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Uncertainty evaluation of on-machine tool measurement on shop floor conditions

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Abstract

For high-value components manufacturing, such as aerospace, automotive, ships and nuclear power parts, there is a significant demand for integrated traceable measurement which could provide fast feedback during the manufacturing processes. Most modern machine tools are equipped with a probing system, meaning that both machining and measurmenting processes could take place on the same machine tool. However, one of the key challenges is that the traceability of in-process measurement on a machine tool is not ensured yet, the measurement results are not reliable enough to provide accuracte and precise process control and product geometry verification. The scientific objective of this study is to evaluate the uncertainty on a machine tool measurement in different environments to understand the uncertainty sources. Therefore, this paper is to test on-machine tool measurement uncertainty in two different conditions on shop floor environment and compare the results.

Keywords: On-machine tool measurement, large machine tool, In-process inspection, uncertainty evaluation

1. Introduction

On-machine tool measurement is one of the promising approaches that offers potential to detect and compensate the errors during the sequence of machining operations. It can enable workpiece geometrical verification against the design and manufacturing standards between various steps to guarantee the designated tolerance of finished parts. This is particularly beneficial to large-volume manufacturing where it is highly desirable to measure in-situ or in-process. The integrated measurement process can significantly reduce the manufacturing time and cost, and prevent safety associated issues, by avoiding the workpiece moving from the manufacturing site to a temperature-controlled coordinate measuring machine (CMM) room.

Most modern machine tools are equipped with a probing system, meaning that both machining and measuring processes could take place on the same machine tool. However, there exist several issues with the on-machine measurement approach. One of the key problems is that the machining and measuring processes suffer the same geometric errors because both of them are performed at the same machine. This will make error sources indistinguishable if no calibration process has been performed before the measurement operations [1]. Therefore, the traceability of the on-machine measurement process is a significant challenge and the measurement results are not reliable for process control and product geometry verification.

2. Measurement uncertainty evaluation methods

Three types of approaches have been considered for uncertainty evaluation on the machine tool. Due to the similarity between a CMM and machine tool, same methods can be used for the assessment of the uncertainty of CMM as well.

1) Calibrated workpiece method

The first approach is based on ISO 15530-3 [2] and substitutes the wokpiece with one calibrated reference artefact then evaluates the uncertainty by means of similarity between the dimension and shape of the artefacts. The manufacturing environment and measurement procedure must be similar during of measurement uncertainty evaluation and actual measurement. This approach is reliable for serial production and usually suitable for small and medium size components. However, this approach is very expensive and arduous for large volume metrology.

2) Numerical simulation method

The second approach introduced by ISO 15530-4 [3] to determine the task specific uncertainty of coordinate measurements. This method is based on a numerical simulation of the measuring process, which considers uncertainty influences and assess the influence quantities. In addition, Monte-Carlo simulation method can be applied for the estimation of measurement uncertainty [4].

3) Uncertainty budget method

This type of methods based on GUM [5]and VDI 2617-11 [6]. In this case, uncertainty evaluation is assessed using an uncertainty budget where the budget should comprise the uncertainty sources that affect the measurement process and the correlation between them.

In the presented research, the approach described in ISO 15530-3 has been selected as the evaluation method as most of the uncertainty influences during the experimental trials are also present on a real on-machine tool measurement. Additionally, ISO 15530-4 and VDI 2617-11 methods require understanding the significance of each uncertainty contributor, which is not guaranteed yet in the shop floor conditions nowadays.

3. On-machine tool measurement uncertainty budget

In general, four type of uncertainty contributors which include systematic errors and random errors should be considered on the uncertainty budget for the on-machine tool measurement [7]:

u_b standard uncertainty associated with the systematic errors of the measurement results;

u_p standard uncertainty associated with the random errors of the measurement results;

u_{cal} standard uncertainty associated with the uncertainty of the workpiece calibration.

u_w standard uncertainty associated with the workpiece material and manufacturing conditions.

Different approaches can be used to assess the systematic error u_b . In our work, systematic error is defined as the difference between calibration value u_{cal} of the measurement results using a CMM and the mean value of the measurement results $\bar{b}$ on the machine tool.

$$u_b = \bar{b} - u_{cal}$$

where $\bar{b} = \frac{1}{n}\sum_{i=1}^{n} b_i$

If the measurement result has not been corrected by the systematic error, the error u_b fully contributes to the uncertainty evaluation.

