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CASE STUDY: THE INFLUENCE OF MACHINE TOOL CONDITION CHANGES ON MEASUREMENT ACCURACY USING A WORKPIECE PROBE

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Abstract
This study evaluates the measurement system capability of a three-axis vertical milling center under three machine conditions with varying positioning accuracy. Using a laser interferometer, probe, and calibrated KOBA artifact, length measurements were taken and corrected for thermal expansion. Results show that while none of the machine states achieved full capability for the given 0.015 mm tolerance, states 1 and 3 were suitable for conformity assessment. State 2, despite better deviation results, was limited by significant nonlinearity, increasing uncertainty. The importance of linearity in evaluating measurement system capability is highlighted, particularly when calculating linearity uncertainty.
Keywords:
on machine measurement, positioning accuracy, capability

1 INTRODUCTION

Measurements on CNC machines tools, together with the expansion of technologies based on Industry 4.0 principles, represent new application possibilities. The ability to measure directly on the machine, known as On Machine Measurement (OMM), offers new potential to save costs on auxiliary times, i.e., costs associated with transport, setup, and temperature stabilization at external measurement stations, particularly for medium and large workpieces. [Schmitt 2016]

The use of workpiece probes combined with CNC machines for measurement operations is not intended to replace traditional methods of measurement on coordinate measuring machines (CMM), which will always be more suitable for these operations. On the other hand, for the application of length measurements on CNC in the OMM mode, it is essential to know the current state of the machine [Blecha 2025]. In the article [Holub et al., 2016], the authors focus on testing and evaluating methods of geometric compensations. The goal of these compensations is to eliminate errors caused by machine geometry deviations, thermal expansion, and dynamic stiffness of the CNC machine. The study assessed the effectiveness of these methods in increasing dimensional and geometric accuracy of workpieces. The results of the compensations were verified through circular interpolation measurements and suggest that a combination of positioning accuracy and volumetric compensation can improve machining precision. In the article [Holub 2017], the authors attempt to reduce the time required for machine calibration measurement using the "On the Fly" method, i.e., continuous measurement without stopping. The results show that this measurement method is up to 50% faster than the traditional trigger mode, with minimal geometric influence between the results. This measurement approach is further explored by the authors [Virostkova 2024], who examine the advantages of dynamic measurement of positioning accuracy of CNC machines compared to static measurement. A laser interferometer XL-80 was used on a three-axis vertical machining center to measure the X-axis. The results confirm that dynamic measurement can achieve accuracy comparable to static measurement but with considerable time savings. This approach could be used in further testing of machine capability, with the goal of reducing not only auxiliary times but also eliminating environmental changes during measurement and compensating of CNC machine errors.

Measurement using workpiece probes on CNC machines is described by the authors [Zhuang 2024]. The article provides a comprehensive overview of the current state and research in the field of On Machine Measurement. The publication includes information on measuring path planning, process optimization, process capability, and various scenarios for using OMM at different stages of the manufacturing process. It presents a comprehensive view of the OMM issue.

The authors [Li 2019; Rępalska 2024] deal with the influence of probe errors on measurement accuracy. The goal of both studies is to identify and minimize probe errors. The authors [Rępalska 2024] focus on analyzing probe errors in various measurement tasks (distance, diameter, etc.), where it is experimentally found that residual errors remain even after probe calibration. In contrast, in [Li 2019], the authors propose a compensation method using a calibration sphere and the creation of a 3D map using the

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weighted least squares method and bicubic Coon's interpolation.

In the case of capability calculation, the authors in [Blecha 2022] decided to use five Johanson gauges. These gauges were measured in different machine´s accuracy states and with different point sampling strategies. Finally, the point-to-point method and four accuracy states were chosen. A method for assessing machine capability was created based on VDA5 and ISO 14253-1:2017 standards. The study emphasizes that the geometric accuracy of the CNC machine, its thermal stability, and the surrounding environment significantly affect the measurement accuracy using a touch probe. The authors [Samelova et al., 2024] examine the capability and usability of two measuring systems in a manufacturing environment with a required tolerance of 0.05 mm. One system is a portable measuring arm, and the other is the CNC machine's touch probe. The aim was to assess whether both systems meet the requirements in a manufacturing environment. The KOBA gauge was used, and capability calculations were performed according to ISO 22514-7:2021 and ISO 14253-1:2017 standards. The study shows that although both measurement systems can be used for on-machine measurement under certain conditions, they do not fully meet the stricter requirements of ISO 22514-7:2021.

