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Comparison of the measurement performance of high precision multi-axis metal cutting machine tools

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Abstract

High precision manufacturers continuously seek out disruptive technologies to improve the quality, cost, and delivery of their products. With the advancement of machine tool and measurement technology many companies are ready to capitalise on the opportunity of on-machine measurement (OMM). Coupled with business case, manufacturing engineers are now questioning whether OMM can soon eliminate the need for post-process inspection systems. Metrologists will however argue that the machining environment is too hostile and that there are numerous process variables which need consideration before traceable measurement on-the-machine can be achieved. In this paper we test the measurement capability of five new multi-axis machine tools enabled as OMM systems via on-machine probing. All systems are tested under various operating conditions in order to better understand the effects of potentially significant variables. This investigation has found that key process variables such as machine tool warm-up and tool-change cycles can have an effect on machine tool measurement repeatability. New data presented here is important to many manufacturers whom are considering utilising their high precision multi-axis machine tools for both the creation and verification of their products.

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Keywords: Machine tool metrology; On-machine Measurement (OMM); On-machine Verification (OMV); Sample inspection; Data-driven manufacturing

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1. Introduction

The synergy between manufacturing and measurement is absolute. Without capability in measurement there cannot be capability in the manufactured product. Classically, measurement within a manufacturing environment is associated to realisation of a manufactured product against its design specification. Modern high precision manufacturing is characterised by low batch, high variety, tight tolerance, and high value products [1]. Capable dimensional measurement is integral for the successful achievement of these requirements [2]. Coordinate-measurement-machines (CMMs) are utilised to perform dimensional measurements due to their metrological capability and flexibility [3]. On-machine probing (OMP) is used frequently as part of the machining cycle effectively replacing the need for manual gauging [4]. These systems are most often used to set machine-workpiece datums and alignments. However there is a now a strong trend to use such systems for on-machine product verification (OMV) purposes [5], driven by an ambition to bring measurement closer to the machining process.

Historically manufacturing organisations ensure quality through product measurement only [6]. This 'gate-keeping' approach does not directly improve or guarantee quality, as it is based on a strategy of defect detection, not prevention. Many therefore argue that measurement of final product attributes after a machining process is too late. Good measurement practice however dictates that measurement systems are independent of manufacturing systems for metrological reasons. For high-precision monolithic products CMMs are the only measurement systems capable to perform with an acceptable level of uncertainty [7]. Manufacturing

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engineers are often frustrated by CMMs as they are a major source of process bottlenecking and inefficiency [5], [8]. As the need for more adaptive and data driven manufacturing increases the feedback delay from the CMM to the machine tool is generally regarded as unacceptable. A reduction in the reliance of CMMs is likely to result in benefits associated to cost and time saving, pro-active process control, elimination of non-value adding tasks and agile manufacturing, as indicated by Table 1.

Table 1 - Benefits associated to on-machine inspection [1],[5],[8]

Benefit	Through
Cost and Time Saving	• Decreasing lead-time required for gauges and fixtures • Minimising need for design fabrication, maintenance of hard gauges, fixtures & equipment • Reducing inspection queue time and inspection time • Reducing part set-ups • Reducing CMM part queuing • Eliminating rework of non-conforming product
Reactive Inspection to Pro-active Control	• Integrating quality control into the product realisation process • Characterised and qualified processes to increase product reliability • Focusing resources on prevention of defects instead of detection in the end (proactive intervention) • Generating real-time process knowledge and control for product quality improvement • Enhancing small batch acceptance capability
Elimination of non-value adding activities	• Reduced final-inspection • Data-driven sampling plans • Part waiting and measurement gate bottlenecking • Design, fabrication and maintenance of hard gauges • Reworking of non-conforming parts
Agile Machining	• Quick responses to product design changes • Rapid integration of new and existing technologies such as probing strategy, error compensation, data analysis software • Fixture design technology can be integrated into the OMI system • Machine health monitoring

2. Theory

On-machine gauging (OMG) has been present on the shop-floor for over 20 years [9]. Today most multi-axis machine tools utilise spindle mounted touch-trigger probing to set-up and adjust co-ordinate and tool offsets. Such systems replace the need for manual gauging necessary for workpiece alignment, tool length calculation, datum setting and in the case of +5-axis systems tool rotation-centre point control [10]. OMP systems can also be used to monitor the size of the features being machined, to validate the part movement, distortion, and feature dimensions [8].

