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Full-aperture measurement of convex surfaces in interferometric test using holographic test plates

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Abstract

We demonstrated experimentally a valid method for full-aperture measurement of large convex surfaces in the interferometric optical test using holographic test plates. The method utilizes the strategy of measuring twice with different pinhole determined by illumination system errors. We adopt this method to relax the requirements for illumination optics and computer-generated hologram of the test system when measuring large-aperture convex aspheric. We have designed and fabricated one optical test system with large errors in illumination optics and low fringe frequency in CGH, and tested a 100-mm diameter convex surface with full aperture by measuring it twice with proper pinholes. It is believed that this method can be used to relax the test system and reduce the cost significantly for even larger convex aspheric.

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Keywords: Interferometer; Computer-generated holograms; Optical testing techniques

1. Introduction

It is useful in many applications to fabricate large and deep convex aspheric for use in modern optical system. However, it is difficult and expensive to measure them with high accuracy by using traditional methods. The interferometric test, based on their focal characteristics in autocollimation arrangements such as the classical Hindle test [1], the Hindle shell [2], and the Fizeau test with aspheric test plate [3], can be used for some convex aspheric. However, these methods often require a very large, fast and accurate sphere, a high homogeneity shell or a test plate with concave aspheric surface that may be expensive and difficult to

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fabricate. One accurate method to measure convex aspheric is the interferometric null test, in which a null lens is used to compensate the aberration of the convex aspheric corresponding to some standard surface [4]. However, refractive index inhomogeneity limits the application of this method to small convex surface. Recent studies showed that null lenses could be replaced with computer-generated holograms (CGHs) [5,6], in which the CGH fabricated on plane substrate is used to compensate the aberration. However, the difficulty of production of the CGH, whose phase is a function of the wavefront gradient of the aberration, limits the test to low aspheric convex surface. A new interferometric test using spherical test plates with CGH has been developed to allow efficient and accurate testing of highly aspheric convex optics [7–10]. This test is a hybrid of two optical measurement techniques; Fizeau test plate interferometry and the fabrication of CGH onto a spherical reference surface, which simplifies the fabrication of the test system. In this test, the central region that unable to be tested is determined by two aspects: one is the pinhole corresponding to the errors in whole illumination optics, another is the separation of orders corresponding to fringe frequency of the CGH. This limits it to test those convex aspherics that have a large central obscuration. For large-aperture convex surfaces with no or small central obscuration, it requires both perfect illumination system with small errors and perfect CGH with high fringe frequency, either of which are difficult and expensive to fabricate.

We analyzed the filtering conditions in the Fourier plane of the illumination optics and draw a method of measuring twice with different pinhole. By using this method, one large-aperture convex aspheric can be measured in a test system that had the illumination optics with large errors and the computer-generated hologram with low fringe frequency. We designed an optical test system and tested a 100-mm diameter convex surface produced by diamond-turning with no obscuration successfully. It is believed that this approach can be used to measure even larger aspheric and relax the requirements for the test system with less cost.

2. Theory of operation

We have designed and fabricated an optical system to test large convex surface. The system had two illumination lenses and a test plate with the CGH fabricated onto a spherical reference surface. Fig. 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.

The first two lenses serve to illumination optics. The third one serves as a test plate with the CGH fabricated onto its spherical reference surface. The

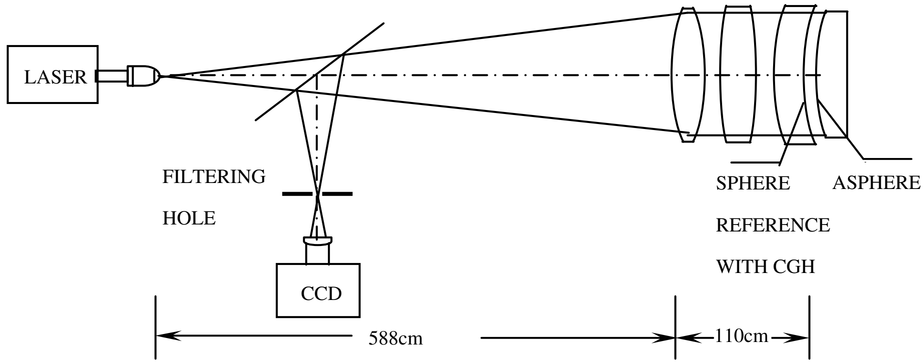

Fig. 1. Layout for measuring convex surface with diffractive optical element and Zygo interferometer.

