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CNC Machine Tool Accuracy and Repeatability Measurement Strategy: Analysis and Statistical Evaluation

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Abstract: Several factors can affect the accuracy and repeatability results of CNC machine tool positioning. One of the factors is to set up a measurement strategy for both linear and rotary axes based on standards such as ISO 230-2:2014 and VDI 3441. Measurement procedures (strategies) can be modified according to the purpose of the measurement, such as for a quick assessment of the current state of the linear axis, or a more time-consuming measurement to increase the accuracy of the linear axis. They can also be measurements designed for various diagnostic purposes and for better analysis of the measured data. This paper describes modern methods of measuring the accuracy and repeatability of the positioning of linear axes of CNC machine tools with statistical evaluation of the data obtained. In the next part of the paper, measurements are performed on small, medium and large CNC machine tools with defined set measurement strategies based on ISO 230-2:2014 standard. The results show that step size influences the measurement result by up to 54 %. The paper concludes by evaluating the results obtained and suggesting further research goals in this area with a focus on On-machine measurement.

Keywords: machine tools; accuracy; positioning; measurement.

1. Introduction

Accuracy and repeatability of the positioning of CNC machine tools are among the main parameters that are given in the technical data sheets of the machines and also have telling information about the behavior of the machine itself [1].

Measurement and evaluation procedures are described by standards such as ISO 230-2, ASME B5.54, VDI 3441, etc. These standards also recommend setting up a measurement strategy with regard to the resultant value. Measurement according to these standards implies static measurement where the machine stops at a given position, goes to measure and move to the next position. To set a smaller step (more measurement points) on the measured axis means an increase in measurement time, which has several negative characteristics. It increases the measurement time and thus increases the costs associated with machine downtime, and it can cause temperature effects on the measured linear axis and thus distort the results. It is the measurement strategies recommended by the above standards that seek to eliminate these negative characteristics in measurement.

With the advancement of technology, On-the Fly measurement [2], [3], or dynamic position measurement [4] of controlled axes is beginning to be used. This measurement method offers continuous measurement without necessary delays and obtains a higher number of measured positions on the controlled axis with a lower measurement time than the static measurement method. However, this measurement method requires

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specific communication between the CNC machine tool and the measuring device due to the need for precise synchronization. The position measured by the laser interferometer is synchronized with the position read from the CNC machine tool measurement. The resulting difference indicates the deviation in the given machine position.

In the present paper, the possible negative influence of the number of measurement points and the measurement time in a static way on the resulting positioning error and the repeatability of the positioning is described. The present study presents results obtained on a small, medium and large CNC machine tool. Further possibilities of applying the presented results to the field of dynamic measurement with an overlap into the field of On-machine measurement are also discussed.

2. State of Art

A considerable amount of research has been devoted to the assessment of the effect of the accuracy and repeatability of positioning on the resulting working accuracy, as well as to dynamic measurement and compensation methods. It is the development of new measuring instruments and higher hardware performance of machine tools that can provide more realistic information on the behavior of CNC machine tools with a more effective compensation method.

The procedure for measuring the accuracy and repeatability of the run in position, including recommendations for test setup, is described in ISO 230-2:2014 [5]. The calculation of the resulting parameters A - positioning error, R - positioning repeatability and E - systematic positioning error was implemented according to this standard.

In publication [3], the procedure of static and dynamic measurement of volumetric accuracy is presented, where the measurement time and the difference between the results were observed. The dynamic measurement saved approximately 50 % of the time, with a difference between the results of 0.6 µm for the EXX error, 9.4 µm for the EYY error and 0.0 µm for the EZZ error evaluation.

The integration of the XL-80 laser interferometer for measuring the accuracy of the homing to the position of the controlled linear axis was addressed in publication [4]. Here, a software application was designed to synchronize data from the laser interferometer and the CNC machine tool itself using an OPC UA platform (Siemens, DE) with a sampling rate of 100 ms. The experiment was implemented only to verify the measurement of the resulting specific distance, while a design with a higher sampling rate would use synchronization already for 10 ms.

In [6] an experiment is presented to analyse and interpret the measured data for a medium sized CNC machine tool, where the resulting error of the run in position was equal to approximately 49 µm. Finally, the results were interpreted according to ISO 230-2 and compared with the specific tolerances of the machine manufacturer according to ISO 13041-4.

For the tests according to ISO 230-2, the LaserTRACER measuring device was used in publication [7], where the measurement procedure and the accuracy and repeatability of the positioning on the resulting determination of the position of the measuring device were investigated. The principle of measurement is described in the introductory part of the publication.

