Accurate roughness measurements by dynamic calibration, VFM-uncertainty calculations and a special calibration specimen

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Abstract. The uncertainty of roughness measurements and calibration is usually rather high. This paper gives some methods to estimate the uncertainty properly and proposes a dynamic calibration device and a special reference specimen to enable more accurate roughness measurements.

1. Introduction
Normally, roughness measurements are carried out with a rather high uncertainty ranging to a few percent up to 10%. This is a rather bad situation considering the accuracy of primary length standards (1:5·10^-11) and common dimensional measurements (1:10^6). In this paper we will show that with proper calibration techniques, proper uncertainty evaluations and a special calibration specimen this situation can be improved.

2. Dynamic probe calibration
As the probe of a roughness measuring instrument moves dynamically, a probe calibration should be carried out dynamical as well, in the same frequency range as in which the probe normally operates. For this, a simple yet very effective dynamic probe calibration device has been designed, where the traceability is achieved by a laser interferometric read-out with 30 kHz and 10 nm resolution. In the past, other devices were developed, however with a lower bandwidth and indirect traceability [1,2]. With this device a probe can be fully characterized for various amplitudes and frequencies.

2.1. Calibration device
For an accurate calibration of a roughness tester, a dynamic calibration device has been designed and built. It is shown in figure 1.
Upon a linear optics set of a laser interferometer, a tube size piezo device (PI S314) has been mounted. This gives a maximum displacement of 15 µm that is about the maximum displacement encountered in normal roughness measurements. On top of the piezo, an optical flat is mounted, together with a corner cube. As the piezo is hollow, the displacement can be measured with a laser beam through the center, so the measurement satisfies Abbes principle. The displacement of the optical flat with corner cube is measured with an Agilent 5529 laser interferometer. It can measure the displacement with a sampling rate of 25 kHZ at maximum. At maximum amplitude the bandwidth is at least 1 kHz. At amplitude of 0.5 µm the bandwidth is still some 10 kHz, more than any mechanical probe used for surface measurements can achieve.

Figure 1. Exploded view of the calibrator. Corner cube \( b \) is glued into optical flat \( a \) which is glued upon the piezotube \( c \). The piezotube is bolted to beam splitter \( e \) via connector plate \( d \). The laser interferometer is completed by the rigid retro reflector \( f \). Top left is a picture of the set up.

2.2. Calibration of a Mitutoyo SV645-3D roughness tester
Various major aspects of a roughness tester can be calibrated with the dynamic calibration device such as the vertical scale calibration, the dynamic probe response and functioning of the software filtering.

2.2.1 Vertical z-scale calibration
For accurate measurements it is essential that the vertical scale, i.e. the probe reading is linear and accurately calibrated. The vertical scale was calibrated using the \( R_q \) parameter for both the laser interferometer and the roughness measurements. The used frequency was 0.4 Hz, and the scanning speed over the piezo was 0.05 mm/s, giving a wavelength of 120 µm, far within the probe bandwidth and well within the Gaussian filtering where the bandwidth is between \( \lambda_c = 0.8 \text{ mm} \) and \( \lambda_s = 2.5 \text{ µm} \). The results showed that the linearity and the deviation are within the tolerance of 2 nm + 1% for very small up to quite large roughness values.

2.2.2 Dynamic response and software filtering
It is also essential that the probe keeps its accuracy throughout its bandwidth. This is, together with the software Gaussian filtering, tested for various frequencies for a sinus signal with an \( R_q \)-value of 0.4 µm. The frequency varies between 20 mHz to 100 Hz, which covers a wavelength range from 0.5 µm up to 2.5 mm for a speed of about 50 µm/s. The results are summarized in figure 2.