Standard uncertainty of random errors u_p can be obtained using

$$u_p = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(b_i - \bar{b}\right)^2}$$

The calibration error of the workpiece using a CMM can be assessed by GUM method, which is introduced later in the paper.

Workpiece material properties, form errors and roughness of materials considered as insignificant, due to the selection of material within its required limits and dimensions of the part, therefore, contribution of u_w is neglected in this case. The workpiece has been measured five times straightafter the machining process and also under quasi-static (no-load) condition, respectively. Thus, the combined uncertainty of measurement system u_{ms} and u_{qs} can be assessed using the same formula:

$$U_{ms} = \sqrt{u_{bms} + u_{pms}^2 + u_{cal}^2} \text{ and } U_{qs} = \sqrt{u_{bqs} + u_{pqs}^2 + u_{cal}^2}$$

The expanded measurement uncertainty of the measurement process can be obtained by $U_{em} = U_m \times 2$, with a coverage factor of k=2.

4. Task specific uncertainty evaluation for on-machine tool measurement

The "task specific uncertainty" in coordinate measurement is the measurement uncertainty that is computed according to the uncertainty evaluation methods, when a specific feature is measured using a specific inspection plan. By evaluating fitness-for-purpose for dimensional measurements of workpieces using on-machine tools, this method will determine whether a machine tool is meeting accuracy specifications and is capable of inspecting and manufacturing features on a part with the required accuracy.

The workpiece was produced and measured on the machine tool under investigation and calibrated afterwards using a CMM. The presented research work is focused on assessing the expanded on-machine tool measurement uncertainty in two conditions: after the machining process and under no-load condition.

5. Experiment and data analysis

5.1. Machine tool and materials

The machine tool selected to perform the experimental test is a large scale floor type milling-boring machine tool. It is SORALUCE FX12000 machine tool (see Fig.1.) with volume: X= 12,000 mm, Y= 5,300 mm, Z= 1,900 mm. The computer numerical control (CNC) is a SIEMENS Sinumerik 840D Solution Line CNC controller. The machine tool is placed in a workshop with roughly controlled temperature, which is about 2-3 ℃ variation all year round.

Figure 1. SORALUCE FX12000 large scale machine tool

S355 Structural steel was selected to manufacture the workpiece artefact because it has good mechanical properties, is easy to machine and is inexpensive. The design of workpiece standard refers to "ISO 10791-7, M1-160", which is defined in the ISO 10791-7:2014 standard [8]. Due to the size of the machine tool, the M1-160 test piece was enlarged about four times to provide a more representative component. Fig. 2 shows the CAD model for the workpiece with measured features. A description of the measured features and the specified tolerances of the workpiece is depicted in Table 1. The total time consumption for workpiece manufacturing is approximately 5.5 hours.

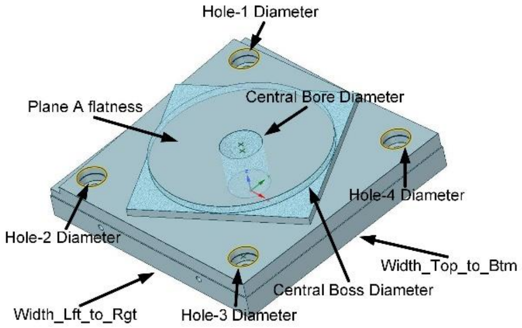


Figure 2. CAD for workpiece with measured geometries

Table 1 Measurement features and specified tolerance for the workpiece

No.	Feature (Unit: mm)	Nominal Value	Tolerance
1	**Plane A flatness**	0	0.080
2	**Central Bore Diameter**	100	±0.070
3	**Central Boss Diameter**	436	±0.070
4	**Width_Lft_to_Rgt**	640	±0.100

5	**Width_Top_to_Btm**	640	±0.100
6	**Hole-1 Diameter**	70	±0.042
7	**Hole-2 Diameter**	70	±0.042
8	**Hole-3 Diameter**	70	±0.042
9	**Hole-4 Diameter**	70	±0.042

A RENISHAW OMP 600 tactile probe was employed on the machine tool to execute the on-machine tool measurement. The software used to collect and process data is HEXAGON PC DMIS-NC. The time for one round of measurement all features, which is defined at Table 1, is half an hour. The measurement was performed five times.

