Reprinted from APPLIED OPTICS, Vol. 14, page 1607, July 1975

Interferometer for measuring power distribution of ophthalmic lenses

J. C. Wyant and F. D. Smith

The use of a lateral shear interferometer in measuring the power variation of ophthalmic lenses is described and demonstrated. It is shown that an appropriate lateral shear interferometer directly measures the power variation of an ophthalmic lens. If the ophthalmic lens has a toric surface, the power for each axis can be measured separately. Individual surfaces can be tested, as well as the whole lens or the different segments of a multifocal lens. The sensitivity of the test can be selected by varying the amount of lateral shear. Because of the demonstrated simple relationship between fringe spacing and dioptric power, qualitative examination of the fringes has proved a useful adjunct to conventional quality control methods.

Introduction

The testing requirements for ophthalmic objectives differ in many ways from the testing requirements for other lenses such as photographic objectives. For example, the eye uses only a small portion of the ophthalmic lens at a given time for high resolution central vision, so that the lens need only provide fractional wavelength optical quality at any instant over a region roughly comparable to the pupil of the eye. Of particular importance is the variation of power (expressed in diopters) as the line of sight moves to different parts of the lens. This power variation, which includes an astigmatic component, depends, for a perfectly fabricated lens, upon the lens design and cannot be made simultaneously zero for all parts of the lens. It is of value to be able to measure this quantity directly.

A test of an ophthalmic lens at full aperture in a Twyman-Green interferometer, for example, would therefore not only be far too sensitive and difficult to use with toroidal wavefronts, but would yield data not easily transformable to the essential parameter of dioptric power. A truly precise measurement of the power variation could be carried out by illuminating the lens with a parallel beam of light and then scanning across the lens with a viewing and measuring system of appropriate aperture (a few mm) that rotates at the nominal rotation center of the eyeball. Such an apparatus would be relatively complex, and data, though they could be directly expressed in diopters, would be somewhat voluminous.

It has been found that a lateral shearing interferometer[1,2] can satisfy the above requirements for testing ophthalmic lenses. The sensitivity of a shearing interferometer test can be selected by varying the amount of shear. Variations in the fringe spacing give an immediate qualitative determination of local dioptric power variation, and this fringe spacing has a simple and direct quantitative relationship to the power variation in the shear direction. The power in each principal meridian of a toric lens can be measured if the lens is oriented so that the appropriate axis is perpendicular to the direction of the shear. The distance and near vision portions of a multifocal lens can be examined. Also, individual surfaces can be tested as well as the whole lens.

In our experience, small optical defects, readily visible to a trained inspector by flaring (visual examination of a lens held in Maxwellian view), can be readily shown, recorded, and quantified with this method.

Concept

Figure 1 shows one method of using a lateral shearing interferometer for measuring the power distribution of a lens. The lens being tested is placed in either a diverging or a converging beam of light so that the light leaving the lens is essentially collimated. This collimated beam is now incident on a plane parallel plate of glass. Part of the collimated beam is reflected from the front surface of the glass and part of it is reflected from the back surface. The two reflected beams are displayed laterally (sheared) a distance S. If the beam leaving the lens is not perfectly collimated, interference fringes will appear in the

When this work was done both authors were with Itek Corporation, Lexington, Massachusetts 02173; J. C. Wyant is presently with the Optical Sciences Center, University of Arizona, Tucson, Arizona 85721.

Received 27 November 1974.

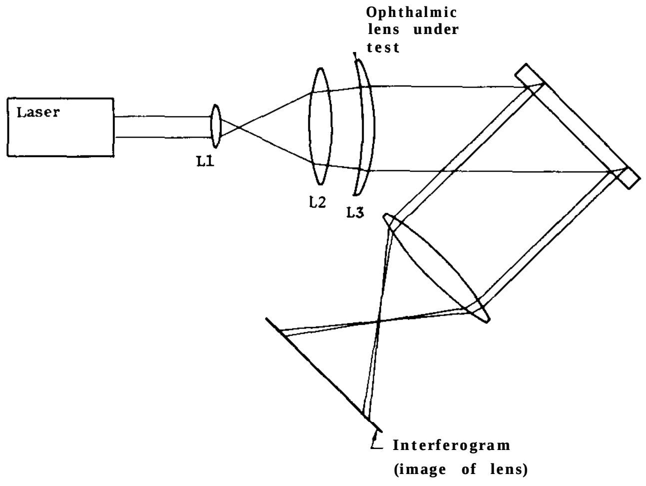


Fig. 1. Lateral shearing interferometer for measuring power distribution of lens.

common area of the two reflected beams.[3] It will now be shown that the spacing of these fringes is inversely proportional to the relative local power of the lens.

