euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020

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Axial calibration of an on-machine focus variation surface texture and form sensor

Subbareddy Darukumalli[1,2], Teguh Santoso[1], Wahyudin P. Syam[1], Franz Helmli[2] and Richard Leach[1]

[1]*Manufacturing Metrology Team, University of Nottingham, UK.*
[2]*Alicona Imaging GmbH, Dr Auner Straße 21a, 8074 Raaba, Austria.*

E-mail: s.darukumalli@bruker.com

Abstract

To address the increase in tight tolerance requirements for small parts produced by precision manufacturing, on-machine optical areal surface topography instruments are emerging. To calibrate these instruments and estimate their measurement uncertainty, their metrological characteristics need to be determined according to ISO 25178 part 600. In this paper, the amplification coefficient and linearity deviation metrological characteristics in the vertical axis of a prototype compact on-machine focus variation areal surface texture and form measurement sensor are determined. With a series of experiments in different positions of the vertical axis using calibrated materials measures with heights from 0.2 µm to 1000 µm, we determine the amplification coefficient and linearity deviation for the vertical axis. In addition, with a procedure derived from ISO 10360 part 8, the maximum permissible unidirectional stationary error of the vertical axis is determined.

Metrological characteristics, axial calibration, on-machine metrology, focus variation

1. Introduction

Advances in precision manufacturing technologies lead to an increase in the tight tolerance requirements of small parts. To measure such tolerances to sub-micrometre accuracy and avoid the measurement instrument's influence on the measured features, in contrast to the traditional contact measurement instruments, commercial non-contact optical areal topography instruments are emerging. On-machine areal topography instruments are becoming popular because surface texture and form errors can be used as the fingerprint of the manufacturing process [1].

Focus variation microscopy (FVM) areal topography measuring instruments provide measurement data using an optical setup along with a high-precision encoder for measurement axis position measurement [2]. To calibrate a FVM instrument, a series of standardised metrological characteristics must be determined [3], where calibration is defined as "an operation, under specific conditions, in a first step required to establish a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and in a second step, uses this information to establish a relation for obtaining a measurement result from an indication" [4]. In practice, calibration of the instrument refers to a series of operations required to establish the contribution of the metrological characteristics to the measurement uncertainty associated with the instrument measurements [5,6].

In this paper, we address the metrological characteristics associated with the on-machine focus variation sensor measurement axis in section 2, the experimental design and measurement procedure are explained in section 3, measurement data and analysis are presented in section 4 and finally the conclusions and future work are given in section 5.

2. Metrological characteristics

The metrological characteristics used for FVM instrument calibration include: amplification coefficient, linearity deviation, residual flatness, measurement noise, lateral period limit and *xy* mapping error [5,6]. In this paper, we address the amplification coefficient, linearity deviation and maximum permissible unidirectional stationary error associated with the on-machine FVM sensor measurement axis (*z*-axis) using calibrated material measures. These characteristics are defined as:

- Amplification coefficient is the slope of the linear regression curve obtained from the response curve [5,6].
- Linearity deviation is the maximum local difference between the line from which the amplification coefficient is derived and the response function [5,6].
- Maximum permissible unidirectional stationary error $E_{UniZ:St:ODS,MPE}$ is determined using a method derived from the ISO 10360-8 maximum permissible error determination procedure (where $UniZ$ indicates the measurement direction, St for stationary, ODS for optical distance sensor and MPE for maximum permissible error) by the measurement of height steps in a single field of view [7].

3. Experimental design

The compact on-machine FVM sensor used is presented in reference [8] and has a magnification 20× (0.4 numerical aperture, working field of view 0.59 mm × 0.59 mm and sampling distance approximately 0.30 µm) objectives lens, together with ring light illumination. The working range of the *z*-axis is 15 mm. Single step height artefacts were measured in five positions within the working range of the instrument and the measurement positions were chosen to cover the total working range. Each step height artefact has measured at 90%

(13.5 mm), 70% (10.5 mm), 50% (7.5 mm), 30% (4.5 mm) and 10% (1.5 mm) of the instrument working range [9].

