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Influence of laser tracker noise on the uncertainty of machine tool volumetric verification using the Monte Carlo method

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ABSTRACT

Verification of workpieces is typically performed in the post-process with coordinate measuring machines, thereby increasing the manufacturing cycle time. However, machine tools presently can perform contact measuring operations by using a probe. Moreover, there is a growing need for in-process inspection of workpieces. Therefore, using the machine tool itself for the verification whilst the workpiece remains clamped to the machine can lead to an improvement in manufacturing efficiency, cost reduction, higher energy saving and better equipment productivity. However, the use of touch probes as a measurement tool in manufacturing requires some preparatory works. Firstly, the accuracy of the machine tool should be improved to reduce the influence of its geometric errors. Secondly, the uncertainties in calibration and measuring procedure should be determined to obtain the measurement uncertainty. This study presents a new tool that can analyse the effect of different verification parameters in calibration uncertainty based on Monte Carlo method. On the basis of the actual tests performed on a milling machine and its geometric errors, the effect of laser tracker measurement noise in calibration uncertainty is investigated.

1. Introduction

Industrial sectors such as aeronautics, automotive, renewable energy and nuclear power, demand manufacturing of components with high accuracy but with minimum costs. The transportation of these components to an environmentally controlled metrological laboratory leads to an increase in manufacturing time, thereby increasing the manufacturing costs. The integration of the workpiece verification process into the machine tool (MT) can reduce the manufacturing time because transportation is not necessary. Moreover, whilst the workpiece remains clamped to the MT, the same coordinate system utilised during the manufacturing process can be used for the measurements and rework. Hence, manufacturing time and machining waste materials are significantly reduced, thereby minimising the costs without affecting the product quality. To reach this goal, traceable dimensional metrology techniques must be incorporated in the MT to ensure that the resultant manufacturing program can produce the required output within the specified tolerance [1].

Through MT calibration, the influence of MT's combined geometric errors is determined. Thus, the MT accuracy is increased and the influence of these systematic errors is reduced through software compensation. The MT geometric error is the difference between the actual response of the MT to a command issued according to the accepted protocol of that machine's operation and the response anticipated by that protocol [2]. Errors are broadly classified into the following two categories: quasi-static and dynamic [3]. Quasi-static errors are those between the tool and workpiece and are related to the structure of the MT. These errors gradually vary with time, caused by sources such as geometric, kinematic and thermally induced errors. Meanwhile, dynamic errors are caused by sources such as spindle error motion, vibrations and controller errors [4]. Each axis of an MT movement can be described by six degrees of freedom, that is, three translations and three rotations. Thus, a three-axis MT has 21 components of geometric and kinematic errors, that is, six errors per axis plus a squareness error between each pair of axes. The notation of the geometric errors is standardised in accordance with the International Organization for Standardization (ISO) 841 [5] and VDI 2617-3 [6].

Each geometric error can be measured individually via direct measurement techniques, or the combined errors can be determined using indirect measurements. UNE-ISO 230-1:2014 [7] is an international standard that specifies the methods for testing the accuracy of MTs by using direct measurements, operating under either no-load or quasi-static conditions. By using direct

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measurement, the influence of each error of each axis is determined in a particular position in the workspace of the MT [3]. By using indirect measurement methods, the combined influence of MT geometric errors is determined on the basis of the multi-axis movement and MT kinematic model [8,9]. Trapet *et al.* [10] proposed in 1991 a method for evaluating all error parameters for three-axis machines by using only a 2D reference object. Whilst direct measurement provides the actual physical behaviour of each error, indirect measurement provides an interrelated set of optimal values. However, with indirect measurements, the relationship between the geometric errors is not investigated, and the approximation functions obtained are directly extrapolated to the entire MT workspace. Similarly, each error needs its own assembly measurement procedure and data processing, hence substantially increasing the verification time. These are the main reasons why volumetric verification based on indirect measurements that use laser tracer [11–13], laser tracker (LT) [14–16], or ball bar [17] as measurement systems is more popular than geometric verification based on direct measurements that use laser interferometer, levels, etc., particularly for evaluating long-range MTs.

MT verification process improves the measurement capability, as well as the associated verification uncertainty value. It characterises the dispersion of results in relation to the geometric errors obtained and the sources of errors that affect them. This verification process is considered particularly in different manufacturing and quality assurance processes [18,19]. This process is also required when the MT is used as the first step in the measurement system to obtain a traceable measurement system.