Where used, on-machine process verification (OMV) via OMP is typically used at the end of a machining cycle whilst the part is still constrained and in the machining environment. This form of OMV can be used to verify that a machining process has performed as expected and produced the correct part geometry. Advantageously, non-conformance can be detected closer to the point of feature creation, and if necessary reworked, in-situ.

The measurements taken by machine tools can be easily affected by errors introduced before and during the measurement process. The sources of such measurement uncertainty is often due to: 1) Errors due to machine tool, 2) Errors due to environment, 3) Probing strategy, 4) Workpiece, 5) Data evaluation strategies and 6) Probing Systems. As illustrated by Figure 1, these sources of error are synonymous with CMM equipment. However the nature in which such errors manifest themselves or are controlled on a machine tool can vary dramatically.

Substantial research programmes have been carried out by academic, national, and international institutes, as well as industrial companies, leading to a number of different methods and technologies aimed at improving the measurement capability of machine tools. Such methods and technology include rapid machine tool calibration and verification techniques, OMM probing systems development, machine tool design and controller optimisation, and off-line OMP design, execution, data processing and analysis software [1], [4]–[6], [8], [11]–[18].

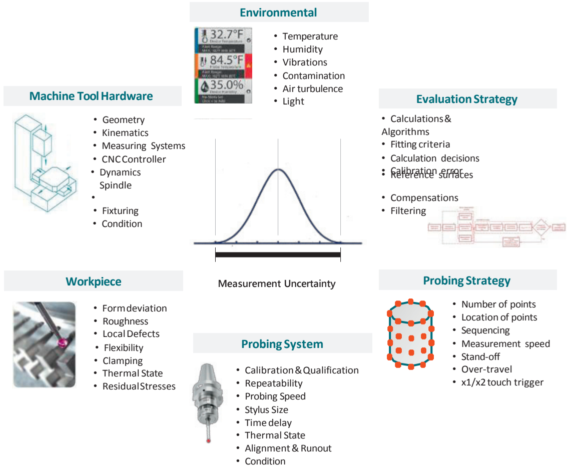


Fig. 1. Measurement uncertainty contributors for machine tools

2.1. Standardised methods for machine tool capability evaluation

Standardised methods to evaluate the performance of multi-axis machine tools have been prepared and published by ISO committee TC39/SC2. Their recent ISO 230:10:2011 standard defines the testing procedures required to evaluate the measurement performance of machine tool contacting probing systems [18]. The standard does not include non-contact probing systems or scanning probes. The standard is also not intended to distinguish between the various causes of measurement error, rather the combined influences of machine probing process variables. The standard however remarks that the main influences on machine tool probing performance are: 1) Repeatability of the machine tool, 2)

Geometric accuracy, 3) Contamination, 4) Probing repeatability, 5) Temperature influences, 6) Feed speed, 7) Standoff and over-travel distances, 8) Time delay between probing signal and readout, 9) Surface of workpiece. This standard specifies that it is up to the user to choose, in agreement with the supplier/manufacturer, the acceptance criteria relating to specific properties of a chosen machine probing systems.

Section 6.4 of the ISO 230:10:2011 standard presents a testing regime for evaluating the repeatability of the relocation of a probing tool after a manual or automatic tool change. The testing involves the probing of a reference ring or sphere before and after a tool change cycle. Although the testing regime is useful as a test there is no indication of what the appropriate tolerances are for acceptance purposes (as this is application specific).

