Scanning Hartmann test method and its application to lens aberration measurement

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A scanning Hartmann test method is proposed and its measurement principle is described. The scanning Hartmann test setup is formed by modifying the Hartmann screen of the conventional Hartmann test setup. With the rotation of the scanning Hartmann screen and the improved hole arrangement, the whole information of the lens to be tested in the full aperture can be obtained. The measurement accuracy of the aberration is improved and the local error of the lens can be got. In the method, no change of the Hartmann screen is needed for measuring the lenses of different aperture sizes. Experimental results of aberration measurements of two lenses are given to verify the usefulness of the setup.

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Currently, the interferometry and the Hartmann test are well-recognized methods for the test of lens aberrations[1−3]. The aberrations of the lens can be obtained accurately by a wavefront interferometer. But the interferometer is an expensive equipment and very sensitive to environmental disturbances. As we know, the Hartmann test is a classical and simple method for lens aberration measurements[4−6]. However, the conventional Hartmann test method has some disadvantages. Firstly, the sampling density for the lens is limited to influence the precision. Secondly, the local error of the lens cannot be obtained from the measurement result. Thirdly, the screens must be changed for the lenses with different apertures and numerical apertures. Based on the conventional Hartmann test method, the Shack-Hartmann method was developed to test optical elements with simple structure and shockproof performance[7]. But the uniformity requirement of the microlenses constituting the microlens array increases their fabrication difficulty. Meanwhile, for testing the lenses of different apertures, the microlens arrays with the different sizes are needed. To compensate shortcomings of the above-mentioned methods, a scanning Hartmann test method is presented in this paper.

The optical arrangement for the scanning Hartmann test consists of a collimator, a scanning Hartmann screen, a lens to be tested, and a charge-coupled device (CCD) camera, as shown in Fig. 1. The collimator has a large aperture to measure large-aperture lenses. In the collimator, a He-Ne laser is used as the light source. There are a number of rows of holes radially located at the scanning Hartmann screen. Every two rows of holes with the same diameters are used to measure a lens of different aperture sizes. For the easy description, only two rows of holes are given in Fig. 2. The two rows of holes are arranged along the horizontally and vertically radial directions of the screen. Holes in each row (expect for a center hole) are spaced evenly. The distance c between the centers of two adjacent holes in the horizontally radial direction is equal to the distance d between those in the vertically radial direction. Each of these holes has a uniform diameter R equal to the space between the adjacent holes. The distance a between the center of hole 1 close to the center hole and the screen center in the horizontally radial direction is twice as the distance b between the center of the hole 2 close to the center hole and the screen center in the vertically radial direction. The distance a is equal to c. When the row of holes in the horizontally radial direction is rotated by 90°, the holes are located at the spaces between the adjacent holes in the vertically radial direction. The center hole is used to align the center of the screen to the optical axis of the collimator. The

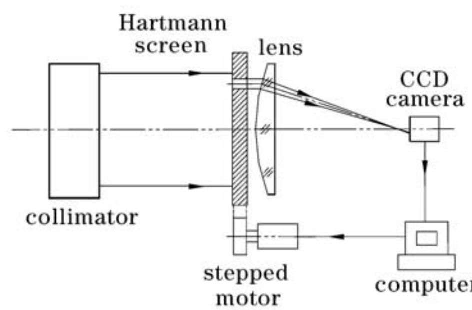

Fig. 1. Optical arrangement for the scanning Hartmann test.

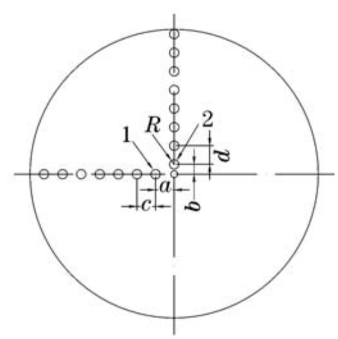

Fig. 2. Scanning Hartmann screen.

screen can rotate around its center driven with a stepped motor. The angular displacement of the screen can be obtained by an encoder. The CCD camera is fitted on a mechanical stage and can move to the desired image plane by adjusting a micrometric screw on the mechanical stage. The displacement can be obtained by the readings of the micrometric screw.

A parallel laser beam is generated by the collimator. It passes the scanning Hartmann screen to form beamlets. Before measurement, the rotation axis of the Hartmann screen and the optical axis of the lens to be tested must be aligned to be coincident with the optical axis of the collimator. The measurement tool is a precise internal focusing telescope based on self-collimation principle with an accuracy better than 6 arc seconds. During measurement, only one hole in the scanning Hartmann screen is opened at a time to enable a beamlet to pass the lens. The beamlet is focused by the lens. The focal spot image of the lens is detected by the CCD camera at a certain image position. When the Hartmann screen rotates, the lens is scanned by the beamlet in a zone and focal spot images in the zone are obtained. When the measurement of the lens in a zone is completed, the hole is closed and the second hole is opened. The scanning process is repeated and the information in the second zone is attained. The holes except for the center hole are opened and corresponding beamlets pass the lens in turn. After all zones are measured, the whole information in the full aperture of the lens is obtained.

