

# TEMPERATURE COMPENSATION DURING CMM INSPECTION

***E. Ratajczyk, M. Dobosz***

Institute of Metrology and Measuring Systems, Faculty of Mechatronics  
Warsaw University of Technology, Chodkiewicza 8 Str. 02-525 Warsaw, Poland

*Abstract: Influence of temperature on CMM inspection results by means of ball-plate or hole-plate is presented. Errors of indication of a CMM for length measurement are analyzed. Internal (by machine hardware and software) and external (by additional temperature sensors and software) methods of compensation are compared with measurement without compensation. Implications for industrial practice are formulated.*

*Keywords: Coordinate Measuring Machines (CMM), process calibration of CMM, ball-plate*

## 1 INTRODUCTION

Ball-plates and hole-plates standards are more and more often used for accuracy inspection of coordinate measuring machines (CMMs) [1]. They allow evaluate all 21 types of geometrical errors of a CMM [2]. In practice, most often and first of all, indication of a CMM for a length measurement are tested. The errors can be determined with end standards such as gauge blocks normal and stepped as well [3]. Recently, ball- or hole-plates, are more and more often used. They allow to estimate CMM accuracy of a length measurement, especially in acceptance procedure or in periodical inspection [3]. In calibration process, the information are obtained concerning the degree of conformity of obtained results with respect to permissible errors determined by lines of a template. The lines characterise permissible errors of indications in length measurements,  $E$ , whose values are established for a given type of an investigated machine. In practice calibration software allows to obtain numerical data characterising the accuracy of the investigated machine and their graphical illustration with respect to a template lines as well. Some software's enable to obtain so-called error maps showing an arrangement of experimental points on a background of 25 nominal points of a ball-plate.

## 2 MEASURING PROCEDURES AND SOFTWARES

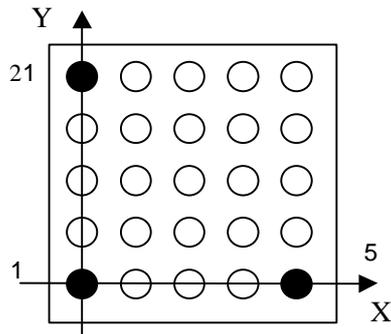
The accuracy of CMMs was tested by means of plate standards. We used first our own software based on Excel (WMP.xls programme [4]) and more recently UX 15 programme integrated with the universal UMESS UX programme of Zeiss working in the UNIX operating system and GUK-K programme elaborated by German Bureau ITI GmbH [5].

Above programmes realise at first measuring procedures to estimate an accuracy of the CMM's probing system (contact system or probe) with the use of a master ball (sphere) or master ring. Next the procedure of evaluation the machine accuracy by using a ball- or hole-plate is performed.

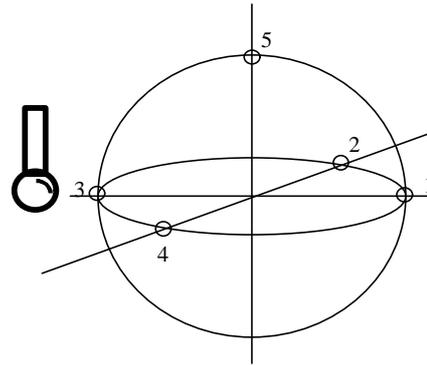
The accuracy of the CMM probe with the use of master sphere is performed throughout measurement at nine points each repeated three times in the case of UX 15 programme and at seventeen points for GUK-K programme. The studies of the CMM probe system with the use of the ring gauge is also based on triple measurements but they need twelve points. In evaluation of probing system results two coefficients are used (denoted by  $U$  in UX 15 programme and by  $M$  in GUK-K programme). One of the coefficients defines the uncertainty of the contact system sampling and the other estimates diameter deviations of the master. Passing to the next steps of studies i.e. to an investigation of the machine accuracy is conditioned by obtaining the probing system results on an appropriate level (the coefficient values should not exceed 1,0), otherwise the CNC programme will be automatically stopped (for UX 15 software), precluding further measurements.

