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Letter

Annular Subaperture Stitching Method Based on Autocollimation

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In this paper, we propose an annular subaperture stitching method based on an autocollimation method to relax the requirements on mechanical location accuracy. In this approach, we move a ball instead of the interferometer and the aspheric surface so that testing results for adjacent annular subapertures are registered. Thus, the stitching algorithm can easily stitch the subaperture testing results together when large mechanical location errors exist. To verify this new method, we perform a simulation experiment. The simulation results demonstrate that this method can stitch together the subaperture testing results under large mechanical location errors.

Keywords: optical testing, aspheric optics, interferometer, annular subaperture stitching, autocollimation

As optical precision manufacturing has developed, aspheric surfaces have been widely used in optical systems. Therefore, research on methods for testing aspheric surfaces is very important. The annular subaperture stitching method is one important method for testing aspheric surfaces and has been widely studied.[1–7] However, the current annular subaperture stitching method requires high mechanical location accuracy. To relax the requirement for mechanical location accuracy, we propose a new annular subaperture stitching method based on an autocollimation method.

Firstly, we describe our new annular sub-aperture stitching method and explain why the mechanical location accuracy requirements can be relaxed. Secondly, we use simulation results to show that this method can stitch together the subaperture testing results under large mechanical location errors. Lastly, we present our conclusions.

In the current annular subaperture stitching method (Fig. 1), the aspheric surface is moved to different locations along the optical axis, and different annular zones of the aspheric surface are tested. Because the aspheric surface is tested at different locations, the annular subaperture testing results must be registered when they are stitched together. Normally, high mechanical location accuracy is required to register the subapertures, even if an algorithm has been used to compensate for mechanical location errors.

To relax the requirement on mechanical location accuracy, we propose a new annular subaperture stitching method based on an autocollimation method. The autocollimation method used to test the parabolic surface is shown in Fig. 2. This method can test the entire parabolic surface at one time. We can use an averaging method to reduce the effect of surface shape errors of the ball. If the parabolic surface is replaced with an aspheric surface, an annular zone of the aspheric surface is tested. In our method (Fig. 3), the ball is moved to different locations along the optical axis, and different annular zones of the aspheric surface are tested at each of these different ball locations.

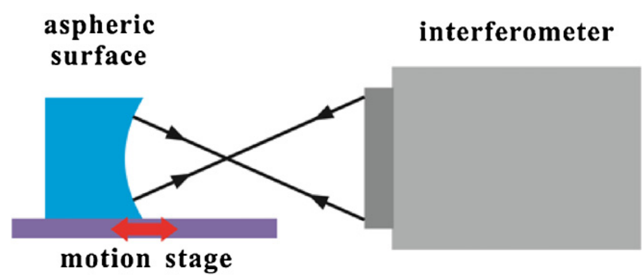

Fig. 1. (Color online) Current annular subaperture stitching method.

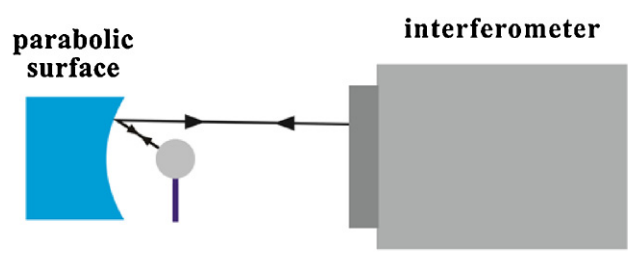

Fig. 2. (Color online) Autocollimation method for testing the parabolic surface.

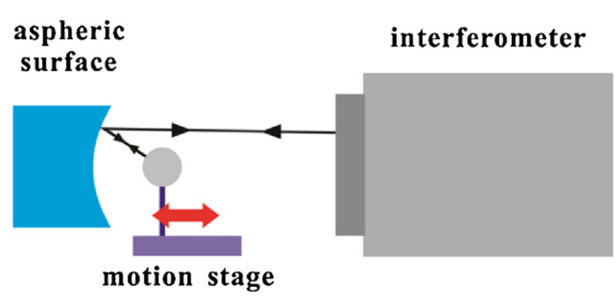

Fig. 3. (Color online) New annular subaperture stitching method based on the autocollimation method.

