Measurement considerations for precise, highly reflective surfaces using a phase-measuring Fizeau interferometer

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Abstract

Stringent surface specifications for highly reflective precision optical surfaces place great demands on interferometric techniques used for surface metrology. Highly reflective test surfaces often produce nonsinusoidal interference fringes when compared to a partially-reflective/absorbing reference surface in Fizeau-type interferometers. This talk will discuss some tradeoffs in choosing phase-measurement techniques for use with noticeably nonsinusoidal fringes when the residual measurement error needs to be on the order of one-hundredth of a wave peak-to-valley. The errors due to the phase calculation algorithm, the phase shift calibration and the reference surface calibration are all coupled making the choices more difficult. Simulated data will be used for most of the discussion. Comparisons to the measurement of uncoated surfaces will be made.

Summary

One of the major projects in the US dealing with very high quality optics is the LIGO (laser interferometer gravitational-wave observatory) project. Recently substantial effort has been made on measurement and calibration of these precise optical surfaces.[1-3] This work has shown that surface irregularity measurements on uncoated surfaces can be made consistently at the nanometer rms level with an interferometer operating at 633 nm.[1-3] These measurements have been made using phase-measuring Fizeau interferometers. Various calibration techniques for use with Fizeau-type phase-measuring interferometers have been developed to deal with the measurement of precise, nearly flat optical surfaces.[4-5] Most calibration techniques are necessarily system dependent and have been tailored to a specific interferometer.

These optical systems not only require precise optical surfaces, but also specify high reflectivities for these surfaces. High reflectivities add difficulty to metrology that already requires very careful measurements. With dielectric coatings the surfaces need to be measured at the wavelength of use. Fringe contrast will noticeably suffer in a Fizeau interferometer when measuring a highly reflective test surface relative to an uncoated reference surface. The reference surface can be coated to yield much better contrast fringes but these fringes will not be truly sinusoidal if the reference surface is designed to be used in both the reference and return positions of a Fizeau interferometer.[6] Nonsinusiodal interference fringes add errors to surface heights calculated from phase-shifted data because phase-measurement algorithms assume sinusoidal fringes.[7] Each application and interferometer has its own set of idiosyncrasies that need to be compensated for by choosing the optimal measurement algorithm. Additionally, the accuracy of the phase-shifter is intimately linked to how well the compensated algorithm with work.

Phase-measurement algorithms that use more samples are likely to have less residual error than those with fewer samples.[8] There is an added advantage in error reduction to have the total phase shift cover more than one wavelength of optical path difference. However, phase shifters have limited displacement ranges so there is a tradeoff between the total phase shift and the phase shift between consecutive samples as well as the length of time it takes to obtain the necessary data. Thankfully, frame acquisition hardware and computer memory have evolved to a point where they aren't a major limitation to the phase-measurement algorithm used.

For this particular work, a Wyko 6000 Fizeau interferometer operating at 1064 nm was utilized to measure 150 mm diameter areas on highly reflective surfaces. The throw of the piezo-electric transducers (PZT) was long enough to encompass phase-measurement algorithms obtaining data over optical path differences of up to 3 wavelengths. Simulations of the interference pattern expected between a reference surface with a Clapham-Dew type coating[6] and a highly reflective test surface were used as input to compare a lot of possible phase-measurement algorithms.[9] Because the PZT phase shifters have a large range and the camera is not being used at its optimal wavelength, there is likely to be some nonlinearity in both the phase shift between samples and the sampled signals at the hundredth of a wave level that needs to be compensated for in the phase calculation algorithm.

After consideration of the tradeoffs, ease of implementation and the magnitude of the anticipated residual phase measurement errors, an 11-sample algorithm derived by Yves Surrel using 60° phase steps was chosen for this system.[8] This talk will discuss the tradeoffs and show simulated results for different algorithms as well as real data that confirm the algorithmic choices.

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References

1. R.E. Parks, C.J. Evans, P.J. Sullivan, L.-Z. Shao and B. Loucks, "Measurements of the LIGO pathfinder optics," *Proc. SPIE* **3134** 95-111 (1997).
2. D.I. Farrant, A.J. Leistner, B.F. Oreb, M.A. Suchting and C.J. Walsh, "Metrology of LIGO pathfinder optics," *Proc. SPIE* **3134** 79-85 (1997).
3. C.J. Walsh, A.J. Leistner, J. Seckold, B.F. Oreb and D.I. Farrant, "Fabrication and Measurement of Optics for LIGO," to be published.
4. C.J. Evans and R. N. Kestner, "Test optics error removal," *Appl. Opt.*. **35**(7) 1015-1021 (1996).
5. P. Hariharan, "Optical flat surfaces: direct interferometric measurements of small-scale irregularities," *Opt. Eng.* **35**(11) 3265-3266 (1996).
6. P.B. Clapham and G.D. Dew, "Surface-coated reference flats for testing fully aluminized surfaces by means of the Fizeau interferometer," *J. Sci. Instrum.* **44,** 899-902 (1967).
7. See, for example, J. Schmit and K. Creath, "Extended averaging technique for derivation of error-compensating algorithms in phase-shifting interferometry," *Appl. Opt.* **34**(19) 3610-3619 (1995).
8. Y. Surrel, "Additive noise effect in digital phase detection," *Appl. Opt.* **36**(1) 271-276 (1997).
9. Simulated interference fringe data provided by Roger Netterfield of CSIRO.