

**TESTING OF ASPHERIC SURFACES WITH A MAGNETO-OPTIC
ACTIVE COMPENSATOR
FIELD OF THE INVENTION**

The present invention relates to the testing of aspheric optical surfaces,
5 and more particularly to an optical arrangement for performing the profiling of a
generally aspheric surface with an optically active compensator.

DESCRIPTION OF THE PRIOR ART

It has been proved mathematically that a spherical surface can never
form a perfect image of a finite object either by reflection or by refraction. The
10 most common type of defects caused by the geometry of a spherical surface is
known as spherical aberration. In order to reduce the spherical aberration and
obtain better imaging performance, several spherical surfaces are usually
employed in the design of an optical system, which may make the system bulky
and heavy. However, using aspheric surfaces in the optical system can reduce
15 this aberration. Aspherics may also be used to correct for other image
aberrations, such as image distortion. Generally speaking, aspherics can be
classified as conic sections, axi-symmetrical aspherics, and general aspherics.
This invention is generic and could be applied to measure the surface profiles of
all kinds of aspherics.

20 As optical fabrication and processing have made much progress,
especially after the advent of precision diamond-turning machines in the
fabrication of aspheric surfaces, the only technological barrier to the prolific use
of aspherics in optical systems is the precise testing and measurement of the
aspheric elements. A brief review of the various techniques can be found in J.
25 C. Wyant, "Interferometric testing of aspheric surfaces", Proc. SPIE Vol.816,
pp616-636 (1987). Amongst the available testing techniques, the most common
method is interferometry. However, when the departure of the aspheric shape
from the best fitting spherical surface is too large, the interference fringes
produced by interferometry can become too dense to be detected. In this case,
30 various techniques have been proposed to decrease the density of the fringes.
Of these available techniques, immersing the test elements into a proper liquid

to reduce the interference fringe density is a very simple, cheap and effective technique. For example, it has been proposed to immerse the aspheric element into oils to reduce the interference fringe density [Zhisheng Yun, Zhongben Liu and Yulin Li, "Aspheric surface testing with a liquid compensatory interferometer", Opt. Eng. Vol 37 (4), pp1364-1367 (1998)]. The disadvantage of this method is a need to mix the two liquids to achieve a matching refractive index with the test element. An improved method is to immerse the test element into a liquid crystal material in a container. By using crystal interference techniques, one can obtain the profile of the test aspheric element [Zhishen Yun, Yee Loy Lam, Yan Zhou, Yulin Li, Zhongben Liu and Jian Liu, "A simple technique to test deep aspheric surfaces", Opt. Eng. Vol 38 (4), pp650-654 (1999)]. However, as the availability of liquid crystal materials is limited, one may not be able to obtain suitable liquid crystals having refractive index differences between the o-rays and the e-rays (i.e. the orthogonally-polarized ordinary rays and the extraordinary rays) to be larger than 0.16. As a result, the dynamic range of the testing method is limited, i.e. the method cannot be used to test aspheric elements with a significant deviation from the best fitting spherical surface or a large slope.

It would therefore be desirable to provide a means of increasing the test dynamic range in an apparatus for the testing of aspheric surfaces. It would be further desirable to provide a method to obtain controllable fringe density in the testing of aspheric surfaces.

SUMMARY OF THE INVENTION

In accordance with one aspect of the invention, there is provided an apparatus for testing aspheric optical surfaces comprising:

- a container for liquid in which an aspheric element to be tested is immersed;
- means for producing and directing a beam of light onto the aspheric element;
- polarizing means for polarizing the beam of light; and

analysing means for analysing the polarized light beam after it has passed through or been reflected by an aspheric surface of the aspheric element;

characterized in that the liquid in which the aspheric element is immersed is a magneto-optic liquid and means is provided for producing a magnetic field
5 in the container.

According to another aspect of the invention, there is provided a method of testing aspheric optical surfaces comprising the steps of:

immersing an aspheric element in a liquid;
producing and directing a polarised beam of light onto the immersed
10 aspheric element; and

analysing the polarised beam of light after it passes through or is reflected from an aspheric surface of the aspheric element;

characterised in that the liquid in which the aspheric element is immersed is a magneto-optic liquid and a magnetic field is produced in the liquid.

15 Preferably, the magnetic field in the magneto-optic liquid is variable so as to achieve tunability of fringe spacing when the polarized light beam is analysed after passing through the liquid in the container and after passing through or being reflected by the aspheric surface. The means for producing and varying the magnetic field in the container preferably comprises a solenoid
20 and an adjustable source of electrical current. By adjusting the current applied to the solenoid, a changeable magnetic flux density can be obtained in the magneto-optic liquid. This enables a larger and adjustable dynamic range to be achieved in measuring the surface profiles of aspheric elements of various shapes.

