



TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. XX, Issue xx, Month, 20xx

TEST BENCH FOR ASSESSING THE ACCURACY AND SYNCHRONIZATION OF CNC AXES

Mihai CIUPAN, Claudiu-Ioan RUSAN, Cornel CIUPAN

Abstract: *The paper presents a test bench for testing a kinematic axes system that is a part of a machine-tool, robot or other technological equipment. It describes the bench structure and the calculation method for loading the kinematic axes with loads equivalent to those to which they are subjected during operation in the real machine. The test bench was actually built and equipped for testing the kinematic axes of a five-axis CNC machine tool. Tests were done regarding the operation of the axes on the bench and the creation of several interpolation programs. The performance and advantages of the research carried out for the study of the feed axes of the 5-axis machine are synthetically presented in the paper.*

Key words: *test bench, CNC axes, accuracy measurement, axes synchronization.*

1. INTRODUCTION

Machine tools represent the most important segment of technological equipment in the field of mechanical processing, because they are involved in making almost all the equipment, parts and machines needed in manufacturing.

A machine tool can be defined as a system of kinematic axes assembled on a frame, in order to achieve correlated movements between the tool and the part.

A robot is a universal, reprogrammable manipulator, designed to move materials, components, tools or specialized systems, through various programmed movements, to perform different tasks.

Similarly to a CNC machine, a robot must take information from the environment (sensors), be easily programmed/reprogrammed (flexible programming), operate autonomously and interact with the operator to execute tasks specific to a process.

The kinematic axis represents a mechatronic subassembly of a CNC machine tool, robot or other automated technological equipment, which performs an elementary movement.

An elementary movement is a linear or rotational movement that is performed on a

trajectory materialized by the guides or bearings of the respective equipment.

In machine tools, an elementary movement is performed by a single motor and is not influenced by another movement of the machine.

In contrast, in some robot structures, there are also situations in which an elementary movement is influenced by another movement, requiring the correlated action of several motors to perform it [1].

Machine-tools are constantly evolving under the influence of customer requirements in this industry [2, 3, 4]:

- low purchase and utilization costs;
- the ability to process parts with unusual dimensions (very large or very small) [5, 6];
- reduced manufacturing time.

These goals can be achieved through a series of measures:

- reduced raw material and labor costs for machine tool construction (e.g. composite structural elements);
- increased machine productivity by using higher cutting speeds and feed rates (high-speed machining / high-performance machining) [7];
- increased machine accuracy [8];
- improved reliability;

- automation of some operating processes (automatic work coordinate system measurement, automatic tool measurement, dynamic adjustment of process parameters depending on cutting conditions) [9];

- machining with as few setups as possible [10];

- simultaneous machining of several parts by increasing the number of kinematic axes;

- improvement of processing speed and adjustment characteristics of electronic control systems;

- possibility of integrating the machine tool into a partially or fully automated production flow [10].

An important factor for a machine tool to meet customer requirements is that it meets high precision requirements, appropriate to the parts it processes. Achieving high precision and accuracy in the manufacturing of parts is an increasingly important challenge for machine tool manufacturers. The precision of the machine tool is affected by the errors with which relative movement is carried out on the machine axes. These occur either due to errors in the relative positioning of the kinematic axes (generally deviations from perpendicularity), or due to kinematic errors in the realization of correlated movements between axes. The latter can come from errors in some parts (for example, lead errors in ball screws) or due to axis control.

In order to measure the accuracy of the CNC machine it undergoes standardized tests:

- ISO 10791-7:2020 Test conditions for machining centres. Accuracy of finished test parts;

- ISO 230 Test code for machine tools, consists of the following parts, under the general title:

- Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions;
- Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes;
- Part 3: Determination of thermal effects;
- Part 4: Circular tests for numerically controlled machine tools;
- Etc.

Testing the machine according to the above-mentioned standards implies that the machine is already built, which presents inconveniences especially in the case of the design of new machines that have 5 or more kinematic axes which have to be correlated in a certain way. For example, in the case of the design of a new machine, it is possible that the kinematic axes (motors, drives, etc.) do not correspond to the load of the machine, which is discovered only after the production and testing of the machine. In this case, solving the design problems and rebuilding of the machine involves additional costs and lengthening of the manufacturing time.

The authors propose the creation of a test bench for testing the assembly of kinematic axes that are part of the machine, so as to avoid the non-conformities in the functioning of the machine tool prototype.