system is optimized at the wavelength of 632.8 nm (He–Ne laser). Small difference in wavelength will introduce some sphere aberration to the system which can be balanced by changing the air gap between the test plate and the aspheric when testing. However, for large difference in wavelength, we should optimize the parameters of the system except for the radius of the reference surface and the air gap, which are used to optimize the CGH. As a Fizeau test, it is not sensitive to the misalignment of the scheme elements including shift and tilt. This test uses the interference between a reference and a test wavefront to determine the shape of the convex surface as shown in Fig. 2. In which 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, giving a high contrast interference pattern. For testing bare glass optics using chrome rulings, the optimum duty cycle (line width/spacing ratio) of CGH is 0.20582 by making the diffraction efficiency of the test beam and reference beam to be both 0.037 in our system.

In this test, a filtering hole placed at the focus of the first order should be large enough to pass 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 and results in non-controlled area of the surface under test. We may achieve a quantitative approach to the filtering conditions by considering the height at which each order's ray hits the filtering plane. To measure this height, we use frequency coordinates, as we are in the Fourier plane of the illumination lenses. The values of this coordinate happen to be also the local frequency of the hologram itself. We shall also consider this height in the filtering plane as a function of the height of this ray when reflecting on the aspheric. Then we establish the relation that links two quantities: r_1, v_c and a function $v_m(r)$ defined as follows:

- r_1 is the radius of the non-controlled area of the surface under test.
- v_c represents the lateral testing resolution as follows: the testing wavefront coming from the aspheric and crossing the hologram in the zero order contains the information about the shape of the aspheric and the errors in illumination system. The filtering hole is a low-pass filter and will suppress this information above its cut-off frequency v_c. In order to pass the testing wavefront without being truncated, the size of the filter should (be) no less than the maximum height of a ray of the zero order reflected from the aspheric on the filtering plane. The size—in frequency coordinate—is equal to its cut-off frequency v_c:

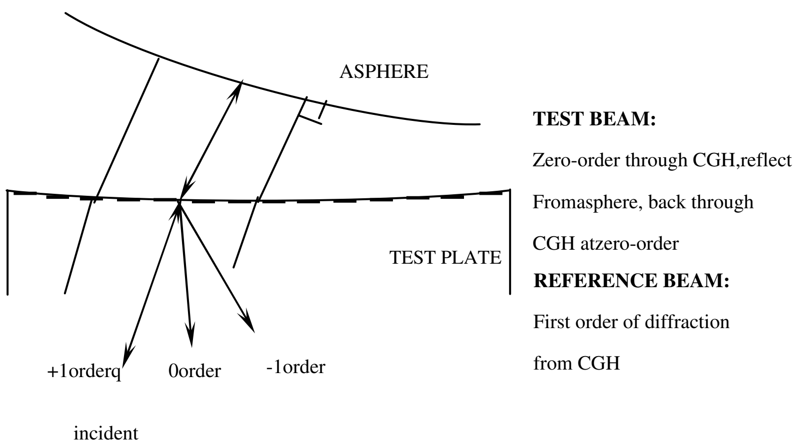

Fig. 2. Definition of reference and test wavefrons.

$$v_c = \max\{v_{ill}(r) + v_{asp}(r)\}, \quad (1)$$

where $v_{ill}(r)$ represents the height of a ray on the filtering plane as a function of the height r of the aspheric, and corresponds to the information about the errors of the illumination system; $v_{asp}(r)$ represents the height of a ray on the filtering plane as a function of the height r of the aspheric, and corresponds to the information about the shape of the aspheric. For a test system with large errors in illumination optics and a smooth surface under test, the values of $v_{asp}(r)$ is small enough to be neglected compared with $v_{ill}(r)$. So v_c can (only) be determined by the errors in illumination optics.

