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Precision evaluation of a common-path interferometer in measurement of optical surfaces*

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Abstract

An optical heterodyne profiler has been developed for measuring surface roughness. The height measurement accuracy and lateral resolution are 0.11 nm and 4 μm, respectively, when a 40X objective is used. A Zeeman-split He-Ne laser is used as the light source. The optical system is designed as a completely common-path interferometer. Optical and electronic common-mode rejection techniques are employed to minimize the effects of environmental conditions. Sample measurements by this heterodyne profiler and other commercial profilers are displayed. The system noise effect is analyzed in detail. the effect of varying the number of samples at each sampling point is shown. The accuracy comparisons of the profiler with different objectives-5X, 10X, 20X and 40X-are presented.

Key words interferometer, optical sarfaces.

1 Introduction

Surface roughness is becoming more and more a concern of scientists who are estimating the characteristics of optical components, especially those of X-ray optics. Several techniques have been developed to test precision surface qualities. These techniques are optical scattering techniques[1], multiple-beam interferometry[2], stylus profiling instruments[3], and optical probe profiling techniques[4~7]. These techniques, however, are usually used for short lateral measurement ranges. The long-trace profiler[8] is an instrument with a scanning range, 2 mm to nearly one meter. The height measurement standard of this profiler, however, has not been clearly presented by any theoretical analysis or experiment. The 2 mm large lateral resolution limits the profilers applications to some particular sample shapes and very rough surface measurements.

This paper describes a long-scanning profiler designed for testing surface profiles, especially those of large X-ray components. The profiler uses a laser heterodyne technique and precision optical phase

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test to achieve 0. 11 nm height measurement accuracy. The lateral resolution is 4 μm when a 40X objective is used. The height accuracy can be further improved by refining the electronics, while the lateral resolution is improved with a higher power objective. The system noise effect is analyzed in detail. The key elements to the profiler are the applications of a longitudinal Zeeman-split He-Ne laser and the special optical head design. Optical and electronic common-mode rejection techniques are employed in the precision optical path test. Environmental effects are minimized by these rejection techniques. Measurement results are obtained in ordinary experimental conditions.

