Using curved hologram to test large-aperture convex surface

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Abstract: A valid optical system with a computer-generated hologram fabricated on a concave lens surface, for measuring large-aperture convex surface, is demonstrated experimentally. The CGH employed in this system has been constructed using a new technology that combines laser direct writing and lithography. This technology allows precise alignment, superior linear profile and high resolution of the gratings that compose the CGH. The particular characteristics of this new type of CGH could derive higher accuracy, efficiency and lower cost for testing aspherics in comparison to other CGH employed previously by other authors. We have designed and fabricated one system and measured a 110 mm-diameter convex surface of errors 300.6 nm P-V after compensating the alignment errors. It is believed that this kind of system can be used to measure even large aperture convex surface.

OCIS codes: (090.1760) Computer holography; (120.6650) Surface measurements, figure; (220.3740) Lithography

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#4627 - $15.00 US
Received 17 June 2004; revised 6 July 2004; accepted 7 July 2004

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1. Introduction

The high performance requirements of modern optical systems have made aspheric elements including large convex surfaces in the design increasingly advantageous. However, it is difficult and expensive to measure them with high accuracy by using traditional methods. Some special conic surfaces can be tested interferometrically by using their focal characteristics in autocollimation arrangements [1]. However, this often involves the use of a too large and high-quality auxiliary mirror. One common method of testing a convex aspheric surface is to make a second optical system that converts the wavefront produced by the element under test into either a spherical or plane wavefront [2]. However, this often needs not only homogeneity of materials for the convex aspheric surface but also expensive null optics. Recent studies showed that null lenses could be replaced with computer-generated holograms (CGHs)[3-5]. Since the CGH is nothing more than a ruling pattern, its errors take the form of spatial distortion in that pattern. The magnitude of the wavefront error due to the distortion is given as the scalar product of the wavefront gradient and the vector distortion [6], leading to

$$\Delta W(x,y) = -m\lambda \frac{\varepsilon(x,y)}{s(x,y)} \tag{1}$$

where $\varepsilon(x,y)$=CGH position error in direction perpendicular to ruled fringe
$s(x,y)$=local center-to-center ruled fringe spacing
$\Delta W(x,y)$ =wavefront phase error due to pattern distortion at position (x,y) on CGH.

Conventional CGHs onto plane substrate tend to be difficult to fabricate in order to satisfy test accuracy, because they have tight fringe spacing that requires small CGH position error. A promising method proposed by J.H.Burge enhances fringe spacing validly by using a computer-generated hologram fabricated onto the spherical reference surface [7-10]. However, the CGH in this method has been constructed using thermally selective oxidization to transfer a CGH pattern onto a metallic film on a curved substrate. The resolution and linear profile of the gratings that compose the CGH are of inferior quality in comparison with that produced by use of lithography. This may decrease significantly surface measurement accuracy.

We have designed an optical test system that had two illumination lenses and a test plate with a CGH fabricated onto a spherical reference surface. The curved CGH in our system is fabricated by using a new technology that combines laser direct writing and lithography [11-14]. The particular characteristics of this new type of CGH could derive higher accuracy, efficiency and lower cost for testing aspherics in comparison to other CGH employed previously by other authors. Especially, after we changed the writing strategy and optimized the width data of the rings, the line width accuracy can be controlled to 1 um and the ring center position accuracy controlled to 0.5 um. This can improve significantly the surfaces measurement accuracy, especially for large diameter and deeply curved convex surfaces. We have tested a 110 mm diameter convex surface produced by diamond-turning with full aperture using our setup. The convex surface was measured to have errors of 300.6 nm P-V after compensating the alignment errors.

2.Measuremental principle and setup

We have designed and fabricated an optical system to test convex surface. The system had two illumination lenses and a test plate with the CGH fabricated onto a spherical reference surface. Figure 1 illustrates the schematic diagram of our system. In this setup the test plate and the illumination optics are slightly larger than the test aspheric. The test plate does not require high quality glass but a high precise concave spherical reference surface. The area of dimensions between the point source and the illumination optics is 588 mm which may be changed according to different aims when designing.

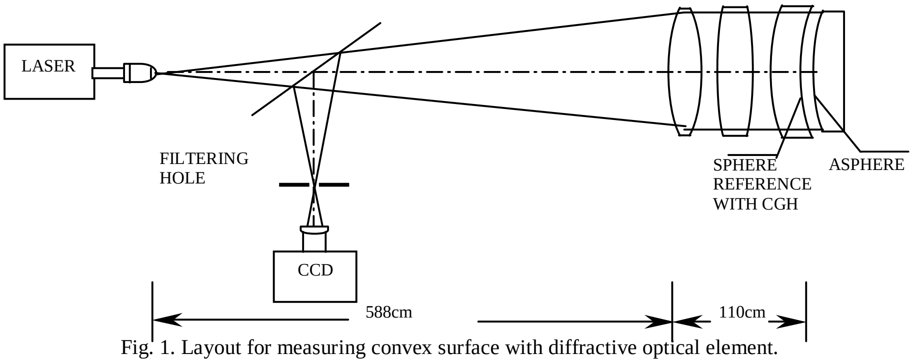

Fig. 1. Layout for measuring convex surface with diffractive optical element.

