FACTORS AFFECTING MEASUREMENT UNCERTAINTY IN INDUSTRIAL CMM WORK

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Abstract. *An investigation is described, aimed at estimating effects of several factors on measurement uncertainty within an industrial environment. The case study concerns mainly tolerance verification on a coordinate measuring machine of a rather complex part. Obtained results highlight the importance of probe qualification in the case at hand, and show how substantial savings in cycle time may be obtained.*

Keywords: *Coordinate measuring machine, Measurement variability, Design of experiments, Industrial case study.*

1. INTRODUCTION

Customer satisfaction requirements and keen competition typical of today's markets make quality assurance programmes and proactive quality management a must in industry. Coordinate Measuring Machines (CMMs) for off-line inspection are widely used in industry; selected points of workpiece surface are probed, and their coordinates or derived quantities compared with specified values. Measurement variability is a major issue, since international tolerance verification standards, e.g. ISO 14253-1:1998, declare conformity and product acceptance, whenever measurement results fall within rated tolerance band, deducting measurement uncertainty at both ends, see Fig. 1. Non conformity is declared and rejection occurs should measurement results fall beyond tolerance band, augmented by measurement uncertainty at either end. Results falling in the "grey zone are best dealt with by

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agreement between supplier and customer, see ASME B89.7.3.1:2001. Estimates of measurement uncertainty - mandatory according to ISO 9004:2009 – are derived mainly in terms of variability of the measurement process.

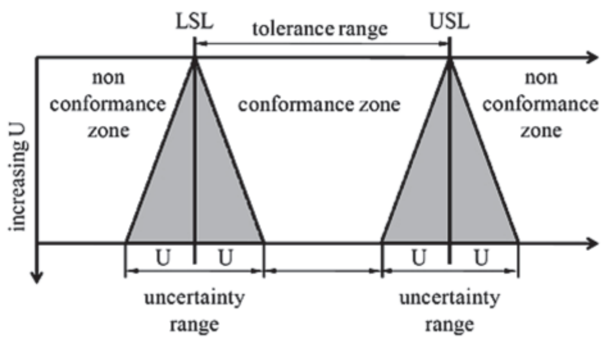

Figure 1: Effect of measurement uncertainty on conformance zone (Lanza *et al.*, 2010)

Measurements of complex parts often exhibit uncertainties exceeding expectations formed in terms of e.g. stated Maximum Permissible Error *MPE* (ISO 10360-2:2001). Checks of geometric tolerances may be plagued by discrepancies quite larger than those pertaining to measurements of length or diameter (Aggogeri *et al.*, 2011). Origins of trouble may be traced to tight time schedules, leading to increase probe speed and cut down on probe qualification and part soaking time, in order to reduce measurement cycle time.

Experimental evaluation of measurement variability on a CMM in an industrial environment involved an automotive component manufacturer, supplying components and subassemblies to leading European automakers. The measurement process was investigated to estimate effects on measurement variability of such factors affecting part flow as *probe speed*, *probe qualification*, and *piece temperature*. Several factors involving metrological and other aspects were observed to cause substantial effects, yielding information on where to look for potential sources of trouble.

2. MEASUREMENT VARIABILITY IN CMM INSPECTION

Control of measurement variability is of paramount importance, since within GUM framework (JCGM 100:2008) results must include information about their uncertainty in order to cater for practical exploitation. Use of properly calibrated and maintained CMM by qualified operators, may not guarantee compatibility among results even obtained under similar conditions (Gentili and Aggogeri, 2004).

The main origin of difficulties is the very versatility of CMM; capability of measuring most dimensional characteristics of elaborate workpieces entails inherent complexity. Measurement setup, strategy, evaluation software, and the measurand interact to each other, contributing to measurement variability.

