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Analysis of accuracy of 5-axis CNC milling machine through standard and modified circular test

Analiza dokładności pięcioosiowej frezarki CNC z użyciem standardowego i zmodyfikowanego testu okrągłości

RYSZARD WOLNY*

In analysis of accuracy of 5-axis CNC milling machine measuring system with telescopic kinematic ball bar was used. Standard measuring test was made. The modified test was proposed with application of investigated inclined basis. The obtained results were compared. The accuracy of machine tool in indirect way was evaluated.

KEYWORDS: 5-axis milling machine, ball bar system, geometric accuracy, circular test

The use of five-axis CNC machine tools for machining objects with complex 3D shapes allows for high geometry accuracy. To avoid machining errors and to obtain high quality of machined parts, an efficient and quick diagnostics of multi-axis machine tools is necessary.

Problems of machine tool diagnostics should be taken into account by their producers and also by users in the current production process. Diagnostic methods use static, dynamic and thermal properties correlated with individual types of machining errors to assess machine health. Errors that should be measured and aimed at their elimination are mainly of a geometrical, kinematic, thermal nature, refer to drive systems and regulators, measurement systems and control [1].

The required accuracy of multi-axis CNC machine tools is provided by diagnostic tests combined with control of servo systems and error compensation implemented by control systems. The methods for testing the accuracy of machine tools were strictly standardized and presented in international standards ISO 230.

The aim of the work was to analyze the accuracy of a five-axis CNC milling machine using a measuring system with a telescopic ball bar type ball bar. A standard measurement test was carried out.

A modified test was proposed with the use of a 45° angled test bed. This innovative approach provided the basis for further research. Measurement results were compared. An indirect attempt was made to assess the accuracy of the machine tool under test.

Kinematic ball bar

The ball bar kinematic ball bar was constructed in 1982 by Bryan [2–4]. It is a measuring device made of two balls and a telescopic rod with a built-in displacement sensor. The balls at both ends act like ball joints, and the measuring rod measures the distance between them with great accuracy. The original purpose of this device was the calibration of coordinate measuring machines.

Since its first use in CNC machining centers in 1985, the ball bar has been widely used because [5]:

- accuracy of the test is higher than the accuracy of the machines,
- device is reliable and easy to use,
- measurement results indicate machine tool errors.

Due to this, it is possible to diagnose sources of errors by analyzing and comparing the obtained measurement profiles on polar charts.

With time, other test methods proposed in [6] were proposed.

In 1994, the test of machine tools using a measuring rod was included in the international standard ISO 230-4.

The accuracy of currently manufactured machine tools increases and is comparable to the accuracy of the measuring rod. Therefore, new methods are sought for measuring accuracy in the roundness test [7].

Accuracy check test

The milling machining center DMU 60 monoBLOCK was selected for the tests (fig. 1). The machine tool, manufactured in 2010, was operated in a modern industrial plant in a three-shift system. The milling machine was equipped with a rotary table and a pivotable spindle and met the criteria of complex multimanic processing in five axes [8].

The accuracy test for the machine tool tested was carried out using the Renishaw wireless ball bar system QC20 – W (fig. 2).

Measurements were made in a climate-controlled hall at 20°C. The machine achieved thermal stability after two hours of unloaded operation.

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Accuracy tests using the ball bar system were carried out in accordance with the ISO 230-4 standard as a standard test [10, 11].

For comparison, a modified accuracy test was carried out, in which the magnetic base of the ball bar device was inclined to the surface of the machine table by an angle of 45° (fig. 3).

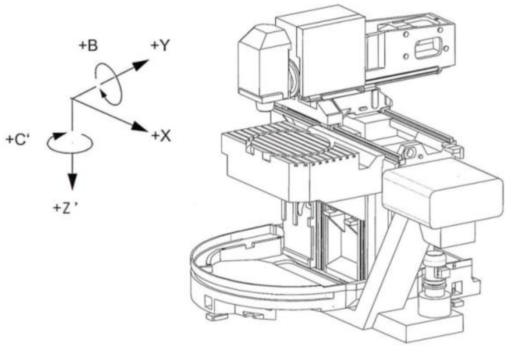


Fig. 1. DMU 60 MonoBLOCK milling center with a control axle system

Fig. 2. System QC20-W ball bar [9]

Fig. 3. Modified accuracy test of the machine tool [8]

The software available in the system did not automatically generate a measurement code for the modified setting. Using the CAM module, a test program for the analyzed measuring case was prepared.

