Diffractive grazing-incidence interferometer

Peter de Groot

I propose a symmetric geometry for grazing-incidence interferometry of flat surfaces using diffraction gratings for beam splitting and recombination. The geometry employs a reference mirror to correct for relative inversion of the measurement and reference wave fronts. Preliminary testing with a 4-μm equivalent-wavelength system shows a 3σ repeatability of 20 nm for both smooth and rough surfaces, including a variety of precision-engineered metal, ceramic, and glass objects. The system has a comfortable working distance and large field of view, suitable for production testing. © 2000 Optical Society of America

OCIS codes: 050.1950, 120.3180, 220.4840, 150.3040.

1. Grazing-Incidence Interferometry

Interferometry at an oblique or grazing-incidence angle is a well-known strategy for extending the precision and full-field topography capability of optical testing to unpolished technical surfaces. Qualitatively, the technique builds on the observation that rough surfaces appear smooth when viewed at a grazing angle. This observation translates quantitatively into an equivalent wavelength Λ for interferometry at grazing incidence in which

$$\Lambda = \lambda/\cos(\alpha), \qquad (1)$$

where λ is the source wavelength and α is the angle of incidence.[1]

The interferoscope invented by Abramson in the 1960's is presently the most important practical example of a grazing-incidence interferometer.[2,3] Abramson's interferometer uses the refractive properties of a large right-angle prism to provide high incident angles on the surface (>80°) while partially correcting for the foreshortening of the image. This distortion correction property is most useful when the test object is circular, e.g., a silicon wafer[4] or a hard-disk blank.[5] Variations of Abramson's interferometer are common in modern commercial instruments and in the literature;[6–8] however, there are important limitations to the design. Principally, it is a near-contact metrology system, requiring that the test object be placed a fraction of a millimeter away from the hypotenuse of the prism. This requirement follows from the desire to maximize the field of view while the aberrations associated with the steep refraction angle at the prism surface are minimized.[9] The short working distance can be inconvenient for production testing and increases the chances of damaging the prism surface that serves as a reference flat.

In the early 1970's, Birch invented a diffractive grazing-incidence interferometer using a pair of linear gratings arranged in a series that has ample working distance.[10] A collimated beam passes through a linear diffraction grating to the object surface, whereas the first-order diffracted beam follows a path that avoids the object and serves as a reference beam. A second grating combines the reference beam with the grazing-incidence reflection of the measurement beam to generate the interference effect. This diffractive optic interferometer achieves good results over large areas with small-aperture optics and is particularly well suited to objects that are rather more long than wide, such as machine tool slide ways. Birch's basic design has been adapted for phase-shifting interferometry[11] and for use with cylindrical optics.[12–14] Alternative diffractive geometries for grazing incidence have been proposed, e.g., by Järisch and Makosch[15] and by Hariharan.[16]

In spite of these advances, there persists an important difficulty common to nearly all single-pass diffractive grazing-incidence geometries. In Birch's interferometer, for example, the measurement beam undergoes a single reflection from the object surface, whereas the reference beam passes straight through to the recombination grating without undergoing re-

---

P. de Groot (peterd@zygo.com) is with the Department of Research and Development, Zygo Corporation, 21 Laurel Brook Road, Middlefield, Connecticut 06455.

Received 30 July 1999; revised manuscript received 3 January 2000.

0003-6935/00/101527-04$15.00/0

© 2000 Optical Society of America

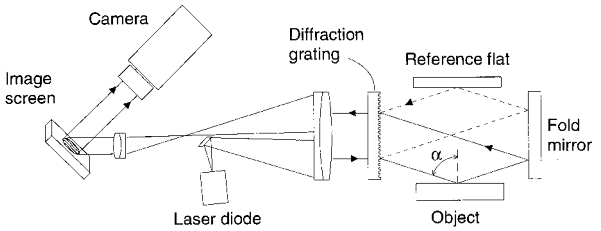

Fig. 1. Diffractive grazing-incidence interferometer. The symmetry of the design, which employs a reference mirror, solves the wave-front inversion problem characteristic of this type of interferometer. The equivalent wavelength is equal to the spacing of the grating lines.

