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THREE DIMENSIONAL PROFILE MEASUREMENT OF FOUR-STEP REFERENCE SPECIMENS USING THE FRINGE SCANNING FOURIER TRANSFORM METHOD

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Abstract − A new method of three-dimensional profile measurement of four-step reference specimens is presented. Instead of measuring only the height difference between central points of the two neighbouring surfaces of the specimen, overall profile of the whole specimen can be measured by using the fringe scanning Fourier transform method. The method to determine step height from its surface profile is proposed.

Keywords: step height, profile measurement, Fourier transform

1. INTRODUCTION

Four-step reference specimens (FSRSs) are one of the widely used reference standards to calibrate the vertical magnification of surface roughness testers. A typical FSRS is shown in Fig. 1. It consists of five flat and mutually parallel surfaces which provide four steps with nominal value of 1 μm, 2 μm, 5 μm, and 10 μm [1].

To calibrate the specimen, usually gauge block interferometers are used, because the configuration of FSRSs is similar to the gauge block wrung on a platen. Among the two surfaces which form the step, the lower surface is regarded as the platen, and the higher surface as a gauge block. Most widely used method of measuring the step heights would be the method of exact fractions, in which excess fraction values are obtained by analysis of interference fringes. [2].

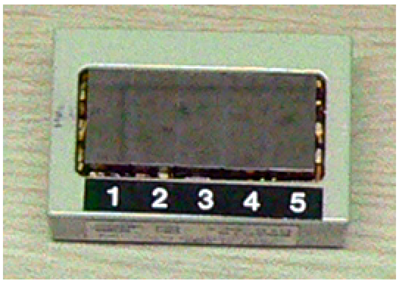


Fig. 1. Four-step reference specimen.

The main difference between the normal gauge block measurement and the step specimen measurement lies in the phase measurement of the interferometric fringes on the platen. In the case of gauge block measurement, the phase of the interference fringe on the platen is measured by averaging the two phases measured at two points on the platen at each sides of the gauge block. On the other hand, in the case of FSRS measurement, the phase of the interference fringe on the platen can be measured only on one side, since another block surface with different height exists on the other side of the gauge block. Except for this, the measurement process is the same as that for gauge block measurement.

There are several methods to measure the excess fraction of the interferometric fringes of the gauge blocks or FSRSs. Some of those techniques are curve fitting method [3], four-point method [4], phase shifting interferometry [5], and Fourier transformation (FT) method [6]. Especially the fringe scanning Fourier transform method (FSFTM) [7] has many advantages such as being insensitive to nonlinearity of the CCD camera, to the number of interference fringes, and to the flatness or parallelism of the surfaces being measured. In KRISS, the FSFTM has been applied to the central length measurement of gauge blocks and the central step height measurement of FSRSs.

Since the users mostly use FSRSs for adjusting the vertical magnification of stylus profilers, reporting in the calibration certificate of FSRS only the step heights measured at central points of neighbouring surfaces might not be sufficient for the customer's use. Since the surface profile obtained by a stylus profiler is used to determine step heights of the specimen, depending on the determination method they use, the measured step height might be different from the value reported in FSRS's calibration certificate measured by optical interferometry. This paper presents a new method to calibrate FSRSs, which can provide the three dimensional surface profile of FSRS, and proposes a standard method to determine the step heights of FSRSs from the measured surface profile. In chapter 2, the old and new methods of FSRS calibration in KRISS will be described, and the experimental results will be shown in

Chapter 3. A proposed method of determining step heights from the surface profile of an FSRS will be described in Chapter 4.

2. CALIBRATION OF FSRSs

The central height measurement method (CHMM) has been used to calibrate FSRSs in KRISS. The CHMM is the same method being used for calibrating central length of gauge blocks at KRISS. The height between the central point of the higher surface and the central point of the lower surface is determined by using optical interferometry with two wavelengths and the method of exact fractions. In order to know not only the height between the neighbouring central points but also the height profile over the whole specimen, a series of measurements have to be made. Figure 2 shows an example of measuring points set to measure the height profile of an FSRS.

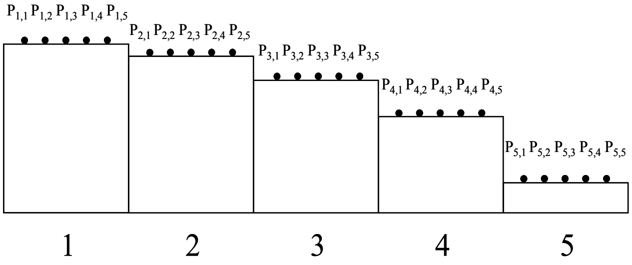


Fig. 2. Measuring points on the surfaces of an FSRS.

