

An Industrial Application of the Sampling Theory - A Novel Algorithm for Interferometric Surface Profiling -

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1. Introduction

There is a method of measuring the fine three-dimensional shape of the sample surface using white light interference [1]. The optical system used for the measurement is shown in Fig.1. The sample surface is illuminated with white light, the reflected light from the sample surface and the reflected light from the reference surface are caused to interfere with each other, and an image is taken by a CCD camera.

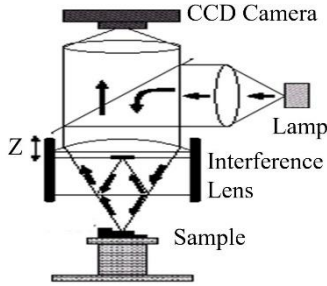


Fig. 1 Optics of interferometric microscope

Here, focusing on the intensity of a specific pixel of the interference image obtained by scanning the sample or the reference surface in the height direction, an interference waveform (interferogram) as shown in Fig. 2 is obtained. Since this peak position corresponds to the height of the sample surface, the height of each pixel in the image, that is, the three-dimensional profile of the surface, can be obtained simultaneously.

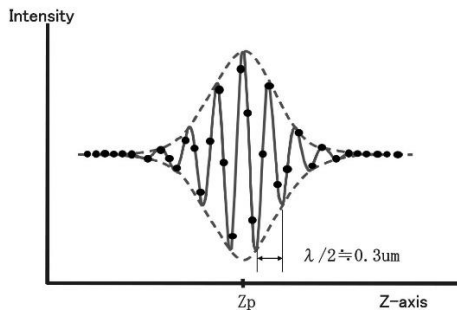


Fig. 2 Interferogram and sampled values

By the way, the data obtained by actual measurement are not continuous data as shown by the solid line in Fig. 2 but discrete sample values as shown by • in the same

figure. There are some proposals as a method for obtaining the maximum contrast position of the interference waveform from the discrete data.

For example, the squared smoothing method [2] is incorporated in a commercial product and put into practical use. The AC component of the interference waveform is squared, and the maximum position of the interference waveform is obtained through a low-pass filter. However, in order to obtain sufficient measurement accuracy using such a method, it is necessary to make the sampling point interval very narrow, and there is a problem that the measurement speed is slow.

2. New algorithm - SEST method - [3][4][5]

Consider to restore the original waveform from the sampled values of the interference waveform shown in Fig. 2. According to Sometani-Shannon's sampling theorem (low-pass sampling theorem), the sampling point interval must be less than or equal to the Nyquist interval for perfect reconstruction.

However, in the case of the interference waveform shown in Fig. 2, the frequency band is limited by the wavelength band of the light source, and low frequency components are not included except for the DC component. It is also possible to limit the band to any band by inserting a band pass filter in the illumination optical path.

Taking advantage of this property, we proposed a new algorithm [named SEST (=Squared Envelope function estimation by Sampling Theory)] that finds the peak position of the interference waveform from the observation values sampled at a much wider interval than the sampling interval that satisfies the Nyquist theorem. The outline of the SEST algorithm is described below.

If the frequency band of the waveform is band-limited to $\omega_c \pm \omega_a$, the band-pass sampling theorem [6] can be applied, and the interferogram $f(z)$ can be reconstructed from its sampled data $f(z_m)$ ($m = [-\infty, \infty]$) as follows:

$$f(z) = \sum_{m=-\infty}^{\infty} f(z_m) \phi_m(z) \quad (1)$$

where $f(z_m)$ is the sampled data at $z_m = (m-1)\Delta B$ with a sampling interval of ΔB . The sampling interval ΔB

must satisfy the following conditions: $\Delta B = \pi / (2\omega_a')$

where

$\omega_c' - \omega_a' \leq \omega_c - \omega_a$; $\omega_c + \omega_a \leq \omega_c' + \omega_a'$; $\omega_c' = (2I + 1)\omega_a'$ and I is a positive integer, and ω_c' , ω_a' are positive real numbers.

Also $\phi_m(z)$ in Eq. (1) is

$$\phi_m(z) = \text{sinc}\left[\frac{\omega_a'(z - z_m)}{\pi}\right] \cdot \cos\left[\omega_c'(z - z_m)\right] \quad (2)$$

By the way, since there are a finite number of sample values in an actual system, if the infinite series of Eq. 1 is truncated from $m = 1$ to M , then the restored function $f_B(z)$ is approximated by

$$f_B(z) = \sum_{m=1}^M y_m \phi_m(z) \quad (3)$$

where y_m is the AC component of the observed values, and defined as $y_m = f(z_m) - f_{\text{average}}$.

From the waveform reconstructed in this way, a function $r(z)$ defined as the squared interference waveform (hereinafter, referred to as envelope function) can be estimated.