The first two lenses serve as illumination optics. The third one serves as a test plate with the CGH fabricated onto its spherical reference surface. The system is optimized at the wavelength of 632.8 nm (He-Ne laser). This test uses the interference between a reference and a test wavefront to determine the shape of the convex surface. The reference beam has an ideal convex wavefront. It originates from the 1th diffraction order of the CGH, reflects off the reference surface of the CGH, and then follows the same path as incidence, finally reaches the charge-coupled device (CCD) camera. The test beam that originates from the 0th order of the CGH has a wavefront that matches the shape of the convex surface under test. After reflecting off the test surface, it reaches the CCD by the same path as incidence. When the convex surface under test perfectly matches the wavefront prescribed by the CGH, a null fringe is observed on the CCD camera. When this is not the case, fringes result in the interferogram. The present fabrication technology is limited to a rotationally symmetric CGH, so only rotationally symmetric aspherics can be measured in this method. Here the CGH normally have many diffraction orders, thus causing disturbing areas in the interferogram. In order to filter the unwanted orders, we place a center pinhole in the filtering plane where the desired orders focus. Thus the desired orders are transmitted and contribute to the interferogram, however, the spurious orders are defocused and most of the corresponding power is stopped by the pinhole. The size of the pinhole can be decided on the filtering conditions [11]. In addition, the alignment between the reference sphere and the test aspheric surface may be difficult in the setup. We compensate the effect of the alignment errors by using Zernike polynomials [12]. Certainly, this algorithm works well assuming an aspheric surface with mainly rotational symmetric errors.

3. Fabrication of holograms

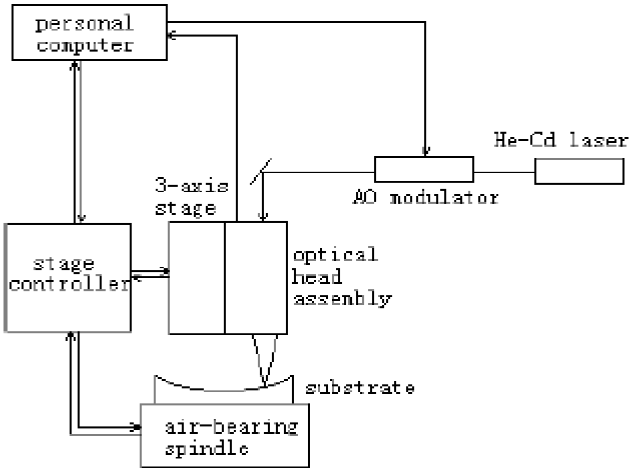

Fig. 2. Schematic of the laser writer system.

Equipment and techniques were developed at our laboratory for fabricating the large computer-generated holograms onto curved surfaces. A schematic diagram of our laser direct writing system is shown in Fig. 2. We used a 150-mW He–Cd laser at a wavelength of 442 nm. Stage (or focal spot) movement was controlled to a precision of 0.2 um in three Cartesian axes by use of feedback from distance measurements with linear encoders from Heidenhain GmbH. By optimization of the intensity data of the beam at the joint, we correct the joint error of the single pass [13]. By selecting proper spin-coating parameters and the method of double exposure, we obtained photoresist film with uniform thickness on the large concave lens surface [14-15]. By adopting the single pass and the screw-lines to fabricate this curved hologram, we saved fabrication times significantly [16]. As we know, the holograms for optical testing should have precise alignment of the gratings to ensure measurement accuracy, and proper line width to ensure high contrast interferograms. Here the ring patterns of the CGH are drawn according to

$$i^{th} \quad ring \quad defined \quad where \quad \phi_{CGH}(r)\begin{cases} \geq i\lambda - \frac{D}{2}\lambda \\ \leq i\lambda + \frac{D}{2}\lambda \end{cases} \tag{2}$$

where $\phi_{CGH}(r)$ is the phase function , r is radial position at spherical reference, and D is the duty cycle defined as the ratio of the metal ring width to the center-to-center band separation. For testing bare glass optics using chrome rulings, the optimum duty cycle D of 0.2 is picked to match the intensities of the test and reference beam, giving a high contrast interference pattern. Here the intensities of the test and reference beam are defined as follow respectively, giving the glass-chrome interface reflects 40% and the glass-air interface reflect 4% without absorbing.

$$I_{1R} = \frac{1-\cos 2\pi m(1-\frac{a}{d})}{2\pi^2 m^2}\cdot 40\% \tag{3}$$

$$I_{0T} = (\frac{a}{d})^2 \cdot 96\% \cdot 4\% \cdot 96\% \cdot (\frac{a}{d})^2 \tag{4}$$

