Diagnostics of CNC machine tool with R-Test system

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ABSTRACT: The paper presents methodology for the diagnostics of the vertical machining centre DMU 65 MonoBlock by DMG company, equipped with a numerical control system SIEMENS - SINUMERIC 840 SL MD. The measuring process was conducted with the use of R-Test system. The article discusses test sequence in static and dynamic measurement, as well as diagnostic evaluation of the tested CNC machine tool. The experimental part was devoted to measuring the value of the kinematic pair centre offset of the C rotary axis of the 5-axis machine tool, as well as squareness errors of axis. The evaluation of the influence of the value of the feed motion speed v_f on the diagnostic test was conducted. Static and dynamic measurement results were compared.

KEY WORDS: CNC machine tools, diagnostics systems, calibration, R-Test, errors of CNC machine tool, numerically controlled axis of CNC machine tools

1.INTRODUCTION

Diagnostics of CNC machine tools is one of the main processes surrounding their use. It is conducted both in maintenance as well as in an entire machine operation time [15]. Deployed diagnostic and calibration systems of CNC machine tools allow marking key parameters (static rather than dynamic), reliability control and therefore provide their constant output maintenance. The issue of evaluation of the static and dynamic CNC machine tool errors is widely discussed in papers [1-12,15,16].

Each numerically controlled CNC machine tool is affected by geometrical and kinematic errors, as well as errors resulting from thermal reactions [1,12-16]. Such errors hinder productivity and high precision machining of elements. The idea of compensation for geometrical inaccuracy resulting from spatial positioning errors of a CNC machine tool was presented in papers [2,3,7,12]. Such errors cannot be completely eliminated but they can be limited or their impact minimised.

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It is done by diagnostic measurements which enable identification of errors, calibration and compensation, as well as other software-machine interactions. The diagnostics constitutes, thus, a process of great importance with regard to influencing the machine capability for manufacturing high dimensional and shape accuracy products.

Conventional diagnostic and calibration methods of 5-axis machine tools which use the supervising measuring probe and the master ball (e.g. 3D quickSET by DMG company or AxiSet™ Check-Up by Renishaw company) enable only static measurement in discreet positions, defined in the steering measuring cycle of the machine, which operates the measuring device [6,8,9]. Static measurement does not include the dynamics of the machine, which is in fact a complex dynamic mass-resilient-dissipation system [4].

Precise acquisition of machine tool error characteristics is usually connected with time-consuming measurements and demands employing independent measuring systems (used for calibration or machine tool condition inspection, static or dynamic measurements) [8-10,12,16]. R-Test (by IBS Precision Engineering company) measurement system is one of the diagnostic systems dedicated both to static and dynamic measurements. The subject of the following paper, R-Test, constitutes an innovative, spatial 3D system, implementing such metrological tasks as: general condition monitoring of CNC machine tool, the estimation of calibration parameters of the rotary table position, as well as dynamic analysis [4,5,7,14].

2. DIAGNOSTICS METHODOLOGY AND TEST SEQUENCE

The paper presents the diagnostics methodology of the vertical 5-axis machining centre. The test object was the numerically controlled CNC machine tool: DMU 65 MonoBlock by DMG company, equipped with SIEMENS - SINUMERIC 840 SL MD (Fig. 1) - numerically controlled forming system.

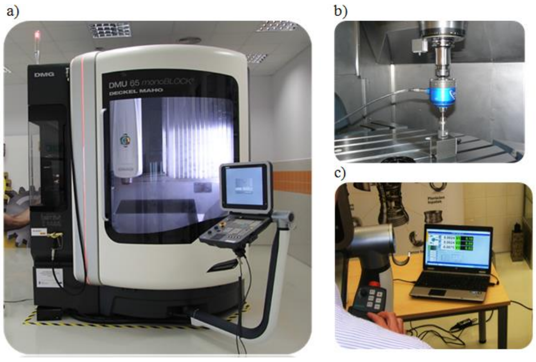

Figure 1. Test object: a) vertical 5-axis machining centre DMU 65 MonoBlock by DMG company, b) R-Test measuring system by IBS Precision Engineering, mounted on the machine tool, c) computer operating MTS-003 software.

