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Fractal surface for calibration of an optical profiler

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ABSTRACT

The surface profiler has become a basic metrology tool for the characterization of high-quality optical surfaces. The unknown effective resolution of the surface profiler is problematic in using the instrument, as it distorts the measured surface profile. In this paper, we suggest and describe the use of a fractal surface as a standard test surface with which to calibrate the effective resolution of a surface profiler. Fractal surfaces have the characteristics of irregularity, self-similarity and low correlation, with the correlation length being approximately equal to the length of the profile; therefore, a log-log plot of the power spectral density curve is a straight line. The power spectral density curves of fractal surfaces, which can be acquired through surface characterization techniques such as atomic force microscopy, are fitted to a straight line to act as a standard with which to calibrate an optical profiler in different ranges. Through calibration, we can obtain the effective resolution of the optical profiler, and the surface profiler is found to have good transmission capacity within the effective spatial frequency range.

1. Introduction

The rapid evolution taking place in areas of astrophysics, high-energy physics and medicine is generating a continuous need for high-resolution imaging [1–7]. High-resolution optical systems require advanced mirror substrates with rigorous specifications, which calls for precise metrology of surface errors at high, mid and low spatial frequencies [8–13]. The advantage of the optical profiler lies in its versatile three-dimensional, non-contact and high-resolution imaging. The optical profiler is thus becoming a basic metrology tool for the characterization of high-quality optical surfaces. A major difficulty in using a surface profiler arises because of the unknown effective resolution of the instrument, which will distort the measured surface profile. Instrument makers prefer to use infinite-contrast targets so that their systems appear to have the finest possible resolution, but noise, aberrations and other factors affect the resolution of the optical profiler. In this case, accurate calibration of the resolution of the optical profiler is important to precise metrology.

The resolution of an optical profiler is restricted by the numerical aperture of optical components and by the detector. We need to determine the effective resolution, which is the minimum size of an object whose properties can be reliably determined. To determine the effective resolution of an optical profiler, it is necessary to know the response of the instrument at a certain frequency. Gratings and spheres have been used to calibrate the responses of optical instruments [14,15]. The basic theory of these methods is to measure the point spread function [16,17], but the methods are restricted to a traceable measurement tool or many calibration artifacts [18]. These methods are too complicated, and we thus discuss a simple way to calibrate the optical profiler using a fractal surface in this paper.

Fractal surfaces have the characteristics of irregularity, self-similarity and low correlation; the correlation length is approximately equal to the length of the profile, and the log-log plot of the power spectral density (PSD) curve is thus a straight line. The PSD curves of fractal surfaces, which can be acquired using surface characterization techniques such as atomic force microscopy (AFM), are fitted to a straight line to act as a standard with which to calibrate the optical profiler in different ranges. The present paper describes fundamental theory and research methods and shows how to determine the effective resolution of the instrument using a fractal surface. Finally, the residual surface error following calibration is presented.

2. Fundamental theory and research method

2.1. Power spectral density and inherent resolution

The surface consists of a number of sinusoid gratings. To obtain these gratings, one expands the surface profile as a Fourier series.

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Table 1
Inherent parameters of the Contour GT-X3.

Objective	$\Delta x = \Delta y$ (μm)	N_A	f_{min} (1/mm)	f_{Ny} (1/mm)	f_{OR}
2.5×	4	0.07	x:0.39 y:0.52	120	215
10×	1	0.3	x:1.59 y:2.13	500	915
50×	0.2	0.55	x:7.69 y:10	2500	1613

f_{OR} – the corresponding spatial frequency of optical diffraction resolution.

The PSD function reflects the proportions of the various spatial frequency components. The PSDs of the one-dimensional and two-dimensional profiles are defined as [19]

$$S_1(f_m) = \frac{\Delta}{M}\left|\sum_{k=0}^{M-1} z(k)\exp(-i2\pi f_m k\Delta)\right|^2, \qquad (1)$$

where $z(k)$ is a digitized profile of height consisting of M points sampled at intervals of Δ, $L = M\Delta$ is the sampling length, m is the spatial frequency index, and $f_m = m/(M\Delta)$ is the spatial frequency.

The minimum and maximum spatial frequencies are associated with the sampling length and Nyquist frequency, respectively; $f_{Ny} = 1/(2\Delta)$. The inherent frequency range of the system is therefore

$$f_{\min} = \frac{1}{M\Delta} \le f_m = \frac{m}{M\Delta} \le \frac{1}{2\Delta} = f_{Ny}$$

The root-mean-square (RMS) roughness of the surface is

$$R_q^2 = 2\pi \int_{f_{\min}}^{f_{\max}} S_2(f) f df \qquad (2)$$

$S_2(f)$ is the PSD of the two-dimensional profile:

$$S_2(f_m, f_n) = \frac{\Delta x \Delta y}{MN}\left|\sum_{k=0}^{M-1}\sum_{j=0}^{N-1} z(k,j)\exp[-i2\pi(f_m k\Delta x + f_n j\Delta y)]\right|^2 \qquad (3)$$

The resolution of an optical profiler is restricted by the numerical aperture of the optical components and by the detector. The resolution of the detector is associated with the Nyquist frequency. The optical diffraction limit is defined as the smallest lateral separation r between two points that can be distinguished, and the resolution is given by the Rayleigh criterion:

$$r = 0.61\frac{\lambda}{NA} \qquad (4)$$

where λ is the wavelength of the incident radiation, and NA is the numerical aperture of the objective lens.

