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A NOVEL NON-CONTACT PROFILER DESIGN FOR MEASURING SYNCHROTRON RADIATION MIRRORS*

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ABSTRACT

A novel optical profiler is described in this paper for measurement of surface profiles of synchrotron radiation (SR) mirrors. The measurement is based on a combination of an optical heterodyne technique and a precise phase measurement procedure without a reference surface. A Zeeman two-frequency He-Ne laser is employed as the light source. The common-path optical system, which uses a birefringent lens as the beam splitter, minimizes the effects of air turbulence, sample vibration and temperature variation. A special autofocus system allows the profiler to measure the roughness and shape of a sample surface. The optical system is mounted on a large linear air-bearing slide, and is capable of scanning over distances covering the spatial period range from several microns to nearly one meter with a high measurement accuracy.

I. INTRODUCTION

Surface roughness is an important factor in evaluating the the performance of optical surfaces. A number of surface profiling techniques¹⁻⁵ have been developed to measure the characteristics of optical surfaces. There are two main measurement techniques: mechanical stylus instruments and optical profilometers. The mechanical stylus is a traditional surface profile measurement technique, which is based on a contact method using a sharp stylus. Its measuring accuracy can be several angstroms or less, but the measurement produces a problem that the hard tip and high pressure contacting the sample can make scratches or digs easily on the measured surface, especially on soft material and super-fine surfaces. The measurement is also tedious. Optical profilometers, on the other hand, are becoming more widely used because they are non-contacting as well as being simple and fast. The measurement accuracy is now at the level of one angstrom. Presently available commercial optical profilers only cover the spatial period range from two microns to ten or twenty millimeters. This is not sufficient for the measurement of large or aspheric super-fine optical surfaces, especially large cylindrical optical surfaces such as those used in synchrotron radiation (SR) applications. A typical SR mirror is sketched in Fig. 1.

To solve the problems of measuring the figure of large cylindrical aspheres, Takacs and collaborators^{6,7} have developed the Long-trace Profiler (LTP) at Brookhaven National Laboratory (BNL), which has opened a new area for surface testing. The LTF based on the pencil-beam interferometer concept, can easily measure large curved optical components with a high accuracy, covering the spatial period range from 1 mm to nearly 1 meter.

This paper describes a novel profiler design which can be used as a long-scanning surface instrument covering a spatial period range from several microns to nearly one meter. The instrument is based on a common-path optical system which employs a common-mode rejection technique without need for a reference surface. The lowest spatial period can be varied through the choice of the microscope objective.

II. PRINCIPLE OF DESIGN

The profiler design is depicted in Fig. 2. A longitudinal Zeeman-split He-Ne laser, used as the light source, produces a common-path beam which contains two beams with equal intensity and a stabilized frequency difference of 250 kHz. One beam is left circularly polarized; and the other is right circularly polarized. Both beams are expanded through a collimating lens, and the collimated beams are partially reflected and partially transmitted by a beam splitter. The

Fig. 1 Diagram of the fused silica cylinder reflect mirror used in synchrotron radiation.

transmitted beams are interfered through a polarizer (P1), received by a photoelectric receiver (R1), where a beat-frequency signal is produced serving as a reference signal which contains the information about the initial phase difference between the two polarized beams. The filter is used to enhance the sensitivity of R1 by controlling the beam intensities. The signal—after amplification—is displayed on an oscilloscope and is fed to a digital phase meter.

Fig. 2 Schematic diagram of the designed optical heterodyne instrument. The optical head is designed by employing a birefringent lens as the special beam splitter and is controlled by the astigmatic autofocus system.

