Shape measurement of aspheric plastic lens with large angle

Dagang Huang (黄大刚)[1,2], Heng Zhang (张 恒)[3], Shah-Rong Lee (李世荣)[4], and Baoguang Wang (王宝光)[1]

[1]*State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072*

[2]*College of Information Technique & Science, Nankai University, Tianjin 300071*

[3]*National Institute of Metrology, Beijing 100013*

[4]*Kuang Wu Institute of Technology, Taipei*

Received November 12, 2004

In this paper, according to the features of easy distortion and scratch for aspheric plastic lens, a non-contact measuring method is raised to test error in shape of the lens. Namely, the distance between a template and its image reflected with tested lens can be measured in nearly the vertical direction of the lens axis when the two-dimensional (2D) template is put near the measured surface. Then, the outline of the central cross-section could be obtained by calculating and curve fitting. Furthermore, three-dimensional (3D) surface can be imitated through rotating the component. A new fitting method of drift measurement is presented to prevent reducing precision when the lens and the template are fixed. The template is adjusted according to the position of the lens. The measurement precision is in the order of magnitued of sub-microns. Rotationally symmetric convex aspheric surface with any angle can be measured by this method.

OCIS codes: 120.6650, 220.1250, 100.0100.

The optical systems with aspheric lenses are widely applied because they are better than traditionally spherical ones in imaging ability, structure, volume, and weight. The injected plastic lenses are welcomer by manufacturers as they are of high efficiency, high stability, and low cost. However, its development is confined by the test technology for aspheric surface now, so a lot of methods were developed.

A compensator is generally composed of a group of spherical lenses in compensation method[1−3]. It changes measuring the shape of aspheric surface into testing spherical radius, optical distance, index of refraction, and the uniformity of materials. Its measurement precision would be very high theoretically and its resolution and repeatability are also very high in laboratory. But for aspheric surface with high order and large angle, there are some immeasurable parameters, such as concentricity, slope in optical axis, and stress, because the compensator is too complex when the compensator is composed of many lenses. Some compensators for high order aspheric may not be made up actually. Holographic compensator[4,5], produced with calculating holographic technology, was developed to simplify the compensator. All kinds of compensators can be made by this method theoretically and are simple in production and cheap. However, its position in measuring system and the shrink of photoreception film are difficult to calibrate. To avoid the trouble of making and testing compensators, shearing-interferometry[6] is also used to measure aspheric surface. They are of very high resolution ($\lambda/10-\lambda/100$). But the measurement precision may be deduced by many factors and some of them cannot be determined.

Ronchi curved bar method[7] is another way for testing aspheric surface, based on the principle of geometry image. Some other methods, such as simple ray tracing method[8], laser deflectometry method[9], and thin beam interferometric method[10], are used to measure optical surface by calculating reflective angles. The resolution is confined by aberrations of reflected beams. Hindle testing of the off-axis convex ashperic surface[11] is a method of testing large angle surface by rotating lens. Long trace profiler[12] can scan 370 mm, the slope resolution is higher than 0.25 μrad, and the measurement precision within whole scanning range is 1.14 μrad. Three-dimensional (3D) coordinates can be read in STM6-LM measuring microscope[13] by non-contact method, the range is over 200 mm and the resolution is 0.1 μm, but the best precision is only 3 μm. Talysurf CCI 3000Å non-contact 3D surface profiler[14] is produced in 2003 by Taylor-Hobson, its vertical resolution is 0.01 nm, lateral sampling resolution is 0.35 μm, but maximum slope is 27.7°, measurement area is only 0.36 × 0.36 (mm). DVD400[15] is made in ZYGO, its quality of transmitted wavefront testing is $\lambda/10$, the repeatability of root mean square (rms) is $\lambda/2000$, measuring scope is $\phi 6$.

