Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 13 (2017) 558–564

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

Manufacturing Engineering Society International Conference 2017, MESIC 2017, 28-30 June 2017, Vigo (Pontevedra), Spain

Evaluation of repeatability and reproducibility of CMM equipment

D. Kubátová*, M. Melichar, J. Kutlwašer

University of West Bohemia in Pilsen, Univerzitní 8, Plzeň 301 00, Czech Republic

Abstract

Requirements for measurement accuracy are constantly increasing, as are the requirements for evaluating quantifiable characteristics measurement systems. Among engineering fields, the highest requirements are placed on measuring systems in the automotive and aerospace industries. Specialized automatic control and measurement devices that evaluate specific parameters of components are being increasingly used in high-volume mass production. The issue of variation and uniformity of measurement results within the supply chain of today is an everyday topic of discussion among quality assurance representatives of both parties. The article describes an experiment, in which an experimental test pattern was gradually measured using CMM in a controlled environment of metrology laboratory and then the test part was measured by a workshop CMM, which was equipped with temperature compensation system, in an uncontrolled environment. After securing a statistically relevant amount of data, both measured files were analyzed to verify repeatability and reproducibility, the parameters which are crucial in terms of production practice.

Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.

Keywords: CMM; repeatability and reproducibility; evaluation of measuring instruments

1. Introduction

In today's industrial production, coordinate measuring machines (CMM) are one of the cornerstones of inspection in most enterprises, being used throughout the manufacturing process. Without a CMM machine, it is difficult to

---

* Corresponding author. Tel.: + 420 721 817 819
E-mail address: kubatova@rti.zcu.cz

2351-9789 © 2017 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the Manufacturing Engineering Society International Conference 2017.
10.1016/j.promfg.2017.09.091

imagine the evaluation of measuring parameters related to simple dimension measurement based on drawings, not to mention more complicated and complex endeavors, such as evaluation of form, location and position deviations or the offset of certain points from a 3D model.

Essentially, 3D measuring machines (CMM) are sophisticated units which are intended to be operated mainly in the controlled environment of a metrology laboratory. As set forth in ČSN 17025:2005, controlled environment is characterized by a temperature of 20±2°C and a temperature gradient of 1°C. Such a stable temperature of the machine, the environment and the specimen is a key underlying parameter of methodologically correct measurement. Under these controlled conditions, CMMs can provide an accuracy of down to 0.5+L/500µm, which is more than sufficient (considering a general-purpose machine) for a majority of commercial technical applications.

The above-described process suffers from a fundamental weakness: the distance between the place of checking and the place of manufacture (production hall). Practice has shown that the most effective approach is to check the product parameters as close as possible to the point where they were created.

For this reason, a number of CMMs with temperature compensation were developed in recent years. This feature is provided by a module which allows high-accuracy measurement to be taken in an uncontrolled environment, such as on the shop floor. A question arises, however: What is the actual accuracy that machines with temperature compensation can provide; and are they a perfect substitute for metrology laboratory conditions?

And for the purposes of comparing the results between individual metrological laboratories or manufacturing plants that use these two different types of equipment, it is important to know the true accuracy that is achieved on individual machines. Whether it is a machine with or without temperature compensations, whether a measurement method is chosen after scanning individual points, as in this article, or whether the dimensioning method is chosen using touch scans.

2. Methodology or Experimental Procedure

2.1 Description of experiments

The goal of this experiment was to determine the accuracy of CMMs with and without temperature compensation. A chosen traceable standard was used – a CMM testing standard (see Fig. 1).

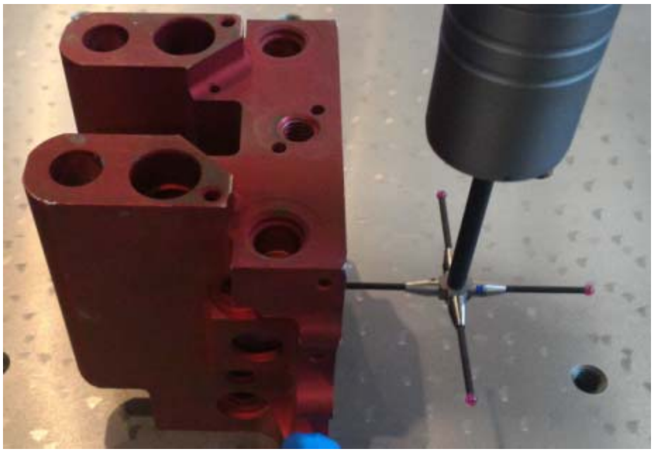

Fig. 1 CMM standard.

