Fast Surface Profiler using Narrow-Band White-Light Interferometry — Application of the Sampling Theorem for Band-Pass Signals —

Katsuichi KITAGAWA, Toray Industries, Inc.
Akira HIRABAYASHI, Hidemitsu OGAWA, Tatsuya MIZUTANI, Tokyo Institute of Technology

Abstract: We have developed a fast surface profiler which uses a new technique to increase the data acquisition and processing speed in a scanning white-light interferometer for surface topography measurement. The technique is based upon the sampling theorem for band-pass signals. The number of sample points required can be reduced to one-tenth of that of the conventional method.

1. Introduction

There is a method to measure the microscopic three-dimensional shape of a sample surface using white-light interference [1][2]. The optical system used for the measurement is shown in Fig. 1. The sample surface is irradiated with white light, the reflected light is interfered with the light from the reference surface, and the interference image is captured by a CCD camera.

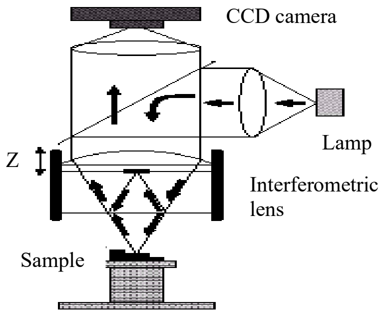

Fig.1 Optical setup of interferometer

If we focus on the brightness of one pixel of the CCD camera when the sample or reference surface is scanned in the z-axis direction, we can obtain the intensity waveform (interferogram) as shown in Fig. 2. Since the peak position corresponds to the height of the surface, the height of each pixel in the image, i.e., the 3D shape of the surface, can be obtained collectively.

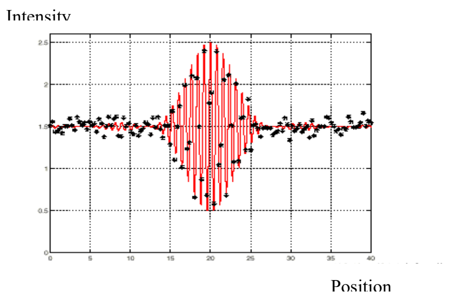

Fig.2 Interferogram and its sampled points

By the way, the actual measurement data are not continuous like the red line in Fig. 2 , but discrete data as shown by the black dots. There are several methods to determine the maximum position of the interference waveform from the discrete data [3][4].

For example, the method proposed by Caber, which has been incorporated into commercial products and is in practical use, squares the AC component of the interference waveform and finds its maximum position through a low-pass filter. Therefore, it is necessary to keep the sample interval small enough to obtain accurate measurements, which results in a slow measurement speed. In this paper, we propose a new algorithm for solving this problem and report the development of the measurement system with the new algorithm.

2. New method −SB algorithm− [5]

We proposed a new algorithm (named the SB algorithm) for finding the peak position of the interference waveform from observations sampled at intervals much wider than the sample point spacing that satisfies the Nyquist theorem (hereafter referred to as the Nyquist interval) [6]. The algorithm requires that the wavelength of white light is band-limited, which can be achieved by inserting a bandpass filter into the illumination unit of the microscope. The SB algorithm is outlined as follows.

If the frequency band of the waveform $f(h)$ is band-limited to $\omega_c \pm \omega_a$, then the bandpass sampling theorem can be applied, and $f(h)$ can be reconstructed from its sampled data $f(h_m)$ ($m = [-\infty, \infty]$) as follows:

$$f(h) = \sum_{m=-\infty}^{\infty} f(h_m)\phi_m(h) \tag{1}$$

where $f(h_m)$ is the sample data at h_m. The sampling interval $\varDelta B$ is calculated by $\varDelta B = \pi/(2\omega_a')$, where ω_a' and ω_c' are positive real numbers that satisfy the following conditions:

$$\omega_c' = (2I+1)\omega_a' \tag{2}$$

$$\omega_c' - \omega_a' \le \omega_c - \omega_a\,, \quad \omega_c + \omega_a \le \omega_c' + \omega_a' \tag{3}$$

where I is a positive integer.

