Instantaneous Interferometry: Another View

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Abstract: Single-camera frame instantaneous interferometry is an alternative optical test method where environmental noise prohibits conventional phase shifting methods. The flexibility and high performance of an optimized spatial carrier fringe method provides a compelling solution.

OCIS codes: (120.3180) Interferometry; (120.3930) Metrological instrumentation; (120.5050) Phase measurement

1. 3D Surface profiling interferometry

Optical testing interferometers profile surfaces by interpretation of the interference signal at each image pixel, leading to an estimate of interference phase at each of these points, which in turn relates to surface height. In the vast majority of instruments, phase estimation involves at least three different intensity images with added relative phase shifts. The dominant technique today involves imparting the phase shifts sequentially over time, often mechanically, using widely-recognized phase shifting interferometry (PSI). In the Fizeau interferometer configuration, PSI has the advantage that in the limit of short interferometer cavities the method is fully common path, providing a high degree of self correction for retrace errors, polarization effects and other optical imperfections.

2. Instantaneous interferometry

As an alternative to the time-based PSI method, instantaneous interferometers impart phase shifts onto the interference signal that are measurable at the same instant in time, or at least within a time window of a single shuttered camera frame, e.g. 1 msec. This method provides environmental insensitivity, and the possibility of capturing dynamically-changing events.

The simultaneous introduction of multiple phase shifts requires that we encode the reference and measurement beams of the interferometer so as to be able to manipulate their relative phase. One method is to separate the reference and measurement beams along differing spatial paths, as in a Twyman Green [1,2], or introduce a tilt angle of the reference beam with respect to the measurement beam, which is also possible in a modified Fizeau [3,4,5]. Another approach is to use two interferometers in tandem, one that has geometrically-separable reference and measurement beams, and a second that includes the test object [6,7]. The encoding involves coherence matching of the two cavities so as to e.g. associate the measurement beam with the test object.

In addition to encoding the reference and measurement beams, we need a detection method for acquiring three or more phase-shifted intensity signals simultaneously for every pixel in the field of view. Known methods include the introduction of dense carrier fringes, on the assumption that the surface height variations as well as the average intensity and fringe contrast variations are negligible over a few pixels [3,8,9,10]. Another method involves three or more duplicate images, side by side on the same camera or directed to multiple cameras, usually phase shifted by polarization [1,2,11]. Most recently, a method for spatial phase shifting on a single camera has been developed that uses a special camera mask or other means to generate phase shifts local to individual pixels using polarization-encoded reference and measurement beams [12,13].

3. The need for calibration

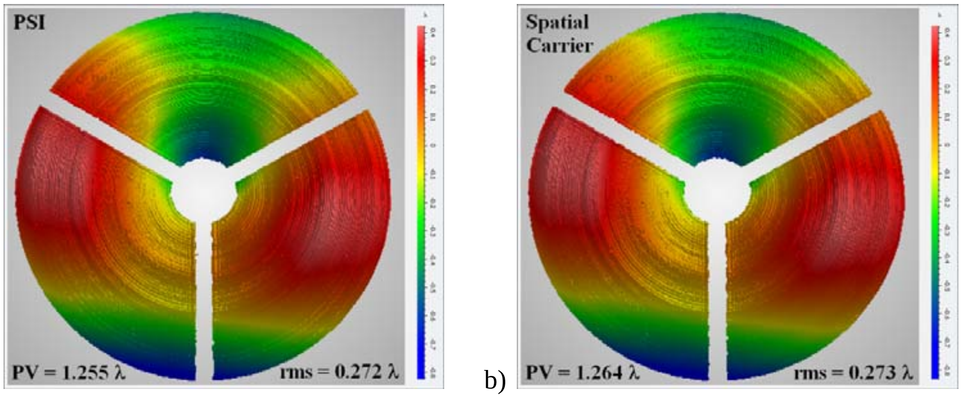
A reasonable question comes to mind when reviewing the various methods summarized in the previous section: Which of the available instantaneous interferometer methods are truly common path, like the traditional phase-shifting Fizeau? The answer is: *None of them are*.

