Compensation Measurement Study for Aspherical Primary Mirror of Space Camera with CGH

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Abstract. With the development of modern optical technology, demands on the performance of optical systems are increasing. Aspherical surfaces are widely used in space optical system considering its excellent ability in correcting aberrations, reducing the optical system weight and simplifying the optical construction. However, the interferometry of this kind of aspherical surface is difficult. To overcome the difficulty in testing aspherical primary mirror of space camera system, we provide a compensation method to accomplish the null testing of the aspherical primary mirror with CGH (Computer generated hologram). Our proposed method is introduced in detail in the theory part. In addition, we provide a detailed design for an actual parabolic surface. The results show that our proposed method can accomplish the testing of aspherical primary mirror in large aperture with satisfactory accuracy.

1. Introduction
Interferometry is the mostly often used method in the optical mirror surface testing. For interferometers, it generally emits a stand plane or spherical wavefront and measures the relative wavefront deviation from planar or spherical wavefronts. When testing a plane surface or a spherical surface, it can be applied directly. However, when testing an aspherical surface or freeform surfaces, a null lens must be adopted to generate a relative wavefront which matches the test surface exactly.

For the null lens method, many researchers have made in-depth studies on this issue and many kinds of null lens such as Doll null lens and Offner null lens are designed [1-4]. Besides null lens, CGH (Computer generated hologram) can also be used to generate a desired wavefront matching the testing aspherical mirror surface exactly. For the CGH, it is a kind of diffractive optical element which is capable of producing wavefront in desired shape. With the developing of the micro-lithographic technology, the CGH can be produced with satisfactory precision and accuracy [5-9]. Many scholars have also made a lot of studies in this kind of testing method [10-14]. For example, Talha used CGH to test aspherical surfaces and the PV of relative wavefront aberration for the first diffraction order is less than 0.0479λ [15]. Li applied the CGH to testing of an off-axis aspherical surface and obtained good results [16].

In this paper, we focus on the CGH testing technique for aspherical primary mirror surface of space camera, including the design methods of aspherical surface and analysis of design results. This paper is organized as follows. In section 2, the basic theory of CGH compensation measurement is introduced. In section 3, we apply our proposed method to an actual aspherical primary mirror of space camera and analysed the design results. The relative conclusion is given in section 4.
2. Theory

For the CGH, it can be treated as a collection of linear gratings with variable spatial frequencies. By adjusting the spatial frequency of relative linear gratings on the CGH, the wavefront of incident light can be transformed to an aspherical wavefront in a desired form.

To simplify the model, we take a linear grating as an example. Considering a binary grating model as shown in Fig.1, the period of the linear grating is \( D \) and the width of the etched area in the grating is \( qD \). \( T_1 \) is the amplitude of the output wavefront from the unetched area of the grating, while \( T_0 \) is the amplitude of the output wavefront from the etched area of the grating. \( \Psi \) is the phase function which represents the phase difference between the peak and valley of the linear grating.

Considering the wavelength of the incident light is much smaller than the period of the linear grating \( D \), for a planar wavefront which comes into the grating at normal incidence, the amplitude of the output wavefront can be described as:

\[
u(x) = T_0 + (T_1 e^{i\Psi} - T_0) \text{rect}(\frac{x}{qD}) \cdot \frac{1}{D} \text{comb}(\frac{x}{D})
\]  

(1)

According to the Fraunhofer diffraction theory, the far-field wavefront function of a planar wavefront which comes into the grating at normal incidence can be expressed as:

\[
U(\xi) = \left\{ T_0 \delta(\xi) + \left[ T_1 \cos(\Psi) - T_0 \right] \cdot q \cdot \sin c(qD\xi) \cdot \sum_{m=-\infty}^{\infty} \delta(\xi - \frac{m}{D}) \right\} + i \left\{ T_1 \sin(\Psi) \cdot q \cdot \sin c(qD\xi) \cdot \sum_{m=-\infty}^{\infty} \delta(\xi - \frac{m}{D}) \right\}
\]

(2)

where \( m \) is the diffraction order, the \( \xi \) represents the spatial frequency.

For the one order,

\[
U(\xi) = \begin{cases} 
T_0 + \left[ T_1 \cos(\Psi) - T_0 \right] \cdot q + i \left[ T_1 \sin(\Psi) \cdot q \right] & m = 0 \\
\{ T_1 \cos(\Psi) - T_0 \} \cdot q \cdot \sin c(qm) + i \{ T_1 \sin(\Psi) \cdot q \cdot \sin c(qm) \} & m \neq 0 
\end{cases}
\]

(3)

As CGH is designed with variable fringe spacing, the design concept of the CGH relative to testing aspherical surface can be shown in Fig.2.

