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Metrological traceability of an ultra-accurate CMM XENOS

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Abstract
In order to guarantee the accuracy of a CMM, it is an essential task to trace back the measurements with the aid of dimensional standards that are calibrated with sufficiently small uncertainties. Thus, different dimensional standards are used for this, such as gauge blocks and step gauges made either of steel or different low thermal expansion materials. These dimensional standards are calibrated by different methods and with different uncertainties. The traceability of an ultra-accurate CMM XENOS using various dimensional standards was investigated and the results and the advantages and disadvantages of use of the different standards are discussed.

Coordinate Metrology, Traceability, Dimensional Standards

1. Introduction

Coordinate measuring machines (CMM) are widely used in research and industrial quality assurance. An example of a CMM pushing the present limits of accuracy is the ultra-accurate CMM XENOS, cf. figure 1. With the use ot the new XENOS, PTB intends to reduce the current achievable uncertainties e.g. for calibration of zerodur hole plates of 0.4 µm + 0.5 µm/m at least by a factor of two. The measuring range of the XENOS at PTB is 0.9 m (X) × 1.3 m (Y) × 0.7 m (Z) and it is equipped with a rotary table. The maximum permissible error (MPE) for 3D length measurements is stated as $E_{0,\,\mathrm{MPE}}$ = 0.3 µm + 1 µm/m according to ISO 10360-2 [1].

For investigation of the new XENOS, different types of length standards were measured. At first, two step gauges of 700 mm in length made of different materials were used. One of them comprised a steel base body with ceramic rolls inserted, while the other one was entirely made of Zerodur®.

In a second step, two sets of gauge blocks ranging from 100 mm to 1000 mm in length and either made of steel or ZeroCera™, respectively, were measured (cf. chapter 4).

Figure 1. CMM XENOS (Zeiss).

2. Test of probing accuracy

The single stylus probing error of the VAST probe used is specified with a single stylus form error $P_{\mathrm{FTU,\,MPE}}$ = 0.4 µm [2] and a scanning mode form error on a sphere with $T_{\mathrm{HP,\,MPE}}$ = 0.6 µm (τ = 40 s) [3] without filtering. The probing accuracy was tested according to ISO 10360-4 [3] and ISO 10360-5 [2] using a reference sphere of 30 mm in diameter. The uncertainty of the diameter calibration is 0.08 µm and the roundness deviation amounts to 0.03 µm with an uncertainty of 0.015 µm (k = 2). A diamond-coated tungsten carbide probe with a nominal diameter of 8 mm was used for all tests.

The results of form error probing tests are $P_{\mathrm{FTU}} \approx 0.1$ µm for single stylus form error and $T_{\mathrm{HP}} \approx 0.5$ µm for scanning mode form error with a scanning mode time of τ = 40 s, respectively. The results of the size error probing tests are $P_{\mathrm{STU}} \approx 0.1$ µm for single stylus size error and for scanning mode size error[1] ≈ 0.15 µm, respectively. The scanning mode form error could be reduced to $T_{\mathrm{HP}} \approx 0{,}3$ µm by using a longer scanning mode time of $\tau \approx 90$ s.

3. Test with step gauges

The length measurement error was, firstly, determined using a common 700 mm step gauge made of steel with inserted ceramic rolls. The calibration uncertainty of the lengths amount to 0.05 µm + 0.25 µm/m (k = 2). The step gauge was measured in different orientations (parallel to the axes and diagonal) and in different heights (on top of the granite plate and 0.4 m above). Figure 2 shows the set-up of a diagonal measurement in 0.4 m height.

Secondly, a step gauge made of Zerodur® was used, but the measurements were carried out at five distances only parallel to the axes in one position each. The calibration uncertainty amounts to 0.04 µm + 0.09 µm/m (k = 2). Figure 3 shows the set-up of this step gauge.

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[1] This parameter is not included in ISO 10360-4:2000. In ISO/DIS 10360-5:2018(E) the appropriate parameter is P[Size.Sph.Scan:PP:Tact].

Figure 2. Set-up of the steel-made step gauge in diagonal orientation and in 0.4 m height.