25 Preferably, the beam of light is a coherent, collimated light beam that may be produced by a laser source and a collimating lens system. Technically speaking, the collimated laser beam is referred to as a planar wavefront. In testing, when the polarised planar wavefront passes through the container with the immersed aspheric element under test (EUT) and with an applied magnetic
30 field, the beam at each point of the wavefront will be resolved into its left-hand (LH) circularly polarised and right-hand (RH) circularly polarised components.

Owing to the magneto-optic effect, a phase delay between these two components will result when the beam propagates through the liquid path and the aspheric EUT. Therefore, the output wavefront will exhibit different polarisation directions at different points of the wavefront, depending on the relative phase delays introduced between the LH and RH circularly polarised components, respectively. In other words, the polarisation direction of the plane wavefront emerging from the container will change according to the profile of the aspheric surface being tested. After passing through the analyser, the fringes formed will carry information on the aspheric profile of the test element. For example, if a rotationally symmetrical optical element is immersed in the container, a rotationally symmetrical fringe pattern will be observed after the analyser. As the aspheric element under test and the magneto-optic liquid have different rotatory powers, the aspheric profile can be derived after analysing the fringes formed by this method. It should be noted that the measurement method is valid for any generally aspheric surface.

When the aspheric surface to be tested is the concave or convex surface of a transmissive element, such as a lens, the polarised beam of light is directed to pass through the aspheric element and the liquid in the container to the analysing means.

Alternatively, when the aspheric surface to be tested is a reflective surface, the polarised beam of light is reflected off said reflective surface to the analysing means. In this case, a beam splitter is preferably provided for splitting the polarised beam of light.

The apparatus in accordance with the invention may further comprise an imaging lens to relay/focus the light intensity distribution after the analyser onto the focal plane of a CCD camera. Preferably, a computerised processing means is also provided for processing the data from the CCD detector to produce a representation of the aspheric surface, which may then be displayed on a display means, such as a monitor.

BRIEF DESCRIPTION OF THE DRAWINGS

Two preferred embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 shows a first configuration of apparatus for optically measuring an aspheric surface in accordance with the invention;

Figure 2 shows the magneto-optic liquid container and the means for producing a variable magnetic field in the container of Figure 1; and

Figure 3 shows a modified configuration of apparatus in accordance with the invention for optically measuring a reflective aspheric surface.

10 DETAILED DESCRIPTION OF THE INVENTION

As shown in Figure 1, a device for optically measuring an aspheric surface according to the present invention includes a laser beam source 10, a beam collimator 20, a polarizer 21, an analyser 22, a magnetic field generator 40, a magneto-optic liquid container 30, an imaging lens 50, a CCD camera 51, a computer 52 and a monitor 53. These components jointly constitute a device for testing an aspheric optical element.

A laser beam emitted by the laser source 10 is focused to a pinhole 12 by a microscope objective lens 14. Then a collimating lens system 20 is used to collimate the laser beam to a parallel-ray beam of a certain beam diameter, which then passes through a uniform but variable magnetic field produced in the container 30 by the solenoid 40. The collimating lens system 20 is preferably a cemented doublet comprising a plano-convex lens 23 and a convexo-concave lens 24.

A transmissive aspheric object 28, such as a lens that is made of a glass or plastic material, is immersed into the liquid 41 in the container 30. The axis of the aspheric EUT can be tilted using a suitable lens holder (not shown) so that its aspheric surface to be measured is aligned perpendicular to the polarised collimated laser beam to produce an interferogram that is circular for a rotationally symmetric aspheric element. The imaging lens 50 and a CCD camera constitute the detecting part of the measurement system, and the

computer 52 and monitor 53 constitute the data processing and output display part of the device.

The container 30 is filled with a magneto-optic liquid 41 having a large Verdet constant and which preferably includes a ferromagnetic material, such a
5 Co Fe₂ O₄, which has the ability to rotate the polarization direction of the collimated beam of light. The ferromagnetic material is dissolved in a liquid carrier, such as dibutyl phthalate. The aspheric EUT 28 is immersed in the magneto-optic liquid 41 between the polarizer 21 and the analyser 22 and at the
10 centre of the solenoid 40 as shown in Figure 2. The solenoid 40 is connected electrically to an adjustable source of direct current (d.c.) 44 so that the uniform magnetic field in the container 30 can be varied.

