that work with coherent or incoherent light is available to cope with the additional challenges caused by the increasing complexity and quality demands of modern industrial products. As the fabrication of extremely accurate surfaces has proliferated, so too has the demand for high-precision measurement technologies. It is a common insight, that one cannot produce surfaces better than it is possible to measure. We present two new approaches for measuring aspheric lenses with increased flexibility. The first is based on a modified Twyman-Green interferometer where multiple sources for the illumination of the aspheric surface with different angles are adopted to achieve a local compensation of the gradient and consequently a reduction of interference fringes. The second is based on a chromatic Fizeau Interferometer with a diffractive element as null-optic for the measurement of EUV aspheres.

Keywords: Optical metrology, asphere testing, dynamic wavefront adaption, dynamic wavelength adaption

1. Introduction

Aspheric lenses have become synonymous with high-performance optics. In fact, many lens vendors have made their aspheric elements a prominent part of their advertising campaigns. Aspheres are increasingly being used in optical systems for all kinds of applications, with varying degrees of asphericities and accuracy requirements. In comparison classical design where only spherical surfaces are used, aspherical elements allow to generate almost any desired wavefront and allow the correction of aberrations in optical systems with increased flexibility and with fewer elements. Thus optical designers are continuously working on new design concepts but are simultaneously challenged to develop new approaches for making and measuring them. Due to the extreme freedom in their design, there is no standard technique to test them. However, especially such technologies are wanted that combine accuracy with flexibility. In that paper current developments such as mechanically free solutions based on non-standard illumination concepts are discussed. The first takes advantage of an array of coherent point sources to generate simultaneously many testing wavefronts [1-3] while the second makes use of a chromatization within a Fizeau Interferometer by using a diffractive element as null-optic for the measurement of EUV aspheres [4].

2. Testing aspheric lenses with multiple illumination sources

A common problem in interferometric testing of aspheres is the extremely high fringe density produced by aspheric elements unable to be resolved by an image sensor. This problem arises due to the high gradients of the surfaces under test which introduce a strong wavefront deviation between test and reference arm of the interferometer. Consequently, the dynamic range of the interferometer is often limited by two effects: the extremely high
interference fringe density and vignetting artifacts. There are several available techniques to overcome these limitations. State of the art is to use a null optic such as a computer generated hologram as compensation element in the test arm of the interferometer in order to reduce or fully eliminate the strong wavefront deviation caused by the surface under test [5, 6]. These elements are extremely flexible and can be used to test a wide range of aspheric and freeform elements. On the other hand, one of the main drawbacks is related to their costs and the necessary time for their fabrication. Each new type of aspheric element requires the fabrication of a new CGH. Another approach to reduce the fringe density is to move either the asphere or the optics of the interferometer [7, 8] generating evaluable interferogram subapertures of the asphere. This involves precisely controlled mechanical movements and many subsequent measurements. Further arrangements for non-null interferometry and measurement of aspheres without compensator have been proposed in [9-12].

In order to avoid the movement of the asphere, recently a solution was proposed [13] where the reference beam of the interferometer is manipulated to compensate the wavefront deviations present in the test arm of the interferometer. This interferometer with a dynamic reference beam allows for an extended measurement range but a high numerical aperture in the imaging optics of the interferometer is also required to avoid vignetting effects in case of higher asphericity. Here a new approach based on a modified Twyman-Green interferometer is presented [1, 3, 14]. The solution adopts multiple sources for the illumination of the aspheric surface with different angles, achieving in this way a local compensation of the gradient and consequently a reduction of interference fringes. During the measurement process different sources are activated while the reference beam remains fixed. This configuration makes possible to deal with strong aspheric departures avoiding at the same time vignetting artifacts and high fringe densities on the detector. The method requires no mechanical motion of the test part and has the possibility to activate multiple sources simultaneously making the measurement time extremely short compared to available techniques mentioned above.

Such a non-null test configuration increases the measurement flexibility. However, since the incidence of the test wavefront is no longer normal to the test surface, the interferometer has to be well characterized to correct errors that result from this mismatch in optical paths. Since the path followed by the test beam in general quite different from the one followed by the reference beam (no common-path configuration), we have to be able to distinguish additional aberrations from the contributions due to the surface being tested. Furthermore, due to the high gradients of the tested surfaces the fringe density increases beyond the limit that the image sensor is able to resolve and effects such as the vignetting of the wavefront must also be taken into consideration.

The interferometer is depicted in Fig. 1. The basic configuration is a Twyman-Green Interferometer with a modification in the test arm of the interferometer. A HeNe Laser source ($\lambda = 632.8$ nm) is filtered by means of a spatial filter and afterwards collimated and split into the reference (upper path) and test beam (lower path) by the beam splitter BS$_1$. A diffractive optical element (PSA- Point Source Array) consisting of a microlens array (MA) on the front side and a matching pinhole array (PA) on the backside of the element fabricated together in a monolithic package, is placed in the test path of the interferometer. This element generates a two-dimensional matrix of point sources that constitute the test beams of the interferometer. The lens L$_2$ collimates these sources, thus generating a set of wavefronts with different tilts. For an asphere that contains a spherical basic shape, it is advantageous to use an additional transmission sphere O to compensate this spherical component of the wavefront. If planar aspherical surfaces were considered (e.g. Schmidt-plate geometry) the transmission sphere would not be necessary. After reflection on the asphere, the wavefront is imaged by lens L$_3$ onto the detector C. The lens L$_1$ focuses the beam from the upper branch of the interferometer.
(reference wave) in the aperture B and generates after lens $L_3$ a plane wave that interferes with the test beam reflected from the asphere. As usual, in the Fourier plane of the imaging optics an aperture B is positioned in order to eliminate those components of the test beam which lead to irresolvable fringes (subsampling) on the detector C.