Several approaches were adopted in measurement variability evaluation using CMM (Weckenmann and Knauer, 1998; Wilhelm *et al.*, 2001). A brief review of the main concepts is presented with particular focus on the main industrial factors liable to impact on the final results. Such factors fall into three main groups, see Fig. 2:

- *MPE:* extreme value of measurement error permitted by regulation, according to definition given in JCGM 200:2008 (VIM). Declared by CMM supplier, may be calculated a priori in measurement uncertainty evaluation. MPE refers to sources of uncertainty caused by errors inherent to CMM design, scales and geometry, probing system and dynamics (Wilhelm *et al.*, 2001).
- *Reproducibility:* inclusive of variability due to factors related to practical measurement activities (VIM 2.24), i.e. environment, operator, measurement setup, strategy, workpiece, software. Environmental influences include deviations from reference temperature, temperature fluctuations and gradients, impacting on workpiece, equipment and readings. Therefore, temperature deviations should be compensated by calculation with respect to measuring equipment and, to some extent, with respect to the workpiece (Weckenmann and Knauer, 1998). Skills of the operator in charge of selecting clamping, positioning, probing force, probe selection, speed, configuration, and measurement task details, are an important factor affecting variability. A further important element is measuring strategy, in terms of number and distribution of measured points; adequacy of sampling, interaction of sampling strategy with form error (Edgeworth and Wilhelm, 1999), interactions of sampling with complex forms and uncertainty due to inadequate datum (Wilhelm *et al.*, 2001) fall within this category, affected by operator's experience. Measurement error due to workpiece is related to such contributions as due to accessibility restrictions, sampling distribution (Bourdet *et al.*, 1993), clamping effects and distortions, contact mechanics, surface finish (Anbari *et al.*, 1990), and elastic deformation due to probing forces, the latter contribution lending itself to software evaluation.
- *Feature Form Errors:* covering departures of actual part shape from nominal geometry. Point measurements would still deviate from nominally perfect shape owing e.g. to manufacturing process signature.

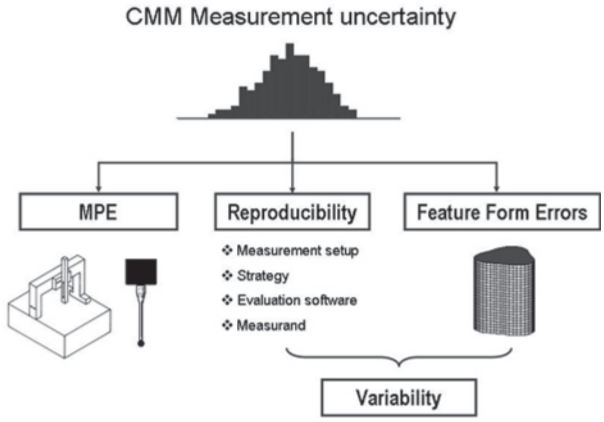

Figure 2: CMM measurement uncertainty (Summerhays *et al.*, 2002).

Uncertainty may either be evaluated a priori, according to statistical criteria and expert assessment as mandated by GUM, or *a posteriori* on experimental evidence, in terms of measurements performed under conditions closely approximating those of actual operation. Straightforward application of GUM is limited to cases where relationships between measurand and measured parameters are known, or may be adequately approximated (Genta, 2010). Among approaches developed to address the problem of uncertainty assessment, a commonly applied one is the "substitution method" (ISO/TS 15530-3:2004), based on comparative measurements with reference to a calibrated artifact, exhibiting all features of concerned workpiece.

International comparisons showed that evaluation of CMM measurement variability can be problematic (Balsamo *et al.*, 1997). Experimental results of industrial applications showed a worst case scenario mainly due to inherent complexity of measurement missions; they are generally related to geometric tolerances verification on manufactured workpieces performed with several machines setups, a limited amount of sampled points and all the other complications that real life cases show off.

3. STATEMENT OF PROBLEM

The case considered, concerning evaluation of measurement variability on a CMM during practical exploitation, entailed unraveling a rather complex pattern of effects. An experimental investigation was carried out to identify main components of measurement variability in verification of geometric tolerances, concerning a platform with a bushing (Fig. 3). This component was also previously investigated (Aggogeri *et al.*, 2011).