Over a small region of the lens, the lens power is essentially constant and the light leaving the lens is either converging to, or diverging from, a point a distance L from the lens. After reflection off the plane parallel plate of glass, the two beams of light appear to be coming from two point sources a distance S (the shear) apart, as shown in Fig. 2. If we assume unit magnification, the image of the lens under test contains interference fringes formed by the two point sources separated a distance S, a distance L away. It is easy to show that if $L >> S$, the separation x of these fringes is given by:

$$x = (\lambda L)/S. \tag{1}$$

Solving for L yields

$$L = (Sx)/\lambda. \tag{2}$$

The interferometer shown in Fig. 1 can be adjusted so that light leaving the center of the lens is essentially collimated. Then, if near the edge of the lens two interference fringes separated a distance x are obtained, the average power of the lens in the direction of shear for the region near these two fringes is different from the power of the lens (measured in the direction of the shear) at the center of the lens by an amount equal to

$$P = 1/L = \lambda/(xS). \tag{3}$$

An equivalent way of showing that the spacing between the fringes in a shearing interferogram is inversely proportional to the local power of the wavefront is the following: The fringes in a shearing interferogram are loci of points where the average slope across the shear distance is equal to an integer number of waves divided by the shear distance. Thus, if ϕ is the phase of the wavefront and $d\phi/dx$ is the average value of the slope over the shear distance,

$$(\overline{d\phi})/(dx) = (n\lambda)/S, \tag{4}$$

where n is an integer. For small slope angles, the curvature or power of the wavefront is approximately equal to the second derivative of the wavefront. The average of the second derivative of the wavefront between two adjacent fringes of orders n and $n + 1$ separated a distance x is given by

$$P = \left.\frac{d^2\phi}{dx^2}\right|_{\text{avg}} = \frac{\left.\frac{d\phi}{dx}\right|_{n+1} - \left.\frac{d\phi}{dx}\right|_{n}}{x}, \tag{5}$$
$$= \lambda/(xS).$$

Thus, Eqs. (3) and (5) give the same result for the power variation as a function of fringe separation x.

Since the interferometer measures power only in the direction of the shear, the power in each principal axis of a toroidal lens can be measured separately when the lens is oriented so that one of the cylinder axes is perpendicular to the direction of the shear. The correct orientation of the axes is obtained by rotating the lens so the fringes in the final interferogram are most nearly perpendicular to the direction of the shear. The power of the second principal axis of a toroidal lens can then be tested by rotating the lens 90°.

Adjusting the interferometer so that the light leaving the center of the lens under test is essentially collimated may produce two problems. First, with this technique only the magnitude and not the sign of the residual power is obtained. Second, it is difficult to determine when two adjacent fringes have the same order number (i.e., one fringe is a continuation of the other), in which case the average powerbetween the two fringes is zero. These two problems can be solved by adjusting lens Ll in Fig. 1 so that all light leaving the lens under test is converging (or diverging). This average power added can be subtracted in the data reduction process.

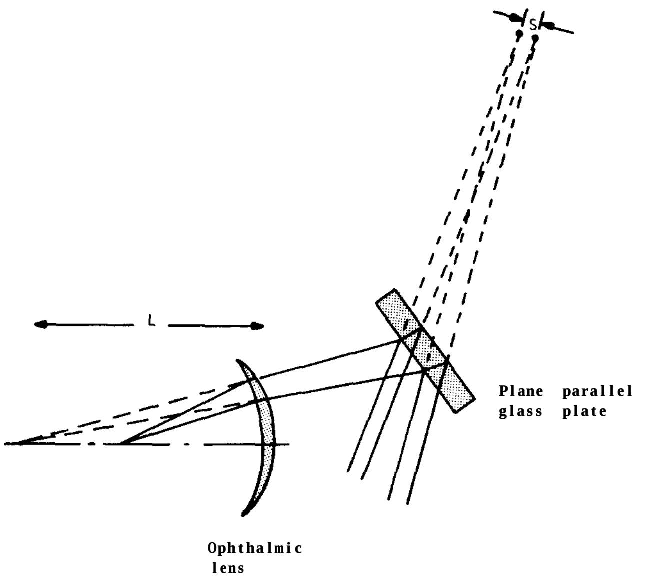


Fig. 2. Two point sources produced by reflection off both surfaces of plane parallel glass plate.