2 Principle of the profiler

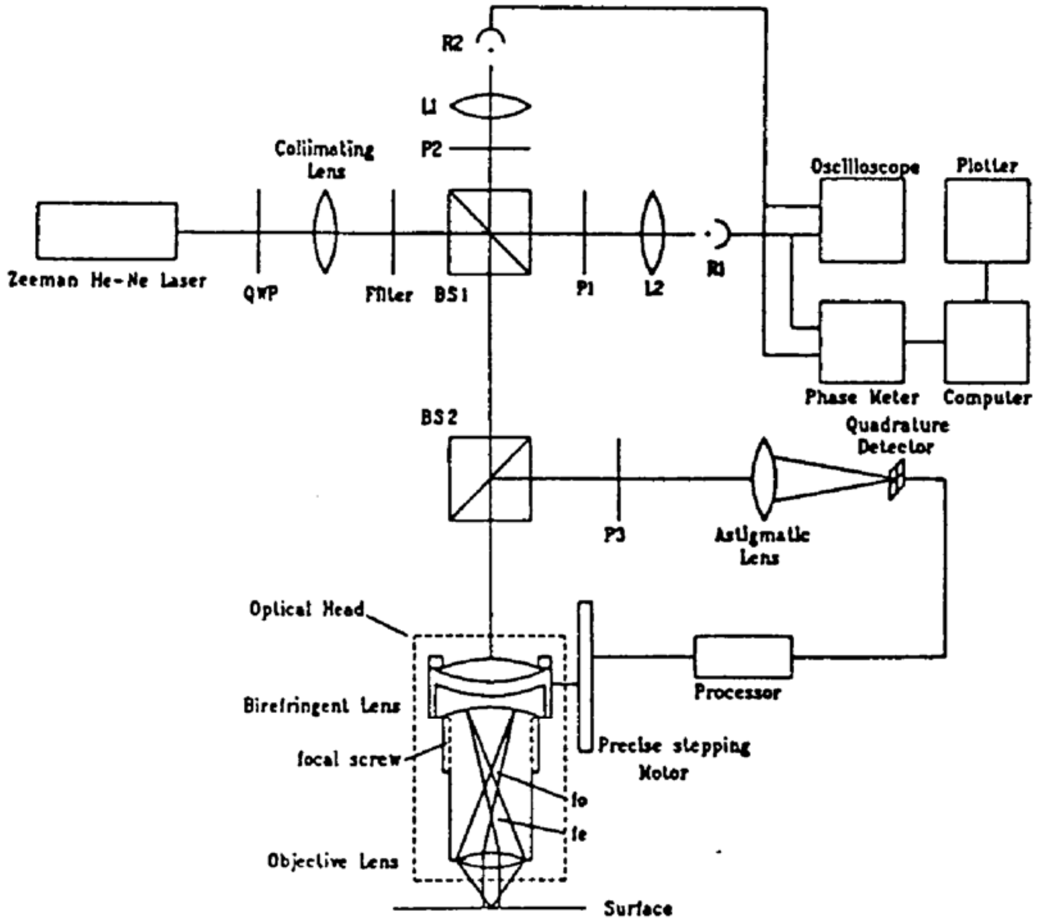

Fig. 1 Schematic of the optical heterodyne profiler

The optical configuration of the heterodyne profiler is shown in Fig. 1. The profiler is a common-path polarization interferometer. The optical head contains a birefringent lens and microscope objective. The birefringent lens is made of calcite crystal. The crystal axis is set perpendicular to the incident beam propagation. The lens has two focal points, f_0 and f_e , corresponding to its ordinary and extraordinary rays. The f_0 and f_e focal lengths are 40. 0735 mm and 87. 8485 mm. The ordinary and extraordinary rays are linearly. orthogonally polarized and concentric when the input beam is collimated. The back focal point of the objective is set at the f_e point. Therefore, the extraordinary rays become a collimated beam to the sample surface while the ordinary beam becomes a focused beam. The collimated and focused beam spots on the surface are 143 μm and 4 μm diameters when a 40X objective is employed. The area ratio of the large spot to small spot is 1250 times. Both reflected polarized beams are combined into a common-path collimated beam after passing through the optical head. The combined beam carries all the characteristics of both polarized beams to the measurement detector system for the translation of sample surface information.

The longitudinal Zeeman-split laser outputs two common-path polarized beams. One beam is left circular, the other is right circular. Both beams have equal intensity and a slight frequency difference stabilized at 1. 8 MHz. They become linearly and orthogonally polarized after passing through a quarter wave plate. The two beam polarizations are parallel to those of the ordinary and extraordinary rays that the birefringent lens yields. A part of both polarized beams is transmitted through a beam splitter, BS1, into a reference detector system. The polarized beams are interfered at the polarizer, P_1, and a 1. 8 MHz beat-frequency signal is produced and input into a digital phase meter. This signal contains the initial phase difference between the polarized beams. The reflected part from the BS1 goes to the optical head. The two polarized beams become ordinary and extraordinary rays through the optical head. The ordinary rays are focused to a small spot on the sample surface and serve as a measurement probe. The extraordinary rays are collimated and serve as a reference beam with a large spot. The large spot is much greater than and concentric with the small one. The small spot represents surface height, and the large spot represents the average height level around the small spot. The reflected beams from these two spots are common-path after passing through the optical head. They are interfered at the polarizer, P_2, in the measurement detector system where a measurement signal is produced. This signal contains the surface profile information and the initial phase difference between the two polarized beams. The precision phase test system compares the phase difference, Φ, between the measurement and reference signals and obtains the surface height information.