For the implementation of the tests, the XL-80 laser interferometer (RENISHAW, UK), which is one of the standard equipment of CNC machine tool manufacturers, was used for the measurements. The measurement uncertainty can be estimated according to the following equation [8]:

$$U_{(k=2)} = 0.2\,\mu m + 0.3 \times L\,\mu m / m, \qquad (1)$$

where L is the measurement length in m.

The aim of the present paper is to determine the effect of the step size of the axis under consideration on measurements with a significantly higher step, complying with ISO 230-2.

3. Experiment Description and Positioning Measurement

The tests of the positioning measurement were carried out on three CNC machine tools with the range of measured axes, 754 mm (small MT), 1220 mm (medium size MT) and 3190 mm (large MT). The size of the machine tools is defined according to [9]. The measurement procedures were taken from ISO 230-2:2014 and modified for the needs of the experiments. For the small machine, the measurement was set as bidirectional measurement with 5 measurement cycles. The test of the medium machine was designed as bidirectional but with only

Table 1: Definition of test parameters.

	Nr. of cycles [-]	Min. positioning of axis [mm]	Max. positioning of axis [mm]	Step [mm]	Nr. of steps [-]
Small MT	5	2	752	1	751
				150	6
Middle size MT	2	-70	1150	1	1221
				244	6
Large MT	5	-3195	-5	1	3191
				290	12

two repetition cycles. For the large machine, the test was set up as a 5-cycle test but only as a one-way test. The step sizes, the number of positions on the axis to be measured, and the runout size of the measured axis are defined in Table 1. The measurements were always performed in a setting with a step size of 1 mm. The evaluation of the data set with a step size of 150 / 244 / 290 mm was carried out in the form of a simulation, where the source files were thrown out from the measurements on the machine with a step size of 1 mm.

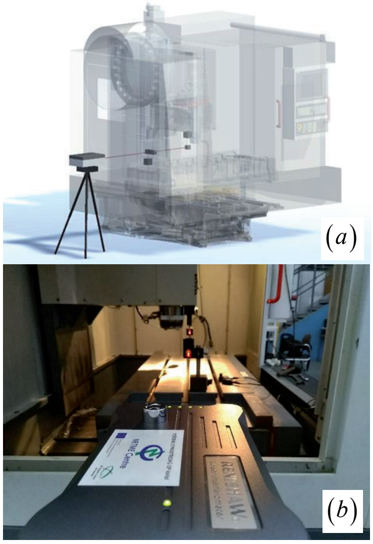

Figure 1: (a) Small Machine Tools - MCV 754QUICK. (b) Measurement on Small MT.

The measurements were carried out according to the settings in the CARTO software (RENISHAW, UK) and the measuring device used was a laser interferometer XL-80 (RENISHAW, UK) with compensator and sensors XC-80 (RENIHSAW, UK). Depending on the size of the measured axis, the total measurement time and the magnitude of the stability range were different. Figure 1 shows schematically the measurement of the linear X-axis of a small CNC machining centre with kinematics chain W(Workpiece)-X-Z-Y-T(Tool) and an example of the implemented measurement using the XL-80 laser interferometer.

3.1. Small Machine Tools

For the small MT, the measurement time was approximately 160 min. and the stability range of measurement was 0.005 mm. Figure 2 shows the result of a bidirectional measurement in 5 cycles with a step size of 1 mm (751 measured positions on the axis). The result shows excellent repeatability and almost no temperature influence on the measurement. The resulting positioning error (A) is 25.97 μm, positioning repeatability (R) is 1.04 μm and systematic positioning error (E) is equal to 24.68 μm.

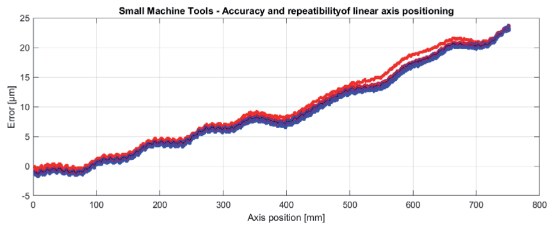

Figure 2: Small MT, step 1 mm.

Using the previous data, adjusting the step size from 1 mm to 150 mm (6 positions per axis), and linearly interpolating the data between points, the resulting waveform is shown in Figure 3. The resulting positioning error (A) for this dataset is 25.44 μm, the positioning repeatability (R) is 1.04 μm, and the systematic positioning error (E) is equal to 24.28 μm.

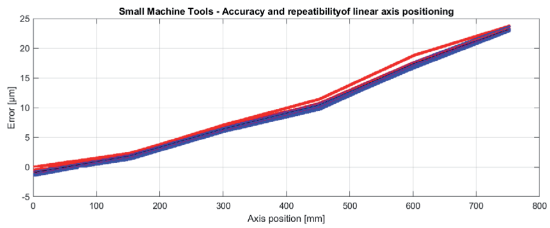

Figure 3: Small MT, step 150 mm.

