Interferometric testing of high-numerical-aperture convex surfaces

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Interferometric tests of convex surfaces for large-N.A. lens systems often present problems. We show how such surfaces can be tested with a reference surface having a much smaller N.A. by making use of the aplanatic imaging properties of a spherical surface.

Introduction

Convex optical surfaces are usually tested in a modified Fizeau interferometer, through the use of a concave reference surface instead of a flat reference surface.\(^1\) As shown in Fig. 1, a group of lenses (commonly known as a test sphere or a reference sphere) brings the beam from the collimator to a focus at the center of curvature of the last surface of the assembly, which is used as the reference surface. If the convex test surface is set so that its center of curvature coincides with that of the concave reference surface, the interference fringes formed by the beams reflected from the two surfaces contour the errors of the test surface.

Although such an arrangement is satisfactory for most routine studies, tests of large-N.A. lens systems often present serious problems. The convex surface of an element for such a system may be very nearly hemispheric, with a N.A. at its center of curvature of as much as 0.9, necessitating a well-corrected reference sphere with an N.A. at least equal to this value. However, the reference sphere with the highest N.A. that is available off the shelf is one with a relative aperture of F/0.75, corresponding to a N.A. of 0.63. This paper shows how one can test a near-hemispheric convex lens surface with a reference sphere with a much lower N.A., by making use of the aplanatic imaging properties of a spherical surface.

Test Configuration

An optical configuration for interferometric tests of a convex surface, using its aplanatic imaging points, is shown schematically in Fig. 3. The test optic is provided with a rear flat surface located at the near-aplanatic point of the front surface and is positioned so that the far-aplanatic point of this surface coincides with the center of curvature of the reference surface in the interferometer. After refraction at the test surface, the spherical wave transmitted by the reference surface, which is converging to the far-aplanatic point of the test surface, then comes to a focus at the flat rear surface. If the test surface is truly spherical then the spherical wave incident on it returns as a spherical wave, producing a uniform interference field.

Analysis

The N.A. that the reference surface must have to handle a given test N.A. depends on the refractive...
Experimental Results

Experiments to confirm the feasibility of this method were carried out with an accurately finished sphere (diameter $2r = 55.0779$ mm) of BK-7 optical glass ($n = 1.515$). A flat surface was generated on this sphere so that the thickness of the resulting lens was approximately 40 µm more than the estimated distance from the front surface to the near-aplanatic point, which we call the aplanatic thickness ($t = 45.7145$ mm).

This test piece was set up in a phase-shifting Fizeau interferometer with an $F/1.1$ reference sphere. The diameter of this reference surface was 108 mm and its radius of curvature ($R$) was 130 mm, corresponding to a N.A. of 0.42. We initially calibrated this reference surface by making a set of measurements with a flat surface at its focus. These values were stored and subtracted from the results obtained with the test piece.

With this arrangement, the height of incidence at the reference surface is related to the height of incidence at the test surface by the expression

$$ h_r = (R/r)h_t/[1 + n^2 + 2n(1 - (h_t/r)^2)^{1/2}]^{1/2}, \quad (4) $$

which is plotted in Fig. 5. As we can see, it is necessary to take into account the nonlinear mapping of the test surface in the interferogram. Preliminary data obtained by ray tracing are presented in Fig. 6, which shows the optical path difference (OPD)
for the marginal ray as a function of the deviation of the thickness of the test piece from the aplanatic thickness.

Measurements were made with the test piece as its thickness was progressively reduced, initially in steps of approximately 5 μm and then in steps of 1 μm, to the aplanatic thickness. Accurate alignment of the reference surface and the test surface was found to be essential for us to obtain good results. Because the beam is flipped over on its return path, we had to be careful to avoid the introduction of shear. Tilt of the reference surface or the test piece resulted in coma. The tolerance on the lateral position of the test piece was found to be approximately 0.1 mm, whereas the focus setting had to be within 1 μm of that for best focus for us to avoid the introduction of spherical aberration.

Figure 7 shows the residual third-order spherical aberration plotted as a function of the deviation in the thickness of the test piece from the aplanatic thickness for a range of N.A.’s. As we can see, the spherical aberration is less than 0.02 λ at the aplanatic thickness, even for a N.A. of 0.91.

Implementation

A schematic of an arrangement that can be used with a vertical beam path to test a high-N.A. lens surface by this method is shown in Fig. 8. Tests are carried out after the front surface of the lens blank has been ground and polished to the required radius. The rear surface of the lens blank, which has been finished flat, is optically coupled to a plane-parallel plate of the same glass by a layer of an index-matching fluid, whose thickness can be adjusted so that the near-aplanatic point of the test surface falls on the rear surface of the glass plate. The entire assembly is set by means of a fine focus adjustment so that the spherical wave transmitted by the reference surface converges to the far-aplanatic point of the test surface. After refraction at the test surface, this wave then comes to a focus on the rear surface of the assembly.

Conclusions

The use of the aplanatic imaging points of a spherical surface makes it possible to test a lens surface having a N.A. of 0.9 with a reference surface having a N.A. of only 0.42. A further advantage is that the lens surface is tested in transmission, which is the way it is to be used.

A drawback of the method is that the reflected wave front is rotated by 180° on its second pass through the test surface. As a result, antisymmetric errors cannot be seen because they cancel out, and only symmetric errors appear in the interferogram. However, because the production techniques used for such high-N.A. surfaces normally ensure that antisymmetric errors are not present, this does not detract significantly from the utility of the method.

It should be noted that digital interferometry is required to implement this method properly. With a digital interferometer, it is possible from a series of measurements to locate the exact setting at which the defocus term is zero and thereby avoid the introduc-
tion of spherical aberration caused by defocus. It is also possible to eliminate the errors contributed by the reference surface. For this, the test assembly is replaced by a plane mirror located at the focus. With typical interferometers this test usually reveals significant amounts of coma, which can completely mask the errors of a well-made lens. The errors caused by the reference surface can then be eliminated by subtracting the data obtained with the plane mirror from the test data.

References