Measurements of the plate master are preceded by determination of the coordinate system of the master through measurements of ball denoted as 1, 5 and 21 (Fig. 1). Usually all the chosen balls are measured automatically. The first three balls used for determination of the plate coordinate system are measured again at the end, in order to check whether or not the master has been shifted. Each ball of the standard is measured at five points as it is shown in Fig. 2. The ball plate is measured from both sides in, at least, three locations, i.e. when the master is placed parallel to the CMM table (XY plane),

parallel to the XZ plane and parallel to the YZ plane. Fig 3 shows the measurements in XY and XZ planes during checking the PRISMO VAST machine.

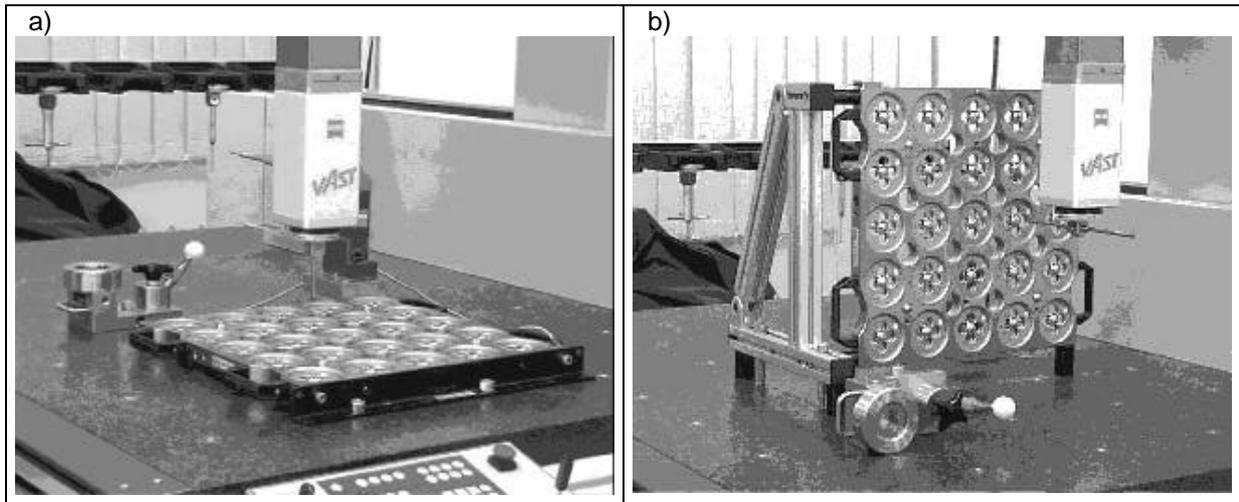


**Figure 1.** Balls used in determination of coordinate system of plate standard.



**Figure 2.** Recommended distribution of measuring points on master ball.

The aim of the plate standard measurements is to estimate the accuracy of a distance measurement. During standard assessment according to VDI/VDE 2617, Blatt 5 every possible distances between all ball centres are determined it means e.g. for 25 balls 300 distances are determined. Each distance calculated from the positions of two ball centres is compared with the calibration value and the difference between them is taken as a distance measurement deviation. The number of exceedings of the acceptable value of measurement uncertainty is given in a certificate and should be equal to zero.



**Figure 3.** The location of ball-plate during inspection of CMM a) in the XY plane, b) in the XZ plane.

The M (or U) coefficient estimating the uncertainty of the distance measurement is determined as the highest ratio of the measured deviation and permissible deviations for a given distance. It is also given in a certificate. The value of the coefficient should not exceed 1.0.

$$M = \max \frac{|L_z - L_{nom}|}{U_3(L_{nom})} \quad \frac{\dot{m}}{\dot{m}} \quad (1)$$

where:

$L_z$  – measured value between two balls in mm,

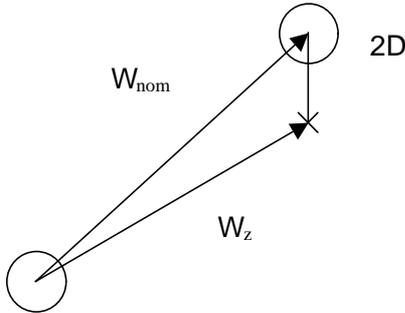
$L_{nom}$  – nominal value between two balls in mm,

$U_3$  – three-dimensional uncertainty of a machine according to eq.2.

$$U_3(L_{nom}) = A + \frac{L_{nom}}{K}, \quad \text{im} \quad (2)$$

The results from two the tested programmes are very similar. The graph of measurement errors with respect to template lines representing the admissible error levels appears in both the programmes.