From the above review, for capability calculation, the following steps are necessary:

- Determine the state (accuracy) of the CNC machine.
- Calibrate the touch probe.
- Evaluate the accuracy of the touch probe.
- Perform measurements for capability calculation.
- Calculate the capability.
- Analyze the results and draw conclusions.

This article evaluates the capability of the measuring system when using the CNC machine as a measuring instrument. The machine is tested at three different positioning accuracy settings known as Condition 1,2 and 3. The results are supplemented with information about the conformity to the specifications and the size of the tolerance field relative to the specified tolerance. Additionally, the minimum tolerance at which the machine would be considered capable and usable is calculated. Proof of capability ensures that the uncertainty of the measurement system is sufficiently low in relation to tolerance. The combined uncertainty is the product of the individual uncertainty components such as calibration, resolution, repeatability, BIAS, linearity, and residual uncertainties. The ANOVA method is used to calculate the uncertainty of linearity, which uses linear regression, which assumes a linear distribution of deviations, which is problematic for a machine tool due to its variability over time. The formula for calculating combined uncertainty is as follows:

$$u_{MS} = \sqrt{u_{CAL}^2 + \max(u_{EVR}^2; u_{RE}^2) + u_{BI}^2 + u_{LIN}^2 + u_{MS.REST}^2} \quad (1)$$

2 CASE STUDY

The study was conducted on an machine MCV 754 Quick, located in the heavy laboratories of the Department of Production Machines, Systems, and Robotics. This three-axis vertical machining center features a C-frame design and a cross table. Two axes (X and Y) move the workpiece, while the Z-axis moves the tool. The machine is operated using a Sinumerik 840D sl control system. The machine specifications, including parameters in accordance with ISO 230-2:2014, are presented in Tab. 1.

Tab. 1: Parameters of machine tool.

Parametres	Value
Axis length X/Y/Z [mm]	754/500/500
Positioning accuracy [mm]	0.012
Positioning repeatability [mm]	0.005

2.1 Equipment of experiment

To measure positioning accuracy according to ISO 230-1:2014, an XL-80 laser interferometer was used. This device enables not only the measurement of positioning accuracy and repeatability but, due to its quick optical component exchange, also supports measurements of straightness, angular errors, flatness, and squareness. With the environmental compensator correcting for temperature, humidity, and atmospheric pressure variations, the system achieves a measurement accuracy of ±0.5 µm/m with 95% confidence under all working conditions.

The machine is equipped with a Renishaw OMP 400 touch probe, which was utilized for tests under ISO 230-10:2023 and ISO 22514-7:2021. This probe is intended for small to medium-sized machining centers. Signal transmission is optical and contact with the measured part is detected using Rengage™ technology, which relies on semiconductor strain gauges. The probe achieves a repeatability of ±0.35 µm, a 2D measurement error of ±0.25 µm, and a 3D measurement error of ±1.75 µm at 2σ. For probe tip diameter calibration, a ring with a diameter of 49.999 mm was used.

To evaluate capability of a the measuring system, a total of three lengths were measured on the KOBA calibration standart placed in the machine tool parallel to the X-axis and approximately in the center of the Y-axis.KOBA is a calibration standard composed of steel with ceramic gauges. According to its calibration certificate, the measurement uncertainty for center-to-center distance is $0.3 + 0.8\times10^{-6}\times L$ (where L is the measured length in mm). For process capability calculations, the highest uncertainty was considered: 0.7 µm. The calibrated lengths used are shown in Table 2.

Tab. 2: Lenghts of the calibration standart.

Nominal Length [mm]	Calibrated Length [mm]
41.3	41,30148
243.5	243,49883
491.1	491.098

2.2 Experimental Setup

The experimental setup is illustrated in Figure 1. The laser interferometer was mounted on the left side of the machine for the duration of the measurements, with the linear reflector fixed in the spindle (static component), while the interferometer was attached to the cross table (moving component). The Y-axis was set approximately at the

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midpoint of its stroke, i.e., position 250 mm in the Machine Coordinate System (MCS). The calibrated KOBA standard was placed beside the optics for positioning accuracy measurement. The "0" gauge of the standard was aligned with the 150 mm position in the MCS. The calibration ring was mounted on the right side, approximately centered relative to the KOBA standard.

