Development of measurement standards for verifying functional performance of surface texture measuring instruments

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Abstract. A new measurement standard is proposed for verifying overall functional performance of surface texture measuring instruments. Its surface is composed of sinusoidal surface waveforms of chirp signals along horizontal cross sections of the material measure. One of the notable features is that the amplitude of each cycle in the chirp signal form is geometrically modulated so that the maximum slope is kept constant. The maximum slope of the chirp-like signal is gradually decreased according to movement in the lateral direction. We fabricated the measurement standard by FIB processing, and it was calibrated by AFM. We tried to evaluate the functional performance of Laser Scanning Microscope by this standard in terms of amplitude response with varying slope angles. As a result, it was concluded that the proposed standard can easily evaluate the performance of surface texture measuring instruments.

1. Introduction

The Design of the surface texture and its realization are of great importance in advanced industrial products. Certain measuring instruments for quality control are necessary at the shipment stage. Consequently, many types of surface texture measuring instruments have appeared on the market. Among them, the optical measurement method occupies an important position because it can achieve the non-contact and fast measurement even in the manufacturing line. Moreover, the areal (3D) measurement instead of a simple profile (2D) measurement is increasingly demanded. Although the optical surface texture measuring instruments have been gradually popularized, they are hardly authorized so far. This is partly because of being based on different measuring principles. To make matters worse, they are not always correlated each other [1, 2]. We previously reported that this causes different response curves against surface wavelengths in every measuring instrument [3].
Since the instrument response curve represents its overall measuring performance, it is obligatory for instrument users to obtain response curves in advance and understand the capability for measuring the surface texture. The working group of ISO/TC213 are being discussed the measurement standards for verifying the instrument measuring performance. Those measurement standards are designed mainly to calibrate the measuring axes of instruments, e.g. X, Y and Z, respectively. However, no measurement standards for evaluating response curves are presented in the working draft. Although the irregular random topography standard derived from a stochastic process is proposed [4], it can not be used for verifying the instrument response characteristic but for checking the overall measuring performance through surface roughness parameter values.

In this paper, we propose a complementary measurement standard for verifying overall measuring performance of areal surface texture measuring instruments in conjunction with response curves against surface wavelengths.

2. Design procedure for measurement standard

2.1. Existing condition

Step height standards and sinusoidal waveform standards are commercially available. In our previous study [3], a number of sinusoidal waveform standards in the longer surface wavelength range and 1-D grating (grid with horizontal spacing) artifacts in the shorter range were utilized for the measurements of response curves of some surface texture measuring instruments on the market. In order to adequately evaluate the instrument response curves, a series of sinusoidal waveform measurement standards composed of various wavelengths and amplitudes are needed. In addition, for the optical instruments, the local slope angle of the facet is an influence factor on the response curve of the instrument. A combination of wavelengths and amplitudes is design parameters to keep the slope angle constant. Then, strongly demanded is just a measurement standard with the sophisticated surface waveform which is similar to the chirp signal.

2.2. Mathematical Model

From the above-mentioned demand, we developed the sinusoidal waveform from the pure chirp signal into the chirp-like waveform with changing amplitudes. A mathematical rule was applied to the processing, that any cosine curves can be continuously connected each other at the point where the derivative is zero.

Let $T_n$ be the surface wavelength to be connected, where $n=1, 2, 3, \ldots, N$. To cover a wide band of wavelengths, the wavelength $T_n$ to be connected is changed in geometric progression as expressed by equation (1).

$$T_{n+1} = aT_n$$

Let $f_n(x, y)$ be the one cycle of the cosine wave term of the wavelength $T_n$, and if its amplitude is normalized to 1, equation (2) is given as follows.

$$f_n(x, y) = \begin{cases} \frac{1}{2} \left\{ \cos \left[ \frac{2\pi}{T_n} \left( x - \sum_{i=1}^{g-1} T_i \right) \right] - 1 \right\} & \text{if } x < \sum_{i=1}^{g-1} T_i \\ 0 & \sum_{i=1}^{g-1} T_i \leq x \leq \sum_{i=1}^{g} T_i \\ \sum_{i=1}^{g} T_i < x \end{cases}$$

(2)
Summing up $f_{n-1}(x, y), f_n(x, y)$ and $f_{n+1}(x, y)$ provides the curve, as shown in figure 1, where the cosine curves of different wavelengths are connected smoothly. In order to keep the slope angle constant, we have changed the amplitude of the cosine wave depending on wavelengths (Figure 1). This is the first notable feature of this measurement standard.