Since the profiler is designed as a common-path optical system, the optical common-mode rejection technique is allowed to minimize the effects of air turbulence, temperature variations and surface vibrations. The phase test system minimizes the effects of the laser intensity variations and other system instabilities. The relationship between the surface height variation, δH, and phase difference variation, $\delta\Phi$, of the measurement and reference signals has been derived[9~10], and the result is given here,

$$\delta H = (\lambda/4\pi)\ \delta\Phi \tag{1}$$

where $H = h - h_0$, h is the surface height at the small focused beam spot and h_0 is the average height level integrated over the large collimated beam spot. The surface profile can be simply described by scanning the sample surface.

The adjustment of the optical head is an important part of the measurement system. A fine screw, 83 threads/inch, is set on the optical head, so that the back focal point of the objective can be adjusted exactly at the f_e of the birefringent lens. This adjustment makes the quality of the collimated beam high at the sample. The sample should be precisely located at the focal point of the ordinary rays of the optical head. An astigmatic autofocus system is employed to test the surface focus position at each sampling point. The focus system contains an astigmatic lens, a quad-cell detector and processor. It is sensitive to the collimation degree of the reflected beam from the focused beam spot on the surface. The quad-cell detector is set between the two foci of the astigmatic lens, so that the beam image on the detector is circular when a collimated beam inputs the focus system. The beam image will be elliptic in vertical or horizontal corresponding to that the incident beam is convergent and divergent. When the surface is out of focus, the focus system will signal a smooth and stable stepping motor system to move the optical head forward and backward until the surface is in focus. The stepping motor system has 0.1 μm resolution in the range of 25 mm. This motor system is very useful in measurements of curved surfaces.

3 Data acquisition system

The heterodyne profiler employs a HP5518A Zeeman-split He-Ne laser as the light source. The laser frequency stability is $2:10^{-8}$. The Zeeman-split frequency is 1.8 MHz, and frequency stability is 10^{-6}. A universal time interval counter SR620 from Stanford Research Systems is used as the phase test system. It has a resolution less than 0.01° to the phase measurement of 1.8 MHz input signals.

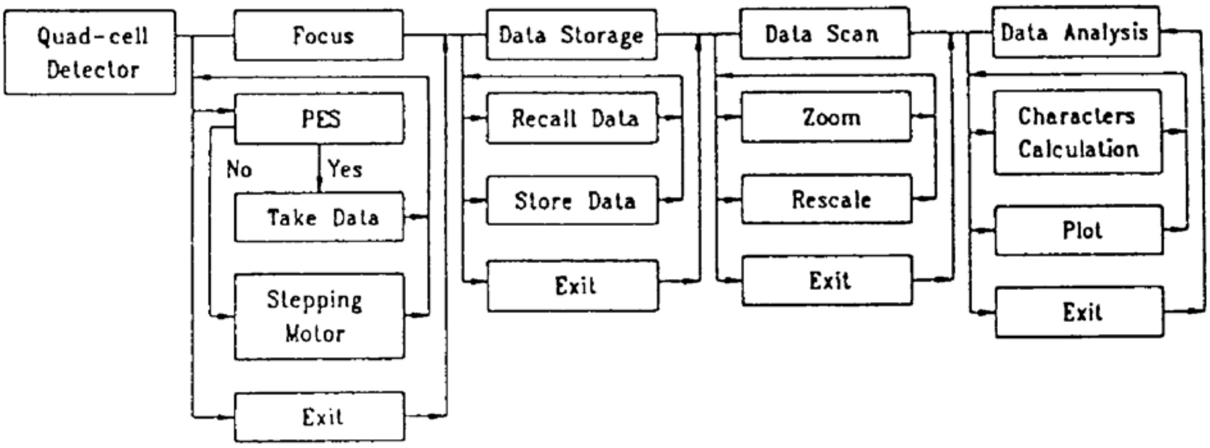

Fig. 2 Block diagram of the system software

An HP9000 computer is used to perform the system control, data acquisition and analysis. A block diagram of the system software is shown in Fig. 2. The "focus" portion is for keeping the optical head focused on the sample during sampling. The PES value is the focus-position error signal of the sample. It is obtained from the quad-cell detector. This error signal is used by the profiler to determine whether to take data or refocus the optical head. The system software is used to save data, retrieve old data, take new data and analyze data. The "data scan" portion determines the sample scan range and speed. The "Data Analysis" portion analyzes data for surface characteristics. The analyzed results can be display on the computer and printed.