GUK-K software introduces additionally two-dimensional deviation (designated as 2D) of position with respect to the ball number 1. It is described by the below given relationship



$$2D = \max |W_z - W_{nom}| \quad \text{im} \quad (3)$$

where:

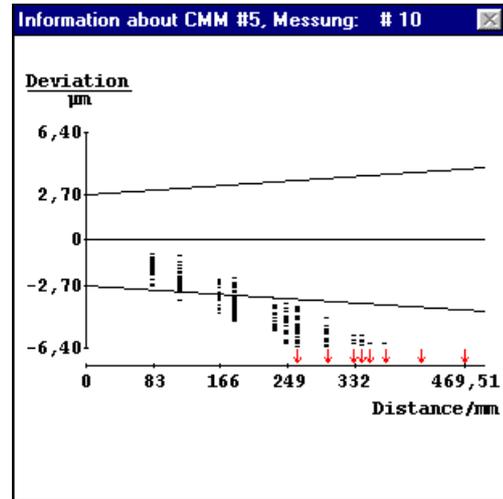
- $W_z$  – measured coordinate of a ball,
- $W_{nom}$  – nominal coordiante from calibration data.

ball number 1

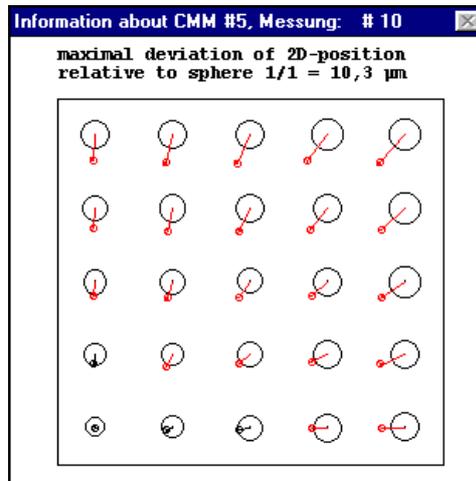
a)

| Information about CMM #5, Messung: # 10         |                          |                         |                 |
|---|--------------------------|-------------------------|-----------------|
| <b>Rating</b>                                   |                          | <b>Numb. of exceed.</b> | <b>M-factor</b> |
| Ring gauge                                      | Span                     | 0                       | ,43             |
| 3 meas per 12 pts                               | Diamet                   | 0                       | ,21             |
| Sphere not measured                             | Span                     |                         |                 |
|   | Diamet                   |                         |                 |
| <b>Diff. pos. of sphere plate 1.-2.meas./mm</b> |                          |                         |                 |
| sphere  | x                        | y                       | z               |
| 1/1   | ,00000                   | -,00040                 | -,00020         |
| 1/5   | ,00030                   | -,00020                 | ,00000          |
| 5/1   | ,00010                   | -,00020                 | -,00010         |
| <b>Evaluation: Distance measurement</b>         |                          |                         |                 |
| number of distances                             | number of exceed. limit. | M-factor                |                 |
| 300   | 205                      | 2,42                    |                 |

b)



c)



**Figure 4.** The indication errors of the PRISMO VAST CMM at 18,03°C with ball-plate situated in the XY plane without compensation: a) fragment of report, b) graph of errors with respect to template lines, c) 2D map of deviations of balls centres relative to nominal positions.

## 2 INFLUENCE OF TEMPERATURE ON CMM CALIBRATION

Ball - plate standard is often used for CMM testing in industrial environment, where the temperature control is not perfect. Thus the special care and effective means should be applied to minimise environment influence on the CMM testing procedure. It is especially important when the older type of machine is checked because the internal temperature compensation has not been used yet. The authors together with their co-workers undertook the experimental studies in order to elucidate the efficiency of various temperature compensation procedures.