![Figure 1. Chirp-like signal model in conjunction with constant slope angle.](image)

If the amplitude of $f_n(x, y)$ is varied to make the local maximum slope angle in one cycle of the cosine wave to be $\theta(y)$, the topography data $Z(x, y)$ of the measurement standard summing up the varied amplitude of $f_n(x, y)$ is expressed by equation (3).

$$Z(x, y) = \sum_{n=1}^{N} \left[ \frac{T_a \tan \theta(y)}{\pi} f_n(x, y) \right]$$

The reason why $\theta(y)$ is expressed by a function of $y$ is to change the value of the local slope angle depending on the position of Y direction. This is the second notable feature of this measurement standard. Consequently, response properties including effects on the slope angle can be verified. Furthermore, to simplify the properties of measurement positions of samples when performing the cross-sectional analysis of measurement results, we changed $\theta(y)$ discretely (in step shape). $\theta(y)$ can be expressed by equation (4).

$$\theta(y) = \Delta \theta \text{floor} \left\{ \frac{by + c}{\Delta \theta} \right\}$$

where, $\text{floor}(x)$ is the maximum integer below $x$ against the actual number $x$, and $\Delta \theta$ is the step width of the discrete local slope angle.

### 2.3. Design Parameters

#### 2.3.1. Surface wavelength

We determined design parameters for the measurement standard by selecting so-called Laser Scanning Microscope (LSM) as the target measuring instrument to be analyzed, and the following measuring conditions were set: objective lens 100x, NA 0.95, light source wavelength $\lambda = 0.405 \, \mu m$.

The optical cut-off wavelength ($\lambda_{oc}$) under these conditions is expressed by equation (5).
Since $\lambda_{oc}$ is a physical diffraction limit wavelength, the wavelength smaller than this cannot be observed. Therefore, we have set the minimum value of the wavelength $T_n$ of the measurement standard as 0.2μm and the maximum value ($= T_0$) as $T_0=2\mu m$ respectively, considering the field of view under the assumed measurement conditions. $T_n$ is defined so that the parameter divides 1 decade from the wavelength 0.2μm to 2μm into 15 wavelengths geometrically. ($T_0=2\mu m$, $n=15$, $a=0.85$)

2.3.2. Local Slope Angle. In general, the measurable maximum slope of the stylus instruments is approximately 30 degrees. Accordingly, we consider the maximum slope angle of measurement standards for optical instruments is also 30 degrees. In this study, we set the large slope up to 45 degrees to check the limitation of measurable steep slope angle.

2.3.3. Consideration for processing. The unit pattern shown in figure 2 is derived from equation (1), (2), (3) and (4). In order to reduce the processing distortions caused by the elimination processing, this measurement standard model is structured by assigning 4 mirror patterns of the unit pattern symmetrically.

The size of patterning region is 24.3μm in X direction and 40μm in Y direction, which can be observed within one field view of 100x of LSM.

![Figure 2](image.png)

**Figure 2.** Measurement standard model designed for laser scanning microscope (LSM). $T_0=2\mu m$, $a=0.85$, $n=15$, $b=-2$, $c=\pi/4$ rad. =45 deg., $\Delta\theta=\pi/36$ rad. =5deg.

3. Fabrication
Measurement standard sample was fabricated by using FIB processing machine (Elionix Inc. EIP-5400). Figure 3 shows the optical microscope image of the fabricated sample surface. Figure 4 compares the designed profile and a measured profile by AFM. Two profiles are in good agreement. This means that the fabrication process was ideally performed.
**4. Measurement results and discussion**

Figure 5 shows the 3D topography measured by LSM (100x NA0.95). In this study, we defined the response as the ratio of LSM data to AFM data. Figure 6 plots LSM amplitude responses per each surface wavelength and per each slope angle. As shown in figure 5 and 6, if the slope angle is below 35 degrees, responses of LSM show the similar tendency, which is almost identical to results derived from our previous measurements conducted on numerous samples [3]. Now, we have made it possible to derive response properties such as figure 6 by only one measurement standard in only one time measurement.

As shown in figure 5, if the slope angle exceeds 35 degrees, it is recognized that spike noises increase gradually. We consider the phenomenon of spike noises recognized in the large slope is peculiar to all optical instruments because the similar case has been reported in the coherence scanning interferometry [6]. So, it is important to evaluate responses against the slope angle of optical measuring instruments accurately, and the measurement standard proposed by us will surely be its practical method.
Figure 5. Bird’s eye view of profiles measured by LSM.

Figure 6. Response curves for the LSM at various slope angles (100x NA0.95).

5. Conclusion

- A new deterministic measurement standard was proposed to verify response properties and created by FIB processing.
- The response properties of Laser Scanning Microscope were evaluated by using the measurement standard.
- Response properties against various surface wavelengths and the effects of the local slope angle can be evaluated in one time measurement, which is proved to be the practical verification system.

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