4 Experimental results

Surface profiles are measured based on the measurement accuracy of the profiler. This accuracy represents the total effect of optical, mechanical and electronic noises and other environmental effects on the system performance. It is measured when the sample surface is statically set in the focus of the ordinary rays in the optical head. Each test is conducted at the same sampling point. Experimental data variations results entirely from the system noise. The system accuracy can be obtained via certain number of tests,

$$Accuracy(m) = \{(1/n)\sum_{i=1}^{n} A_i^2(m)\}^{1/2} \tag{2}$$

where m is the number of samples per test, or $m = \#$samples/test, n is the number of tests, or $n = \#$ tests, and A_i is the average tested value of the system noise via the number of the samples per test.

The accuracy shown in Fig. 3 is measured when the optical head has a 40X objective. The variations of the system noise via different number of samples per test is presented. The number of tests is 100, and m varies as 20, 50, 100, 200, 500, 1000 to 2000. When m gets larger and larger, the system accuracy gets better and better. This shows that the random noise effects of the electronics, temperature variations and other environmental effects are reduced while m increases. The error-bar represents a drift range of the accuracy over certain numbers of samples per test. The error-bar is reduced as m gets larger. The system accuracy obtained at $m = 200$ is 0. 11 nm with a very tiny error-bar. This shows that the system accuracy is quite reliable. The phase test system employed has a very fast sampling speed, so that measurements can be taken quickly even with large number of samples per test.

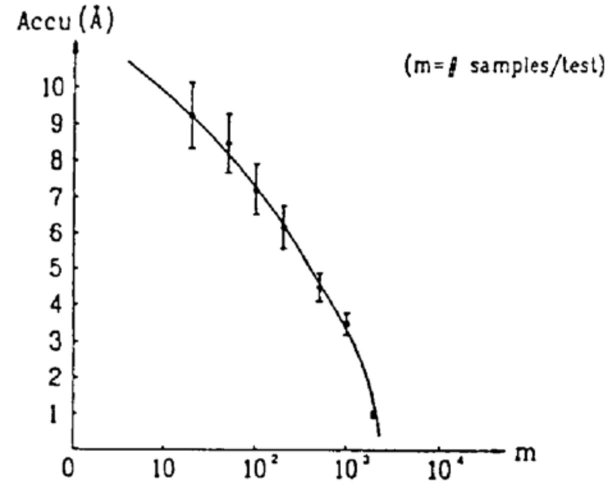

Fig. 3 System accuracy level at different number of samples per test

The system accuracies are shown in Fig. 4 and 5 when $m = 200$ and 2000, respectively. The horizontal axis is the number of tests. The accuracy values are 0. 62 nm and 0. 11 nm in these two figures. The average values in both measurements are very small. Therefore, only a small data drift is caused by the various system error effects.