The reflected beams from the beam splitter (BS) pass through a quarter wave plate (QWP) where they become two collinear beams which are linearly and orthogonal polarized. The QWP is orientated with its axes at 45 degrees to the crystal optical axis of the birefringent lens. The two beams are then passed through the optical head, which consists of the birefringent lens and a microscope objective. The birefringent lens has two focal points, f_o and f_e ($f_o = 40.0735$ mm, $f_e = 87.8485$ mm), corresponding to the ordinary and extraordinary rays, respectively. One beam, working as an ordinary ray in the birefringent lens, becomes a focused beam; the other beam, the extraordinary ray, becomes a collimated beam. The surface to be measured is located in the ordinary-ray focal plane of the optical head. The focused beam is reflected from a small spot; the collimated beam is reflected from a large spot when a 40X microscope objective is used. The area of the large spot is much greater than, and concentric with that of the small one. The area ratio of the large spot to the small spot is 1250.

Both reflected beams are recombined and collimated through the optical head. A small fraction of the return beams, consisting of the two orthogonal linearly polarized beams with a phase difference produced by surface roughness, is reflected by a special beam splitter to the autofocus system which then adjusts the focus of the optical head on the sample surface. The two transmitted beams are passed through the QWP and become orthogonal circularly polarized. They are then interfered through the BS and a polarizer (P2), received by a photoelectric receiver (R2) where a beat-frequency signal is produced serving as a measurement signal which contains the information about the surface roughness. The digital phase meter compares the phase angles between both incoming signals from R1 and R2, respectively, with a very high resolution, up to 0.001 degree. This permits the quantitative measurement of the optical path difference between the average surface levels of the focused and parallel beam spots to high accuracy. The surface profile is created by scanning the optical head over the surface.

III. OPTICAL HEAD DESIGN

The optical common-mode rejection technique employed in this profiler and the novel optical head design are critical elements in achieving the high measuring accuracy. The birefringent lens is made of calcite crystal with the optical axis at 90 degrees to the incident beam. It produces two orthogonally polarized, concentric beams. Both linearly polarized beams emerging from the QWP are brought to the ordinary and extraordinary focal points, f_o and f_e , respectively, as shown in Fig. 3. As the back focal point of the microscope objective is located at the same position

Fig. 3 Optical head configuration. The back focal point of the microscope objective is located at the same position as that of the extraordinary ray of the birefringent lens. The reflected beams from the surface under testing are recombined and collimated through the optical head.

as f_c , the extraordinary ray becomes a collimated beam passing through the objective; the ordinary ray beam is focused on to the sample surface. The area of the large parallel beam spot (~ 143 microns diameter) is 1250 times greater than that of the small focused beam spot (~ 4 microns diameter) when using a 40X microscope objective.

When the two reflected beams are recombined through the optical head, the phase, Φ , of the beam reflected from the small spot is determined by the surface level, H , and the phase, Φ_0 , is determined by the average level integrated over the collimated beam spot which can be viewed as a reference level, H_0 . When the beams scan across the surface, the phase difference follows the surface irregularity. As both beams are always concentric to each other, sample vibration, air turbulence and temperature variation cause the same optical phase changes to each beam. The common-mode rejection minimizes these perturbations in the optical heterodyne phase measurement. The measured surface roughness, described by the relationship between $(H-H_0)$ and $(\Phi-\Phi_0)$ which is $(\Phi-\Phi_0) = 4\pi(H-H_0)/\lambda$ (λ is laser wave length), is not sensitive to beam intensity variations. Hence, the designed profiler can work with a very high degree of measuring accuracy in the ordinary laboratory condition.

IV. AUTOFOCUS SYSTEM

An astigmatic autofocus system³ is used to keep the optical head at the position where the ordinary ray is focused on the surface being measured. The astigmatic system is combined with a group of cylindrical lenses. Astigmatism occurs when the tangential and sagittal images of an object do not coincide. In the presence of astigmatism, when a collimated beam enters the system, the image is not a focal point, but takes the form of two separate focal lines. Between the astigmatic foci the image is an elliptical or circular blur. A quadrature detector is located at the position between the two foci where the image is a circular blur. When incident beam is convergent or divergent, the image lines will be moved back or forward. The spot pattern on the detector will be elliptical blur, shown in Fig. 4.

