

MEASUREMENT OF THE DIAMETER VARIATION AND REFRACTIVE INDEX INHOMOGENEITY OF A FUSED SILICA SPHERE USING FOUR-SURFACE PHASE-SHIFTING INTERFEROMETRY

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Abstract: The diameter variation and refractive index inhomogeneity of a fused silica sphere were measured with a frequency-shifting Fizeau interferometer in a four-surface configuration. The phase-shifting algorithms to analyze the interference signals for each basic cavity were designed using the characteristic polynomial theory. We describe the experimental setup and preliminary results.

Keywords: phase-shifting interferometry, characteristic polynomial, sphere measurement, diameter variation, refractive index inhomogeneity.

1. INTRODUCTION

Accurate measurement of the form error or diameter variation of ultra-precision spheres is important for many applications, such as the calibration of transmission spheres for interferometry, density standards for mass metrology, and spherical gyroscope rotors. Whereas opaque spheres can be measured using optical interferometry, transparent spheres are difficult to measure due to the interference of light reflected by the “back surface” of the sphere. Using the characteristic polynomial (CP) theory, phase-shifting algorithms (PSAs) can be designed that are sensitive to specific cavities, enabling measurement of the diameter variation (DV) and refractive index variation (RIV) [1]. In this paper we describe the measurement approach for a fused silica sphere and show preliminary results.

2. EXPERIMENTAL SETUP

The experimental setup consists of a Fizeau interferometer in a confocal four-surface configuration, as shown in Figure 1. The average diameter of the test sphere is 38 mm, and the f-numbers of the transmission sphere and reflection sphere are 1.3 and 0.75, respectively. Equal phase shifts are generated by stepping the frequency of the tunable laser source, whose voltage was calibrated and monitored using a reference Fabry-Perot cavity.

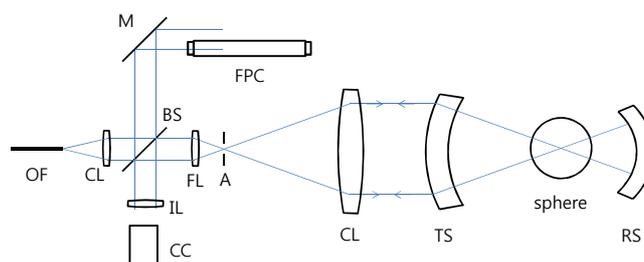


Figure 1: Confocal four-surface configuration of the interferometer. OF: optical fiber; CL: collimating lens; BS: beam splitter; FL: focusing lens; A: aperture; IL: imaging lens; CC: CCD camera; M: mirror; FPC: Fabry-Perot cavity; TS: transmission sphere; RS: reflection sphere.

3. PHASE-SHIFTING ALGORITHMS

The CP theory, introduced by Surrel, provides a systematic approach to analyze and optimize a PSA’s frequency response [2]. When the intensity of the k -th phase-shifted interferogram is denoted as I_k ($k=0, 1, 2, \dots, M-1$), the phase can be calculated as:

$$\phi = \tan^{-1} \left[\frac{\sum_{k=0}^{M-1} b_k I_k}{\sum_{k=0}^{M-1} a_k I_k} \right], \quad (1)$$

where the constants a_k and b_k are the real and imaginary parts of the coefficients of the CP, $P(x)$:

$$P(x) = \sum_{k=0}^{M-1} (a_k + ib_k)x^k. \quad (2)$$

We designed three PSAs to estimate the phase maps of the full cavity, the sphere cavity (cavity formed by the surfaces of the fused silica sphere), and the empty cavity (the cavity without the sphere). The roots of the respective CPs are chosen such that each PSA is sensitive to the intensity modulation frequency of the cavity of interest and insensitive to all other fundamental harmonics. Each PSA is

based on 107 buckets, corresponding to two waves of intensity modulation for the smallest cavity.