2. TEST BENCH PRESENTATION

2.1 Test bench description

The bench (figure 1) consists of a support 1 provided with n slots in which all the n kinematic axes $AC_1, AC_2, \dots, AC_n$ that are part of a CNC machine tool, a robot or another automation system are mounted.

Each kinematic axis AC_i , which is mounted on the bench, contains all the components of the kinematic axis specific to the machine of which it is part, except for the moving parts that are part of the structure of the machine itself.

Each kinematic axis AC_i consists of an electric motor 2 and a drive 3, with the role of moving and controlling the axis in order to achieve an elementary movement of the machine tool (X, Y, Z , etc.). The bench in figure 1 has six kinematic axes $AC_i, i=1\dots6$, three axes for linear movements (X, Y, Z) and three axes for rotational movements (A, B, C). The bench can be designed for any number of kinematic axes.

To test the AC_i axes as close as possible to their operation while mounted on the machine, the bench is equipped with a loading system consisting of discs 7 and electromagnetic brakes 8, which are mounted on the axis 2b of the motors 2.

The electromagnetic brake 8 has a movable part 8a, which is coupled to shaft 2b of motor 2 and a fixed part 8b which is fixed to support 9 using screws 10.

The discs 7 are sized for each kinematic axis AC_i ($i=1\dots n$) so as to ensure a moment of inertia I_i ($i=1\dots n$) which produces a torque equivalent to that produced by the forces and moments of inertia that occur in the operation of the axis in the machine assembly.

The electromagnetic brakes 8 are chosen so as to ensure the maximum load for each kinematic axis. The braking force achieved by

the electromagnetic brakes 5 can be modified by supplying them with a variable current.

Support 1 and support 9 are fixed to a bench table, not shown in the figures.

The power supply of drivers 3 is made from a network 11 through cables 12. Network 11 can be a single-phase or three-phase network, depending on the specifications of the drives.

The command and control of the axes $AC_1, \dots, AC_n$ is done using the CNC controller 13 which communicates with drives 3 through a bus 14, using the EtherCAT protocol.

