Accuracy and analysis of long-radius measurement with long trace profiler

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The long trace profiler (LTP) is proposed to measure radius of curvature (R) and surface figure of a long-radius spherical surface in an optical shop. Equipped with a motorized rotary stage and a two-dimensional tilt stage, the LTP scans the full aperture and calculates the absolute radius of curvature of each scanning line based on the least square method. Nonlinear error and manufacture error difference between center and the edge are obtained by comparing R results. The R-limit is validated and expressed as D/R, where D is the aperture of the mirror under test. A full-aperture three-dimensional figure is also reconstructed based on triangle interpolation.

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Large optical observing systems and huge laser installations demand numerous large-scale spherical and aspherical lenses with long focal length. Array laser installations, in particular, strictly demand consistency of focal length. Metrology for long focal length lens has considerable influence on the performance of these optical systems. Focal length can be calculated from the radius of curvature. Thus, developing an instrument for direct long-radius surface measurement can ensure precision of the long focal length and improve manufacturing efficiency.

Several metrology approaches exist for spherical mirrors in an optical shop, including knife-edge tester, spherometer, and laser spherical interferometer[1]. These instruments can afford high-precision measurement for a range of spherical mirrors. However, each has its own limitation on metrology for long-radius spherical mirrors. For example, the knife-edge tester is only for concave mirrors. Spherometer presents high precision for short-radius optics but not for long-radius optics. Laser spherical interferometer is widely used for spherical mirror metrology after polishing. The interferometer, however, needs to be equipped with multilevel standard spherical surfaces and a long enough slideway for long-radius surfaces. Spatial filters used in inertial confinement fusion (ICF) installation, for example, have the largest radius of curvature of approximately 70 m and a size of 410 × 410 (mm). The precision demand of these components is above 0.25%, which cannot be realized using existing equipments. In summary, a novel metrology instrument is urgently needed for long-radius mirrors.

Long trace profiler (LTP), which is commonly used in synchrotron radiation, has enormous potential for long-radius mirrors metrology as an extended application. Based on absolute scanning test, LTP does not require large-aperture incident wavefront or reference, thus greatly reducing test cost and difficulty. The scanning length exceeds 1 m, enough to test large-scale optics. Using interferential pattern to realize orientation and reference surface to eliminate system error greatly improves the test precision[2,3]. Utilizing the instinctive capability of long-radius measurement for spherical mirrors in an optical shop has huge market possibilities.

LTP was initially developed at Brookhaven National Laboratory, evolving from the pencil beam interferometer built by Von Bieren[4,5]. Nowadays, LTP has become commercial. In our experiments, we employ laboratory-based LTP of multiple functions LTP-MF at the National Synchrotron Radiation Laboratory (NSRL) of China. Figure 1 shows the schematic of the test principle, and Fig. 2 shows the photograph of LTP at NSRL[6].

The collimated laser beam is split into two beams by the polarizing beam splitter (PBS). The test beam is directed down to the mirror under test (MUT), and the reference beam is sent out to a stationary mirror to eliminate partial system error. After being reflected off each mirror, the two beams enter the PBS again and are directed to the Fourier lens together. A linear charge-coupled device (CCD) located at the focus receives the interferential pattern. The slope data are then calculated.

LTP measures the slope data of each scanning point directly. Height distribution is determined by integrating the linear fitting slope curve and identifying the discrete height data of each scanning point. Based on circular equation and least-square fit method, the radius of curvature is calculated from height data.

LTP is a one-dimensional scanning instrument; therefore, its results just reflect the radius of the scanning line, which cannot satisfy full-aperture processing

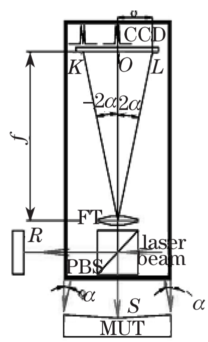

Fig. 1. Schematic of the test principle.

Fig. 2. LTP-MF at NSRL.