For geometrically-encoded systems, the differing spatial paths mean that the reference and measurement beams do not follow the same paths through the optical system. For the coupled cavity systems, there are dissimilar paths in at least one of the tandem interferometers. Polarized interferometers, which in addition to these considerations rely on polarized reference and measurement beams, must contend with the polarizing properties of optical components both inside and outside of the instrument enclosure that contribute offsets and cyclic errors [14,15].

Thus the choice of instantaneous interferometer solution comes down to how effectively we can calibrate and compensate for errors, together with the cost and complexity of the solution.

4. Spatial carrier fringe solution

Given its potential simplicity and low cost, and its well established performance on high-precision instruments [8,9], there are compelling reasons to focus on and optimize the classical method of spatial carrier fringes for instantaneous interferometry. Recognizing that the key issue with instantaneous interferometry is non-common path errors, Zygo has developed *in-situ* calibration and compensation for predictable and repeatable correction to less than 5-nm PV (or 0.008λ PV) for static errors arising from spatially non-common path geometries, without the need for calibration artifacts. Spatial carrier fringes set to ½ Nyquist in X and Y, combined with a conventional Fizeau interferometer and accurate compensation (either by design or correction), provide total measurement uncertainty that is consistent with uncompensated temporal PSI acquisition. As a practical demonstration, Fig. 1 shows excellent correlation between sequential measurements acquired with a spatial carrier and conventional PSI; a pixel-by-pixel difference of the two maps yields a ΔPV < λ/50!

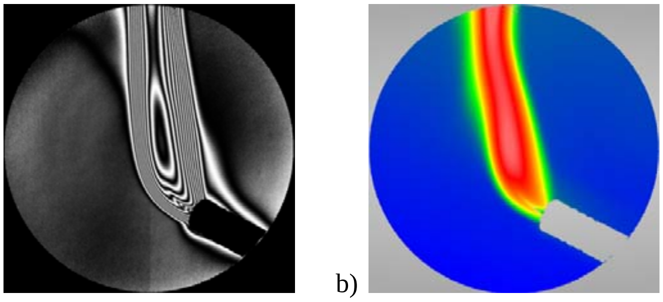


a) b)

Fig. 1. Diamond-turned parabolic surface tested in a classic null configuration with collimated wavefront reflected from the parabola towards a reference sphere (held by a "spider"): a) with 13-bucket PSI; b) with a modern, optimized spatial carrier algorithm. A pixel-by-pixel difference of the two maps, measured sequentially, yields a ΔPV < λ/50.

A well-designed implementation of spatial carrier fringe solutions is essential to provide the ease-of-use and confidence-in-metrology that users have come to expect and demand of commercial interferometers. The graphical user interface should provide alignment with real-time "null" fringes. This synthetic view addresses at least three needs: (1) a familiar fringe interpretation for the classically trained optician; (2) alignment reproducibility consistent with "on-axis" solutions; and (3) high contrast viewing fringes even at exposure times < 200 μsec. In the absence of automated motion, software provides a target mechanism for the user to rough align to within 20 tilt fringes of the proper spatial carrier frequency and direction prior to final alignment. Given these tools, setup and alignment for a spatial carrier algorithm is familiar, efficient, and precise without the need for any special hardware or alignment mechanisms. Because systematic errors associated with spatial carrier fringes are well understood and easily modeled, system checks should warn a user if calibration or alignment is suspect.

Acquisition, processing, and averaging of phase in the presence of vibration and turbulence is the most common use for instantaneous interferometry. An additional attraction is the ability to view, capture, and analyze dynamic events in real time, as illustrated in Fig. 2.



a) b)

Fig. 2. Single-frame capture of dynamic thermal gradients viewed a) as interference fringes; b) as a processed 3-dimensional map. These results are viewed live through high-speed data processing to facilitate interpretation of rapidly-changing, dynamic events.

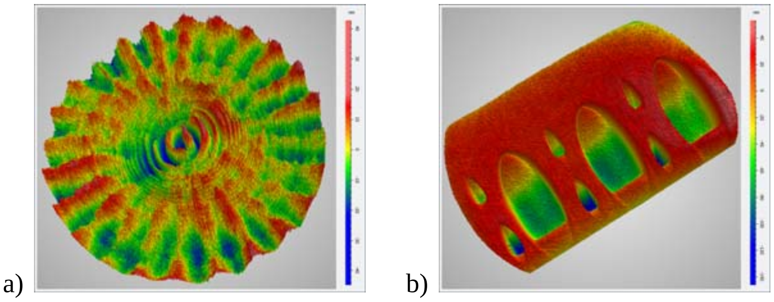


Fig. 3. 3-dimensional height maps demonstrating lateral resolution capabilities on a 1000x1000 detector array using an optimized spatial carrier algorithm: a) an optical flat showing mid-spatial frequency errors generated by small-tool polishing; b) a “spot” block used to characterize the polishing footprint for deterministic polishing correction.

