Measurement accuracy verification of aspheric surface test with computer-generated hologram

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A convex aspheric surface using a computer-generated hologram (CGH) test plate fabricated with novel techniques and equipment is tested. However, the measurement result is not verified via comparison with other methods. To verify the accuracy of the measurement, a perfect sphere surface is measured by the following. The measurement result is quantified into four parts: the figure error from the tested spherical surface; the figure error from the reference spherical surface; the error from the hologram; and the adjustment error from misalignment. The measurement result, removed from the later three errors, shows agreement to 4-nm RMS with the test by Zygo interfermeter of the same surface. Analysis of the CGH test showed the overall accuracy of the 4-nm RMS, with 3.9 nm from the test plate figure, 0.5 nm from the hologram, and 0.74 nm from other sources, such as random vibration, various second order effects, and so on. Thus, the measurement accuracy using the proposed CGH could be very high. CGH can therefore be used to measure aspheric surfaces accurately.

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The use of large and deep convex aspheric surfaces in reflective optical system allows improved performance with fewer elements. However, measuring them accurately with traditional methods is difficult and expensive[1,2]. Recently, a valid method using computer-generated hologram (CGH) test plates has been studied[3−5]. In this method, the CGH is constructed using thermally selective oxidization to transfer a CGH pattern onto a metallic film on a curved substrate. However, the resolution and linear profile of the gratings that compose the CGH is of inferior quality compared with that produced by lithography. The inferior quality may decrease surface measurement accuracy significantly. The technology to transfer a large CGH pattern onto a concave lens surface with precise alignment had been reported[6−11]. The technology combines laser direct writing and lithography. A convex aspheric surface with a CGH test plate had been fabricated by this method[12]. However, the measurement error has not been analyzed, and the measurement result has not been verified by comparing with that of other methods.

In this letter, an optical test system is built to measure a perfect sphere surface with diameter of 100 mm and curvature radius of 279 mm. The system has two illumination lenses and a test plate with a CGH fabricated by transferring a large CGH pattern onto a concave lens surface with precise alignment. The errors existing in the test are analyzed, especially the performance of the CGH. The measurement result is then quantified into four parts. One is the figure error from the spherical surface under test, which can be acquired via the absolute test method using a Zygo interferometer. The second one is the figure error from the spherical reference surface, which can also be obtained with the absolute test method using a Zygo interferometer. The third part is the error from the hologram, and it can be verified by confirming the ring positions. The last one is the adjustment error from misalignment, which can be removed using the method of Zernike polynomials, fitted and measured twice[13]. The measurement result, removed from the later three errors, shows excellent agreement with the test by Zygo interferometer of the same sphere surface. This verifies that the novel method can be used to measure aspheric surfaces accurately.

Figure 1 illustrates the schematic diagram of the proposed system. Two lenses serve as parts of an illumination system. A third one serves as a test plate with a CGH fabricated onto its concave spherical surface. The system is optimized at the wavelength of 632.8 nm (He-Ne laser). The current test uses the interference between a reference and a test wavefront to determine the shape of the convex surface. The zero-order, through the CGH and reflected from the convex surface, forms the test beam to match the wavefront of the convex surface. The first order, reflected back from the CGH, forms the reference beam to match the ideal test wavefront. As a Fizeau test plate interferometer, the quality of the illumination optics and the test plate, except for the back surface, is not critical because both the reference beam and the test beam travel through them together. The back surface

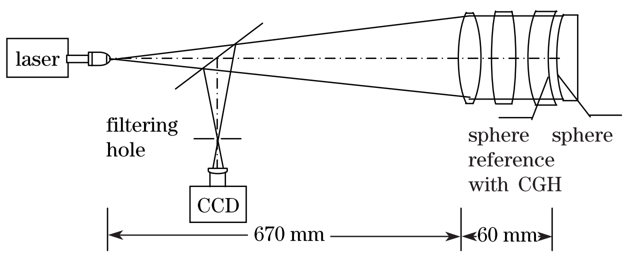

Fig. 1. Layout for measuring convex surfaces with diffractive optical element.

of the test plate is a sphere with CGH, and it should be configured accurately. The width of the rings of the CGH is designed to match the intensities of the test and reference beams as well as to yield a high contrast interference pattern. Although the described setup belongs to common path interferometer, it should be put on a vibration isolation plate, and in a room with constant temperature and humidity, in order to obtain high precision measurement results.