Fig. 1: Experimental setup

2.3 Experiment strategy

The case study consists of three machine conditions, each differing primarily in terms of positioning accuracy. Prior to testing, the laser beam was aligned with the X-axis travel of the measured machine. The KOBA standard was inserted into the machine's workspace. For alignment, a Magnetscale linear encoder with a peak-to-peak accuracy of 0.4 µm (per calibration certificate) and the touch probe were used. In the first phase, the KOBA was aligned to be parallel to the X-axis travel (error E_{KOBAY}), as shown in Fig. 2 (top two and lower left). Additionally, it was necessary for the first gauge to be located at the 150 mm in MCS. This was achieved using a combination of the touch probe and linear encoder (Fig. 2, lower right), where the probe determined the MCS position, and if a deviation (E_{KOBAX}) was found, the KOBA fixture was adjusted in the X-direction. The encoder, positioned at the second-to-last block, recorded the displacement. The final alignment in the Z-axis (E_{KOBAZ}) was performed using the touch trigger probe only. After the initial alignment, the errors were: E_{KOBAY} 0.001 mm, E_{KOBAX} 0.001 mm, E_{KOBAZ} 0.005 mm.

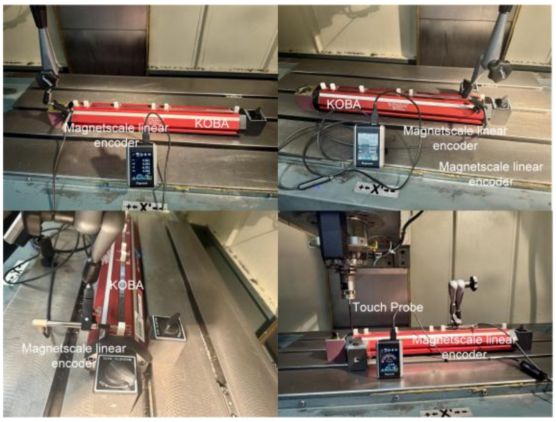

Fig 2: KOBA alignment

Once the KOBA fixture was aligned, the calibration ring was placed in the measurement space. Throughout the experiment, temperatures of the machine, environment, and calibration standards were continuously recorded.The measurement strategy was as follows:

a) Measurement of positioning accuracy and repeatability according to ISO 230-2:2014. Software compensation was applied only in Condition 3.
b) Verification of KOBA alignment using the touch probe. Before each measurement, alignment errors E_{KOBAY}, E_{KOBAX}, and E_{KOBAZ} were checked.
c) Calibration of the probe tip diameter.
d) Measurement of probe repeatability and time delay error according to ISO 230-10:2023.
e) Measurement of three lengths on the KOBA fixture for process capability calculation per ISO 22514-7:2021.

The number of points for positioning accuracy and repeatability followed the standard. A total of 11 bidirectional points were measured with five repetitions each. Each length on the KOBA standart was measured a total of ten times in order to comply with the standard requiring a minimum of thirty measured data points. Each test was performed once. Step size was variable to match the KOBA gauges positions. Since three lengths (41.3, 243.5, and 481.1 mm) were measured, the measurement strategy had to be adapted accordingly. For example, from machine position 0 to 150 mm, the step was 75 mm. The first gauge position was at 150 mm in MCS (see Fig. 3). The next step, corresponding to the first measured length. Between the second and third lengths were two intermediate positions spaced 67.4 mm apart. And between the third and last lengths one intermediate position was used with a step of 85.1 mm. The final machine position was at 716.2 mm. These specific points were also used for applying the software compensation in Condition 3. The goal was to align the positioning accuracy measurement points (within tolerances) with the KOBA length measurements.

