Evaluation of Uncertainty in Angle Measurement performed on a Coordinate Measuring Machine

Rajamani R, Vignesh R, Mouliprasanth B[1]

{rajamani.vrr@gmail.com, vigneshrethinam29@gmail.com, bmouliprasanth@gmail.com[1]}

Department of Production Engineering, PSG College of Technology, Coimbatore, India, Department of Manufacturing Engineering, College of Engineering Guindy, Chennai, India [1]

Abstract. Coordinate Measuring Machine (CMM) is a universally accepted instrument that is widely used for inspection in industries and laboratories. Evaluation of uncertainty in dimensional measurement is very important for any measurement process. The components and the parts of the mechanical systems must have the accurate dimensions to meet the functional requirements. The environmental conditions and measurement methodhighly influence the accuracy of measurement process.This paper focuses on estimating the uncertaintyin angle measurementscarried out using CMM. In this study, anglegauge blocks are used as the reference materials for assessing the uncertainty in measurement using a CMM. An uncertainty estimation is carried out according to the guide to the expression of uncertainty in measurement (GUM). The influence of position accuracy, environment temperature, vibration, measurement and probing strategies are analysed and uncertainty in angle measurement is estimated as 40 arc seconds.

Keywords: Coordinate measuring machine, uncertainty estimation, angle measurement, GUM.

1 Introduction

Inspection of part dimensions and geometric features are integrated with the manufacturing processes. In manufacturing industries, Coordinate Measuring Machine are mostly used for inspecting the Geometric Dimensioning &Tolerancing (GD&T) features of semi-finished and finished components. Tomeet the growing demands of tight tolerances in part dimensions computerized inspection systems are widely used in the industries. All the measuring processes have some quantification of doubt about the measurement result which is termed as uncertainty in measurement. Uncertainty value should be taken into account with all measurements without which, the measurement result is only an approximate value of the measured.

Measuring process is divided into direct and indirect measurement processes. Indirect measurement processes require certain algorithms to get the measured values. Coordinate measuring machine is one of the popular inspection devices that give more accurate and precise results by indirect method. The coordinate points of mechanical parts are recorded quickly and accurately using CMM. The desired features are then measured with the help of CMM software. Even though it gives better results, many factors influence the measurement accuracy of CMM such as hardware error, environmental temperature, vibration and

evaluation strategy etc. Hence it is essential to consider the measurement uncertainty for an efficient measurement by CMM.

Many studies are available for analysis of form features, parameter influencing the CMM measurement, angle measurement strategies and uncertainty evaluation in CMM. Some of these are discussed in this section. An extensive study on the influence of form deviations in uncertainty measurement was clearly presented by Choi et al.[1] and Jack et al.[2]. Amato et al.[3] presented the indirect measurement of angles and evaluation of uncertainty using CMM. A Monte Carlo simulation method was used for error analysis by many investigators [4], [5] and [6]. Gyula Hermann[7] developed an algorithm for geometric error correction in coordinate measurement. Sartori et al.[8]established a method to compensate the thermal effect during measurement in CMM. Bourdet et al.[9] conducted experiments to locate the best fit sphere using data point distribution and statistical model.Gaska et al. [10] presented a method to estimate the uncertainty of five axis measuring system using virtual models and results of virtual model are validated with the experimental results.

Ito et al. [11] proposed a new method to calculate the form error of a probe tip ball. Uncertainty due to form error of probe ball is estimated as less than 0.5 μm.Patricio [12] analysed the effect of position error, random error and straightness error on accuracy of CMM. The study shows that the random error can be neglected when the straightness error of the CMM is less than one micrometer.

Branko[13] investigated the effect of environment temperature on measurement uncertainty in CMM measurements and results show that temperature has significant effect dimensional measurement and less effect on roundness measurement.Płowucha[14]presented a point to straight line distance model to evaluate the measurement uncertainty using CMM. Senin et al. [15]proposed a statistical model with of Monte Carlo simulation to estimate the measurement uncertainty in coordinate measuring system.