The ISO has developed and published various guidelines for the representation of measurement uncertainty, such as the UNE-ISO/TR 230-9 [20] standard for measurement uncertainty estimation for machine tool test and ISO/TS 14253-2 [21], which are widely accepted. These standards combine the estimation of different error sources and their associated typical uncertainties to determine the uncertainty associated with the overall process. Thus, the accuracy and metrological characteristics of an MT as a measurement system are related to the measurement system, MT and calibration conditions used. The "Guide to the expression of uncertainty in measurement" (GUM) [22] provides the basic framework for evaluating the uncertainty in measurement, but it is not suitable in nonlinear processes such as MT calibrations based on volumetric verification. The Monte Carlo method is recommended to obtain the uncertainty for each point of the MT workspace in the case of a 3D measurement system. The obtained shape is ellipsoid with axes $u_x(P)$, $u_y(P)$ and $u_z(P)$. The ellipsoid represents the volume in which determining the true value of the measured point is possible.

In metrology, the value of a measurement must be given with its uncertainty value. The uncertainty value is a quantitative indication of the quality of the measurement result. Recent research has focused on the study of uncertainty of MTs and coordinate measuring machines (CMMs). Liebrich *et al.* [23] used a simulation to investigate the influence of geometric errors of the CMM on the calibration of a 3D ball plate. Jankowski and Woźniak [24] proposed the use of master artefacts in 2D and 3D for testing the performance of probes for MTs and CMMs. Radlovački *et al.* [25] used the Monte Carlo method to evaluate the uncertainty in measuring flatness based on the repeatability of sample coordinates of a point.

This study uses a simulation software developed by the authors to verify how the different factors with influence on the volumetric verification affect the calibration uncertainty. The software allows the use of different probabilistic distribution functions (PDFs) to characterise the behaviour of each error source. Among the various uncertainty sources, this study focuses on the influence of LT measurement noise. Hence, actual tests are performed using a milling machine with the XFYZ configuration, an LT (Leica LTD 600) as the external measurement system, a touch probe as the onboard measurement system and the software developed by the authors.

2. Comparison of GUM and Monte Carlo methods to determine the uncertainty of MT volumetric verification process

2.1. Volumetric verification and influencing factors

Volumetric verification is based on an intensive process of identification of parameters by using a kinematic model of the MT. By minimising the difference between the theoretical and actual pairs of points by using the MT kinematic model, the combined influence of MT geometric errors is obtained. Their behaviours are modelled, and the mean square volumetric error of the machine (Ve_{LT}) is minimised using nonlinear optimisation techniques [8].

As shown in Fig. 1, the principal uncertainty sources that influence MT verification are divided into three groups, namely, MT, measurement and verification and measurement system uncertainties.

2.2. Main differences between GUM and Monte Carlo methods

The GUM provides a framework for evaluating and expressing measurement uncertainty. Supplement 1 to the GUM describes the problem of uncertainty evaluation in terms of probability density functions. It provides the procedure to obtain the best estimate.

Whilst the GUM focuses on evaluating Type A, Type B and combined uncertainties, the Monte Carlo method uses a large number of samples, with different probabilistic functions, to obtain the final uncertainty distribution through the measurement equation (Fig. 2). The Monte Carlo method uses the computational capacity of modern computers to simulate a large number of pseudo random numbers. Thus, it allows simulation of complex systems from a probabilistic point of view [26].

However, the estimation of uncertainties by using the GUM relies on assumptions that are not always fulfilled. The adequacy limitations of the GUM are as follows:

- The mathematical model that describes the process is nonlinear. When the model presents strong elements of nonlinearity, the approximation made by the GUM approach may not be sufficient to estimate the uncertainty value correctly.
- The central limit theorem states that, in most situations, the combination of a large number of distributions results in a normal distribution. However, the resultant distribution in various actual cases presents an asymmetric behaviour, thus invalidating the assumption used in the central limit theorem.
- The expanded uncertainty calculated by the GUM does not always present an analytical solution.
- The input quantities are not symmetrical, or some of the input sources are much larger than the others.
- The order of magnitude of the estimated output variable and that of the associated standard uncertainty are approximately the same.

Supplement 1 of the GUM provides the steps to be followed when the Monte Carlo method is used (Fig. 3).

1. Definition of the measurand and input quantities: Several sources of uncertainty affect the MT volumetric verification. The principal contributions are uncertainty associated with the MT (e.g. environmental conditions, MT characteristics, etc.), uncertainty related to the measurement system