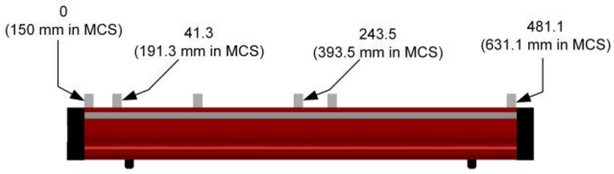

Fig. 3: KOBA alignment with MCS

The probe tip calibration was performed using the CYCLE976 function. Immediately afterward, the ring diameter was measured to verify correct diameter calibration. Then, the tests of probe repeatability and time delay error were performed according to ISO 230-10:2023. Both tests used the same KOBA gauges—0 and 481.1 mm. The probe contacted the surface 10 times. For the time delay test, the X-axis was shifted by 0.01 mm after each measurement. Block 0 was approached in the positive X-direction, and block 481.1 in the negative direction. Finally, the three KOBA lengths were measured for process capability assessment. Each length was measured 10 times, meeting the standard's requirement. The length and probe error measurements were programmed using the

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MEAS function. This function records the position upon probe trigger but does not compensate for the stylus diameter and deflection. But in the calculations these parameters are accounted for. After the length measurements, the process capability and the minimum allowable tolerance were calculated—the threshold at which the machine is considered capable of measurement under these conditions. The initial tolerance zone was set to 0.015 mm (±0.0075 mm), which corresponds to the tightest value found in the M3 test piece of ISO 10791-7:2021. Additionally, for each machine condition, the acceptance zone was calculated according to ISO 14253-1:2023. This determines whether an acceptance zone exists for the given tolerance and how big it is compared to that tolerance. The total time including initial KOBA alignment and measurements for Conditions 1, 2, and 3 was approximately 2.5 hours. To validate the length deviations and process capability results, measurements were repeated on a CMM ZEISS Eclipse 1000, which has a maximum permissible error E_0,MPE of ±4.9 + L/200 (where L is length in mm). For the largest dimension of 481.1 mm, the measurement error is ±0.00731 mm.

3 RESULTS AND DISCUSSION

This section presents the results of the study. A total of 30 values of lengths were obtained for each condition. Results include the machine's positioning accuracy (from laser interferometry) and the results of length measurements using the touch trigger probe (probe repeatability, time delay error, process capability, etc.). During the entire measurement process, the temperatures of the machine, the environment, and the KOBA standard were recorded. Since lengths were being measured on the KOBA standard, they had to be corrected according to the current temperature with uniform rectangular distribution.

3.1 Condition 1

For this condition, the bi-directional positioning accuracy of an axis "A" was 0.0398 mm, mean reversal error of an axis "B" was 0.0002 mm and the bi-directional positioning repeatability of an axis "R" was 0.0008 mm. The repeatability error of the touch probe was determined at two positions: $R_{C1,0,SPT,X}$ 0.00015 mm and $R_{C1,481,SPT,X}$ 0.00012 mm. The time delays error at the same positions were $E_{C1,0,SPT,TD,X}$ 0.00033 mm and $E_{C1,481,SPT,TD,X}$ 0.00117 mm respectively. During length measurements, the recorded temperature of the KOBA standard was 21.08°C. Therefore, the calibrated lengths were adjusted accordingly, resulting in the following compensated values:

- $L_{C1,41.3}$ 41.302 mm.
- $L_{C1,243.5}$ 243.50191 mm.
- $L_{C1,481.1}$ 481.10408 mm.

The deviations from the calibrated lengths were:

- $ERR_{C1,41.3}$ -0.00633 mm.
- $ERR_{C1,243.3}$ -0.01646 mm.
- $ERR_{C1,481.1}$ -0.03048 mm.

The measurement system capability ratio ($Q_{MS,C1}$) for the specified tolerance was calculated to be 67.7%, and the capability index of the measurement system ($C_{MS,C1}$) was 0.2954. The minimum tolerance for which the system is considered capable under these conditions was determined to be 0.0677 mm.

3.2 Condition 2

For this condition, the bi-directional positioning accuracy of an axis "A" was 0.019 mm, mean reversal error of an axis "B" was 0.0002 mm and the bi-directional positioning repeatability of an axis "R" was 0.0007 mm. The repeatability error of the touch probe was determined at two positions: $R_{C2,0,SPT,X}$ 0.00033 mm and $R_{C2,481,SPT,X}$ 0.00033 mm. The time delays error at the same positions were $E_{C2,0,SPT,TD,X}$ 0.00015 mm and $E_{C2,481,SPT,TD,X}$ 0.00127 mm respectively. During length measurements, the recorded temperature of the KOBA standard was 21.15°C. Therefore, the calibrated lengths were adjusted accordingly, resulting in the following compensated values:

- $L_{C2,41.3}$ 41.30204 mm.
- $L_{C2,243.5}$ 243.50211 mm.
- $L_{C2,481.1}$ 481.104447 mm.