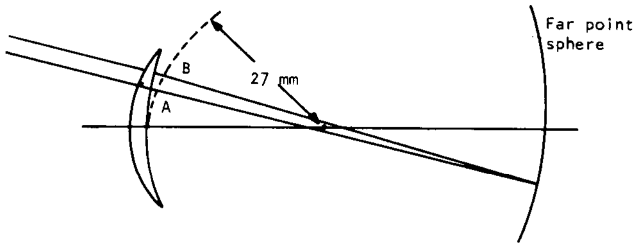


Fig. 3. Ideal test of periphery power.

Equation (5) is valid only for unity magnification; i.e., the interferogram is the same size as the lens under test. If the interferogram is M times as large as the lens, both the shear S and the distance x between fringes on the interferogram are M times as large as the corresponding distances on the lens under test. Therefore, if M is the magnification of the system and x and S are measured on the interferogram, the power variation of the lens is given by

$$P = (M^2\lambda)/(xS). \tag{6}$$

Equation (6) gives the power variation of lens used in transmission, or the power of the lens surface when the surface is tested in reflection. If a single surface of a lens is tested, the contribution of the surface to the transmission power variation of the lens is given by

$$P_S = [(n-1)/2](M^2\lambda/xS) \sim \tfrac{1}{4}(M^2\lambda/xS). \tag{7}$$

Corrected curve lenses are meniscus in shape to minimize variations in power as the eye looks through different portions of the lens. In design of the lens it is assumed that the eye rotates about a fixed point, typically 27-30 mm away. As shown in Fig. 3, the power in the periphery that should be measured is the curvature of the wavefront at the region AB of the vertex sphere center 27-30 mm from the lens. Since this measurement is difficult to perform in practice, most of our measurements to date have been performed at either infinite conjugates, as shown in Fig. 1, or preferably by illuminating the lens with a point source that is located approximately 27 mm away. This will give a close approximation to the ray paths of Fig. 3. The residual error in testing in this way or at incorrect conjugates can be computed as long as the ophthalmic lens design is known. We have not found this procedure necessary, however, for practical use of the method. Even without any computer calculations, the general regularity of the lens can be measured and expressed in diopters. Also, all surface power variation measurements can be performed, since all measurements are made relative to the center of curvature.

Experimental Setup

Figure 4 shows a diagram of the lateral shear interferometer that can be used for both transmission and surface measurements of ophthalmic lenses. A small flat mirror M_1 should be mounted so that it can be swung into the position shown when surface measurements are made. The mirror should be swung out of the system when transmission measurements are made. To make surface measurements, lenses L_1 and L_2 must be used to expand the laser beam so it fills the aperture of lens L_3. After the light beam is collimated with lens L_2, it is transmitted through parallel plate Pl to lens L_3. Lens L_3 is used to focus the collimated beam. The lens under test is placed so that the center of curvature of a portion of the surface being tested is at the focus of lens L_3; i.e., if a convex surface is being tested, the lens is placed at the appropriate position between lens L_3 and the focus of lens L_3. When a concave surface is being tested, the lens under test is placed at the appropriate position after focus. The light is reflected off the

