THE USE OF MONTE CARLO SIMULATION IN EVALUATING THE UNCERTAINTY OF FLATNESS MEASUREMENT ON A CMM

Abstract: Due to their flexibility, precision, accuracy and level of automation, coordinate measuring machines (CMMs) are a leader among measuring instruments in production metrology. As they are essentially based only on sampling coordinates of points, they can measure any macro-tolerance indicated on the drawing. Among different form tolerances, flatness tolerance is the one that is often present in technical documentation. Although CMMs have metrological characteristics of high quality, these measuring instruments are not without measurement error. Since measurement error is generally unknown in practice, measurement uncertainty is considered a quantitative indicator of measurement error. It is generally believed that Monte Carlo simulation is the best method for numerical evaluation of measurement uncertainty. This paper presents a developed model for the evaluation of measurement uncertainty in the process of measuring flatness on a CMM. The presented model is used with a concrete measuring machine and concrete workpiece.

Key words: flatness, measurement uncertainty, coordinate measurement machine, Monte Carlo simulation

1. INTRODUCTION

Due to their flexibility, precision, accuracy and level of automation, coordinate measuring machines (CMMs) are a leader among measuring instruments in production metrology. With adequate equipment, coordinate measuring machines can be used for measuring any macro-tolerance indicated in technical documentation since a CMM basically perceives only coordinates of those points which are on the surface of the measured object. When the coordinates of points have been determined, an independent software analysis is performed to determine associative geometry of the workpiece using basic geometric primitives (line, circle, plane, etc.) The associative elements are determined by means of applying appropriate algorithms to the coordinates of the sampled points.

Flat form is one of the most frequent forms whose specification has to be checked. After sampling the total number of points, flatness error can be determined according to two associative criteria: least squares (LS) and minimum zone (MZ) [1]. The LS method is more superior in comparison to the MZ method from the aspect of simplicity and duration of calculating. The LS generally overestimates the shape error which can result in dismissing good parts. On the other hand, the MZ tends to underestimate the shape error and is very sensitive to peaks which can, if they go unnoticed, lead to bad results. The LS does not follow the standards carefully and cannot guarantee that the minimum zone solution is specified in the standard [2, 3]. The standard recommends that the form tolerances should be evaluated based on the concept of the minimum zone, but it does not offer the methodology of evaluation, so the MZ solution is not uniform. There are more than ten different approaches to flatness evaluation based on the minimum zone method [4-6]. For the purpose of investigation in this paper, the LS method will be used. The evaluation will be performed using the LS method. Every measurement is subject to uncertainty. The measurement result makes sense only when it is accompanied by a statement of uncertainty. GUM defines uncertainty as a parameter associated with the result of measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand [7]. Uncertainty can be described as a probability distribution of the values of the measured quantity which enables the determination of the limits of the measured quantity with any level of confidence. These limits define the so-called expanded uncertainty. The evaluation of measurement uncertainty in CMM measurements is a complex task due to a number of factors and their interactions which affect it. It is...
generally believed that Monte Carlo simulation is the best method for numerical evaluation of uncertainty. Therefore, this simulation method is applied in the evaluation of uncertainty when measuring flatness on a CMM.

2. METHODOLOGY

The use of Monte Carlo simulation for evaluating uncertainty of CMM measurements is currently in the focus of investigation. Numerous models and approaches have been developed for that purpose. A pioneer in the field is the VCMM (Virtual Coordinate Measuring Machine) developed by PTB (Physikalisch-Technische Bundesanstalt) [8]. The VCMM works on the principle of imitating the measuring strategy and physical behavior of a CMM in virtual reality (Figure 1). The role of Monte Carlo method is to randomly sample probability density functions that describe possible scenarios of the factors that influence measurement uncertainty. The result of this is several thousands of simulation measurement results whose 95% confidence interval represents the expanded measurement uncertainty. Input parameters are usually allocated an adequate probability density function. A similar principle has been applied in the development of the expert CMM [9]. Generally, the use of simulation tools for the evaluation of measurement uncertainty on a CMM is identical with the operation of a real CMM. Actually, its operation can be divided into two steps. The first step is determining the uncertainty of the sampled points, whereas the second step is the propagation of these uncertainties through the part program. Therefore, special attention is paid to the modeling of hardware errors of CMMs which are the commonest reason of uncertainty of a sampled point. In order to determine the uncertainty of sampled points, Gaska used the laser system Laser Tracker [10] for geometric errors of a CMM and for measuring the reference sphere for sensor errors. To define hardware errors of CMMs, Kruth used the measurement results obtained with a laser interferometer for twenty-one geometric errors and sensor errors from verification tests [11]. Although these models proved to be efficient in evaluating measurement uncertainty, their development is not simple since it requires time-consuming experiments. However, there are investigations whose focus was not on modeling point uncertainty, but Monte Carlo simulation was applied efficiently anyway. Dhanish introduced a simplification, considering that the uncertainties of the measurement points are independent, identical, characterized by normal distribution and equal to the specified standard uncertainty of a CMM [12]. Wen introduced the same assumption, with the uncertainty value being evaluated from the measuring equipment (CMM) and measurement environment [13].