The test method involved measurement at multiple points using a fixed probe without indexing in order to maximize the sensing accuracy.

The measurement and data acquisition was carried out by a single operator who operated both CMMs. Operator error was therefore eliminated from the measurement. Measurement runs were repeated. In randomly chosen repeated measurement runs, a set of statistically significant values were obtained and used as input to further evaluation. 25 readings were obtained and statistically verified using the gross error filter μ±3σ.

The environment of the CMM without temperature compensation had a temperature of 20.5°C and a thermal gradient of <1°C per hour.

The experiment was then replicated using a CMM with temperature compensation. The same standard was repeatedly measured in a production hall environment at a temperature of 25°C, without the possibility to determine temperature gradient. Under identical conditions (an equivalent measuring schedule, probe, probe tip, speeds, operator and others), a set of 25 measurement readings has been obtained with subsequent statistical gross error verification ofμ±3σ.

Tab. 1 gives a summary of parameters for the CMM without temperature compensation and for the CMM with temperature compensation.

Table 1 Measurement parameters

	CMM without temperature compensation	CMM with temperature compensation
Dimension under measurement	16.7 mm – inner diameter	16.7 mm – inner diameter
Number of measuring points	8 points	8 points
Measured at depth	-5 mm	-5 mm
Filter employed	Elimination of outliers	Elimination of outliers
Number of operators	1	1
Temperature of environment	20.5°C	25°C

Although they were not the subject of direct observation, deviations of the readings are plotted in Fig.2. This graph is not quite relevant to the comparison of measurement methods, given the fact that the standard changes its shape and dimensions in response to variations in temperature and gradient. The only purpose of the graphical comparison is to provide a rough indication of agreement between values and verification of profiles of readings for both CMMs.

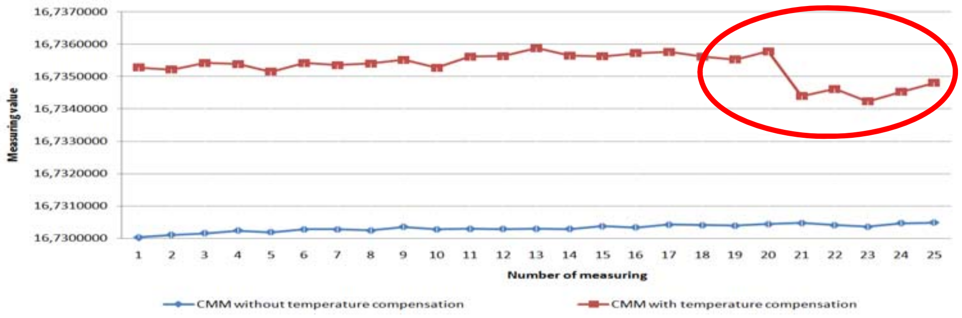

Fig.2. Comparison of readings

The red oval in Fig. 2 indicates an issue which is very likely to occur in the CMM with temperature compensation, due to its placement in a production hall. Here, impurities adhered to the probe tip and distorted the readings.

A different method was chosen for identifying suitable CMM types. Here, both machines were tested with respect to Cg (repeatability) and Cgk (bias) indices. These indices represent a well-know and recognized method of verification of suitability of measuring elements for specific applications.

2.2 Verification procedure

The accuracy of the standard used here is known but it is not of importance to this calculation, and therefore has been neglected. Indices Cg and Cgk were verified for both machines in conjunction with chosen tolerances, as indicated in Table 2.The qualification limit was chosen as Cg, Cgk>1.33. [5]

Table 2 Variation of tolerance

Tolerance width	0.01 /mm/	0.005 /mm/	0.008 /mm/
Upper tolerance limit (USL)	16.74	16.735	16.738
Lower tolerance limit (LSL)	16.73	16.73	16.73
Actual value	16.73	16.73	16.73

The method chosen for calculating the Cg and Cgk parameters was the one developed by Ford company. It involved the strictest statistical conditions, which is useful for evaluating high-accuracy machines, such as CMM machines.

Fig. shows the relationships between capability indices and tolerance. The upper part of the figure shows the tolerance range T of the measurand and its limits LSL and USL. (T = USL - LSL). In evaluating the measuring instrument in this case, only a part of this range is considered, represented in Fig. as 20%, i.e. 0.2T. The values tested here were 10, 20 and 30, which equals the entire permitted range. The bottom of the figure shows an enlarged representation of this segment of the range. It contains the average value from readings taken repeatedly on the measurement standard x̅g and the reference value of the standard xr, which is sometimes referred to as xm. The 6sg interval should be sufficiently smaller than the segment of the specification field under consideration. The value of 6sg represents an interval, in which – assuming Gaussian distribution of the error of measurement – contains 99.73% of measured values.