The container 30 is preferably formed from five glass plates which constitute the base and side walls of the container. Preferably, the front and rear side walls 31, 32 through which the collimated polarized beam passes are
15 working glass plates and are precisely processed. Their surface error and the parallel error are to be very small, and their flatness is controlled to within $\lambda/15$.

After the light beam passes through the liquid crystal container 30, as shown in Figure 1, the polarization direction of the plane wave will change according to the thickness profile of the immersed aspheric test element. As the
20 analyser 22 is positioned after the container, the LH and RH circularly polarised components of the emerging wavefront will interfere at the analyser to form a fringe pattern that bears information on the surface profile of the aspheric EUT.

A rotationally symmetrical fringe intensity distribution will be seen if the test element is rotationally symmetric, and a general fringe pattern will be formed
25 by a general aspheric.

The imaging lens 50 located behind the analyzer 22 is used to image the interference fringes on to the CCD panel of the camera 51, and the image is processed and analysed mathematically by the computer 52. The display monitor 53 is the output of the device for showing the interference fringes and
30 the three-dimensional profile of the aspheric test surface.

The mathematical analysis is demonstrated as follows, according to cylindrical coordinate system. Supposing the thickness of the EUT is $d(r, \theta)$ and the centre thickness of it is d_0 . The Verdet constant of the liquid is V_1 and the Verdet constant of the EUT is V_2 . B is the uniform magnetic flux density at the EUT in the container. If $m(r, \theta)$ fringes are counted at the test point (r, θ) from the center, then the thickness function $d(r, \theta)$ can be expressed as

$$d(r, \theta) = \frac{C m(r, \theta)}{(V_2 - V_1) B} \pm d_0 \quad (1)$$

where C is a constant that depends on the convention of units used, and the scaling effect due to any imaging effects.

The dimensions of the above variables are lengths d and d_0 in mm, Verdet constants in min/gauss.mm, and B in Gauss.

When one surface of the test element is a plano surface and the other is an aspheric surface, the aspheric surface depth can be expressed by

$$Z(r, \theta) = \frac{C m(r, \theta)}{(V_2 - V_1) B} \quad (2)$$

When the second surface of the EUT is a spherical surface, the aspheric surface depth of the front surface can be expressed by

$$Z(r, \theta) = \frac{C m(r, \theta)}{(V_2 - V_1) B} \pm \left(R_0 - \sqrt{R_0^2 - r^2} \right) \quad (3)$$

where R_0 is the radius of the spheric surface. If the spheric surface is concave, the sign in the above equation is plus, otherwise the sign is minus. After the fringe order from the center to the test point (r, θ) is determined, the depths of a set of discrete points of the test surface can be obtained by using Eq. (2) or (3).

Fitting the discrete points by Zernike polynomial or otherwise, the user can obtain the aspheric surface profile.

An apparatus for testing a reflective aspheric surface, such as a surface of a mirror, is depicted schematically in Figure 3. The apparatus is similar to that of Figure 1 and corresponding reference numerals have been applied to corresponding parts. As described in testing a transmitting aspheric element such as a lens as mentioned above, the laser beam 10 is collimated by the collimating system 20 and propagates through a polarizer 21. The apparatus for testing a reflective aspheric surface also includes a beam splitter 25. Then it passes through the front glass plate 31 and the magneto-optic liquid 41 and reaches the aspheric EUT 38. The beam is reflected back through the front glass plate 31 of the container 30 and directed by the beam splitter 25 onto the analyzer 22. The reflected beam contains the information of the aspheric surface under test after being reflected by the aspheric EUT. The analyser 22 is used to form the fringes introduced by the reflective aspheric surface. Following that an imaging lens 50 located behind the analyzer 22 is used to image the interference fringes on to the CCD panel of the camera 51 which is processed and analysed mathematically by the computer 52. A monitor 53 will show the interference fringes and the three-dimensional profile of the aspheric test surface.

For testing a reflective aspheric surface, the mathematical analysis is given in the following. If the fringe order number at a test point (r, θ) is $m(r, \theta)$, the depth of the test point can be expressed as

$$Z(r, \theta) = \frac{C m(r, \theta)}{2(V_2 - V_1)B} \quad (4)$$

After the depths of a set of discrete points of the test aspheric surface are obtained by the above equation, fitting the discrete points by Zernike

polynomials or otherwise will allow the profile of the reflective aspheric surface to be determined.

In each of the embodiments described above, the strength of the magnetic flux density B in the liquid 41 can be varied by adjusting the direction and the
5 magnitude of the electric current through the solenoid 40 so that the fringe spacing and direction of movement of the interference fringes can be tuned in a controllable manner, thereby controlling the dynamic range of testing of the apparatus.

