INTERFEROMETRIC TESTING OF STEEP CYLINDRICAL SURFACES WITH ON-AXIS CGHS

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Abstract

We present a new approach for testing cylindrical optical surfaces using a Null-test. We suggest using a Computer Generated Hologram (CGH) in combination with a Transmission Sphere. It is shown that in such an optical layout the period of the diffractive structure is larger than in the case of a conventional scheme using a collimated beam. Therefore, this kind of hologram enables the test of cylinder surfaces with higher numerical apertures.

Keywords: diffractive optical elements, computer-generated hologram (CGH), laser writing, methods for DOE fabrication, cylinder metrology surface testing.

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Introduction

The past years has shown a significant progress in manufacturing and testing of optical surfaces with nanometer precision. The high accuracy is necessary for producing compact optical system with high resolution [1, 2]. Obviously, the inspection tools should provide a high accuracy. Interferometry is the method of choice for precise testing of optical surfaces. However, standard interferometers are covering only the test of flat or spherical surfaces. For testing surfaces with more complex shapes such as cylindrical, aspherical and freeform surfaces, more complex interferometric methods have to be used, such as scanning methods along the optical axis [3], analysis means of large number of fringes [4], lateral stitching [5] and methods based on diffractive null-correctors using Computer Generated Holograms (CGHs) [6, 7]. Although the null-testing method using CGHs provides the highest accuracy, it is sometimes economically ineffective because it requires the fabrication of individual CGHs for each specific surface under test. Thus, the mentioned methods besides CGHs are quite attractive. However, there is a peculiarity at the cylindrical surfaces testing. These surfaces are widely used in imaging systems and for line forming [8]. As a CGH converts a plane or spherical wavefront into a cylindrical one, it can be used both for concave and convex cylinders with different curvatures. Therefore, the use of CGHs for testing cylindrical optics is the "golden standard" today in optics metrology.

The principle of the well-known Null-test for cylindrical surfaces using a CGH [7] is shown in Fig. 1*a*. A plane wavefront from a Fizeau interferometer passes a wedged optical flat, called Transmission Flat (TF). By diffraction at the CGH surface, the wavefront is converted into a cylindrical wavefront to fit the surface under test. After that, it is reflected from the cylindrical surface under test, passes the CGH again and is converted back into a plane wavefront. Therefore, when the cylinder is perfect, the resulting interferogram shows a constant phase and fringes are equal to zero or are “nulled”. If the result is not Null, the surface deviation derived from the interferogram is used to further improve the quality by local polishing [9]. Common test configuration are realized with a CGH which is typically inclined relative to the optical axis by a tilt angle of approximately 1°, in order to remove unwanted reflections from higher orders of diffraction. This tilt axis leads to a pattern '1' that looks like a cylindrical Fresnel Zone Plate with an additional linear carrier frequency as shown in Fig. 1*b*. In order to verify for the correct tilt of the CGH a linear reflective grating pattern '2' is used on a ring like area surrounding the main pattern.

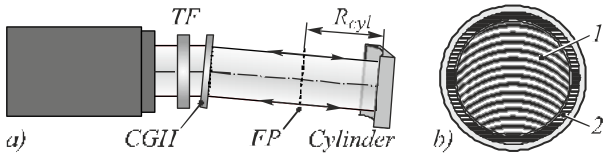

Fig. 1. Schematic diagram of a standard Null-test for cylindrical surfaces using a CGH (a). Main CGH structure '1' and grating pattern '2' for alignment (b)

This test configuration can be easily aligned, especially for cylinders with large curvature. However, in the case of steep cylindrical surfaces, the distance between CGH and cylinder will be short. In addition, it will not be possible to eliminate ghost’s reflections from higher orders of diffraction, typically appearing as a bright line in the central part of the interferogram.

If there is no tilt angle introduced to the optical axis behind the CGH, the diffractive CGH structure is just consisting by purely grating like straight lines with different grating period. In this case, a strong linelike ghost reflection exactly in the center of the interferogram is partly preventing a phase measurement of the interferogram. However, it can be fabricated by e-beam technology with high precision and short time. Therefore, in some applications it can be reasonable to use this geometry.