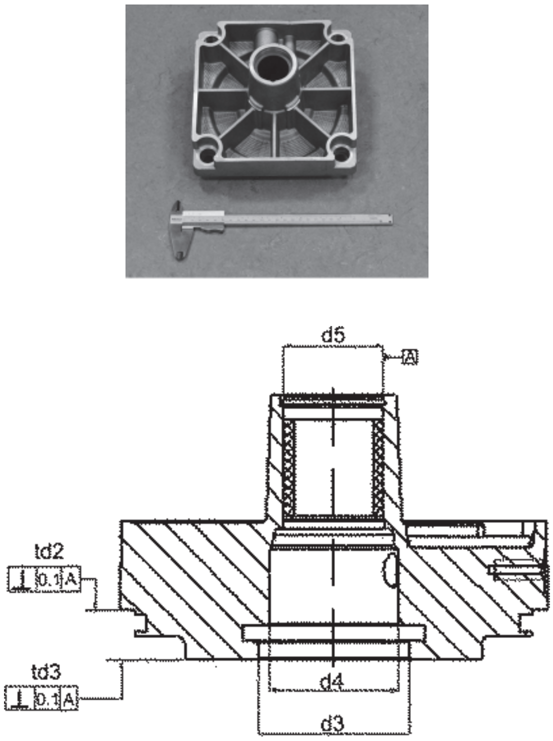

Figure 3: Measured workpiece (a), and cross section showing main dimensions and features with tolerances *td2* and *td3* considered (b);
td1, *td4*, *td5* and *td6* (concentricity on datum *A*, *td1* on side of *d5*, *td4* on large diameter between surfaces of *td2* and *td3*, *td5* on diameter *d3* and *td6* on diameter *d4*) are not shown.

Factors and levels were selected on account of potentially achievable advantages in terms of time and cost reduction, CMM speed and qualification process being often critical in terms of flow cycle time and productivity. An increase of CMM speed of 30%, and dispensing with CMM qualification process for every batch exchange, may increase production rate by as much as 5%. And, control of piece temperature effect on measurement variability may enable moving CMM process control straight on the manufacturing line, instead of confining measurements to metrological laboratory. Labour and time consuming shuttling parts may thus be dispensed with, and timely information on process deviations may be delivered right on the spot, impacting further on production efficiency. The measurement process was investigated with a balanced design, aimed at estimating of single and combined effects of factors considered, namely *probe speed*, *probe qualification* and *piece temperature*, on measurement variability. Factors were considered at two levels; two quantitative, namely probe speed (0.9 mm/s and 1.2 mm/s), piece temperature (19 °C and 23 °C), and another qualitative, probe qualification (Y, N) indicating whether qualification is performed immediately before every measurement task, or dispensed with altogether. The eight treatment combinations were carried out on the six tolerated features with five replications.

Selection of factors and levels was performed involving company managers, operators and researchers in a brainstorming session, considering the trade-off between increase of productivity (reducing control phase cycle time) and measurement quality. Six tolerance verification tasks were considered, four concerning position (concentricity) and two orientation (perpendicularity), specification limit for all being 0.1 mm. According to features inspected two different probes with spherical tips were used. Measurements were carried out by an expert operator using a fixed bridge DEA Global Status CMM, suitable for complex workpieces, with an operating volume of x=905 mm, y=1005 mm and z=605 mm. Maximum permissible error MPE_E - as stated by the manufacturer, verified according to ISO 10360-2:2001, and guaranteed within a given temperature range - is (2.9 + L/250) µm, L being the measured length in millimeters.

4. DATA ANALYSIS

Tab. 1 shows the main statistics of tolerated features, compared with the medians of the SIT Calibration Centre readings which provided a reliable reference. Median was preferred, providing a more robust estimate of central tendency than arithmetical average, and almost as efficient as the latter for small sample sizes as in the case at hand. For each tolerated feature, the specification limit equals 0.100 mm. Boxplots depict main characteristics of data in a compact manner (Fig. 4). Substantial discrepancies appear in Fig. 4, besides the rather broad range of results exhibited for tolerance verification. In particular four tolerated features show verification results with a large variability, entailing substantial chances of rejection of sound pieces or acceptance of nonconforming ones. Furthermore, scatter concerning *td1* is substantially different from those pertaining to the other tolerated features. Some outliers also appear there.

Table 1: Statistics pertaining to tolerated features for the complete data set, and in qualified probe condition.

