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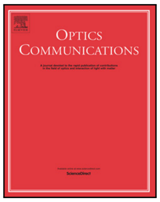

Experimental study on subaperture stitching testing of convex hyperboloid surface

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ABSTRACT

We propose a non-null subaperture stitching method to measure the convex aspheric surfaces. In the method, the non-null configuration avoids the introduction of auxiliary optical elements which must be specially designed and customized, and their compensating effects cannot be independently measured. In order to obtain the full aperture result, a non-null stitching algorithm based on ray tracing method and least square method is developed to stitch all phase data together. Both simulation and experimental results justify the proposed method.

1. Introduction

Aspheric optical surface has broad applications for its capability in correcting aberrations, improving image quality and reducing the size and weight of the system [1]. Precise and efficient measurement of aspheric optical surface is necessary. Among different surface characterization techniques, interferometry is playing a more and more important role. In interferometry, null testing using null lens or computer-generated hologram (CGH) is an efficient test configuration for small-aperture optical surfaces [2–7]. However, for testing large-aperture optics, especially convex aspheric surfaces, the null testing to the aspheric surface is hard because it is difficult and time consuming to manufacture required large aperture auxiliary elements such as null lens or computer-generated hologram. Instead, the sub-aperture stitching (SAS) testing and the non-null testing can be combined to accomplish the interferometry of the convex aspheric surfaces.

SAS testing has been developed to overcome the aperture size limitations of interferometers. It can obtain the full aperture map without testing the whole mirror at one time, thus it is widely used in measuring large flat mirrors, large convex surfaces and aspheric surfaces exceeding the vertical range of the interferometer. The SAS testing method was first proposed by Kim in 1982, and significantly expanded the dynamic range of an interferometer [8]. According to the testing region shape of the subaperture, there are two major stitching methods: one is the annular stitching method which is widely used in the stitching testing for concave rotational symmetric aspheric surfaces [9–12], and the other one is the circular stitching method which has better generality and expandability [13,14].

In this paper, we propose a simple, efficient non-null stitching technique with circular subapertures to test convex aspheric surfaces. With the proposed method, we characterized a ϕ 260 mm convex hyperboloid surface. The stitching accuracy can be evaluated by the simulation and the experimental results. The paper is organized as follows. In Section 2, the basic theory of the stitching technique involving the retrace error calculation and the stitching algorithm is introduced. In Section 3, the effectiveness of our method is shown in simulation. In Section 4, we demonstrate the technique by testing a ϕ 260 mm convex hyperboloid surface. Finally, the conclusion is given in Section 5.

2. Theory

2.1. The principle of the retrace error correction

The retrace error in the non-null testing can be calculated with ray tracing method. Unlike the null testing, the testing rays in the non-null testing follow different paths from the reference rays. The resulting extra aberration between the measured and the real surface maps is the retrace error. The retrace error should be corrected before stitching as it is not manufactory surface error but an artificial extra aberration due to the non-null testing.

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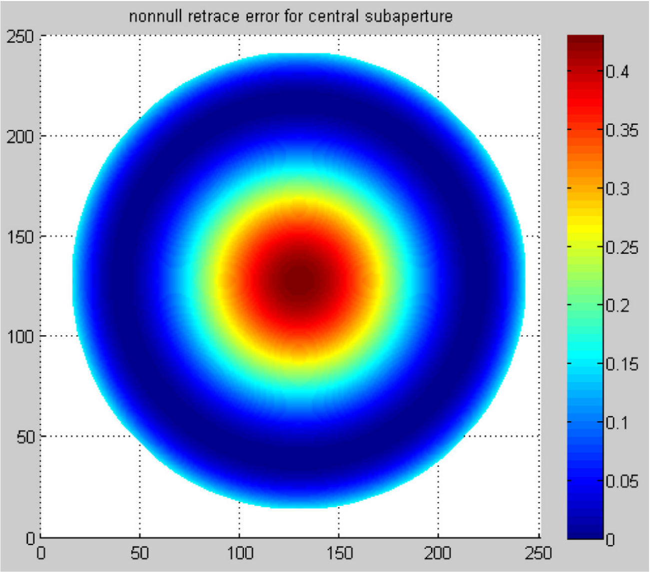

Fig. 1. Retrace error for rotational symmetric subapertures.