The difference between the results of such processed data is equal to 0.53 µm for A, no change for R and 0.4 µm for E. These values are evaluated on the basis of the whole waveform.

In terms of local changes, which are not apparent at a glance from the results obtained above, an analysis of the change in position was performed. The resulting plot is shown in Figure 4, where the difference on position with a change of 3.37 µm can be seen. This local error represents approximately 13 % of the total error.

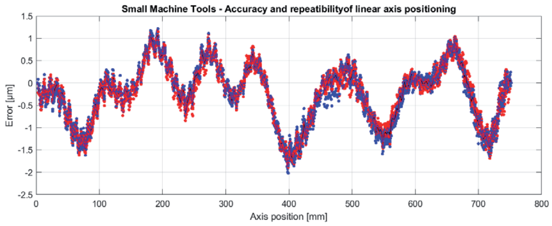

Figure 4: Small MT, resid.

3.2. Middle size Machine Tools

For the medium-sized MT with kinematics chain W-C-q-X-Z-T, the measurement time was approximately 320 min. and the stability range of measurement was 0.01 mm. Figure 5 shows the result of the bidirectional measurement in two cycles with a step size of 1 mm (1221 measured positions on the axis). The result shows a degraded repeatability value compared to small MT and almost no temperature influence on the measurement. The resulting positioning error (A) is 31.09 µm, positioning repeatability (R) is 13.29 µm and systematic positioning error (E) is equal to 23.40 µm.

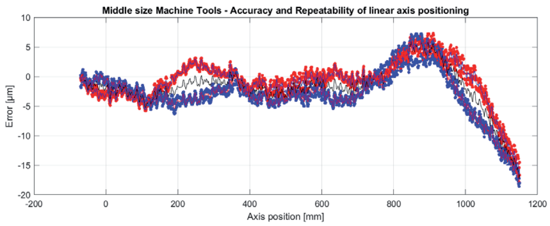

Figure 5: Middle size MT, step 1 mm.

Using the previous data, adjusting the step size from 1 mm to 244 mm (6 positions per axis), and linearly interpolating the data between points, the resulting plot is shown in Figure 6. The resulting Position Error (A) for this dataset is 26.47 µm, the positioning repeatability (R) is 6.69 µm, and the systematic positioning error (E) is equal to 21.25 µm.

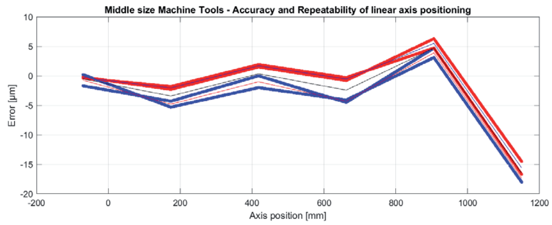

Figure 6: Middle size MT, step 244 mm.

Using the previous data, adjusting the step size from 1 mm to 244 mm (6 positions per axis), and linearly interpolating the data between points, the resulting plot is shown in Figure 7. The resulting Position Error (A) for this dataset is 26.47 µm, the positioning repeatability (R) is 6.69 µm, and the systematic positioning error (E) is equal to 21.25 µm.

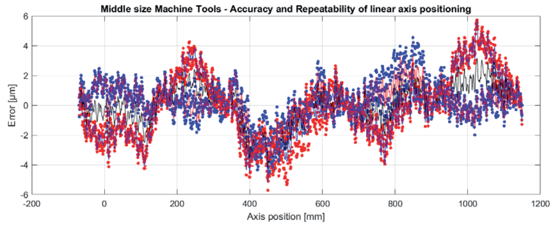

Figure 7: Middle size MT, resid.

3.3. Large Machine Tools

For the large MT with kinematics chain W-X-Y-Z-T, the measurement time was approximately 440 min. and the stability range was 0.01 mm. Figure 8 shows the result of a single-cycle measurement in 5 cycles with a step size of 1 mm (3191 measured positions on the axis). From the result, the repeatability value is degraded due to the measurement period and the thermal envelope of the mechanical structure of the linear axis. The resulting positioning error (A) is 106.20 µm, positioning repeatability (R) is 57.70 µm and systematic positioning error (E) is equal to 71.0 µm.

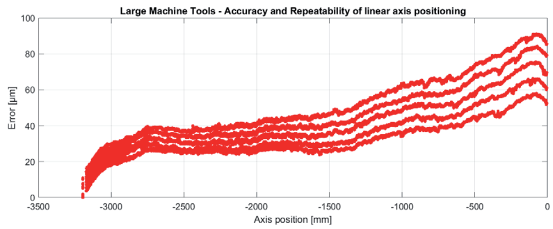

Figure 8: Large MT, step 1 mm.