5.2. Setup

The workpiece has been manufactured followed by on-machine tool measurement in the same chucking using a RENISHAW OMP 600 tactile probe. The workpiece has been measured five times on the machine tool after machining. Additionally, the workpiece was measured five times next day on the machine tool under no-load conditions. In both conditions, the measurements results were compensated using integrated software. Fig. 3 shows on-machine tool manufacturing and measurement processes and Fig. 4 shows the workpiece calibration process using a CMM.

Figure 3. Workpiece manufacturing and on-machine tool measurement

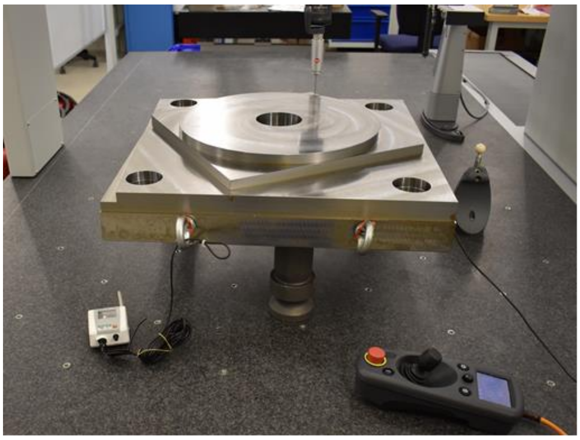


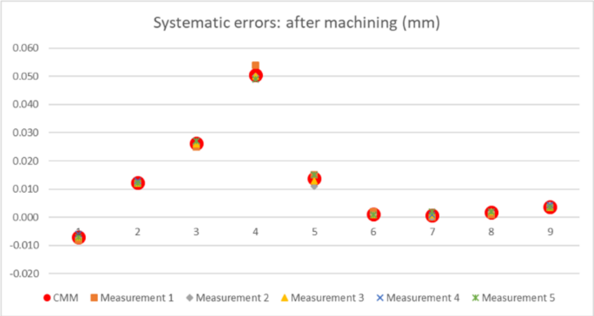
Figure 4. Workpiece calibration using CMM

Finally the workpieces was calibrated using a Hexagon DEA Global Silver CMM, the calibration uncertainty for each measurement feature has been assessed by means of the GUM method.

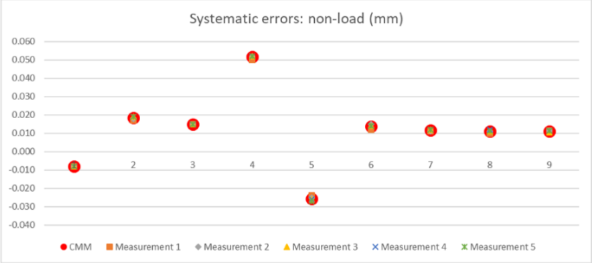
5.3. Experimental uncertainty budget assessment

(1) Systematic error uncertainty (u_b)

The systematic errors (u_b) of the measurement results after machining and under no-load condition are shown in Fig. 5 (a) and (b), respectively. It depicts the mean systematic error of each measured feature. Experimental results show that the biggest systematic error is 0.05 mm, which occurs on length measurement (left to right, X direction), while the mean value for the rest of features is within 0.03 mm.



(a) Systematic errors of the measurement after machining



(b) Systematic errors of the measurement under non-load conditions

Figure 5. Systematic errors of the measurements

(2) Measurement procedure uncertainty (u_p)

In general, the results show a very good repeatability in both conditions. The maximum measurement repeatability after machining is 0.002 mm while the maximum repeatability under non-load conditions is only 0.001 mm. This means the compensation algorithm is very effective. Temperature variation has been recorded two hours before and during the measurement process. The maximum of variation of environment temperature is 2.2 °C after machining and 1.2 °C under non-load conditions. The measurement procedure uncertainties are shown in Fig. 6.

