INVESTIGATION CMM MEASUREMENT PARAMETERS EFFECT TO THE MEASUREMENT ERROR

Asli G. BULUTSUZ [1], M. Emin YURCI[1], M. Numan DURAKBAŞA[2]

[1] Yildiz Technical University, Mechanical Engineering Department İstanbul Turkey,
asligunaya@gmail.com , meyurci@yahoo.com
[2]Vienna University of Technology, Institute for Production Engineering and Laser Technology,

Department for Interchangeable Manufacturing and Industrial Metrology,

Vienna Austria, durakbasa@mail.ift.tuwien.ac.at

Abstract − High measurement accuracy with optimum measurement procedure is a significant requirement in advanced fields of interchangeable manufacturing and precision engineering. This study presents optimum parameter selection for lowest measurement error. Moreover a mathematical model was obtained to predict measurement error according to the selected measurement parameters. The proposed prognostic model provided a well-suited method and gave promising results in predicting measurement errors by monitoring the parameters such as optimum probed point numbers, probing speed, probe radius and measurement angle of probe.

Keywords: Measurement Error, Uncertainty, CMM, Optimization

1. INTRODUCTION

Today Coordinate Measuring Machines are capable of adapting in many usage areas such as advanced manufacturing environments to check out the process quality, reverse engineering areas for specifying geometrical specifications [1-2]. Coordinate Measuring Machines (CMMs) are indispensable because of their high accuracy for identifying geometrical dimensions. There are barely kind of geometries that cannot be measured by CMMs. A productive usage of CMM decreases measurement costs since their high accuracy, high flexibility and short measurement procedure times.

For improving the measurement productivity, determining the measurement error is a key factor for improving measurement quality and reliability. Measurement techniques cannot measure the physical quantities without errors. The crucial point is stating measurement error correctly with the evaluated result. To reduce measurement costs and improve the measurement accuracy the relationship between the measurement parameters and measurement uncertainty is a must to identify.

New developed high manufacturing technologies need integration of high precision measuring systems. For example in reverse engineering area scanned final model need to be acquired accurately since the smallest difference between the geometry and model effects the final machined work piece.

The measurement values need to be as close as possible to the work piece geometry as stated in Technical drawings— Geometrical Tolerancing, ISO 1101, 1983-12-01 (3,4). Concurrently this output also must be traceable in international area. Thus there are plenty of standardization for testing CMMs performance like ISO 10360 [5], German VDI/VDE 2617 [6], American ANSI/ASME B89.4.1 [7].

The versatility and machine complexity of CMMs also bring difficulties while determining measurement error. This value can be determined by statistical techniques (by using a theoretical model), comparison method (by using calibrated artifacts), and performance test methods (by designating artifacts and a criterion), [8]. Under these main groups there are many different methods have been developed until today to specify CMM measurement accuracy. For statistical techniques; Weckenman and et. al. observed a mathematical-physical model like a kind of virtual functional gauge to provide better measurement accuracy of surfaces [9]. Hansen and et. al. used a AFM-CMM integrated system to illustrate geometrical model systematic errors by means of a mathematical model [9]. Chen and et al. developed a statistical model for measurement uncertainty analysis which indicated the true value of measurand (10). Aggogeri and et. al. use a simulation method based on Monte Carlo technique which enables to simulate errors in the coordinates of each measured point, using CMM part program to propagate measurement uncertainty from point coordinates to measurand (11). Ahmari and et. al. used Design of Experiment (DOE) techniques to optimize procedure parameters of surface reconstruction in Reverse Engineering technology for freeform surfaces (12).

Generally these methods have been used for accurately measurement and simulation for reversal engineering which is all explained in the ISO 15530 series of standards. (13)

In this study, a statistical method was applied to determine selected parameters effect of measurement error. Determining errors sources and their effects enables to decrease measurement errors for customized measurements. For this purpose, a case study was performed conventional type of CMM. Firstly the most effective CMM operating parameters selected according to the practical experience of

manufacturers and literature. Afterwards the relationship between the measurement error and the measurement parameters are identified by means of Taguchi Technique. Then regression method used to develop an empirical model which enables understanding parameters effect quantitatively. The aims are the inspection of the most powerful error components, optimizing process parameters and planning the measurement process more intuitively, accurately and user friendly.

2. MATERIALS METHOD

For the experimental study conventional type of CMM (HERA SC 15.10.09) was used in a manufacturing area. The CMM was calibrated and interim check was made by an accredited calibration service (CERMET, Italy). According to the report the machine was ready for usage with 3.7 µm maximum permission error (Upper limit was: 4 µm) due to ISO 10360-2:2009 [14]. For measurements a calibration ball was used as a spherical surface. Spherical surfaces have an important role in precision engineering as they are used in precision machines and instruments. In this experimental study, three different probe diameters were used to measure spherical specimen, steel ball, having high precision technical structures manufactured by surface grinding and lapping.