Lateral resolution is important to those interested in measuring more than figure error. Fig. 3 provides two practical examples of the lateral resolution capability of an optimized carrier fringe algorithm. Lateral features < 300 microns are clearly resolved in Fig. 3a (and Fig. 1) on a 100 mm aperture. Additionally, the sharp edges of “spot” samples are well defined in Fig. 3b.

A spatial carrier implementation, as outlined above, can have the significant advantage of retaining full compatibility with a Fizeau interferometer configured for conventional PSI, thus providing flexibility in measurement method. Advantages of this flexibility include: (1) certain environments, and/or setups, may only need vibration correction applied to PSI—allowing measurement with the highest precision available [16]; (2) live phase might be used to align an optical system through real-time Zernike or Seidel feedback, while final measurement reverts back to PSI; and (3) it is common practice to validate the metrology integrity of an instantaneous interferometer by comparing it directly with a PSI measurement, as in Fig. 1.

5. Summary

Instantaneous interferometry enables high-resolution metrology for applications where environmental noise, separated metrology platforms, and/or cavity length prohibit conventional PSI measurements. In our view, an optimized spatial carrier fringe solution has and can serve both of these areas without compromise, with the added benefits of lower complexity and cost when compared to other approaches.

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6. References

[1] R. Smythe and R. Moore, “Instantaneous Phase Measuring Interferometry,” Opt. Eng., 23, 361-364 (1984).

[2] C. L. Koliopoulos, “Simultaneous phase shift interferometer,” Proc. SPIE 1531, 119-127 (1992)

[3] L. L. Deck, “Environmentally Friendly Interferometry,” Proc. SPIE 5532, 159-169 (2004)

[4] J. E. Millerd and J. C. Wyant, “Simultaneous phase-shifting Fizeau interferometer,” US Patent 7,230,718 (2007)

[5] P. Szwaykowski, “Interferometric system with reduced vibration sensitivity and related method,” US Patent Application 20060146341(2006)

[6] M. Küchel, “Interferometer for measuring optical phase difference,” US Patent 4,872,755 (1989).

[7] B. Kimbrough, J. Millerd, J. Wyant, and J. Hayes, “Low Coherence Vibration Insensitive Fizeau Interferometer,” Proc. SPIE 6292:15 (2006)

[8] M. Takeda, H. Ina and S. Kobayashi “Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry” J. Opt. Soc. Am. 72, 156-160 (1982)

[9] M. Küchel, “The New Zeiss Interferometer,” Proc. SPIE 1332, 655-663 (1990).

[10] K. Freischlad., R. Eng., J. B. Hadaway, “Interferometer for testing in vibration environments,” Proc. SPIE 4777, 311-322 (2002)

[11] J. Hayes, “Dynamic interferometry handles vibration,” Laser Focus World 109-113 (March 2002)

[12] J. L. McLaughlin, B. A. Horwitz, “Real-time snapshot interferometer,” Proc. SPIE 680, 35-43 (1986)

[13] J. E. Millerd “Pixelated phase-mask dynamic interferometers,” in Fringe 2005 edited by W. Osten, (Springer, New York, 2005), pp 640-647.

[14] M. Novak, J. Millerd, N. Brock, M. North-Morris, J. Hayes, and J. Wyant “Analysis of a micropolarizer array-based simultaneous phase-shifting interferometer,” Appl. Opt. 44, 6861 (2005)

[15] C. Zhao, D. Kang, and J. H. Burge, “Effects of birefringence on Fizeau interferometry that uses a polarization phase-shifting technique,” Appl. Opt. 44, 7548-7553 (2005)

[16] L. L. Deck, “Suppressing phase errors from vibration in phase-shifting interferometry,” Appl. Opt. 48, 3948-3960 (2009)