The present invention has been described hitherto with exemplary
10 preferred embodiments. However, it is to be understood that the scope of the present invention need not be limited to the disclosed above preferred embodiments. On the contrary, it will be appreciated that various modifications may be made to the apparatus and methods described above without departing from the scope of the invention as defined in the following appended claims.

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CLAIMS

1. Apparatus for testing aspheric optical surfaces comprising:
5 a container (30) for liquid in which an aspheric element (28; 38) to be tested is immersed;
means (10, 20) for producing and directing a beam of light onto the aspheric element (28);
polarising means (21) for polarising the beam of light;
10 analysing means (22) for analysing the polarised light beam after passing through or being reflected by an aspheric surface of the aspheric element;
characterised in that the liquid in which the aspheric element is immersed is a magneto-optic liquid (41) and means (40) is provided for producing a magnetic field in the container (30).
15
2. Apparatus according to claim 1 further comprising means (44) for varying the magnetic field in the container (30) of magneto-optic liquid.
3. Apparatus according to claim 2 wherein the means for producing and
20 varying the magnetic field comprises a solenoid (40) and an adjustable source of electrical current (44).
4. Apparatus according to claim 1 wherein the magneto-optic liquid (41) includes a ferromagnetic material having a high Verdet constant.
25
5. Apparatus according to claim 4 wherein the ferromagnetic material comprises $\text{Co Fe}_2\text{O}_4$.
6. Apparatus according to claim 4 or claim 5 wherein the ferromagnetic
30 material is dissolved in a liquid carrier.



7. Apparatus according to claim 6 wherein the liquid carrier is dibutyl phtalate.
8. Apparatus according to claim 1 wherein the means for producing a beam
5 of light comprises a laser source (10) and a collimator lens system (20).
9. Apparatus according to claim 8 wherein the collimator lens system (20) includes a cemented doublet comprising a plano-convex lens (23) and a convexo-concave lens (24).
10. Apparatus according to claim 1 wherein the container has at least one
10 wall (31) formed from a glass plate of optical grade glass.
11. Apparatus according to claim 10 wherein said glass plate (31) is
15 precisely processed with very small surface error, parallelism error, and surface flatness error.
12. Apparatus according to claim 1 wherein the aspheric surface to be tested
20 is the concave or convex surface of an aspheric lens (28) and the polarised beam of light passes through the aspheric lens (28) and the liquid (41) in the container to the analysing means (22).
13. Apparatus according to claim 1 wherein the aspheric surface to be tested
25 is a reflective surface of a reflective aspheric element (38), and the polarised beam of light is reflected off said reflective surface to the analysing means (22).
14. Apparatus according to claim 13 further including a beam splitter (25) for splitting said polarised beam of light.



15. Apparatus according to claim 1 further comprising an imaging lens (50) for focusing light from the analysing means (22), and a camera (51) for detecting the focussed light.
- 5 16. Apparatus according to claim 15 further comprising a processing means (52) for processing data from the camera (51) to produce a representation of the aspheric surfaces.
- 10 17. Apparatus according to claim 16 further comprising a display means (53) for displaying the representation of the aspheric surface.
18. A method of testing aspheric optical surfaces comprising:
immersing an aspheric element (28; 38) in a liquid (41);
producing and directing a polarised beam of light onto the immersed
15 aspheric element; and
analysing the polarised beam of light after it passes through or is reflected from an aspheric surface of the aspheric element (28; 38);
characterised in that the liquid in which the aspheric element (28; 38) is immersed is a magneto-optic liquid (41) and a magnetic field is produced in the
20 liquid (41).
19. A method according to claim 18 wherein the magnetic field in the magneto-optic liquid (41) is variable.
- 25 20. A method according to claim 18 wherein the beam of light is a coherent, collimated light beam.
21. A method according to claim 18 wherein the aspheric surface to be tested is the concave or convex surface of an aspheric lens (28), and the beam of light
30 is directed to pass through the aspheric lens (28).



22. A method according to claim 18 wherein when the aspheric surface to be tested is a reflective surface, and the beam of light is reflected off the surface of the aspheric element (38).

5 23. A method according to claim 22 further comprising the step of splitting the beam of polarised light.

24. A method according to claim 18 further comprising the steps of focussing and detecting the beam of light after it passes through or is reflected
10 from the aspheric surface and analysed.

25. A method according to claim 24 further comprising the step of processing data obtained from detecting the light wave distribution to produce a representation of the aspheric surface.

15 26. A method according to claim 25 further comprising the step of displaying the representation of the aspheric surface.

