CALIBRATION OF 5 AXIS CNC MACHINE TOOL WITH 3D QUICKSET MEASUREMENT SYSTEM

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ABSTRACT: The paper presents results of calibration measurements, which enable evaluation of the impact of table rotation angle on 3D quickSET (DMG) diagnostics system measurement results. The theoretical section is devoted to presenting characteristics and description of other systems in the diagnostic-calibration systems group, i.e. 3D quickSET (DMG) and AxiSet™ Check-Up (Renishaw). Each system was analysed and presented in terms of test procedure, structure and components as well as advantages and disadvantages. The practical part focuses on estimation of the value of the kinematic pair centre offset of rotary axes of the 5-axis machine tool. The object of research was a vertical machining centre diagnostic DMU 65 MonoBlock by DMG company, equipped with numerical control measurement system SIEMENS - SINUMERIC 840 SL MD. Obtained test results enabled calibration of both C rotary and A swivel axes of the machine table. The conducted tests indicate the correlation between the test angle and calibration measurement result.
KEY WORDS: CNC machine tool, diagnostics systems, calibration, 3D quickSET, AxiSet™ Check-Up, CNC machine tool errors, coordinates of rotary axes, numerically controlled axis of CNC machine tools

1.INTRODUCTION

Alignment and rotary axis positioning control constitutes an immensely important issue with regard to multi-axis CNC machine tool machining [6-14]. In recent years there has been a significant increase in the application of multi-axis machines in different branches of the industry [1-5,15-20]. This is largely due to the development of aircraft and automotive industry. The application of multi-axis machine tools and precise geometry of machined elements shape require precise error modelling of rotary and linear axis pivot point of the machine tool (Fig. 1). This factor conditions high precision of machine milling performed on such machines. During interpolation on 5-axis rotary, axis pivot points location (Fig. 1b) influences the machining process, in particular dimensional and shape accuracy of geometrically complex workpiece surface. [1, 4-7, 10-15].

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Lack of detailed information or any data concerning ‘pivot points’ (kinematic centres) hampers the CNC steering system reliable control of the position of the tool or the workpiece during rotational axis movement. This fact leads to common machining errors in geometrically complex surface of the workpiece. The key to high-precision machining is the ability to determine precisely axis pivot point deviation in relation to the linear axis of the machine tool A. [18-20]

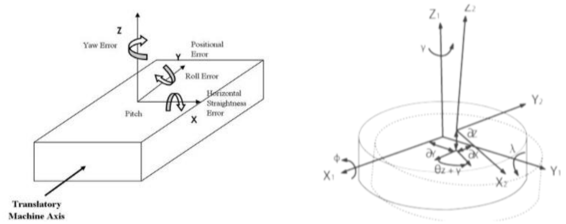

Figure 1. Linear and rotational axis errors:
a) linear and angle errors along machine axis, b) numerically controlled pivot point position error (kinematic centres of rotational axis) [19]

Until recently there was a lack of tools for automatic control and calibration of rotational axes and, as a result, identifying errors resulting from incorrect machine tool setup, collision as well as wear was time-consuming and considerably complicated. [4,6] However, as the practical application of multi-axis machine tool was gaining popularity, multiple systems for diagnostics, measurement and calibration of CNC machine tool rotational axes were invented. [8,9,17-19]. Among other existing systems those worth mentioning are laser ones allowing quick and accurate determination of kinematic centres positioning, such as AxiSet™ Check-Up by Renishaw and 3D quickSET by DMG [16].

2.CNC MACHINE TOOLS AXIS CONTROL AND CALIBRATION

As it was already mentioned in the opening section, AxiSet™ Check-Up produced by Renishaw as well as 3D quickSET produced by DMG provide quick and accurate assessment of the kinematic centre positioning. (Fig. 2) [16]. All tests performed with the instruments in question involve touch trigger probes of the workpiece fixed to a spindle's ending. Such probes are commonly one of the elements of multi-axis machine tool equipment.

Figure 2. Diagnostic and calibration systems tools of multi-axis machine tools:
a) AxiSet™ Check-Up by Renishaw [16],
b) 3D quickSET by DMG

Testing is performed with the use of measurement procedures (cycles). In the case of AxiSet™ Check-Up, the measurement procedures are generated with special software using measurement macro-procedures. 3D quickSET, on the other hand, requires defining SM_QSET 3D quickSET measuring cycle implemented in the control system of the machine tool. DM_QSET 3D quickSET is provided as a component of a machine tool set, however, not in all configurations. 5-axis machine tool control systems such as Siemens 840D, Heidenhain iTNC 530 or Heidenhain MillPlus are equipped with SM_QSET 3D quickSET cycle. Operating AxiSet™ Check-Up requires 'external separate' software provided together with the check-up. In both systems the measuring probe, after measuring the ball and determining its centre point follows the master ball (or spindle) mounted on the magnetic chassis.

