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THE ANALYSIS OF THE ACCURACY AND EVALUATION MEASUREMENT UNCERTAINTY OF CMM USING BALL BAR

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Abstract: In order to estimate the accuracy of coordinate measuring machines (CMM), the recommendation of the ISO 10360-2 standard is to use gauge blocks, but other reference (calibration) gauges can be used. Besides the accuracy estimation, in this way the metrological traceability of current measuring systems is maintained and measurement uncertainty is determined, but only for these measurement tasks. Due to the complex hardware, the accuracy of these measuring systems varies from the orientation and length of the calibrated gauges. This paper presents a ball bar that is used as a reference gauge and CMM that is used for analyzing the influence of number of points for defining the center of the balls. In order to test the significance of parameters, full design of experiment (DOE) factors were used. Also, the measurement uncertainty of CMM was evaluated using the ISO 15530-3 guidelines for comparing measurement errors that are considered, for this measuring task, and the associated measurement uncertainty.

Keywords: error, measurement uncertainty, CMM, ball bar

1. INTRODUCTION

The verification processes of the geometric product specification are mainly performed on the coordinate measuring machines (CMM). CMM have high flexibility, which enables computer-aided inspection of all the macro characteristics that are defined at the design stage of the manufacturing process. However, the CMM measuring principle is not consistent with Abbe's principle, the accuracy of CMM is not sufficient for some measurement tasks such as the measurement of reference gauge [1]. In addition, the measurement process itself is very complex and there are many influencing factors that reduce the quality of measurement, these are manifested as measurement errors and measurement uncertainty. The accuracy of the CMM measurement can be increased using reversal techniques that successfully eliminate most of the sources of systematic errors. Examples of reversal techniques are the calibration of ball plates, square angles, reference cylinder or straight edges [2].

Reversal techniques i.e. multiple orientation techniques cannot eliminate the scale error. That's why it is necessary to use substitution measurements of the reference lengths. The CMM through performance tests is specified on the basis of measurement of reference lengths, as contained within the ISO 10360-2: 2011 [3]. According to the mentioned standard, the CMM value of the reference length measurement must not exceed the specification expressed over the maximum permissible error (MPE). Gauge blocks are mainly used for measureing reference length according to the standard. It is known that the values obtained by this measurement also represent the CMM uncertainty for measuring the distance between two points. Many authors suggested the use of the ball bar gage as the reference standard instead of gauge blocks. The reference length represents the distance between the ballpoint centers that are located at the ends of the ball bar in the current case [4]. Research on this topic considered length and orientation as influential factors to the value of the reference length, but the impact of the number of sample points that are the basis for obtaining the ball bar point center was not considered.

In this paper, authors present the approach for accuracy estimation and determining measurement uncertainty for the measurement task distance between two points using the ball bar reference gauge. Using the DOE, the influence of the input factors and their interaction on the response value was considered.

2. METODOLOGY

According to the performance test, research of the CMM hardware error are used measuring different reference lengths in a particular position and certain orientations relative to the machine axes according to reference standards. It is believed that the orientation factors and the position of the reference standard, as well as its length, mostly effect on machine errors due to CMM geometric errors that vary depending on the position of the sampled point in the CMM working area [5]. In addition, it would be interesting to examine whether the number of points and the interaction with the length and orientation of the ball bar is related to the measurement results. The standard does not specify how to select a strategy for measuring the ends of the ball bar. Namely, the calibrated balls and the center of the ball are determined by the least squares (LS) method according to the reference standard. Each sampled point has its own uncertainty and it is the resultant of the CMM geometric errors. There are twenty-one CMM geometric errors. Since the balls that are being sampled are significantly small, it is possible to use simplifications, at the first the sampled points from the surface of the ball have the same measurement uncertainty and at the second there is no correlation between them. However, if we imagine that the diameter of the ball is reduced to zero, the coordinates of the fitted center have a greater uncertainty of space than the sampled point, then it is considered that the impact of the number of points in the sampling strategy is significant. Also, due to the ball bar construction, a calibrated ball is not possible measured over the entire surface, but it is possible by segment. It is obvious that in this way uncertainty is also increased in the coordinates of the center of the ball. As previously described, it can be concluded that the reference distance between the ball centers is very dependent on the position, the number of points in the measurement strategy and the orientation in the CMM workspace. Additionally, if the reference length variation is added, an experiment can be performed according to the selected experiment plan which will determine the significance of the prior parameters and their relations on the error of measuring of the distance between two points and the associated measurement uncertainty. It has been previously mentioned that in this measurement task, the measurement error is also the same measurement of uncertainty. The measurement uncertainty will be assessed according to the ISO 15530-3:2011 standard [6].