By the way, what we finally want to find is the peak position of $r(z)$, and the interference waveform itself is not necessary. Therefore, we derive an equation to obtain a direct estimate $r_B(z)$ of $r(z)$ from the sampled values of the interference waveform.

When z is a sampling point, that is, in case of $z = z_j$ (j is an integer; $1 \leq j \leq M$), it becomes a simple formula with only algebraic operations as

$$r_B(z_j) = (y_j)^2 + \frac{4}{\pi^2} \left\{ \sum_{m=1}^M \frac{y_m}{j-m} \right\}^2 \quad (4)$$

where $\sum_{m=1}^M$ means the sum of the following terms: if $j = \text{even}$, $m = \text{odd}$, and if $j = \text{odd}$, then $m = \text{even}$.

The maximum point of the envelope function $r(z)$ can be obtained by finding the maximum point of the sample point $r_B(z)$ by Eq. (4) and performing an interpolative search for a peak near that maximum point.

3. Surface profiler SP-500 [7][8]

Figure 3 shows the photo of the profiler incorporating the above algorithm, and Fig. 4 shows the configuration. The interference optical system is a commercially available microscope with an infinity focus system combined with an interference objective lens. The Z-axis scanning system has a structure in which the objective lens is moved by a piezo actuator. The displacement of the piezo is feedback-controlled by a precision displacement sensor.

A halogen lamp was used as an illumination light source, and an interference filter with a center wavelength of 600 nm and a half width of about 40 nm

was inserted into the light source unit of the microscope.

The TV camera is a monochrome CCD camera. The image signal is digitally converted in the image processing board, and one image is stored in the memory as data of 512×480 pixels \times 8 bits. The image processing operation is performed by the CPU of the personal computer.



Fig. 3 SP500

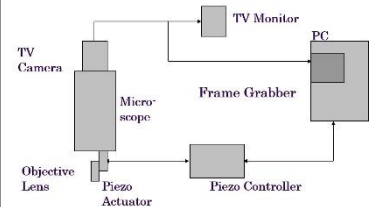


Fig. 4 Configuration

4. Actual sample measurement results

Figure 5 shows the results of measuring the standard step ($9.95 \mu\text{m}$) at a measurement speed of $25.5 \mu\text{m/s}$ (sampling interval $0.85 \mu\text{m}$). This sampling interval is about 6 times wider than the Nyquist interval, but accurate surface topography is measured. The average value of the step was $10.03 \mu\text{m}$, the repeatability (σ ; pixel-pixel) was about $0.1 \mu\text{m}$, and the height measurement time of 128×120 pixels was 0.8 s .

Figure 6 shows an example of the sampled intensity data, reconstructed waveform and envelope function.

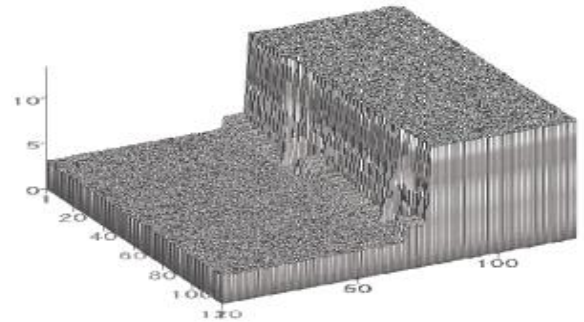


Fig. 5 Measured standard step

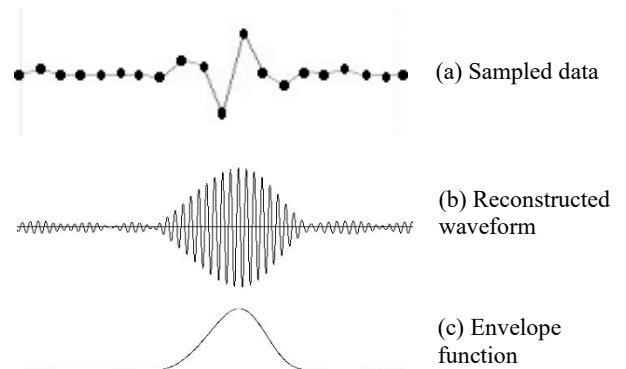


Fig. 6 From sampled data to envelope function

5. Conclusion

In order to measure the surface profile using white light interference at high speed, we devised a new algorithm to find the peak position from the interference waveform. The bandpass sampling theorem is applied to directly calculate the envelope function of the interference waveform from the sub-Nyquist sampling data. We have developed and commercialized a surface profiler incorporating this algorithm and confirmed its practicality.

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(original in Japanese; translated by the author)

These results are achieved by a joint research with Hidemitsu Ogawa, now Professor Emeritus of Tokyo Institute of Technology, and Akira Hirabayashi, now Associate Professor of Yamaguchi University.

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Toray Inspection System Home Page (visited in 2006)