2.2. Virtual machine measurement simulation

Virtual measurement simulation software, also referred to uncertainty evaluation software (UES), is gaining popularity in industry [3], [19], [20]. The market need for UES is driven by a joint need to adhere to ISO 9000 standard requirements and reduce cost and time associated to the validation and planning of measurement activities.

The computational simulation of task specific uncertainty estimation for multi-axis measurement devices is predicted as the next paradigm change with respect to manufacturing process control and quality assurance [19], [21]. However where UES systems have been validated caution has been recommended in terms of the impact of variables which may not have been considered, the generalising of results and the relevance of them to ‘real-world’ conditions. Despite this, UES is considered state-of-the-art for CMM equipment and will continue to be significant in the foreseeable future.

As OMM becomes more popular some have attempted to repurpose CMM UES systems for machine tool measurement applications [19], [21], [22]. However, those who have, conclude that such software is still immature for machine application due to a number of key process variables not yet being considered.

Where UES has been complicated to develop for CMM applications it is expected to become more so for machine tools. Typically UES systems are built up using empirically approximated methods, consulting from experienced metrologists, numerical experimentation, and statistical evidence. In the case of machine tool measurement the knowledge base from all these sources is sparse due to the expansive variability of; machine tool configurations, their operating conditions, products, and processes. This is further compounded by the understandable need for machines to be used for machining rather than experimentation.

Despite this, should UES capability be developed to include such variables, the user is still left to decide what the acceptable tolerances for key process variables such as tool change repeatability, pallet change repeatability, warm-up, cool-down where little or no data or guidance exists other than what is provided by the original equipment manufacturer (OEM) or assumed.

Therefore this paper aims to explore, quantify and gain experience in terms of current capability of state-of-the-art multi-axis machining centres when utilised as measurement devices. During this research exercise we have investigated the impact of tool change and machine warm-up/cool-down on the measurement performance of multi-axis machine tools, both critical performance variables for on-machine measurement.

3. Experimental methodology

The experimentation has been split into two stages. In stage one, the measurement capability of six different 5-axis machine tools (from 4 different OEMs), all of XYZBC configuration, were validated against a calibrated artefact at various stages of their warm-up cycles. In stage two, the repeatability of the OMP systems due to tool change was tested on the same five machine tools.

Every effort was made to ensure a consistent process has been used throughout testing. All machine tools utilised for testing were considered as ‘new’ and are located at separate facilities and are operating in conditions approved by the respective OEM i.e. vibration, noise, temperature variance, cleanliness and humidity variance effects measured as negligible. All machine tools have been installed, commissioned, and calibrated by respective OEMs.

A calibrated Zeiss KMG CMM Check® artefact has been utilised in all testing (Figure 2). The equipment is designed for performing measurement checks on CMM equipment. The artefact comprises of a series of calibrated features mounted to a plate, including: a Ø50mm ring gauge, a Ø50mm cylinder, three Ø30mm spheres, and two length bars (50mm and 400mm).

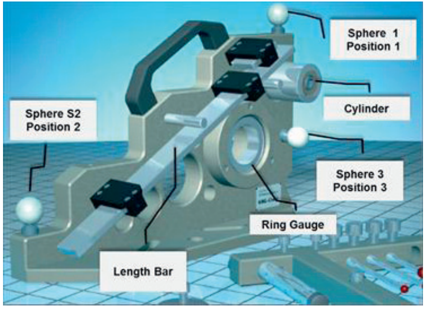


Fig. 2. Zeiss KMG Check Artefact®

Renishaw OMP 400 and MP700 touch trigger strain gauge probing has been used in all tests. Renishaw Inspection Plus software has been used in all cases. The probing system is checked as per manufacturer guidelines before all tests were carried out i.e. tightness of screws, cleanliness. The probing stylus is clocked true to the spindle within 0.005mm T.I.R.

The probing system is qualified on all machines with the same Ø25mm calibration sphere. Two touch probing technique is used in all cases. The experimental results and analysis in this study is limited to the dimensional measurement of a single 30mm Sphere, a 400mm length bar, and the volumetric distance between the centre points of two spheres.