After the first step has been defined, it is necessary to define a criterion for determining results, i.e. for determining associative geometry-step 2 (Figure 1). Unlike the previous models, in this paper, a simulation model for the evaluation of measurement uncertainty in measuring flatness was developed whose input quantities (x, y, z coordinates of the sampled points) are based on the repeatability of the sampled point. Namely, the uncertainty of coordinates of points is described by an adequate probability density function based on the repetition of the sampled point on the examined surface.
Likewise, the model involves the influence of shape error using an adequate distribution function. Earlier researches have shown that the shape error, in interaction with the number and position of the measured points, represents a factor that influences measurement uncertainty to a great extent [11, 14]. The inputs in the model which are defined this way will contain CMM hardware errors in the interaction with the environment. However, this pilot study is restricted to a concrete measurement location, measurement strategy and workpiece. Namely, the study was conducted on optical glass whose form error is defined in calibration certificate. For the defined number of points in the measurement strategy and the position of the workpiece in the measurement volume, each point was sampled ten times. Checking for normality showed that the repeatability of each point can be described using normal distribution. Added to this, a uniform distribution which describes the shape error of the workpiece was added to z variable. From the mentioned distributions, N Monte Carlo samplings were generated with the aim of obtaining N least squares reference planes from which N flatness error was determined. 2.5% quantile and 97.5% quantile were used to define the 95% interval of the expanded uncertainty. The difference of these percentages is the width of the uncertainty interval. The proposed model was tested according to ISO-15530-4 [15].

3. VERIFICATION OF THE PROPOSED MODEL

The model was tested on optical glass which represents the standard of flatness with \( d = 50 \) mm and specified flatness error \( y_{cal} = 0.068 \) µm. Flatness calibration was carried out with Zygo Verifier MST interferometer and the result was \( U_{cal} = 0.02 \) µm. The measurement was performed on Carl Zeiss UMS 850 coordinate measuring machine in the Laboratory for Dimensional Metrology at the Faculty of Mechanical Engineering in Maribor. The maximum permissible error \( (MPE_{k}) \) was \( 2.1 + L/330 \) µm \((L \) is the length expressed in mm). The workpiece was measured in ten points. Based on \( m = 10 \) repeated measurements of coordinates for each point, normal distributions for \( x_i \), \( y_i \), \( z_i \) \((i=1,2,3,...,10)\). Gaussian distributions were defined based upon the calculated mean values \( \overline{x}_i \), \( \overline{y}_i \), \( \overline{z}_i \) and standard deviations \( \sigma_{x_i} \), \( \sigma_{y_i} \), \( \sigma_{z_i} \). For each distribution, a sample of \( N \) elements \((N=1000)\) was generated (simulated). The procedure was repeated for all \( N \) sampled values from the Gaussian distributions so the result was \( N \) equations of the plane and \( N \) values for flatness error. Based on the \( N \) values of flatness error, a histogram of frequencies was constructed (Figure 3). The measurement uncertainty amounted to \( U = 0.001135 \) mm for 95% probability \((k=2)\).

3.1. Testing the proposed model

In accordance with ISO 15530-4:2011 recommendation which refers to the method of testing software for evaluation of uncertainty, the measurement results were tested in relation to the expanded uncertainties estimated by the proposed model. It was necessary to meet the following criterion:

\[
\frac{\sqrt{y - y_{cal}}}{\sqrt{U^2_{cal} + U^2}} = 0.69 \leq 1.
\]

According to the results of the experiment which involved measuring and evaluation of flatness error on a CMM several times with the aim of finding \( y \) the criterion was met. Thus, it can be concluded that the proposed model gives reliable evaluation of measurement uncertainty on a CMM.
4. CONCLUSION

A measurement result is incomplete if it is not accompanied by a statement of uncertainty and compliance/non-compliance with the specification cannot be proved without it. Monte Carlo method is a very efficient simulation tool for the evaluation of measurement uncertainty, especially in CMMs because of a number of factors and their interactions which affect uncertainty. The use of Monte Carlo method implies the development of a mathematical model of the measurement process. This paper includes a model developed for the evaluation of uncertainty in measuring flatness, based on the repeatability of the sampled coordinate of a point. The proposed model was verified on the standard for flatness - optical glass. The testing recommended by the standard proved the validity of the model. Further research will focus on the interaction of CMM uncertainty with the size of sampling, distribution of sampling and involving different shape deviations as characteristics of the production process.

5. REFERENCES


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