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Uncertainty of measurement for design engineers

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Abstract

Paper presents simple software for evaluation of uncertainty for measurements carried out on CMMs. The input data are coefficients from MPE_E formulae for CMM as well as metrological characteristic (type of dimension or geometrical deviation). The evaluated uncertainty enables the designer preliminary judgement if the available measuring equipment enables proper verification of the products (if the assumed tolerances are not too narrow comparing to possibilities in the range of product verification). Attention is brought to the fact that on up-to-date technical drawings, to achieve unambiguous interpretation, more often tolerances of position and tolerance of profile any surface are used. The operation of the EMU-CMMUncertainty™ software is discussed. On a few examples of coordinate measurement models the software principle of work is explained and uncertainty budgets presented.

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Keywords: coordinate measuring machines, uncertainty evaluation, geometrical product specifications

1. Introduction

Most of geometrical measurements in machine building industry is carried out by means of coordinate measuring systems, in particular coordinate measuring machines (CMM). The uncertainty of coordinate measurements depends on many factors, as in the case for any other measurements. The most important factors are accuracy of measuring machines, environmental conditions, measuring strategy (differing by designer of the measuring process and, to a certain extent, geometrical shape of the workpiece), as well as the workpiece itself (e.g. its stiffness, form deviations, surface roughness, CTE) [1,2]. It is often not duly realized that measurement uncertainty for different geometrical characteristics can differ significantly even if carried out on the same measuring machine.

According to standards ISO 8015 [3] and ISO 14405-1 [4], it is important that designer defines the accuracy requirements in an unambiguous way because otherwise it can generate additional source of uncertainty. This means especially that the designer should avoid using toleranced dimensions and instead apply tolerance of position and/or profile any surface.

Designer, when specifying the requirements for manufacturing accuracy (tolerances), takes into account the function of the object. Moreover, he should know the measurement capability of the manufacturer i.e. achievable measurement uncertainty. He must also remember that it is commonly accepted that the ratio of the measurement uncertainty and the tolerance shall not be greater than 1:5.

Two methods of uncertainty evaluation of coordinate measurement are known and standardized to certain extent. First is the experimental method based on the multiple measurement of the calibrated workpiece having similar form to the manufactured workpiece. The second is the simulation

Nomenclature

CMM	coordinate measuring machine
CTE	coefficient of thermal expansion
u	standard uncertainty
U	expanded uncertainty
MPE_E	maximum permissible error of indication
x, y, z	coordinates
A, B, C, D, S	characteristic points
R	radius
l	geometrical deviation
$\partial l/\partial r$	sensitivity coefficient

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technique which in the online version enables evaluating the uncertainty after performing the measurement. However, the designer needs to know estimations of the measurement uncertainty already at the design stage, when setting tolerance values for particular characteristics.

Authors recommend that designers use the software for offline evaluation of measurement uncertainty of coordinate measurements presented in this publication. Use of the software requires basic knowledge in coordinate measuring technique. In particular the knowledge about how to design the measuring process as well as about the CMM types and working principle.

2. Geometrical characteristics of machine parts

The geometrical characteristics of machine parts are dimensions and geometrical deviations, i.e. deviations of form, orientation, location and run-out. Up-to-date approach to geometrical product specification (GPS) assumes that toleranced dimensions should only be applied to so called features of size [4,5]. In other cases one should use geometrical tolerances [6,7,8,9], where a special role has the tolerance of position and the tolerance of profile any surface.

Tolerances of dimensions for elements which are not features of size shall only be applied in case of low requirements (e.g. in case of using general tolerances [10]), i.e. in case where the lack of unambiguous specification of geometry does not interfere with the proper acceptance or rejection of the product [11].

3. Coordinate measuring systems

Now-a-days the term coordinate measuring systems is applied to [12]: classical CMM, measuring arms, optical and multisensor machines, laser and structured light scanners, CTs, laser-trackers, and others in which the measurement information are coordinates of points in certain coordinate system. This information is next processed by special software installed on a computer being integral part of the measurement system, in order to evaluate necessary geometrical characteristics.

The information processing is usually two-stage. On the first stage, from sets of points the definition parameters of geometrical features (planes, circles, cylinders etc.) are calculated. The parameters are vectors determining location and orientation of the features and one or two scalars describing linear or angular dimensions of the features. On this stage various association criteria are used (e.g. Gaussian, minimax). Some parameters are directly geometrical characteristics to be measured (e.g. diameter of a cylinder o circle, cone angle).

On the second stage, using geometrical links (constructions) further characteristics are evaluated which describe the relations between two or more geometrical features (e.g. position deviation of hole's axis in regards to datum system). The software of coordinate measuring machines includes functions and options which enable evaluation of necessary characteristics.

4. Accuracy of coordinate measuring systems

To describe the accuracy of any measuring device one or more metrological characteristics can be defined [13]. For example, for well-known device which is a micrometre, following characteristics are defined [14]:

- full surface contact error (limited by MPE_J),
- repeatability (limited by MPE_R),
- partial surface contact error (limited by MPE_E).

Basic metrological characteristics for coordinate measuring machines are:

- error of indication for size measurements E (limited by MPE_E) [15,16],
- probing error P (limited by MPE_P) [17].

In 2009, the standard concerning performance tests for classical CMMs [16] introduced new characteristics:

- length measurement error with zero ram axis stylus tip offset, E_0 (limited by $E_{0,\mathrm{MPE}}$),
- length measurement error with ram axis stylus tip offset of L, E_{150} (limited by $E_{L,\mathrm{MPE}}$),
- repeatability range of the length measurement error, R_0 (limited by $R_{0,\mathrm{MPL}}$).

Other parts of the standard ISO 10360 dealing with acceptance and reverification tests for coordinate measuring systems introduce many other metrological characteristics, specific for different types of these systems. E.g. for CMMs with optical distance sensors [18] among others one can find:

- $P_{\mathrm{S:X:Opt}}$ – probing size error (limited by $P_{\mathrm{S:X:Opt,MPE}}$),
- $E_{\mathrm{Bi:X:Opt}}$ – bi-directional length measurement error (limited by $E_{\mathrm{Bi:X:Opt,MPE}}$).

A few new parts of the standard are under development.

5. Uncertainty of coordinate measurement

In the literature concerned with uncertainty of geometrical measurements [1] many sources of errors (uncertainty components) are mentioned. Usually as the most important following influence groups are mentioned: measuring equipment, environmental conditions, operator and the measured workpiece.

As mentioned in Introduction, the uncertainty of coordinate measurements depends mainly on accuracy of the measuring machine, environmental conditions, measuring strategy and characteristics of the workpiece (shape, dimensions, CTE). The measurement strategy applied by the CMM operator is the element which is highly determined by the designer considering the up-to-date geometrical product specification.

The difficulty in the evaluation of uncertainty of coordinate measurements comes, in great extent, from the fact that in general case the uncertainty of measurement of different geometrical characteristics even measured on the same measuring machine is different and for each characteristic must be evaluated separately.

Two method of uncertainty evaluation of coordinate measurement are known. First method is experimental consisting on multiple measurements of calibrated workpiece od the shape and dimensions similar to the manufactured workpieces [19,20]. Second is simulation technique [21,22]. The on-line version of the simulation software is part of the