The deviations from the calibrated lengths were:

- $ERR_{C2,41.3}$ -0.00317 mm.
- $ERR_{C2,243.3}$ -0.00413 mm.
- $ERR_{C2,481.1}$ -0.01448 mm.

The measurement system capability ratio ($Q_{MS,C2}$) for the specified tolerance was calculated to be 291.96%, and the capability index of the measurement system ($C_{MS,C2}$) was 0.0685. The minimum tolerance for which the system is considered capable under these conditions was determined to be 0.292 mm.

3.3 Condition 3

For this condition, the bi-directional positioning accuracy of an axis "A" was 0.0009 mm, mean reversal error of an axis "B" was 0.0002 mm and the bi-directional positioning repeatability of an axis "R" was 0.0007 mm (Fig.4). The repeatability error of the touch probe was determined at two positions: $R_{C3,0,SPT,X}$ 0.00014 mm and $R_{C3,481,SPT,X}$ 0.0003 mm. The time delays error at the same positions were $E_{C3,0,SPT,TD,X}$ 0.00018 mm and $E_{C3,481,SPT,TD,X}$ 0.00135 mm respectively. During length measurements, the recorded temperature of the KOBA standard was 21.25°C. Therefore, the calibrated lengths were adjusted accordingly, resulting in the following compensated values:

- $L_{C3,41.3}$ 41.30208 mm.
- $L_{C3,243.5}$ 243.50238 mm.
- $L_{C3,481.1}$ 481.10501 mm.

The deviations from the calibrated lengths were:

- $ERR_{C3,41.3}$ 0.00096 mm.
- $ERR_{C3,243.3}$ 0.0015 mm.
- $ERR_{C3,481.1}$ 0.00159 mm.

The measurement system capability ratio ($Q_{MS,C3}$) for the specified tolerance was calculated to be 21.52%, and the capability index of the measurement system ($C_{MS,C3}$) was 0.9293. The minimum tolerance for which the system is considered capable under these conditions was determined to be 0.0215 mm.

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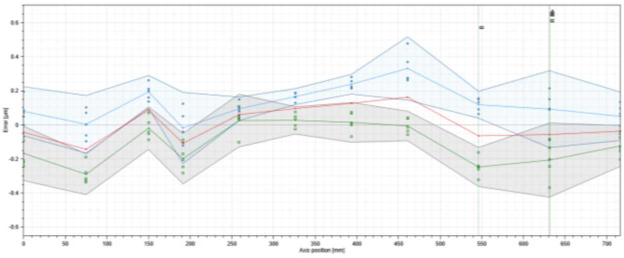

Fig. 4: Positioning accuracy of Condition 3

3.4 CMM results

During the length measurements, the temperature of the KOBA artifact was found to be 21.48 °C. The length compensation of the KOBA artifact was carried out automatically in the CMM software, as was the temperature compensation on the individual axis encoders, which were at 22 °C. The deviations from the calibrated lengths were therefore:

- $ERR_{CMM,41.3}$ –0.00051 mm.
- $ERR_{CMM,243.3}$ –0.00026 mm.
- $ERR_{CMM,481.1}$ –0.00263 mm.

The measurement system capability ratio ($Q_{MS,CMM}$) for the specified tolerance was calculated to be 84.85%, and the capability index of the measurement system ($C_{MS,CMM}$) was 0.2357. The minimum tolerance for which the system is considered capable under these conditions was determined to be 0.0849 mm.

3.5 Discussion

From the measurements, it is evident that the best positioning accuracy results were achieved in condition 3. This is due to the software compensation that was uploaded into the machine. Repeatability remained the same across all conditions since this error cannot be corrected be the compensation and the reversal error was so small that it should have only a minimal effect on the final positioning accuracy.