The experiments have been performed with the use of the medium accuracy machine KEMCO E 400 manufactured by Keeling Company (England) and the high accuracy machine PRISMO VAST manufactured by Zeiss (Germany). Both the machines were checked by means of the ball-plate MB400 type B manufactured by Retter (Germany) and by the hole-plate manufactured by IMMS (Warsaw University of Technology).

Temperature was changed step by step by 2 degrees from 16°C to 26°C. Experiments were started, for every given temperature, after stabilisation for 24 hrs. Two series of experiments were performed without and with temperature compensation. Temperature gradient within the machine space during one measuring cycle did not exceed 0,1°C. Time of measurements for one location of master was 15 min.

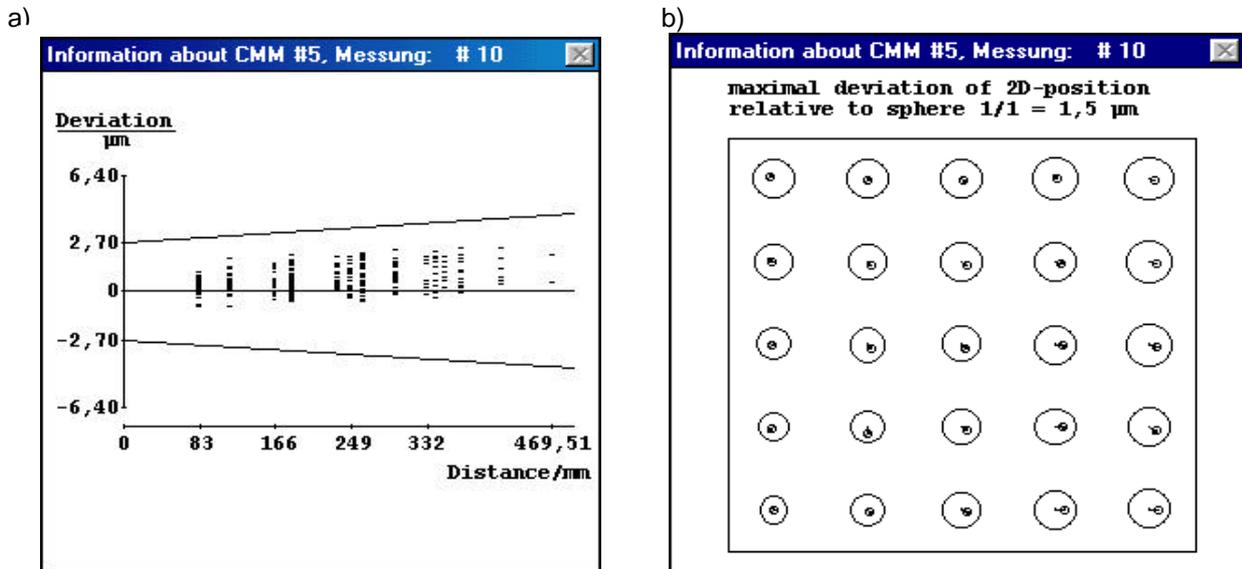
The effectiveness of the temperature compensation by GUK-K software has been also tested. The exemplary results of tests of a ball master situated on a machine table in the XY plane are illustrated in Fig. 4 and 5.

Temperature change by two degrees causes, as can be seen from Fig. 4c, the rise of the length errors by about  $2D = -10,3 \mu\text{m}$  and the M coefficient achieves value as high as 2,42. Within the entire range of investigated temperatures i.e. from 16°C to 27°C the error values expressed as 2D deviation change from  $-19,7 \mu\text{m}$  at 16,1°C to  $36,3 \mu\text{m}$  at 27,2°C.

The M coefficient in this temperature range changes from 0,71 to 9,07. The high values of errors and M coefficient make the measurement without temperature compensation quite unusefull.

The effectiveness of the temperature compensation by GUK-K software is shown in Fig.5.