The optical test system is designed with software Zemax. In this system, an accurate sphere surface is used as the tested surface to analyze measurement accuracy using CGH. The parameters of the sphere are: R=279 mm and D=100 mm. To obtain a smaller central obscuration, R_{sph} is set at 300 mm and d at 10 mm, which enlarge the amount of power of the CGH.

The test and the reference wavefronts coincide everywhere in the system, except in the gap between the convex surface and the test plate[4]. Thus, the setup measures the difference in these two wavefronts shown as follows:

$$W_{\text{result}} = 2W_{\text{test-sph}} - 2W_{\text{ref-sph}} - W_{\text{CGH}} + W_{\text{adjust}}, \quad (1)$$

where W_{system} is the system error from the common path, W_{adjust} is the adjustment error from the misalignment of the tested surface, $W_{\text{ref-sph}}(x, y)$ is the figure error from the concave spherical reference surface, $W_{\text{CGH}}(x, y)$ is the error from hologram, and $W_{\text{test-sph}}(x, y)$ is the figure error from the tested convex spherical surface.

The measurement result includes four parts: the figure error from the spherical surface under test, the figure error from the reference concave spherical surface, the error from the hologram, and the adjustment error from misalignment. To obtain high measurement accuracy, the last three errors must be removed or controlled to be very small. The figure error from the concave spherical surface can be measured using the absolute test method before fabricating CGH on it; the figure error can then be subtracted from the measurement result. The adjustment error from misalignment may be removed using the method of Zernike polynomials, fitted and measured twice, for an aspheric surface[10]. The error from the hologram may be obtained by analyzing the performance of the CGH. Considering that the tested surface is spherical, the adjustment error may be too small, and thus, negligible. The measurement result includes three main parts as

$$\Delta W = \frac{1}{2}\sqrt{2\,(\Delta W_{\text{ref-sph}})^2 + (\Delta W_{\text{CGH}})^2 + 2(\Delta W_{\text{test-sph}})^2}. \quad (2)$$

The performance of a CGH may be directly related to the diffraction characteristics of a linear grating[11]. The surface relief of the linear grating is shown in Fig. 2, where a_0 and a_1 correspond to the amplitudes of the output wavefront from the peaks and valleys of the grating, respectively. The phase function ϕ represents the phase difference between light from the peaks and that from the valleys of the grating. The value of ϕ is determined by the phase shift of the reflective light at the grating interface. The duty-cycle D of the grating is defined as $D = b/s$ ($0 < D \leqslant 1$).

For linear grating with chrome rulings on glass BK7

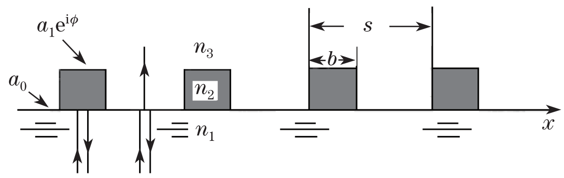

Fig. 2. Surface relief of the linear grating.

