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Absolute interferometric test for high numerical-aperture spherical concave surfaces: Gravitational effect

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ABSTRACT

Spherical concave surfaces with high numerical apertures are required in industry for lithography optics at ultraviolet and X-ray wavelengths. Among the systematic errors in these spherical-surface test, the gravitational deformation has not been separated from the other optical aberrations. We utilized a two-surface comparison method to quantify the gravitational deformation in a vertical Fizeau interferometer. Certain aberrations vary with rotation around the optical axis. We averaged the ordinary aberrations and isolated the aberration caused by gravitational deformation. Experimental results show that a 4-in concave surface with an *F*-number 0.75 reveals to have a gravitational deformation of 7 nm peak-to-valley.

1. Introduction

Accurate spherical concave surfaces have been required in industry for commercial interferometers to test aspherical surfaces with high numerical apertures (NAs), for calibration standards in coordinate measuring machines, and for lithography and spectroscopy optics at ultraviolet and X-ray wavelengths. A typical accuracy necessary for spherical reflective mirrors in ultraviolet (UV) lithography (at 150 nm wavelength) is, according to the Maréchal criterion, equal to $\lambda_{uv}/30$ or 5 nm root-mean-squares (RMS). Moreover, in high-energy physics research, surface accuracies of less than 1 nm are often required.

Ordinary spherical test in commercial interferometers is a relative measurement in which the deviation of a test spherical surface from the standard spherical surface is measured. The measurement accuracy is then limited by the accuracy of the standard surface shape. A typical accuracy of the spherical standards available in present commercial interferometers is 15–30 nm. However, the gravitational deformation discussed in this paper was shown to be an order of 5 nm, which is much smaller than the accuracy of the spherical standards. Therefore, in this paper, we used an absolute sphericity measurement to determine the surface shapes instead of a relative comparison with the commercial standard surfaces. The uncertainty of the present absolute measurement was $\sim$4 nm which is better than that of the ordinary relative measurement.

Several conventional techniques have been reported for the absolute measurement of spherical surfaces [1]. In particular, these concern the comparison of two concave surfaces with one convex surface, the comparison of two concave surfaces along three different positions [2], the synthesis of the reference surface by rotating a spherical ball [3], and so on. Among these techniques, the triple positional-measurement method for comparing two concave surfaces is often used because it does not need an extra convex sphere and the accuracy can be as high as $\sim\lambda_{HeNe}/120$, where $\lambda_{HeNe} = 633$ nm is the wavelength of a HeNe laser. The measurement accuracy of the spherical test has been inferior to that of the flatness test (1–10 nm), because there are several additional error sources: namely, the two test surfaces cannot be positioned close together while the two centers of the surfaces should be coincided perfectly; the illuminating beam is not a collimated beam but must be a converging beam; the converging optics has aberrations; and the phase modulation applied by a piezoelectric modulator (PZT) becomes spatially non-uniform. One of the most significant uncertainties occurring in the flatness test is gravitational deformation (called "sag"), which is not typically discussed in the literature [4,5]. After overcoming the major systematic errors, we can thus expect similar gravitational effects in the spherical test, although to the best of our knowledge the gravitational deformation for small-aperture spherical interferometers has not been reported.

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In this study, we detected the sag for a 4-in diameter spherical surface with a 48 mm radius of curvature (NA = 0.66) in a vertical Fizeau interferometer. The surface deviations of two identical spherical surfaces from an ideal sphere were measured by the absolute test of three positional measurements. The spherical surface was then rotated around the optical axis and the corresponding interference phase was averaged. The gravitational effect was then separated from the other sources of aberration by the difference of axial symmetry around the optical axis.

We should note that the gravitational deformation cannot be detected in a similar manner with a horizontal Fizeau interferometer. In a horizontal placement, the deformation is axially symmetric around the optical axis and thus cannot be distinguished from the residual spherical aberration of the converging optics. In a vertical placement, however, the deformation is asymmetric and can be detected after we eliminate the asymmetric component of optical aberration by a rotational average. We also discuss the tolerance for the alignments of test spherical surfaces in Section 2.2 and estimate the uncertainty of the measurement in Section 4.

2. Gravitational aberration detection in a spherical fizeau interferometer

2.1. Absolute spherical test: two surface-comparison

Commercial Fizeau interferometers are equipped with reference spherical surfaces that can be compared against a test surface. The measurement result is the sum of the deviations of the test surface and the reference surface from each ideal sphere surface. A typical accuracy (we call the "sphericity") of these spherical references is $\lambda/20$, or 30 nm peak-to-valley (PV). Therefore, when we discuss the surface shape deviation with an accuracy better than 5 nm (for example), we are forced to determine the surface shape directly by an absolute spherical test. Among several test methods, here we used the comparison of two concave surfaces at three separate positions.