In this paper, we describe a new approach for testing steep cylindrical surfaces using a Transmission Sphere (TS)

(Fig. 2*a*). In this case, the CGH operates in a divergent beam and the diffractive pattern '1' shows a pattern depicted in Fig. 2*b*. In order to place the CGH precisely relative to the TS, a reflective auxiliary ring hologram '2' is used.

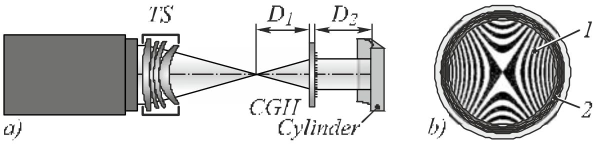

Fig. 2. Optical layout of a Null-Test for cylindrical surfaces using a TS and a CGH (a), main CGH structure '1' and ring CGH '2' for alignment (b)

This test set-up does not show any linelike ghost reflection, as the Transmission Sphere acts as a spatial filter. In order to further reduce stray light from higher orders of diffraction, it is possible to put a pinhole in the focus of the TS.

The general advantage of this set-up is that the required minimal period of diffraction of the CGH is larger than in the standard set-up. Because of the use of a TS instead of a TF, the CGH needs also to be aligned laterally in x- and y-direction, z-direction being the optical axis. However, in some cases this layout is the only possibility to test steep cylindrical surface.

1. Optical layout

Figure 3 shows a schematical raytracing model of the proposed optical layout. In the XZ-view in Fig. 3*a* the angles of incidence on the CGH change from zero in the center, to α_1 at the edge. Fig. 3*b* shows the YZ-view of the set-up, where the light behind the CGH is perfectly collimated.

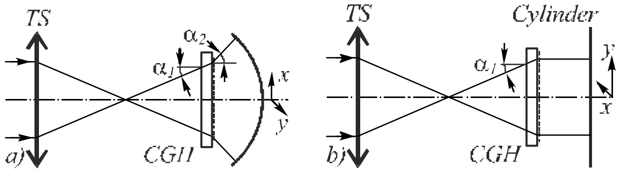

Fig. 3. Optical scheme of the cylinder Null-Test with TS and CGH. XZ-view (a) and YZ-view (b)

The minimal period Tx in the XZ-view can be calculated as:

$$T_X = \lambda/(\sin\alpha_2 - \sin\alpha_1) \quad (1)$$

with the numerical aperture of the TS lens NATS = sin(α1), the numerical aperture of the cylinder under test $NA_{Cyl} = \sin(\alpha_2)$, and λ being the wavelength of the interferometer. Along the y coordinate of the CGH the smallest period of diffraction can be calculated as:

$$T_Y = \lambda/\sin\alpha_1 \quad (2)$$

The periods of diffraction of the CGH which are at least required for realizing the proposed layout is obtained when TX and TY are balanced: TX = TY. This can be reached for the case $\sin\alpha_1 = \sin\alpha_2/2$. For this case we can calculate the smallest period of diffraction as:

$$T = 2\lambda/\sin\alpha_2 \quad (3)$$

In the case of the standard Null-test layout using a collimated beam, the smallest required period of diffraction T_0 of the CGH is defined only by the numerical aperture of the cylinder:

$$T_0 = \lambda/\sin\alpha_2 \quad (4)$$

From equations (3) and (4) we can see, that it is possible to increase the minimal required period of diffraction by a factor of ×2 by using the proposed "hybrid" layout.

In many cases there is no Transmission Sphere available which has a NA which is twice smaller than the NA of the cylindrical surface under test. In this case the diffractive pattern is not symmetrical and would be stretched in x or y direction in order to fit the available TS (Fig. 2*b*).

