Interferometer Calibration using the Random Ball Test

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Abstract: Two different approaches (systematically and randomly rotating the CaliBall^{TM} to calibrate a Fizeau interferometer transmission sphere) are demonstrated with similar calibration results. Thus, the random approach is preferred as a quicker and easier measurement procedure.

OCIS codes: (120.6650) Surface measurements, figure; (220.4840) Optical testing

1. Introduction

In interferometric testing, the measured optical path difference (OPD) is the difference between the reference and the optics under test. Since the reference has errors on the order of the magnitude of the optic under test, the reference must be calibrated in order to achieve the best estimate of the quality of the optic under test. One method of performing the calibration is the random ball test (RBT) [1], where randomly selected patches of a high quality spherical ball are measured and the resulting OPD maps are averaged to obtain an estimate of the reference because the errors in the ball average to zero in the limit. The RBT is the exact analog for spherical wavefronts as is the calibration method described by Creath and Wyant [2], for determining the reference error in a surface roughness microscope using patches of a plane surface as the random variable. Practical hardware for performing the RBT uses the commercially available CaliBall and kinematic mount shown in Fig. 1.

As with other methods of calibrating interferometers [3,4], the expected accuracy of the calibration should depend on the care with which the calibration is done. In this paper we mention systematic errors that can arise and do affect the results. We also show that some random errors resulting from lack of care do not seem to affect the accuracy of the calibration.

Fig. 1 CaliBall and mount

2. Random Ball Test Calibration Issues

As described by Griesmann et al. [5], the RBT can be realized using a ball manipulator that automates the testing procedure. Their paper models several schemes for systematic ball rotation and shows the method of rotation weakly affects the convergence of the estimate of the reference. Use of the RBT by Burke et al [6], showed that the convergence is somewhat more rapid than would be expected by pure statistics but no explanation for this is given.

In this paper, we first point out several other systematic errors that can affect the results of the calibration, and then describe a surprising (to us) result that has to do with the care in which the ball is cleaned and rotated between measurements. We performed the measurements using a one inch CaliBall in its kinematic mount and a WYKO 6000 Fizeau interferometer with 6 inch, f/3.2 transmission sphere.

Zhou et. al. [7] point out that several factors degrade the accuracy of the RBT and that these factors become issues when attempting to do calibrations for slow (high f/#) systems. A combination of retrace errors and physical optics issues become larger for slow systems. In fact, the RBT is more suited to the calibration of fast systems (f/8 and faster) while methods such as that described by Jensen [3], and Kestner and Evans [4]are better for slower systems. At the fast f/#'s for which the RBT works best it is critical that the ball be well aligned to the interferometer in tilt and focus.

As Evans [8] has pointed out, in some interferometers the aberration coefficients of the measured wavefront depend on the amount of tilt in the wavefront, or the distance between the focus of the transmission sphere and the center of curvature of the optic being measured. For all interferometers, an axial difference between the transmission sphere focus and center of curvature will introduce spherical aberration because the sphere is not being tested at correct conjugate. In both cases, the errors increase with the NA of the measurement. Although these errors are small, it is important to position the ball in the RBT so there is as little tilt and focus error as practical. The kinematic mount for the CaliBall aids in this requirement.

3. Measurement procedure using the RBT

The Grade 5, silicon nitride, CaliBall is not perfectly spherical but has an RMS roundness error of less than 125 nm. By randomly rotating the ball about its center test to test, different areas of the ball contribute to the OPD data for any particular test. When the OPD maps of many tests are averaged, the random features of the ball average to zero in the limit of an infinite number of tests.

To minimize the alignment errors mentioned in Section 2, the ball was positioned where the measured tilt and power Zernike coefficient values were minimum. Before doing the actual calibration, we performed a repeatability test taking measurements without rotating the ball. We found a 0.7 nm RMS residual noise by averaging 15 OPD maps.

In order to see if the averaging of the features on the ball depends on the method of rotating the ball, we first used clean, nearly featureless surface areas for the measurements as shown in the fringe map in Fig. 2 (left). The ball was systematically rotated using a Q-tip by about half of the previous ball surface area. Then, we cleaned the surface with isopropyl alcohol until there were no visible defects on the fringes. If the surface had an obvious defect we simply moved another step or two steps before making a measurement of a clean patch. We measured 30 OPD patches on the ball in this way.