Five equidistant points are selected from each surface. In Fig. 2, $P_{i,j}$ denotes the jth point on the ith surface. Heights of points $P_{1,1}$, $P_{1,2}$, $P_{1,3}$, $P_{1,4}$, and $P_{1,5}$ with respect to reference point $P_{2,1}$ are measured, and then that of $P_{2,1}$, $P_{2,2}$, $P_{2,3}$, $P_{2,4}$, and $P_{2,5}$ with respect to $P_{3,1}$, and so on. Finally, heights between $P_{4,5}$ and $P_{5,1}$, $P_{5,2}$, $P_{5,3}$, $P_{5,4}$, and $P_{5,5}$ were measured individually. In each measurement, the specimen was aligned so that the fringe on the reference point became perpendicular to the longer edge of the reference block.

Figure 3 shows the interferometric fringes of a FSRS, and some part of the measurement results is shown in Table 1. Although the CHMM can in principle produce the surface profile along a single line, using this method is somewhat tedious and time consuming.

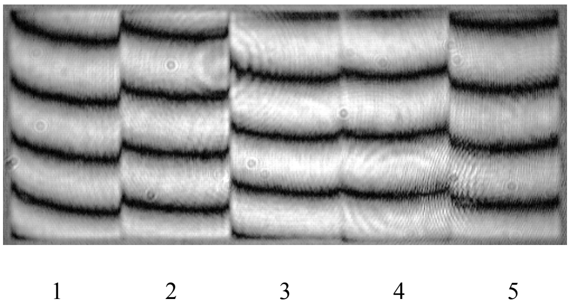


Fig. 3. Interference fringes of an FSRS.

Table 1 . Part of measured values of the FSRS shown in Fig. 3.

Measured points	step (μm)	Measured points	step (μm)
$P_{5,1}$ - $P_{4,5}$	10,049	$P_{4,1}$ - $P_{3,5}$	5,067
$P_{5,1}$ - $P_{4,4}$	10,061	$P_{4,1}$ - $P_{3,4}$	5,065
$P_{5,1}$ - $P_{4,3}$	10,066	$P_{4,1}$ - $P_{3,3}$	5, 050
$P_{5,1}$ - $P_{4,2}$	10,064	$P_{4,1}$ - $P_{3,2}$	5, 038
$P_{5,1}$ - $P_{4,1}$	10,054	$P_{4,1}$ - $P_{3,1}$	5, 019
$P_{5,5}$ - $P_{4,5}$	10,047	$P_{4,5}$ - $P_{3,5}$	5, 070
$P_{5,4}$ - $P_{4,5}$	10,040	$P_{4,4}$ - $P_{3,5}$	5,058
$P_{5,3}$ - $P_{4,5}$	10,033	$P_{4,3}$ - $P_{3,5}$	5, 052
$P_{5,2}$ - $P_{4,5}$	10,035	$P_{4,2}$ - $P_{3,5}$	5,056
$P_{5,1}$ - $P_{4,5}$	10, 050	$P_{4,1}$ - $P_{3,5}$	5,066

Moreover, it has low spatial resolution. In order to increase the spatial resolution of the measurement, the number of measuring points should be increased accordingly, and also the measuring time. To overcome this shortcoming, we decided to measure the whole surfaces of the FSRS. Some candidates for the surface measurement of FSRSs would be the phase shifting interferometry (PSI), or the Fourier transform method (FTM). The PSI is a very effective tool under the assumption that the phase steps between two phase shifted images are accurate, typically being $\pi/2$, or that the phase steps are arbitrary but equidistant [8]. The FTM is also a very powerful method but the filtering in the frequency domain might cause measurement error especially at the edge part of the interferograms.

As an alternative to the normal FTM, we adopted the fringe scanning Fourier transform method (FSFTM) for FSRS measurement. The FSFTM is different from the normal FTM in that it does not use the spatial intensity data. Instead, it makes use of the temporally varying intensity data at a fixed point. This technique has been used for measurement of central length of gauge blocks. We extended the FSFTM to all points on the FSRS so that its overall profile could be obtained with high spatial resolution.