3.1. Sphere 1 (S1) measurement (30mm)

Single sphere position (S1) is measured using 4 points at 90° around circumference and 1 point on top, as per Figure 3.

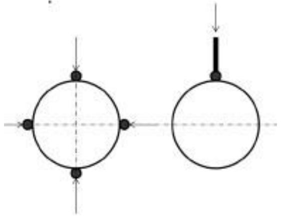


Fig. 3. Sphere position probing routine

Sphere size (S1) is then measured by probing 12 points at 30° intervals on sphere centreline, as per Figure 4.

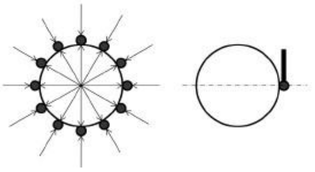


Fig. 4. Sphere size probing routine

3.2. Length bar measurement (400mm)

Angle of length bar (Figure 5) is calculated by probing two points at either end of length bar. A measurement is taken at each end of the length bar using the calculated angle.

Fig. 5. Length bar size probing routine

3.3. Sphere-to-Sphere (S1-S2) centre distance measurement (~447mm)

The position of a second sphere on the KMG artefact is measured as per the probing routine described earlier in this paper. The volumetric distance between the centre points of the two spheres is calculated as:

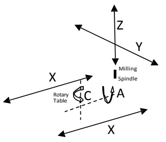
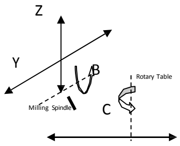
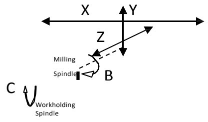
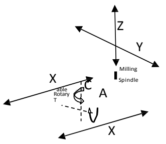
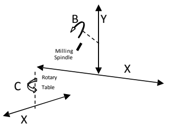
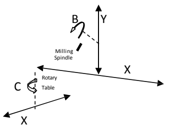
$$\sqrt{\qquad\qquad\qquad} \tag{1}$$

Where 1 and 2 indicate spheres 1 and 2 respectively.

3.4. Machine testing

Table 2 indicates the configuration of each machine, NC details are also provided. Machine tool manufacturer and make specification is not disclosed for commercial and confidentiality reasons.

Table 2 - Machine tools used in testing

Machine	Controller	Axis Configuration
1	Fanuc	
2	OEM	
3	OEM	
4	Siemens	
5	Siemens	
6	Siemens	

Before all experiments; the artefact and probing were checked and cleaned; the probing shank adjustment screws and stylus were checked for tightness; the artefact was securely held on the machine table. The artefact was measured using a temperature gauge each time before it was used to check that its temperature had stabilised to ambient conditions. Probing was clocked to the spindle and qualified before all tests were carried out. Once qualified, machine probing was used to align the artefact to machine axes.

Probing was completed using a two-touch method: Fast feed (3000mm/min) onto the surface, retract, and slow feed (30mm/min) to surface to measure.

4. Results & Analysis

4.1. Test 1: Measurement performance before/after warm up

A set of 10 measurements were performed on each machine before and after a one hour warm-up cycle had been run. Each machine had not been used for a period of at least 12 hours before being switched on. Probing systems were qualified on each machine before use and the artefact was not removed at any time once it was fitted to the machine table. Due to machine configuration and type identical warm-up cycles could not be applied to all machines; warm up details for each machine is presented in Table 3. Warm-up cycles either met or exceeded OEM requirements.