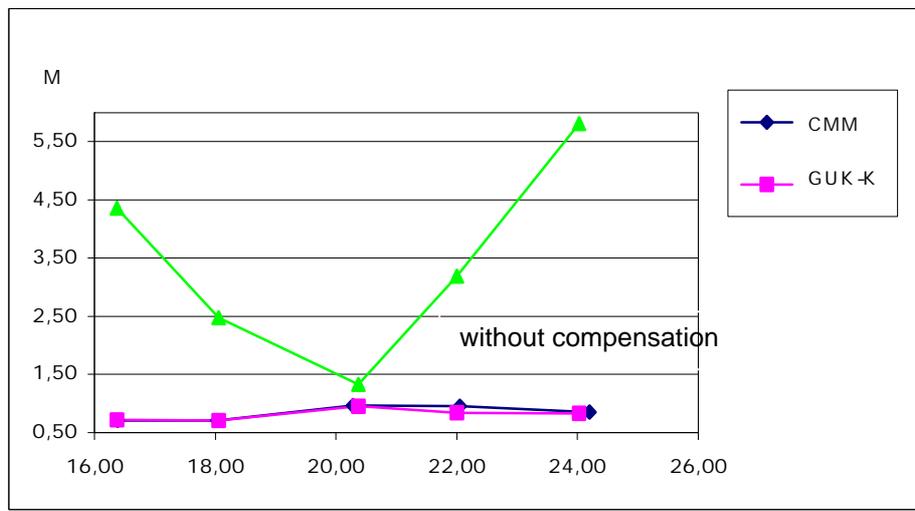
As a result of the compensation the error value (at 18,03°C) drops from  $-10,5 \mu\text{m}$  to  $1,5 \mu\text{m}$  and M coefficient from 2,42 to 0,59. Also in other temperature ranges the computer assisted temperature compensation is very effective. This allows checking CMMs in industrial conditions provided the temperature and thermal expansion coefficients of masters are known.



**Figure 5.** The indication errors of the PRISMO VAST CMM at 18,03°C with external temperature compensation by GUK-K software: a) graph of errors with respect to template lines, b) 2D map of errors deviations.

The efficiency of different method of temperature compensation is shown in Fig. 6. The changes of M coefficient, defined as a ratio of the measurement error to the permissible value of the error, are presented as function of environment temperature. Triangles represent the results obtained without

temperature compensation, diamonds with the internal temperature compensation available in the PRISMO VAST model of machine and squares with the external temperature compensation by GUK-K software.



**Figure 6.** The efficiency of temperature compensation: CMM compensation, GUK-K-software compensation.

The efficiency of temperature compensation by using GUK-K software is comparable with the efficiency obtained with the internal compensation of the PRISMO VAST machine. This can be seen from the data presented in Table 1 and 2. The results concern measurements of the plate in XY position. In the case of GUK-K software the environment temperature value was introduced into the software, and in the case of internal compensation, temperature values were automatically transferred from the gauges located on the master and in the measuring space of the machine. In both the cases the values of thermal expansion coefficient of the master were introduced.

**Table 1.** The results of measurements with external temperature compensation by GUK-K software.

|    |                 |                    |      |      |      |      |      |
|----|-----------------|--------------------|------|------|------|------|------|
| XY | Temp. °C        | 16,1               | 18,1 | 20,5 | 22,3 | 24,0 | 27,2 |
|    | s <sub>T</sub>  | ± (0,02 ÷ 0,06) °C |      |      |      |      |      |
|    | Coeff. M        | 0,66               | 0,59 | 0,66 | 0,60 | 0,76 | 0,61 |
|    | s <sub>M</sub>  | ± (0,02 ÷ 0,06)    |      |      |      |      |      |
|    | Dev. 2D µm      | 1,8                | 1,5  | 2,2  | 2,1  | 2,0  | 2,5  |
|    | s <sub>2D</sub> | ± (0,05 ÷ 0,5) µm  |      |      |      |      |      |

**Table 2.** The results of measurements with internal temperature compensation by PRISMO VAST.

|    |                 |                    |      |      |      |      |      |
|----|-----------------|--------------------|------|------|------|------|------|
| XY | Temp. °C        | 16,1               | 17,4 | 20,5 | 22,1 | 23,9 | 27,1 |
|    | s <sub>T</sub>  | ± (0,01 ÷ 0,05) °C |      |      |      |      |      |
|    | Coeff. M        | 0,67               | 0,61 | 0,65 | 0,58 | 0,71 | 0,53 |
|    | s <sub>M</sub>  | ± (0,011 ÷ 0,06)   |      |      |      |      |      |
|    | Dev. 2D µm      | 1,8                | 1,9  | 1,9  | 2,2  | 2,0  | 2,0  |
|    | s <sub>2D</sub> | ± (0,06 ÷ 0,37) µm |      |      |      |      |      |