Then

$$h_m = (m-1)\varDelta B \tag{4}$$

and

$$\phi_m(h) = \mathrm{sinc}\frac{\omega_a'(h-h_m)}{\pi}\cos\omega_c'(h-h_m) \quad (5)$$

By the way, since there are a finite number of sample values in the actual system, the infinite series of Eq. (1) is truncated at the Mth term, and y_m is defined as the AC component obtained by removing the DC component from the observed value z_m, that is, $y_m = z_m - z_{average}$, then the restoration function is represented by

$$f_B(h) = \sum_{m=1}^{M} y_m \phi_m(h) \quad (6)$$

On the other hand, what we want to obtain is not the interference waveform but its envelope function $r(h)$, which is called the envelope function. We can derive the estimated envelop function $r_B(h)$ directly from the sample value. For example, if h is a sample point, i.e., $h = h_J$ (J is an integer of $1 \le J \le M$), then it becomes a simple expression with only algebraic operations, as follows:

$$r_B(h_J) = \frac{1}{2\omega_a'^2}\left\{(\omega_a' y_J)^2 + \left(\sum_{m=-\lfloor \frac{J}{2} \rfloor}^{\lceil \frac{M-J}{2} \rceil - 1} \frac{y_{J+2m+1}}{h_J - h_{J+2m+1}}\right)^2\right\} \quad (7)$$

Although there are several methods to obtain the maximum position of the envelopment function $r(h)$, it is easy to calculate $r_B(h)$ at the sample points by Eq. (7) and interpolate them near the maximum point.

3. System configuration

The configuration of the developed system is shown in Fig. 3. The system is composed of a commercial microscope with an infinite focus system and a Mirau interference objective, and the objective lens is moved by a piezo actuator for z-axis scanning. The displacement of the piezo is controlled by a position sensor. The standard lamp (halogen lamp) of the microscope was used as the illumination light source, and an interference filter with a central wavelength of 630 nm and a half-width of about 40 nm was inserted into the light source unit of the microscope as a narrow bandpass filter.

The TV camera was a standard monochrome CCD camera. The frame grabber unit converts the camera signal into digital data and captures one image as 512 × 480 pixels × 8 bits data. The image processing operation is performed by a Pentium III (600 MHz).

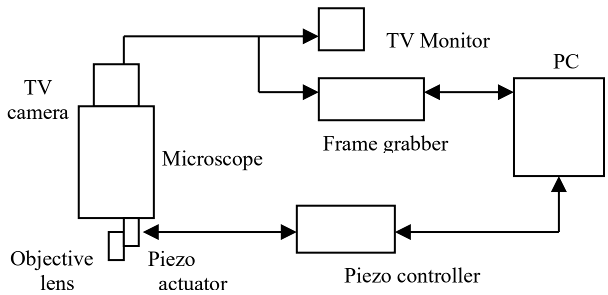

Fig.3 Configuration of the surface profiler

4. Experimental results

Actual samples were measured using the above apparatus. The standard step (9.947 µm) was measured at a sampling interval of 0.85 µm (measurement speed of 25.5 µm/sec), and the results are shown in Fig. 4. The sampling interval is about six times the Nyquist interval, but the surface profile has been measured almost exactly.

Examples of intensity data, restored waveforms, and envelope waveforms are shown in Fig. 5. The latter two waveforms were recalculated at sufficiently fine intervals for performance verification and display.

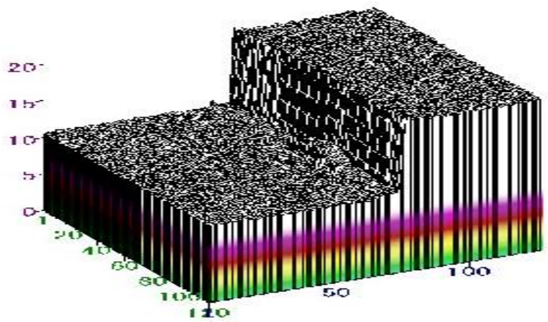

Fig.4 Three dimensional profile of a step height measured by our new profiler

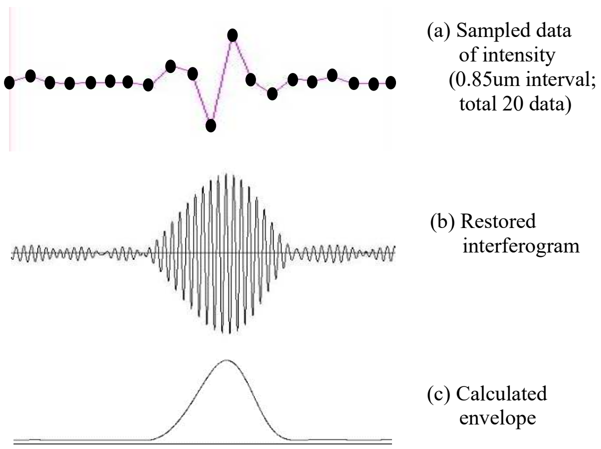

Fig.5 Restored interferogram and its envelope calculated from the sampled data

5. Conclusion

A new algorithm for determining the peak position from the interferogram is proposed to speed up the measurement of surface topography using white-light interferometry. The bandpass sampling theorem is applied to recover the interferogram and obtain its envelope function from a much smaller number of sample points than required by the Nyquist criterion. A measurement system incorporating the algorithm is developed, and it is confirmed that the surface topography of a real sample can be accurately measured from sampled data with an interval of six times the Nyquist interval.

References

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