Laser scanning confocal microtechnic[16] can also be used to measure aspheric surface. The measurement range, precision, and repeatability are mainly depending on the precision of mechanical system. Its minimum scanning step is 0.1 μm.

Aspheric surface with super large angle is difficult to measure with above methods except off-axis Hindle. But 3D non-rotationally-symmetric template is required in off-axis Hindle method. It is more difficult to test the template than to measure lens itself.

The last four methods cannot be used to measure aspheric surface with large angle because they are all confined by numeric aperture (NA) of objective, though there are with respective outstanding characteristics in measurement range, precision, or repeatability.

Plastic convex aspheric lenses are often used in many systems with large aperture or large field of view. To solve the problem of testing aspheric surface with large angle, a new method with two-dimensional (2D) template is presented in this paper. The rotationally symmetric aspheric surfaces with any angle can be measured by this method. Both of the precision and the repeatability are in the order of magnitude of sub-microns.

The image of a plane template is reflected by a surface when the template is put near the surface. The distance between the template and its image can be measured through an objective, as shown in Fig. 1. When the central axis of the tested surface coincides with the central axis of the template, the distance between template and its image can be measured at first, then the distance from the template to the surface can be calculated according to optical formula, and the outline of central cross-section of the surface can be fitted. Rotating the lens and repeating the work, some groups of curves can be measured. 3D surface can be imitated by these curves.

The aspheric surface is defined as

$$z=\frac{-(x^2+y^2)}{R+\sqrt{R^2-(1+k)(x^2+y^2)}}+\sum_{i=2}^{6}A_{2i}(x^2+y^2)^i, \quad (1)$$

where R is the radius of top curve, k is square curve constant, A_{2i} $(i=2,3,\cdots,6)$ are the coefficients of aspheric mending, z is the coordinate of rotationally symmetric axis, x and y are other two coordinates. The coordinate origin is the top of aspherical surface.

The curve of template is processed according to the design data of tested surface. Assume a is the distance between the template and the surface in z direction

$$z=\frac{-y^2}{R+\sqrt{R^2-(1+k)y^2}}+\sum_{i=2}^{6}A_{2i}y^{2i}+a. \quad (2)$$

The distance between the surface and the template can be calculated based on geometric relation of optical lines by the distance, which can be measured directly, between the template and its reflective image.

Figure 2 is the top view of Fig. 1, where C is the position of the template, CE is the distance between the template and the surface. The optical axis of charge-coupled device (CCD) camera is vertical to the optical axis of the tested surface. On cross section $y=y_0$,

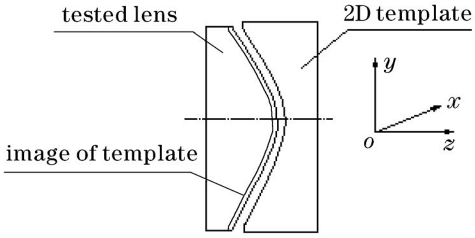

Fig. 1. Principle of measurement.

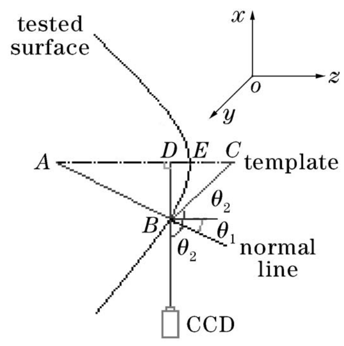

Fig. 2. Geometric relation of rays.

$$\frac{z_C-z_B}{x_B}+\tan\left\{2\tan^{-1}\left[-(2x_B(R+\sqrt{R^2-(1+k)(x_B^2+y_0^2)}+\frac{(1+k)x_B(x_B^2+y_0^2)}{\sqrt{R^2-(1+k)(x_B^2+y_0^2)}}))\Big/(R+\sqrt{R^2-(1+k)(x_B^2+y_0^2)})^2+\sum_{i=2}^{6}2iA_{2i}x_B(x_B^2+y_0^2)^{i-1}\right]\right\}=0. \quad (3)$$