- $v_m(r)$ is the height of the of a ray of the spurious orders m ($m \neq 1$) on the filtering plane as a function of the radius r of the aspheric. For small air gap between the test plate and the aspheric under test, it can be defined as

$$v_m(r) = (m-1)v_{CGH}(r) + v_{ill}(r), \quad (2)$$

where $v_{CGH}(r)$ represents the height of a ray on the filtering plane as a function of the height r of the aspheric, and corresponds to the information about the CGH. The height—in frequency coordinate—is equal to the local frequency of the CGH. Since the CGH compensates the difference between the test plate and the aspheric in this method, the test plate radius of curvature can be changed and accommodated by changing $v_{CGH}(r)$. Assuming a non-controlled area of the aspheric with radius r_1 is permitted, we must impose the following condition: "all spurious ray that would blur the interferogram outside r_1 must be stopped by the pinhole". Mathematically, this condition may be written (as)

$$\text{for all } r \geqslant r_1, \quad |v_m(r)| \geqslant v_c. \quad (3)$$

The value of v_c being constant for an illumination optics with errors, we must increase power in the CGH to satisfy this condition, which may make the hologram difficult to fabricate.

In order to test a large-aperture convex aspheric with no obscuration by using such a test system that has large errors in illumination optics and low fringe frequency in CGH, we measure the aspheric twice with different pinhole. According to Eq. (3), we may choose a filtering hole whose cut-off frequency is equal to $v_m(r_1)$ as the filtering hole. Only the central region of the aspheric may be measured, because $v_m(r_1)$ is smaller than v_c, and its size may be calculated by Eq. (1). Then using another pinhole cut-off frequency that equals to v_c, we may measure the other region of the aspheric. By utilizing this approach, the requirements for the illumination optics and CGH of test system are relaxed significantly. For large aspheric, it will decrease the cost efficiently.

3. Experiment

In our optical system, the air gap is set at 10 mm, and the convex aspheric being tested is ellipsoid with a focal length (of) 500 mm and *f*/5. The radius of non-controlled area must to be limited to 2 mm to realize (the) full-aperture measurement [11]. The CGH for testing the aspheric, fabricated on the sphere reference surface of the test plate with 11*f*/50 by using a laser direct writer [12,13], requires 160 rings, with spacing varying from 4000 to 200 μm. The radius of the reference is set at 500 mm to keep the orders separated by 2 mrad. Here $v_{ill}(r)$ corresponding to the information about the errors in illumination system is shown in Fig. 3(a), in which the maximal value is 1.05 mm^{-1}; $v_m(r)$ is shown in Fig. 3(b), in which the second order has the same effect as zero order, and several other high-order diffraction effects are small enough to be negligible. According to Eq. (3), the radius of non-controlled area is 11 mm by using a filtering hole whose cut-off frequency is equal to 1.05 mm^{-1} and the corresponding interferogram is shown in Fig. 4.

Taking into the characteristic of the errors slope of our illumination optics shown in Fig. 3(a), we separated the aspheric into two parts. The rationale for the two parts is calculated as follow: In order to satisfy the condition given by Eq. (3), we should choose a pinhole with cut-off frequency of 0.2 mm^{-1}. From Figs. 3(b) and (a), we can know that the radius of the non-controlled area of the aspheric is equal to 2 mm, and the radius of the