2. Fabrication of the Computer-Generated Hologram

To verify the proposed method, we have designed an optical layout and have calculated and manufactured a CGH for testing a cylindrical surface with concave radius r = 19.46 mm and a size of 11 × 11 mm. The phase function was calculated by raytracing according to the layout shown in Fig. 3. For generation of the convergent wavefront a Transmission Sphere with F / 3.3 was used. The distance between the focal plane of the TS and the CGH has been chosen to $D_1 = 55$ mm, and the distance between the CGH and the cylindrical surface to $D_2 = 5$ mm. The smallest period of diffraction was T = 3 μm. For the precise aligning of the CGH in the diverging beam, a ring area with an auxiliary reflective hologram was designed around the main hologram. When the CGH is perfectly aligned, the ring hologram will perfectly reflect the incident wavefront back into the interferometer and produces a constant phase in the ring area.

The CGH was fabricated using a circular laser writing system (CLWS) [10]. The system is able to process optical substrates with maximum substrate diameter up to 240 mm. During one laser lithographic writing process we have manufactured a set of four small and identical CGHs on one substrate with 60 mm in diameter [11].

The complete manufacturing process (Fig. 4) consists of these main steps:

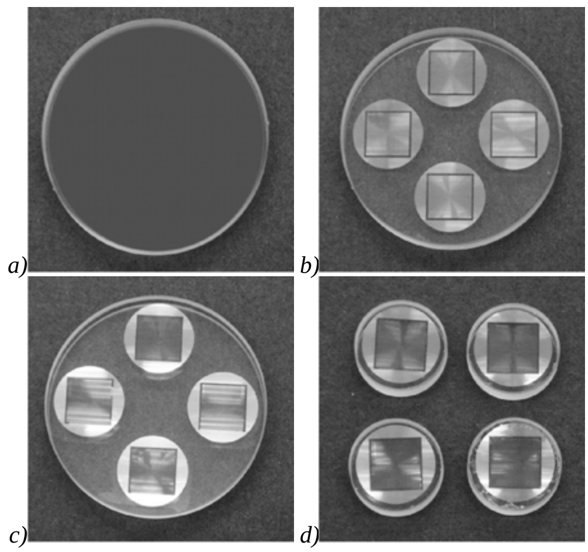

Fig. 4. Main fabrication steps of the CGH: deposition of chromium layer (a), laser writing (b), reactive ion etching (c), separating of the fabricated CGHs by drilling (d)

- Deposition of a 50 nm chromium layer by magnetron onto a 60-mm fused silica optical flat substrate with 1/20-wave PV surface quality and with a prism error below 1 arcsec.
- Lithographic patterning of the CGH into the chromium layer by direct laser writing technology [12], and wet etching of the chromium layer.
- Transferring the chromium structures into the substrate with reactive ion beam etching (Plasmalab 80+) in order to get a pure phase CGH, with subsequent removal of the residual chromium layer.
- Separation of the fabricated CGHs by drilling.
- Fig. 5*a* shows a photographic image of the final CGH. Fig. 5*b* shows a microscope image of the grating like chromium pattern with 2.5 µm spacing at the border of the CGH, which is used for aligning the tilt of the CGH. Fig. 5*c* shows a microscope image of the phase structures at the border of the main CGH with 3 µm period. Fig. 5*d* shows a 3D representation of the binary phase structure in the central part of the main CGH with a relief depth of 700 nm, using a white light interferometer.