Numerical value x_B can be solved from Eq. (3) through aspheric parameters R, k, A_{2i} $(i=2,3,\cdots,6)$, given value y_0, measured value z_C-z_B. Then the distance a can be calculated by

$$a=\frac{y_0^2}{R+\sqrt{R^2-(1+k)y_0^2}}-\frac{x_B^2+y_0^2}{R+\sqrt{R^2-(1+k)(x_B^2+y_0^2)}}+\sum_{i=2}^{6}A_{2i}((x_B^2+y_0^2)^i-y_0^{2i})-(z_C-z_B). \quad (4)$$

$a(y_0)$ can be fitted into a straight line in the y_0-a plane by least square method. The distance between measured value $a(y_0)$ and the line is approximate longitudinal error of the surface.

Other cross section curves under different rotating angles can be obtained by rotating lens by same way. The whole 3D surface can be fitted with these curves.

The structure of the measuring device is shown in Fig. 3. A stepping motor is installed in the support. A lens seat, the tested lens, and an opto-electronic encoder are driven by the motor to rotate along x-axis. The template is adjusted roughly on 3D platform and adjusted finely by two groups of piezoelectric ceramic plates to move along y-direction or to rotate along z-axis. The support and the 3D platform are both installed on the main support. The position of the lens and the template are adjusted through 2D platform on x-y plane to ensure the tested area is in the center field of the objective when the lens is measured spot by spot. The lens and the template can be rotated a 180° angle together on the turnplate to test the eccentric value of the template opposite the lens at z direction.

The drift measurement is used to simplify the device and get the sub-micron precision. Firstly, the lens is installed traditionally. The eccentricity is less than 0.02 mm and the angle between lens' axis and mechanical axis

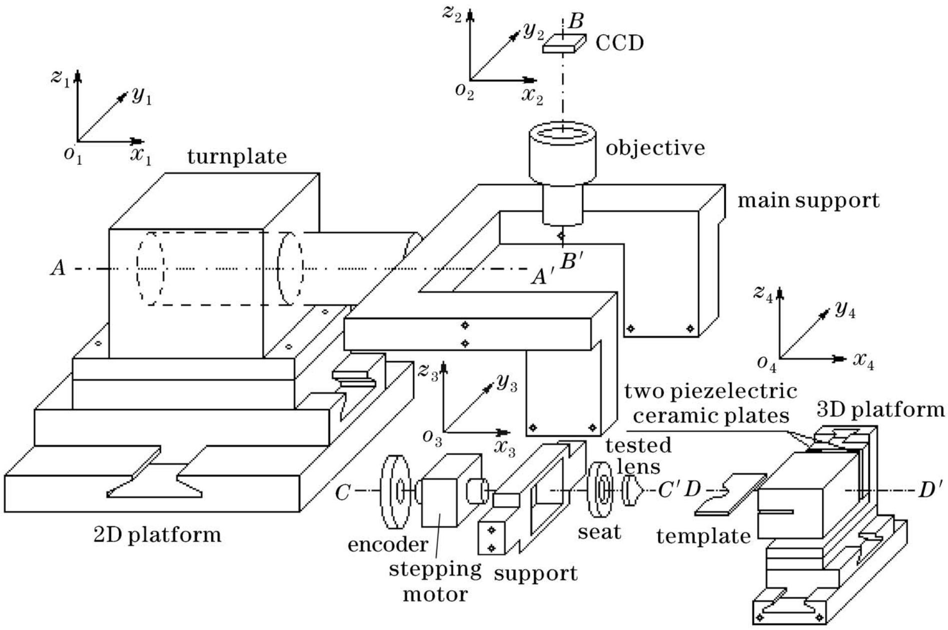

Fig. 3. Schematic of the measuring device.

is controlled within 1'. Secondly, the template is roughly adjusted though 3D platform after the template is rotated. To coincide the symmetric axis of the template and the rotationally symmetric axis of the tested surface, the two groups of piezoelectric ceramic plates are controlled to move template a little along y-axis and to adjust it finelyly rotating along z-axis. The coordinates are measured and 3D curvature surface is fitted at last.