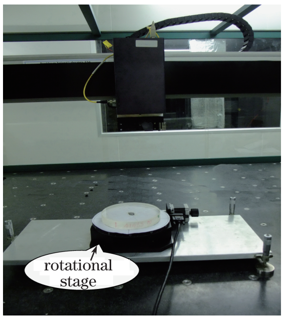

Fig. 3. Measuring equipment.

demand. An additional mechanical stage is thus designed to realize two-dimensional (2D) scanning. The additional stage is a rotational circular stage aiming for circular optical elements (Fig. 3) because quadrate elements make it easy to realize 2D measurement. The tilt stage under the rotational stage is used for 2D tilt adjustment. In our experiments, the rotational stage and the scanning head together fulfill a scanning map under a polar coordinate (Fig. 4). Every time the stage carrying a test mirror rotates 30°, the optical head (OH) scans the diametrical line once and the radius is obtained. Then, after rotating 360°, radius distribution of the full aperture is obtained. In such a manner, each scanning line will be tested twice starting from opposite ends.

The experimental elements are two Φ150-mm spherical mirrors, with radii of curvature of R_1=–37.108 m and R_2=+4.988 m, respectively.

The R repeatability of R_1 is tested when the rotational stage is at 330°. In Fig. 3, the OH repeatedly scans the 330° scanning line 12 times, with each scanning length at 140 mm, because the margin is too irregular to be detected. Figure 5 shows the measured R results of 12 scans. The peak-valley R deviation is 0.02 m and the standard deviation is 0.006 m. Hence, the relative R deviation is 0.05%, satisfying the 0.25% demand in the optical shop. The authority repeatability of this LTP is 0.01%, possible as a result of practical conditions such astemperature and reference beam location influencing the precision. Improving some test settings can thus help us achieve higher precision in future applications.

Inside the LTP OH, there is a Fourier transform (FT) lens, transforming slope data a of the scanning point into displacement d on the CCD, also called $f-\theta$ lens. The linear relation between a and d is $a = d/2f$, where f is the focal length of the FT lens (Fig. 6)[7]. However, this relation merely holds true when the slope is small enough. Nonlinear error will be brought into the results when the slope exceeds the linear range. In our optical shop, the largest radius is about 70 m, which is far less than the radius of synchrotron optical elements. The edge slope probably exceeds the linear range. Thus, the nonlinear error should be particularly considered.

In our experiments, nonlinear error is determined by comparing the central and the edge results. First, we test the central, right edge, and left edge of the spherical mirror. Each scanning line is 20 mm. Corresponding radius results and CCD displacement are then recorded. Next, we tilt the tilt-stage, tilt the center at an angle, and adjust the corresponding displacement on CCD to be the same as either the right edge or the left edge. This enables us to calculate the nonlinear error difference between center and edge without regard to manufacture error. The entire operation steps are shown in Fig. 7. Nonlinear error difference between center and right edge is 0.114 m, and 0.124 m between center and left edge. Total R-measuring difference between center and right edge is 0.182 m, and 0.273 m between center and left edge. Nonlinear error difference subtracted from total R-measuring difference gives manufacture difference between center and edge.

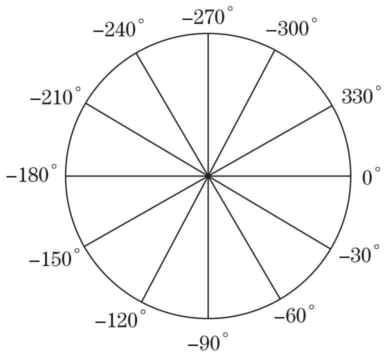

Fig. 4. Scanning line map.

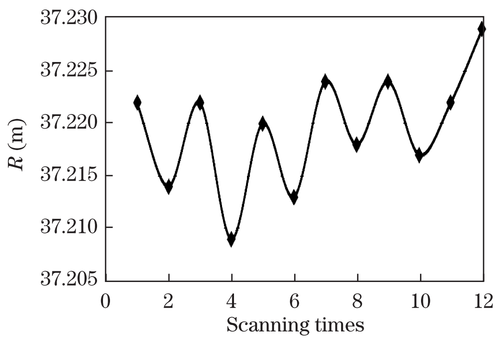

Fig. 5. R-repeatability of R_1 at 330°.

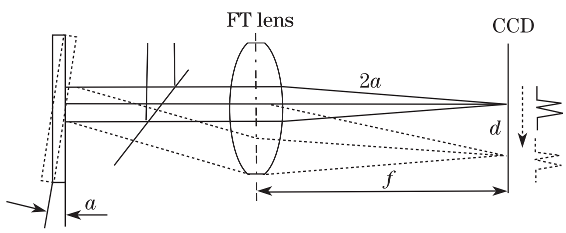

Fig. 6. Relationship between surface slope a and displacement d on CCD.

