Design of a novel hologram for full measurement of large and deep convex aspheric surfaces

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Abstract: We proposed a valid method with a novel computer-generated hologram (CGH) to test large-aperture convex aspheric. The CGH consisted of two zones with different amounts of power: the central zone has a larger amount of power than the marginal zone. Compared with other CGHs used for convex aspheric testing [SPIE.2576.258 (1995)], it could overcome the difficulty of measuring the central region of the convex surface under test, while relaxing the requirement for the illumination optics and CGH of the test system. We have designed an optical test system with the novel CGH to test a 150 mm-diameter convex surface with full aperture by using optical design software Zemax. The simulated result verified the efficiency of the novel CGH. It is believed that this kind of CGHs can be used to measure any large and deep convex surface with full aperture.

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

Reference and links

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1. Introduction

It is well known that the use of large and deep convex aspheric surfaces in reflective optical system allows improved performance with fewer elements. However, this kind of aspheric surface is notoriously difficult to fabricate because of the cost and difficulty of making accurate measurements with traditional methods. The convex hyperbolic surfaces may be tested with the Hindle test [1] or the Silvertooth test [2] according to their special focal characteristic. However, large and high-quality auxiliary mirror is needed in these methods. The convex aspheric surface in a lens may be measured by using a null lens looking through the back surface. However, refractive index inhomogeneity limits the application of this test to small convex surface. A Fizeau test with test plates may be used to measure any convex aspheric surfaces [3]. However, a concave aspheric surface is needed to form the test plate, and the application of this method is limited. Recent studies showed that a new interferometric test can measure any convex aspheric surfaces efficiently and accurately [4-7]. This test is a hybrid of two optical measurement techniques -- Fizeau test plate interferometry and the CGH fabricated onto a spherical surface -- which simplify the fabrication of the test system. In this test, the central region untested is determined by the errors of the illumination optics and the fringe frequency of the CGH. For large-aperture convex surfaces with no or small central obscuration, perfect illumination system with small errors and perfect CGH with high fringe frequency are both needed. However, they are difficult and expensive to fabricate. In order to solve this problem, we have proposed a method in our previous paper [8]. In this method, we used a small pinhole as the filter to measure the central part of the surface under test, and used a large pinhole as the filter to measure the marginal part of the surface under test, according to the error characteristics of the illumination optics. However, this method is limited to the some special optical systems, in which the slope of the errors of the illumination optics is small in central region and large in marginal region.

In this paper, we analyze the principle of this test system and draw a valid method with a novel computer-generated hologram (CGH) to test large-aperture convex aspheric in any case. The novel CGH consists of two zones, the central zone has a larger amount of power than the marginal zone. It can be constructed using a new technology that combines laser direct writing and lithography [9-12]. One large and deep convex aspheric surface can be measured in a test system with the help of it, although the system has an illumination system with large errors and a computer-generated hologram with low fringe frequency. We have designed an optical test system with such a novel CGH to test a 150 mm-diameter convex surface with full aperture by using optical design software Zemax. The simulated result verifies the efficiency of the novel CGH. It is believed that this novel CGH can be used to measure any large and deep convex surfaces with full aperture.

2. Theory of operation

We have designed an optical system that had an illumination system and a test plate with the novel CGH fabricated onto a spherical reference surface to test large convex surface. Figure 1 illustrates the schematic diagram of this system. The first two lenses serve as illumination system, and the third lens serves as test plate. They are all slightly larger than the aspheric surface under test in aperture.

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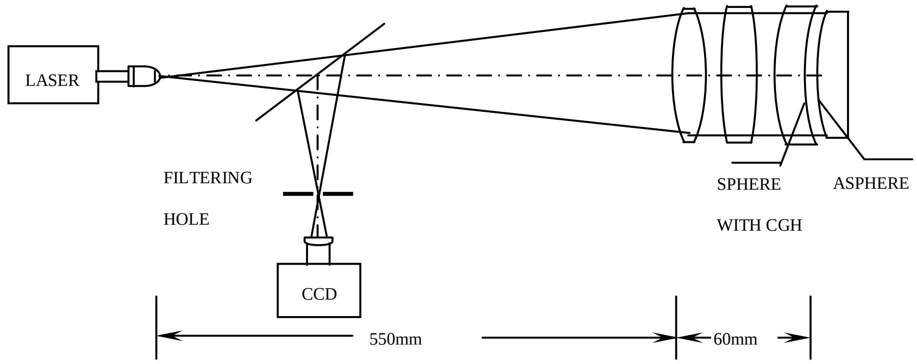

Fig. 1. Layout for measuring convex surface with diffractive optical element.