As shown in Table 1, eight different step height artefacts with nominal heights from 0.2 µm to 3000 µm were chosen for the measurements. The nominal 3000 µm step height was built with two gauge blocks and calibrated with a focus variation instrument with a calibrated axial response [7]. The 0.2 µm to 7.5 µm step height artefacts were calibrated at PTB using an interference microscope according to VDE/VDI 2655, the 24 µm and 50 µm step heights were calibrated at PTB using a traceable stylus instrument and the 1000 µm step height artefact was calibrated at a DKD calibration laboratory using a gauge block measurement system.

Table 1 List of used step height artefacts.

Artefact	Calibrated height/µm	Uncertainty/µm at *k* = 2
Step height 1	3000.46	±0.50
Step height 2	1000.00	±0.10
Step height 3	49.75	±0.25
Step height 4	23.97	±0.15
Step height 5	7.51	±0.15
Step height 6	2.4	±0.15
Step height 7	0.75	±0.15
Step height 8	0.24	±0.10

As we are using the prototype version of the FVM, before starting the measurement, the instrument was adjusted for field curvature correction by estimating the form error and by removing it using the software settings for the used objective lens. All measurements are performed with the same measurement settings. Measurements were performed in a low noise laboratory environment.

Table 2 Estimation of measurement uncertainty budget.

Measured step height/ µm	Calibration certificate uncertainty /µm	Estimated instrument uncertainty /µm	Measurement procedural uncertainty /µm	Computed Test uncertainty /µm
1000	0.1	0.2	0.017	0.233
50	0.25	0.2	0.165	0.360
24	0.15	0.2	0.068	0.259
7.5	0.15	0.2	0.044	0.253
2.4	0.15	0.2	0.031	0.251
0.75	0.15	0.2	0.008	0.250
0.24	0.1	0.2	0.011	0.223

As shown in Table 2, the estimated measurement uncertainty at each measurement step was noted and the maximum standard deviation of the squared sum of these values is computed as the measurement test uncertainty, i.e. ±0.360 µm. This includes the measured step height uncertainty value from calibration certificate using a traceable instrument, the estimated uncertainty of the measuring instrument and measurement procedure, including the profile analysis (which includes the direction of the profile selection, profile width, orientation of the profile width, choosing the rectangle area to apply the levelling to the workpiece coordinate system, and choice of the measuring points for the step height measurement). It is difficult to measure the expansion coefficient of the instrument at this stage of the prototype development; therefore, the expansion coefficient is not considered for the uncertainty estimation.

The measurement procedure of the step height value determination is explained below and an example procedure is shown in Figure 1.

