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An improved phase retrieval algorithm for optical aspheric surface measurement

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ABSTRACT

In order to overcome the measurement and calculation difficulty for aspheric surface with phase retrieval technology, an improved phase retrieval algorithm was proposed. Due to significant departure from sphere surface, reflected light from different part of the aspheric surface under test will overlap in some areas in the collected images by CCD with general phase retrieval measurement setup, which will lead to the failure to recover the surface phase. The proposed algorithm will only use those areas without light overlapping in each image in the iteration process and employ several defocused images to recover the whole surface. This algorithm can improve the measurement range for aspheric surface with phase retrieval technology. The experimental system was established and a 180 mm diameter, f/1.6 parabolic mirror and a 180 mm effective diameter, f/1.33 hyperboloid mirror were tested by the proposed method. The experimental results show that the retrieved surface errors are in good consistent with that obtained by interferometer, which confirms the validity of the proposed algorithm.

1. Introduction

Phase retrieval is a wave front sensing method that uses a series of intensity measurements to reconstruct wave front [1]. Due to its outstanding performance such as simple optical arrangement, comparatively high accuracy, insensitive to vibration [2], phase retrieval technology has been applied successfully in many fields such as electron microscopy, wave front sensing, astronomy, X-ray crystallography, etc. As an optics metrology tool, phase retrieval was first employed in the application of surface testing for large aperture mirrors owing to their special working conditions unsuitable for the use of interferometer, such as aberrations measurement for the Hubble Space Telescope [3], segments testing and alignment for the James Webb Space Telescope [4,5], and ground based astronomical telescopes testing [6]. Recently, phase retrieval has been received more and more research attentions to make it become a general optical metrology tool for ordinary optical components [7]. Usually phase retrieval method will utilize a point source or a standard spherical wavefront to illuminate the testing optics, therefore this method can be directly applied to spherical mirror testing with special developed iterative algorithms such as GS iterative algorithm[8], gradient search algorithm [9], input–output algorithm[1], hybrid diversity algorithm [4]. So far some research works have been conducted by Fienup group to test general spherical optics with phase retrieval technology [2,7,10]. However, for aspheric optics, especially for small f number aspheric optics, which have many advantages over spherical optics and are widely used in a lot of fields, few documents are found to address the measurement problem with phase retrieval method. In conventional interferometric testing for aspheric optics, usually specially designed auxiliary optic components (null components) are involved to compensate the aspheric aberration [11]. However, those auxiliary optical components are difficult to manufacture for their high accuracy requirements, which make aspheric optics surface measurement still to be a difficult task at present. And vibrations degrade the accuracy of interferometry. Theoretically, phase retrieval is capable of measuring aspheric surface with very simple optical arrangement and inherently tolerant of vibration effects; however, in practice, duo to significant departure from spherical surface, the collected intensity image may be too complicated to recover the phase information, and research works for this issue is very limited. In this paper, an improved approach based on GS iterative algorithm for phase retrieval technology is proposed to measure the aspheric mirror's surface without any auxiliary optical elements. This approach uses high precision spherical wave to illuminate the test mirror and a CCD camera to capture the reflective beam from the test mirror. In the proposed algorithm, several images were used, and for each image, only parts of the data which are called valid data are employed to retrieve the aspheric wave front from the test surface. This approach can improve the measurement range of phase retrieval and makes it possible to measure aspheric optics. This paper is organized as follows: firstly Section 2 introduces the basic measurement principle with phase retrieval and GS iterative algorithm; Section 3 describes the general implementation of phase retrieval and difficulties for aspheric optics testing. In Section 4, we

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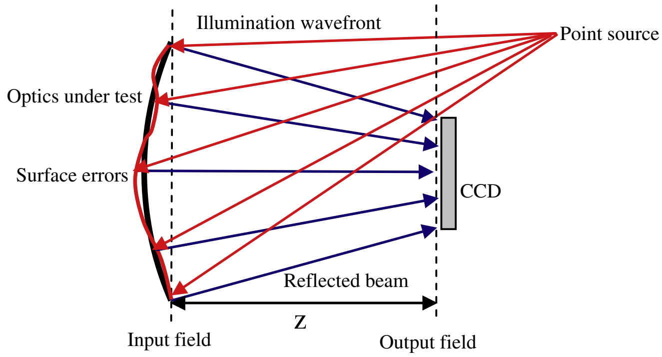

Fig. 1. Schematic of phase retrieval technology for optics testing.

will present the improved algorithm for aspheric optics testing with phase retrieval. Section 5 gives experimental results, the surface of a 180 mm diameter, f/1.6 parabolic mirror and a 180 mm effective diameter, f/1.33 hyperboloid mirror were measured by the proposed method; discussion for this algorithm is given in Section 6. Finally, Section 7 draws conclusions of this paper.

2. Basic principle and algorithm of phase retrieval

Phase retrieval technology uses intensity measurements to recover phase information of test surfaces; the basic theory employed in this approach is diffraction propagation theory, such as Fraunhofer, Fresnel transforms or angular spectrum approach. The measurement principle is illustrated in Fig. 1.