An optical profiler, the model Contour GT-X3 from Bruker, has three magnifications of the objective lens: 2.5×, 10× and 50×. The data from each scan are stored in a 640 × 480 pixel array. Table 1 lists the inherent parameters of the Contour GT-X3.

In Table 1, the minimum distance between features is determined by the Nyquist frequency for the 2.5× and 10× objectives but by the optical resolution for the 50× objective. Thus, the inherent spatial frequency and resolution are as presented in Table 2.

Table 2
Inherent spatial frequency range and resolution of the Contour GT-X3.

Objective	Inherent spatial frequency range (1/mm)	Inherent resolution (μm)
2.5×	x:0.39–120 y:0.52–120	8.3
10×	x:1.59–500 y:2.13–500	2
50×	x:7.69–1613 y:10–1613	0.62

2.2. Characteristics of the fractal surface and research method

According to fractal theory, fractal surfaces have characteristics of irregularity and self-similarity. Ideal fractal surfaces have low correlation, and the correlation length is approximately equal to the length of the profile; therefore, the PSD curves do not have breakpoints [20].

The PSD of the surface with spatial frequency (f) mostly follows a fractal model, which obeys the inverse power law [21]:

$$S_1(f_x) = \frac{K_n}{f_x^n} = \frac{S_1(1)}{f_x^n} \qquad (5)$$

K is the spectral intensity. Eq. (5) reveals that a log-log plot of the PSD is a straight line with slope ($-n$) and value $S_1(1)$ at $f_x = 1$, which can be acquired through surface characterization techniques such as AFM, and used as a standard to calibrate the optical profiler in different effective ranges. The special index $n = 1, 2,$ and 3 represents the extreme fractal, the Brownian fractal, and the marginal fractal, respectively [22].

The fractal model has been extensively used and provided satisfactory results in calibration work. In what follows, the optical profiler is calibrated using silicon with a super-smooth surface as a calibration sample. In the next part, we introduce the calibration in detail.

3. Experimental results

The surface morphology of Si with thickness of 1 mm (denoted Si-I) was characterized employing AFM (MultiMode SPM from Veeco) and an optical profiler (Contour GT-X3 from Bruker). The AFM scans were made over areas of 10 × 10, 5 × 5, 2 × 2 and 1 × 1 μm^2, and the data from each scan were stored in a 256 × 256 pixel array. The isotropic surface had the same variation of the PSD curve in the x and y directions, and we thus only consider the PSD in the x direction. The PSD functions were calculated according to Eq. (1) for all the scan areas.

Fig. 1(a) depicts the PSD of Si-I obtained by AFM along with its fitting in accordance with the fractal model given by the inverse power law of Eq. (5). The figure shows that the experimental PSD data obtained by AFM fit well with the fractal model. We consider using this fitting line as a standard to calibrate the optical profiler in different effective ranges.

Fig. 1(b) depicts that the PSD of Si-I obtained by the optical profiler remained almost unchanged in the rear parts. Fig. 1(c) describes the progress of calibration. It is clear that the resolution is responsible for the large deviation between the results obtained with the profiler and the standard line in the rear parts. For the three objective lenses used in the spatial frequency ranges of $\Delta_1 f_{2.5} = 0.39 \times 10^{-3}$ to 0.025 μm^{-1}, $\Delta_1 f_{10} = 0.59 \times 10^{-3}$ to 0.075 μm^{-1} and $\Delta_1 f_{50} = 7.69 \times 10^{-3}$ to 0.28 μm^{-1}, the experimental PSD data deviate slightly from the standard line in Fig. 1(d), and the thickness of Si substantially affects the figure errors.

The experiment was repeated for Si with thickness of 3 mm (denoted Si-II). As AFM has strict requirements of the test conditions, the test area was smaller, the electrical noise and environmental effect were greater, and the AFM scans were made over areas of 10 × 10, 5 × 5 and 2 × 2 μm^2.

In Fig. 2(b), for the three objective lenses used in the spatial frequency ranges of $\Delta_2 f_{2.5} = 0.39 \times 10^{-3}$ to 0.029 μm^{-1}, $\Delta_2 f_{10} = 0.59 \times 10^{-3}$ to 0.089 μm^{-1} and $\Delta_2 f_{50} = 7.69 \times 10^{-3}$ to 0.33 μm^{-1}, the experimental PSD data obtained by the optical profiler fitted well with the standard line. Such analysis indicates that the thickness of the Si may strongly correlate with the fractal properties. The maximum spatial frequencies of $\Delta_1 f$ and $\Delta_2 f$ were almost consistent, and we used average values to determine the maximum frequency.