Each machine tool meets linear as well as rotation axis errors. In the analysed case, a machine tool with integrated swivel rotary table, the errors interact. Fig.2 presents kinematic centre offset errors of the C rotary axis. Kinematic centre offset of the C rotary axis (Fig. 2) was marked XOC, YOC, ZOC, and rotation angles of the respective numerically controlled axes were marked AOC, BOC, COC, where X, Y, Z are linear axes numerically controlled in original position, A, B, C are the rotary axes in original position, C' is a new position of the C rotary axis.

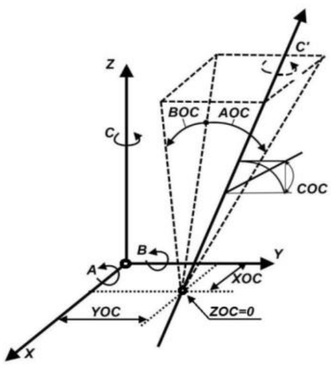

Figure 2. Kinematic centre offset errors of the C rotary axis

The tests employed diagnostic and calibration R-Test measurement system allowing both static and dynamic measurements (including the dynamic performance of the machine tool). The R-Test measurement system set (Fig. 1, 3 and 4) consists of: MT-Probe measuring head, MT-Interface unit (MTI-0010) system, registration R-Test software (MTS-003), a 22 mm diameter master ball fixed to a 75 mm arbor (roundness error < 0.5 μm), alignment device and a magnetic chassis. MT-Probe measuring head of the R-Test system was fixed to a spindle ending (Fig. 1b) (BT40 taper holder). The use of the MT-Probe measuring head of the R-Test system allows the measuring of the centre location of the master ball fixed to an arbour in a magnetic chassis. The master ball with the chassis was fixed to a machine rotary table (Fig. 1b). On the basis of conducted measurements, estimation of the value of the kinematic pair centre offset of the C rotary axis of the 5-axis machine tool, as well as squareness of axis (errors) deviation was conducted. The static measurement was implemented by the MT-Probe measuring head in a XY plane of the CNC machine (Z = const) (Fig. 3). During the dynamic measurements the motion was implemented at a constant mode in 3 numerically controlled axes, simultaneously activated (at 2 linear X, Y axes and a C rotary axis of the machine table). During both, static and dynamic measurements the rotary axis was localised relatively to linear axes. Table 1 presents the metrological specification used during the testing of the MT-Probe measuring head.

Table 1. Metrological specification of MT-probe measuring head

Measuring range	1 mm
Resolution	0.1 μm
Sampling rate	6.5 kHz
Measurement uncertainty	U1 = 0.6 μm (k = 2)
Measuring head shaft (mounting) diameter	D = 16 mm
Dimensions	length 56 mm; diameter 75 mm; weight 375 gram

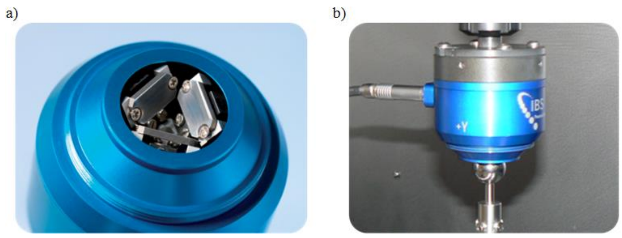

Figure 3 R-Test - CNC machine tool diagnostic system:a) MT-Probe measuring head, b) Master ball and measuring head

During R-Test system testing, the 3D measuring head (MT-Probe consisting of 3 eddy current sensors – Fig. 3a) was in constant contact with the master ball (Fig. 3b). Fig. 4 presents the structural diagram of the MT-Probe measuring head of R-Test system. It shows that eddy current sensors in the measuring head are tilted relative to the vertical plane at an angle of 45° (assuming that the probe axis is in a vertical position) and (eddy current sensors) are placed at an angle of 120° in relation to each other.