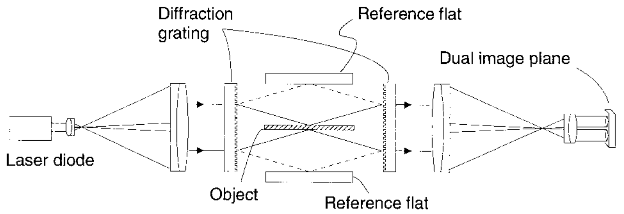

Fig. 2. Proposed dual-sided flatness tester.

flection. As a consequence, the reference and measurement beam wave fronts are inverted with respect to each other. The instrument is therefore undesirably sensitive to the wave-front uniformity and flatness, which is determined by the quality of the source beam, the collimating optics, the beam-splitting grating, and even the air turbulence prior to wave-front division. The wave-front inversion and the unequal paths of the measurement and reference beams also impose undesired requirements on the spatial and temporal coherence of the source.[17]

2. Noninverting Diffractive Geometry

I propose in Fig. 1 a geometry for diffractive grazing incidence that does not suffer from relative wave-front inversion between the measurement and the reference beams.[18] By means of a fold mirror, a single linear transmission grating serves as both a beam splitter and a beam combiner. The reference and measurement beams correspond to the ±1 diffraction orders of the zero-order-suppressed grating. A key element is the reference mirror which restores symmetry to the beam paths by equalizing the number of reflections and the optical path lengths. Similar symmetric geometries appear in optical encoders[19] and in the context of achromatic fringe generation for velocimetry and particle counting.[20]

It is straightforward to show that the equivalent wavelength of the proposed instrument (Fig. 1) is equal to the grating period, as is the case for Birch's interferometer. The instrument is therefore achromatic in the determination of the equivalent wavelength. This, together with the noninverting, equal-path geometry, relaxes the coherence requirements so that one can use a multimode laser diode and a rotating diffuser as the light source. A low-coherence source eliminates speckle noise and other coherent artifacts.

The new design shares with Birch's interferometer a comfortable working distance and a relatively large field of view compared to the size of the diffractive optic. However, the design also suffers from the anamorphic distortion or image foreshortening characteristic of grazing incidence. Depending on the application, this can be considered an advantage (long, thin objects) or a significant problem to be overcome (circular parts). If the foreshortening is undesirable, it is not difficult to correct the aspect ratio by projecting the image onto a tilted screen or grating and then viewing the screen at normal incidence, as shown in Fig. 1.[15,21]

A number of variations of this design are possible. For example, one may dispense with the fold mirror and employ two gratings in series while preserving the role of the reference mirror.[22] The diffraction gratings can be either reflective or transmissive, or a combination of the two.[23] One can also imagine using different diffraction orders to reduce or increase the relative size of the reference mirror in comparison with the object. By means of an extended source, e.g., a defocused laser spot on a rotating diffuser, one can localize the fringe pattern and measure transparent optical flats without the troublesome internal Fizeau fringes that complicate conventional laser-based interferometry. Figure 2 shows a configuration for measuring simultaneously the front and back surfaces of a flat object such as a silicon wafer.[24] Finally, by means of reference cylinders and axicon gratings, one can extend the concept to cylindrical objects while retaining all the advantages of the noninverting design.

3. Experimental Results

I constructed an experimental demonstration of Fig. 1 using a 250-groove/mm grating and a 100-mW, 680-nm multimode diode. A 640 × 480 pixel CCD captures the distortion-corrected image of a 60 × 100 mm field of view on a plain-paper screen tilted at the same 80° angle as the incident angle α to the object. The $\Lambda = 4$-μm equivalent wavelength is large enough to accommodate a wide variety of surface textures and reflectivities, resulting in high-contrast fringes over several millimeters of height range. The test object rides on a stainless-steel stage driven by a piezoelectric transducer for phase shifting, and the measurement is under computer control.

The plano–convex singlet lenses in the experimental system generate several micrometers of abberation in the illumination wave front. The resultant system error as determined by one measuring the flatness of a high-quality aluminized mirror is less than 0.1 μm, demonstrating that the new geometry is insensitive to initial wave-front quality, as expected. The system error increases with tilt, particularly horizontal tilt (i.e., tilt that changes the angle of incidence), which I attribute to ray trace errors through the singlet optics.

A fundamental performance test is simple repeat-

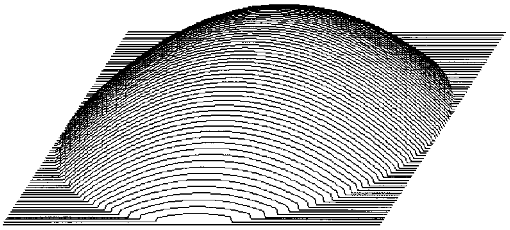

Fig. 3. Profile of a 60-mm-diameter area of a 15.7-m-radius spherical test plate. The peak-to-valley departure is 29.6 μm.