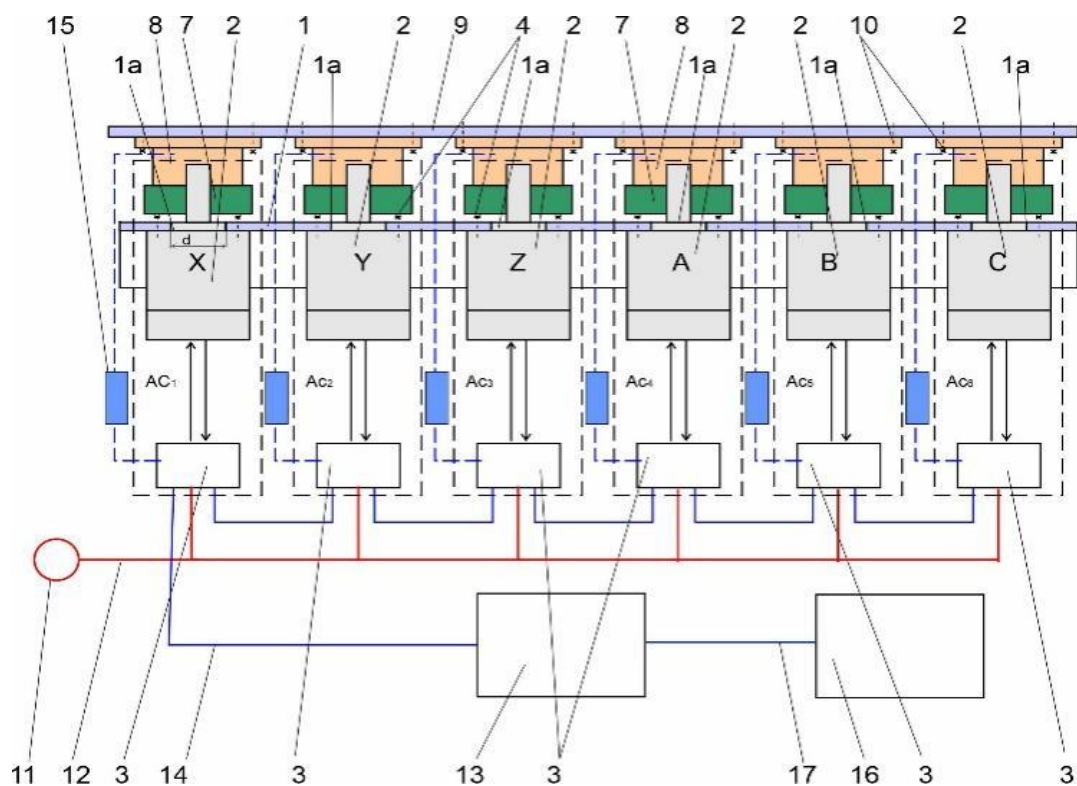


Fig. 1. The test bench for 6 kinematic axes

The machine is controlled from a PC 16 connected to CNC controller 13 through a network cable 17. The communication between the computer 16 and the CNC controller 13 is done through the Ethernet (LAN) protocol.

PC 16 is a standard computer with a Windows operating system. An application provided by the CNC controller manufacturer is installed on the PC. The application has a graphical interface that allows writing CNC instructions/programs and manual operation of the machine. PC 16 sends information to the

CNC controller and receives information about the position and load of the CNC axes.

2.2 Calculating the corresponding load for each axis

During the first stage, based on the kinematic structure and the load on each axis within the machine, the following are determined:

- torque value M_1 at the shaft of each motor 2, which represents the resistive torque produced by the forces and moments of inertia

resulting from the operation of the axis within the machine;

- torque value M_2 at the shaft of each motor 2, which is the resistive torque produced by the forces and torque resulting from the machining process of the part being considered.

During the second stage, the equivalent load of each kinematic axis AC_i that is mounted on the bench is determined.

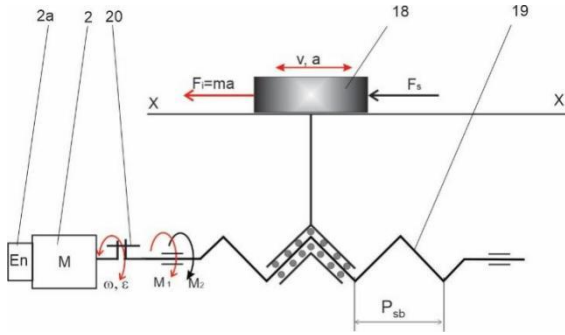


Fig. 2. The diagram of a linear kinematic axis

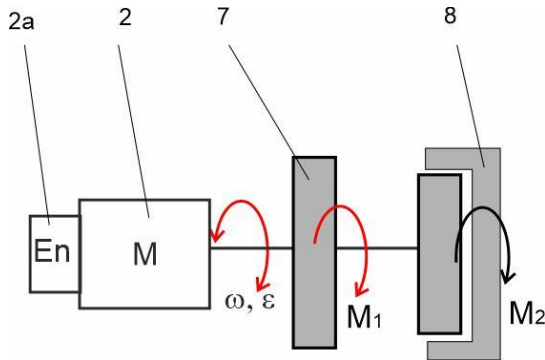


Fig. 3. The diagram of a test bench axis that is equivalent to the axis in figure 2

An example of determining the loading of a linear kinematic axis is presented in relation to figures 2 and 3.

The inertia force F_i will produce at the axis of the ballscrew 19 a torque M_1 , given by the following equation:

$$M_1 = m \cdot a \cdot \frac{d_s}{2} \cdot \tan(\beta_m + \varphi) \quad (1).$$

Similarly to the inertia force, the feed force F_s will produce a resisting torque M_2 at the ballscrew shaft 19, given by equation:

$$M_2 = F_s \cdot \frac{d_s}{2} \cdot \tan(\beta_m + \varphi) \quad (2).$$

where: m - moving mass 18; a - acceleration; d_s - the working diameter of ballscrew 19; β_m - the angle of the spiral of ballscrew 19 thread; φ - the friction angle.

For the equivalent axis in figure 3, the resistive torque values at motor shaft 2 are determined using the following equations:

$$M_{1e} = I \cdot \varepsilon \quad (3)$$

$$M_{2e} = c \cdot M_{Fmax} \quad (4).$$

By combining equations (1) and (3), the moment of inertia I with which the disks 7 are dimensioned is determined. Similarly, using equations (2) and (4), the correction coefficient c is obtained. The electromagnetic brakes 8 are chosen to produce a braking moment above the maximum load of the kinematic axis. Since the electromagnetic brake 8 is oversized compared to the braking moment M_{2e} that is applied to the equivalent axis, it will be supplied with a reduced current compared to the nominal current. The supply current is proportional to the correction factor c . The correspondence between the supply current and the correction factor c is made through a calibration process.