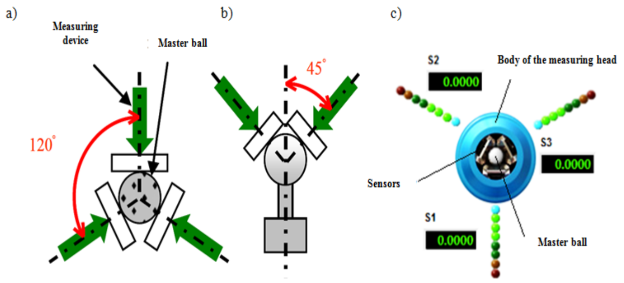

Figure 4. MT-Probe measuring head of R-Test system [13]: a) top view, b) end view, c) bottom view

During static measurements, after each step at a digitised Ci angle rate, e.g. 30°, motion was stopped for about 2 seconds and a point measurement result was registered. The MT-Probe measuring head of R-Test system measures actual 3D localisation simultaneously. The master ball placement is precisely defined in space by X, Y, Z coordinates. The differences between these displacements are treated precisely as errors – positioning inaccuracies. Errors resulting from machine kinematics as a result of deviation in measurement are defined (calculated) with the use of specialised software for measurement data acquisition and then with analysis software, according to a special algorithm. Used R-Test software analyses measurement data and allows specifying the kinematic centre of the rotary axis placement, the squareness error of rotary axis, FFT analysis in X, Y and Z direction, as well as a wide range of possibilities to present measurement results and analyses (linear and polar characteristics, axis and longitudinal displacements). Furthermore, measurement results may be compared and listed on a single diagram (both, static and dynamic).

In dynamic measurement, the C rotary axis of the machine tool was activated and the linear axes followed this movement. Computer and system communication was via USB 2.0 bus. The measuring head, fixed to the CNC machine tool spindle (measuring the real location of the master ball centre) was static during the test, i.e. no rotary motion was performed. Measurement results were presented onscreen with the use of proper software. The sampling rate during the dynamic measurement equalled 6.5 kHz. It allowed an online measurement and simultaneously an estimation of the feed motion speed vf influence on the precision of acquired results. This impact can be extremely significant during the test. In the dynamic measurements presented in the paper the following values of the feed motion speed vf were adopted (250 mm/min, 800 mm/min, 2500 mm/min, 4000 mm/min).

3. DIAGNOSTICS RESULTS AND ANALYSIS

3.1. Static measurement of C axis

Static diagnostic measurements of the C rotary axis were implemented at a range of one full turn (0-360o) with an angle digitisation equal to Ci = 30o. The measurement results were registered at a specific angle position, where motions of the machine tool sets (rotary, rectilinear) were stopped for a few seconds (2s.). For the diagnostic results analysis, R-TEST ANALYSIS V.2.13 software was used. Fig. 5 presents the program interface as well as the static measurement results made during angle positioning of the table at every 30° at full angle range of the test.

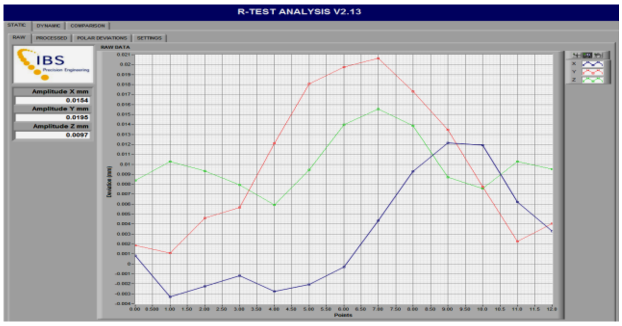

Figure 5. Displacement of the master ball centre point making a discreet rotary motion relative to C axis in respect to the measuring head sensors during the static measurement