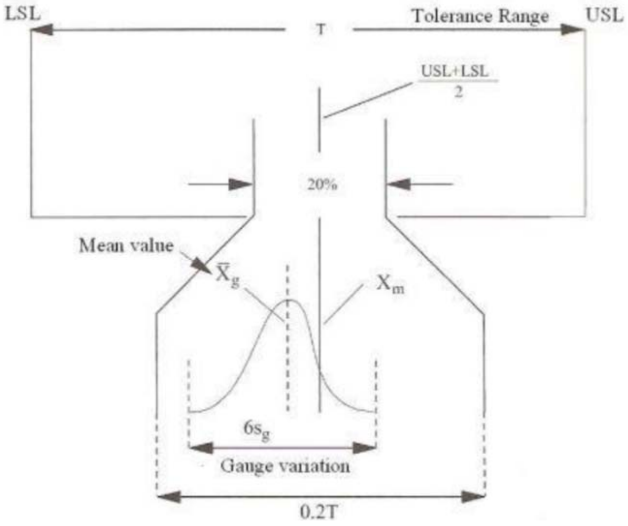

Fig. 3 Measure uncertainty

Ford method formulae for calculation with the tolerance range T:

a) Sample standard deviation $S_g = \sqrt{\frac{1}{n-1}\sum(x_i - \overline{x})^2}$

b) Variance $S = {s_g}^2$

c) Arithmetic mean value $\bar{x} = \frac{1}{n}\sum x_i$

d) Repeatability $c_g = \frac{K*T}{6s_g}$

e) Bias $c_{gk} = min\left\{\frac{(x_r+0{,}075T)-\bar{x}}{3s_g}\middle|\frac{\bar{x}-(x_r 0{,}075T)}{3s_g}\right\}$

n… number of measured values
xi…value of xth reading
x bar … arithmetic mean value
xr…reference value of the standard
T…tolerance range width
K…constant in the range of 10–30% defines the width of the tolerance range for calculation

3. Evaluation of the experiment

The measurement results were recorded in the table for each tolerance field value and for each tolerance width /%/ see tab. 3 and 4. According to these tables it is possible to decide whether it is possible to use the machine at all for the desired tolerance field value.

3.1 CMM without temperature compensation

In the case of a machine without temperature compensation, it is possible to use the machine according to the test without worrying when measuring the values with the tolerance field width of 0.007 mm and the widths of the tolerance field from 20% or more. Which is the normal tolerance field width value. The 10% value is only used in the aerospace industry where the emphasis on the accuracy of the measure is very high. At a lower tolerance field, although the machine can also be used, it is necessary to choose a higher tolerance field width of at least 30%. This can be used where I know that the reliability of the measured values is not required.

Table 3 Results of validation CMM without temperature corection

Tolerance width	0.01			0.005			0.007		
Tolerance range width K /%/	10	20	30	10	20	10	20	10	20
Variance S2	1.252×10-8			1.252×10-8			1.252×10-8		
Sample standard deviation S	0.00011			0.00011			0.00011		
Repeatability Cg	1.459	2.919	4.378	0.729	1.4595	0.729	1.4595	0.729	1.4595
Bias Cgk	0.548	2.008	3.467	-0.18	0.548	-0.18	0.548	-0.18	0.548
Result	NOK	OK	OK	NOK	NOK	NOK	NOK	NOK	NOK

For easier orientation is here this Fig.4 that describe the same as table 3.

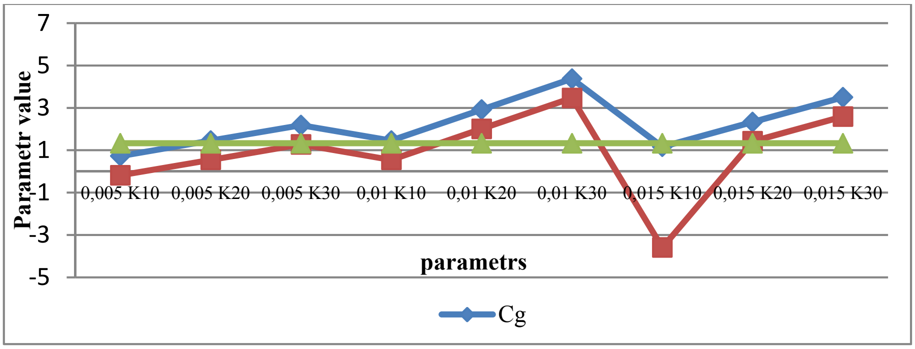

Fig. 4. Cg and Cgk calculated form measuring at CMM without temperature correction.