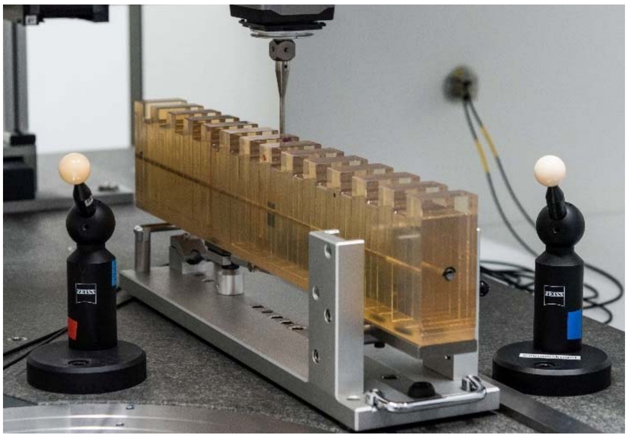

Figure 3. Set-up of the Zerodur® step gauge parallel to the Y axis of the CMM.

The results of the measurements with the steel-made step gauge are shown in figure 4. The dashed blue lines denote the maximum permissible length measurement error $E_{0,\,\mathrm{MPE}}$ as specified by the CMM manufacturer. The blue and green curves represent the deviations parallel to the X and Y axes, while the red graphs give the deviations in diagonal orientations in both heights described above. The error bars represent the test uncertainty, which is dominated by the uncertainty contribution of the temperature measurement, cf. chapter 6.

At this step gauge all distances of all 35 gaps were evaluated. Therefore, deviations of uni- and bidirectional deviations are mixed in the graphs. The visible up and down of the deviations is due to the local form deviations of the probing sphere which directly influence length measurements results when measuring distances only with two single points.

The deviations are clearly within the specifications. For the first 300 mm length there is a similar form of the graphs visible. A test in 3D orientation of the step gauge is an upcoming task. The results of the second step gauge made of Zerodur® are presented together with all other results in chapter 5.

The advantages of using step gauges for determination of length measurement deviations are the large number of sampling points and the easy use of the step gauge. Moreover, the measurement strategies for these test measurements and the calibration are nearly the same and no further influences from this have to be considered. In contrast to this, the time for temperature equalisation is relatively long.

In some calibration laboratories the uni- and bidirectional deviations are given separately with a slightly decreased uncertainty of the unidirectional deviation due to the lack of influences of the probe diameter during calibration [5]. Nevertheless, the calibration uncertainty of step gauges is relatively large with respect to the length measurement deviation specified for the XENOS (factor ≈ 1/5) and should be decreased in future to a factor of 1/10.

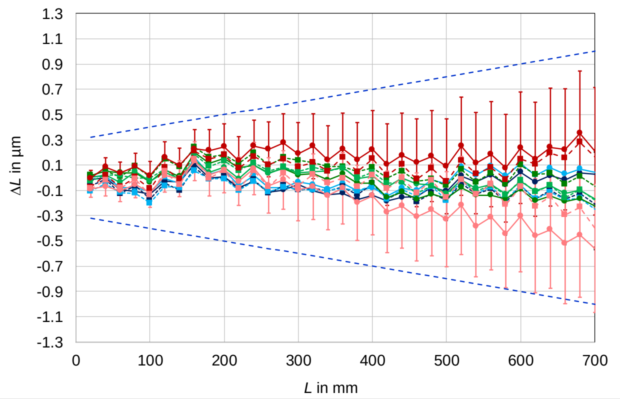

Figure 4. Results of length deviations obtained from measurements of a 700 mm steel step gauge in 12 different positions and orientations, respectively. The error bars represent the test uncertainty.

4. Test with gauge blocks

Gauge blocks are the most common length standards and are available from different materials either with a significant thermal expansion coefficient (CTE) α, such as steel, or with it nearly zero like Zerodur®. Gauge blocks are calibrated according to [6] either by interferometry or by comparison. The lowest uncertainties can be achieved by interferometry.

In the presented investigations gauge blocks were used in length of 100 mm up to 1000 mm. Firstly, two different sets of gauge blocks made of steel where used. The first set was calibrated by comparison with an uncertainty of 0.05 µm + 0.25 µm/m (k = 2). The second set was calibrated by interferometry with an uncertainty of 0.03 µm + 0.12 µm/m (k = 2).