Table 3 - Machine tool warm up conditions

M/c	Warm Up Cycle	Temp. During Testing
1	Machine workholding spindle 1000rpm continuous. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Milling spindle warmed-up.	18-21°C
2	The artefact was located within the machine volume throughout the warm up cycle. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Milling spindle warmed-up.	18-21°C
3	The artefact was located within the machine volume throughout the warm up cycle. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Milling spindle warmed-up.	19-22°C
4	The artefact was located within the machine volume throughout the warm up cycle. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Milling spindle warmed-up.	19-22°C
5	The artefact was not located within the machine volume throughout the warm up cycle. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Turning spindle was warmed up. Milling spindle warmed-up.	21-24°C
6	The artefact was not located within the machine volume throughout the warm up cycle. X,Y,Z traversed to their extremes bi-directionally at 25% maximum feedrate. Turning spindle was warmed up. Milling spindle warmed-up.	21-24°C

4.2. Analysis methodology

Normality (Anderson-Darling), Variance (Levene's or F-test), and T-test (Equal or Non-equal variances) hypothesis tests have been performed in order to asses variance and changes to mean value. Choice of the statistical tool chosen is based on firstly checking before and after data for normality (Anderson-Darling). If the null hypothesis is rejected for either data set (i.e. p<=0.05) then a Levene's test is used to assess variance of both sets of data, otherwise a F-test is utilised. A means test is subsequently performed based on a T-test, where variances are pooled where the null hypothesis had not been rejected for the variance of the data set (i.e. variance p<=0.05).

4.3. Inverted Type 1 gauge study

An inverted Type 1 gauge study analysis is performed on all data sets based on equation (2). This equation is used to calculate a tolerance which would give a capable system.

$$/ \qquad |^{-} \qquad | \qquad (2)$$

Where:

- Cgk = 1.33 (Based on a requirement for 6-sigma capability)
- K = Percentage of tolerance required (=20)
- $\bar{}$ = The mean of all measurements where these are errors from reference
- = The reference value (=0 since error is from reference)
- L = Number of standard deviations to represent half the process spread (=3)
- s = Standard deviation of all measurements

The equation is therefore rearranged to calculate tolerance, as per (3).

$$- \qquad | \quad | \qquad (3)$$

Hence measurement capability is estimated for each machine tool measurement based on feature being measured.

4.4. Sphere 1 measurement

Figure 6 illustrates the range of measurement data of sphere 1 size to nominal for each machine before and after the warm-up cycle has been completed.

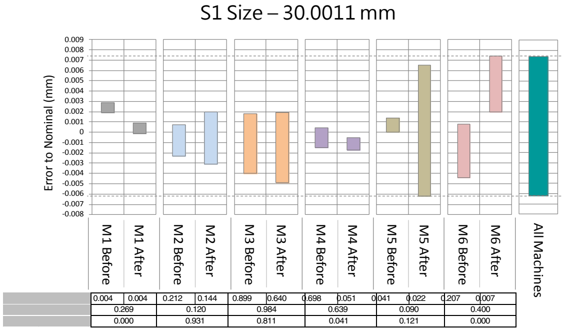
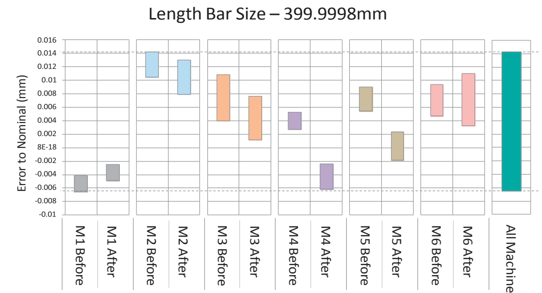


Fig. 6. S1 Size Measurement Before and After Warm-up

As indicated by Figure 6 all machines have measurement variation within ±0.010mm of nominal with all demonstrating different properties before and after warm up. The spread of the data was the same before and after warm-up for all machines. Therefore with sample size no evidence is seen where warm-up improves or degrades the precision of the measurement systems. Indicated by T-test results; the mean of measurements taken by machines 1, 4 and 6 were altered by warm-up.

On calculation of capable tolerances, according to (3), the average full width tolerance was 0.064mm (±0.032mm) with worst case value being 0.127mm (±0.064mm), and best being 0.023mm (±0.017mm).