This system is optimized at the wavelength of 632.8nm (He-Ne laser). This 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. The width of the rings of CGH is picked to match the intensities of the test and reference beam, so as to give a high contrast interference pattern. As a Fizeau test plate interferometer, the quality of the illumination optics and the test plate except for its back surface is not critical because both the reference beam and the test beam travel through them together. The back surface of the test plate is a sphere with CGH and it should be figured accurately.

In this test, a filtering hole placed at the focus of the first order should be large enough not to cut both the reference beam and the test beam. The spurious orders are out of focus and aberrated, so only the central region makes it through the pinhole. This results in non-controlled area of the surface under test. We have achieved a quantitative approach to the filtering conditions by considering the height at which every order's rays hit the filtering plane [8].

$$v_c \approx \max\{v_{ill}(r)\} \tag{1}$$

$$v(r) = v_{CGH}(r) + v'_{ill}(r) \tag{2}$$

where v_c represents the cut-off frequency of the pinhole; v(r) is the wavefront slope (frequency) of the adjacent order of the desired one (0 or 2 order); $v_{ill}(r)$ represents the slope errors of the desired order caused by the illumination system; $v_{CGH}(r)$ corresponds to the space frequency of the CGH; $v'_{ill}(r)$ represents the slope errors of the adjacent order caused by the illumination system. These four variables are all as the function of the radius r of the aspheric on the filtering plane. Assuming a non-controlled area of the aspheric with radius r_1 is permitted, we must impose the following condition: "all spurious rays that would blur the interferogram outside r_1 must be stopped by the pinhole." Mathematically, this condition may be written:

$$for\, all\, r \geq r_1, \qquad |v(r)| \geq v_c \tag{3}$$

According to above analysis, two methods can be used to reduce the non-controlled area. One is to decrease the slope errors of the illumination system, so as to decrease v_c. However the perfect illumination system requires high cost and much time to fabricate. The other one is to increase the amount of power in the CGH to satisfy this condition. However, larger amount of power requires more rings with tighter spacing, which makes the hologram difficult to fabricate. In order to solve this problem, we design a novel hologram with two zones, whose central zone has a large amount of power $\phi_{p1} = a_{CGH1} r^2$ and marginal zone has a small amount of power $\phi_{p2} = a_{CGH2} r^2$, where a_1 and a_2 are constant. It can not only measure the center areas of the aspheric surface under test, but also reduce the cost of the optics required for performing this test.

For rotationally symmetric and reflective CGH, its phase function ϕ_{CGH} can be obtained with the well-known holography equation:

$$
\begin{aligned}
\phi_{CGH}(r) &= 2[\phi_{out}(r) - \phi_{in}(r)] \\
&= 2[\phi_{sph}(r) - \phi'_{asph}(r)] \\
&= 2[(a_{sph1} r^2 + a_{sph2} r^4 + a_{sph3} r^6 + \cdots) - (a'_{asph1} r^2 + a'_{asph2} r^4 + a'_{asph3} r^6 + \cdots)] \\
&= 2(a_{sph1} - a'_{asph1}) r^2 + 2(a_{sph2} - a'_{asph2}) r^4 + 2(a_{sph3} - a'_{asph3}) r^6 + \cdots
\end{aligned}
$$

$$
a_{sph1} = \frac{1}{2R_{sph}} \qquad a'_{asph1} = \frac{1}{2(1+k)R'_{asph1}} = \frac{1}{2(1+k)(R_{asph} + d)} \tag{4}
$$

So the amount of power of CGH is determined by the coefficient as follow:

$$
a_{CGH} = \frac{1}{R_{aph}} - \frac{1}{(k+1)(R_{asph} + d)} \tag{5}
$$

where R_{sph} is the radius of curvature of the sphere with CGH; R_{asph} and k are the vertex radius of curvature and the conic constant of the convex aspheric surface under test respectively. And d is the gap between the test plate and the convex aspheric.

From Eq. (5) we draw that different values of d correspond to different amounts of power in the CGH, for a definite convex aspheric to be tested with given k and R_{asph} and a definite sphere with CGH with given $R_{sph.}$ So we can follow the process to design the novel CGH. At first, calculate the cut-off frequency of the pinhole v_c according to the slope errors of the illumination system. Then set the gap d as d_1. Now the remaining degree of freedom to con troll the power of the CGH is R_{sph}. By varying R_{sph}, we optimize the power of the CGH to make the wavefront slope of the zero or first order at the edge equal v_c. By making so choice, the spacing may remain loose and constant over most of the CGH. However, this leads to very loose spacing near the center of the CGH. So the wavefront slope of the unwanted orders becomes very small, and the central region of the convex aspheric surface is difficult to test.