By the rotation of the scanning Hartmann screen, the lens is scanned in the circumference direction by a beamlet in a zonal height. Using the improved hole arrangement, the zone of the scanning is continuous in the radial direction. Therefore the whole information in the full aperture of the lens can be obtained, with which the measurement accuracy of the aberration can be improved. At the same time, the local errors of the lens can be acquired, which is very useful for the fabrication of the lens. Many rows of holes with different sizes can be set in a Hartmann screen, thus the screen need not be changed when the lens of different aperture size is tested.

One of important applications of the scanning Hartmann test setup is to measure the aberration of a focusing lens. Figure 3 shows the schematic diagram of the aberration measurement of the focusing lens. When a beamlet with a zonal height h passes the focusing lens, several image planes (e.g. four, AA, BB, CC, and DD) perpendicular to the optical axis are chosen in the neighborhood of focus. The positions of these image planes along the optical axis are represented by Z_1, Z_2, Z_3, and Z_4, respectively. When the lens is scanned by the beamlet,

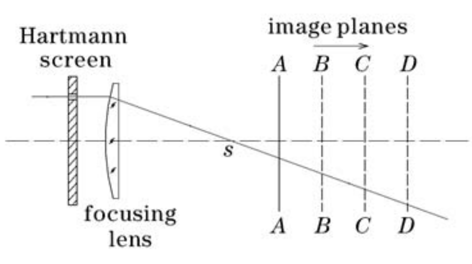

Fig. 3. Schematic diagram for testing spherical aberration.

focal spots in each image plane distribute circularly. The positions of focal spot centers are fitted to a circle in each image plane using the least square method and the radius of the circle is obtained. The radii of the four circles in the four image planes can be expressed as R_1, R_2, R_3, and R_4 and four coordinates (Z_1, R_1), (Z_2, R_2), (Z_3, R_3), and (Z_4, R_4) are acquired. With the four coordinates, a linear equation can be derived and the equation is a function of the position Z and radius R. When the value of R is equal to zero, the position Z is the intersection (point s in Fig. 3) of the beamlet with zonal height h with the optical axis. With focal spots in different zonal heights, a series of intersection positions of the beamlets with different zonal heights with the optical axis are obtained. Therefore a relationship curve of spherical aberration versus the zonal height can be obtained. For the focusing lens, only spherical aberration exists. The wavefront aberration W of the lens can be obtained from the spherical aberration $\delta L'$ using the relationship[8]

$$W = \frac{h_{\mathrm{m}}^2}{2f'^2} \int \delta L' \mathrm{d} \left(\frac{h}{h_{\mathrm{m}}} \right)^2, \qquad (1)$$

where h_{m} is the maximum radial height which can be tested, f' is the focal length. If the curve of spherical aberration is moved along the coordinate axis of the spherical aberration, the wavefront aberration will be changed. The position where the peak-to-valley value of the wavefront aberration reaches the minimum is the best focal plane. Then the wavefront aberration in the best focal plane can be determined.

In experiments, the spherical aberrations and wavefront aberrations of a collimating lens of a Fizeau plane interferometer and a target lens used in high power laser facilities are measured using the scanning Hartmann test setup. The collimating lens contains a flat surface and an aspheric one and its clear aperture and focal length are 154 and 401.2 mm, respectively. The target lens contains a spheric surface and an aspheric one. It has a clear aperture of 250 mm in diameter and its focal length is 784.3 mm. Because the edges of these lenses are used for fixation, the apertures for measurement are smaller than the clear apertures in fact. In the scanning Hartmann test setup, the collimator has an aperture of 300 mm in diameter. In the scanning Hartmann screen, the diameter of the center hole is 8 mm. Other holes have a 10-mm diameter and the space between the adjacent holes is 10 mm. The distance from the hole 1 to the screen center is 20 mm. The distance between the centers of two adjacent holes in the horizontally radial direction is 20 mm. The pixel number of the CCD camera (MTV-1881EX) is 795(H) $\times$ 596(V).

Experimental results of the aberration measurements of two lenses are shown in Figs. 4 and 5. Figure 4 shows the spherical aberrations of the collimating lens and the target lens. The theoretical spherical aberrations of the two lenses are given by the optical design software Zemax. The maximum differences between the measured and theoretical values are 14.6% in the zonal height of 40 mm for the collimating lens and 12.4% in the zonal height of 87.5 mm for the target lens. It is obvious that the measurement results are in good agreement with the results of optical design of the two lenses. Figure 5 shows the wavefront aberrations of the collimating lens and the

