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Modelling uncertainty associated with comparative coordinate measurement through analysis of variance techniques

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Abstract
Over the last few years, various techniques and metrological instruments have been proposed to achieve accurate process control on the shop floor at low cost. An efficient solution that has been recently adopted for this complex task is to perform coordinate measurement in comparator mode in order to eliminate the influence of systematic effects associated with the measurement system. In this way, more challenging parts can be inspected in the shop floor environment and higher quality products can be produced while also enabling feedback to the production loop. This paper is concerned with the development of a statistical model for uncertainty associated with comparative coordinate measurement through analysis of variance (ANOVA) techniques. It employs the Renishaw Equator comparative gauging system and a production part with thirteen circular features of three different diameters. An experimental design is applied to investigate the influence of two key factors and their interaction on the comparator measurement uncertainty. The factors of interest are the scanning speed and the sampling point density. In particular, three different scanning speeds and two different sampling point densities are considered. The measurands of interest are the circularity of each circular feature. The present experimental design is meant to be representative of the actual working conditions in which the automated flexible gauge is used. The Equator has been designed for high speed comparative gauging on the shop floor with possibly wide temperature variation. Therefore, two replicates are used at different temperature conditions to decouple the influence of environmental effects and thus drawing more refined conclusions on the statistical significance.

Keywords: comparator gauge, measurement uncertainty, design of experiments, analysis of variance, regression analysis, scanning, circularity.

1. Introduction

In traditional manufacturing, dimensional inspection is performed either using manual methods such as hard gauges or using automated systems such as coordinate measuring machines (CMMs). Although CMMs are considered as accurate and flexible metrological systems, most cannot maintain their measurement capability on the shop floor because they have not been designed for operating in varying temperature conditions. On the other hand, inspecting manufactured parts using hard gauges is time consuming and inflexible, requires costly hardware changes when the design of the parts changes, and usually leads to high measurement uncertainties.

The demand in manufacturing for inspecting complex parts with tighter tolerances, at higher speeds, in shop floor conditions, has led to many developments in industrial dimensional metrology during the last few years. In particular, motivated by the need for in-process feedback and the fact that one of the most critical factors affecting CMM performance on the shop floor is the ambient temperature, Renishaw has patented a novel software-driven gauging system called Equator to fill the gap between CMM measurement and custom hard gauging. The Renishaw Equator is an adjustable variable gauge that employs the comparator principle through software to account for the influence of systematic effects associated with the coordinate measuring system (CMS) [1, 2]. Therefore, the problem of evaluating the uncertainties associated with complex mechatronic systems such as CMMs, which are influenced by both random and systematic effects, is simplified to a great extent. The Equator gauging machine is based on an easily scaleable and adaptable parallel kinematic structure to minimise the machine's dynamic errors at high measurement speeds. The two main compare methods employed by the Equator flexible gauge are the Golden Compare and the CMM Compare. The Golden Compare method requires a reference (master) artefact to calibrate the Equator, whereas the CMM Compare method uses a production part that has been previously calibrated by an accurate CMS such as a CMM.

The purpose of this paper is to study the performance of the Equator in evaluating circularity using the design of experiments (DOE) approach and develop a statistical model for uncertainty associated with comparative coordinate measurement.

2. Experimental work

A full factorial design was performed, using the Renishaw Equator operating in Golden Compare mode, to investigate the influence of scanning speed and sampling point density on the comparator measurement uncertainty when evaluating circularity. The part (Figure 1) used is a production part that has thirteen circular features: six small-size holes with a nominal diameter of 3.6 mm, six medium-size holes with a nominal diameter of 6 mm, and a large circle with a nominal diameter of 80 mm. The measurands of interest were the circularity of all circular features: the circularity of small-size holes $Y_1, \dots, Y_6$, the circularity of medium-size holes $Y_7, \dots, Y_{12}$, and the circularity of large circle Y_{13}. For the factor of scanning speed, three levels were used. In particular, the first level corresponds to: 5 mm/s for the small-size holes, 10 mm/s for the medium-size holes, and 25 mm/s for the large circle. Levels 2 and 3 are the double and quadruple values, respectively, of the scanning speeds used for level 1. Regarding the factor of sampling point density, two levels were used: level 1 corresponds to a sampling distance (the distance between sample points on the scan path, in the current units) of 0.5, and level 2 to a sampling distance of 0.1. The measurement of the part was followed immediately after mastering and repeated 20 times, without re-mastering used to compensate for any shop floor temperature change. To decouple the influence of environmental effects two replicates were used. The first experimental run was performed at 28.5 °C ± 0.5 °C while the second at 22.5 °C ± 0.5 °C.

