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Calibration and optimization of the effective resolution of an optical profiler using the white-noise method and a median filter

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ABSTRACT

Scattering effects from residual optical fabrication errors at mid-spatial frequencies limit the resolution of optical systems. An optical profiler is a useful tool for characterizing residual surface roughness in mid-spatial frequencies. The calibration of an optical profiler's resolution is critical for accurate optical metrology. Empirical methods are restricted to a traceable measurement tool or many calibration artifacts, which are complicated, incompatible and time-consuming. In past work, we used the fractal method to obtain the calibration results for the effective resolution and demonstrated a good transmission capacity within the effective spatial frequency range of the optical profiler. However, this method also requires another instrument, and it does not address the areas of ineffective parts. In this context, this paper proposes a fast, simple and universal method to solve these problems. This paper makes two main contributions to the literature. First, it calibrates the effective resolution of the optical profiler using only a common ultra-smooth surface. The calibration method is based on the primary spectral characteristics of white noise and the fractal surface. Second, it uses a median filter to extend the ranges of the effective spatial frequency, which optimizes the capability and utilization of the optical profiler.

1. Introduction

There is great interest in the precise characterization of the errors for very short wavelengths in high-resolution optical systems [1–5]. Scattering effects from surface errors at high, mid and low spatial frequencies limit the optical performance of optical systems. High- and low-spatial-frequency errors have little effect on the width of the image core. However, the mid-spatial-frequency (MSF) surface irregularities produce small-angle scattering, which broadens the image core and degrades the image contrast, thereby drastically reducing the resolution of the optical system [6–9].

The MSF errors are usually measured by an optical profiler, which is a basic metrology tool that uses the principle of light interference to measure a range of heights and create a three-dimensional surface profile without physically touching the surface. In practice, noise, aberrations and other factors result in considerable blurring of the image such that the effective frequency is usually beyond the reach of the Nyquist frequency or the corresponding spatial frequency of the optical diffraction resolution. In this case, calibration of the resolution of the optical profiler is important for accurate metrology.

Calibration seeks to determine the relationship between the values measured by the instrument and the real values, providing a method to determine the accuracy of the instrument. Therefore, we must find a method that provides the best approximation of this real value. The optical transfer function (OTF) of an optical profiler is the transmission capacity of the system, which can be used to determine the effective resolution. The OTF is the normalized Fourier transform of the point spread function (PSF) [10]. A straightforward way to obtain the OTF is to measure the PSF. Gratings and spheres have been used to calibrate the responses of optical instruments in this way [11,12]. However, these methods are restricted to a traceable measurement tool or many calibration artifacts [13]. These methods are complicated, incompatible and time-consuming.

In past work, we discussed a method with which to calibrate the effective resolution of an optical profiler using a fractal surface and demonstrated good transmission capacity within the effective spatial frequency range of the optical profiler [14]. However, this method also needed another instrument and it did not address the areas of ineffective parts. In this context, in this paper, we propose a fast, simple and universal method to solve these problems.

To suppress the white noise to limit the resolution of the optical profiler, MATLAB is used to simulate the power spectral density

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Table 1
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

(PSD) of white noise and compare it with the fractal surface results obtained by optical profiler without measuring the PSF or using any other calibration instrument. The second section of this work will address some aspects of the theory of measurement. In the third section, processes and methods of calibration will be discussed, and the results of the different calibration methods will be compared. Finally, an appropriate filter will be chosen to reduce the noise and extend the effective resolution of the optical profiler.

2. Fundamental theory and research method

2.1. Inherent spatial resolution

The resolution of an optical profiler is restricted by the optical diffraction limit and by the detector; thus, the spatial frequencies are associated with the Nyquist frequency and the Rayleigh criterion.

A Contour GT-X3 optical profiler from Bruker features three objective lens magnifications: 2.5×, 10× and 50×. The data from each scan are stored in a 640 × 480 pixel array. The inherent spatial frequency and resolution are presented in Table 1.

2.2. PSD characterization of white noise and fractal surfaces

2.2.1. White noise

The term noise refers to an unwanted signal that tends to disturb the transmission and resolution of optical profiler systems. Depending on the causes, the sources of noise may be external or internal to the system. The external noise includes man-made noise, atmospheric noise and other radiating electromagnetic signals. The internal noise includes thermal noise, mechanical noise and electrical noise [15]. In optical profiler systems, the internal noise, which is customarily described as white noise, is strongest.