Because the technique performs the measurement violating the null-test condition, strong retrace errors contributions to the measured wavefront are expected. As previously mentioned, this implies that the calibration of the interferometer to separate the contributions of the interferometer itself and the surface to be measured is an unavoidable step of the measurement procedure. Since the complete characterization of every single element that the interferometer contains is extremely complex and time-consuming [15] (fabrication parameters, positioning, etc.), a new method has been implemented [16, 1, 14] to avoid this tedious procedure. The main idea is to characterize the aberrations of the wavefronts propagating to the test space (the volume where the test surface is positioned) and from the test space to the detector. For each source of the array we position a reference sphere in the test space of the interferometer such that the number of fringes on the detector will be minimized. For that purpose a precise air bearing translation stage made by AEROTECH is used. The measured wavefronts and sphere positions are then used in combination with the nominal design of the interferometer in an optimization process. The result is a set of parameters that describe the aberrations of the system for all possible propagation directions.
through the interferometer. Once we are able to systematically calculate the aberrations introduced by the interferometer we can also calculate the expected interferogram for a given asphere prescription. At this stage an additional optimization process takes place. Corrections for each of the parameters that describe the aspheric surface are calculated until they match the measured phase on the detector.

It is important to mention that adjacent light sources generate interferograms which correspond to adjacent areas on the asphere. Due to diffraction effects at the edge and overlapping, a pitch between the individual sub-interferograms is desired. Thus, each source generates a group of zones covering different parts of the test element. An example of such zone arrangement is depicted in Fig. 2. Figure 3 shows the sub-interferograms for the central domain of the asphere while Fig. 4 illustrates the measurement sequence.

As example a rotationally symmetric asphere with a deviation of approximately 900 µm from its best-fit sphere and 1 µm deviation from its design prescription is measured experimentally with the proposed interferometer. A source array with $15 \times 15 = 225$ sources
and a spacing of 2.5 mm between them was used. We generated each source with microlenses with a numerical aperture of 0.2 and a pinhole of size 30 µm. A JENFizar 4” f # 0.75 (NA = 0.67) transmission sphere was used to compensate for the spherical component of the wavefront, as previously explained. The detector is a 4 megapixel CCD camera with a pixel pitch of 7.4 µm.

![A](image1)

b) Cut along the line AA’ of the two-dimensional map shown in a)

Fig. 5. Experimental results.

For the calibration, we used a reference sphere with an accuracy of λ/20 and almost 90 calibration positions. The results are shown in Fig. 5. The achieved measurement accuracy is in the order of 0.13 λ P-V. Further improvement is on the way to ensure finally λ/30 P-V. The current accuracy of the system is limited by the mechanical stability of this first demonstrator setup. We crosschecked these results with measurements obtained using a computer-generated hologram calculated for the asphere. It is important to note that the optimization algorithm delivers corrections for the polynomial description of the asphere. High frequency details of the surface are not modeled by this approach. Hence, an additional step is required, in which we calculate the difference between the measured phase and the one expected from the shape of the asphere obtained from the optimization.

3. Testing aspheric surfaces with a chromatic Fizeau interferometer

In current interferometric systems the center wavelength typically is kept constant with high accuracy, or sometimes used as means to implement phase shifting or control the coherence properties. However, the wavelength can be tuned without mechanical movement in the measurement setup and the exact wavelength can be determined with a high dynamic of 10⁶. This is the idea in the presented approach: to use the wavelength for the flexibilisation of asphere metrology [17]. Here we propose a chromatic Fizeau interferometer where the static laser is replaced by a tunable coherent light source [4].

Figure 6 shows the measurement setup with a diffractive optical element (DOE) as null optic. Due to the principal similarity to standard Fizeau setups, experiences with the monochromatic Fizeau interferometer can be directly adopted. At the camera the test beam and the reference beam which is reflected from the Fizeau plane in the cavity interfere. Because this is to a large extent a common-path setup, disturbances in the cavity have the same effect on both beams and do not disturb the measurement.
The coherence length of the laser has to be long enough to span twice the radius dependent path difference between Fizeau plane and asphere. Optionally, an external cavity is needed to adjust the path differences. In this case one bit dynamic range of the camera is lost due to the incoherent background light. A titanium-sapphire laser meets the demands of high beam quality, coherence length and wavelength adjustability larger than 100 nm. In the following simulations a Sirah Matisse Titan Saphire Laser is used, which offers a tunable range of 740-880nm with the same mirror set. The idea is to measure the asphere with a set of different wavelengths. With each wavelength a different part of the asphere can be measured in a null test environment. If the asphere is radially symmetric, this means that with each wavelength another ring zone can be measured. Depending on the wavelength, the diffraction angle at the DOE and therefore the incidence angle at the asphere change. Calculations of the wavelength dependent diffraction angle, a detailed description and simulation of the measurement principle and first measurement results are presented in [4, 18].

4. Conclusion

We presented two new techniques for the testing of surfaces by optical metrology. In the first case a novel interferometer for the characterization of steep aspheric wavefronts coming from optical surfaces was introduced. Due to the inherent parallelization resulting from the use of multiple sources, the full-field measurement of a surface can be performed extremely fast in comparison to other techniques. The interferometer configuration was designed to characterize elements with up to 1000 μm SAG deviation, ± 10° slope deviation with an aimed accuracy of λ/30 P-V. The current accuracy of the system is limited to 0.13 λ due to the mechanical stability of this first demonstrator setup. The chromatic Fizeau interferometer is based on the well known monochromatic method. The profound experiences for the construction and operation of such a measurement system can be directly transferred in many aspects to this new type of measurement system. But the chromatic variant is far more flexible. In [19, 20] was shown that the measurement of at least four different aspheres is possible in one setup.

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References