XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

EXPERIMENTAL ANALYSIS OF UNCERTAINTY OF SQUARENESS CALIBRATION ON A CO-ORDINATE MEASURING MACHINE

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Abstract – Co-ordinate measuring machines (CMMs) are often used for calibrating different kinds of squares. A procedure for calibrating squares on the CMM Zeiss UMC 850 was developed in our laboratory to cover primarily industrial needs. The uncertainty analysis that was performed for this procedure is introduced in the article. The most important uncertainty contributions were evaluated experimentally. Many experiments were also performed in order to find the most appropriate calibration position in the CMMs measurement space. About 2000 measurement points were taken in order to get reliable results for uncertainty components. The analysis results expressed as the best measurement capability were checked by participation in the Euromet 570 project, which has not been finished yet. The current value of the best measurement capability is 0,9 arc sec.

Keywords: squareness, uncertainty, calibration

1. INTRODUCTION

Squares of different shapes and sizes made of different materials like granite, steel and ceramics are used in laboratories and in industry for materializing squareness [1]. Uncertainty of calibration of a square represents a limitation for its use. Since the uncertainty mostly depends on the measurement instrument and the procedure used for calibration, it is very important how to calibrate squares with different requirements regarding accuracy.

In our laboratory we mostly calibrate squares for industrial use and squares for checking axes squareness on CMMs. Considering the required limit uncertainties we decided to develop a procedure for calibrating squares on our CMM Zeiss UMC 850 [2]. The uncertainty analysis has shown that this procedure can cover all the current needs. It is important to mention at this place that similar methods have already been developed in different laboratories. However, an original approach for evaluating uncertainty regarding the measuring position was developed and validated for this procedure.

2. CALIBRATION PROCEDURE

The square is fixed on the fixing plate in the predefined position in X-Y plane of the CMM. The shorter edge should be parallel to X axes.

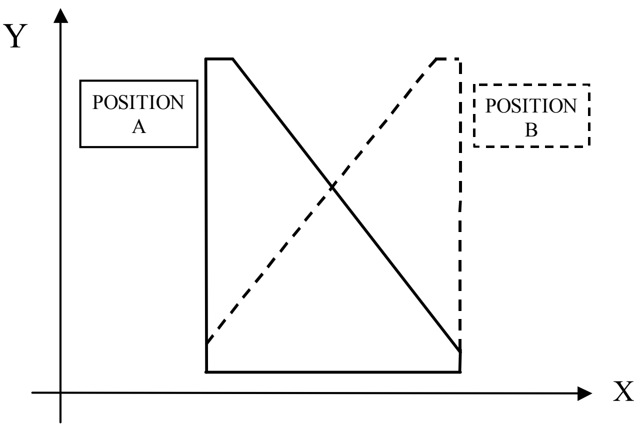

Fig. 1. Square measurement positions

This position was defined by experimental evaluation of measurement results. Fifteen different positions were tested (5 in X-Y plane, 5 in X-Z plane and 5 in Y-Z plane). In each of these positions we have tested 2 reversal positions regarding the reference and the measured edge. The tests were performed several times in different environmental conditions in order to extract systematic influence of the square position.

The criterion for the selection of proper position was repeatability of the results in single points. The stability of moving elements and the probing system were tested in this way. Every edge was probed in 50 predefined points. The calculated repeatability results for three positions in each co-ordinate plane are presented in Table I.

TABLE I. Repeatabilities of angle measurements in different locations of the 3D measurement space

Location	Plane	Repeatability in arc. sec.
1	.	1,2
2	X-Y	0,8
3		0,6
6		1,7
7	X-Z	2,4
8		2,8
11		1,8
12	Y-Z	1,4
13		1,9

Location 3 from Table I was chosen as a calibration location. The intersection corner of measured lines (the lower left corner of position A in Fig. 1) has the co-ordinates X = 200 mm, Y = -950 mm and Z = -400 mm in the CMM's co-ordinate system. Those co-ordinates do not need to be set very precisely.