The optics under test is illuminated by a known wavefront such as spherical wavefront, and the phase of the reflected beam will be modulated by surface errors. For a concave surface, the reflected beam will converge to the focus and collected by a bare CCD placed near the focus to acquire the intensity image. According to the diffraction theory, the relationship between the complex fields of pupil plane and image plane is a Fourier transform; hence the first step for phase retrieval technology is modeling the diffraction propagation between the input field and output field depicted in Fig. 1 using Fresnel transforms or angular spectrum approach. If the wavefront field at the surface under test is denoted as $g_m(x, y)$ and the wavefront field at the defocus plane is denoted as$g_d(x, y)$, then according to Fresnel diffraction theory, the propagation from $g_m(x, y)$ to $g_d(x, y)$ can be described by Eqs. (1)–(3) [12].

$$F_m\left(v_x, v_y\right) = \iint g_m(x, y)\, exp\left(-j2\pi v_x x - j2\pi v_y y\right) dxdy \qquad (1)$$

$$F_d\left(v_x, v_y\right) = F_m\left(v_x, v_y\right) exp\left[-j\pi\lambda\left(v_x^2 + v_y^2\right)z\right] e^{jkz} \qquad (2)$$

$$g_d(x, y, z) = \iint F_d\left(v_x, v_y\right) exp\left(j2\pi v_x x + j2\pi v_y y\right) dv_x dv_y \qquad (3)$$

where $F_m(v_x, v_y)$ is the frequency domain of $g_m(x, y)$; $F_d(v_x, v_y)$ is the frequency domain of $g_d(x, y)$; z is the propagation distance.

With the above propagation model, in order to reconstruct the phase information or equivalently surface errors, a certain phase retrieval algorithm is needed. The most well known iterative algorithm is GS algorithm and its retrieval process is shown in Fig. 2.

The algorithm starts from a random or zero phase and computes iteratively Fourier transform (FT) and inverse Fourier transform (iFT) between pupil plane and image plane. During iterations, uniform amplitude is applied to the pupil plane as pupil constraints, and CCD captured image data are applied to image plane as intensity constraints. If the difference between estimated image plane and real image plane is small enough, then the iteration will stop and the computed phase of complex field for the pupil plane at this time is used as the final output. The GS algorithm is simple and effective, since it was proposed in 1970s, GS algorithm and its modified versions have been applied in many fields successfully.

3. Aspheric surface measurement with phase retrieval

A practical measurement setup for phase retrieval is shown in Fig. 3.

The testing surface is illuminated by a point source or spherical wavefront and the reflected light is collected by a CCD camera through a beam splitter. The CCD is usually placed at the position near the focus plane and several images are collected at different defocused planes. Then those images are used as the input for the phase retrieval algorithm to reconstruct surface errors.

For an ideal spherical surface, if the point source is placed at the center of the sphere, then reflected light will converge to a point at the focus plane, as shown in Fig. 4. Therefore, even intensity distribution image will be obtained at defocus planes. However, for an aspheric surface, for example parabolic surface, the center of curvature for the surface is not unique as sphere. If the point source is placed at the center of the vertex curvature, then reflected light will converge to the caustic region, not to a point, as shown in Fig. 5a. Rays reflected from different areas overlap in the caustic region, which makes the intensity distribution of focus images very complex. Defocused images near the caustic region also have complicated intensity pattern. The intensity patterns representing asphericity are obvious, but those representing surface errors are faint. And owing to great departure from the best fit spherical surface, the outer part or the inner part of the defocused images may be so bright as to saturate the CCD pixels, shown in Fig. 5b and c. Generally, the high dynamic range image with saturation pixels is not suitable for phase retrieval. Because there is no intensity change in saturated area, that will bring in incorrect restriction for phase retrieval algorithm. Therefore, aspheric surfaces testing with phase retrieval is still a difficult task, especially for small f

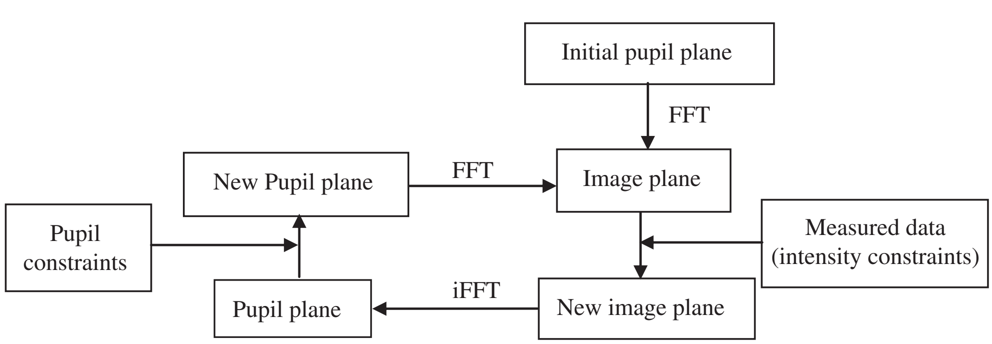

Fig. 2. Block diagram of GS algorithm.