Because the aspheric surface and interferometer do not move during the testing process, testing results for adjacent annular subapertures are registered.

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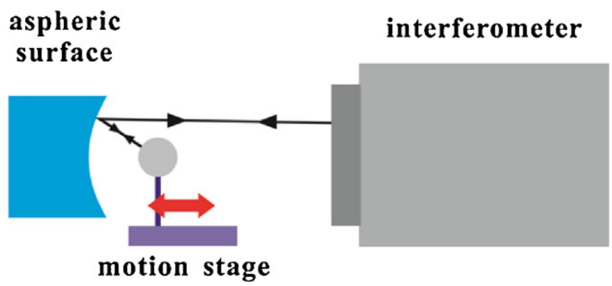


Fig. 4. (Color online) Calculating the optical path length.

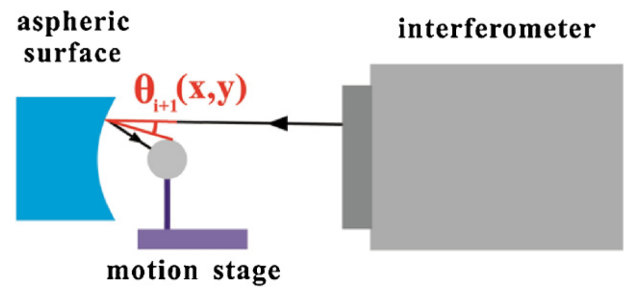


Fig. 5. (Color online) Angle of incidence.

Although it is very important to know the exact location of the ball for each measurement, it is not necessary to use a motion stage with high mechanical location accuracy. The reason for this is that the algorithm accurately calculates the location of the ball on the premise that annular subaperture testing results are registered.

The new method's stitching algorithm is an iterative optimization algorithm based on ray tracing. In our algorithm, the subapertures are stitched from the center to the edge. For example, we consider the $(i+1)$th subaperture. When we begin to stitch the $(i+1)$th subaperture, the ith subaperture has been stitched and is used as a reference subaperture. In the overlapping area, the stitching result of the ith subaperture is $R(x, y)$, and the testing result of the $(i+1)$th subaperture is $z_{i+1}(x, y)$, where x and y are the coordinates of the pixels. To stitch the $(i+1)$th subaperture, we must calculate the optical path length for each pixel of the $(i+1)$th subaperture. Thus, we use the ray tracing method to obtain the optical path length $o_{i+1}(x, y, x_B, y_B, z_B)$, shown in Fig. 4, where x_B, y_B, and z_B are the coordinates of the ball.

The locations of the ball are calculated in a way that minimizes the mismatch of the overlapping area between adjacent subapertures, that is, the ith and $(i+1)$th subapertures:

$$\sum_{i\cap i+1}\Bigg(\Bigg(z_{i+1}(x,y)+o_{i+1}(x,y,x_B,y_B,z_B)+\frac{\partial o_{i+1}(x,y,x_B,y_B,z_B)}{\partial x_B}\Delta x_B+\frac{\partial o_{i+1}(x,y,x_B,y_B,z_B)}{\partial y_B}\Delta y_B+\frac{\partial o_{i+1}(x,y,x_B,y_B,z_B)}{\partial z_B}\Delta z_B+P_{i+1}\Bigg)\Bigg/(2\cos\theta_{i+1}(x,y))-Q_i-R(x,y)\Bigg)^2\to\min, \tag{1}$$

where P_{i+1} is the piston of the $(i+1)$th subaperture, Q_i is the piston of the ith subaperture, and $\theta_{i+1}(x, y)$ is the angle of incidence (Fig. 5). Using Eq. (1), we can obtain Δx_B, Δy_B, and Δz_B. Then, we update x_B, y_B, and z_B:

$$\begin{cases} x_B = x_B + \Delta x_B \\ y_B = y_B + \Delta y_B \\ z_B = z_B + \Delta z_B \end{cases}. \tag{2}$$