Table1. The set of selected parameters and their levels

Level	1	2	3
Probe Diameter (mm)	1	2	4
Measurement Velocity (mm/sec)	10	50	100
Probed Point Number	5	15	25
Measurement Angle (°)	X0Y0	X90Y0	X45Y45
Approach Distance (mm)	5	10	15

As seen Table 1, the set of parameters and their levels used in the present study are summarized as probe diameter, measurement velocity, approach angle and probed point number. Taguchi method for design of experiments [15] was employed in order to optimize the number of simulations. The test matrix defined according to Taguchi L_{27} orthogonal array, that requires 27 runs at three levels in the present case in accordance with ISO 16336:2014 [16]. The output data was selected as the difference between the CMM result and calibration certificate value of steel ball diameter. The experimental data were analysed by using the signal to noise (S/N) ratio and the analysis of variance (ANOVA). Afterwards regression analysis applied in order to obtain a mathematical model. S/N ratio enables understanding optimum parameters according to output signals. The ANOVA analyse was used to find the contribution of the input effects on output, measurement error. Quality characteristic was selected as the smaller is the best for the

investigation of S/N ratio (Eq. 1). In the equation 1, n is the number of observations, and y is the observed data.

Table 2. Experimental runs and measurement error value as

	Control Factors and levels					
	Probe Diameter	Velocity	Probed Point	Angle	Approach Distance	Error
1	1	1	1	1	1	3,38
2	1	1	1	1	2	3,58
3	1	1	1	1	3	3,38
4	1	2	2	2	1	1,78
5	1	2	2	2	2	1,60
6	1	2	2	2	3	1,79
7	1	3	3	3	1	0,99
8	1	3	3	3	2	1,19
9	1	3	3	3	3	0,99
10	2	1	2	3	1	2,02
11	2	1	2	3	2	2,12
12	2	1	2	3	3	2,26
13	2	2	3	1	1	3,08
14	2	2	3	1	2	2,98
15	2	2	3	1	3	2,78
16	2	3	1	2	1	3,96
17	2	3	1	2	2	3,87
18	2	3	1	2	3	3,96
19	3	1	3	2	1	1,79
20	3	1	3	2	2	1,78
21	3	1	3	2	3	2,20
22	3	2	1	3	1	2,79
23	3	2	1	3	2	2,59
24	3	2	1	3	3	3,00
25	3	3	2	1	1	2,90
26	3	3	2	1	2	3,81
27	3	3	2	1	3	3,81

an output

3. RESULTS AND DISCUSSION

The aim of experiment was to optimize the measurement parameters to get better measurement accuracy with the lowest measurement error. Table 2 shows the actual data for measurement error which was obtained from the difference of measurement result and certificate value of calibration ball diameter.

Smaller is the best characteristic: $\frac{S}{N} = -10\log\frac{1}{n}(\sum y^2)$ (1)

Table 3. Response table for S/N ratios (smaller-is-better) for Measurement error

Level	Probe Diameter	Velocity	Angle	Probed Point	Approach Distance
1	-5,333	-7,682	-10,323	-10,523	-7,416
2	-9,285	-7,657	-7,428	-7,381	-7,718
3	-8,473	-7,751	-5,340	-5,187	-7,957
Delta	3,953	0,095	4,983	5,336	0,540
Rank	3	5	2	1	4

The graphical representation of the S/N ratios of the five process parameters is shown in Fig. 1. It is evident from Fig. 1 that measurement error is the minimum at the first level of probe diameter (A1), the first level of measurement velocity (B1), the first level of probed point number (C3), the third level of measurement angle (D3), and the first level of approach distance (E1). 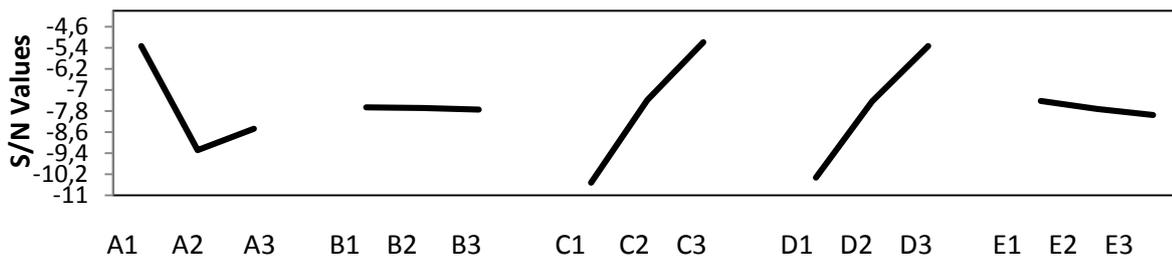Among these parameters, according to the response table for S/N ratio, probed point number found to be the most effective parameter as shown in Table 3.