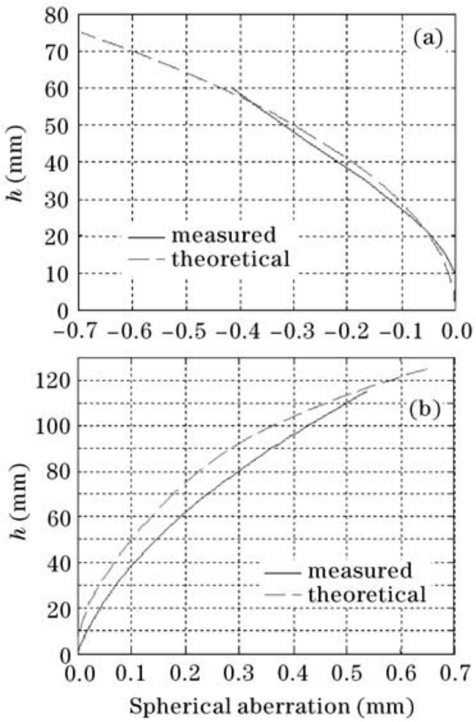

Fig. 4. Spherical aberrations of the collimating (a) and target lenses (b).

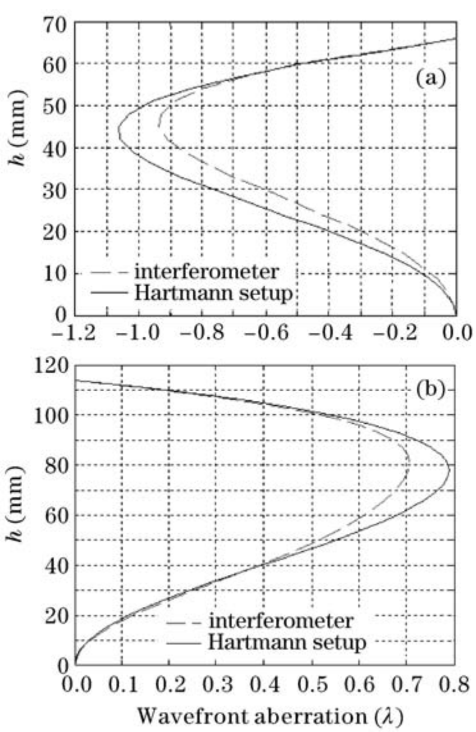

Fig. 5. Wavefront aberrations of the collimating (a) and target lenses (b).

target lens. For each lens, the wavefront aberration is measured by the scanning Hartmann test setup and a Wyko (RTI4100) laser interferometer, respectively. In Fig. 5(a), the peak-to-valley values of the wavefront aberration are respectively 1.0663λ and 0.9348λ in the best focal plane measured by the scanning Hartmann test setup and the interferometer. The difference of two wavefront aberrations is 0.1315λ and the relative measurement error is 14.1%. In Fig. 5(b), the peak-to-valley values of the wavefront aberration are respectively 0.7922λ and 0.7060λ in the best focal plane achieved by the scanning Hartmann test setup and the interferometer. The difference of two wavefront aberrations is 0.0862λ and the relative measurement error is 12.2%. It can be seen that the measurement results of the two methods agree well. Under current experimental conditions, the total measurement periods of the collimating lens and the target lens are about 15 and 30 minutes, respectively. If the speed of the motor is increased, the measurement time can be shortened.

The factors causing measurement errors of the spherical aberration generally contain the deviation of the hole position in the Hartmann screen, misalignment of the optical axis of the lens to be tested, etc.. An analysis about the measurement accuracy of the spherical aberration of the collimating lens is performed by choosing two image planes perpendicular to the optical axis in the neighborhood of focus. It can by calculated by the error transfer formula[9]

$$\sigma_z = \pm \frac{f'}{2h_n}\sqrt{\left(\frac{R_1}{d}\right)^2 \sigma_d^2 + \frac{\sigma_R^2}{2}}, \tag{2}$$

where σ_z is the mean square deviation of the spherical aberration of the collimating lens, σ_d is the mean square deviation of the distance d between the two image planes, σ_R is the mean square deviation of the radii of the circles in the two image planes. It can be seen that under ideal measurement conditions, the measurement accuracy is inversely proportional to the radial height h_n. In our case, h_n is 10 mm, σ_d is 0.01 mm, σ_R is 3.71 μm, f' is 401.2 mm, d is 2 mm, and R_1 is 40.03 μm. By substituting them into Eq. (2), the accuracy of spherical aberration is ± 52.76 μm. As the choice of four image planes in our experiment, the final accuracy of spherical aberration is increased twice, i.e. ± 26.38 μm. According to the above discussion, the maximum difference between the measured value and theoretical value is ± 27.6 μm. The measurement error of spherical aberration of the collimating lens with the scanning Hartmann test setup is in good agreement with the theoretical error.

In conclusion, a scanning Hartmann test method has been proposed. With this method, the measurement accuracy of the aberration is improved and the local errors can be acquired. In this method, no change of the Hartmann screen is needed for the measurement of the lenses of different aperture sizes. In experiments, measurement results of the spherical aberrations of a collimating lens and a target lens agree well with those of optical design, and measurement results of the wavefront aberrations of two lenses are in good agreement with those obtained by interferometer. The usefulness of the scanning Hartmann test setup is verified. Furthermore, if spot diagrams of a series of lens image planes are analyzed, some important performance parameters, such as intensity distribution and local errors, can be also derived.

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