3. EXPERIMENT

The experimental setup, which is the gauge block interferometer, is shown schematically in Fig. 4. A DC motor translates an optical wedge which is placed within the reference arm of the interferometer, and this causes temporal linear displacement of the interference fringes. During the fringe movement, the intensity variation data at all points on the interferogram are acquired. At each point, the intensity variation data are Fourier transformed by using the fast Fourier transform algorithm.

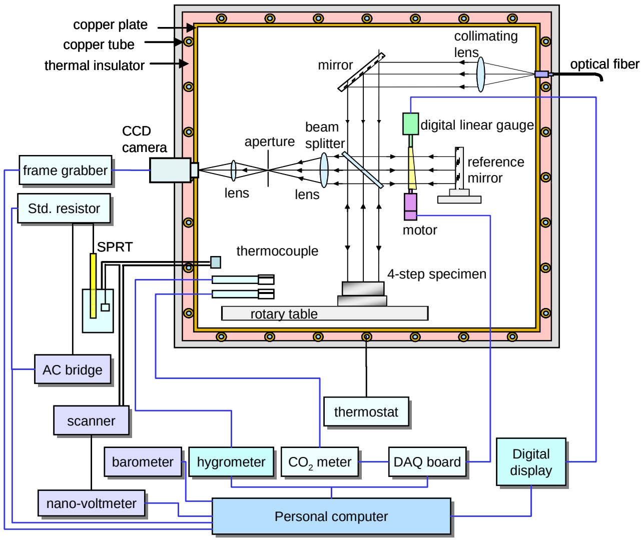
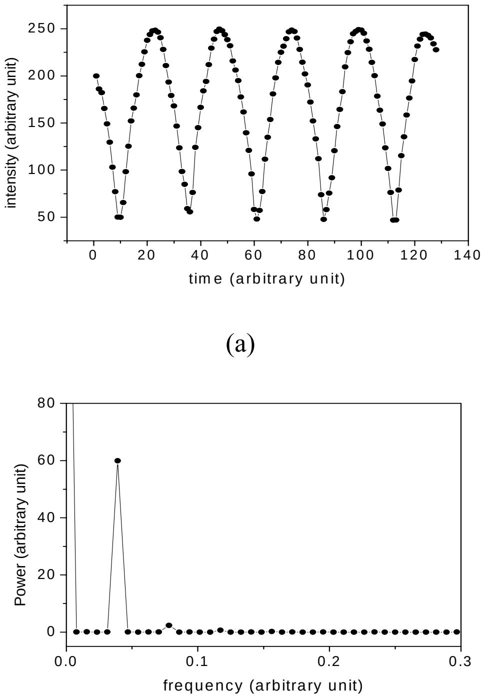


Fig. 4. Schematic diagram of the measuring system.

An example of intensity variation data measured at one point on the block is shown in Fig. 5(a), and the power spectrum of its Fourier transform is shown in Fig. 5(b).

From the Fourier transformed data, the carrier frequency component is filtered out and moved to the origin of the frequency domain. Inverse Fourier transform of this impulse spectrum would produce a constant complex number throughout the time domain. The arctangent of the ratio between the imaginary part and the real part of the complex number would give the initial phase value of the interference fringe at a given point on the specimen.



(a)

(b)

Fig. 5. Intensity variation at a fixed point (a), and its power spectrum of Fourier transformation (b).

When this process is carried out over the whole area of the specimen, the phase map is obtained. Since this phase map has the 2π ambiguity due to the arctangent function, a phase unwrapping algorithm is applied to remove the ambiguity. The unwrapped phase map with its tilt removed is shown in Fig. 6. This whole procedure is repeated with the second laser wavelength. The phase maps are divided into five areas according to the location of the five surfaces, and the method of exact fractions is applied to the neighbouring areas to find out the height profile of the FSRS.