4. MEASUREMENT OF DV AND RIV

The DV and RIV of the sphere can be calculated as:

$$DV = (\phi_{EC} + \phi_S - \phi_{FC}) \times \lambda / (4\pi) \quad (3)$$

$$RIV = [\phi_S - n \times (\phi_{EC} + \phi_S - \phi_{FC})] \times \lambda / (4\pi D) \quad (4)$$

where, ϕ_{FC} , ϕ_{EC} and ϕ_S denote the phase maps obtained from the full cavity, empty cavity, and sphere cavity, respectively, λ is the average wavelength of the laser (632.81 nm), n is the average refractive index of the sphere (1.457), and D is the average diameter of the sphere.

Figures 2 to 4 show the estimated phase maps of the sphere cavity, full cavity, and empty cavity, respectively. The circular spots are fiducials on the test sphere. The “bull’s-eye” pattern is due to internal reflections in the transmission sphere that was used as a reflection sphere.

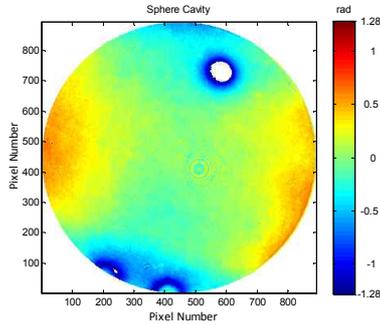


Figure 2: Phase map of the sphere cavity

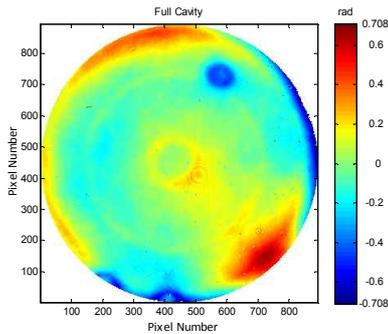


Figure 3: Phase map of the full cavity

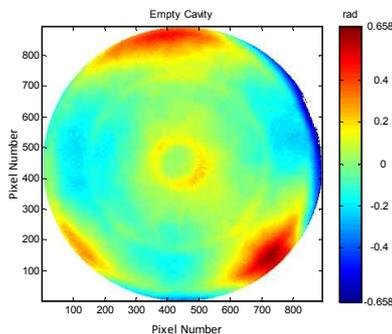


Figure 4: Phase map of the empty cavity

The phase maps were combined according to equations (3) and (4) to obtain the DV and RIV. The results are depicted in Figures 5 and 6.

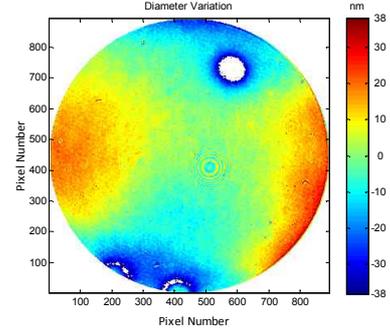


Figure 5: Diameter variation

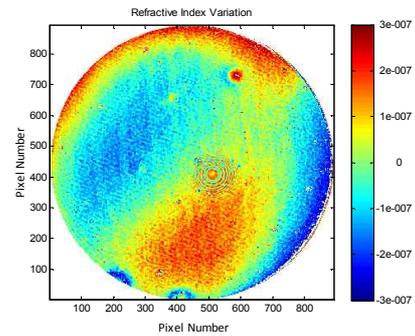


Figure 6: Refractive index variation

5. CONCLUSION AND FUTURE WORK

We have shown that the DV and RIV of a fused silica sphere can be measured using a frequency-scanning phase-shifting Fizeau interferometer in a confocal four-surface configuration. The estimated RIV map shows a relatively small variation in the average refractive index for rays through the sphere center, and seems correlated with the DV map. Ongoing research is aimed at characterizing uncertainties and reducing this correlation through, e.g., improved control of cavity geometry and phase shifts. The DV and RIV of the complete sphere will be obtained by stitching maps obtained at different angular orientations of the sphere.

6. ACKNOWLEDGEMENTS

The authors would like to thank Dr. Tom Langenstein and Dr. Daniel DeBra at Stanford University for providing the fused silica sphere, and Dr. Jack Stone and Dr. Patrick Egan at NIST for supplying the Fabry-Perot cavity.

7. REFERENCES

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