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In order to realize full aperture test, we reoptimize the amount of power near the central CGH by changing the gap to d_2, while remaining the value of R_{sph} gotten above. This will leads to a novel CGH that includes two parts with different amounts of power. So the convex aspheric surface has to be tested two times by using it. When measuring the marginal part of the convex aspheric surface, we use the marginal part of the CGH and set the gap between the test plate and the convex aspheric surface as d_1. When measuring the central part of the convex aspheric surface, we use the central part of the CGH and set the gap as d_2. Synthesizing two measurement results, we realize to measure the convex aspheric surface with full-aperture. Certainly, the CGH can be divided into more than two zones when a larger and deeper convex aspheric surface is to be measured, using an illumination system with larger slope errors or a CGH with a smaller amount of power.

3. Designed example

In our system shown in Fig. 1, the separation between the point source and the illumination optics is 550mm, the duty cycle (line width /spacing ratio) of the CGH is set as 0.2 by making the diffraction efficiency of the test beam and reference beam to be both 0.037, and the surface under test is a convex aspheric surface with vertex radius of curvature R_{asph}=500mm, conic constant k=1.6, and clear aperture D=150mm. The radius of non-controlled area is set as 3mm to realize full-aperture measurement [13].

Here $v_{ill}(r)$ corresponding to the slope error in illumination system is shown in Fig. 3(a). According to this figure, the cut-off frequency of the pinhole v_c is set at 1/mm. For the marginal zone, the gap d_1 is set as 10mm. The plots of the wavefront slope of the adjacent orders v(r) are shown in Fig. 3(b). The different curves correspond to different amounts of power in the CGH by changing the radius curvature of the sphere surface with CGH R_{sph}. When R_{sph}=503.35, the wavefront slope (frequency) at the edge is about 1/mm. Using this curve, the marginal zone with a small amount of power should be outside the radius 13 mm. Then change the gap in this setup to increase the power of the CGH. When d_2=27, the radius of non-controlled area is controlled to 3mm. The plot of the wavefront slope of the adjacent order v(r) inside the radius 13 mm is shown in Fig. 3(c). After deciding the parameters, the ring frequency of the whole CGH is fully defined as Fig. 4. It should be noted that the frequency of the whole hologram does not continue at the interface of two components where r equals to 13mm. Period (center to center ring spacing) is the reciprocal of frequency. It ranges from 2400 μm to 270 μm in the central zone area and ranges from 990 μm to 378 μm in the marginal zone area. The smallest period is 270 μm . Contrastively, the smallest period will be 59 μm if the CGH only consists of the same amount of power as the central one. It is evident that our hologram not only decreases areas unmeasured validly, but also ensures large fringe spacing.

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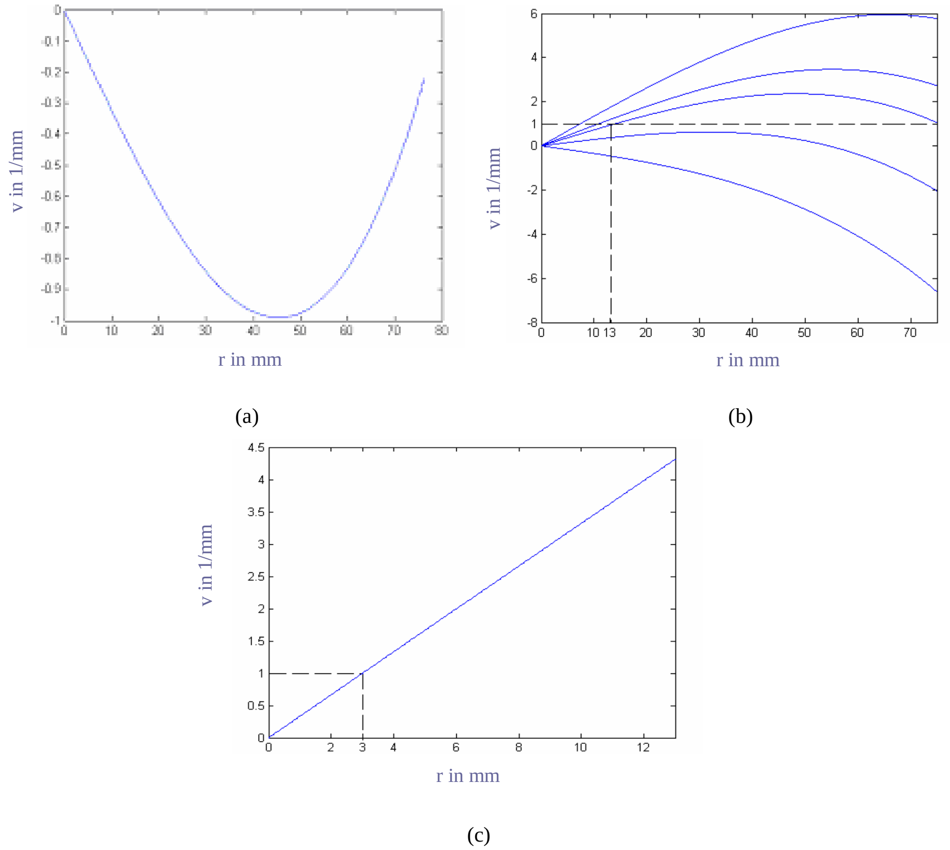