2.1. Measurement of deviations

The square is mechanically adjusted along the shorter edge in the position A (Fig. 1) before measurement. The deviation of final adjustment (difference of Y co-ordinates of two probed points) should not exceed 0,3 μm. When the square is adjusted, a straight line is probed on the longer edge. Starting and ending probing points should be 30 mm apart from the edges of the square. The measurement is repeated three times. After that the measurement procedure is repeated in the position B. New mechanical adjustment is necessary when turning the square for 180° in position B. It is very important that the reference (shorter) line is on the same location as in the position A. It is also important that the probing points in position B has the same co-ordinates along probed lines as in the position B. Positions of probing points (co-ordinates X and Z for the shorter line and co-ordinates Y and Z for the longer line) are preprogrammed.

Squareness deviation between the CMM's X and Y guides is eliminated from the final result by turning the square from position A to B. Since the guides also have some straightness deviations, the squareness of different segments of X axis to Y axis may differ. Zherefore it is very important that the square is put exactly into the same segment of X axis after being turned into position B.

2.2. Calculation of measurement results

Arithmetic means of the angles of measured lines (from three measurements) in positions A and B are calculated. The results are recorded into the table of measurement certificate. Standard deviation of these results comprises the repeatability of the CMM as well as the quality of the square edges. If the result is negative, the straight line is in second quadrant. This means that the angle of the square is greater than 90° in position A and smaller than 90° in position B. Square angle deviation from 90° is calculated by the equation:

$$\Delta\alpha_{\text{square}} = \frac{\alpha(B) - \alpha(A)}{2}\,. \tag{1}$$

where:

$\alpha(A)$ - angle in position A indicated by the CMM

$\alpha(B)$ - angle in position B indicated by the CMM

Indicated angles $\alpha(A)$ and $\alpha(B)$ comprise angular deviation of the asquare and the CMM measurement deviation (error). In position A the CMM error is added to the angular deviation of the square, while in position B it is subtracted from the angular deviation of the square, as explained in Fig. 2. It is very important to consider the way the CMM express measured angle (+ /-) in order to get right sense of the square angle deviation. The case in Fig. 2 is drawn for the measuring position X-Y (Fig. 1).

Equation (1) is used for establishing the mathematical model of measurement in the uncertainty evaluation.

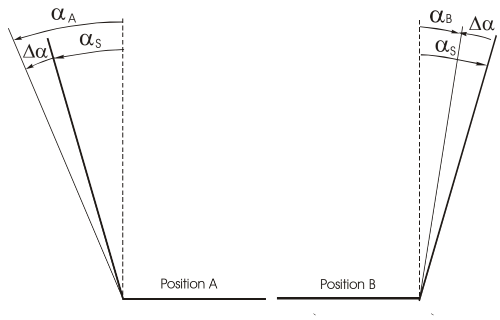

Fig. 2. Indicated angles (α_A, α_B), square angle (α_s) and CMM error ($\Delta\alpha$)

3. UNCERTAINTY OF MEASUREMENT

3.1. Mathematical model of measurement

Angular deviation $\Delta\alpha_{\text{square}}$ (calibration result) is given by the equation:

$$\Delta\alpha_{\text{square}} = \frac{(\alpha_{p2} + \alpha_{p1})_B - (\alpha_{p2} + \alpha_{p1})_A}{2}\,. \tag{2}$$

where:

α_{p2} - measured angle between the longer square edge and Y axis of the CMM (measurement result)

α_{p1} - actual angle between the shorter square edge and X axis of the CMM (supposed to be 0, because the square is mechanically adjusted)

Indexes A in B define measurement position (see Fig. 1)

Thermal deviations are not considered in the above equation because their influence on angular measurement is not significant. It is supposed that the square material is isotropic and that the shape is not changed when the temperature deviates.

3.2. Standard uncertainties of the input values

In (1) we can see that there are 4 input values in this measurement. Equation for calculating combined stabndard uncertainty in [3] gets in our case the following form:

$$u^2(\alpha_{\text{kotnika}}) = c_{\alpha p2B}{}^2 u^2(\alpha_{p2B}) + c_{\alpha p1B}{}^2 u^2(\alpha_{p1B}) + \\ + c_{\alpha p2A}{}^2 u^2(\alpha_{p2A}) + c_{\alpha p1A}{}^2 u^2(\alpha_{p1A}) \tag{3}$$

where c_i are partial derivatives of the function (2):

$c_{\alpha p2B} = \partial f / \partial \alpha_{p2B} = 0{,}5$

$c_{\alpha p1B} = \partial f / \partial \alpha_{p1B} = 0{,}5$

$c_{\alpha p2A} = \partial f / \partial \alpha_{p2A} = 0{,}5$

$c_{\alpha p1A} = \partial f / \partial \alpha_{p1A} = 0{,}5$

Standard uncertainties of influence (input) values are calculated (estimated) from experimental measurements in LTM on CMM UMC 850 as standard deviations.