Using the previous data, adjusting the step size from 1 mm to 290 mm (12 positions per axis), and linearly interpolating the data between points, the resulting plot is shown in Figure 9. The resulting positioning error (A) for this dataset is 100.29 μm, the positioning repeatability (R) is 51.48 μm, and the systematic positioning error (E) is equal to 65.50 μm.

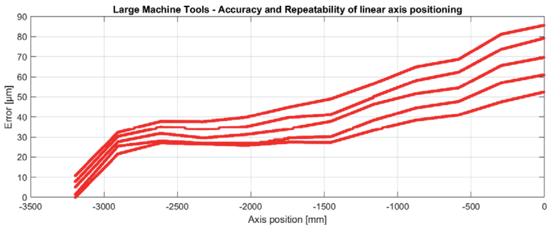

Figure 9: Large MT, step 290 mm.

The difference between the results of the data processed in this way is equal to 5.91 μm for A in favour of the test with a step of 290 mm. The positioning repeatability of R has reached an improvement of 6.22 μm for the measurements with the higher step and for E the difference is 5.5 μm. These values are evaluated on a full run basis.

In terms of local changes that are not apparent at first glance from the results obtained above, a change on positioning analysis was performed. The resulting plot is shown in Figure 10, where the difference on position with a change of 15.94 μm can be seen. This local error represents approximately 15 % of the total error.

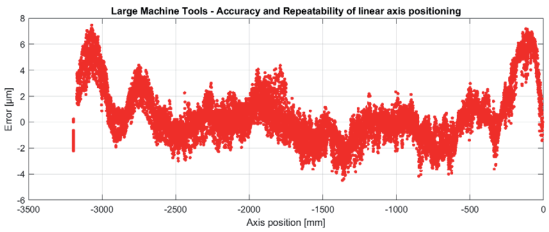

Figure 10: Large MT, resid.

4. Results and Discussion

For data obtained from individual measurements, it can be stated unequivocally that local errors can significantly affect the resulting positioning error. Table 2 summarizes the results from the individual measurements. For the small CNC machine tool, the resulting difference A is equal to 0.53 μm, but when compared to each other on the positioning, the local maximum difference is already 3.37 μm, a difference of 13 %. For a medium-sized machine, the difference in positioning error A is already 4.62 μm and, compared to the local maximum error of 14.31 μm, already represents a contribution of 54 %. For the large machine, the difference in error A is equal to 5.91 μm and compared to the local maximum of 15.94 μm, the difference is 15 % of the error. It is clear that finer measurement results obtained with finer step settings worsen the resulting error of A, R, and E. Only small MT did not degrade the repeatability of R. Thus, applying a finer step size setting should result in better capture of local errors and thus increase the efficiency of future compensation. However, the disadvantage of very fine step adjustment is the overall time consumption, which is reflected in the thermal influence on the mechanical part of the linear axis and the deterioration of the repeatability parameter R and E, and thus the deterioration of the measured data. For the machines tested in normal workshop operation, these drifts can be observed especially in Figure 8 and Figure 9.

These disadvantages of measurement could be systematically eliminated by the possibilities of on the fly measurement or dynamic measurement of the accuracy and repeatability of positioning. Another disadvantage of compensation data may be too large compensation table setups with

Table 2: Definition of test parameters.

			ISO 230-2:2014			
	Range [mm]	Nr. of steps [-]	A [μm]	R [μm]	E [μm]	A – local error max. [μm]
Small MT	750	751	25.97	1.04	24.68	3.37
		6	25.44	1.04	24.28	
		-	0.53	0	0.40	-
Middle size MT	1220	1221	31.09	13.29	23.40	14.31
		6	26.47	6.69	21.25	
		-	4.62	6.60	2.15	-
Large MT	3190	3191	106.20	57.70	71.0	15.94
		12	100.29	51.48	65.50	
		-	5.91	6.22	5.5	-

increased hardware power requirements for the necessary data processing.

5. Conclusions and Outlook

Experimental verification of the influence of the resulting accuracy and repeatability of positioning by laser interferometry on a small, medium and large CNC machine tool. The proposed experiment showed that tests with smaller step settings can describe local errors with magnitudes up to 20 % of the total error than the step settings recommended by ISO 230-2:2014. This cycle carries a major negative, namely in the length of the test itself, which is unacceptable from a practical point of view, and when the temperature of the machine axis is changed, the results themselves will be affected, as has been shown for a large CNC machine tool. These drawbacks could be eliminated by deploying a dynamic measurement mode or on the fly measurement. Research into the measurement of medium and large CNC machine tools should continue in this direction.

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