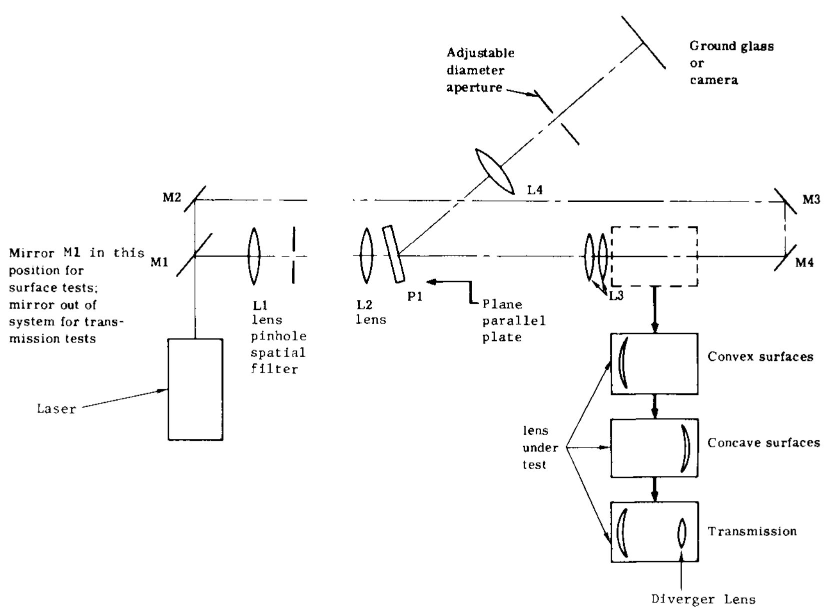
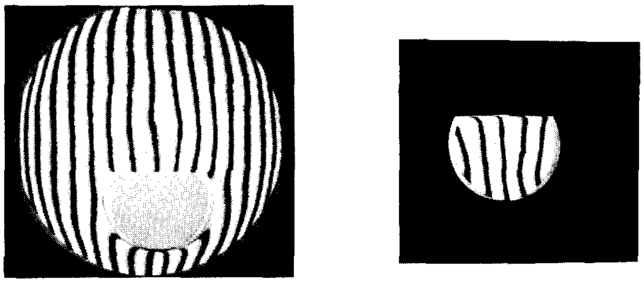


Fig. 4. Lateral shear interferometer for performing both transmission and surface power measurements of lenses.



Lens with segment Segment

Fig. 5. Shearing interferograms obtained testing ophthalmic lens and segment in transmission.

surface being tested back through lens $L3$, where it is again recollimated. If the surface being tested is not perfect, or if it has astigmatism, the light will not be perfectly collimated. After the collimated beam leaves lens $L3$, it is reflected off both surfaces of the plane parallel plate P1. Thus, two sheared beams are obtained that produce interference fringes. The amount of shearing is controlled by the thickness and tilt of this plate.

Lens $L4$ is used to image the surface being tested onto either a ground glass screen or a camera. An adjustable aperture should be placed in the back focal plane of lens $L4$ so as to reduce the stray light caused by reflection off the surface of $L3$. Since the position of the lens being tested changes as different radius-of-curvature surfaces are being tested, the final image position will change. Thus, it must be easy to change the position of the camera so as to always keep the image of the surface under test in focus.

It should be mentioned that by changing the distance between lens $L3$ and the lens surface under test (i.e., introducing defocus), the zero point of the power variation can be moved to any place. That is, defocusing changes the final interferogram and the relative power measured at any given point. It adds, however, the same amount of power to each point. Thus, the difference in power between two points remains constant, and if a plot were to be made of the power variation vs position, defocusing would move the curve up or down, but the shape of the curve would not change.

When a lens is to be checked in transmission, mirror M_1 is moved out of the laser beam so that the beam reflects off mirrors M_2, M_3, and M_4. A diverger lens is then placed between lens $L3$ and M_4. The lens under test is placed between the diverger lens and lens $L3$. The diverger lens should be positioned so the light leaving lens $L3$ is essentially collimated. When the light is collimated and the lens under test is correctly oriented, the transmitted beam will come into focus at the pinhole placed at the focus of $L1$. Just as for reflection measurements, lens $L4$ should be adjusted so the lens under test is focused on the camera. The resulting interferogram gives the power variation of the lens. Equations (6) or (7) can be used to convert the fringe spacing to power variation.

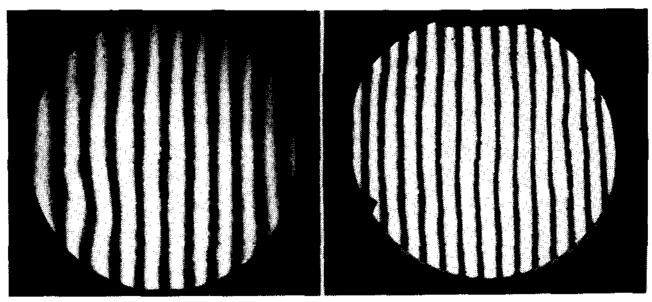
Experimental Results

Figure 5 shows the results for testing an ophthalmic lens and segment in transmission. On the original photos, which were taken at unit magnification, the shear was approximately 1.5 mm. Since the wavelength was 0.6328 μ, Eq. (6) shows that the power variation is given by

