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Developments in automated flexible gauging and the uncertainty associated with comparative coordinate measurement

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Abstract

Traditional manufacturing uses coordinate measuring machines (CMMs) or component-specific gauging for in-process and post-process inspection. In assessing the fitness for purpose of these measuring systems, it is necessary to evaluate the uncertainty associated with CMM measurement. However, this is not straightforward since the measurement results are subject to a large range of factors including systematic and environmental effects that are difficult to quantify. In addition, machine tool errors and thermal effects of the machine and component can have a significant impact on the comparison between on-machine measurement, in-process measurement and post-process inspection. Coordinate measurements can also be made in a gauging/comparator mode in which measurements of a work piece are compared with those of a calibrated master artefact, and many of the difficulties associated with evaluating the measurement uncertainties are avoided since many of the systematic effects cancel out. Therefore, the use of flexible gauging either as part of an automated or manually-served workflow is particularly beneficial.

Keywords: gauging, comparator, measurement uncertainty

1. Introduction

Coordinate measuring machines (CMMs) or component-specific gauging are used, in traditional manufacturing, for in-process and post-process inspection. However, it is necessary to evaluate the associated measurement uncertainty. While in principle, one can apply the uncertainty evaluation methodologies presented in the Guide to the Expression of Uncertainty in Measurement [1] to CMM measurement [2], this is not straightforward since the measurement results are subject to a large range of influence factors, such as systematic and environmental effects, which are difficult to quantify. In addition, machine tool errors and thermal effects of the machine and component in particular can have a significant impact on the comparison between on-machine measurement, in-process measurement and post-process inspection.

Coordinate measurements can also be made in a gauging/comparator mode in which measurements of a work piece are compared with those of a calibrated master artefact [3]. The main advantage is that the measuring system has only to provide relative measurements, not absolute measurements: the absolute reference is provided by the master artefact. In addition, many of the difficulties associated with evaluating the uncertainties associated with measurement systems operating in absolute mode are largely avoided since many of the systematic effects associated with the system cancel out.

The purpose of this paper is to discuss uncertainty evaluation associated with comparative coordinate measurements and to assess the advantages of the comparator method. The paper also explores the potential of modern automated gauging in comparison with traditional gauging systems.

2. An uncertainty model for coordinate measuring

A general approach for modelling uncertainty associated with coordinate measuring systems (CMSs) is given in [4]. The model enables us to construct a $3m \times 3m$ variance matrix V associated with a set of m data points $\boldsymbol{x}_i = (x_i, y_i, z_i)$. The variance matrix has up to three components, a random component that depends on the repeatability of the system, a systematic component perhaps derived from an error model and constructed in terms of empirical functions describing, for example, scale and squareness errors and other kinematic errors, and a component reflecting spatially-correlated effects that compensate for behaviour not accounted for in the error model. The degree of spatial correlation depends on a length scale parameter λ. If the distance between two points is small relative to λ, then the machine errors at those two points are highly correlated, otherwise they are mutually independent.

3. Uncertainties associated with comparator measurements

The idea of using a CMS in comparator mode is as follows. The CMS measures a calibrated master artefact and a test artefact, nominally having the same geometry as the master artefact, to provide data sets $\{\boldsymbol{x}_i^*\}$ and $\{\boldsymbol{x}_i\}$, $i = 1, \ldots m$, respectively. We also assume that the nominal geometry can be used to determine the normal vectors $\boldsymbol{n}_i^*$ to the master artefact at the measured points. The CMS uses the same fixturing and measurement strategy for both artefacts so that the two sets of measurements are nominally the same and are in the same coordinate system (or frame of reference). The differences between the two sets of measurements are primarily due to the small differences or form error in the geometry of the two artefacts. The goal of the comparator-mode measurement is to transfer the calibration information associated with the master artefact to that for the test artefact.