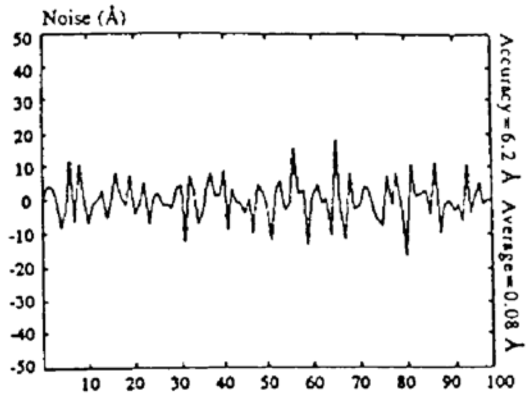

Fig. 4 System accuracy at $m = 200$

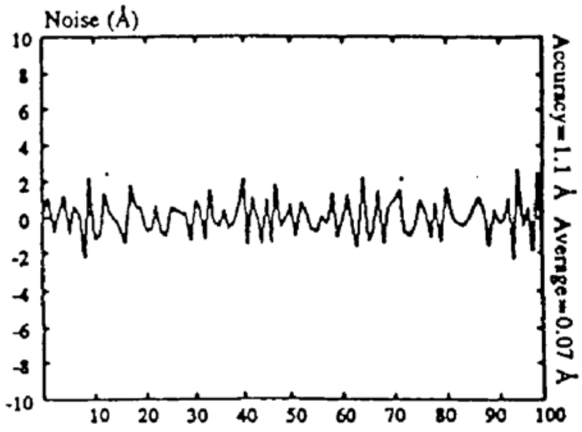

Fig. 5 System accuracy at $m = 2000$

The comparisons of the system accuracies are made with different objectives-5X, 10X, 20X and 40X-and the result is shown in Fig. 6. These are obtained at $m = 500$ and 2000, respectively. The accuracies in both cases agree very well with previous results.

The measurements of sample surface profiles with our heterodyne profiler and the WYKO NCP-1000M digital optical profiler are presented in Fig. 7. The WYKO profiler offers 0. 1 nm vertical accuracy and 5 μm lateral resolution with a 2. 5X objective. It does static measurement in a 5 mm diameter spot. The heterodyne profiler measures the samples with a 40X objective. Its scanning range is set at 5 mm, corresponding to the range of the WYKO profiler. The number of samples per point is 2000. The 4 μm focus-beam spot acts as a measurement proble. The autofocus system keeps the

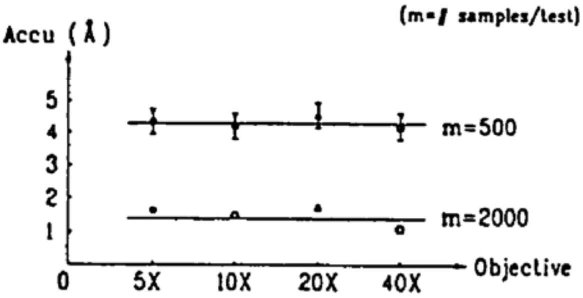

Fig. 6 Comparisons of the system accuracy with different objectives-5X, 10X, 20X and 40X

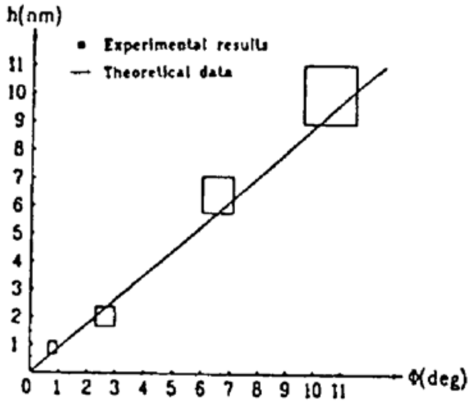

Fig. 7 Sample measurements by the heterodyne profiler and the WYKO profiler

sample surface in good focus while data is taken at each sample point. The phase test system measures the phase difference between the measurement and reference signals. Since the areas on each sample measured by both profilers cannot be completely the same, measurements are taken many times on each sample.

The horizontal axis in Fig. 7 repersents the surface phase RMS (root mean square) values measured by the heterodyne profiler; The vertical axis represents the surface height RMS values measured by the WYKO profiler. The experimental data of four samples are displayed. Each sample data shown in the figure has two vertical and horizontal error-bars because the surface height is different over different ares. The RMS values of the heights and phases measured by the profilers vary in the ranges of their error-bars. The solid line represents the theoretical data derived from Eq. 1. It passes through the data rectangle area of each sample. The experimental results and theoretical analysis are in a good agreement. The heterodyne profiler is also calibrated well with the commercial WYKO profiler.