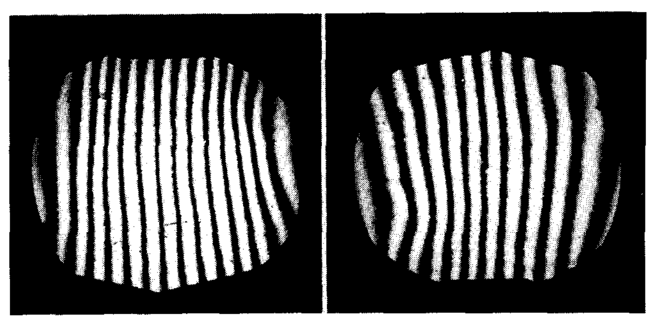
$$P \simeq 0.4/x \text{ diopters}, \tag{8}$$

where x, the distance between fringes, is measured in millimeters. If we use the above equation, the maximum power variation over the entire lens surface is approximately 0.12 diopter. The add-on power of the segment is found to be approximately 1.5 diopters. The right-hand photograph in Fig. 5 was obtained by adjusting the position of the diverger lens shown in Fig. 4 to subtract an additional 1.5 diopters of power in order to obtain a shearing interferogram of the segment, which contains fewer fringes and gives a better idea of the power variation of the segment.

Figure 6 shows some typical shearing interferograms obtained by testing ophthalmic lenses in transmission. The two top photos were made of lenses having only spherical power, while the lenses tested



-2 Diopters -6 Diopters



+2 Diopters Spherical
+1 Diopter Cylinder

-2 Diopters Spherical
+l Diopter Cylinder

Fig. 6. Typical shearing interferograms obtained testing glass ophthalmic lenses in transmission.

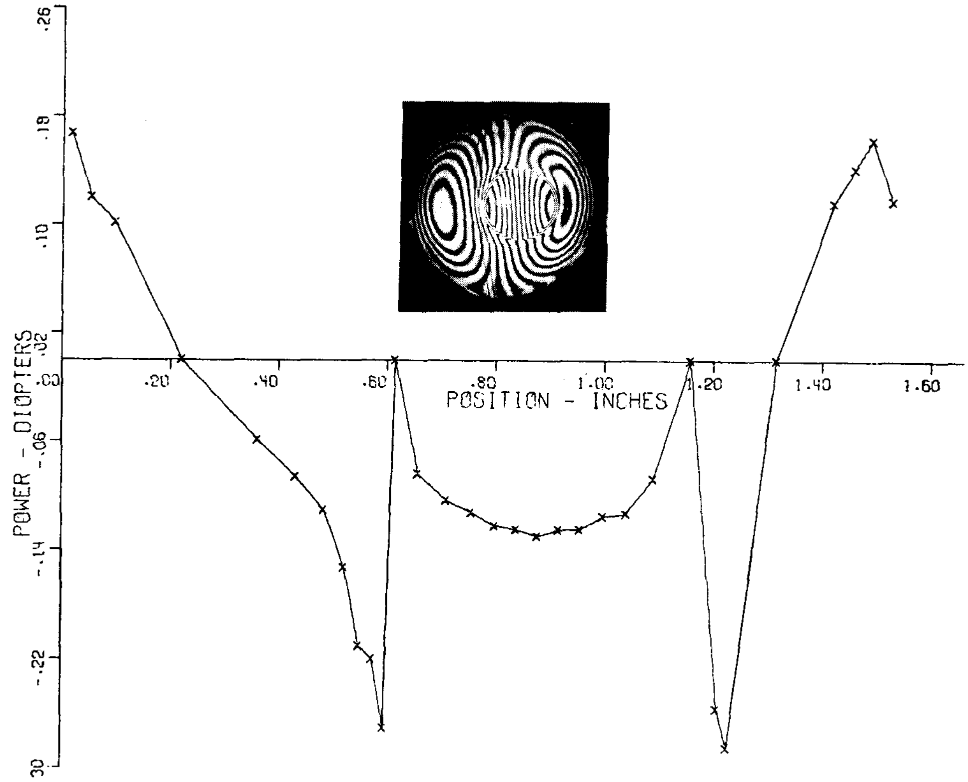


Fig. 7. Power variation of convex surface of plastic ophthalmic lens.