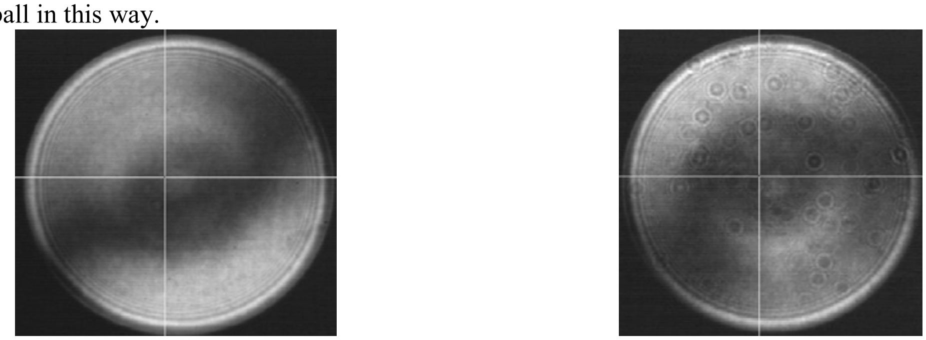

Fig. 2 A typical fringe map from a good CaliBall surface area and randomly picked CaliBall surface area with dust and defects

Because we felt that this systematic method of rotating the ball was not representative of how the calibration might be done in a typical case, we then tried a purely random approach. We rotated the ball an arbitrary amount, and made an OPD measurement. Although some of the measurements were made using an area with dust or visible defects as shown in Fig. 2 (right), we did not discard the measured OPD data. Again, a total of 30 OPD measurements were made.

4. Calibration Results

In the case where we systematically rotated the ball, 30 measurements were made. Any single map was different from the others because we were using a different area on the ball and the air turbulence in the beam path was not the same. In order to cancel out the ball features and air turbulence effects, we averaged the maps. The average of 30 maps gave an estimate of the error in the interferometer to the level of the noise of 0.7 nm rms. The reference surface OPD map obtained in this case is shown in Fig. 3.

We performed a staticstical analysis to find the relationship between the uncercainty of the measurement and the number of maps averaged. We randomly picked N maps, and averaged them. The averaged map was subtracted from the average of all 30 to get the residual noise rms. This is shown in Fig. 4 (left) with the variation plotted as an error bar. For N = 30 the residual rms noise was ~0.7 nm. This data was also plotted in log-log space as shown in Fig. 3 (right). The slope of the trend line was ~-0.5 which means that the noise sources were un-correlated and the total noise followed a Gaussian distribution. (Note: If the noise in the measurement is proportional to $N^{-1/2}$, where N is the number of maps averaged then the noise follows a Gaussian distribution.)

The same measurements and data analysis were performed for the random approach mentioned above. We randomly rotated the ball in the kinematic mount without cleaning the surface each time. Also, the measurements were made even if there were visible defects in the fringe map. The result is shown in Fig. 5.

The diffraction rings around the edge of the OPD map is caused by the diffraction of the aperture of the transmission sphere. With an F/3.2 transmission sphere and a 25 mm CaliBall, the error from edge diffraction is about 0.2 nm rms.[7] If Fig. 3 and 5 are compared, they are very similar. Also, the noise level in the graph in Fig. 6

is almost the same as that in Fig. 4. In both cases, the slopes in log-log space are ~-0.5 with similar y-intercept values (0.66 and 0.68). Further, they both agree with the simulation results in Griesmann's paper [5]. Thus, the quick and easy random measurement procedure gives essentially the same result as the systematic approach.

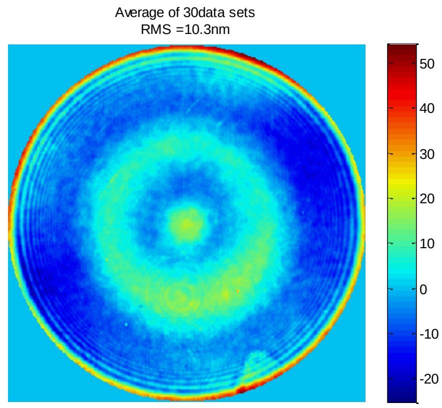

Fig. 3 Averaged OPD map using 30 single maps from the systematic method.