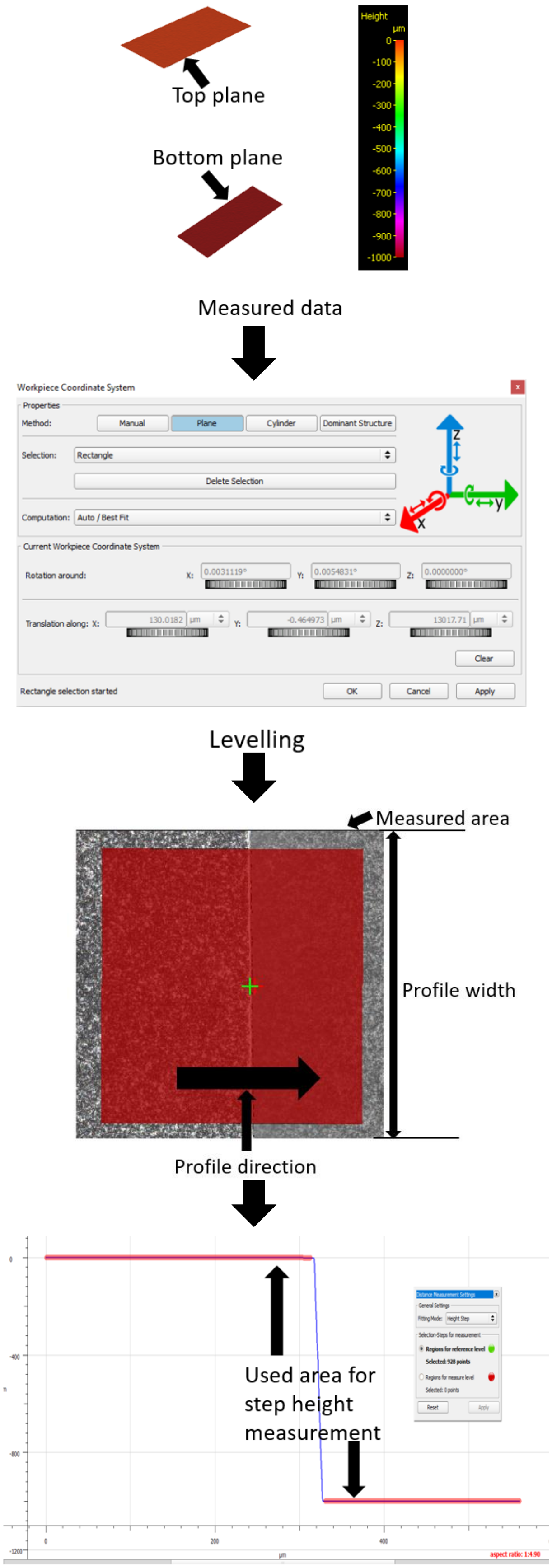

Figure 1. The procedure of the step height measurement analysis

The measurement procedure for the calibration is as follows.

1. Clean the measurement artefact and place it at the focus plane.
2. Select the desired measurement position from the live view and configure the appropriate software settings for measurement.
3. The measured areal data is analysed using commercial software provided by Alicona (Alicona Measure Suite).
4. The measured data is levelled to the workpiece coordinate system.
5. A profile width is chosen to cover most of the measurement area.
6. Step height is extracted from the chosen profile area.
7. With a derived method from the ISO 5436-1 [10], step height artefact profile analysis procedure, the step height value is computed for single step height measurement.

4. Results and analysis

A total of forty measurements were performed with the eight step heights measured at five different positions. Due to the measurement test uncertainty caused by the prototype optical setup and illumination, the 3000 µm step height measurement does not contain enough high quality measurement data (measurement data contains many missing points, as it is unable to choose the profile area without holes for profile analysis) to do the profile analysis. Due to the small field of view of the working objective lens, the bottom plane of the step height is unable to focus properly with ring light illumination which leads to the missing points in the measured data. Therefore, the results from the 3000 µm step were not taken into consideration for further analysis.

To estimate the repeatability of the measurement, at one measurement position, each step height is repetitively measured five times. The repeatability value is computed as the standard deviation of the mean of the measured values at the same measurement position, and was found to be 0.012 µm.

Table 3 Measurement error by comparing the measured height step values to the reference values at different measurement positions.

Measured Step height	90% Error/ µm	70% Error/ µm	50% Error/ µm	30% Error/ µm	10% Error/ µm
1000 µm	0.052	0.075	0.1	-0.044	-0.056
50 µm	-0.082	-0.072	-0.059	-0.021	-0.032
24 µm	0.001	-0.13	-0.033	0.005	0.106
7.5 µm	-0.015	-0.091	-0.105	-0.048	-0.016
2.4 µm	-0.049	-0.088	-0.078	0.014	-0.011
0.75 µm	0.002	-0.011	0.007	-0.019	-0.009
0.24 µm	-0.011	0.001	0.002	-0.005	0.006

Step height measurement errors were computed by comparing the step height measurements with their reference values and errors are plotted in Figure 2. A maximum error of 0.13 µm was reported at 70% of the working range for the 24 µm artefact and the minimum error of 0.001 µm was reported at 70% of working range for the 0.241 µm artefact. As shown in Table 3, the measurement errors show that all the measured values were in the range of the reference uncertainty values of the measured artefacts.