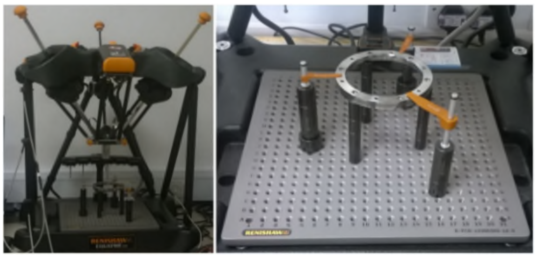

Figure 1. Test setup on Renishaw Equator gauge.

3. Statistical modelling

The three different scanning speeds can be labelled as $S_i (1 \leq i \leq 3)$ and the two different sampling point densities as $D_j (1 \leq j \leq 2)$. Consequently, six different sample mean values $\bar{x}_{ij} (i = 1, \dots, 3;\ j = 1, 2)$ and associated standard uncertainties $u(x_{ij}) = s(\bar{x}_{ij}) = \frac{s}{\sqrt{n}}$, where s is the sample standard deviation and n is the number of repeated measurements for each i and j, can be obtained for each replicate and measurand $Y = \{Y_1, \dots, Y_{13}\}$. However, $\bar{x}_{ij}$ is a random variable due to a random, uncorrelated effect ϵ with $p(\epsilon) = \mathrm{N}(\epsilon \mid 0, \sigma^2)$. In particular, S_i and D_j are the controlled factors, while ϵ is an uncontrolled or unassigned factor. In order to investigate whether S_i and D_j have a significant influence on the measurand Y, consider the following model:

$$y_{ijn} = \mu + S_i + D_j + (SD)_{ij} + \epsilon_{ijn} \quad (1)$$

where y_{ijn} is the nth observed value of each measurand for each i and j, μ is the population mean value and $(SD)_{ij}$ is the effect of the interaction between the factors. Consequently, y_{ijn} is also Gaussian (at least for a relatively large number of repeated measurements n), and this was verified by performing a normality test for each measurand. Considering the uncertainty evaluation methodology for substitution measurement [3], the statistical model for the uncertainty component associated with the measurement procedure can be obtained by:

$$u(x_{ij}) = \frac{\sqrt{\frac{1}{n-1} \sum_{r=1}^{n} (x_{ijr} - \bar{x}_{ij})^2}}{\sqrt{n}} \quad (2)$$

Therefore, the expanded combined uncertainty can be given by:

$$U_{ij} = k\sqrt{u(x_{ij})^2 + u(cal)^2 + u(b)^2 + u(w_{ij})^2} + |b| \quad (3)$$

where k is the coverage factor, $u(cal)$ is the standard uncertainty obtained by the calibration of the master artefact, $u(b)$ is the standard uncertainty associated with the systematic error $b = \bar{x}_{ij} - y_{cal}$, and $u(w_{ij})$ is the standard uncertainty associated with material and manufacturing variations. Considering the standard uncertainty of the mean value of the measurements for $k = 2$, Table 1 includes the analysis of variance (ANOVA) results where R^2 is the percentage of the response variable variation explained by the linear regression model in Minitab. The statistically significant factors and second order factor interactions for 95% confidence level (p-values < 0.05) are highlighted with bold.

Table 1. ANOVA results.

Measurands	**p-values**			R^2
	S_i	D_j	$(SD)_{ij}$	
Y_1	**0.000**	**0.002**	**0.020**	98.28 %
Y_2	**0.001**	0.097	**0.020**	92.71 %
Y_3	**0.001**	**0.020**	0.843	92.31 %
Y_4	**0.011**	**0.030**	0.730	83.37 %
Y_5	**0.000**	**0.000**	**0.007**	98.55 %
Y_6	**0.000**	**0.002**	**0.024**	99.04 %
Y_7	**0.000**	**0.005**	0.597	93.78 %
Y_8	**0.002**	**0.032**	0.431	89.71 %
Y_9	**0.000**	**0.010**	0.333	94.33 %
Y_{10}	**0.000**	**0.003**	0.092	97.55 %
Y_{11}	**0.000**	**0.000**	0.602	98.34 %
Y_{12}	**0.000**	**0.019**	0.412	95.00 %
Y_{13}	**0.000**	0.642	**0.033**	98.47 %

Based on Table 1, it can be concluded that the scanning speed has a higher influence on the comparator measurement uncertainty than the sampling point density and that their interaction is of less statistical significance. Finally, the main effects plots for all the measurands showed that the comparator measurement uncertainty associated with circularity increases as the scanning speed and sampling point density increase.

4. Conclusions

This paper has developed a statistical model for comparator measurement uncertainty associated with circularity and shown that the influence of the factors and their interaction on the comparator measurement uncertainty vary with feature size.

Further work is required to quantify the influence of other factors on the uncertainty associated with comparative coordinate measurement.

References

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