Tab. 3: Results of positioning, reversal and repeatability accuracy

Condition	A [mm]	B mean [mm]	R [mm]
1	0.039	0.0002	0.0008
2	0.019	0.0002	0.0007
3	0.0009	0.0002	0.0007

The results of the testing according to ISO 230-10:2023 were very similar across all machine conditions, as shown in Fig. 5. From this, we can conclude that changes in positioning accuracy do not affect the repeatability error and time delay error of the touch probe. The higher error of time delay in position 481.1 is most likely caused by backlash (reversal error) in the measured axis. Since the standard does not define a threshold value considered acceptable, the evaluation must be based on the probe's specifications. In this case, the touch probe was declared sufficiently accurate for measurement.

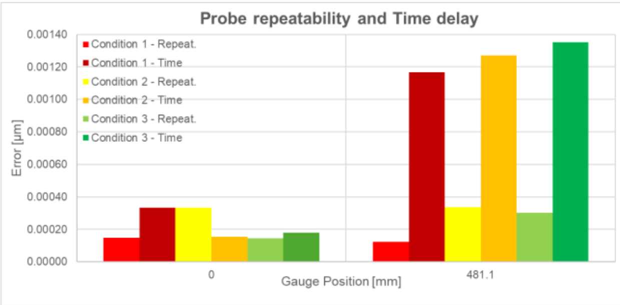

Fig. 5: Probe repeatability and time delay error results of all conditions

The results of the length deviations of the calibrated KOBA artifact (Fig. 6) mirror the positioning accuracy results. This means that the worst deviations from the calibrated lengths occurred in machine Condition 1, and with improved positioning accuracy, the length deviation results also improved. In the case of the best and worst machine conditions (1–3), the positioning accuracy improved by an impressive 97.74%, which was reflected in the length deviation results from the calibrated values: $DIF_{C1-C3,41.3}$ by 84.91%, $DIF_{C1-C3,243.5}$ by 90.88%, and $DIF_{C1-C3,481.1}$ by 94.77%

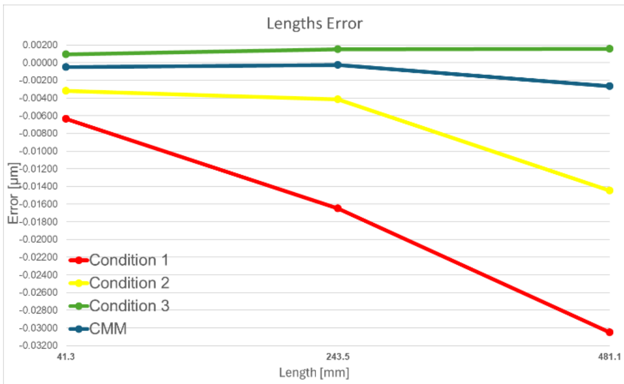

Fig. 6: Lengths deviations of all conditions

The capability results for machine conditions 1 and 3 follow the trend described above. Both conditions have acceptance zones for the selected tolerance of 0.0066 mm (Condition 1) and 0.0123 mm (Condition 3). In percentage terms relative to the selected tolerance, this corresponds to 44.15% for Condition 1 and 82.24% for Condition 3. Therefore, it can be stated that the measuring system is usable for conformity assessment within this tolerance for both machine conditions. However, neither one is fully capable for this tolerance level, as the capability indices $C_{MS,C1}$ and $C_{MS,C3}$ were 0.2954 and 0.9293, respectively.

The results for Condition 2 are interesting in that, as with the other two states, the deviation from the calibrated length follows the same trend. Compared to the worst condition (Condition 1), improvements in length deviations were: $DIF_{C1-C2,41.3}$ by 49.87%, $DIF_{C1-C2,243.5}$ by 74.92%, and $DIF_{C1-C2,481.1}$ by 52.50%. These results indicate that improving positioning accuracy leads to improvements in measured length deviations. This trend holds for all three conditions; however, the linearity of the results varies. It is this linearity or non-linearity of results that significantly impacts the calculated uncertainty of linearity (u_{LIN}), which in turn leads

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to a large combined measurement uncertainty. Due to this uncertainty, no valid acceptance zone exists, and thus it must be concluded that the system is not suitable for conformity assessment in this case.

Furthermore, the minimum tolerance for which the measuring system is considered capable was calculated to be 0.290 mm—this is 77% and even up to 93% greater than for Condition 1 and 3, respectively. The uncertainties of linearity were:

- $u_{LIN,C1}$ 0.0025 mm.
- $u_{LIN,C2}$ 0.0109 mm.
- $u_{LIN,C3}$ 0.0007 mm.