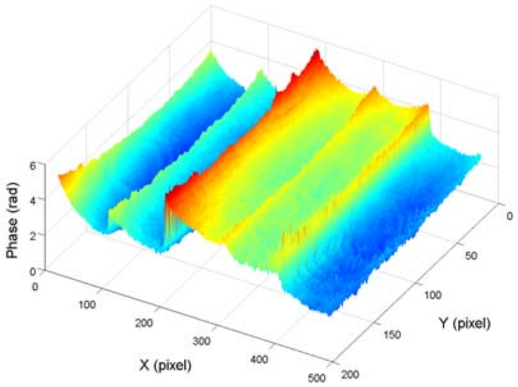
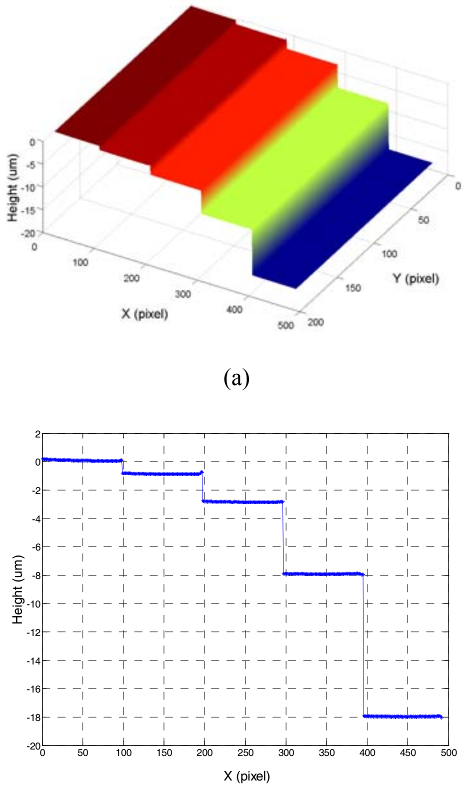


Fig. 6. Unwrapped phase map of the interference fringes shown in Fig. 2.



(a)

(b)

Fig. 7. Measured profile of the the FSRS. (a) 3D profile of the FSRS, (b) 2D profile at the central row.

Fig. 7(a) shows the three-dimensional surface profile of the FSRS, and its two-dimensional height profile at the central row is shown in Fig. 7(b). The central step heights calculated from the profile shown in Fig. 7 are compared in Table 2 with the step heights measured by the CHMM. It is found that the two methods do not always provide consistent results.

Table 2 . Step heights measured with two methods for the FSRS whose interference fringes are shown in Fig. 3.

Nominal step (µm)	Measured step with CHMM (µm)	Measured step with FSFTM (µm)	Difference (µm)
1	1.022	0.960	-0.062
2	2.055	1.978	-0.077
5	5.063	5.054	-0.009
10	10.063	10.047	-0.016

4. DETERMINATION OF STEP HEIGHTS FROM THE SURFACE PROFILE OF FSRS

The disagreement of measured step heights obtained with the two methods comes from the fact that the step heights are not calculated according to the same rule. In the CHMM, the specimen's tilt was adjusted so that interference fringe on the central region of the reference surface was perpendicular to the longer side of the reference block. In the FSFTM, however, a step height was calculated from the surface profile of the whole specimen, as the vertical distance between central points of the neighbouring surfaces.

Since usually neighbouring surfaces are not parallel to each other, as can be seen in Fig. 3, the step height, h_C, measured by the CHMM, and h_F, measured by the FSFTM, will in general be different.

If the tilt angles of the first and second surfaces are denoted as θ_1 and θ_2, respectively, the step heights h_C and h_F can be expressed as

$$h_C = h_0 \times \cos(\theta_2 - \theta_1) + \frac{W}{2} \times \sin(\theta_2 - \theta_1) \qquad (1)$$

$$h_F = h_0 \times \cos(\theta_2 - \theta_1) - \frac{W}{2} \times (\sin\theta_1 + \sin\theta_2) \qquad (2)$$

where h_0 is the height of the riser of the step, and W is the length of shorter side of the surfaces (Refer to Fig. 8).

Thus unless $\theta_1 = \theta_2 = 0$, h_C differs from h_F. This means that even if the three-dimensional profile measurement provides maximum information on the FSRS, there should be a standard method to determine the step heights from the surface profile in order to have robust definition of the steps of the FSRS.

During the optical calibration process and also when the users make profile measurement of the FSRS with stylus type surface roughness testers, the same rule of determining the step heights from the surface profile shall be used.

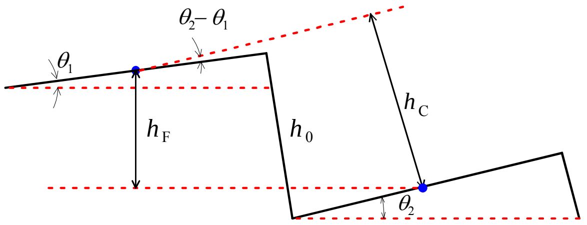


Fig. 8. Difference between step heights measured with the CHMM and FSFTM when the two surfaces are not parallel to each other.

However, there is no standard rule to determine step heights of the FSRS yet. Referring to the definition of groove depth of type A1 standard specimens, given in the ISO standard [9] we propose a definition of step heights of FSRSs as follows.