Table 1. Full Factorial design 3^3

Factor	Level		
Ball Bar length, mm	100	150	300
Ball Bar orientation	X	XY	XYZ
Number of points	20	60	100

For the purpose of determining the significance of the factors considered as well as their interactions, a full factor design of 3^3 with repetition in each experimental point was used. The full factor design is need 3 × 3 × 3 = 81 experiments. The experiment was completely randomized and performed in one block. The factors and their corresponding levels are shown in Table 1. The experiment plan set-up and processing of results was performed in the Minitab 17 software.

The levels adopted for the length of the ball bar are the available values of the length of the transducer ball bar and they are in the following order 100 mm, 150 mm, and 300 mm. The levels adopted for orientation are oriented along the X-axis, plane diagonal of XY axis and spatial diagonal of XYZ axis in working volume. The levels adopted for the number of points according to the measuring strategy of the balls are 20, 60 and 100 points that are randomly distributed over the available surface of the ball.

Figure 1. Reference gauge and ball bar fixed in fixture

Table 2. Calibration values

	Nominal values in mm		
	100	150	300
Reference (calibrated) values in mm	100.0012	149.9958	299.9951

Ball bar called QC10 by Renishaw company is used for measuring length according to standard. The basic purpose of the ball bar is to perform motion diagnostics of control numerically controlled machine (CNC) that is presented in Figure 1. During the experiment, the ball bar is fixed into the fixture. This clamp only provides to establish the reference point. In the case when the reference gauge is not fixed in the fixture, the length of the ball bar is undefined since one ball has the possibility of axial movement over the spring direction. The calibration values are given in Table 2. Measurement errors are calculated as the difference between the measured and calibrated ball bar lengths. The ball bar ball geometrical shape error and their standard uncertainty are ignored in this case. The experiment was performed on the CMM Carl Zeiss Contura G2 RDS, with manufacturer's specification for measuring the distance between two points are $MPE_E = (1.9 + L / 330)$ μm (L is the measurement length expressed in mm).

3. RESULTS AND DISCUSSION

The ball bar lengths are measured according to DOE settings and the distribution of measurement errors, depending on the factors, that are shown in Figures 2a-2c. It can be noted that the error distribution is uniform for all investigated factors and that almost every CMM measurement has an error, ie. values are different from the ball bar length.