It can be concluded that not only the deviations from the calibrated lengths, but also the linearity of these results plays a crucial role in evaluating the measurement system's capability. Even though the CMM used for verification was not the most accurate, it should still be more precise than the MCV machine, for which only Condition 3 and only one out of 21 geometric errors were compensated. The results of length deviations, capability ratios and index, and the minimum tolerance of the CMM in comparison with machine Conditions 1, 2, and 3 are listed in Table 4.

Tab. 4: Results of all measurements

Lenghts [mm]	Con. 1	Con. 2	Con. 3	CMM
41.3	-0.00633	-0.00317	0.00096	-0.00051
243.5	-0.01646	-0.00413	0.0015	-0.00026
481.1	-0.03048	-0.01448	0.00159	-0.00263
Q_{MS} [%]	67.7	291.96	21.52	84.85
C_{MS} [-]	0.2954	0.0685	0.9293	0.2357
TOL_{min} [mm]	0.0677	0.292	0.0215	-

An important question arises when evaluating the uncertainty of linearity. It is calculated using regression analysis, where a regression curve is fitted to a dataset and residuals are determined. The linearity uncertainty parameter is then calculated from these residuals using ANOVA. Alternative methods for calculating linearity uncertainty are described in the article [Potanko et al., 2024]. A total of 16 regression models were considered. The authors demonstrated that, by selecting suitable models, it is possible to reduce the uncertainty u_{MS} by up to 50%. Based on this, a general straight line model 'O' was identified and tested:

$$y=b1+b2*x+b2*x^2+b4*x^3 \quad (2)$$

Using this model, the linearity uncertainty was significantly reduced to the 13th order of magnitude.

The results obtained from these measured data indicate that all three machine states are now capable, with the newly calculated minimum tolerances being $TOL_{min,C1}$ 0.0109 mm, $TOL_{min,C2}$ 0.0099 mm, and $TOL_{min,C3}$ 0.0127 mm. By applying this regression function, the previously best-performing machine condition became the worst-performing, although it still barely passed the capability criteria.

In the article by [Blecha et al., 2025], a systematic approach for evaluating the applicability and capability of a measurement system (MS) based on the acceptance zone relative to the required tolerance was proposed. According to that approach, the results can be interpreted as follows: for machine Conditions 1 and 3, the system is conditionally applicable but not capable, requiring stricter control of manufacturing centering; for machine Condition 2, the system is neither applicable nor capable. See Table 5 for details.

4 SUMMARY

The measurement system capability testing was conducted on a three-axis vertical milling center. The machine was tested in three different Conditions, each differing in positioning accuracy, which was measured using a laser interferometer. A capability assessment was performed using a workpiece probe and a calibrated KOBA artifact on which three lengths were measured, each ten times. This fulfilled the requirement for capability calculation. Before each measurement, the probe ball diameter was recalibrated. The results show that none of the machine conditions were capable of meeting the specified tolerance of 0.015 mm. Conditions 1 and 3 have acceptance zones and can therefore be used for conformity assessment, while Condition 2 cannot. This is due to the nonlinearity of the deviation results from the calibrated lengths. Despite having smaller deviations than Condition 1, this uncertainty made the measurement system incapable for conformity assessment. Additionally, the minimum tolerance for which the system in this state is capable was found to be high. This raises the question of whether the standard linearity uncertainty model is appropriate for machine tools.For this reason, a regression function was selected and the capability parameters, including the minimum tolerance, were recalculated. The results changed significantly: the condition that was previously best (Condition 3) became the worst, and the worst (Condition 2) became the best.

Tab. 5: Results of evaluation of applicability and capability

Condition	Result [%]	Acceptance zone in % of tolerance	Evaluation of the applicability and capability	Requirement for production centering
2	-70.4	*pAZ* < 34%	Not applicable, incapable	Extreme requirement for production centering
1;3	60; 85.41	34% ≤ *pAZ* < 87.6%	Conditionally applicable, Incapable	Increased requirement for production centering
-	-	*pAZ*≥ 87.6%	Applicable, capable	Standard requirement for production centering

Why did Condition 2 perform better than 3 in this recalculation? This could be due to other components of uncertainty. Further research in this area should focus on identifying a regression model that is suitable for capability assessment of devices where linearity of results cannot be guaranteed.

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