The values of M coefficient in both cases are small. The differences do not exceed the value of 0,08. In most the cases they do not exceed 0,02 and lie within the mean square deviation  $s_M \leq 0,06$ . The 2D deviation values are also comparable. In the tables, mean square errors of measurements of temperature,  $s_T$ , 2D deviation,  $s_{2D}$ , and M coefficient,  $s_M$ , are given as well.

In order to estimate the significance of the differences, statistical test based on commercially available software (STATGRAPHICS) was applied. Two-Sample Comparison was performed,

analysing differences between means  $\mu_1$  and  $\mu_2$  obtained for two distributions.  $\sigma_1^2$  and  $\sigma_2^2$  variances for both distributions were compared by Fisher-Snedecor test and variances equality was confirmed with 0.05 significance level. The analysis allowed to state that, there are not observed statistically significant differences between the efficiency of temperature compensation with the two investigated methods.

Moreover, some experiments were done on the influence of the measuring mode (CNC or Manual) on the accuracy of calibration process. One can presume that the CNC mode, because of shorter time of a measurement, the same speed of the gauge approach to the measured surface and unequivocal position of probing points, should be more accurate one. It was confirmed that the error of estimation of 2D deviations is five times larger in the Manual mode than in CNC and the spread of M coefficient four times larger.

### 3 SUMMARY

Some of the results of the study of accuracy of PRISMO VASTY CMM have been presented. The ball-plate MB 400 type B master produced by Retter (Germany) and GUK-K software developed by ITI GmbH (Germany) were used. Some of the experiments were performed with the hole-plate master manufactured at the Institute of Metrology and Measuring Systems of Warsaw University of Technology using GUK-K software and UX 15 software integrated with the programme of UMESS UX by Zeiss. Computer assisted temperature compensation is very effective and allows to calibrate CMM's under industrial conditions.

However, the evaluation of length errors with the use of plate standards and mentioned software is of qualitative character because it gives the machine assessment through the values of coefficients and the error level is referred to the permissible level given by template lines. It is not possible to estimate errors for individual axes and also the requirements of En ISO [3] such as error inspection at seven different locations of the master are not fulfilled.

### REFERENCES

- [1] T. Pfeifer, *Koordinaten Messtechnik für die Qualitätssicherung*. VDI Verlag, Düsseldorf 1992, 282p.
- [2] E. Trapet., F. Wäldele.: A reference object based method to determine the parametric error components of coordinate measuring machines and machine tools. *Measurement* Vol 9, No 1, Jan-Mar 1991, p.17-22.
- [3] EN-ISO 10360-2. *Coordinate metrology – Part 2: Performance assessment of coordinate measuring machines*, 1995.
- [4] E. Ratajczyk, The study of Accuracy of CMMs with the Plate Master – Procedures and Softwares (in Polish). *Proceeding of the Conference MWK'97* (Zegrze k/Warszawy, Poland, 19-22 may 1997), v.3,p.175-182.
- [5] E. Ratajczyk, Methods of checking on the accuracy of coordinate measuring machine. Procedures and programs for determining the errors of length measurements by means of plate master. Part IV. *Mechanik* 11 (1999), p.757-765.
- [6] H.H Plath, Checking Accuracy of 3D-CMMM by Use of Different Types of Calibrated Artifacts – a Comparative Report of Industrial Experiences. *Proceedings First International Work-shop on Coordinate Measuring Machine Calibration*. Prague (Czech Republic), June 1-2, 1999. p.36-42.

**AUTHORS:** Prof. Dr. Eng. Eugeniusz RATAJCZYK and Dr. Hab. Eng. Marek DOBOSZ, Institute of Metrology and Measuring Systems. Faculty of Mechatronics, Warsaw University of Technology, Chodkiewicza 8 str. 02-525 Warszawa, Poland, Phone (+48 22) 660 83 47, Fax (+48 22)949 99 36  
E-mail:dean@mp.pw.edu.pl