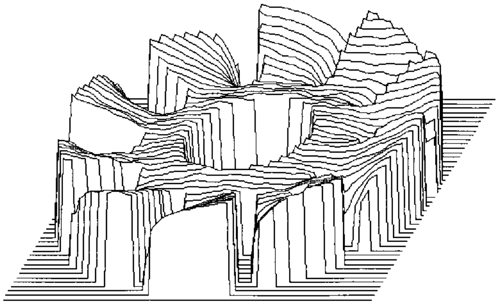

Fig. 4. Profile of a 30-mm-diameter machined pump component having a peak-to-valley flatness of 3.13 μm.

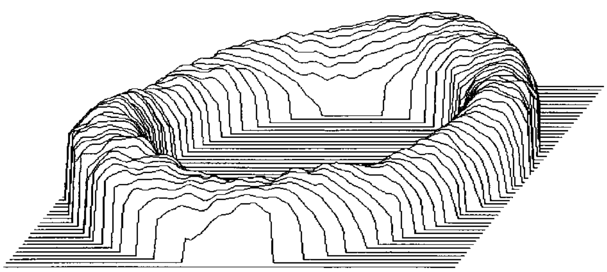

Fig. 5. Profile of a 31-mm-diameter ceramic seal having a peak-to-valley flatness of 1.33 μm.

ability, for which the instrument performs a sequence of 10 measurements of one after the other. For these tests, I use three phase averages and a three-pixel low-pass averaging of the final image. On a wide variety of test objects, including both smooth and rough surfaces, the resultant 3σ simple repeatability is <20 nm. Another fundamental test is the measurement of a known spherical object, for which I chose a 15.7-m-radius test plate (see Fig. 3). The measured peak to valley in the experimental instrument is 29.6 μm over a 60-mm-diameter measurement area, as expected. Subtraction of the best-fit sphere reveals a 2-μm peak-to-valley saddle-shaped system error. This error is small enough to have come from a variety of imperfections in the experiment, including something as simple as an imperfectly flat image screen. However, it is known that 6:1 foreshortening complicates the interpretation of interference images from spherical surfaces at grazing incidence.[25]

One of the main purposes of the instrument is to measure nonoptical or technical surfaces, such as are encountered in the manufacture of precision-engineered components of engines, pumps, fuel systems, appliances, and so on. Figure 4 shows profile data from a 30-mm-diameter pump part, and Fig. 5 is the profile of a diffusely reflecting ceramic ring. Figure 6 provides an even more unusual profile image, this time of a component for a hair clipper. All these parts (Figs. 4–6) have a surface roughness beyond the reach of conventional He–Ne-based Fizeau interferometers.

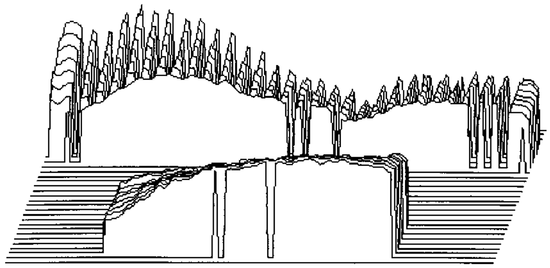

Fig. 6. Profile of a mechanical hair-cutting blade with a peak-to-valley flatness of 3.49 μm.

4. Summary and Conclusions

The proposed geometry has the large working distance and field of view of diffractive grazing-incidence interferometry while solving the problems of wavefront inversion and source coherence. Experimental testing demonstrates the technique's potential on a wide variety of surface types. However, the new design shares with traditional grazing-incidence interferometers the inability to measure recessed surfaces and metrology problems associated with the steep viewing angle. Assuming that these difficulties are acceptable or can be overcome with further improvements, the diffractive grazing-incidence interferometer shown in Fig. 1 may be an interesting addition to the optical metrology toolbox for production flatness testing.

The author acknowledges the stimulating discussions and assistance of J. Biegen, X. Colonna de Lega, L. Deck, D. Stephenson, and C. Zanoni during the development of the concept and experimental system described in this paper.