4.5. Length bar measurement



	M1 Before	M1 After	M2 Before	M2 After	M3 Before	M3 After	M4 Before	M4 After	M5 Before	M5 After	M6 Before	M6 After
Normality (p-value)	0.176	0.639	0.858	0.782	0.780	0.074	0.309	0.741	0.033	0.766	0.367	0.847
Variance (p-value)	0.887		0.571		0.760		0.161		0.584		0.423	
T-test (p-value)	0.002		0.018		0.095		0.000		0.000		0.807	

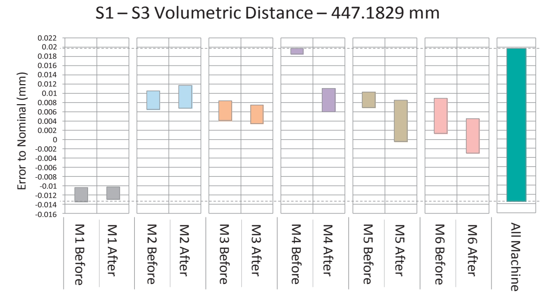
Fig. 7. Length Bar Size Measurement Before and After Warm-up

Figure 7 indicates the measurement variation for all machines when measuring the KMG check length bar before and after warm-up. As indicated by the chart, all machines have a variation within ±0.015mm of nominal. Again, as like with the measurement of S1, all machines demonstrate differences in measurement performance before and after warm-up. In 5 out of 6 case measurement accuracy appears to improve after the warm up cycle has been completed. This may be due to the fact the machines may have been calibrated in their warm state.

On observation of results from the statistical analysis, again results show no change in spread of the measurement data collected before and after machine warm-up for all machines. T-test results indicate that machines 1, 2, 4 and 5 have been affected by warm-up, where a change in mean value has occurred.

On calculation of capable tolerances, according to (3), the average full width tolerance was 0.115mm (±0.058mm) with worst case value being 0.163mm (±0.082mm), and best being 0.046mm (±0.023mm).

4.6. S1-S3 volumetric distance



	M1 Before	M1 After	M2 Before	M2 After	M3 Before	M3 After	M4 Before	M4 After	M5 Before	M5 After	M6 Before	M6 After
Normality (p-value)	0.122	0.963	0.637	0.122	0.004	0.342	0.054	0.832	0.040	0.050	0.004	0.154
Variance (p-value)	0.214		0.710		0.540		0.000		0.224		0.809	
T-test (p-value)	0.512		0.463		0.437		0.000		0.000		0.001	

Fig. 8. S1-S2 Volumetric Distance Before and After Warm-up

Figure 8 indicates the measurement variation for all machines when measuring the centre-points of Sphere 1 and 3 of the Zeiss KMG check artefact before and after warm-up. In this case the overall spread of data for all machines sits between a maximum of 0.020mm and minimum -0.014mm from nominal. In almost all cases the measurement accuracy appears to improve after warm up. Statistical analysis shows that only Machine 4 showed a change in spread of data before and after warm up, where T-testing has shown that machines 4, 5, and 6 show a definitive change in mean value before and after warm-up.

When calculating capability tolerances according to (3), this showed should all machines be used for measurement purposes within a cell, the full width tolerance would be 0.133mm (±0.067mm). Depending on machine, worst case tolerance is 0.203mm (±0.102) and best 0.084mm (±0.042mm). When considering typical tolerances for high precision aerospace components, this would generally be unacceptable for the majority of applications.

4.7. Test 2: Repeatability on tool change

To test the probing repeatability a point on the KMG artefact is measured 10 times in the X, Y and Z plane. Between each measurement a tool change is performed. All machines are run at the same feedrates where all tool change cycle-times are comparable for all machines. In this test only 5 of the 6 machines were tested. All machines have been tested from 'cold' i.e. they have not been utilised or warmed-up for more than 12 hours from commencement of testing.

Figure 9 presents the measurement results from the experiment. It can be seen that all machines are behaving differently on subsequent tool change iterations. Only one of the 5 machines tested show a consistency of reading (within ±0.005mm) in all three planes between tool change cycles.