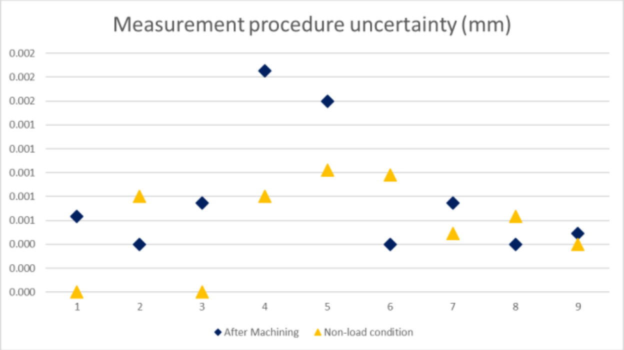


Figure 6. Measurement procedure uncertainties

(3) Calibration uncertainty (u_{cal})

For the CMM measurements, the observed maximum temperature deviation from standard reference temperature (20°C) is 0.1°C. The combined standard uncertainty, calculated according to [5], is 0.001 mm.

(4) Uncertainty budget

Fig. 7 shows the combined task-specific uncertainty assessment on shop floor conditions. The U_{ms} and U_{qs} values are shown in Table 2. Expanded uncertainty results are obtained by $U_{ems} = 2 \times U_{ms}$ and, for a coverage factor of k = 2.

In this test, systematic errors uncertainty (u_b) contributor is the main contributor to the on-machine tool measurement uncertainty budget on shop floor condition.

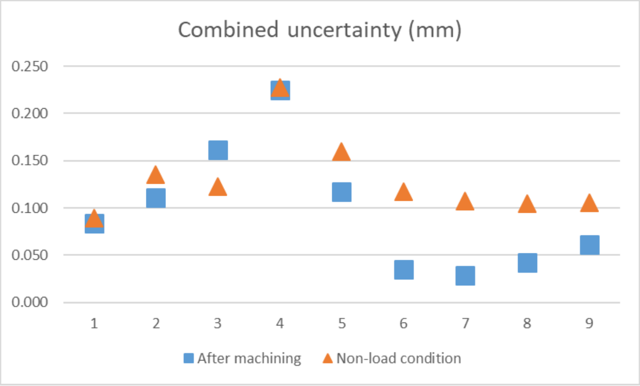


Figure 7. Combined uncertainties (U_m)

Table 2 Combined uncertainties and expanded uncertainties (k=2)

No.	**Feature (Unit: mm)**	**U_{ms}**	**U_{ems}**	**U_{qs}**	**U_{eqs}**
1	**Plane A flatness**	0.084	0.167	0.089	0.167
2	**Central Bore Diameter**	0.110	0.221	0.136	0.221
3	**Central Boss Diameter**	0.162	0.324	0.122	0.324
4	**Width_Lft_to_Rgt**	0.225	0.449	0.227	0.449
5	**Width_Top_to_Btm**	0.117	0.235	0.160	0.235
6	**Hole-1 Diameter**	0.035	0.069	0.117	0.069
7	**Hole-2 Diameter**	0.028	0.057	0.108	0.057
8	**Hole-3 Diameter**	0.042	0.085	0.105	0.085
9	**Hole-4 Diameter**	0.062	0.123	0.106	0.123

6. Conclusions

Reliable on-machine measurements are desirable by industry for effective process control and quality assurance, especially for manufacturing of large scale components. However, the traceability of the on-machine tool measurement is not ensured yet on the shop floor conditions because the process is affected by multiple error sources.

This research explored the uncertainty budgets for on-machine tool measurement under two different conditions in a shop floor environment. For that purpose, the workpiece which is a scaled up version of an artefact referred to in the ISO 15530-3:2011 standard, has been designed and machined as an experimental test artefact. In general, the uncertainty contributors are similar under both conditions.

Experimental results show that systematic error uncertainty (u_b) is the main contributor to the on-machine tool measurement uncertainty budget on shop floor condition, after calibration of probe and temperature compensation. The biggest systematic error (u_b) is about 0.050 mm which happens in the X axis direction. This could be explained by several reasons: measurements are executed on the workshop with temperature values close to 20 °C and the temperature changes relatively slowly. The machining time has been also relatively long (minimum 5.5 hours). In addition, both the machine tool and parts are large so the heat dissipation is relatively quick.

In both conditions, the machine tool shows a good (less than 0.002mm) repeatability and represents a minor error source on the presented experimental exercise. This is because the measuring probe has been always calibrated before inspection and temperature values are close to 20 °C and relatively stable. However, temperature variation could represent another major error source in a measurement scenario where large parts are measured in an environment with temperature values far from 20 °C.

Future work should focus on a fast and reliable calibration of the machine tool geometric errors, which would help to keep systematic errors under control.

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