The supply of the electromagnetic brakes is done through electronic devices 15, connected to drives 3. Drives 3 control the moment and duration when brakes 8 are applied. Figure 4 shows an image of the test bench, and figure 5 the graphical control interface.



Fig. 4. Test bench for evaluating a 5 axis CNC machine



Fig. 5. Graphical interface for the CNC application

3. RESULTS

The authors have established a method for bench testing the kinematic control system of a machine-tool or robot which consists of the following steps:

- a standard test program is chosen or a customized program is designed; it's motions should simulate different usage scenarios, especially those which are most probable to yield high error;
- data is acquired from the 2a encoders of the motors of each axis and plotted;
- the resulting trajectory is compared with the programmed trajectory;
- the errors between the programmed trajectory and the resulting trajectory are calculated.

Figure 6 shows the results for repetitive movements on the X axis between positions 0 and 10 mm with a feed of 600 mm/min and a return with rapid speed, 2500 mm/min in this case (G00 X0; G01 X10 F600 ;).

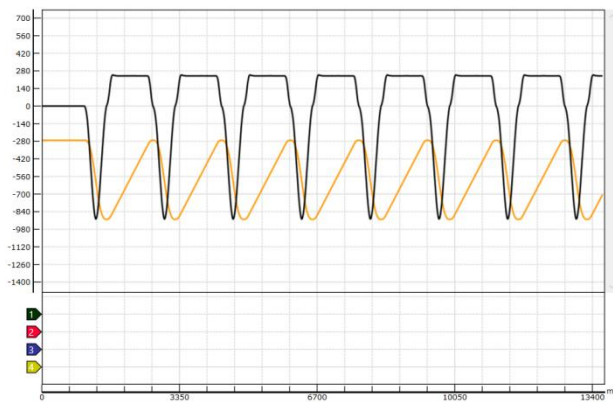


Fig. 6. Axis position and deviation for 600 mm/min feed

The orange line indicates the actual commanded position in encoder divisions, but its actual dimension is not shown on the vertical scale. The black line represents the deviation between the commanded and actual position and the values on the vertical axis correspond to it. It is possible to see that the deviation is much smaller when feeding with a speed of 600 mm/min compared to the rapid traverse. An error of approximately 280 divisions out of the total of 8,388,608 represents 0.003% of an entire rotation of the motor. At a ballscrew pitch of 5 mm this equates to 0.17 μm which is well below the 5

μm error in most modern average size CNC machines.

Figure 7 shows the results for repetitive movements on the X axis between positions 0 and 10 mm with a feed of 2400 mm/min, 4 times higher than the previous example, and a return with rapid speed, 2500 mm/min in this case (G00 X0; G01 X10 F2400 ;).

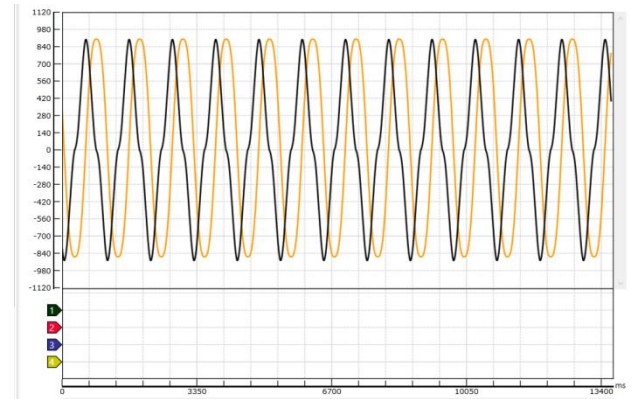


Fig. 7. Axis position and deviation for 600 mm/min feed

The error in the second example is higher, about 3.5 times than in the first example, but still well below the threshold for accurate machines.

4. CONCLUSIONS

The test bench presented in the paper offers the following advantages:

- the possibility of testing the functioning of a system of kinematic axes before building the technological equipment of which they are part of;
- avoiding design errors before building the assembly;
- optimizing the functioning of the machine;
- the possibility of using the bench for teaching purposes to simulate the functioning of various technological equipment (machine tools, robots, etc.).