3.2 CMM with temperature compensation

The CMM machines with temperature corrections with our possible range of tolerance fields and their propagation did not use either result. As can be seen from Fig. 5 or Table 4, therefore, the tolerance field was artificially extended to the value where the tolerance field width was 20%. That is, in this case, the tolerance field size is 0.015 mm.

Table 4 Results of validation CMM with temperature corection

Tolerance width	0.01			0.005			0.007		
Tolerance range width K /%/	10	20	30	10	20	30	10	20	30
Variance S2	1.978×10-7			1.978×10-7			1.978×10-7		
Sample standard deviation S	0.00045			0.00045			0.00045		
Repeatability Cg	0.376	0.734	1.101	0.183	0.367	0.550	0.294	0.587	0.881
Bias Cgk	-3.534	-3.167	-2.800	-3.717	-3.534	-3.351	-3.607	-3.314	-3.020
Result	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK

For easier orientation is here this Fig. 5 that describe the same as table 3.

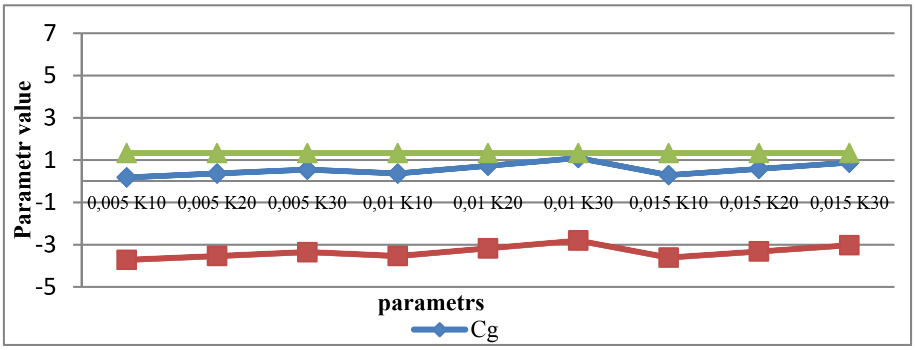

Fig. 5. Cg and Cgk calculated form measuring at CMM without temperature correction

4. Conclusions

Due to the specific properties of the real CMM and the enviromental conditions of the laboratory, it is not appropriate to analyze the results obtained in the interlaboratory comparison with another CMM. However, it was advisable to compare the results with a similar experiment in the field of continuous scanning. Deviations of outputs, if any, will be the basis for further research - the influence and distribution of the sensing points on the accuracy of the measurement of the basic characteristics.

Therefore a research programme at the Regional Technological Institute of the Faculty of Mechanical Engineering of University of West Bohemia, the performances of CMM machines with and without temperature compensation were compared. The experiment was based on the theory of measurement repeatability. It has relatively clearly shown that the practical boundary for application of CMMs with temperature compensation (provided that the feature is enabled) exceeds the accuracy of an equivalent machine without compensation almost three times. It has become clear that even today it is more suitable to evaluate micrometre-scale parameters in a controlled-environment metrology laboratory, when it comes to measuring high-precision critical parts (e.g. in automotive and aviation engineering and other sectors). The reason is that relevant results cannot be obtained due to the step-increase in the uncertainty of measurement.

Acknowledgements

The article contribution has been prepared under project LO1502 ‘Development of the Regional Technological Institute under the auspices of the National Sustainability Programme I of the Ministry of Education of the Czech Republic aimed to support research, experimental development and innovation.

References

[1] M. Melichar, D. Kubátová, J. Kutlwaše, CMM measuring cycle and human factor, Proceedings of the 27th DAAAM International Symposium, ISBN 978-3-902734-08-2, 2016.

[2] J. Pernikář: Assessment of the competence of control means. Available at: http://gps.fme.vutbr.cz/STAH_IN FO/31_Pernikar_VUTBR.pdf (November, 2016).

[3] W. Płowucha, W. Jakubiec, M. Wojtyła, Possibilities of CMM Software to Support Proper Geometrical Product Verification, Procedia CIRP, 43 (2016) 303-308.

[4] M. E. Barini, G. Tosello, L.Chiffre, Precis. Eng. 34 (2010) 16-21.

[5] Jiroušek, Pavel, 2012. Eligibility of measurement system in the gearboxes production of Škoda auto a.s. Available at: https://is.savs.cz/lide/clovek.pl?zalozka=13;id=148; studium=2015. Diplomová práce. ŠKODA AUTO a.s. vysoká škola (March, 2017).