Secondly, a set of gauge blocks made of ZeroCera™ was used. ZeroCera™ is a ceramic with $\alpha \approx 0\ \mathrm{K}^{-1}$ [7][8]. These gauge blocks were calibrated by interferometry. The calibration uncertainty amounts to 0.035 µm/400 mm, 0.051 µm/700 mm and 0.07 µm/1000 mm, respectively, each k = 2. Figure 5 shows a set-up of four gauge blocks made of ZeroCera™ (100 mm to 1000 mm) on XENOS in diagonal orientation.

For interferometrical calibration the gauge block is wrung to an auxiliary plate which serves as a reference for the unidirectional determination of the distance between two planes. When measuring on a CMM, both end faces of the gauge block are probed. One of them serves as the reference plane and either the distance between the planes or between single points is determined. As the principles differ, there are some influences to be considered:

a) the method to determine the length of the gauge block,
b) the reference base plane with CMM probing is relatively small and angle deviations result in a cosine error,
c) the probing forces result in elastic compression that has to be corrected.

There are several additional influences but in this work these three influences are discussed in further detail only.

Figure 5. Set-up of four gauge blocks made of ZeroCera™ (100 mm to 1000 mm) placed diagonally in the measurement volume of the CMM.

a) With interferometry the length of a gauge block is determined as the perpendicular distance of the balance point of a small area on the bare plane of the gauge block to the plane of the auxiliary plate surrounding the gauge block wrung on this plate. In contrast, the CMM allows different methods of length determination. The one, which seems to match the calibration by interferometry most closely is performed in three steps: firstly, a tangent plane is fitted to the reference plane points; secondly, the balance point on the plane on the other side is determined and, finally, the perpendicular distance of the latter to the tangent plane is determined.

However, this method is predominantly influenced by the measured form deviation because the tangent plane is defined by three points only and is, therefore, shifted into the material free direction, i.e. the length of the gauge block is determined too large. For this reason, a least-squares fit plane was used to evaluate the reference plane. The length of a gauge block was finally determined by the cartesian distance of two single points in the centre of the planes on both sides and by using either the left or the right plane of the gauge block as a reference plane.

b) The error in length measurement due to cosine error is $\delta L = L\cdot(1-\cos\varphi)$ [9] and depends on the measured angle φ between the opposite planes of the gauge block. This angle depends, firstly, on the geometrical errors of the gauge block and, secondly, on the measured form deviations of the reference plane.

To investigate this influence both planes of the gauge block were used successively as a reference plane and the planes were probed both with 5 × 3 single points, and with about 2000 scanning points in three parallel traces, respectively. The resulting form errors amount to less than 30 nm for single point probing and less than about 150 nm for scanning probing. The lengths determined with the different reference planes and with different probing strategies were compared.

The differences between the lengths determined by single point probing and scanning were in the range of a few nanometers only and, therefore, negligible. The difference between the lengths determined either with the left side reference plane or the right side reference plane were less than one nanometer for $\varphi \le 10$ arcsec and about 0.08 µm for the 1000 mm-sized gauge block with $\varphi \approx 80$ arcsec. These measured values agree with the theoretical values as shown in figure 6. Finally, the length of a gauge block was determined as the average of the two lengths determined using both the left side, and the right side as a reference plane, respectively. This is also common practice for interferometrical calibration. Thereby, both sides of a gauge block are wrung successively to the auxiliary plate and the determined lengths are averaged.

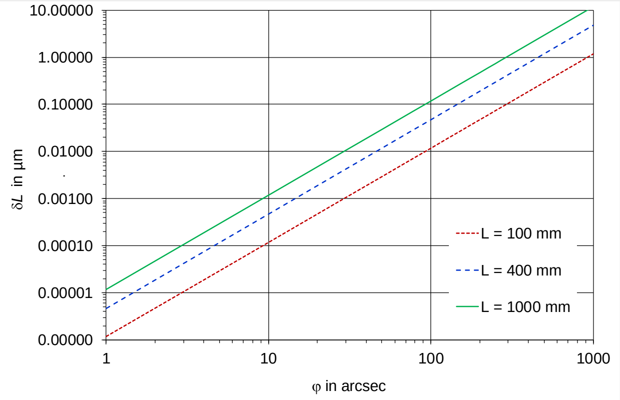

Figure 6. Cosine error depending on angle between opposite planes of the gauge block.

c) The elastic compression was determined according to [10]. The value for a tungsten carbide probing sphere of 8 mm diameter and with a contact force of 100 mN on a steel plane amounts to -0.036 µm. During referencing of the probing system the elastic compression at the ceramic reference sphere is about -0.023 µm. Consequently, only the difference between both elastic compressions must be considered.