Before starting the test, the QC20-W was calibrated on a 150 mm long pattern.

The course of auxiliary operations preceding the measurements included:

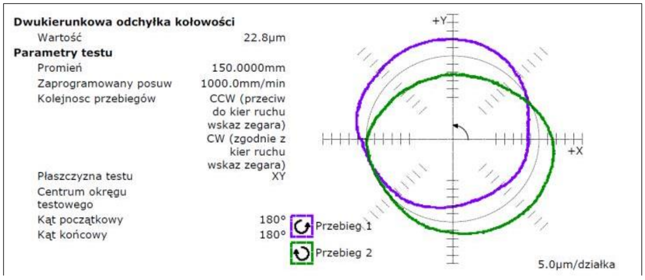
- fixing the magnetic spindle in the machine spindle and setting the base on the machine's rotating table,
- determination of the feed rate 1000 mm/min on the machine tool,
- determining the amount of thermal expansion of the machine tool,
- loading the test machine of the machine into the memory,
- selection of a measuring rod with a length of 150 mm,
- connection of the QC20-W device with a computer,
- starting the measurement program.

Results of measurements of the standard accuracy test

The results of the measurements were analyzed in detail. The diagnostic test included basic values of errors and deviations as well as their percentages in the total deviation of machine tool roundness.

The graphic runs of the bidirectional circular deviation, the value of which was determined as 22.8 μm, are shown in fig. 4*a*. The remaining values of the main errors and deviations formed the basis for the analysis of the measurement results (fig. 4*b*).

a)



Dwukierunkowa odchyłka kołowości

Wartość 22.8µm

Parametry testu

Promień 150.0000mm

Zaprogramowany posuw 1000.0mm/min

Kolejnosc przebiegów CCW (przeciw do kier ruchu wskaz zegara) CW (zgodnie z kier ruchu wskaz zegara)

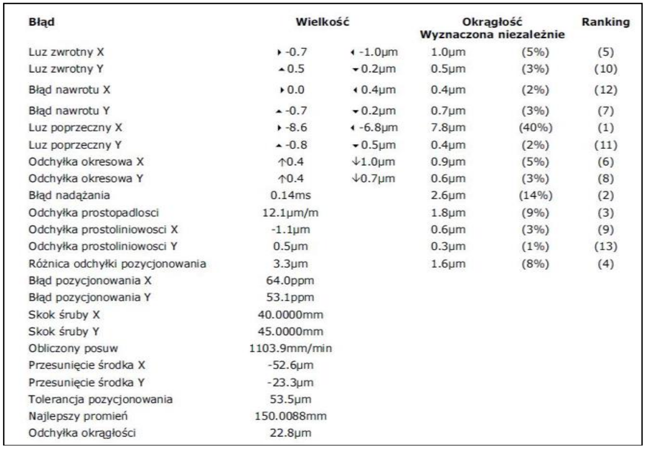
Płaszczyzna testu XY

Centrum okręgu testowego

Kąt początkowy 180°

Kąt końcowy 180°

b)