From the literature, it is obvious that quantification of error is inevitable in any measuring process. In this paper, a systematic study is carried out to estimate uncertainty in angle measurementperformed on a CMM and angle gauges are used as a reference standard. To evaluate the uncertainties, coordinate points of angle gauges are recorded andedges of gauges are constructed using a least square algorithmthen the angle between the edges are calculated. Finally, the results are presented in the form of uncertainty budget and expanded uncertainty.

Uncertainty in Measurement

Uncertainty is the suspicion concerning the measurement result which means the lack of true value of measurand. The reasons for the errors are sources like hardware, environmental temperature, vibration, measurement methods and work pieces. Though CMM measure the parts precisely, uncertainty needs to be evaluated in CMM. Some of the sources which affect the measuring results are shown in Fig.1.

A. Hardware

Hardware errors arise from the inherent design of the machine, its scale, probing system and the place where the machine is placed.

B. Environment

The environmental condition of CMM is an important source of uncertainty measurement. Due to change in temperatures, machine structure / component to be inspected will elongate or contract. This affects the measurement accuracy. To minimize the error due to thermal effects the part to be measured are held in the laboratory environment for a few hoursbefore measurement. The other machines which are installed near the CMM will make the floor vibration and that will affect the results of CMM. So, preventive activity has to be taken before inspection.
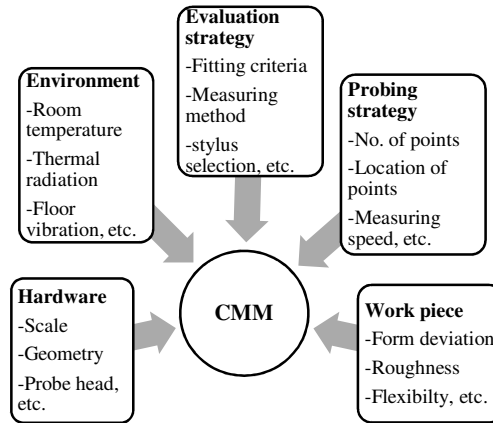
Fig. 1. Sources of uncertainty

C. Evaluation Strategy

Different measuring methods and fitting criteria are used to measure the measurand in CMM and each method differs from the others. So, this may lead to error in measured results. Other factors like selection of algorithm, filtering method etc. also affect the results.

D. Probing strategy

This source of uncertainty depends on the position in which coordinate points are measured, number of measuring points and measuring speed. Probing strategy will play a role on measuring results.

C. Work piece

Measurand is a one of the important sources of uncertainty in measurement. Due to the form deviation and surface imperfections, the measurement results may vary. In this work, five potential sources of uncertainties are evaluated which will influence the angle measurement. The sources of uncertainties are found to be calibration, probing error, reading error and temperature effect.

2 Experimental Work

A. CMM and Angle Gauges

The CMM machine used for this study is a moving bridge CMM, Carl Zeiss CONTURA G2 RDS (700mm x 1000mm x 600mm). The complete measuring system was maintained at the controlled temperature (20±1°C). Brown & Sharp Steel angle gauge blocks are used as a measurand which has nominal angle values of1°, 3°, 5°, 10°, 15°, 30°. The angular accuracy of the gauge is 0.0003″ and uncertainty considered for the experiments is ±30 arc second. Fig.2 shows the measurement setup with angle gauges and magnetic V Block.

Fig. 2. Measuring Setup.

For measuring the angle, gauge blocks are fixed on a magnetic V-block and datum has been set up that is necessary for taking the coordinate points on the angle gauge blocks. The possible errors that may occur during the measurement process are shown in Fig.3. The angle between the indicated and the reference plane is measured using the 3mm diameter probe.
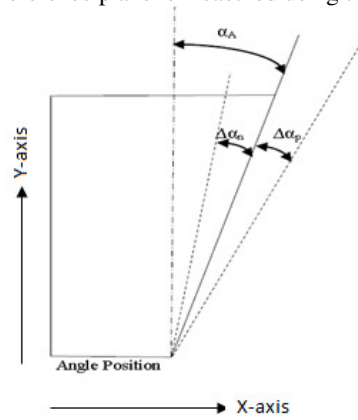

Fig. 3. Gauge value (αA), positive error ($\Delta\alpha_p$) and negative error (($\Delta\alpha_n$).