Fig. 5 presents detected displacements of the master ball centre point making a discreet C rotary motion relative to Z axis in respect to the measuring head sensors (the static measurement). Proper curves relate to axes of the CNC machine tool X, Y, Z. Values of the deviation, registered during the measurement, were marked on the axis of ordinates, and on the axis of abscissae- points 0 to 12 stand for consecutive angle positions of the machine tool table Ci in relation to Z axis. Respective points i correspond to the consequent angle position, according to the rule i = 0→ Ci = 0°, i = 1→ Ci = 30°, i = 2→ Ci = 60°,…, i = 12→ Ci = 360°. The above digitisation can be noted as a formalised equation Ci = i·30°, where i = 1, 2, 3, ….,12,and Ci is the consequent angle position of the table (presented in angle degrees) in which the measurement was made. Based on Fig. 5, it is possible to claim that the values of the displacement of the master ball centre point (amplitudes at the range of a full test 0÷360o) are formed at a very low level. The deviation (amplitude, maximum displacement) in the X axis direction equals 1.54 µm, in the Y axis direction→1.95 µm and in the Z axis direction→0.95 µm. Low values of actual deviations prove high kinematic and geometric accuracy of the machine. The same measurement data was represented in a circle diagram at a XY plane, as well as XZ and YZ planes. Fig. 6 presents measurement results with diagrams. The presented characteristic (Fig. 6) indicates that the kinematic centre offset error of the C rotary axis in the direction of X axis equals XOC = 3.8 μm and in the direction of YOC axis equals 11.1 μm. These values are most frequently used for controller setting changes (offset errors) and are identified as the parameters which boost positioning accuracy, thus they improve production accuracy. Simultaneously, conducted measurements and their analysis indicate that the squareness error of C rotary axis (Z linear) relative to A axis (X linear) equals AOC = 4.2 μm, and in relation to B axis (Y linear) BOC = 1.1 μm. The squareness error of axis is marked with the use of least square method on the basis of the collected data (measurement). Fig. 6 presents the straight line fitting according to the measurement data in the ZY plane (top left diagram, Fig. 6) and ZX (top right diagram, Fig. 6).

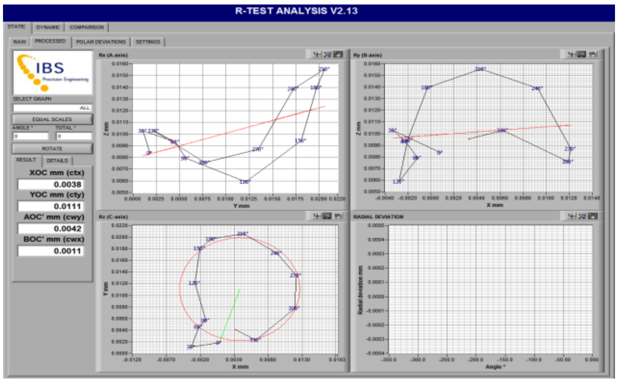

Figure 6. Graphic representation of static measurements results

For an ideal machine tool, the value of errors XOC, YOC, AOC, BOC should equal zero (XOC = 0 □m, YOC = 0 □m, AOC = 0 □m, BOC = 0 □m). Collected measurement results indicate subtle kinematic centre offset of the C rotary axis of the tested CNC machine tool.

3.2. Dynamic measurement of the C axis

Dynamic measurements were implemented for various feed motion speed vf (250 mm/min, 800 mm/min, 2500 mm/min, 4000 mm/min). The measurement results were registered in constant motion throughout which there was a constant contact of the master ball and the measuring head sensors. Fig. 7 presents the displacement of the centre point of the master ball which is in constant C rotary motion relatively to Z axis in respect to the measuring head sensors (dynamic measurement).