and normal incident light (the CGH used in the current test is in the same condition), the glass-chrome interface reflects about 52% of the light with a 180° phase shift, while transmitting at zero intensity. The glass-air interface reflects 4% intensity and 0° phase shift, while transmitting at about 96% intensity. These values are calculated according to Fresnel equations with n_1=1.5151, n_2=3.34+i4.31, and n_3=1 at wavelength of 632.8 nm. In the current work, only the wavefronts of the 1 reflected diffraction order and the 0 transmitted diffraction order are studied because they are used in the test. For the 1 reflected diffraction order, $a_0 = 0.04^{0.5}$, $a_1 = 0.4^{0.5}$, and $\phi = 180°$, assuming that the intensity of the incident light equals 1. The light of the 1 reflected diffraction order is expressed as

$$u_{r1}(x) = A'_{r1}\exp[\text{i}W_{r1}(x)], \quad (3)$$

where $A'_{r1} = [0.6328D^2\sin\text{c}^2(D)]^{0.5}$ and $W_{r1}(x) = \pi + \sum_{i=1}^{N}\text{i}2\pi\frac{x}{\sum_{j=1}^{i}s_j}$.

Thus, the wavefront phase error due to the grating is

$$\Delta W_{r1} = -\lambda\frac{\varepsilon}{s}, \quad (4)$$

where ε=grating position error along axis x.

For the 0 transmitted diffraction order, $a_0 = 0.96^{0.5}$, $a_1 = 0$, and $\phi = 0°$, assuming that the intensity of the incident light equals 1. The light of the 0 transmitted diffraction order is

$$u_{t0}(x) = A'_{t0}\exp[\text{i}W_{t0}(x)], \quad (5)$$

where $A'_{t0} = 0.96^{0.5}(1 - D)$ and $W_{t0}(x) = 0$.

Thus, the wavefront phase error due to the grating is $\Delta W_{t0} = 0$. (6)

According to Eqs. (4) and (6), the wavefront phase error from the CGH is only introduced into the reference wavefront. Its magnitude at position (x, y) on the CGH is

$$\Delta W_{\text{CGH}}(x, y) = -\lambda\frac{\varepsilon(x, y)}{s(x, y)}, \quad (6)$$

where $\varepsilon(x, y)$=CGH radial position errors, and (x, y)=local period.

By optimizing the writing strategy of the rings, the ring center position accuracy could be controlled to less than 0.5 μm. Thus, the maximum local wavefront phase error from the CGH is only about 0.01 λPV for the grating pattern with spacing that varies from 10 mm to 50 μm. The wavefront phase error from the CGH may be very small as to be ignored; this can be verified by a specific measurement process. To obtain a high-contrast interference pattern, the intensities of the test and reference beams should be equal. Thus, the optimum duty cycle D of 0.2 is selected.

The present study aims to obtain a grating pattern consisting of 550 rings with spacing varying from 10 mm to 50 μm. Its duty cycle is 0.2, and is fabricated on a concave surface with diameter of 105 mm and curvature radius of 300 mm. The fabrication process is divided into five parts: photoresist coating, laser exposing, developing, chrome deposing, and photoresist stringing.

After treating the plate surface, fabrication begins by spin-coating a photoresist layer onto the surface with a spreading machine. The aim is to obtain photoresistance of approximately 1 μm in thickness on a substrate that is 100 mm in diameter. The Shipley S1813 Microposit photoresist is used, and this is diluted with Shipley Type P Microposit thinner at a volume ratio of 1:4 (photoresist layer: thinner). The spin rate is maintained for 50 s, after which it is controlled to reach 2 000 rpm within 10 s.

After, UV exposure commences with a laser direct writing system. A 150 mW He-Cd laser at a wavelength of 442 nm is used. Stage movement is controlled to precisely 0.1 μm in three Cartesian axes. For writing lines ranging from 10 to 50 μm in width, four difficulties must be overcome during the process, namely, high-precision alignment between the coated lens, as well as the air-bearing spindle and the optical head; joint error of the single pass line; high fabrication efficiency; and precise locating line center position. These are ensured via selected methods[8,9,13,14]. The entire exposure process lasts about six hours.