In this process, coordinate points and measurement results are obtained by absolute control mode and incremental control mode using the control panel. Through the coordinate points (Absolute control mode), angle value is calculated using a linear least square algorithm. Mathematical representation of distance between the points is given in (1)

$$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (1)$$

Angle between two points are given by (2), (3) and (4)

$$\cos \alpha = \frac{x_2 - x_1}{L} \qquad (2)$$

$$\cos \beta = \frac{y_2 - y_1}{L} \qquad (3)$$

$$\cos \gamma = \frac{z_2 - z_1}{L} \qquad (4)$$

Where L is a distance between two points, α,β and γ are angle between two points and x, y& z are the coordinate points.

The result obtained from CMM are compared with the reference values that gives the error in measurement. Then the error sources such as calibration error, probing error, reading error, error due to temperature and linear error are studied and finally uncertainty of CMM is calculated using GUM method.

C. Deviation in angle measurement by CMM Calibration

Thecoordinate points of the edges of slip gauge are recordedand measured values of the angle gauge are read from the CMM software. The CMM software (CALYPSO) usesthe non-linear least square method for constructing the best fit line then the angle between the lines are measured. Table 1 shows the actual value, measured value and deviation taken from the CMM software.

Table 1. Angle deviation in CMM calibration

Sl. No	Angle gauge value	Measured value	Deviation
1	1°	0° 59' 16"	- 0° 0' 44"
2	1°	0° 59' 56"	- 0° 0' 4"
3	1°	0° 59' 51"	- 0° 0' 9"
4	1°	1° 0' 42"	0° 0' 42"
5	3°	2° 59' 44"	- 0° 0' 16"
6	3°	3° 0' 14"	0° 0' 14"
7	3°	2° 59' 58"	-0° 0' 2"
8	5°	5° 0' 50"	0° 0' 50"
9	5°	4° 59' 52"	-0° 0' 8"
10	5°	5° 0' 11"	0° 0' 11"

The CMM uncertainty has been calculated using GUM method which is explained in the next section. Standard uncertainty value and expanded uncertainty value are indicated in Table.2.

3 Results and discussions

GUM method is followed to estimate uncertainty in measurement. Angle measurement model considered in this studyis expressed asfollows[15]

$$Y = X + K_{CAL} + K_{PROB} + K_{READ} + K_{TEMP} + K_L \qquad (5)$$

Where X is a measured angle value, $K_{CAL}$is the calibration error, $K_{PROB}$is probing error, $K_{READ}$is the reading error, $K_{TEMP}$is temperature difference and $K_L$is the distance error.

Combined uncertainty is evaluated based on law of propagation of uncertainty as expressed in (6):

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{df}{dx}\right)^2 . u^2(x_i) \qquad (6)$$

Where $u(x_i)$ is standard uncertainty and df/dx is sensitivity coefficient.

The combined uncertainty is expressed as:

$$u_c^2 = c_1^2 \cdot u_{CAL}^2 + c_2^2 \cdot u_{PROB}^2 + c_3^2 \cdot u_{REP}^2 + C_4^2 \cdot u_{TEMP}^2 + \qquad c_5^2 \cdot u_L^2$$

(7)

Where u_{CAL} is uncertainty due to uncertainty of CMM calibration, u_{PROB} is uncertainty due to probing error, u_{REP} is the uncertainty due to repeatability, u_{TEMP} is uncertainty due to temperature gradient, u_L is uncertainty of the distance error.