2.1 AxiSet™ Check-Up

AxiSet™ Check-Up by Renishaw allows assessing the technical condition of multi-axis machine tools (5-axis milling centres as well as multi-purpose lathe-milling machines) through estimation of NC rotary axis centre positional errors (e.g. rotary tables, swivel tables, spindles – also in lathe machines). Determining the kinematic centre offset to the rotary axis is crucial particularly in terms of dimensional and shape accuracy of elements machined on multi-axis machine tools. The deviation estimated using AxiSet™ Check-Up is of great importance when elements with high qualitative requirements are machined with 5-axis interpolation. Among key advantages of AxiSet™ Check-Up quick measurement and diagnostic assessment process as well as the possibility to detect and report errors must be mentioned. The reports can be presented in incremental and absolute reporting modes.

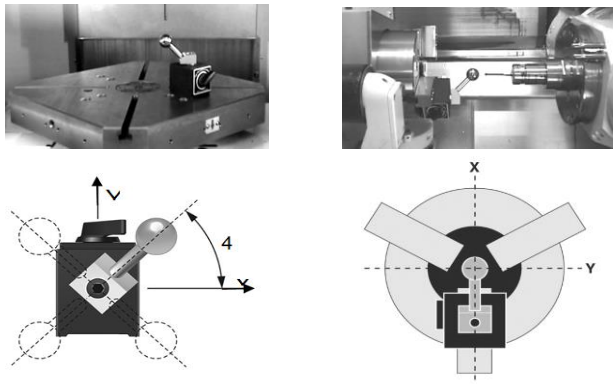

Figure 3. AxiSet™ Check-Up by Renishaw during C-axis calibration: a) on a mill, b) on a lathe, c) mounting the ball on a mill, d) mounting the ball on a lathe [16]

Fig. 3 shows AxiSet™ Check-Up by Renishaw during C-axis calibration on a milling machine (Fig. 3a and 3c) as well as on a lathe (Fig. 3b and 3d) [16].The measurements taken with AxiSet™ Check-Up enable creating logs of machine errors. This advantage allows monitoring technical parameters in time, observing trends of CNC condition as well as schedule maintenance procedures.

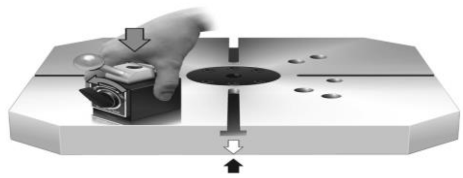

Figure 4. Mounting the master ball on the machine tool table [16]

The collected data concerning technological condition of a machine tool allowed conducting analyses and comparing different operation periods as well as predicting future condition of the tool based on the registered trends [16]. The readings are presented in a graphic form, which, when combined with tolerance control, ensures quick identification of changes in technical parameters caused by collisions or setting errors.

Testing angles defined by the user allow testing the machine tool in critical positions; while the tolerance function increases the confidence level prior to proper machining of key elements begins.

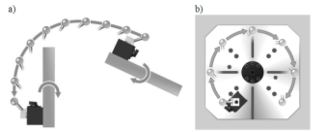

Figure 5. Schematic diagram of a measurement on a milling centre.

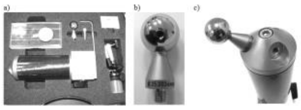

Figure 6. Diagnostic and calibration set 3D quickSET by DMG

Test conducted with AxiSet™ Check-Up comprises the following actions: installation of macro-procedure software on the CNC and software on a PC (prior to the first run only), configuration of macro-procedure software (prior to the first run only), probe calibration (according to macro-procedures – prior to the first run only), settings verification, reading the software manual guide enclosed to the macro-procedure software, mounting the master ball on the magnetic chassis (Fig. 4), entering test parameters with macro-procedures, performing measurement macro-procedure (macro-programs) (Fig. 5), transferring the results to a PC (data transmission), analysis of results and printing reports (technical condition of the machine tool, comparison of the results with tolerance, history check etc.) [16]

2.2 DMG 3D quickSET

DMG 3D quickSET is a device produced by DMG for precise rotation axis centre determination on 5-axis machine tools (Fig. 6).