Błąd	**Wielkość**		**Okrągłość Wyznaczona niezależnie**		**Ranking**
Luz zwrotny X	▸ -0.7	◂ -1.0µm	1.0µm	(5%)	(5)
Luz zwrotny Y	▴ 0.5	▾ 0.2µm	0.5µm	(3%)	(10)
Błąd nawrotu X	▸ 0.0	◂ 0.4µm	0.4µm	(2%)	(12)
Błąd nawrotu Y	▴ -0.7	▾ 0.2µm	0.7µm	(3%)	(7)
Luz poprzeczny X	▸ -8.6	◂ -6.8µm	7.8µm	(40%)	(1)
Luz poprzeczny Y	▴ -0.8	▾ 0.5µm	0.4µm	(2%)	(11)
Odchyłka okresowa X	↑0.4	↓1.0µm	0.9µm	(5%)	(6)
Odchyłka okresowa Y	↑0.4	↓0.7µm	0.6µm	(3%)	(8)
Błąd nadążania	0.14ms		2.6µm	(14%)	(2)
Odchyłka prostopadlosci	12.1µm/m		1.8µm	(9%)	(3)
Odchyłka prostoliniowosci X	-1.1µm		0.6µm	(3%)	(9)
Odchyłka prostoliniowosci Y	0.5µm		0.3µm	(1%)	(13)
Różnica odchyłki pozycjonowania	3.3µm		1.6µm	(8%)	(4)
Błąd pozycjonowania X	64.0ppm				
Błąd pozycjonowania Y	53.1ppm				
Skok śruby X	40.0000mm				
Skok śruby Y	45.0000mm				
Obliczony posuw	1103.9mm/min				
Przesunięcie środka X	-52.6µm				
Przesunięcie środka Y	-23.3µm				
Tolerancja pozycjonowania	53.5µm				
Najlepszy promień	150.0088mm				
Odchyłka okrągłości	22.8µm				

Fig. 4. Results of machine accuracy measurements in the standard test: *a*) two-way circular deviation, *b*) basic errors and deviations of the measurement test

In the measured deviation of the machine tool roundness, the largest shares showed:

- lateral clearance of the *X* axis (40%),
- lag error (14%),
- rectangular deviation (9%),
- difference in positioning deviation (8%),
- backlash of the *X* axis (5%).

Cross-lateral play (lateral play) of the *X*-axis is an error that results in uneven movement of the machine tool assemblies along the guides during reversing movements. The main cause of lateral play ("lateral") is the defect of the machine tool guides. This is a different error than the backlash, which is loose axle.

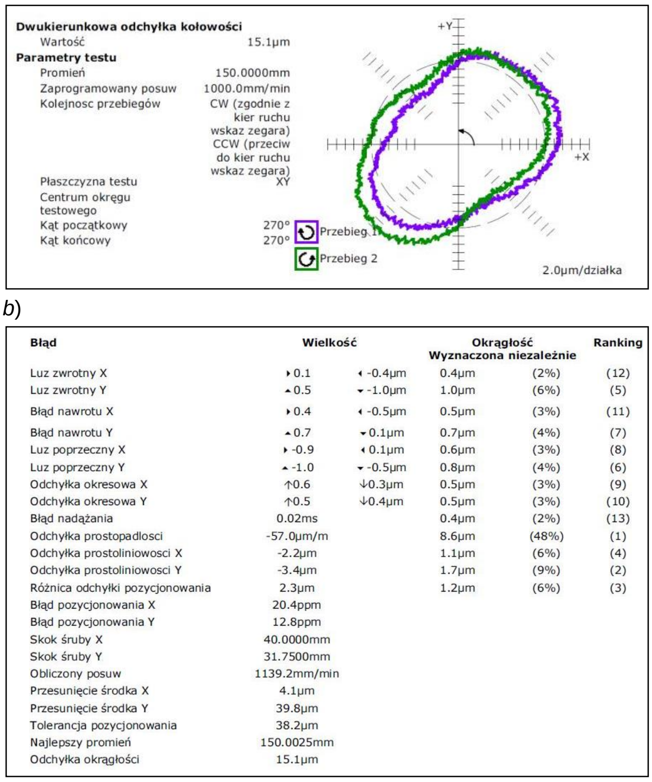
The lag error (servo mismatch) arises as a result of improper selection of the drive parameters of the *X* and *Y* axes. The result of this error is that the interpolation path is not a circle. Using small feed values minimizes the lag error.

The lateral clearance of the *X* axis and the lag error were 54% in the roundness deviation of the standard machine tool test.