However, the standard uncertainties of input values in point A are evaluated in the same way as in point B. Therefore it is supposed that the values of the uncertainties in point A are equal to uncertainties in point B (*u*(α_{p2B}) = *u*(α_{p2A}) and *u*(α_{p1B}) = *u*(α_{p1A})). Consequently, we deal only with two uncertainty components *u*(α_{p2}) *and u*(α_{p1}), but the first one is influenced by two CMM geometric uncertainties.

TABLE II. Uncertainty components

Uncertainty component	Influences	Final expression
$u(\alpha_{p2})$	uncertainty of probing and calculating the line *u(t)*	$u(\alpha_{p2}) = \sqrt{u(t)^2 + u(s)^2}$
	uncertainty of squareness between x and y axis *u(s)*	
$u(\alpha_{p1})$	uncertainty of mechanical adjustment *u(m)*	$u(\alpha_{p1}) = u(m)$

All uncertainty components are of type A [3]. The uncertainties of probing (influence of the probing system) and calculating (calculation algorithm) are joint, since the calculating algorithm is not exactly known and is therefore hard to evaluate the uncertainty.

4. EXPERIMENTAL ANALYSIS OF STANDARD UNCERTAINTY

All standard uncertainties of input values (Table II) were evaluated by statistical analysis of measurement results [4].

4.1. Standard uncertainty $u(\alpha_{p2})$

Standard uncertainty for probing and calculation of the line was evaluated as a standard deviation of thirty measurements on one line in a fixed position. Twenty measurement points were taken along the measured line. The positions of measurement points were the same (within certain positioning uncertainty) in all measurements in order to eliminate the influence of the square shape deviations. A line angle was calculated after each measurement of the edge in 20 points. The standard deviation from 30 line angle calculations (Fig. 3) was: $s = u_t = 0{,}15$ arc. sec..

Standard uncertainty of squareness between X and Y axes was evaluated as a standard deviation of thirty measurements on the same square in the same measurement line in different positions of the square. The square was moved after each line measurement (in 20 points) in X axis for about 10 mm and the measurement was repeated in the next position in the same points as in previous measurement. The standard deviation from 30 line angle measurements (Fig. 4) was: $s = u_t = 0{,}26$ arc. sec..

Considering the equation in Table II, the standard uncertainty of the angle of line p_2 is: $u(p_2) = 0{,}3$ arc. sec..

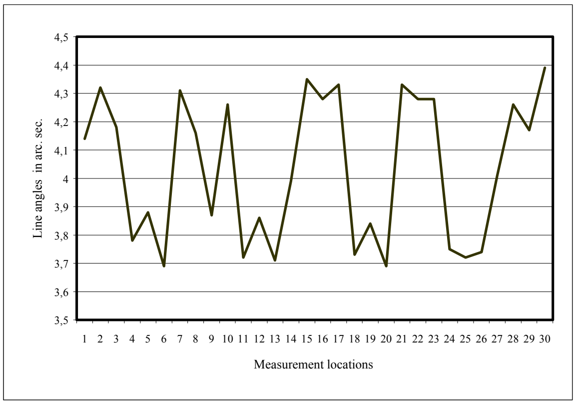

Fig. 4. Results of 30 line angle measurements on different locations

The results shown in Fig. 3 and Fig. 4 show random behaviour. No trends or correlations can be observed between different measurements. An obvious conclusion is that the main influence on measurement deviations is caused by repeatability of the linear measurement system and the probing system.

4.2. Standard uncertainty $u(\alpha_{p1})$

Standard uncertainty was evaluated as a standard deviation of thirty line angle measurements on the adjusted square edge. The lines were calculated from 20 points. Such experiment was performed in different measurement positions. The standard deviation from 30 line measurements was: $s = u_t = 0{,}51$ arc. sec..