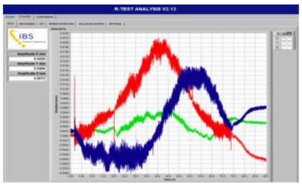

Figure 7. The displacement of the centre point of the master ball which is in constant C rotary motion relatively to Z axis

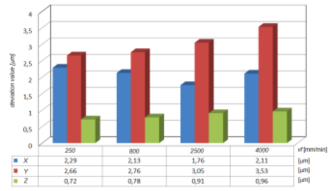

Figure 8. The deviation of the centre point of the master ball which is in constant C rotary motion relatively to Z

For the tests carried out in feed function, the results collected allowed an estimation of the influence of the feed motion speed v_f value on the displacement values during dynamic diagnostic measurement. Fig. 8 presents results gathered for four feed motion speed v_f values.

The presented processes show that there exists nonlinear dependency between the deviation of the centre point of the master ball which is in constant rotary motion (C axis) and the measuring head sensors. Furthermore, it can be stated that the values of these deviations (for various feeds) appear at a very low level (the deviation in the direction of X axis is between 1.76÷2.29μm range, in the Y axis direction 2.66÷3.53μm and in the direction of Z axis 0.72÷0.96μm. Low actual deviations (displacements) values indicate high kinematic and geometric precision of the machine.

Fig. 9 shows sample graphic presentation of dynamic measurement results. The adjustment of the straight line (red colour), marked with the use of least square method, to the measuring data in the ZY plane is presented in the top left diagram and in the ZX plane – top right diagram (Fig. 9). Fig. 9 presents, in addition, the results of the measurements against the ideal circle in a XY plane shown at a circle diagram.

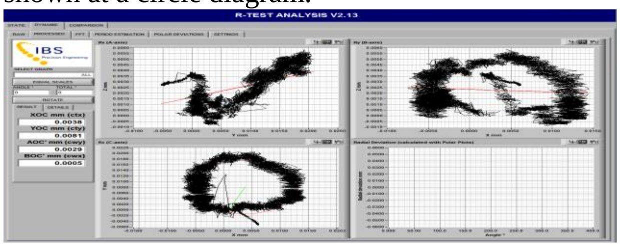

Figure 9. Graphic representation of dynamic measurement results: red colour was assigned to the adjustment of the straight line, marked with the use of least square method

On the basis of presented results (Fig. 9), it can be stated that the value of the kinematic centre offset error of the C rotary axis in the direction of X axis equals XOC = 3.8 μm and in the direction of Y axis Y→YOC = 8.1 μm (offset errors). The analysis of the measurement result, presented in Fig. 9 permits the interpretation that the squareness error of C axis

(Z linear) relative to A axis (X linear) equals AOC = 2.9 μm, and relative to B axis (Y linear) equals BOC = 0.5 μm. Similarly to static measurements, these values are usually used for controller changes and are treated as parameters boosting the positioning accuracy.

Fig. 10 presents obtained results of the dynamic measurement of the kinematic centre offset error of the C rotary axis in the direction of X axis equals XOC and the Y axis equals Y→YOC (offset errors) in the function of feed motion speed v_f. The presented characteristics (Fig. 10) show nonlinear character of changes in the function of the feed motion speed. The highest values of the kinematic centre offset errors of the C rotary axis were observed in the Y axis direction Y→YOC for the feed of v_f = 250 mm/min (YOC = 8.1 μm) and v_f = 2500 mm/min (YOC = 9.5 μm). The lowest and comparable error values were registered for the direction of axis X→XOC (XOC = 2.8÷3.8 μm) for all values of the feed motion v_f speed as well as other values of feeds in the direction Y→YOC (YOC = 1÷1.1 μm).

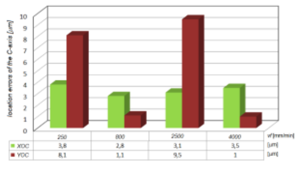

Figure 10. Changes of the kinematic centre offset error of the C rotary axis in the direction of axis X→ XOC and Y→ YOC

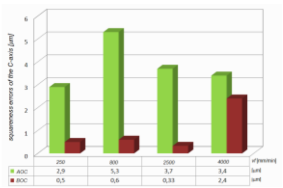

Figure 11. Changes of the squareness error of AOC axis relative to A axis and BOC relative to B axis in the function of feed motion speed v_f

Fig.11 presents process of changes of the value of the squareness error of AOC axis relative to A axis (X linear) and BOC relative to B axis (Y linear) in the function of feed motion speed v_f. On the basis of gathered characteristics, the nonlinear dependency of AOC and BOC errors to the value of the feed motion speed v_f can be stated.