In this figure, 3 aspects are important:
1. The accuracy when the response should be about 1: in the 10 – 200 µm wavelength range the deviations are within 1%.
2. The accuracy around the cut-off frequency \( \lambda_c \), also here in the 200-2000 µm wavelength range, deviations are within 1%.
3. The accuracy around the cut-off frequency \( \lambda_s \). Here the deviations are somewhat larger, where it should be noted that these wavelength seldom appear in materials to a large extent, and part of this will also be removed by the mechanical filtering of the probe itself.
3. VFM uncertainty calculation

The result of the dynamic calibration can be used as major input for a complete ‘Virtual Form measurement (VFM)’ uncertainty calculation as is published before [3],[4]. Here the calculation for the $Ra$ parameter for two Halle type D, specimen, a Mitutoyo sinusoidal and a Rubert fine roughness specimen are given. Filtering conditions are $\lambda_s = 2.5 \, \mu m$ for all samples, $\lambda_c = 250 \, \mu m$ for the Rubert sample and $\lambda_c = 800 \, \mu m$ for all other samples. The evaluation length is $5\lambda_s$.

Table 1 Uncertainty budget for the $Ra$ parameter for several roughness specimen

|                | Halle 1 in nm | Halle 3 in nm | Mitutoyo in nm | Rubert 502 in nm | Optical flat in nm |
|----------------|---------------|---------------|----------------|------------------|-------------------|
| Measured $Ra$  | 144.4         | 1563          | 2954           | 32.9             | 2.2               |
| $z$-linearity (0.58 %) | 0.80          | 90            | 17             | 0.19             | 0.02              |
| $\lambda_c$ (0.58 %) | 0.05          | 10            | 2              | 0.03             | 0                 |
| $\lambda_s$ (3%) | 0.16          | 0             | 0              | 0.15             | 0.02              |
| $R$ (2 ± 1) $\mu m$ | 0.70          | 0.5           | 5              | 0.32             | 0                 |
| Ref/noise      | 0.13          | 0.1           | 0.1            | 0.03             | 1.0               |
| inhomogeneity  | 0.90          | 6             | 10             | 0.54             | 0.03              |
| $U (k=2)$      | $2 = 1.4\%$  | $30 = 2\%$   | $40 = 1.3\%$  | $1.3 = 4\%$     | $2 = 90\%$       |

In table 1, some influencing factors that proved to have a negligible influence, such as measuring force, and sample spacing and calibration of the x-axis, are omitted. The table shows that the noise has hardly influence except when the roughness becomes as small as the noise itself. Striking is the large influence of the cut-off wavelength in the Halle 3 specimen. For smaller roughness values the radius influence can be significant. The inhomogeneity is taken as a single standard deviation for measurement taken at different areas of the specimen. For a neat sinusoidal sample, only the $z$-calibration and the inhomogeneity are important, so these samples can best be used for calibration of the probe.

4. Calibration specimen

Apart from what can be calibrated with the dynamic calibration device, from section 3 it is obvious that other aspects, especially probe tip radius and measurement force are essential for a proper performance of a roughness tester. In order to calibrate all aspects, a special calibration object was designed and patented [5] by which all aspects of a roughness tester can be calibrated. It is depicted in figure 4 and the properties are listed in table 2.
Figure 4. Lay-out of specimen. Different sections are explained in table 2

| Section | Properties | Used for |
|---------|------------|----------|
| 1 Flat  | Set up probe |
| 2 Sinuses: Amplitudes 10, 8 5 and 2 µm, wavelength 800, 400, 250 and 80 µm | Filters, x-axis, z-axis, parameter calculation |
| 3 Grooves, 1, 3 and 10 µm depth | z-axis |
| 4 Quasi random profile | Overall check |
| 5 Ramp | z-axis linearity |
| 6 Optical flat (gauge block) | Probe and reference guidance noise |
| 7 Leaf spring | Measurement force |
| 8 Razor blade | Stylus tip radius |

Some specimen were prepared by a precision diamond turning process and showed good homogeneity. The measuring force can be determined from the bending of the leaf spring, as is illustrated in figure 5.

Figure 5. Measurement of part of the artifact. Left is measured with a probe with radius of 2 µm and measurement force of 0.7 mN probe, right is measured with a radius of 5 µm and a force of 3.4 mN.

References

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