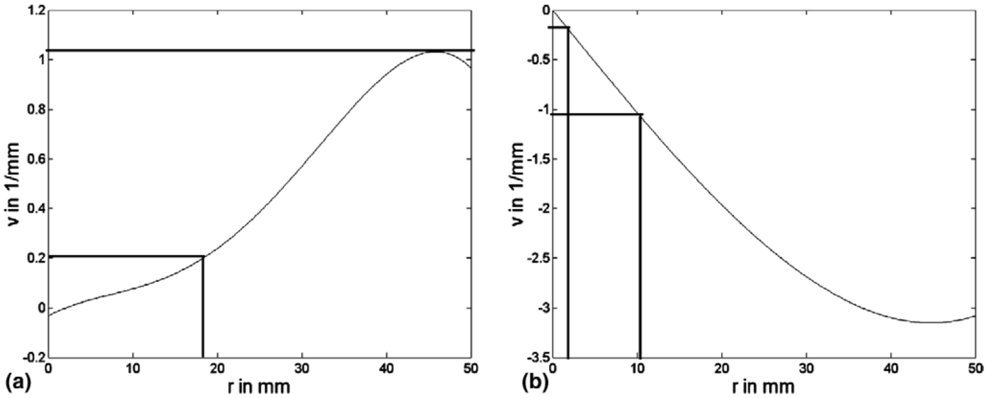

Fig. 3. (a) Slope errors of illumination optics in fringes by mm, (b) local frequency of zero-order.

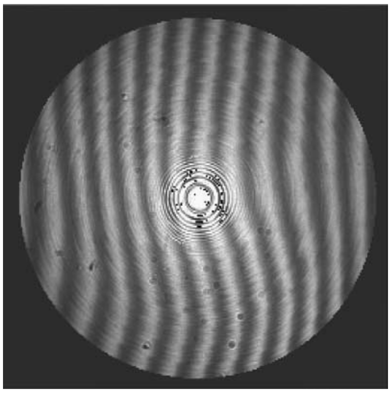

Fig. 4. Interferogram of the surface under test by using a pinhole with cut-off frequency 1.1 mm^{-1}.

area able to be measured is 18 mm if we use the pinhole as the filter. In experiment, we screen the outside of the aspheric by using optical stop. The interferogram gotten in this measurement is shown in Fig. 5(a). It is evident that the non-controlled area is small enough to be neglected. Then we measure the other area of the aspheric by using a pinhole with cut-off frequency (of) 1.05 mm^{-1}. The interferogram gotten in this measurement is shown in Fig. 5(b). If we want to full-aperture measure the surface one time with this optical system, the CGH requires 550 rings, with spacing varying from 3300 to 55 μm. If we want to measure it one time with the CGH we have fabricated, the maximum slope errors of illumination optics

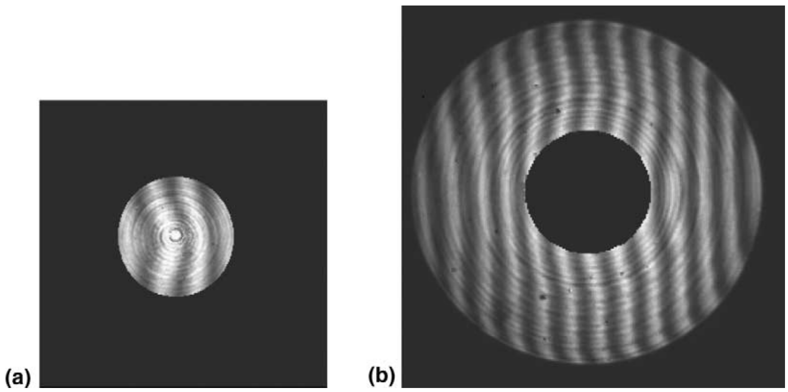

Fig. 5. Interferogram of the surface under test corresponding to (a) the central part (b) the marginal part.

should be no more than 0.2 mm^{-1}. It is obvious that the requirements for the illumination optics and the CGH are relaxed in our method.

4. Summary

We have successfully measured a convex surface by utilizing the strategy of measuring twice in the interferometric test using holographic test plate. Through calculation, we chose a pinhole with cut-off frequency of 0.2 mm^{-1} as the stop to measure the central part, and a pinhole with cut-off frequency of 1.05 mm^{-1} to measure the marginal part. As a result we are able to measure a convex surface with full aperture by using a test system with low requirements for the illumination optics and the CGH. It is obvious that this method can relax the test system and reduce cost significantly for even larger convex aspheric.

This method is limited to the optical system with an illumination optics, in which the slope of the errors is often very small in central region. However, this kind of illumination optics can be easily produced in practice.

Acknowledgements

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