Additional to Taguchi analysis ANOVA analysis was employed to understand statistically significance level of parameters on measurement error. Moreover Regression analysis used to build up a mathematical model. The statistical results of the analysis according to the regression analysis are shown in Table 4. As seen in the Table 4, P test and the Fisher's F test were applied to determine statistically the relative significance of the process parameters under the investigation on the measurement error. F_{crit} value according to the experimental run number is determined from standardized F distribution table $F_{0.05,4,\ 26}$= 2,975 for α= 0.05 significance level. F value should correspond bigger than $F_{0.05,4,\ 26}$ to have a significant effect on measurement error according to the null hypothesis. The adequacy of the experimental set is provided at the 95 % confidence level same as the F-test.

Figure 1. Main Effect Plot for SN ratios for E_m

Table 4. Analysis of Variance for Measurement Error

Source	Degree of Freedom	Seq SS	Adj MS	Adj SS	F	P	Percent (%)
A	2	4,1045	2,0522	4,1045	42,30	0,000	18,06
B	2	0,6924	0,3462	0,6924	7,14	0,006	3,04
C	2	7,7224	3,8612	7,7224	79,58	0,000	33,99
D	2	9,3015	4,6507	9,3015	95,86	0,000	40,94
E	2	0,1192	0,0596	0,1192	1,23	0,319	0,52
Error	16	0,7763	0,0485	0,7763			3,41
Total	26	22,7161					100

To assess significant parameters for low measurement error value; P values should not exceed or should be equal to α value (0.05) for the contribution of that factor on the basis of given quality characteristic hypothesis. F test and P test reveal that only approach distance (E) found to be insignificant based on the selected parameter levels. That means approach distance is not an effective parameter for measurement error. The rest of the process parameters are significant. The adequacy of ANOVA analysis found as R-Sq = 96, 58%.

A mathematical model to predict measurement error (E_R) was derived by general regression with the independent variables of process parameters; probe diameter (A), measurement velocity (B), probed point number (C), measurement angle x, y, z (D1, D2, D3), approach distance (E). Measurement angles were used separately as inputs. Z was same for all experimental sets hence this direction was not shown in the regression equation.

The linear equation that best predicted measurement error E_r is given below:

$$E_r = 3,59368 + 0,171672\ A + 0,00384624\ B - 0,0706448\ C - 0,0085884\ D1 - 0,0203545\ D2 + 0,0162358\ E \tag{2}$$

Proportion of total variability in the Ra deviation can be explained by Eq. (3) is;

$$\text{R-Sq} = SS_{Model}/SS_{Total} = 0.8190 \tag{3}$$

In this quation the SS is the abbreviation of "sum of squares" for model and total.

Finally the validity of the results was checked though confirmation experiment with same environmental conditions (Table 5). Three repetitive measurements were applied in order to test optimal process parameters.

Table 5. Confirmation test results

Measurement	1	2	3
E_r (µm)	0,962	0,892	1,150

4. CONCLUSIONS

In this paper a statistical approach was presented for determining measurement errors related process parameters of coordinate measuring machines. According to the experimental runs the following conclusions may be drawn:

-The optimum process parameters to minimize measurement error were obtained by means of L27 orthogonal array and Taguchi analysis. The optimal process parameter levels for minimum measurement errors were observed at A1B1C3D3E1 (at a 95% confidence level, i.e., probe diameter= 1 mm, velocity= 10 m/sec, measurement angle= A45B45, probed point number= 25 and approach distance= 15 mm).

-The minimum measurement error was found as 0,988 µm by Taguchi's optimization method.

- Confirmation test also applied experiment in order to obtain measurement error. Results showed that Taguchi parameter design successfully verified the optimum measurement parameters (A1B1C3D3E1), with a measurement error result 1,005 µm (E_r).

-Taguchi, ANOVA and regression analysis were successfully applied in the presented work. Taguchi analysis revealed optimum parameters for lowest measurement error with very limited number of experiments.

-According to the results of ANOVA analyses, it was found that the probed point number was the most significant parameter for measurement error with a percent of 40, 94. The correlation coefficient concluded as R-Sq=96, 58% for ANOVA analysis.

-Developed regression model demonstrated a very good relationship with high correlation coefficients (R-Sq = 0.8190) between the measured and predicted values for measurement error. This model enables to predict measurement error based on selected process parameters. This equation provides an insight into the relation between selected process parameters and measurement error.

-According to the confirmation test results, measured values were within the 95% confidence interval.

This technique predicts process parameters effect on measurement error such as selected probe diameter, probing speed, measurement angle and probed point number. Method can be customized according to the user selections and enables decreasing measurements error by means of optimizing measurement parameters such as probe diameter and probing point number.

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