'The equation:

$$Z = \alpha \times X + \beta + h' \times \delta \qquad (3)$$

with unknowns α and β, is fitted by the method of least squares to a profile equal in length to 4/3 times the width of the surfaces (See Fig. 9). The variable δ takes the value +1 in region A and the value -1 in the region B (see Fig. 9). The step height *h* is twice the estimated value of *h*′. To avoid the influence of any rounding of the corners, the surfaces will be assessed over only the central third of each surface. The portions to be used for assessment purposes are those shown as A and B in Fig. 9.'

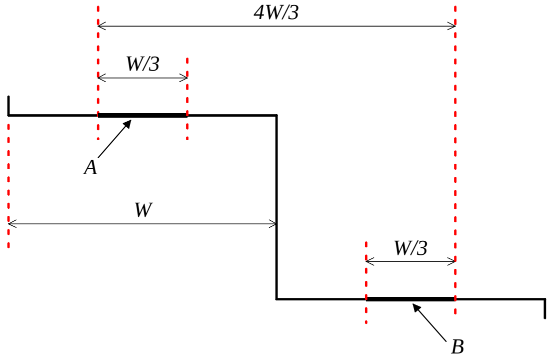


Fig. 9. Determination of the step height from the surface profile.

Considering the difference between groove depth specimens and FSRSs, we chose the central third of each surface's shorter side to be used for the step height calculation.

Even if the step height is defined to be found from the central profile, a narrow strip along the central line of the FSRS is to be used for determining the step height when measured by optical interferometry. The width of the strip may be one third of each surface's shorter side as shown in Fig. 10.

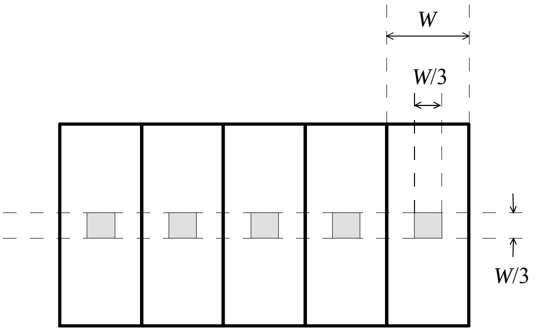


Fig. 10. Areas to be used for determining step heights of an FSRM by using optical interferometry.

In this case, the definition of the step height would be:

‘The equation:

$$Z = \alpha \times X + \beta \times Y + \gamma + h' \times \delta \tag{4}$$

with unknowns α, β, γ, and h', is fitted by the method of least squares to a surface profile equal in length and width to 4/3 times the width of the surfaces (See Fig. 9 and Fig. 10). The variable δ takes the value +1 in region A and the value -1 in the region B (see Fig. 9). The step height h is twice the estimated value of h'. To avoid the influence of any rounding of the corners, the surfaces will be assessed over only the central third of each surface. The portions to be used for assessment purposes are those shown as A and B in Fig. 9.’

Thus, central areas of size approximately 2 mm × 2 mm of the neighbouring surfaces are used for calculating step heights, and two-dimensional plane fitting is used for step height determination by using (4).

The step heights obtained with this determination method is shown in Table 3. Since the expanded uncertainty with level of confidence of approximately 95 % ($k = 2$) for the CHMM is 0.040 μm, the measured step heights of the FSRS obtained by FSFTM are in good agreement with that obtained with the CHMM within the measurement uncertainty of CHMM.

Table 3. Step heights calculated by applying the proposed method of step height determination

Nominal step (μm)	Measured step with CHMM (μm)	Measured step with FSFTM (μm)	Difference (μm)
1	1.022	1.030	0.008
2	2.055	2.032	-0.023
5	5.063	5.072	0.009
10	10.063	10.046	-0.017

5. CONCLUSION

We have presented a new method to measure three-dimensional surface profile of FSRSs. Compared to the CHMM where only the height difference between two central points of the neighbouring surfaces is given, the new method provides surface profile with high spatial resolution which might be more useful to users than simple step height data. The gauge block interferometer which has an optical wedge within the reference arm was used for the measurement. By translating the optical wedge linearly, the interference fringe moved in one direction constantly, and the intensity variations at all points on the image were acquired. The extension of applying FSFTM to the whole interference image of the FSRS allowed us to obtain three-dimensional surface profile of the FSRS with high spatial resolution. We have proposed a standard method of determining step heights of FSRSs from its surface profile. This method can be applied to both optical interferometry and the stylus profilometry, and would eliminate discrepancy in step height values measured by different methods.

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