Uncertainty of distance error is calculated using (11),

$$u^2(L) = L^2 \frac{E_k^2}{3} + \frac{E_G^2}{3} + \frac{R^2}{3}$$

(8)

Where E_k(E_K=)is maximum permissible measuring error of measuring volume = $\left(1.8 + \frac{L}{300}\right)$ µm and E_G is maximum permissible probing error =1.8 µm and R is the resolution of the CMM = 0.2 µm.

Uncertainty due to calibration error is expressed as,

$$u_{CAL} = \frac{U_{CAL}}{k}$$

(9)

Where U_{CAL} is expanded uncertainty of calibration error with coverage factor k = 1.96, for 95 % confidence level.

Uncertainty of probing error is expressed as,

$$u_{PROB}^2 = u_F^2$$

(10)

Where u_F is uncertainty of workpiece error.

The uncertainty due to repeatability is expressed as,

$$u_{REP}^2 = \sqrt{\frac{\sigma^2}{n}}$$

(11)

Where σ is the standard deviation of the readings.

The standard uncertainty due to resolution of thermometer is calculated as,

$$u_{resol} = \frac{resolution \; x \; thermal \; coefficient \; X \; gauge \; length}{\sqrt{3}}$$

(12)

The sensitivity coefficient expressed as the partial derivative of (2), (3), and (4).

$$\frac{\partial(\cos\alpha)}{\partial x}, \frac{\partial(\cos\beta)}{\partial x} \text{ and } \frac{\partial(\cos\gamma)}{\partial x}$$

(13)

Combined uncertainty has been calculated using (7). Expanded uncertainty which is expressed as,

$$U = k \cdot u_c(y)$$

(14)

Using these formulas uncertainty due to various sources of error are estimated and the results are summarized in table 2. It is observed that expanded uncertainty in angle measurement at 95 % confidence level is 0.0112°(40 arc seconds).

Table 2. Sources of uncertainty values

Uncertainty sources	Standard uncertainty values (mm)	Probability distribution	Sensitivity coefficient	Uncertainty value (°)
Calibration	3.2×10^{-3}(mm)	normal	1.6×10^{-2}(°/mm)	5.12×10^{-5}
Probing error	1.8×10^{-3}(mm)	normal	1.6×10^{-2} (°/mm)	2.88×10^{-5}

Repeatability	5.17 x10^{-3}(°)	normal	1.0	5.17 x10^{-3}
Resolution of thermometer	8.76x10^{-2}(mm)	rectangular	1.6x10^{-2} (°/mm)	1.40x10^{-3}
Temperature (Avg. std. &Avg. room temp)	5.09x10^{-2}	rectangular	1.6x10^{-2} (°/mm)	8.144x10^{-4}
Temperature (CMM &gauge)	8.76x10^{-2}(mm)	rectangular	1.6x10^{-2} (°/mm)	1.40x10^{-3}
Distance	7.17x10^{-2} (mm)	rectangular	1.6x10^{-2} (°/mm)	1.14x10^{-3}
Combined uncertainty (k=1)				5.71 x 10^{-3}
Expanded uncertainty at 95% confidence level (K = 1.96)				**1.12 x 10^{-2}**

Conclusions

Expanded uncertainty in angle measurement is calculated using CARL ZEISS CONTURA G2 RDS CMM according to the series standards ISO 10360 and GUM guide. In this work angle gauge blocks are used as a reference material. Angle deviationsfrom the CMMreadings and gauge blocks reference value are calculated. Standard uncertainty is calculated using the repeated measurements.Then the calibration error, probing error, reading error andtemperature gradient are considered as sources of error in CMM measurement. Using the GUM method, the combined uncertainty is evaluated.

Expanded uncertainty in angle measurements iscalculated for 95% confidence level (coverage factor, k=1.96).Expanded uncertainty is found to be 40 arc seconds. In this scenario, the larger uncertainty is arisen from the repeatability error. So,uncertainty measurement should be evaluated periodically.This work focusses on a few sources of errors foruncertainty estimation and other sources of error can also be included in the uncertainty estimation.

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