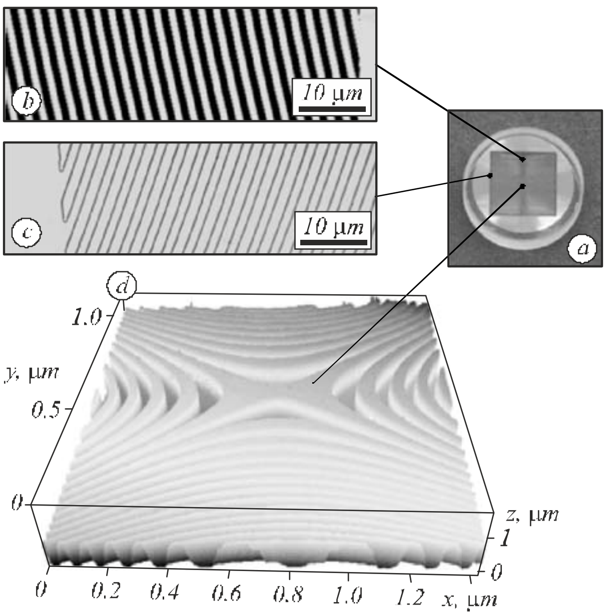

Fig. 5. Fabricated final CGH (a), amplitude pattern of the alignment area (b), phase pattern of the main area at the border (c), 3D representation of the central part of the main CGH (d)

The resulting interferograms were made on Zygo interferometer and phase maps are shown in Fig. 6. The interferogram of the on-axis amplitude alignment hologram, which operates in reflection, is shown in Fig. 6*a*. The wavefront error of this align-area is below 0.07λ (PV). Fig. 6*b, c, d* shows an interferogram, a phase map and a cross-sections (1 and 2) of a high precision cylindrical mirror. The resulting wavefront error is approximately 0.15λ (PV).

Conclusion

We have proposed a new interferometric layout for testing cylindrical surfaces using a CGH in combination with a Transmission Sphere.

The required period of the diffractive pattern is approximately two times larger in comparison to the standard layout using a collimated beam. Therefore, cylinder surfaces with larger NA can be tested.

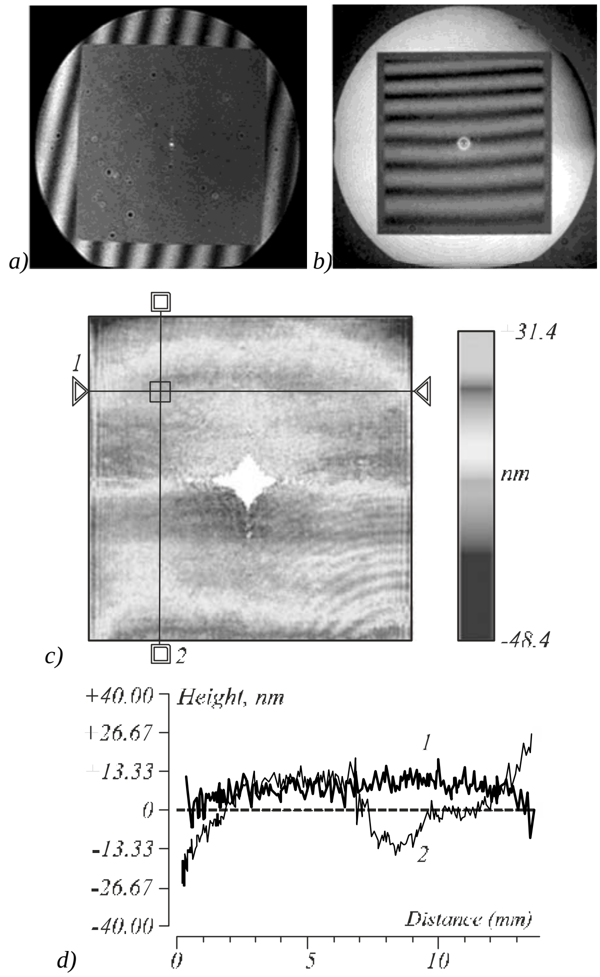

Fig. 6. Interferograms of the alignment hologram (a) and a high precision cylinder surface (b), phase map (c) and cross sections (d)

The disadvantage of this method is a more complicated optical layout and the need for additional alignment axis of the CGH. However, this layout offers the test of cylinders with higher numerical aperture at the same period of diffraction when using the standard layout.

A set of binary phase CGHs has been fabricated and experimentally tested using high precision cylindrical lenses with a f-number f/1.8. An additional Transmission Sphere with f-number f/3.3 was used. We obtained an interferogram with good contrast and without line-shape ghost reflection. The measured wavefront quality was 0.15λ (PV).

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