Code	Ref. Median/	**Median**/mm		**Mean**/mm		**St. Dev.**/mm		**Range**/mm	
	mm	**All**	**Qual.**	**All**	**Qual.**	**All**	**Qual.**	**All**	**Qual.**
td1	0.064	0.059	0.060	0.057	0.060	0.007	0.004	0.030	0.013
td2	0.015	0.032	0.028	0.060	0.029	0.042	0.005	0.111	0.020
td3	0.004	0.014	0.012	0.028	0.011	0.022	0.003	0.060	0.011
td4	0.005	0.017	0.015	0.046	0.014	0.043	0.005	0.112	0.019
td5	0.005	0.024	0.019	0.055	0.019	0.048	0.006	0.127	0.025
td6	0.006	0.018	0.014	0.043	0.014	0.039	0.005	0.102	0.018

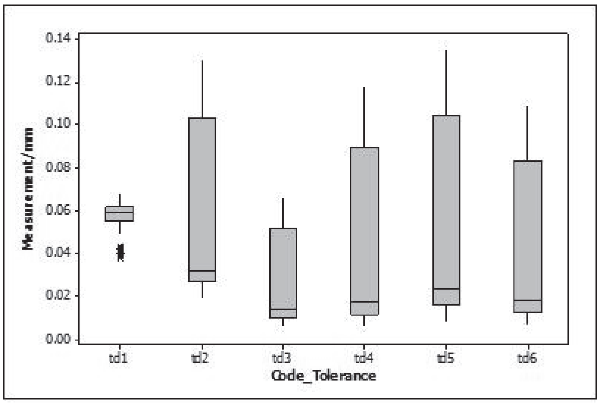

Figure 4: Boxplot of results corresponding to tolerated features for the complete data set.

Data unstacked by probe qualification status (N/Y) are plotted in Fig. 5 (a) and (b). Systematic effects may be observed, traceable to whether probe qualification was performed, or not, prior to every measurements task, particularly in terms of reproducibility (mostly discontinuity, as shown in Fig. 5(a)). Only *td1*, among the measurements performed without prior probe qualification, shows a different pattern. An explanation may be found in peculiar geometrical features pertaining to *td4*, *td5* and *td6*, whose references, being located on opposite sides of the piece, entail a particular sequence of probe orientation.

