Calibration of Interferometer Transmission Spheres

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Background: As the tolerances on optical figure get tighter and as the need to provide traceable test methods to fulfill ISO 9000 standards becomes greater, the more there is the need for a robust and reliable method to determine the residual error in interferometer test optics. This paper describes an inexpensive, quick and self-consistent method of calibrating spherical transmission optics where there is a real focus of the diverging test beam outside the transmission optic. The method is self-consistent in the sense that any given test result provides a means of calculating the variance of the result and requires no additional optic that must be calibrated or traced to another standard.

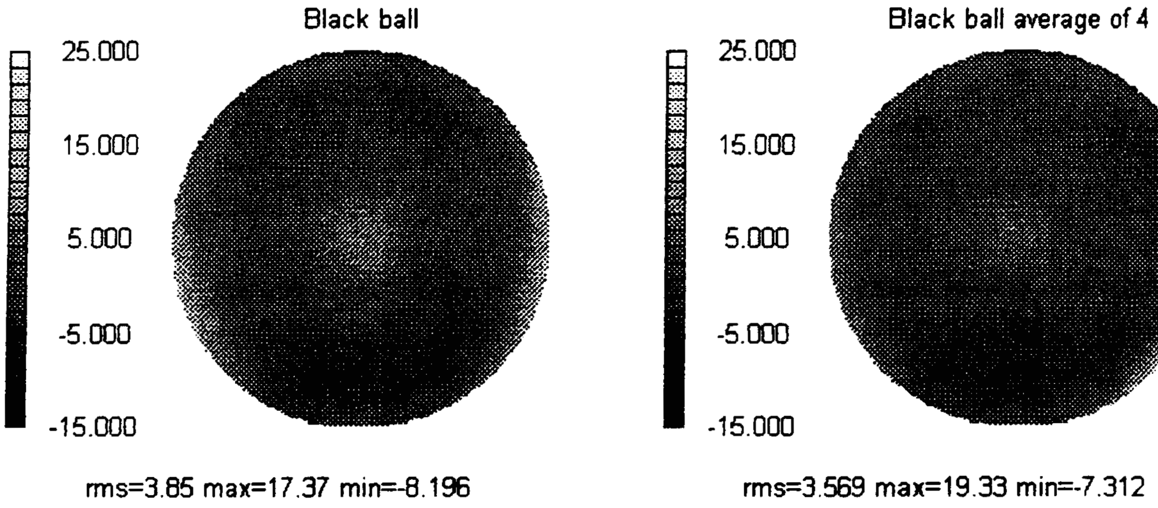
Method: The method, quite simply, is the spherical equivalent to the methods described by Creath and Wyant[1] for calibrating a surface roughness measuring interferometer using a well polished, plano test piece. In the Creath method, an interferogram of a region on the test piece is taken and saved. Then the test piece is moved to a non-overlapping region and another interferogram taken and stored. This is repeated a sufficient number of times so that when an average is taken of the statistically uncorrelated interferograms, the average represents the errors in the test device to the desired level of certainty.

For interferometer transmission spheres, we use a chrome steel ball about 25 mm in diameter placed so its center of curvature is coincident with the focus of the transmission sphere. To maintain alignment upon rotating the ball to other locations on the surface, it is set on a kinematic support consisting of 3 smaller balls arranged in an equilateral triangle. The support is set on a x-y-z stage for alignment to the interferometer transmission sphere.

Just as in the piano example, the ball support stage is adjusted to break out one fringe and an interferogram taken and stored. The ball is then picked up with a gloved hand, rotated to a new position and set back down on the 3 small balls and another interferogram taken and stored. The process is continued until sufficient interferograms are taken to reduce the random errors in the

The best way of doing this is to save the data from each position of the ball. Then calculate the x and y components of coma versus x and y tilt as well as spherical aberration versus focus. Apply these corrections to the data, that is find the wavefront error in the absence of all tilt and focus, and then average the data to find the error due to the transmission sphere.

The results of calibration are illustrated in Figure 2. In (a) we show the opd map resulting from one measurement, while in (b) we show the result of averaging 4 sets of data after removing the effect of tilt and focus from each of the 4 wavefronts. In (c) we show the difference between the average and the individual measurement to give an idea of the magnitude of the residual errors in the ball and what they look like. Figure 3 shows why the effects of tilt and focus must be removed. Here we have plotted residual spherical as a function of focus to show that there is a , systematic and finite effect on the calibration.



(a) (b)

Fig. 1 OPD map of a single measurement of a ball with an f/0.7 transmission sphere (a), an average of measurements of the same ball after removing the effects of tilt and focus (b), and the difference between an individual measurement and the average to give an idea of the errors in the ball (c). Units are nm.

ball to the desired level. When the interferograms are averaged, the errors in the ball average in the limit of many tests to zero while the errors in the transmission sphere add coherently.

