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A practical method for determining the accuracy of computer-generated holograms for off-axis aspheric surfaces

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A B S T R A C T

To design a computer-generated hologram (CGH) to measure off-axis aspheric surfaces with high precision, two different design methods are introduced: ray tracing and simulation using the Zemax software program. With ray tracing, after the discrete phase distribution is computed, a B-spline is used to obtain the phase function, and surface intersection is a useful method for determining the CGH fringe positions. In Zemax, the dummy glass method is an effective method for simulating CGH tests. Furthermore, the phase function can also be obtained from the Zernike Fringe Phase. The phase distributions and CGH fringe positions obtained from the two results were compared, and the two methods were determined to be in agreement. Finally, experimental outcomes were determined using the CGH test and autocollimation. The test result (PV=0.309λ, RMS=0.044λ) is the same as that determined by autocollimation (PV=0.330λ, RMS=0.044λ). Further analysis showed that the surface shape distribution and Zernike Fringe polynomial coefficient match well, indicating that the two design methods are correct and consistent and that the CGH test can measure off-axis aspheric surfaces with high precision.

1. Introduction

Spherical and rotationally symmetric aspheric surfaces cannot satisfy the quality requirements of optical systems. However, in this respect, off-axis aspheric surfaces are a good choice. As special freeform surfaces, off-axis aspheric surfaces have extensive applications, such as three-mirror anastigmatism (TMA) [1, 2], astronomical telescopes (GMT, TMT, E-ELT, etc.) [3, 4, 5], and extreme ultraviolet (EUV) imaging [6, 7], as shown in Fig. 1. All of these systems require high-quality off-axis aspheric surfaces, and the design of these surfaces depends on the corresponding detection technology. To solve this problem, a null test using a computer-generated hologram (CGH) and an interferometer has been successfully applied to measure surfaces with high precision. CGH is a high-precision test method developed over 40 years that can modify a spherical wavefront into any desired wavefront [8].

In the design of a CGH, the phase function is necessary. The Zernike polynomial is a traditional method for rebuilding wavefronts in optical measurements that offers high precision for circular apertures and rotationally symmetric wavefront distributions [9, 10]. However, for non-rotationally symmetric wavefront distributions, the Zernike polynomial is not the best choice. B-spline functions represent a simple method for reconstructing a surface from clutter data that has also been used to obtain the phase functions of freeform surfaces. Studies have shown that the cubic B-spline has a higher fitting precision than the Zernike polynomial [11, 12]. Moreover, the cubic B-spline is only a third-order sequence convergence that is second-order continuous; therefore, it is easy and convenient to address B-spline surfaces. Hence, we used B-splines in our research.

In this study, we developed a CGH design method for off-axis aspheric surfaces via ray tracing and simulation in Zemax and compared the phase distributions and CGH fringe positions obtained from the two methods. With ray tracing, the discrete phases of the sampling points were calculated, and these phases were then fitted using a B-spline function to obtain the CGH phase function. Surface intersection was then used to compute the two-dimensional coordinates of every CGH fringe. In Zemax, after inputting the parameters into a dummy glass model, we could obtain the coefficients of the Zernike Fringe Phase through optimization such that the CGH fringe position could also be calculated. Then, we compared the positions obtained by these two different methods and analyzed the experimental results.

2. CGH design method

2.1. Principle of the CGH test

The null test is a very useful method for measuring aspheric surfaces, in which the compensator and CGH are the most familiar optical elements. Both compensate for aberration by changing a spherical wavefront into an aspheric wavefront. In contrast to the

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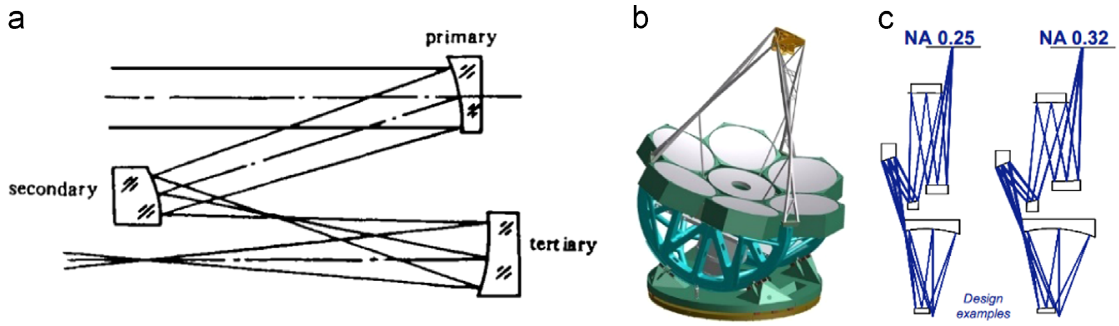

Fig. 1. Examples of systems with off-axis aspheric surfaces: (a) TMA, (b) GMT, and (c) EUV.