The right edge is 0.042 m and the left edge is 0.054 m. These results may guide us in optical elements manufacture. All results are the average results of 12 scans.

LTP is well-known for its high-precision measurement of long-radius synchrotron elements, from hundreds of meters to several kilometers. Owing to its geometrical structure, such as the aperture of FT lens and the size of CCD, LTP cannot detect too large surface slopes. As a result, LTP cannot measure small radius elements. Using the known slope maximum, we calculate the measurable R-limit theoretically, which is expressed as D/R, where D is the aperture (Fig. 8). The arrow shows the incident light to the edge of the mirror. The tangent line slope via this incident point is a. From the angle relation in this figure, a can be denoted as

$$\sin a = \frac{D}{2} \Big/ R = D \big/ 2R. \quad (1)$$

When a is small enough, $\sin a \approx a$. Hence, a can be expressed as $a = D/2R$. The max a of this LTP is 16 mrad. Thus, D/R is 0.032. D is 150 mm for our test mirrors, so the R-limit is 4.688 m.

We take an experimental mirror with R=+4.988 m to validate the design data. As shown in Figs. 3 and 4, the rotary scanning experiments are also conducted for this mirror. The scanning line is 70 mm and the R-average is +4.999 m. Therefore, D/R is 0.014, approximately half of the design data. This result is actually coincident with the design data because only half CCD is employed in our experiments.

The slope error is calculated by subtracting the optimal linear fitting slope data from the original slope data. By interpolation and integration, the surface figure error is extracted from the slope error. The interferometer results are used for comparison. The X axis and Y axis correspond to 0° and 90° in LTP, respectively.

By establishing a triangle matrix counter-clockwise along the surface and interpolation, the three-dimensional (3D) figure of R_1=–37.108 m is reconstructed (Fig. 9). As the increment in rotational scanning is 30°, the reconstruction topography is rough, losing high-frequency details. In contrast to the figure obtained by interferometer (Fig. 10), the reconstructed 3D figure approximately reflects the real surface of the two long-radius mirrors.

Although LTP is instinctively proper for long radius of curvature measurement, it is still not being used for ordinary optics. We propose to employ LTP for long-radius optics metrology in an optical shop as an extended application out of the synchrotron radiation laboratory.

In conclusion, a rotational stage is designed to fulfill the full-aperture radius measurement of two long-radius mirrors. Repeatability results show that the consistency of LTP measurements is higher than the processing demand by an order of magnitude. Nonlinear error and manufacture error of R_1=–37.108 m are calculated from

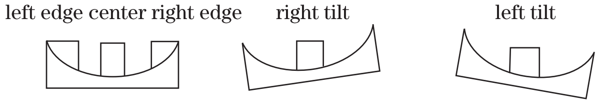

Fig. 7. Operation steps for nonlinear error measurement.

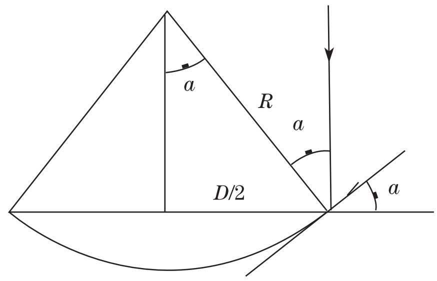

Fig. 8. Relationships among a, D, and R.

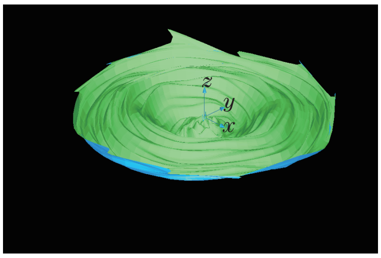

Fig. 9. 3D figure of R_1 with LTP.

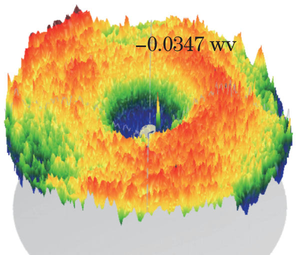

Fig. 10. 3D figure of R_1 with interferometer.

LTP data, which may give directions in our manufacturing process. The R-limit is also obtained, helping us understand this instrument in the round. A comparison of the 3D figure between LTP and interferometer further validates the capability of LTP in metrology long-radius optics. However, there still exists some unresolved problems, such as more automatic mechanical stages and practical influences in an optical shop. Further research will be undertaken about these problems.

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