In the case of isotropic surfaces, the spectrum depends on the spatial frequency and not its direction, and we can express the results in terms of the one-dimensional power spectrum [16]. The primary spectral characteristic of white noise is that it has a random signal with a flat PSD. In other words, the values of the PSD are the same for all frequencies, as illustrated in Fig. 1. The PSD of white noise can be expressed as

$$S_w(f) = \frac{N_0}{2}. \tag{1}$$

The dimensions of N_0 are related to Boltzmann's constant and the equivalent noise temperature of the receiver [15]. The factor of 2 is included to indicate that it is the two-sided PSD.

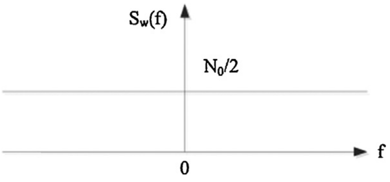

Fig. 1. Power spectral density of white noise.

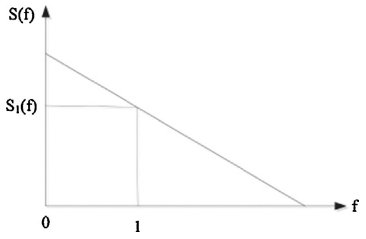

Fig. 2. Power spectral density of fractal surface.

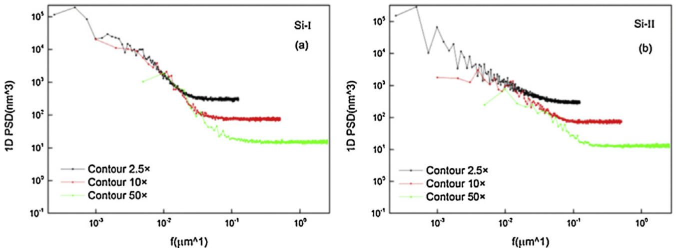

Fig. 3. PSD curves of (a) Si-I and (b) Si-II obtained by Contour GT-X3.

2.2.2. Fractal surface

The correlation length of an ideal fractal surface is approximately equal to the length of the profile; therefore, the PSD curves do not have breakpoints [17]. The one-dimensional PSD of a fractal model obeys the inverse power law [18]:

$$S_1(f_x) = \frac{K_n}{f_x^n} = \frac{S_1(1)}{f_x^n}. \tag{2}$$

as illustrated in Fig. 2. Here, K is the spectral intensity. Eq. (2) reveals that a log–log plot of the PSD is a straight line with slope ($-n$) and value $S_1(1)$ at $f_x = 1$.

Comparing Figs. 1 and 2, it can be seen that the PSD of the fractal surface and the white noise were quite different. We may model the noise process using MATLAB as white noise to suppress the unwanted signal in the sample, allowing the calibration of the effective resolution of the optical profiler.

In a previous study, the PSD curves of fractal surfaces, which can be acquired through surface characterization techniques, such as atomic force microscopy (AFM), were fitted to a straight line to act as a standard with which to calibrate an optical profiler in different ranges [14]. To compare the findings of the current study with those of the aforementioned previous study, we used the same calibration samples, namely, the surface of Si wafers with thicknesses of 1 mm (denoted Si-I) and 3 mm (denoted Si-II). In what follows, the optical profiler is calibrated using the power spectral density of the white noise. In the next section, we introduce the calibration in detail.

3. Experimental results

Si-I and Si-II were characterized using the optical profiler (Contour GT-X3 from Bruker) based on phase scanning interferometry (PSI). The PSI model has a very fast measurement rate (approximately 1 s per measurement). The isotropic surface has the same PSD curve variation in the x and y directions, and we thus only consider the PSD in the x direction. The PSD results are given in Fig. 3.

Fig. 3(a) shows the PSD of Si-I obtained by the optical profiler and its fitting in accordance with the fractal model given by the inverse power law of Eq. (2) in the low-frequency range. The higher-frequency component exhibited little variation and corresponded well with the white noise. Fig. 3(b) shows approximately the same result as Fig. 3(a).