Figure 1. Linear grating model of CGH

Figure 2. Phase function calculation model of CGH.

For the aspherical surface testing, the output wavefront is exactly the same with the aspherical equation, which can be used to guide the designing of CGH.
As shown in Fig. 2, \( KA \) is a ray of light passes through any point of the CGH and it is also in the normal direction of the point \( A \) in the aspherical surface. Then the phase of point \( K \) can be expressed as the difference between reference light \( K_0A_0 \) and light \( KA \) as follows:

\[
\phi(x, y) = \phi(K) = \frac{2\pi}{\lambda} (\text{opl}[K_0A_0] - \text{opl}[KA])
\]

(4)

where \( \lambda \) represents the wavelength of incident light and \( \text{opl}[\bullet] \) represents the optical path of the corresponding rays. Considering that the phase function of the incident rays used to reconstruct the wavefront on the CGH plane is:

\[
\phi(x, y) = \phi(K) = \frac{2\pi}{\lambda} (\text{opl}[JK] - \text{opl}[JK_0])
\]

(5)

Then the phase function that the CGH needs to encode can be expressed as:

\[
\psi(x, y) = \phi(x, y) - \varphi(x, y)
\]

\[
= \frac{2\pi}{\lambda} (\text{opl}[K_0A_0] - \text{opl}[KA]) - \frac{2\pi}{\lambda} (\text{opl}[JK] - \text{opl}[JK_0])
\]

(6)

The diffraction pattern design can be accomplished according to the above mathematical model.

3. CGH design of a parabolic mirror

In this part, combined with an actual engineering example, we designed a CGH for an aspherical primary mirror of space camera. The primary mirror is a parabolic surface. The clear aperture of it is 865mm and the vertex radius of curvature \( R \) is 2638.4mm.

The departure between the parabolic mirror and its best-fit sphere is shown in Fig.3.

![Wavefront Function](image)

Figure 3. Departure of parabolic mirror.

It can be seen from Fig.3 that the PV (peak-to-valley) and RMS (Root mean square) of the departure is 101.4064\( \lambda \) and 29.8213\( \lambda \) respectively, where \( \lambda \) is 632.8nm.

According to our proposed model described in section.2, the optical path for CGH testing can be described as shown in Fig.4.
In the above optical path, the basic parameters are as follows:

- The carrier frequency of interferometer focus: \((x,y) = (0,-5)\);
- The distance between the interferometer focus and CGH: \(L_{FC} = 150\) mm;
- CGH substrate thickness: \(T_c = 8\) mm;
- The distance between CGH to the parabolic mirror: \(L_{CM} = 2500\) mm;
- Aperture of CGH: \(D = 80\) mm;
- F number of standard lens in the interferometer: \(F\# = 1.5\);

The residual map of the testing area is shown in Fig. 5.

It can be seen from Fig. 5 that the PV and RMS of the residual map is \(0.0002\lambda\) and 0 respectively, which means the parabolic mirror can be tested in null with CGH in satisfactory accuracy.

In the designing of CGH, each diffraction order should also be separated from each other, which avoids the extra interference in the aspherical surface testing. The separation of diffraction orders for our parabolic mirror is shown in Fig. 6.
It can be seen from Fig.6 that each diffraction order is separated from the testing diffraction order very well.

To accomplish the alignment between CGH and testing interferometer, we also designed the special alignment area on CGH. The relative alignment optical path is shown in Fig.7 and the residual map of the alignment area is shown in Fig.8.

In actual testing, considering the interferometer can be aligned with CGH accurately, each diffraction order is separated from the testing diffraction order and the residual map of the testing area
is negligible, the parabolic mirror surface can be tested with our proposed method with satisfactory accuracy.

4. Conclusion
We have provided a CGH design method to accomplish the null testing of aspherical primary mirror of space camera. To evaluate the designing accuracy of our proposed method, an actual engineering example (parabolic mirror surface) is taken as a design goal. Combined with our design method and considering actual designing demands such as the accurate alignment between interferometer and CGH, the separation of diffraction orders, the design residual is negligible and the design result is satisfactory. As the design analysis is now only for aspherical surfaces, further theoretical and experimental studies for freeform surfaces will be taken.

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