There are two steps to adjust the template. The template's eccentricity and the inclination opposite tested surface in x-y plane are adjusted by n average collection in the whole work range of the template and the distances d_i ($i = 1, 2, \cdots, n$), from template to the surface, are measured. The square error is $\varepsilon = \sum_{i=1}^{n}(d_i - \overline{d})^2$, where $\overline{d} = \frac{1}{n}\sum_{i=1}^{n} d_i$.

To make the square error within the planned limit, the position of the template on x-y plane is adjusted finely by two groups of piezoelectric ceramic plates.

The second, the lens and the template are rotated 180° together round x-axis, the square error is measured and calculated. The axis of the template is eccentric in z direction if the two results are not consistent. The position of the template needs to be adjusted.

To verify the way presented in this paper, a convex spherical component with given curvature radius is measured. The radius is $R = 11.246 \pm 0.034$ (mm), its efficient diameter is $D_o = \phi 13.5$ mm, the processing precision of the radius is $N = -2$, the collected image and its partial enlarged picture are shown in Figs. 4(a) and (b). The measuring and calculating results are listed in Tables 1 and 2, respectively. The final result is obtained by interative algorithm after calculating several times and the curvature radius is 11.2463 mm.

The measurement error could be caused when the rotationally symmetric axis of the tested surface is installed inclined the on x-z plane.

Half-angle is less than 45° in most optical systems. Assume the arc height of the tested surface is $R/2$, where R is a standard aspheric parameter. The maximum error in x direction can be calculated from geography relation

$$\varepsilon = (R/2) - (R/2)\cos\Delta\theta, \tag{5}$$

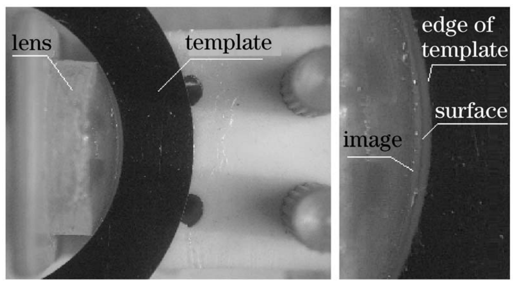

Fig. 4. Collected image and partial enlarged view.

Table 1. Measuring Results

	P_1	P_2	P_3
Template (x, z)	(257,125)	(0.0,170)	(−257,106)
Image (x, z)	(257,106)	(0.0,141)	(−257,82)
$z_C - z_B$	19	29	24

Table 2. Results of Calculation

	P_1	P_2	P_3
Template (x, z)	(257,125)	(0,170)	(−257,106)
x_B	95.83	107.48	102.22
a	−19.05	−29.06	−24.05
Surface (x, z)	(257,105.95)	(0,140.94)	(−257,81.95)

Table 3. Permitting Value of Inclination Angle $\Delta\theta$ for R

R (mm)	5	10	20	50	100	200	500	1000
$\Delta\theta$ (arc-min)	14	10	7	4	3	2	1.4	1.0

Table 4. Permitting Value of Eccentricity Δz for R

R (mm)	5	10	20	50	100	200	500	1000
Δz (mm)	0.020	0.028	0.040	0.063	0.089	0.126	0.200	0.283

where $\Delta\theta$ is the angle from mechanical axis to the rotationally symmetric axis of the tested aspheric surface.

Rewrite Eq. (5) to $\Delta\theta = \cos^{-1}(1 - \frac{2\varepsilon}{R})$. Assuming $\varepsilon = 0.02$ μm, the permitting value of inclination angle $\Delta\theta$ for R can be calculated, as Table 3 shows.