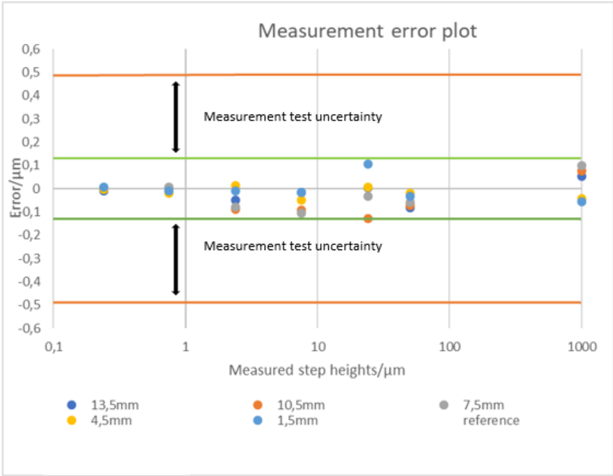

Figure 2. Measurement error plot: the green lines indicates the maximum permissible error limit from the measurement errors and the orange lines indicates the maximum permissible error limit including the measurement test uncertainty for the measurement axis.

As we can see in the measurement error plot, all the measurement errors lie between the -0.13 µm and 0.13 µm and the estimated measurement test uncertainty is 0.360 µm. The maximum permissible unidirectional stationary error of the measurement axis $E_{UniZ:St:ODS,MPE}$ (derived from the ISO 10360-8 maximum permissible length measurement error procedure [8]) is computed as the sum of the measurement test uncertainty, maximum error value and a length coefficient. This is given by $E_{UniZ:St:ODS,MPE} = 0.49\ \mu\text{m} \pm \frac{L}{2500}$ (where L is the length of the sample in millimetres).

The amplification coefficient is determined by fitting a line to the determined step heights using the least-squares method [5]. Linearity deviation is computed as the maximum local difference between the line from which the amplification coefficient is derived and the response function. At the different working ranges of the measurement axis, the amplification coefficient and linearity deviation values are computed and listed in Table 4.

Table 4 Amplification coefficient and the linearity deviation at the different positions of the measurement axis.

Measurement position/mm	Amplification coefficient	Linearity deviation/µm
90 % ~ 13.5	1.0000	0.129
70% ~ 10.5	1.0001	0.208
50% ~ 7.5	0.9998	0.168
30% ~ 4.5	0.9998	0.077
10% ~ 1.5	0.9998	0.110

The amplification coefficient of the whole measuring range is computed as the mean of the amplification coefficient at different measurement positions, i.e. 0.9999. This shows that the measurement axis response is close to the ideal response curve with less than 0.0001% of deviation.

The maximum linearity deviation 0.208 µm is reported at 70% of the working range and the minimum linearity deviation 0.077 µm is reported at 30% working range of the measurement axis. The linearity deviation of the whole working range of the measurement axis is computed as the absolute maximum of the linearity deviations at different measurement positions, i.e. 0.208 µm.

5. Conclusion

In this paper, the amplification coefficient, linearity deviation and maximum permissible unidirectional stationary error of an on-machine focus variation sensor measurement axis are determined using single-step height artefacts. The results show that the mean amplification coefficient is 0.999 and the linearity deviation is 0.208 µm. The measurement error values show that all the measured values are in the uncertainty range of the measured artefacts.

In this experiment, the measurements were carried out with a prototype version of the optical setup to evaluate the performance of the measurement axis. In the near future, we are planning to determine the whole sensor metrological performance with the fully developed optical setup, which is corrected for aberrations and distortions.

Acknowledgements

This work has received funding from the European Union Horizon 2020 Marie Skłodowska Curie ITN projects PAM^2 and MICROMAN under the grant agreement numbers 721383 and 674801.

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