When applied to the both-sided elastic compression on a steel-made gauge block, the correction amounts to about +0.026 µm, which can be considered negligible for most applications.

5. Summary of test measurement results

The results of length measurements obtained using different standards are presented in figures 7 to 9. The results of measurements parallel to the X axis are shown in figure 7. The error bars represent the test uncertainty according to [4], cf. chapter 6. There is a very good conformance between the results up to 400 mm. The results of the 700 mm gauge blocks made of steel and ZeroCera™ differ from each other. The fault analysis is still in process.

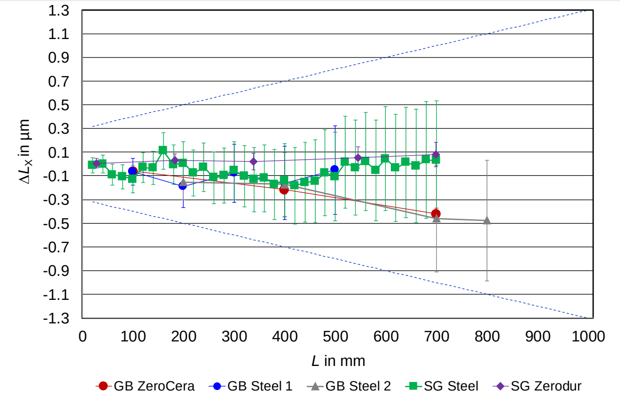

Figure 7. Length measurement deviations of gauge blocks (GB, set 1 and set 2) and step gauges (SG) measured in X direction of the CMM.

The results of measurements parallel to the Y axis are depicted in figure 8. Here, the results agree also for the lengths longer than 400 mm. The results of the two series of measurement of the ZeroCera™ gauge blocks carried out in two-months interval shows the very good reproducibility of the length measurements, also in the longer term.

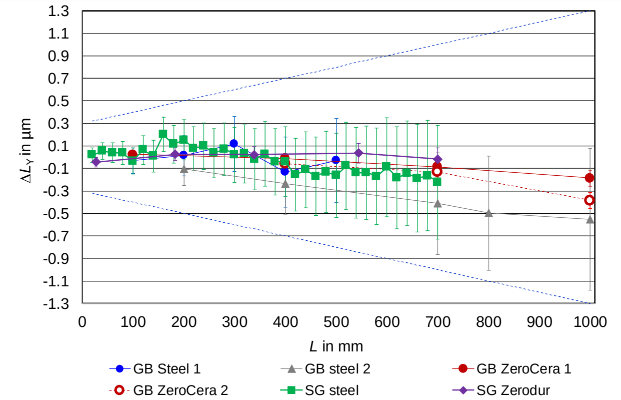

Figure 8. Length measurement deviations of gauge blocks (GB, set 1, set 2 for steel and ZeroCera™) and step gauges (SG) measured in Y direction of the CMM.

The results of measurements in diagonal orientation are shown in figure 9. There is a good conformance between the results of right- and left-tilted orientation, respectively. The differences between these results may be caused by a residual error of squareness in the XY plane.

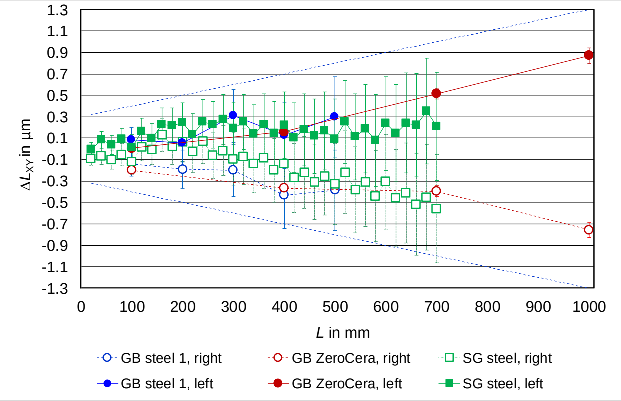

Figure 9. Length measurement deviations of gauge blocks (set 1 and ZeroCera™) and step gauge (SG) measured in XY plane of the CMM tilted by 45° to the right and left, respectively.