Fig. 4 Optical spot pattern on the quadrature detector when the sample surface position is (a) too far, (b) in focus, (c) too close.

The sign and amplitude of the focus-position error signal produced by the detector system is determined by the difference between the signal sums from quad cells A and C and quad cells B and D. A linear-encoded stepping motor is employed to transfer the optical head up and down according to the focus-position error signal. When a small part of both reflected beams is input to the autofocus system, a polarizer (P3), whose polarization direction is oriented at 90 degrees to the polarization of the reflected beam from the large spot, will only let the reflected beam from the small focused beam spot pass through the astigmatic lens to the quadrature detector. When the sample surface is located in the focal plane of the ordinary ray of the optical head, the resulting pattern on the detector is a circle and the focus-position error signal is zero. When the surface is out of focus, too far or too close, the reflected beam from the small spot will be convergent or divergent. The resulting pattern on the detector surface will be an ellipse, with a larger vertical than horizontal axis or reverse. Hence, the focus-position error signal will be positive or negative, and the stepping motor will move the optical head up or down. The translation distance of the present stepping motor is 25 mm with a resolution of 0.1 micron, which should allow for the measurement of curved optical surfaces.

The optical system will be mounted on a large linear air-bearing slide which is nearly one meter long. The tilt angle error of the dynamical optical head caused by its own weight and other factors when moving can be measured in real time by a sensitive electronic autocollimator. The height error caused by the tilt angle error can be corrected, which has already been used in LTP.⁶ This height error correction can be used in the present profiler also. The spatial period range of this instrument is, therefore, from 4 microns to nearly one meter when a 40X microscope objective is chosen.

V. COMPARISON WITH OTHER SURFACE PROFILERS

The optical common-mode rejection technique is also utilized in other profilers such as Huang's⁴ and Downs'⁹ profilers, (Figs. 5(a) and (b), respectively). In Huang's profiler, it is used to reduce the perturbation of surface vibration. But the reference and measurement signal optical paths are only partially common path so that the measurement is still affected by air turbulence and temperature variation. The spatial period range of that profiler is small, only from 2 to 50 microns, which is limited by the spot sizes.

Fig. 5(a) C. C. Huang's Profiler. The expanded beam works as a measurement beam. The reduced beam works as a reference beam. Both expanded and reduced beams are focused to the small and large spots on the surface, respectively.

The Downs' profiler employs a completely common optical path, and achieves the high measurement sensitivity of 1 Å. The optical head is figured out in Fig. 5(c). In that case, however, the reference beam is a convergent, unfocused beam. When the reference beam reaches the sample which can be supposed a perfect smooth surface, each ray has a different phase value, which produces an error factor attached to the reference level integrated over the defocused beam spot. The factor is dependent on the character of the surface profile. The factor and both sizes of defocused and focused spots, 10 and 1.54 microns, limit the spatial period range of the profiler only from 0.5 to 15 microns.

The profiler described in this paper combines a completely common-path optical system with optical heterodyne technique. The common path eliminates errors caused by perturbations in environmental condition. The reference beam is a collimated beam, so that there is no added error produced over the large reference spot. Hence, the large spot height level accurately represents the reference level of the surface being measured. When a 40X objective is chosen, the area ratio between reference and signal spots is 1250, much larger than those of the profilers mentioned above. The large spatial period range from 4 microns to near one meter, makes it possible to describe the entire range of surface roughness period on synchrotron radiation mirrors and other large optical elements.

Fig. 5(b) M. J. Downs' Profiler.

Fig. 5(c) Interferometer focus configuration of M. J. Downs' Profiler. The focused and defocused beams work as measurement and reference beams, respectively.

VI. PRESENT STATUS

As the writing of this paper, the astigmatic autofocus system is being produced. Optical elements are assembled. The phase meter has been checked out. The software design for system control and data analysis is done. The experimental results and analyses will be reported in the near future. The optical system will be installed on the large Dover Model 850 linear air-bearing slide, which is now employed for LTP in our laboratory.

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