After exposure, developing is initiated to dissolve the exposed photoresist layer. The lens is immersed into NaOH solution for 30 s. Then, the lens is flushed with deionized water for 60 s, and blown with oil-less compressed gas until the residual solution disappears. The expected grating pattern of the bare photoresist layer then remains. Figure 3 shows a micrograph of a small section of the pattern obtained by a microscope. The striations in the picture appear as straight lines; they are only a small section of whole rings on the CGH.

As the last step, pattern transfer is started, including chrome depositing and photoresist stripping. Chrome is deposited on the surface of the lens, and then the lens is immersed into a NaOH solution of 3 g/L for about 1 min to dissolve the remaining photoresist layer. A CGH with chrome grating pattern is thereby formed.

An optical test system was built to measure a perfect sphere surface with diameter of 100 mm and curvature radius of 279 mm. Before fabricating CGH, error from the concave spherical reference surface was measured with a

Fig. 3. Micrograph of a small section of the CGH.

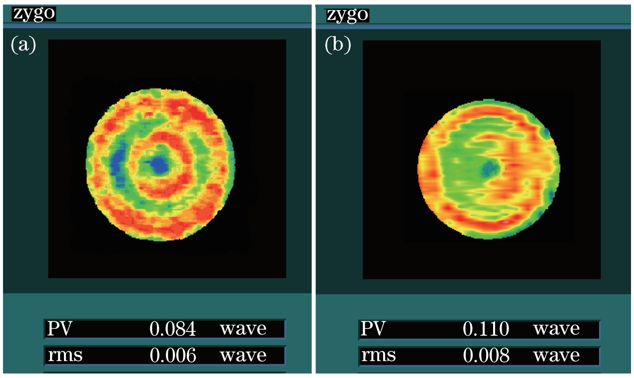

Fig. 4. Figure error of the sphere surface under test. (a) Measured with a Zygo interferometer and (b) with a CGH test plate.

Zygo interferometer using the absolute test method, and the result was 0.006 λ RMS. To test a perfect spherical surface, the CGH was designed to be fabricated onto a spherical surface so that the light diffracted into every diffractive order appears as a perfect spherical wavefront.

The accuracy of CGH was measured using a Zygo interferometer. Firstly, the first order of reflective diffraction was used to obtain a measurement result of 0.012 λ RMS. Then, the second order of reflective diffraction was used to yield a measurement result of 0.008 λ RMS. The difference between the two measurements was used to determine the error due to the CGH. Writer position errors caused mostly axisymmetric errors, which were only about 0.0028 λ RMS.

The perfect sphere surface was measured with a Zygo interferometer; the measurement result was 0.006 λ RMS, as shown in Fig. 4(a). The measurement result using CGH should be according to Eq. (2):

$$\begin{aligned}\Delta W &= \frac{1}{2}\sqrt{2\,(\Delta W_{\text{ref-sph}})^2 + (\Delta W_{\text{CGH}})^2 + 2(\Delta W_{\text{test-sph}})^2} \\ &= 0.0085\lambda\,\text{RMS}.\end{aligned}$$

The results agree with the real measurement result shown in Fig. 4(b). Thus, measurement accuracy using a CGH test plate may be very high compared with that using a Zygo interferometer.

In conclusion, the CGH fabricated in the present study has the advantages of a small radial position error of 1 μm, superior linear profile, and high resolution of the gratings. This type of CGH derives higher accuracy and efficiency as well as lower cost for testing aspherics, in comparison with CGHs employed previously by other authors. With the help of this type of CGH, a perfect sphere surface is measured, which shows agreement with 4-nm RMS of a Zygo test of the same surface. Analysis of the CGH test showed overall accuracy of the 4-nm RMS, with 3.9 nm from the test plate figure, 0.5 nm from the hologram, and 0.74 nm from other sources, such as random vibration, various second order effects, and so on. Thus, the measurement accuracy using the CGH test plate may be very high when considering the figure error from the sphere surface with CGH.

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