References and Notes

1. D. Malacara, *Optical Shop Testing*, 2nd ed. (Wiley, New York, 1992), pp. 76, 259–260.
2. N. Abramson, "The Interferoscope: a new type of interferometer with variable fringe separation," Optik (Stuttgart) **30,** 56–71 (1969).
3. T. E. Carisson, N. H. Abramson, and K. H. Fischer, "Automatic measurement of surface height with the interferoscope," Opt. Eng. **35,** 2938–2942 (1996).
4. J. Schwider, R. Burow, K.-E. Elssner, J. Grzanna, and R. Spolaczyk, "Semiconductor wafer and technical flat planeness testing interferometer," Appl. Opt. **25,** 1117–1121 (1986).
5. Y. Zhao, D. Li, M. Cao, and J. Wang, "Noncontact measuring profile of magnetic disk with optical methods," in *Second International Conference on Optoelectronic Science and Engi-*

neering '94, D.-H. Wang, A. Consortini, J. B. Breckinridge, eds., Proc. SPIE **2321,** 235–237 (1994).

6. J. D. Briers, "Interferometric flatness testing of nonoptical surfaces," Appl. Opt. **10,** 519–524 (1971).
7. Y. Otani, T. Kuwahara, M. Yamamoto, and T. Yoshizawa, "Precise measurement of nonoptical surface by oblique incidence interferometer," in *Laser Interferometry IX: Techniques and Analysis*, M. Kujawińska, G. M. Brown, and M. Takeda, eds., Proc. SPIE **3476,** 214–217 (1998).
8. C. Joenathan, B. Franze, and H. J. Tiziani, "Oblique incidence and observation electronic speckle-pattern interferometry," Appl. Opt. **33,** 7307–7311 (1994).
9. G. Spür, L. Nyarsik, and K. Körner, "Imaging characteristics of prism interferometers," in *16th Congress of the International Commission for Optics: Optics as a Key to High Technology*, G. Akos, T. Lippeny, G. Lupkouvcs, and A. Podmaniczky, eds., Proc. SPIE **1983,** 702–703 (1993).
10. K. G. Birch, "Oblique incidence interferometry applied to nonoptical surfaces," J. Phys. E **6,** 1045–1048 (1973).
11. M. Hizuka, "Oblique incidence interferometer with fringe scan drive," U.S. patent 5,786,896 (28 July 1998).
12. J. Schwider, "Verfahren und Anordnung zur Prüfung beliebiger Mantelflächen rotationssymmetrischer Festkörper mittels synthetischer Hologramme," German patent WP 106 769 (4 January 1972).
13. T. Dresel, J. Schwider, A. Wehrhahn, and S. Babin, "Grazing incidence interferometry applied to the measurement of cylindrical surfaces," Opt. Eng. **34,** 3531–3535 (1995).
14. J. H. Bruning, "Interferometric measurement of surfaces with diffractive optics at grazing incidence," U.S. patent 5,654,798 (5 August 1997).
15. W. Järisch and G. Makosch, "Interferometric surface mapping with variable sensitivity," Appl. Opt. **17,** 740–742 (1978).
16. P. Hariharan, "Improved oblique-incidence interferometer," Opt. Eng. **14**(3), 257–258 (1975).
17. J. Schwider, "Spatial coherence in interferometry for optical testing," Lehrstuhl für Optik Annual Report, University of Erlangen-Nürnberg (Druckerei Lengenfelder, Erlangen, Germany, 1998), p. 25.
18. U.S. and foreign patents pending.
19. K. Patorski, *Handbook of the Moiré Fringe Technique* (Elsevier, Amsterdam, 1993), p. 107.
20. S. Kaufman, F. D. Dorman, D. C. Bjorkquist, and M. R. Rinn, "Laser optical measuring device and method for stabilizing fringe pattern spacing," U.S. patent 4,948,257 (14 August 1990).
21. J. Magner, "Full aperture interferometry for grazing incidence optics," U.S. patent 5,268,742 (7 December 1993).
22. A similar geometry employing two gratings in series with a reference mirror has been considered independently at the University of Erlangen-Nürnberg. T. Dresel and N. Lindlein (personal communication, 20 September 1999).
23. K. Eissner, J. Grzanna, and J. Schwider, "Anordnung zur interferometrischen Ebenheitsprüfung technischer Oberflächen," DDR patent 261422A1 (25 October 1988).
24. J. Schwider, "Measurement of curvature and thickness variations of flat cuboids by grazing incidence interferometry," Lehrstuhl für Optik Annual Report, University of Erlangen-Nürnberg (Druckerei Lengenfelder, Erlangen, Germany, 1998), p. 30; W. Järisch and G. Makosch, "Interferometric thickness analyzer and measuring method," U.S. patent 4,653,922 (31 March 1987).
25. K. G. Birch, "Application of the "Interferoscope" to spherical and aspherical surfaces," Optik (Stuttgart) **36**(4), 399–409 (1972).