Fig. 3. (a). Slope error in illumination system (b) Wavefront slope of the adjacent order (c) Wavefront slope of the adjacent order inside the radius 13 mm.

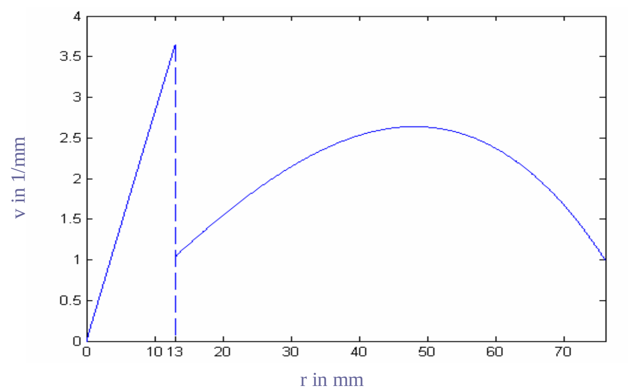

Fig. 4. Line frequency vs Aperture of the two-zone hologram.

We have simulated the test result by using Zemax and Matlab. To begin with, the central area of the convex surface is tested with the central part of the CGH, and a 0.27mm-diameter pinhole, after adjusting the gap between the test plate and the aspheric surface under test to d_2 (27mm). The interferogram gotten in this measurement is shown in Fig. 5(a). It is evident that the disturbing areas are so small as to be neglected. Then the marginal area of the convex

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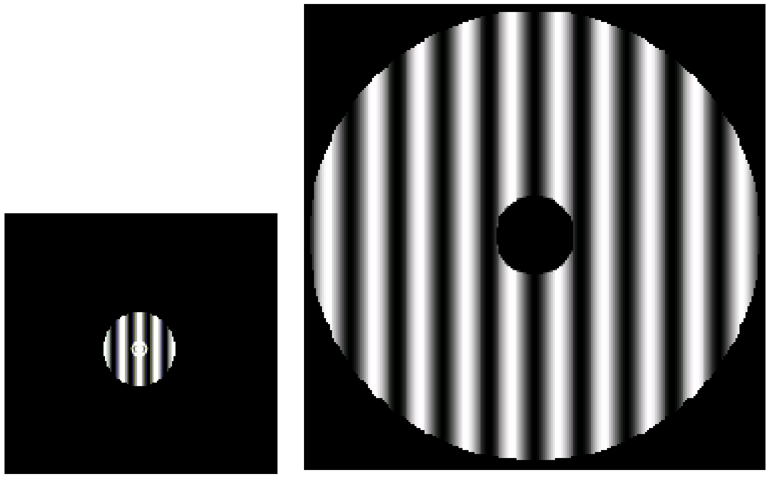
surface is tested with the marginal part of the CGH and a 0.27mm-diameter pinhole, after adjusting the gap to d_1 (10mm). At this time, the interferogram gotten is shown in Fig. 5(b).



(a) (b)

Fig. 5. Interferogram corresponding to (a) the central zone of the surface under test (b) the marginal zone of the surface under test.

4. Conclusion

We have successfully designed a novel CGH for full measurement of large and deep convex aspheric surfaces. This CGH consists of two zones with different amounts of power. With the help of it one large and deep convex aspheric surface can be measured with full aperture, in a test system with low requirements for the illumination optics and CGH. We have simulated the test process with Zemax and Matlab, and the results agree well with principle. It is believed that this method can also be used to test even larger convex surface accurately by choosing proper hologram pattern that consists of several zones with different amounts of power.

Acknowledgments

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