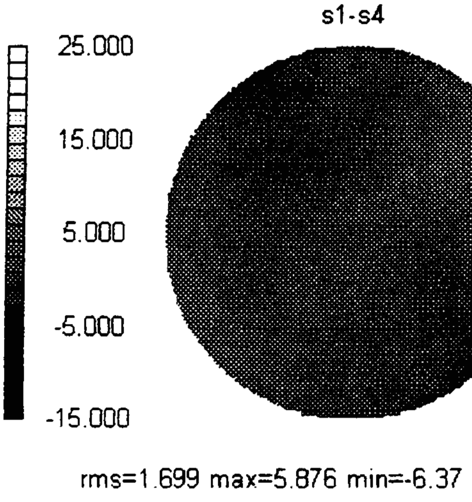
Implementation of the method: There are a few practical details relating to the method. The first concerns the ball. Grade 3, chrome steel 25 mm diameter balls are commercially available' for about $100. Grade 3 balls are round and made to the specified diameter to 75 nm^3. Of course, the absolute diameter is largely unimportant so the size one gets often depends on availability. To get to this degree of roundness, the finish is also quite good and gives high contrast fringes once the protective oil is cleaned from the surface. The balls should be handled with gloved hands to avoid fingerprints and should be stored in soft containers to avoid damage to the surface. The plastic 35 mm film canisters work well for this.

Of course, the detector plane in the interferometer should be focussed on the object under test, the ball. For most fast transmission spheres, the surface of the ball is within the focus range of the interferometer. If the ball is not within the focus range, the size of the sphere must be changed so the surface will appear in focus. Another aspect of calibrating transmission spheres is that this method calibrates out to the edge of the aperture of the transmission sphere. Optics then tested with the transmission sphere will usually form the stop in the test and just that part of the transmission sphere actually used in the test should be removed from the test results. In most cases, this happens automatically but one should be aware this is not always the case depending on the actual test setup.

We have found that the Grade 3 balls measure about 40 nm peak-to-valley when using an f/0.7 transmission sphere and about 5 nm rms. To reduce the residual error due to the ball to 1 nm rms in the calibration of the transmission sphere, 25 interferograms should be taken. The finish of the Grade 3 balls is plenty good enough in our experience as obtained from the manufacturer when calibrating a fast transmission sphere because each pixel in the detector is mapped on to a relatively large area of the surface. As the transmission spheres get slower, the finish of the ball becomes more important as the detector can start to resolve individual surface defects and these contribute to the figure error of the ball.

The finish (and to a certain extent, the roundness) of the balls can be improved by polishing with fine diamond paste in cup laps. We use a cup on a polishing spindle and a second driven in the opposite direction by a slow speed electric drill for the other. The cup diameter should be about 0.7 times the ball diameter and the cutting edge lined with something soft like lead that has been lightly serrated with a razor blade so the diamond paste can lock in the serrations. Oscillating the drill will keep the ball rotating randomly between the cups and make a dramatic improvement in the finish^4. Of course, the better the finish the more easily it is damaged.

Experiment: When actually performing the calibration, there is a systematic error source that must be accounted for. As pointed out by Evans' and others, residual tilt and focus in the alignment of the ball to the interferometer will lead to small amounts of coma and spherical aberration in the measured wavefront. These residual errors must be calculated and removed before averaging the data to determine the error due to the transmission sphere.



(c)

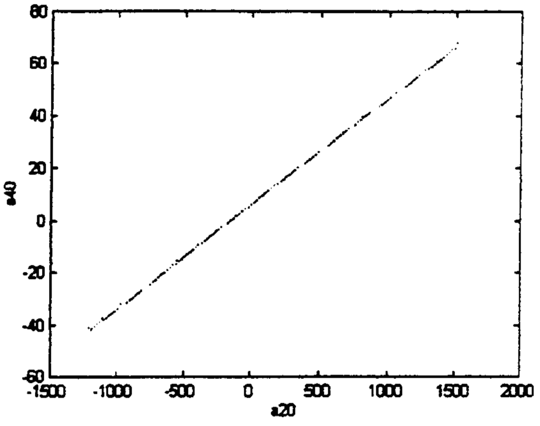


Fig. 2 Spherical aberration as a function of defocus for the f/0.7 transmission sphere used. Units are nm.

References:

[1] K. Creath and J. C. Wyant, “Absolute measurement of surface roughness”, Appl. Optics, ***29,*** 3823-7, (1990).

[2] Micro Surface Engineering, 1550 E. Slauson Ave., Los Angeles, CA 90011. (The reference is not an endorsement by NIST, but merely included as convenience for the reader.)

[3] ISO 3290: 1975

[4] R. E. Parks, “Optical tests using fibers, balls and Ronchi gratings“, OF&T Workshop, Mills College, Oakland, CA, June 1980.

[5] C. J. Evans, “Compensation for errors introduced by non-zero fringe densities in phase measuring interferometers”, CIRP Annals, 42/1, 577-80, (1993).