For the dynamic measurement, the squareness of axis error is marked with the use of least square method. It must be remarked that this is estimated on the basis of a larger amount of data collected in dynamic measurements compared to static measurements. Fig. 11 shows that the deviation of the C axis squareness (Z linear) relative to X axis (AOC = 2.9÷5.3 μm) is much higher than in the case of Y axis (BOC = 0.5÷2.4 μm). Identically as with reference to the static measurements results for an ideal machine tool, the value of errors XOC, YOC, AOC, BOC should equal zero (XOC = 0 μm, YOC = 0 μm, AOC = 0 μm, BOC = 0 μm).

Fig. 12 presents comparative summary of the analysed results of static measurements and the mean value of deviations and errors from dynamic measurements.

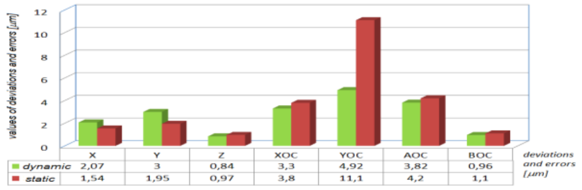

Figure 12. Comparative summary of analysed results of static measurements and mean value of errors and deviations (amplitudes) from dynamic measurements

The comparative analysis (Fig. 12) of the mean value of tested errors and deviations (amplitudes) from dynamic measurements (Fig. 7÷Fig. 11) with static measurements results (Fig. 5 and Fig. 6), shows a comparable level of machine tool inaccuracy..

4. CONCLUSIONS

Diagnostics and calibration of numerically controlled machine tools is an issue of great significance throughout proper long-term operation of CNC machine tools. Its importance is reflected in that it secures constant capacity maintenance and therefore their operational reliability. This is particularly essential in high-precision machining of elements of vital operational importance. Diagnostics and calibration of numerically controlled machine tools are required particularly after a collision or machine tool relocation. The implementation of R-Test system to the CNC machine tools diagnostics guarantees time efficiency and cost effectiveness of the service by automatic measurement and the ability to use the measurement results during calibration. R-Test measurement system usage allows both dynamic and static measurement. It is an undeniable advantage of the system. Dynamic measurement is faster and the results are more precise (errors estimation is based on a great number of results).

Conducted experimental tests allow estimation of the kinematic pier of the C rotary axis placement as well as C axis (Z rotary) squareness errors relative to X and Y axes. Moreover, the tests enable evaluation of the influence of the feed motion speed vf on the result of measurement, with the use of diagnostics and calibration R-Test system. The measurements presented showed non-linear character of changes of the measured values of errors in the function of feed motion speed vf. This non-linearity illustrates the necessity of always accurate dynamic measurements in the feed motion function in calibration of a machine tool in industrial conditions. The deviation of the C axis squareness (Z linear) relative to X axis is much higher (approximately 3 times) than in the case of Y axis. On the basis of comparative analysis, it can be stated that higher values of deviations (amplitudes) in X, Y, Z axes apply to dynamic measurement, which can be explained by the superposition of kinematic errors of the machine as well as lower values of the placement and squareness errors in relation to the static measurement. It indicates higher accuracy of dynamic measurement (a great number of results of the measurement, on the basis of which the errors were marked).

Measurements and calibration of a machine tool with the use of R-Test device ensure high geometric accuracy of a machine tool and quick correction of kinematic centre offset errors of rotary axes as well as squareness of axis errors. The registered low values of actual deviations (displacements) in X, Y, Z axes and the defined errors prove high kinematic and geometric accuracy of the tested CNC machine tool.

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