After several iterations, this process yields an accurate location of the ball. Using the ball location, we can calculate P_{i+1} and Q_i as follows:

$$\sum_{i\cap i+1}((z_{i+1}(x,y)+o_{i+1}(x,y,x_B,y_B,z_B)+P_{i+1})/(2\cos\theta_{i+1}(x,y))-Q_i-R(x,y))^2\to\min. \tag{3}$$

Thus, we obtain the stitching result of the $(i+1)$th subaperture $T(x, y)$:

$$T(x,y)=(z_{i+1}(x,y)+o_{i+1}(x,y,x_B,y_B,z_B)+P_{i+1})/(2\cos\theta_{i+1}(x,y))-Q_i. \tag{4}$$

In the simulation, we use a 100-mm-caliber aspheric surface, the height of which is written as

$$Z(r)=\frac{r^2/R}{1+\sqrt{1-(1+K)r^2/R^2}}+Ar^4+Br^6+Cr^8+Dr^{10}, \tag{5}$$

where r is the distance from the center of the aspheric surface, $R = -550$, $K = 0$, $A = -1.7030421 \times 10^{-8}$, $B = -6.4297839 \times 10^{-13}$, $C = -2.41051097 \times 10^{-17}$, and $D = 2.9657867 \times 10^{-22}$.

The measurement result (an image with a size of 775×775 pixels, as shown in Fig. 6) is first divided into six annular subapertures, and the annular subapertures are then stitched together using our algorithm. For convenience, we only discuss one pair of adjacent annular subapertures. The first annular subaperture [Fig. 7(a)] is used as a reference; the second subaperture, which is being stitched, is shown in Fig. 7(b). We add random noise (with an amplitude range of $[-0.0005\lambda, 0.0005\lambda]$, where λ is the wavelength of the light used by the interferometer). Then, we begin testing the results using the simulation. In Table 1, we present the ball location and radius when the second annular subaperture is tested. In Table 2, we present the initial values of the ball used in the iterative calculation. After five iterations, the location of the ball is computed by our algorithm, as shown in Table 3. Thus, our approach allows us to accurately calculate the location of the ball. With an accurate location of the ball, we can easily stitch together the testing results for the subapertures.

In conclusion, we proposed a new annular subaperture stitching method based on an autocollimation method to relax the mechanical location accuracy requirements. The

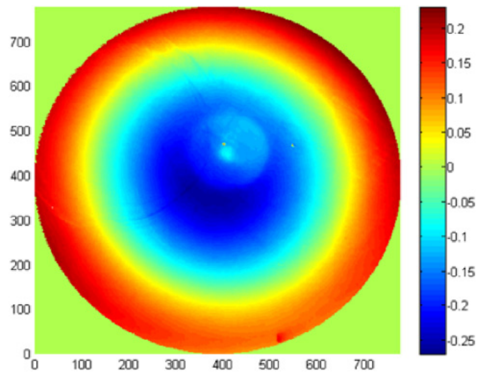
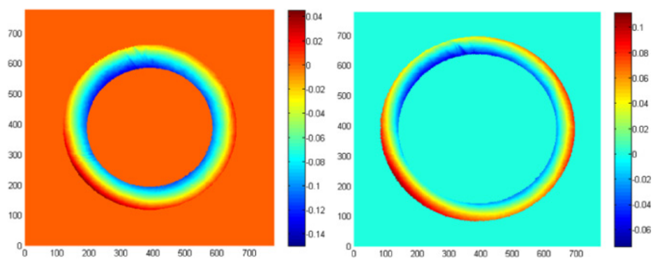

Unit: wavelength

Fig. 6. (Color online) Measurement result.


(a) (b)

Unit: wavelength

Fig. 7. (Color online) Two adjacent annular subapertures: (a) reference subaperture, (b) subaperture being stitched.

simulation results showed that this method can stitch together the testing results for subapertures in the presence of large mechanical location errors.

Table 1. Actual ball information when the second annular subaperture is tested (unit: mm).

x_B	y_B	z_B	Ball radius (R_B)
2.1	1.9	260	25.001

Table 2. Initial values used in the simulation to determine ball information when the second annular subaperture is tested (unit: mm).

x_B	y_B	z_B	Ball radius (R_B)
0	0	265	25

Table 3. Calculated ball location (unit: mm).

x_B	y_B	z_B
2.100025	1.900022	260.000182

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