The 3D quickSET includes a measuring sensor with measurement allowance equal to 2 µm and pressure 0.25 N/m (Fig. 6a). It is used for probe calibration. 3D quickSET has a 25.0034 mm diameter ball fixed at the end of a threaded arbor (Fig. 6b). The ball is fixed to the threaded arbor in a socket located at the end of the main body of the 3D quickSET. (Fig. 6c) Sockets distribution in the main body of 3D quickSET allows fixing the ball in various positions: at 0° (vertically), 45° as well as 90° angles making the system universal in a sense. The position of master ball is significant during measurement in various configurations of rotary as well as swivel rotary tables.

The underlying goal of a DMG 3D quickSET test is to determine the coordinates of the point based on which the system calculates the physical rotational axis centre (Fig. 7). The process is performed to achieve correct rotation of the machine based on the turning cycle, and consequently, to achieve accurate workpiece dimensions. Therefore, the physical rotational axis centre acquires high machining accuracy especially with regard to finishing operations. Using DMG 3D quickSET seems well-founded in the following circumstances: when the workpiece has low dimensional or shape accuracy tolerance and the machining profile is frequently changed (various material types, mechanical properties, i.e. toughness, surface layer properties), in the case of spindle collision (tool) with the table (workpiece), after extended machine operation, when machining discontinuous surfaces (discontinuous machining), after machine tool relocation etc

The machine tool must have a point according to which it transforms the system in multi-axis machining. Until recently, without the 3D quickSET, the process was performed by maintenance worker who used sensors and a measuring instrument measured and manually positioned the rotational axis and manually entered measurement results to the kinematic table of the machine. These tables are usually beyond the reach of a user, therefore, the calibration had to involve service technician making it complicated.

3D quickSET system allows direct saving the measurement result in the machine kinematic table. The application of 3D quickSET requires highly precise calibration of the measuring probe. Only a carefully calibrated measuring probe can be used in test conditions with 3D quickSET software and will ensure expected test results.

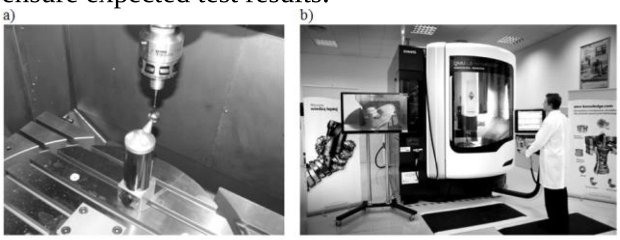

Figure 7. Installation of DMG 3D quickSET calibration system

3. METHODOLOGY AND EXPERIMENTAL TESTS

The research object of the presented paper is a 5-axis vertical machining centre DMU 65 MonoBlock, equipped with numerical control measurement system SIEMENS - SINUMERIC 840 SL MD. Numerical control permits the realisation of DM_QSET 3D quickSET measuring cycle. DM_QSET 3D quickSET cycle consists in selecting the cycle and defining its parameters. As a result 3D quickSET master ball measurement is realised with a calibrated measuring probe, with a turn by angle α (usually 90° or 180°) as well as rotation axis centre determination and its transfer to the kinematic table of the machine.

In the conducted tests the calibration test angle value α(interval 15°) was accepted for both A-axis and C-axis calibration measurements. A-axis measurements, owing to its kinematic properties were realised in the range of 90°÷ +90°, whereas C-axis in the range of -180°÷ +180°, clockwise (0°÷ +90°, 0°÷ +180°), or counter clockwise (-90°÷0°; -180°÷0°), with angle growth of α=15°. Measurement conditions are presented in Table 1.

Table 1. Conditions at A-axis and C-axis calibration measurement of CNC machine tool

angle test α in A-axis calibration (feed motion speed v_f=const, probe position in relation to machine rotary table CNC b=220mm)													
α	-90°	-75°	-60°	-45°	-30°	-15°	0°	15°	30°	45°	60°	75°	90°

angle test α in C-axis calibration (feed motion speed v_f=const, probe position in relation to machine rotary table CNC b=220mm)																									
α	-180°	-165°	-150°	-135°	-120°	-105°	-90°	-75°	-60°	-45°	-30°	-15°	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°	180°

Preparation of measurement software (DM_QSET 3D quickSET cycle, (Fig. 8) realised with adherence to the following procedure, including indications mentioned in 2.2:define 3D quickSET position on rotary table; mount the master ball in a 45° socket; situate 3D quickSET on the machine tool table, 220 mm form its axis (Fig. 7a); perform calibration of the measuring probe (head) (Fig. 7b); select DM_QSET 3D quickSET cycle in the numerical control system of the machine (Fig. 8a,b); define cycle parameters :define measurement type (rotary axis measurement); set ball diameter at 25.0034 mm; set angle test α; select measurement mode: 0 – only measurement; conduct measurement procedure. Fig. 8c shows defined parameters values set in a model measurement.