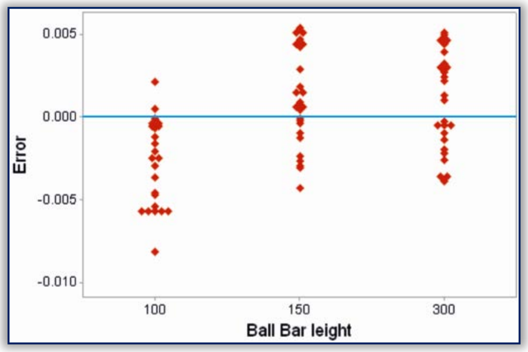


Figure 2a. Distribution of errors according to the length of the ball bar

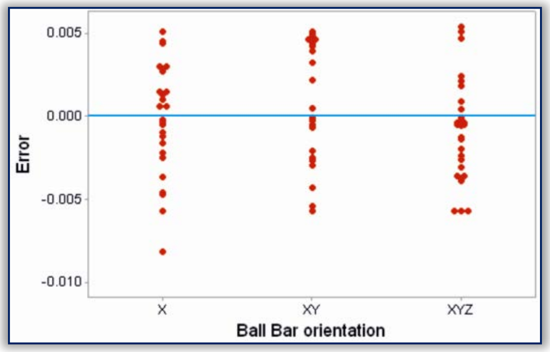


Figure 2b. Distribution of errors depending on the orientation of the ball bar

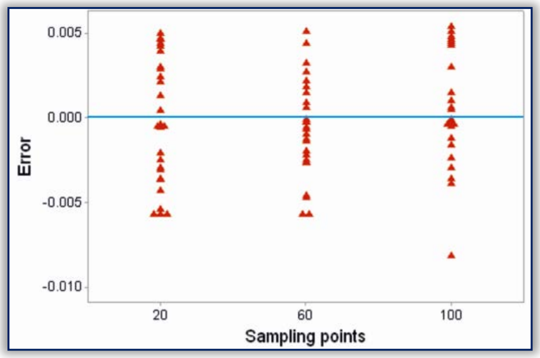
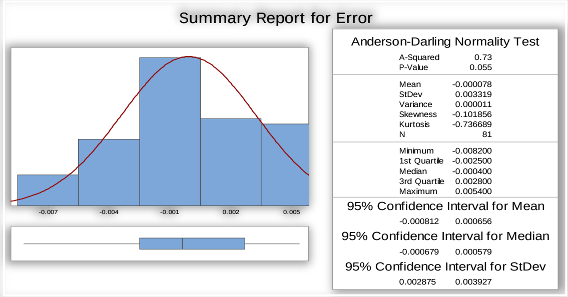


Figure 2c Distribution of errors according to the number of points in the measuring strategy



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Anderson-Darling Normality Test
A-Squared      0.73
P-Value        0.055

Mean           -0.000078
StDev           0.003319
Variance        0.000011
Skewness       -0.101856
Kurtosis       -0.736689
N                     81

Minimum        -0.008200
1st Quartile   -0.002500
Median         -0.000400
3rd Quartile    0.002800
Maximum         0.005400