The surface profile of our fine sample is measured by the heterodyne profiler and shown in Fig. 8. The RMS value of the surface height is 0.74 nm.

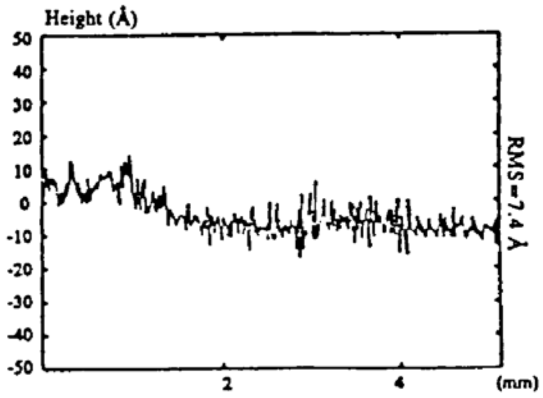

Fig. 8 Sample surface profile measurement

5 Conclusions

An optical heterodyne profiler has been presented. It uses a common-path optical system and a highly accurate phase test system. The system accuracy has been discussed. The common-mode optical rejection technique minimizes the effects of surface vibration, air turbulence and temperature variations. Measurements can be taken with a good height accuracy in ordinary experimental conditions. The experimental results and theoretical analysis are in a good agreement. Further work will be done to improve the electronics in the profiler. Two high quality lock-in amplifiers from the Stanford Research System are planned to replace the current amplifiers. This improvement will be useful for reducing the electronic noise effect and speed up measurements. The arrangement of the profiler mounting on a long air-bearing slide is being considered. The profile, therefore, will be able to characterize the surface figures and roughness of large curved optics with its autofocus system.

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7 References

[1] H. E. Bennett, Scattering characteristics of optical materials. *Opt. Enging.*, 1978, **17**: 480～488

[2] J. M. Bennett, Measurement of the rms roughness, autocovariance function and other statistical properties of optical surfaces using a FECO scanning interferometer. *Appl. Opt.*, 1976, **15**: 2705～2721

[3] J. M. Bennett, J. H. Dancy, Stylus profiling instrument for measuring statistical properties of smooth optical surface. *Appl. Opt.*, 1981, **20**: 1785～1802

[4] C. C. Huang, Optical heterodyne roughness measurement system. *U. S. patent*, 1989, **4848908**: 18

[5] B. Bhushan, J. C. Wyant, C. L. Koliopoulos, Measurement of surface topography of magnetic tapes by Mirau interferometry. *Appl. Opt.*, 1985, **24**: 1489～1497

[6] Y. Lin, Z. Zhou, R. W. Wang, Opto-heterodyne measurement of the optical surface roughness. *Chinese Physics-Laser*, 1989, **16**: 482～497

[7] D. Pantzer, J. Politch, L. EK, Heterodyne profiling instrument for the angstrom region. *Appl. Opt.*, 1986, **25**: 4168～4172

[8] P. Z. Takacs, S. K. Feng, E. L. Church *et al.*, Long trace profile measurements on cylindrical aspheres. *Proc. SPIE*, 1988, **966**: 354～364

[9] Y. Lin, P. Z. Takacs, R. W. Wang, A novel non-contact profiler design for measuring synchrotron radiation mirrors. *Proc. SPIE*, 1990, **1333**: 168～174

[10] Y. Lin, P. Z. Takacs, R. W. Wang, Development of optical surface profiling instrumentation. *Proc. SPIE*, 1992, **1776**

共光路外差干涉法精密测量光学表面

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提 要

报道了光学外差法测量表面起伏精度及横向分辨精度达到 0.11 nm 及 4 μm. 本文采用的是完全共光路外差干涉系统，阐述了它的原理、构造及噪声的影响，并将测量结果与其它商品仪器测量结果作了比较.

关键词 干涉仪， 光学表面.

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