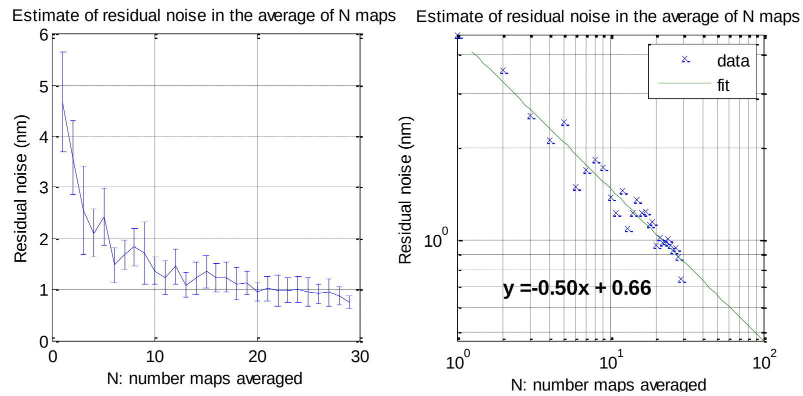

Fig. 4 The estimate of residual error in the average of *N* maps from the systematic method.

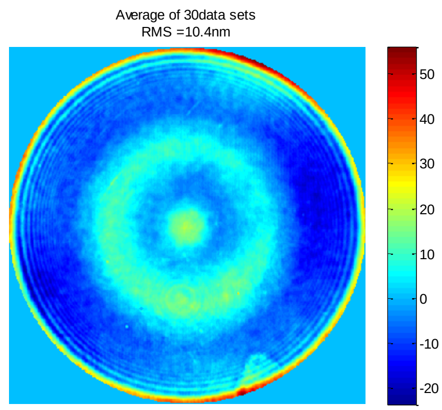

Fig. 5 Averaged OPD map using 30 single maps from the random method

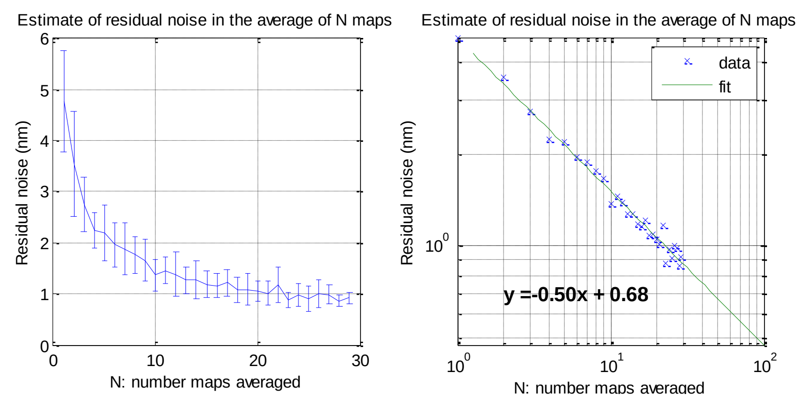

Fig. 6 The estimate of residual error in the average of *N* maps from the random method

5. Conclusion

This paper provides a comparison of two different methods of calibrating interferometer transmission spheres. As long as the ball center lies very close to the interferometer focus, the analysis of the residual noise shows the precision of the measurements and shows that randomly rotating the CaliBall without carefully cleaning the ball surface will give good calibration results.

6. Acknowledgement

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7. References

[1] Parks, R. E., Evans, Chris and Shao, Lianzhen, "Calibration of Interferometer Transmission Spheres", **OSA,** OF&T, Hawaii (1999).
[2] Creath, K. and Wyant, J. C., "Absolute measurement of surface roughness", Appl. Optics**, 29**, 3823-7, (1990).
[3] Jensen, A. E., "Absolute Calibration Method for Laser Twyman-Green Wavefront Testing Interferometers," JOSA, **63,** 1313 (1973).
[4] Evans, C. J. and Kestner, R. N., "Test Optics Error Removal", Appl. Optics, **29,** 1015-21, (1996).
[5] Griesmann, U., et. al., "A simple ball average for reference sphere calibrations", SPIE **5869**, 58690S1-8 (2005)
[6] Burke, J., et. al., "Fabrication and test of a high-precision concave spherical mirror", Proc. SPIE, **7064,** 7064OE (2008).
[7] Ping Zhou., James H. Burge, "Limits for interferometer calibration using the random ball test", SPIE **7426**, 74260U-1 (2009)
[8] Evans, C. J., "Compensation for errors introduced by nonzero fringe densities in phase-measuing interferometers", CIRP Annals 42/1, 577-580 (1993)