Fig. 1 shows the optical setup of the three positions used in this test. According to this procedure, at least, one of the two spherical surfaces must be a transmission element. In this particular case, spherical surface A is a transmission element. The transmission element consists of a converging lens and a spherical surface such that the back focus of the lens is adjusted to be coincident with the center of curvature of the spherical surface.

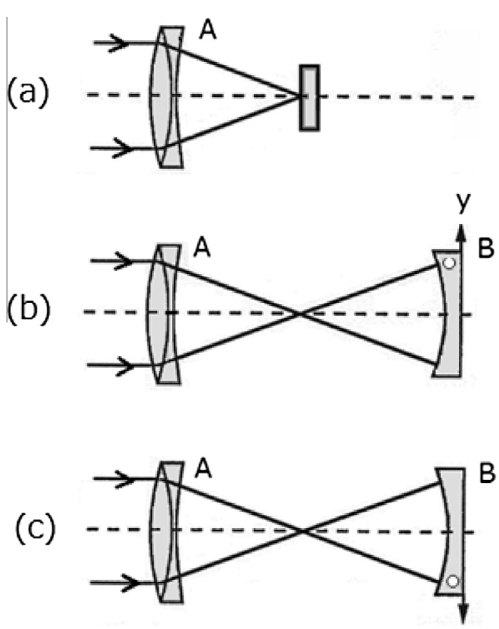

Fig. 1. Optical setup of the three positions for the absolute spherical test. (a) Cat's-eye position, (b) confocal position, and (c) second confocal position. The circular fiducial mark identifies the rotation of surface B by 180° around the optical axis.

In the first measurement (see Fig. 1(a)), the transmission element with spherical surface A is illuminated with a collimated beam from the left, and a plane mirror is located at the back focus of the surface A (cat's-eye position). The partial reflections from the surface A and from the plane mirror go back along the same path and are overlapped to generate interference fringes on a diffuser screen placed on the left of the surface A, which is not shown in the figure and will be discussed in Section 3.

In the second measurement (see Fig. 1(b)), the other spherical surface B is located so that its center of curvature is coincident with that of the spherical surface A (confocal position). The partial reflections from surface A and from surface B go back along the same path and are overlapped to generate interference fringes. The third measurement (see Fig. 1(c)) is similar to the confocal position, except that surface B is rotated by 180° around the optical axis.

If we denote the surface deviations from each ideal sphere of the two spherical surfaces by ϕ_A and ϕ_B, the aberration of the illuminating collimated beam by ϕ_I, and the aberration of the converging lens of the transmission element A by ϕ_L, the phases of the observed interference fringes on the screen for these three measurements (φ_1, φ_2, and φ_3, respectively) are given [2] by

$$\varphi_1(x,y) = \frac{2\pi}{\lambda}(\phi_A(x,y) + \phi_A(-x,-y)) + \frac{2\pi}{\lambda}(\phi_L(x,y) - \phi_L(-x,-y)) + \frac{2\pi n}{\lambda}(\phi_A(x,y) - \phi_A(-x,-y)) + \frac{2\pi}{\lambda}(\phi_I(x,y) - \phi_I(-x,-y)), \quad (1)$$

$$\varphi_2(x,y) = \frac{4\pi}{\lambda}(\phi_A(x,y) + \phi_B(-x,y)), \quad (2)$$

$$\varphi_3(x,y) = \frac{4\pi}{\lambda}(\phi_A(x,y) + \phi_B(x,-y)), \quad (3)$$

where λ is the source wavelength, n is the refractive index of the converging lens medium, the z-axis is the optical axis, and the y-axis is normal to the horizontal plane. It should be noted that in these measurements the spatial tilt and defocus of the plane mirror or the second surface were adjusted so as to be minimized by the alignment. The spatial tilt and defocus were so adjusted because these components produce additional aberrations in the measured phases, which are discussed in the next section.

From Eqs. (1)–(3), the deviations of the two spherical surfaces can be calculated as:

$$\phi_A(x,y) = \frac{\lambda}{8\pi}(\varphi_2(x,y) - \varphi_3(-x,-y)) + \frac{\lambda}{8\pi}(\varphi_1(x,y) + \varphi_1(-x,-y)), \quad (4)$$

$$\phi_B(x,y) = \frac{\lambda}{8\pi}(\varphi_2(x,-y) + \varphi_3(-x,y)) - \frac{\lambda}{8\pi}(\varphi_1(-x,y) + \varphi_1(x,-y)). \quad (5)$$

It should be noted that the aberrations of the illuminating beam and of the lens do not affect the surface deviations due to their asymmetry. The residual tilt and defocus components resulting from the misalignment in the measurement were subtracted in these calculations.