The research shows that the following tests can be performed on the test bench:

- accuracy of machines operating under no-load (without discs 7 and brakes 8);
- accuracy and repeatability of positioning of numerically controlled axes with equivalent load

- linear, circular and helical interpolation plus rigid tapping synchronization for numerically controlled machine tools.

ACKNOWLEDGMENT

This work was supported by the “Improving the performance of CNC machine tools for the educational field using mineral casting structural elements” grant funded by the National Grant Competition - GNaC ARUT 2023.

8. REFERENCES

- [1] <https://www.kuka.com/ro-ro/produse-servicii/robotics-systems/industrial-robots>
- [2] Alberti, M., Ciurana, J., Rodríguez, C. A., & Özel, T. (2009). *Design of a decision support system for machine tool selection based on machine characteristics and performance tests*. Journal of Intelligent Manufacturing, 22(2), 263–277. doi: 10.1007/s10845-009-0286-6.
- [3] Chung, C., & Peng, Q. (2004). *The selection of tools and machines on web-based manufacturing environments*. International Journal of Machine Tools and Manufacture, 44(2-3), 317–326. doi: 10.1016/j.ijmachtools.2003.09.002..
- [4] Athawale, V. M., & Chakraborty, S. (2010). *A TOPSIS Method-based Approach to Machine Tool Selection*. Proceedings of the 2010 International Conference on Industrial Engineering and Operations Management.
- [5] Aggogeri, F., Borboni, A., Merlo, A., Pellegrini, N., & Ricatto, R. (2017). *Vibration Damping Analysis of Lightweight Structures in Machine Tools*. Materials, 10, 297. <https://doi.org/10.3390/ma10030297>.
- [6] Chavoshi, S. Z., Goel, S., & Morantz, P. (2017). *Current trends and future of sequential micro-machining processes on a single machine tool*. Materials & Design, 127, 37–53. doi: 10.1016/j.matdes.2017.04.057.
- [7] Grainger. (n.d.). *What Is High-Speed Machining - Grainger KnowHow*. Retrieved May 7, 2020, from <https://www.grainger.com/know-how/industry/metalworking/kh-what-is-high-speed-machining>.
- [8] Simon, A., & Lima, C. R. (2015). *Computer numeric control machine-tools utilisation by metalworking companies in Brazil*. International Journal of Manufacturing Research. doi: 10.1504/IJMR.2015.071625.
- [9] Kim, H. S., Park, K. Y., & Lee, D. G. (2000). *A study on the epoxy resin concrete for the ultra-precision machine tool bed*. Retrieved from <https://www.sciencedirect.com/science/article/pii/S092401369401705>.
- [10] REMSsystems. (n.d.). *Achieving the Rewards of Machine Tool Automation*. Retrieved from <https://remssystems.co.uk/2017/07/27/achieving-the-rewards-of-machine-tool-automation/>.
- [11] Ciupan, M. (2020). *Ph.D. thesis: Contributions regarding the design of structural components made of composite materials for modern machine tools*.

The test bench for assessing the accuracy and synchronization of CNC axes

Lucrarea prezintă un stand pentru testarea și măsurarea preciziei unui sistem de axe cinematice care fac parte din structura unei mașini-unelte CNC, a unui robot sau a altor echipamente tehnologice. Lucrarea prezintă structura bancului de testare și metoda de calcul pentru încărcarea axelor cinematice cu sarcini echivalente cu cele la care sunt supuse în timpul funcționării în mașina reală. Bancul de testare a fost construit și echipat efectiv pentru testarea axelor cinematice ale unei mașini-unelte CNC cu cinci axe. S-au efectuat teste privind funcționarea axelor pe banc și crearea mai multor programe de interpolare. Performanțele și avantajele cercetărilor efectuate pentru studiul axelor de avans ale mașinii cu 5 axe sunt prezentate sintetic în lucrare.

Mihai CIUPAN, Ph.D. Eng., lecturer, Technical University of Cluj-Napoca, Dept. of Design Engineering and Robotics, mihai.ciupan@muri.utcluj.ro

Claudiu-Ioan RUSAN, Ph.D. Eng., lecturer, Technical University of Cluj-Napoca, Dept. of Design Engineering and Robotics, claudiu.rusan@ipr.utcluj.ro

Cornel CIUPAN, Ph.D. Eng., Professor, Technical University of Cluj-Napoca, Dept. of Design Engineering and Robotics, cornel.ciupan@muri.utcluj.ro