The measurement error may be caused when the rotationally symmetric axis of the tested surface is installed eccentrically in z direction. Assume the arc height of the tested surface is also $R/2$. The maximum error of arc height Δh can be deduced by the relation of $\Delta h = 1/2 \cdot \Delta R$, where ΔR is the variation of R.

Assuming the eccentricity is Δz, the relation is $(R - \Delta R)^2 = R - (\Delta z)^2$. It is simplifyed as

$$\Delta z = 2\sqrt{R\Delta h - (\Delta h)^2}. \tag{6}$$

Assuming $\Delta h = 0.02$ μm, the permitting value of eccentric Δz for R can be calculated, as listed in Table 4.

Based on above analysis, the measurement error is only 0.02 μm when the eccentricity of the lens or the template is 0.02 mm and the inclination is 1' on x-z plane. The adjusted precision of nanometer order moving and 0.01" order rotation can be realized by 3D platform and two groups of piezoelectric ceramic plates to adjust the relative position from the tested surface to the template on x-y plane. The error of 2D template is another important factor for measurement result. The measurement error is less than 0.05 μm for testing the template and writes down marks on it, the system error caused by template processing can be eliminated. The readout device is composed of an objective, a CCD, and a computer. The magnifying power of the objective is 40 and the interval of adjacent pixels on CCD is 7.5 μm. Therefore the interval in objective space is 0.19 μm. Sub-pixel order position can be measured by image processing and edge gray distribution. Resolution of 0.02 μm can be obtained when 1/10 pixel is distinguished. The error from remain aberrations of objective can be eliminated by moving the lens and the template together to the center field of the objective for each measurement. The position error of pixel on CCD is 0.25 μm. The corresponding error on objective plane is 0.006 μm. The final measurement precision is 0.2 μm in conclusion.

This work was supported by the National Natural Science Foundation of China under Grant No. 59875066.
The authors' e-mail addresses are bgwang@21cn.com (B. Wang) and huangdagang@nankai.edu.cn (D. Huang).

References

1. R. Freimann, B. Dörband, and F. Höller, Opt. Commun. **161,** 106 (1999).
2. W. Zhao, P. Wang, Z. He, and P. Hao, Journal of Tongji University (in Chinese) **31,** 1509 (2003).
3. H. Cheng and Y. Wang, Aviation Precision Manufacturing Technology (in Chinese) **40,** (4) 8 (2004).
4. H. Liu, Z. Lu, F. Li, and Y. Xie, Opt. Commun. **241,** 131 (2004).
5. J. Chang, F. Li, Z. Weng, Z. Zhang, H. Jiang, and X. Cong, Acta Opt. Sin. (in Chinese) **23,** 1266 (2003).
6. S.-W. Kim, W.-J. Cho, and B.-C. Kim, Meas. Sci. Technol. **9,** 1129 (1998).
7. C. Zhou, Appl. Opt. (in Chinese) **18,** (5) 8 (1997).
8. H. Wang, Y. Li, L. Zeng, C. Yin, and Z. Feng, Opt. Commun. **232,** 61 (2004).
9. Q. Zhu and Q. Hao, Opt. Technique (in Chinese) **128,** (11) 22 (2002).
10. M. Zhang and H. Chen, Opto-Electronic Eng. (in Chinese) **26,** (Sup.) 1 (1999).
11. P. Wang, W. Zhao, M. Hu, H. Zhang, and P. Hao, Opt. Precision Eng. (in Chinese) **10,** 139 (2002).
12. Z. Li, Y. Zhao, D. Li, Acta Opt. Sin. (in Chinese) **22,** 1224 (2002).
13. http://www.olympus.com.
14. http://www.taylor-hobson.com.
15. http://www.Zygo.com.
16. Y. Chen, X. Huo, J. Lin, and H. Xu, Acta Laser Biology Sin. (in Chinese) **9,** 154 (2000).