The uncertainty methodology allows us to evaluate/calculate the variance matrix associated with the differences $\Delta\boldsymbol{x}_i = \boldsymbol{x}_i - \boldsymbol{x}_i^*$ and the uncertainties associated with the distances $\Delta d_i = (\boldsymbol{x}_i - \boldsymbol{x}_i^*)^{\mathrm{T}}\boldsymbol{n}_i^*$. The fact that the two sets of data are close to each other means that the systematic effects are highly (positively) correlated with each other, so that in evaluating the uncertainties, these largely cancel out and the main uncertainty contribution comes from the repeatability of the CMS. If the repeatability of the CMS is σ mm (k = 1), then the uncertainty associated with Δd_i will be of the order of $\sqrt{2}\sigma$ mm, (k = 1). If the form error at $\boldsymbol{x}_i^*$ on the master artefact is estimated to be f_i^* as a result of the calibration, then the form error f_i at $\boldsymbol{x}_i$ on the test artefact is estimated by $f_i^* + \Delta d_i$, with associated uncertainty $u(f_i)$ given by $u^2(f_i) = u^2(f_i^*) + u^2(\Delta d_i)$. Thus, the uncertainty associated with a statement about the test artefact has a component brought in from the calibration of the master artefact. The results of numerical simulations similar to those reported in [4] involving models of a CMM and a comparator typically showed that $u(f_i^*)$ =0.002 5 mm while $u(\Delta d_i)$ is in the range 0.001 5 mm to 0.002 5 mm with the upper value being associated with a model of a comparator representing a performance considerably poorer than most practical systems. The results show that the uncertainties associated with the test artefact tend to be dominated by the brought-in component, with the comparator contributing to a modest increase in uncertainty.

A two-level full factorial design was performed to investigate the effect of (A) measurement mode in scanning and touch-trigger probing (TTP), (B) part-alignment procedure in terms of the number of contact points used for each geometric feature measured, and (C) part misalignment from rotation between master and measure coordinate frames, on the length comparator measurement uncertainty. The study was carried out using a 100 mm gauge block and the Renishaw Equator gauging system, operating in Golden Compare mode (assumes the master part is produced to drawing nominals). The gauge block was measured immediately after mastering and repeated ten times without re-mastering. Table 1 shows the measurement results with their associated expanded uncertainties for k=2 and a 95% confidence level.

Table 1. Results from the experimental design.

Factors			Mean value [mm]	U [µm]
A	B	C		
Scanning	Large	0.57°	99.99987	0.21
TTP	Large	0.57°	99.99954	0.59
Scanning	Minimum	0.57°	99.99960	0.49
TTP	Minimum	0.57°	100.00016	0.27
Scanning	Large	1.15°	99.99981	0.31
TTP	Large	1.15°	100.00035	0.47
Scanning	Minimum	1.15°	99.99964	0.45
TTP	Minimum	1.15°	100.00032	0.52

The results in Table 1 show the measurement uncertainty of the comparator technique (at 24°C ± 0.5°C temperatures), which are lower than would be expected from an absolute measurement under workshop conditions.

4. Coordinate measurement in a shop floor environment

The traditional approach to process control in the shop floor environment is based on hard gauging. However, CMSs, in particular, CMMs are being increasingly employed because of their flexibility, assuming that supporting form and tolerance assessment software is available and can produce reliable, accurate results. The flexibility and accuracy are dependent on the development of error correction models and their calibration using measurements of standards that are themselves calibrated and traceable to the standard for length. The calibration allows an error map to be constructed for the complete working volume of the CMM and, in principle, enables the accurate measurement of a range of geometries. The calibration can be characterised as *global* since it involves the complete measuring volume, applies to the measurement of any geometry, accounts for changes in probe stylus and is assumed to hold over a significant period of time, usually many months. However, the error map is valid only if there is no change in the CMM kinematic behaviour and the environmental conditions are controlled within specified limits. These environmental conditions are unlikely to be met in a shop floor environment.

The use of a calibrated master artefact by a CMS in comparator mode can be thought of as a *local* calibration of the CMS, local in the sense that it need only apply to that part of the working volume in the near-neighbourhood of the surface of the master/test artefact, and local in time. The variability of the environmental conditions will determine the frequency at which the master artefact is measured, relative to measurements of the test artefacts. The validity of the comparison does not depend on the validity of complex error models that describe the global behaviour of the CMS. The extrapolation from master to test artefact depends only on small length scales over which these errors can be assumed to be highly correlated, as described in the uncertainty model [4]. This also means that the specification of the environmental conditions can be relaxed considerably, so long as both the master and test artefacts experience the same conditions. In a machining environment, finite element models/measurements can be used to predict when a machined test artefact will equilibrate thermally to the ambient environment and enable an accurate comparison to be made.

5. Conclusions

This paper has discussed uncertainty modelling associated with coordinate measurement in comparator mode and how it can be used to assess the uncertainty contribution from the comparison of a test artefact and a master artefact. The combination of an accurately calibrated master artefact and comparator mode measurements goes a considerable way to achieving accurate form and tolerance assessment in shop floor conditions, with potentially significant shortening of feedback loops in machining environments.

Further work is required to quantify the benefits that can be achieved in a production environment and to develop best practice and supporting documentary standards.

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