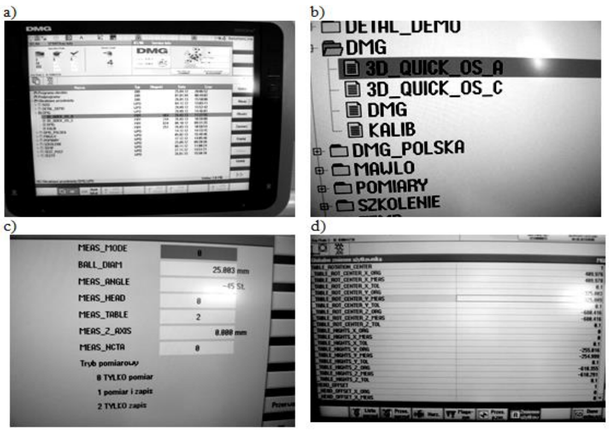

Figure 8. DM_QSET 3D quickSET cycle interface: a) control system catalogue structure, b) DM_QSET 3D quickSET cycle selection, c) cycle parameters selection, d) measurement results in machine kinematics table

The major issue in measurements conducted with 3D quickSET software is thermal strain of the calibration and measurement system, the measuring head and the machine tool.

4. TEST RESULTS AND ANALYSIS

Conducted experimental tests permitted formulation of characteristics of changes of calibration coordinates X_m, Y_m values (measured) in the function of test angle α in A-axis and C-axis calibration of the analysed machine tool. Conducted tests enabled defining the value of coordinates saved in the kinematic table of the machine, for digitised values of the calibration test angle α. They also illustrate that the calibration precision is conditioned not only by the level of calibration accuracy of the measuring probe (head) used in 3D quickSET measurement, but also by the angle of table rotation α throughout A and C rotary axis calibration.

4.1. A-axis calibration

Fig. 9 presents the sequence of changes of the measured value of the coordinate Xm in the function of measurement angle α during calibration of the rotary A-axis of the numerically controlled (by 3D quickSET device) machine tool. The measurement results were presented against the original value of this coordinate Xorg, put in the kinematic table of the machine.

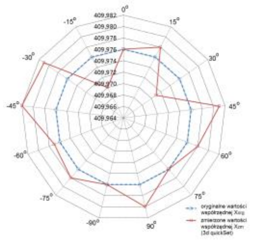

Figure 9. The sequence of changes of the value of the coordinate X_m

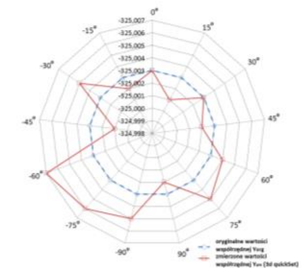

Figure 10. The sequence of changes of the value of the coordinate Y_m

The analysis of the diagram (Fig. 9) shows that maximal values of Xm coordinate were registered at a measurement angle of α=+45°, α=-15°, α=-30° as well as α=-45°. At the same time, an absolute error value ΔX of the of Xm coordinate location in the function of measurement angle α (Fig. 11) is the highest for the above mentioned angle placements α. This shows that there exists dependency of the value of the measurement of the rotary axis centre on the measurement angle α.The analysis of consecutive diagrams (Fig. 9-14) also illustrates that these dependencies demonstrate nonlinear character. It has to be noted, that the repeatability of collected measurement results, for constant value of the measurement angle $\alpha$was, for all conducted tests with 10 times repetitions, in the range of 97÷99%.

Fig. 10 presents the sequence of changes of the value of the coordinate Ym in the function of the measurement angle α during calibration of the rotary A-axis numerically controlled. Similarly to the Xm coordinate (Fig. 9), measurement results were presented against the original value Yorg, from the machine's kinematic table. Maximal coordinate values were registered at α=-60° and α=-75°.

Fig. 11 and 12 present the values of absolute errors (ΔX, ΔY) of the measured axes: Xm and Ym. Fig. 11 presents the sequence of changes of the value of the absolute error ΔX of the Xm coordinate location in the function of the measurement angle α during calibration of the rotary A-axis numerically controlled by 3D quickSET device.