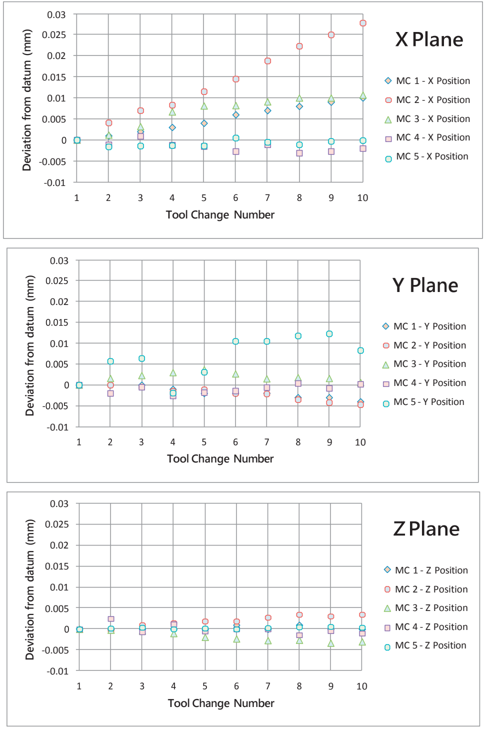


Fig. 9. Machine Tool Probe Repeatability in X,Y & Z

Machine 2 shows the most significant deviation from nominal, where the error in X direction is seen to incrementally increase up to 0.027mm from datum. Machines 1, 3 and 5 also show a similar cumulative incremental deviation in either one or more directions, although less significant than that of Machine 2. Machine 4 shows stability within ±0.005mm in X,Y and Z planes on all 10 tool changes.

4.8. Analysis

Machines have different spindle taper types in some cases. Not enough machines were tested to speculate if tool taper type is a significant factor. The increase in positional deviation could be due to a warm-up of the machine or environmental warm up. Conclusion would be that a probe qualification would be required on every tool change, unless a study has been completed where evidence shows that the machine is stable enough for it not to be required (this dependant on measurement task).

5. Conclusions

Today it is expected that when procuring a state-of-the-art multi-axis machine tool a probing system will be delivered with it. Tolerance permitting, it is not presumptuous to believe that the machine tool can be used as a measurement system, when considering the claims of precision made by equipment providers.

In this study we have taken a tentative step to explore the current capability of state-of-the-art machining centres as measurement devices. A total of six high precision 5-axis machine tools have been experimented on, all current, all produced by different manufacturers, and all located within pre-production environments i.e. influences from other locally operating plant machinery is negligible.

All such machine tools were procured with the purpose to produce high precision monolithic aerospace components and all have demonstrated their capability to do so. When considering these same machine tools as measurement devices we have found that the measurement performance 5 of 6 machines has been affected by tool change and all show evidence of measurement performance deviation from cold to warm. In many cases machines appeared more accurate after warm-up. This is not surprising as it is expected that machines are calibrated in their warm state as per ISO 230 requirements.

Although it is not customary to derive product tolerance from measurement task, we have seen that should a Type 1 gauge study be performed on these machine tools collectively, to achieve a Cgk =1.33, tolerance bands would have to potentially be in the order of ±0.032mm for Ø30mm spherical features and ±0.058mm for lengths of about 400mm.

We have also observed that 4 out of 5 machines have experienced a cumulative deviation on subsequent tool change cycles. The root-cause of this incremental deviation may or may not be the same for all machines. It would therefore be recommended that a probe qualification routine is performed on each tool change, which would subsequently increase cycle-times. Alternatively having a different probing location system (i.e. not reliant on machine spindle taper condition) may be a future consideration.

These machines are considered as state-of-the-art and in a ‘pre-production’ state. Equipment already in production similar or non- are expected to perform less precisely in an industrial setting and deteriorate over their lifetimes. It can therefore be argued that despite ambitions utilising machine tools as measurement devices may still be immature. This study also has implications for any UES software being designed for machine tool measurement application, where effects of probing scheduling considering tool change and machine thermal state will have to be accommodated for.

Acknowledgements

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