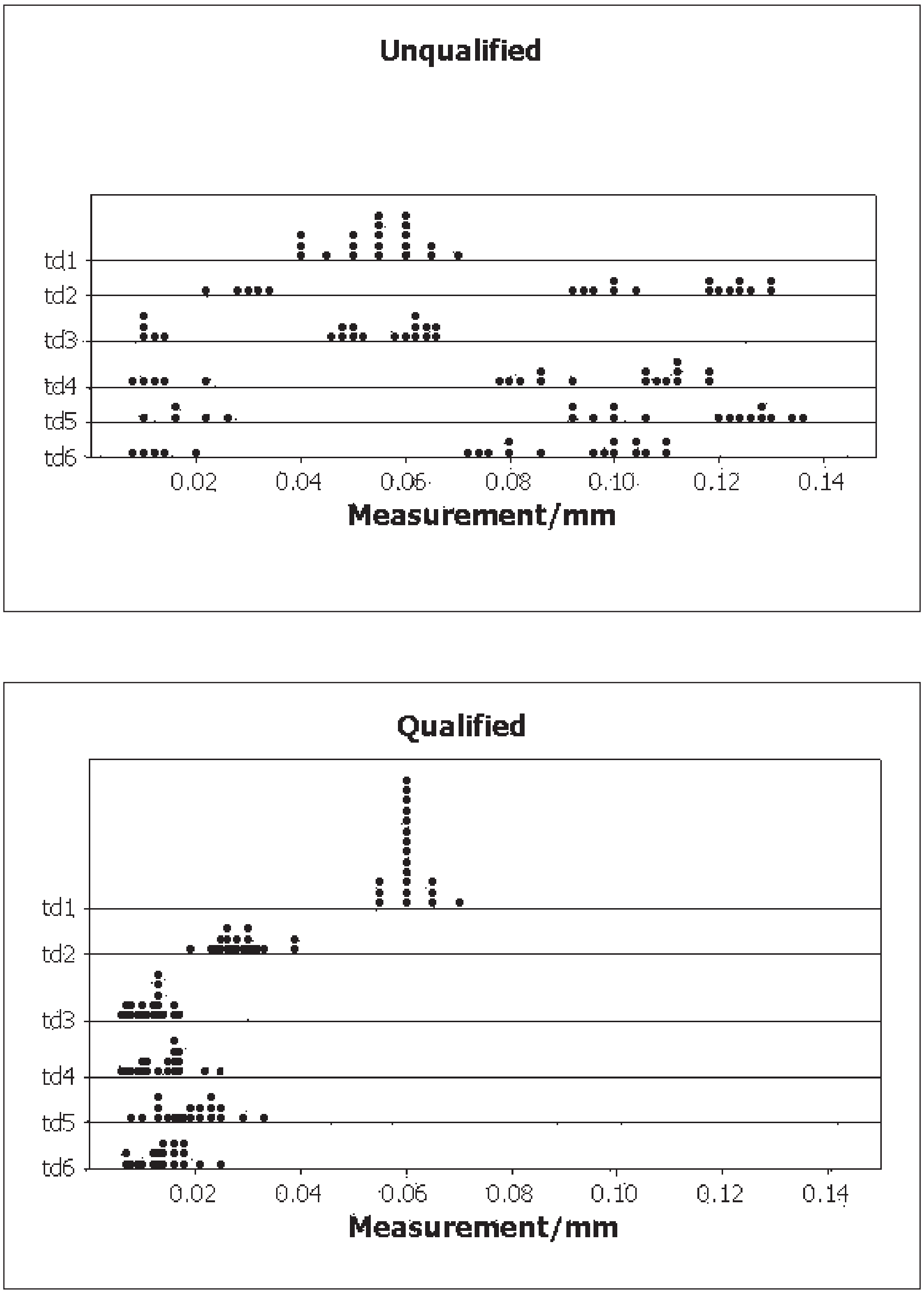

Figure 5: Dotplot of verification values for tolerated features in unqualified (a) and qualified probe condition (b).

As suggested by the results of EDA – Exploratory Data Analysis (Tukey, 1977) – an *F*-test concerning the variability of *td1* and that pertaining to the group of the other tolerated features was performed. The difference between readings and reference value provided by the SIT Calibration Centre, per verified tolerance, was considered as response (DIFF). Since the null hypothesis of equal variability may be rejected at a very high level, data concerning *td1* were excluded from further analysis.

Subsequently, another *F*-test pertaining to variability in unqualified and qualified probe conditions was performed, considering as response DIFF after excluding data concerning *td1*. Again, the null hypothesis of equal variability may be rejected at a very high level, pointing out to a systematic effect due to *probe qualification*.

Let us now consider data in a qualified probe condition only. According to chi-square test, the hypothesis of normality for data concerning the response DIFF may not be rejected unless taking a risk of error exceeding 10%. Main statistics for the data subset considered are listed in Tab. 1, exhibiting a significant reduction of the system variability for every verified tolerance, as shown also in Fig. 6 (where *td1* is also included for the sake of completeness). In those conditions the possible existence of systematic effects of probe speed and piece temperature on measurement variability may be investigated.

Two main factors are considered, *probe speed* and *piece temperature*, the type of tolerance being considered as a covariate.

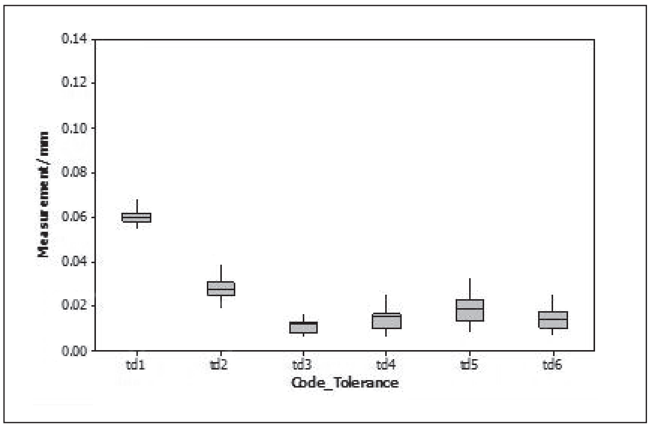

Figure 6: Boxplot of results obtained for tolerated features in qualified probe condition.