Standard deviations were very similar on different positions. Worst case was used as an uncertainty component. Results of this worst case are shown in Fig. 5. As in both measurements on the long edge, no systematic behaviour of the results can be observed here. Even when the CMM was turned off and on again, no systematic deviations could be found. Comparison of the results on Fig. 5 with those on Fig. 3 shows better repeatability of the probing system in X than in Y direction. The same conclusion has been made during number of calibrations of the probing system on short gauge blocks. The test of the algorytm for calculating the line through 30 points using least square method has shown negligible influence on the result.

Fig. 3. Results of 30 line angle measurements on fixed location

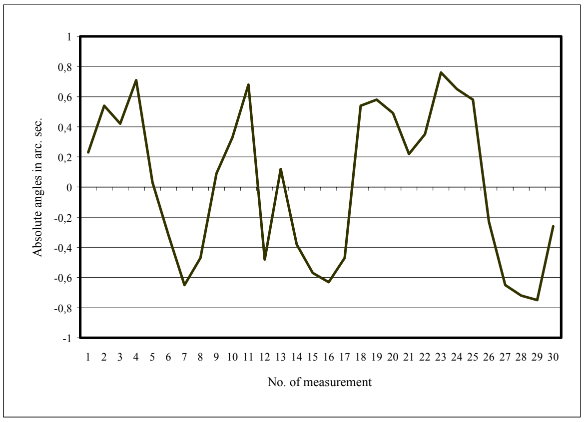

Fig. 5. Results of 30 angle measurements on the short line

TABLE III: Uncertainty budget

Value X_i	Standard uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
α_{p2B}	0,30 arc. sec.	normal	0,5	0,15 arc. sec.
α_{p1B}	0,51 arc. sec.	normal	0,5	0,26 arc. sec.
α_{p2A}	0,30 arc. sec.	normal	0,5	0,15 arc. sec.
α_{p1A}	0,51 arc. sec.	normal	0,5	0,26 arc. sec.
			Total:	0,42 arc. sec.

4.3. Combined standard uncertainty

The calculation of the combined standard uncertainty is presented in Table III. Normal distribution was taken for the experimental results although the results have shown very random behaviour. Total (combined) uncertainty was calculated using equation (3).

5. EXPANDED UNCERTAINTY

Coverage factor [3] k=2 was used for the calculation of the expanded uncertainty. This factor is recommended by EAL in order to assure 95 % level of confidence to the clients. It is rounded up to:

$$U = 0{,}9 \text{ arc. sec.}$$

5. INFLUENCE OF THE CALIBRATED OBJECT

The uncertainty budget presented in chapter 4 does not include influence of the square shape. It is evaluated for an ideal case and can be also expressed as the best measurement capability of the laboratory respective to the CMM, environmental conditions and the calibration procedure. However, in reality we deal with very different artefacts. Some of them have damaged surfaces or are made in low quality. It is not possible to state the above uncertainty (U = 0,9 arc. sec.) for such bad squares. Therefore, the quality of both measured edges is checked before each measurement. The checking procedure is not as detailed as the procedure described in chapter 4. A quick check of repeatability is made in 10 points for each measured edge. Each point is probed 4 times. Repeatability is evaluated by standard uncertainty. If this value is greater than the predefined value (see the above description), this value is taken for the uncertainty evaluation. Special excel programme was written and evaluated for such cases.

6. CONCLUSIONS

The analysis has shown that the uncertainty is strongest influenced by the repeatability of the probing system and by the X guide deformations. This deformation causes changes of squareness between X and Y axes while moving the probe along X axis. Therefore it is very important how to locate the square before calibration. Since it is expected that these two parameters are changing with time, regular tests are planned to be performed every year and of course after each calibration and any adjustment made on the CMM. Current results show sufficient accuracy of the procedure for our (current) customers. It is important to mention that the results were rounded up and that worst cases of experimental results were taken as uncertainty components in order to be on "the safe side". Our opinion is that the uncertainty could be even lower for special calibration locations and by applying advanced experimental evaluation. But first we will wait for the Euromet interlaboratory comparison results, which will indicate the correctness of the uncertainty evaluation in the best possible way.

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