The ring center position – halfway between the two edges – is very important for the CGH to ensure surface measurement accuracy. The line width of the rings is important to ensure high contrast interferogram. In order to fabricate the CGH with precise ring center position and proper line width, we adopt the strategy of symmetric writing one ring about the center position. For instance, to write the ring with width of 100 um and center position of 5 mm by single pass with width of 5 um, the writing process will be: firstly, precisely move the beam to the radial position of 4.955 mm; then write the width of 51 um inside by using combination of single pass and screw-lines; thirdly, precisely move the beam to the radial position of 5.045 mm; then write the width of the 51 um outside with the same strategy. In this process, we posited precisely the radial positions twice to ensure they are exactly symmetric about the center position; we adjusted the radial positions which should have been 4.950 mm and 5.050 mm according to the width of single pass to ensure proper line width; we increased the writing widths of the two times which should have been 50 um to ensure no joint error. By using this symmetric writing strategy, most error sources of the writing system can be balanced. Its accuracy is mainly determined by the stage movement precision and the asymmetry of the focal spot at the two edges of the ring. In our experiment the writer accuracy can be controlled to 0.5 um, and the width variation can be controlled to 1 um. We have certified the writer accuracy by using the method proposed in reference [17].

4. Measuring results using CGH

A curved CGH has been fabricated with about 5 hours and used to measure a convex surface. The CGH, consisting of 330 rings with spacing varying from 45 um to 800 um, was fabricated on the reference surface with 110 mm in diameter and 500 mm of radius of curvature. The convex surface under test is an elliptic mirror with 110 mm in diameter and 500 mm of vertex radius. The interferogram gotten in our optical test system is shown in Fig. 3 and the phase map is shown in Fig. 4. The errors analyzed by static fringe method are 51.26 nm rms and 356.266 nm P-V. Most of the errors are coma and spherical aberration. After compensating the alignment errors, the measured result is 300.6 nm P-V.

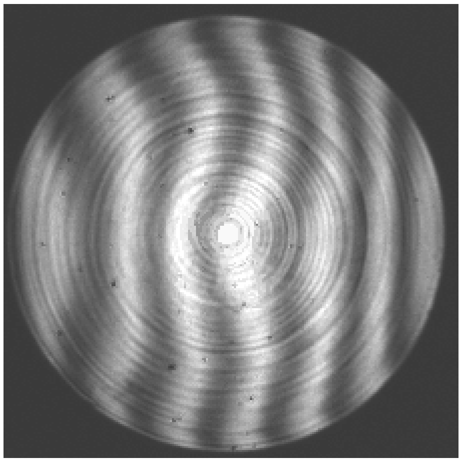

Fig. 3. Interferogram

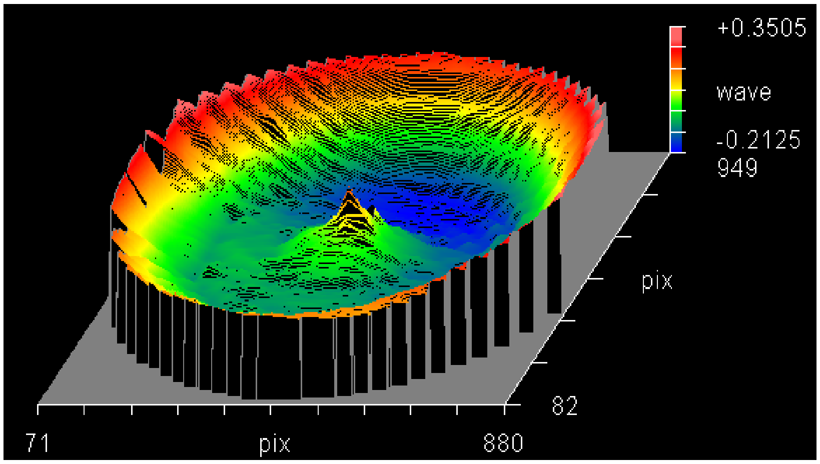

Fig. 4. Phase map of the convex surface under test

By using a pinhole of 0.3 mm in diameter at the filtering plane, the central disturbing area in the interferogram caused by unwanted diffractive orders of the CGH is about a fraction 1/20 of the whole interferogram in diameter. The size of the disturbing area may be decreased, if we adjust the phase function of the CGH and the errors of the illumination optics [8]. The scratching on the interferogram is caused by the convex surface under test fabricated by diamond-turning. It is believed that even larger convex surface can be measured with high accuracy, efficiency and low cost by using the CGH fabricated with our equipment and techniques.

5. Conclusion

We have designed and fabricated an optical system with curved computer-generated hologram to test convex surface. The CGH fabricated with our equipment and techniques -- optimization of the intensity data of the beam at the joint, selecting proper spin-coating parameters and double exposure, combining the single pass and the screw-lines, especially symmetric writing one ring -- has the advantages of precise alignment with accuracy of 0.5 um, superior linear profile and high resolution of the gratings. This type of CGH derive higher accuracy, efficiency and lower cost for testing aspherics in comparison to other CGH employed previously by other authors. We have successfully tested a convex surface with error of 300.6 nm P-V after compensating the alignment errors.

Acknowledgments

This study is supported by the National Natural Science Foundation (60078006) and State Key Laboratory of Applied Optics of the Chinese Academy of Science.

Received 17 June 2004; revised 6 July 2004; accepted 7 July 2004