Main effects are summarised in Fig. 7(a). While speed exhibits definitely an effect on the response, temperature however plays also a substantial role, as shown in Fig. 7(b), through its interaction with speed.

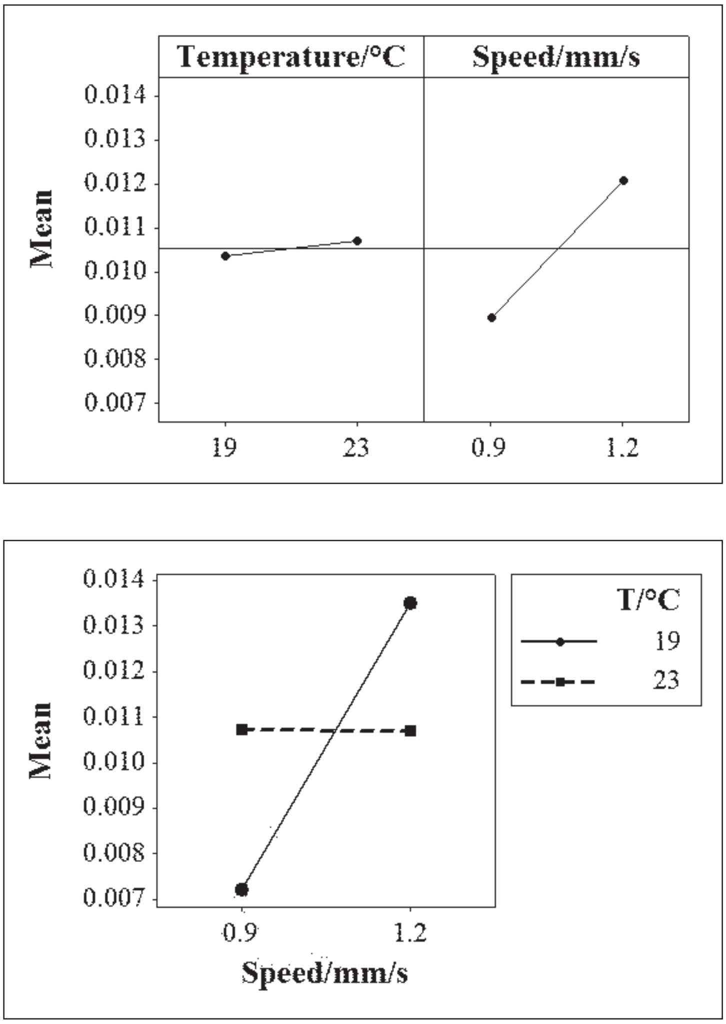

Figure 7: Main effects of quantitative factors (temperature and speed) on measurement variability (a), and relevant interaction (b).

While the effects of probe speed and its interaction with temperature are clearly visible, their contribution to overall variability is however rather small, explaining about 10% of total variation only. Therefore, in a qualified probe condition, a substantial increase of speed does not downgrade unduly results, a finding of substantial industrial relevance.

5. DISCUSSION

This paper was addressed to an industrial problem: how to improve measurement processes by controlling variability factors, concerning mainly process reproducibility and feature form errors? A factorial experiment was exploited to estimate single and combined effects on measurement variability of probe speed and qualification, and piece temperature. Factors and levels were selected in the light of expert opinion.

Some observations are in order concerning apparently disturbing features of the data set at hand. As typical of quantitative information pertaining to real world, departures from classical assumptions must be reckoned with. Non linearity, heteroschedasticity and mavericks are part and parcel of nature, and inevitably spill into experimental data; they may however be taken care of by subsetting data into less objectionable groups, on which conventional analysis may be legitimately performed. EDA was also exploited to derive meaningful information even from less than ideal data sets.

Variability of results was found to be strongly affected by probe qualification, underlining its importance particularly for pieces with complex shape. Data analysis pertaining to a subset of tests with previous probe qualification shows clearly the effects of speed and its interaction with temperature. Increasing probe speed is shown to be a viable option, leading to substantial advantages in terms of productivity and lead time reduction. Application of the proposed approach in variability evaluation using CMM is discussed, underlining relationships between system measurement variability and tolerance verification.

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