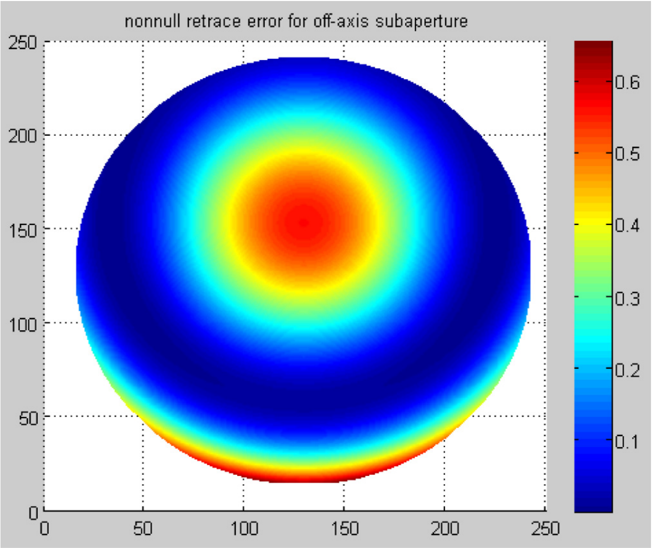

Fig. 2. Retrace error for off-axis subapertures.

The wavefront tested by the interferometer includes both the surface error of the testing aspheric surface and artifacts such as the retrace error, the alignment error, and the retrace coordinate error [15,16]. So the wavefront obtained from the interferometer can be expressed as:

$$W_{\mathrm{inter}ferometer} = W_{retrace} \oplus W_{alignment} \oplus W_{coordinate} \oplus W_{test} \tag{1}$$

where $W_{\mathrm{inter}ferometer}$ is the measured wavefront from the interferometer, $W_{retrace}$ is the retrace error, $W_{alignment}$ is the alignment error between interferometer and the testing aspheric surface and W_{test} is the surface error of the testing aspheric surface. Note that "$\oplus$" in Eq. (1) denotes the variables not simply added up. Thus, the total interferometer error $W_{\mathrm{inter}ferometer}$ depends on all of the retrace error, the alignment error, the retrace coordinate error and the surface error of the aspheric surface.

Assuming an aspheric mirror to be characterized has a subaperture aperture of D_{sub} and a vertex radius of R, the F number of the standard lens should be:

$$F \geq \frac{R}{D_{sub}} \tag{2}$$

According to the designed optical testing path, the retrace error can be calculated in the optical simulation tools such as Zemax or Code V with ray tracing method.

For rotational symmetric subapertures, the retrace error behaves like a combination of power and spherical aberrations as shown in Fig. 1. For the off-axis subapertures, the behavior of the retrace error is shown in Fig. 2.

After calculating the retrace error of each subaperture with the ray tracing method, the retrace error and the retrace coordinate error can be removed from the subaperture testing map at the same time [15,16]. The alignment error of each subaperture will be separated with the stitching algorithm introduced in Section 2.2.

2.2. Stitching algorithm

In order to obtain a full aperture map, a stitching algorithm is developed to stitch each subaperture map together to a whole map.

Currently there are several types of stitching algorithms such as maximum likelihood estimation method, the least square method, and the iteration method. The maximum likelihood estimation method is mainly used in flat mirror stitching, and can calculate the test map and the reference map simultaneously [17]. In the least square method, the full aperture map is reconstructed by compensating the alignment error of each subaperture [18,19]. The iteration method is based on the three-dimensional coordinate transformation [20,21].

Different from the above methods, we propose an algorithm combining the iteration calculation and the least square method.

Our proposed stitching algorithm shown in Fig. 3 is based on the least square method [18,19]. First according to the subaperture arrangement, each subaperture is tested with interferometer and non-null errors are calculated according to the parameters of the vertex radius and the aperture of each subaperture. With the method introduced in Section 2.1, non-null errors can be removed from each subaperture testing result and all the coordinates of each subaperture can be unified in a global coordinate at this time. Then stitching coefficients of each subaperture except the standard one can be calculated with the stitching algorithm discussed in Section 2.2. To improve the stitching accuracy, the residual map of every two adjacent maps is calculated after stitching. If the RMS of the residual map satisfies the criteria, stitching is accomplished. If not, two-dimensional cross-correlation between every two adjacent subapertures is calculated to get a more accurate positioning of each subaperture and the stitching coefficients of each subaperture will be recalculated until the residual meets the requirement.

Assuming there are N subapertures in the measurement. We take the Nth subaperture as a reference, then the ith subaperture can be expressed as:

$$\Phi_i'(x,y) = \Phi_i(x,y) + \sum_{k=1}^{L} a_{ik} f_k(x,y) \tag{3}$$

where $\Phi_i(x,y)$ is the ith subaperture testing map, $f_k(x,y)$ can be any predefined functions, a_{ik} is the stitching coefficient and L is the term number to be fitted. In the non-null stitching, the term number to be fitted between subapertures is nine and the function $f_k(x,y)$ can be written as:

$$\begin{cases} f_1(x,y) = x \\ f_2(x,y) = y \\ f_3(x,y) = x^2 + y^2 \\ f_4(x,y) = xy \\ f_5(x,y) = x^2 - y^2 \\ f_6(x,y) = x(x^2+y^2) \\ f_7(x,y) = y(x^2+y^2) \\ f_8(x,y) = (x^2+y^2)^2 \\ f_9(x,y) = 1 \end{cases} \tag{4}$$