Measurement results of the modified accuracy test

Fig. 5*a* presents the results of measurements of two-dimensional circular deviation and its value of 15.1 µm, i.e. by 33.8% less than obtained in the standard test.

a)



Dwukierunkowa odchyłka kołowości

Wartość	15.1µm
Parametry testu	
Promień	150.0000mm
Zaprogramowany posuw	1000.0mm/min
Kolejnosc przebiegów	CW (zgodnie z kier ruchu wskaz zegara) CCW (przeciw do kier ruchu wskaz zegara)
Płaszczyzna testu	XY
Centrum okręgu testowego	
Kąt początkowy	270°
Kąt końcowy	270°

b)

Błąd	**Wielkość**		**Okrągłość Wyznaczona niezależnie**		**Ranking**
Luz zwrotny X	▸0.1	◂-0.4µm	0.4µm	(2%)	(12)
Luz zwrotny Y	▴0.5	▾-1.0µm	1.0µm	(6%)	(5)
Błąd nawrotu X	▸0.4	◂-0.5µm	0.5µm	(3%)	(11)
Błąd nawrotu Y	▴0.7	▾0.1µm	0.7µm	(4%)	(7)
Luz poprzeczny X	▸-0.9	◂0.1µm	0.6µm	(3%)	(8)
Luz poprzeczny Y	▴-1.0	▾-0.5µm	0.8µm	(4%)	(6)
Odchyłka okresowa X	↑0.6	↓0.3µm	0.5µm	(3%)	(9)
Odchyłka okresowa Y	↑0.5	↓0.4µm	0.5µm	(3%)	(10)
Błąd nadążania	0.02ms		0.4µm	(2%)	(13)
Odchyłka prostopadlosci	-57.0µm/m		8.6µm	(48%)	(1)
Odchyłka prostoliniowosci X	-2.2µm		1.1µm	(6%)	(4)
Odchyłka prostoliniowosci Y	-3.4µm		1.7µm	(9%)	(2)
Różnica odchyłki pozycjonowania	2.3µm		1.2µm	(6%)	(3)
Błąd pozycjonowania X	20.4ppm				
Błąd pozycjonowania Y	12.8ppm				
Skok śruby X	40.0000mm				
Skok śruby Y	31.7500mm				
Obliczony posuw	1139.2mm/min				
Przesunięcie środka X	4.1µm				
Przesunięcie środka Y	39.8µm				
Tolerancja pozycjonowania	38.2µm				
Najlepszy promień	150.0025mm				
Odchyłka okrągłości	15.1µm				

Fig. 5. Results of machine accuracy measurements in a modified test: *a*) two-way circular deviation, *b*) basic errors and deflections of the measurement test

The machine's roundness deviation was determined by the following components (fig. 5*b*):

- perpendicular error (48%),
- *Y*-axis straightness deviation (9%),
- difference in position deviation (6%),
- deviation of the straightness of the *X* axis (6%),
- *Y*-axis backlash (6%).

The squareness error is the deviation of the direction of the machine axis (e.g. *X* and *Y*) from the right angle, which may be local or be the result of incorrectness of the guides along the entire length. The axes of the machine tool may exhibit vertical deformation (i.e. concavity, convexity, inclination) and excessive wear resulting in increased slack during movement. As a result of the perpendicular error on the machine, there is a deviation of the perpendicularity of the milled planes and problems with the shaping of cylindrical surfaces, both external and internal.

The *Y* axis straightness distortion occurs in the case of local distortion of the machine tool guides. It is probably caused by their wear or damage. The amount of rectilinearity error does not depend on the speed of feed motion.

The perpendicularity error and the *Y*-axis straightness deviation had a 57% share in the roundness deviation for the machine tool in the modified test.

The proposed modified test measuring the accuracy of a multi-axis CNC machine using a ball bar measuring bar system was an alternative to machining a test item in the form of a truncated cone inclined to the plane of the machine table.

Preliminary results of machine tool accuracy tests by machining test objects and measurements using a modified test showed a good correlation, which may be a prerequisite for further measurement tests and their analysis.

The method of indirect evaluation of the accuracy of machine tools with the use of machining of test objects is presented in detail in [12].

Conclusions

Diagnostic tests of five-axis CNC machine tools with the use of the QC20 – W ball bar measuring system were aimed at improving the technical condition of the used machines.

Based on the results of the standard and modified accuracy test, it can not be unambiguously determined that the machine tool under test meets the requirements. It resulted from a limited number of diagnostic measurements.

The results of roundness deviations measurements for the tested machine (lower than 25 µm) did not exceed the permissible values.

The presented modified measurement test for an indirect assessment of the accuracy of machine tools should be subjected to further testing and careful analysis.

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