Whereas, Fig. 12 presents the nature of changes of the value of the absolute error ΔY of the Ym coordinate location in the function of the measurement angle α during calibration of the rotary A-axis numerically controlled by 3D quickSET device.

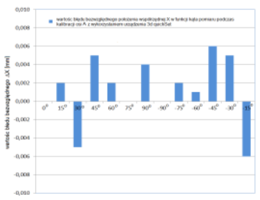

Figure 11. The sequence of changes of the value of the absolute error ΔX

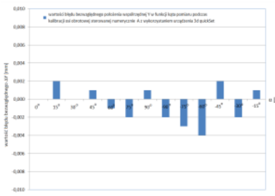

Figure 12. The sequence of changes of the value of the absolute error ΔY

4.2. C-axis calibration

The presented (Fig. 13 and Fig. 14) characteristics describe the nature of changes of the measured values of calibration coordinates (Xm, Ym) during calibration of C-axis of the numerically controlled machine tool. Fig. 13 presents the nature of changes of the measured value of Xm coordinate in the function of the measurement angle α during calibration of the C rotary axis numerically controlled with the use of 3D quickSET device.

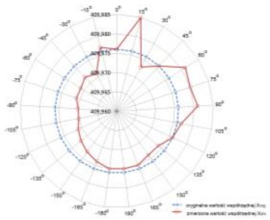

Figure 13. The sequence of changes of the value of the coordinate Xm

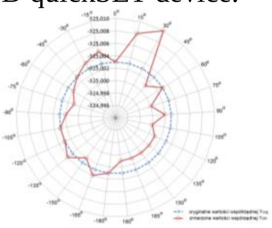

Figure 14. The sequence of changes of the value of the coordinate Ym

The presented values of calibration coordinates Xm, Ym (Fig. 13-14) show the highest values at α=15°, 60°, 75°, 90° (for Xm) and α=15°, 30° (for Ym).

Fig. 15 and 16 present the values of absolute errors (ΔX, ΔY) of the measured calibration coordinates Xm and Ym for C-axis. Fig. 15 shows the sequence of changes of the value of the absolute error ΔX of the Xm coordinate location in the function of the measurement angle α during calibration of the rotary C-axis numerically controlled by 3D quickSET device.

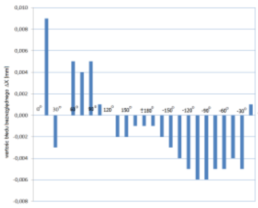

Figure 15. The sequence of changes of the value of the absolute error ΔX of the Xm

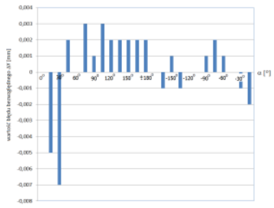

Figure 14. The sequence of changes of the value of the absolute error ΔY of the Ym

The obtained results show that the maximal values of absolute errors for particular calibration coordinates Xm, Ym during calibration of the C-axis take higher values than during calibration of A-axis. Maximal values of errors are in the range of 7÷9μm, where for A-axis the values were in the range of 4÷6μm. Calibration of rotary axes, conducted with the use of diagnostic R-Test system Due to the overly considerable range of tests, these results will be presented in the next article of our quarterly.

5. CONCLUSIONS

The measurements and calibration of a machine tool, with the use of 3D quickSET device allow the maintenance of high kinematic accuracy of a machine tool and a quick correction of kinematic errors. This is an extremely significant task throughout the machine's operation process, especially during its long-term performance, precise machining of the workpiece or after a collision or a machine tool's relocation. The use of 3D quickSET system allows time saving and cost reduction of the service by automatic and independent measurement. It enables, indirectly, the maintenance of high quality demands of produced elements as well as a narrow tolerance of the constituted geometric dimensions of the workpiece. The detailed description of the test, presented in this paper, forms a useful tutorial of 3D quickSET system usage. It allows users an effective implementation of tests and therefore allows improvement of the production accuracy during 5-axis machining. The obtained results of the experimental tests enable stating that the result of calibration measurement is conditioned not only by the precision of calibration of the measuring probe (head), used during tests, but also by the angle test realisation α , during the location calibration of the rotary axes centres (by 3D quickSET) and the path direction. The results demonstrated the nonlinear nature of changes of the coordinates measured in the function of the angle test. It indicates that the measurements and calibration of multi-axis machine tool, with the use of 3D quickSET, should be preceded by the study of the angle test α influence on the measurement result. The optimization of the calibration data collected during the tests will allow to reduction of the frequency of the conducted calibration tests, excluding situations of calibration inevitability after a collision or relocation of a machine tool.

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