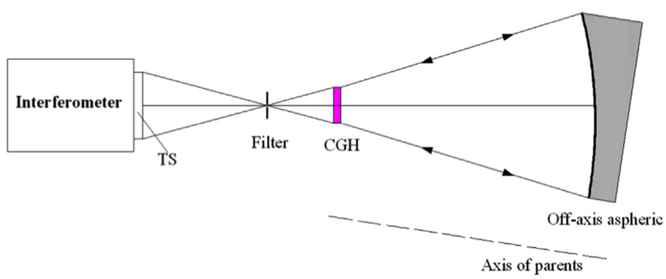

Fig. 2. Testing an off-axis aspheric surface using a CGH.

compensator, the CGH is a diffractive optical element and transforms wavefronts by diffraction. To reduce aberration and the number of CGH fringes, the CGH should shift and rotate the off-axis aspheric surface being tested and ensure that the center of the aspheric surface lies on the test optical axis and vertical to it [13]. Fig. 2 shows the optical path used to test off-axis aspheric surfaces using a CGH. Here, the filter eliminates the unwanted orders of diffraction.

The CGH design is mainly used to calculate the position coordinates of every CGH fringe on the CGH substrate. The off-axis aspheric surface under test is not rotationally symmetric; thus, its corresponding CGH is also not rotationally symmetric. Therefore, many points must be computed for every CGH fringe, and each point is a two-dimensional coordinate, which requires a large number of complex calculations. Two design methods can be used to achieve this goal: ray tracing with an intricate program and simulation in Zemax. To describe the design methods clearly, we used an off-axis paraboloid under the conditions of our laboratory. The parameters were as follows: the aperture was 50 mm, the off-axis distance was 35 mm, and the radius of the curve of the parent vertex R_0 was 573.788 mm. This off-axis paraboloid was also used in our experiment.

2.2. Designing CGH using ray tracing

The CGH test produces an aspheric wavefront that matches any desired off-axis aspheric surface being tested to measure the structure. Because of the lack of rotational symmetry of the surface, the phase of every point in the CGH fringe is different from the others. Therefore, we should calculate the discrete phases of the sampled points by ray tracing, fitting the data to obtain the phase function using the B-spline, and finally, computing the two-dimensional coordinates of the fringes in the CGH test. Ray tracing is a common method for calculating the discrete phases of sampled points. In the coordinate system, we chose OABC as the reference light beam. After obtaining the sampled points from an off-axis aspheric $P(x, y)$, the key is to calculate the coordinates of the points $E(xe, ye)$ and $D(xd, yd)$ from the sampled light beam [14].

In Fig. 3, the optical path difference between the sampling and reference light beams is easy to determine. Consequently, we can

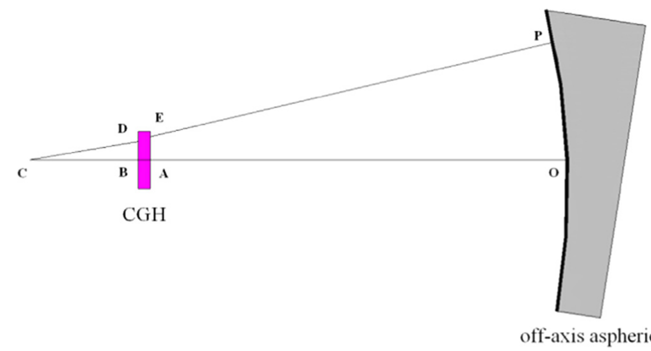

Fig. 3. Calculating the discrete phases of the sampled points on an off-axis aspheric surface.

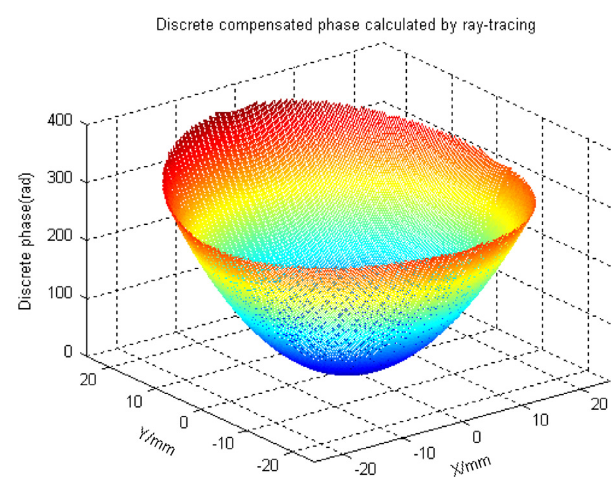

Fig. 4. The discrete compensated phase distribution calculated by ray tracing.

determine the discrete phase distribution from the optical path difference:

$$\Delta\text{Phase}(x, y) = \frac{2\pi}{\lambda}|PE(x, y) + n\cdot ED(x, y) + DC(x, y) - OA - n\cdot AB - BC| \quad (1)$$

Here, n is the refractive index of CGH and ΔPhase(x, y) is the discrete compensated phase, which is a function of sampled points $P(x, y)$. Using the parameters of the off-axis paraboloid in our experiment, ΔPhase(x, y) can be calculated, as shown in Fig. 4, which is the discrete compensated phase distribution, and the number of sampling points is 201×201.

To design the CGH, a continuous phase function is required and the discrete phase must be fitted using a proper method. B-spline represent a useful method for fitting discrete data and have been applied