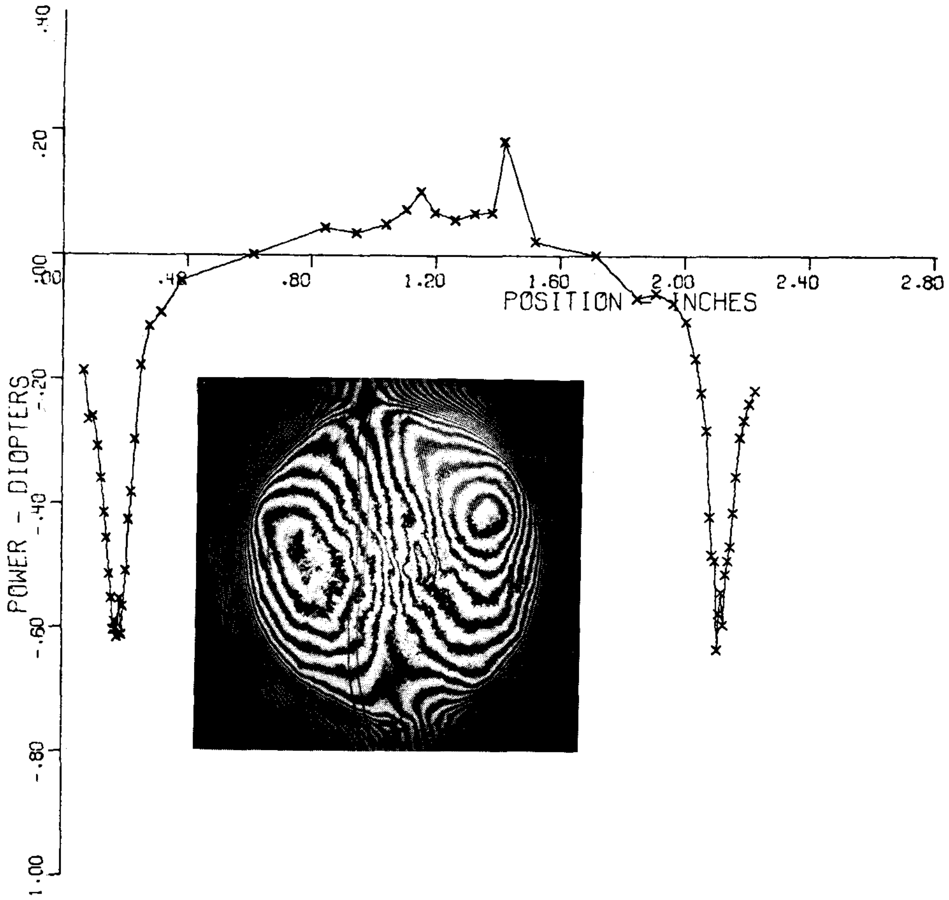


Fig. 8. Power variation of concave surface of plastic ophthalmic lens.

to obtain the bottom photos had 1 diopter of cylinder present. When the toroidal lenses were tested, the cylinder axis was in the shear direction. Equation (8) gives the power variation for all the lenses shown in Fig. 6.

Although most lenses tested were of good quality, Figs. 7 and 8 are included to show some results obtained from testing some inferior lenses. Figure 7 shows the results of a test of the convex surface of a plastic ophthalmic lens. The computer plot of the power variation was obtained by measuring the fringe spacing along a horizontal line drawn through the center of the interferogram. The interesting feature seen in the center of the interferogram is a near discontinuity in the lens curvature. This curvature change, which shows up clearly in the interferogram, could also be seen with difficulty by looking at light reflected off the surface of the lens. The curvature change is likely due to premature mold release.

Figure 8 shows the results of testing the concave surface of a plastic ophthalmic lens. As in Fig. 7, the power variation plot shown gives the power variation across the center of the lens. For this lens, the power is essentially constant in the center of the lens, but changes rapidly at the edges. An interesting feature of the interferogram shown in Fig. 8 is the structure of the fringes in the center of the interferogram. Although it was difficult to notice with the naked eye, the interferogram shows that the center of the lens has a rough surface.

Conclusion

A lateral shear interferometer provides a convenient way of evaluating ophthalmic lenses, since it directly measures the power variation of the lens. The sensitivity of the test can be controlled by varying the amount of shear. The lateral shear interferometer measures power in only the shear direction, so the power of each axis of a toric lens can be measured separately by orienting the lens so that one toric axis is perpendicular to the shear direction. Individual surfaces, as well as the whole lens, can be tested.

References

1. W. J. Bates, Proc. Phys. Soc. (London) 59, 940 (1947).
2. O. Bryngdahl, in *Progress* in *Optics,* E. Wolf, Ed. (North-Holland, Amsterdam, 1965), Vol. 4, p. 37.
3. M. V. R. K. Murty, Appl. Opt. 3, 531 (1964).