TECHNICAL NOTE

Phase-shifting errors in interferometric tests with high-numerical-aperture reference surfaces

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The errors introduced by moving a spherical reference surface to generate a phase shift between the beams in a Fizeau interferometer are discussed.

Key words: Optical testing, Fizeau interferometer, phase shifting.

Fizeau interferometers are widely used to test convex optical surfaces against a concave reference surface.[1] As shown in Fig. 1, the beam from a collimator is brought to a focus by a lens assembly (commonly known as a test sphere) at the center of curvature of its last surface, 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.

The same optical arrangement is also used in phase-shifting Fizeau interferometers.[2] However, it can produce significant errors with high-numerical-aperture (NA) surfaces. The aim of this Note is to present data on the magnitude of these errors and discuss methods of minimizing them.

Systematic errors arise when testing large NA surfaces with the phase-shifting technique because translation of the spherical reference surface along the axis to generate the required phase shifts results in a phase shift that is not the same over the whole surface.[3] The phase shift is less at the edge than at the center, and the magnitude of the difference is a function of the NA of the reference surface.

Figure 1 shows that for a ray making an angle α with the axis, Δp, the change in the optical path along the normal to the reference sphere is related to Δz, the distance through which the reference surface is moved, by

$$\Delta p = \Delta z \cos \alpha, \qquad (1)$$

which can be rewritten in the form

$$\Delta p = \Delta z[(R^2 - y^2)^{1/2}/R], \qquad (2)$$

where y is the height at which this ray is incident on the reference surface and R is its radius of curvature.

Figure 2 shows the values of the actual phase shift obtained from Eq. (2) as a function of the normalized height of incidence for a phase shift of 90° on the optical axis and for spherical reference surfaces with NA's of 0.42, 0.63, and 0.90. As can be seen, the magnitude of the phase-shift error increases rapidly with the NA of the reference surface.

The resulting error in the measurements depends on the value of the phase at the measurement point and on the phase calculation algorithm employed.[4] In the upper part of Fig. 3 the maximum values of the measurement errors with the usual four-frame algorithm are shown. It is apparent that with the

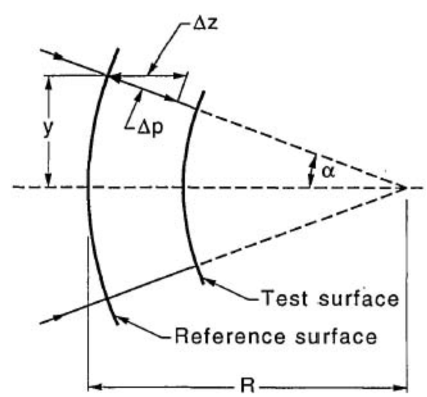

Fig. 1. Fizeau interferometer modified for testing a convex surface against a concave reference surface.

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Received 6 January 1993; revised manuscript received 28 June 1993.

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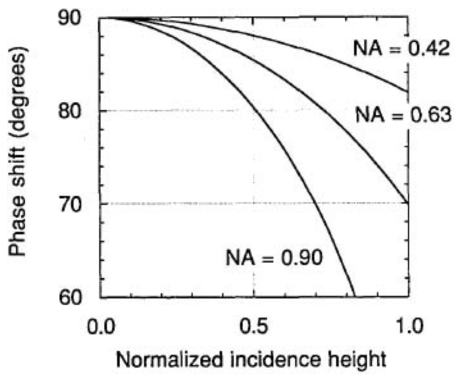

Fig. 2. Phase-shift error as a function of the normalized incidence height for concave reference surfaces with NA's of 0.42, 0.63, and 0.90.

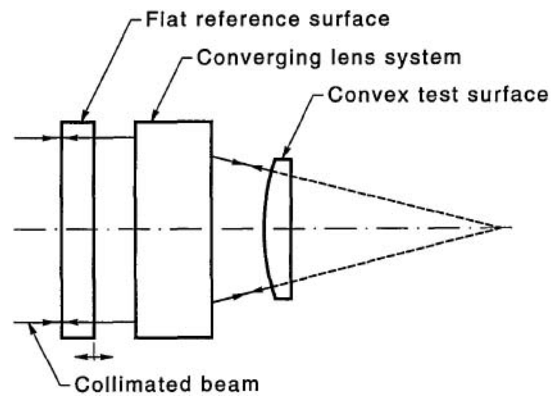

Fig. 4. Modified optical system using a plane reference surface and a well-corrected converging lens system.

four-frame algorithm the measurement errors are significant even with a NA of 0.42.

Since the actual values of the phase shift at each value of the incidence height can be calculated from Eq. (2), it is possible in principle to reduce the phase errors by programming the computer to use these values, instead of the nominal value of 90°, while calculating the phase of the test wave front at each data point.[3]

A simpler way to reduce the measurement errors is to use a five-frame algorithm[5] that is relatively insensitive to deviations in the actual phase shifts from the nominal value of 90°. As shown in the lower part of Fig. 3, the measurement errors then become noticeable only for NA's of > 0.63.

For larger NA's, one can reduce the measurement errors by using an algorithm that implicitly evaluates the actual phase shift at each data point and uses this value of the phase shift to calculate the phase difference at that point.[6,7] However, difficulties can arise with such an algorithm at points where the phase difference between the beams is close to $m\pi$, where m is an integer.

Errors from the variation of the phase shift with the incidence height can be eliminated with the modified optical system shown schematically in Fig. 4, which uses a flat reference surface and a well-corrected converging lens system. Since the flat reference surface is located in a collimated beam, movement of this surface along the axis does not result in any variation in the phase shift over the entire aperture.

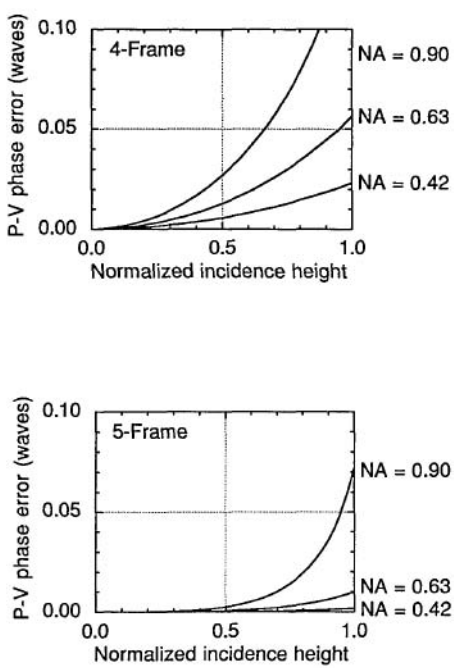

Fig. 3. Errors in the measured values of the phase for concave reference surfaces with NA's of 0.42, 0.63, and 0.90: (top) with a four-frame algorithm and (bottom) with a five-frame algorithm. P–V, peak to valley.

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