95% Confidence Interval for Mean
-0.000812      0.000656
95% Confidence Interval for Median
-0.000679      0.000579
95% Confidence Interval for StDev
0.002875       0.003927
```

Figure 3. Statistical indicators for the distribution of the CMMs measurement error

Statistical data processing has been established as a linear model with the interaction of factors (p Lack of Fit value is much less than 0.05). Significant factors and signification interactions are shown in table 3.

The ANOVA table indicates significant evidence of main effects (length of the ball bar and orientation) as well as significant evidence of interaction effects at a = 0.05□□. There is no significant evidence for the influence of the number of points. If the experimental values and values

Table 3. ANOVA table

Sourse	DF	Adj SS	Adj MS	F	P
Model	8	Seq SS	0.000050	7.41	0.000
Linear	4	0.000398	0.000071	10.52	0.000
Ball Bar leight	2	0.000282	0.000125	18.66	0.000
Ball Bar orijentation	2	0.000251	0.000016	2.38	0.05
2 – Way interactions	4	0.000032	0.000029	4.31	0.004
Ball Bar leight × Ball Bar orijentation	4	0.000116	0.000007	4.31	0.004
Error	72	0.000116	0.000005		
Lack – of – Fit	18	0.000483	0.000007	0.7	0.795
Pure Error	54	0.000092			
Total	80	0.000392			

obtained by the model are compared, it can be concluded that the experimental model was well represented by the prediction model. The comparison demonstrated that the prediction model yields somewhat smaller results (Figure 4).

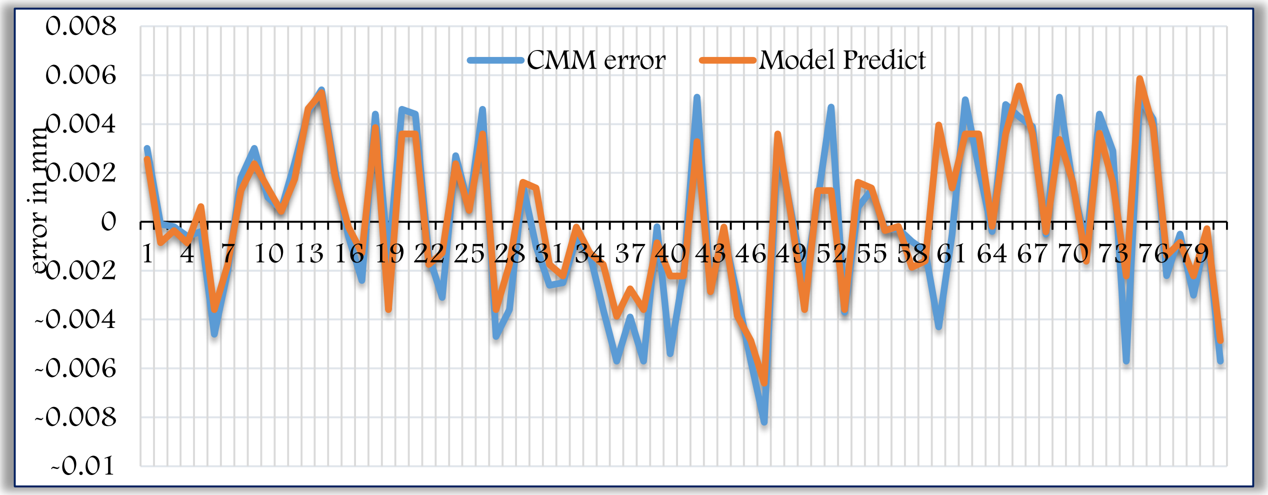

Figure 4. Comparison of experimental results with the predict model results

4. EVALUATION OF MEASUREMENT UNCERTAINTY

The maximum permissible error (MPE) can be regarded as a measurement of uncertainty in the event of a distance measurement of two points. As there are three different reference lengths in this case, according to MPE, measurement uncertainties are as follows:

$$MPE_{100} = 1.9 + 100/330 = 2.20\ \mu m$$

$$MPE_{150} = 1.9 + 150/330 = 2.35\ \mu m$$

$$MPE_{300} = 1.9 + 300/330 = 2.81\ \mu m$$

Measurement uncertainty can also be evaluated following the guidelines of ISO 15530-3. According to this standard, expanded measurement uncertainty is presented in equation (1):

$$U = k\sqrt{u_{cal}^2 + u_p^2 + u_b^2 + u_w^2} \qquad (1)$$

where k is a coverage factor (usually k = 2, for a confidence interval of 95.45 %); u_{cal} represents the uncertainty of workpiece calibration that is specified in the calibration certificate; u_p represents the standard uncertainty obtained from the conducted experiments and contains the uncertainty factors associated with CMM hardware; u_b represents the standard uncertainty associated with the systematic error of the measurement process and u_w is the standard uncertainty that relates to variations related material and production. According to the expression 1 expanded measurement uncerainties are:

$$U_{100} = 2.59\ \mu m$$

$$U_{150} = 2.96\ \mu m$$

$$U_{300} = 3.02\ \mu m$$

On the basis of the results, it can be concluded that the uncertainties of the evaluate ISO 15330-3 are somewhat higher than the MPE and from the aspect of the CMM specification, measurement uncertainty values are not acceptable. However, to show the overall measurement result, the measurement result plus the expanded measurement uncertainty, for measurement in industry it is possible to, with a certain level of confidence, confirm the initial claim, that when measuring distance, the maximum permissible error value can be adopted as measurement uncertainty. In this way, complex experiments required by ISO 15530-3 are avoided, and the experiment can be conducted in the absence of reference gauges.

5. CONCLUSION

In this paper, the DOE was used to examine the impact of the three factors on the CMM measurement error. The calibrated gauge of the ball bar was placed in fixture during measurement time. The experimental results have shown a strong influence on the length of measurement and orientation on the measurement error as well as their interaction. The maximum permissible error and measurement uncertainty is compared, according to the obtained ISO 15530-3. The results confirm the claim that for measurement tasks where the distance between two points is measured, MPE can be taken as measurement uncertainty.

Note:

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References

[1] Štrbac, B., Radlovački, V, Spasić- Jokić, V., Delić, M., Hadžistević, M. (2017) The difference between GUM and ISO/TC 15530-3 method to evaluate the measurement uncertainty of flatness by a CMM, Journal Metrology Society of India - MAPAN, vol. 32, p. 251–257.

[2] Liebricha, T., Bringmann, B., Knapp, W. (2009) Calibration of a 3D-ball plate, Precision Engineering, vol. 33, p. 1–6.

[3] ISO10360-2:2009. Geometrical product specifications (GPS)—acceptance and reverification test for coordinate measuring machines (CMM)—Part 2: CMMs used for measuring linear dimensions. International Organization for Standardization. Geneva.

[4] Piratelli-Filhoa, A., Di Giacomo, B. (2003) CMM uncertainty analysis with factorial design, Precision Engineering, vol. 27, no. 3, p. 283-288.

[5] Sładek, J.,Gașka, A. (2012) Evaluation of coordinate measurement uncertainty with use of virtual machine model based on Monte Carlo method, Measurement, vol.45 no.6, p. 1564-1575.

[6] ISO/TS 15530-3:2011. Geometrical product specifications (GPS) – coordinate measuring machines (CMM): technique for determining the uncertainty of measurement – part 3: use of calibrated workpieces or standards.

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