6. Test uncertainty

The test uncertainty $U(E)$ is estimated according to [4]:

$$U(E)=k\sqrt{\begin{array}{l}u^2(\varepsilon_{\mathrm{cal}})+u^2(\varepsilon_\alpha)+u^2(\varepsilon_{\mathrm{t}})\\ +u^2(\varepsilon_{\mathrm{align}})+u^2(\varepsilon_{\mathrm{fix}})\end{array}}, \quad (1)$$

with

k coverage factor, usually $k = 2$,
$\varepsilon_{\mathrm{cal}}$ deviation of calibration,
ε_α deviation of CTE,
ε_{t} deviation of temperature measurement,
$\varepsilon_{\mathrm{align}}$ deviation caused to alignment,
$\varepsilon_{\mathrm{fix}}$ deviation caused to fixing.

The uncertainties of calibration $u(\varepsilon_{\mathrm{cal}})$ are given in the calibration certificates. The actual uncertainties of the standards used are stated already in chapter 3 and 4.

The CTE of the standards used are either calibrated or specified to be nearly zero. The calibration uncertainty of CTE of a steel gauge block of 500 mm in length amounts to $0.07\cdot10^{-6}$ K^{-1} ($k = 2$). The deviations from zero-CTE for Zerodur® or ZeroCera™ are specified to be less than $0.02\cdot10^{-6}$ K^{-1}. With a typical temperature deviation $|t - 20\ °\mathrm{C}| \leq 0.1$ K the resulting uncertainty contribution for the steel gauge block of 500 mm amounts to $u(\varepsilon_\alpha) \approx 2$ nm and is, therefore, negligible.

The uncertainty of temperature measurement depends on the (uncorrected) systematic deviation of the sensors at calibration with Pt25 (< 0.02 K), the uncertainty of calibration (≈ 0.01 K) and, essentially, on the thermal coupling between the standard and the sensor which is estimated to ± 0.025 K with an rectangular distribution. This results in an standard uncertainty of temperature measurement of 0.026 K and, finally, for the steel gauge blocks in a length measurement uncertainty $u(\varepsilon_{\mathrm{t}}) \approx 0.3$ µm/m, which is the main contribution to the test uncertainty. For the standards made of Zerodur® or ZeroCera™ this influence is negligible.

Misalignment results in a cosine error as outlined in chapter 4. The deviation caused by fixing was estimated by an experiment in which a 700 mm gauge block of ZeroCera™ was repeated fixed with different clamping forces in any possible orientation. The variation in length found out was less than 0.02 µm. Both influences may be neglected in this context.

The test uncertainty for the steel gauge blocks calibrated by comparison as well as for the steel step gauge amounts to $U(E) = 0.05$ µm + 0.65 µm/m, and for the steel gauge blocks calibrated by interferometry to $U(E) = 0.03$ µm + 0.6 µm/m, respectively, each $k = 2$. For the standards made of Zerodur® and ZeroCera™ it is assumed that $U(E) \approx 2\cdot u(\varepsilon_{\mathrm{cal}})$.

7. Summary and outlook

The traceabilty of length measurements with an ultra-precision CMM XENOS was investigated in PTB using different standards. Gauge blocks and step gauges of different materials, such as steel, ZeroCera™, and Zerodur® were used. The test uncertainty according to ISO / TS 23165 [4] was estimated. Some specific influences were treated for the measurement with gauge blocks.

All results are clearly within the specified maximum permissible error considering the respective test uncertainty. The test uncertainty for standards made of steel is relative large due to the uncertainty contribution of temperature measurement for length correction to 20 °C.

The issue of forthcoming investigations are tests with gauge blocks and step gauges in 3D-orientation and, moreover, tests with 2D-standards, such as hole plates and ball plates. In combination with the results obtained up to now these investigations shall provide a data base to better correct the residual errors of the XENOS, e.g. the residual error from squareness.

References

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