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TEST BENCH AND PROGRAM FOR SIMULATING THE OPERATION AND ACCURACY OF CNC KINEMATIC AXES

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Abstract: *The paper presents a test bench for testing a system of kinematic axes that are part of some technological equipment. It shows the bench development and the calculation algorithm for loading the kinematic axes with equivalent loads to those to which they are subjected during operation in the real machine. The bench consists of a support in which all the motors of the kinematic axes of the machine are mounted and a table that supports the other elements of the control system. Discs and electromagnetic brakes that are mounted on the motors' shafts ensure loads equivalent to those during the machine's operation. The loading of the motors with inertial loads and static loads is done by appropriately sizing the inertial discs and the braking factor, elements that result from a program developed by the authors. To optimize the control system of the axes the program calculates the load for variable input data. The bench was actually built and equipped for testing the kinematic axes of a five-axis CNC milling machine for the purpose of testing the machine through several interpolation programs. The advantages of the conducted research are summarized in the paper.*

Key words: *test bench, CNC machine-tool, servomotor, CNC axis loading, CNC control accuracy.*

1. INTRODUCTION

1.1 Machine-tool requirements

Machine-tools are the most important technological equipment, because they are necessary for the production of other industrial equipment or other products [1]. A machine-tool consists of an assembly of kinematic axes mounted on a frame and a manual or CNC control equipment. The kinematic axes of the machine form an integrated system that performs the relative movements between the tool and the workpiece in order to obtain defined surfaces.

The machine-tool makers are subject to constraints from their clients and users [2, 3, 4]:

- low purchase, use and maintenance costs;
- the ability to efficiently process parts of different sizes [5, 6];
- increased productivity;
- reduced machine building time, especially for specialty machines.

To meet the requirements of the beneficiaries, machine-tool manufacturers are continuously innovating:

- cheaper raw materials and technologies for the production of large structural elements (composite frames);
- different machining strategies to increase productivity (high-speed machining / high-performance machining) [7];
- increased machine precision [8];
- improved reliability;
- automatic measurement of the part, the tool and dynamic adjustment of process parameters [9];
- machining the part in a single setup or in as few setups as possible [10];
- integration of machines into partially or fully automated production systems [10].

Two of the most important factor for a machine-tool are precision and productivity.

The precision of a CNC machine-tool is affected by a series of errors that occur in the mechanical and the control structure of a machine. The mechanical errors are given by inaccuracies of the motion transmission mechanisms, geometric deviations produced by the machining of its components, thermal and elastic deformations, but these do not represent the subject of the current paper.

This paper focuses on another category of errors, the ones given by the CNC control system - the accuracy of the encoders, the control strategy, the speed of computing, etc.

Several closed-loop control strategies are known, in which the motion parameters are measured and adjusted in real time. The most frequently used strategy for controlling the position, speed and acceleration of the axes is the Proportional-Integral-Derivative (PID) feedback control. Adaptive control is another strategy where the system automatically adjusts its control parameters depending on the dynamic variations of the machine. Predictive control (Model Predictive Control - MPC), calculates optimal commands based on a mathematical model of the system, taking into account various speed restrictions, torque, etc.

The CNC equipment also influences the accuracy of the machine-tool through motion control and error correction, stability and repeatability, adaptation to variable conditions, etc.

Buyers choose a machine-tool based on their production needs and characteristics. There are standard tests that verify whether a machine tool meets the required technical characteristics: ISO 10791-7:2020 “Test conditions for machining centres. Accuracy of finished test pieces”, ISO 230 “Test code for machine-tools”.

The main disadvantage when developing machine-tools is that until the final stages of the process, the machine isn’t built and isn’t available for testing using the above mentioned standards. This is especially inconvenient in the case of new machines with short production and delivery times. When designing a new machine, it is possible that the kinematic axes do not correspond to the machine’s characteristics. If this is only discovered after the machine has been manufactured and tested, fixing the machine involves high costs and extended delivery times.

For these reasons, bench testing the assembly of kinematic axes formed of servomotors, drives and CNC control before manufacturing the actual machine-tool avoids costly errors, servosystem faults and substandard performance.

1.2 Test bench design

The test bench (figure 1) consists of a support 1, with n slots 1a in which the kinematic axes AC1, AC2, ..., ACn that are part of the considered CNC machine-tool are mounted.

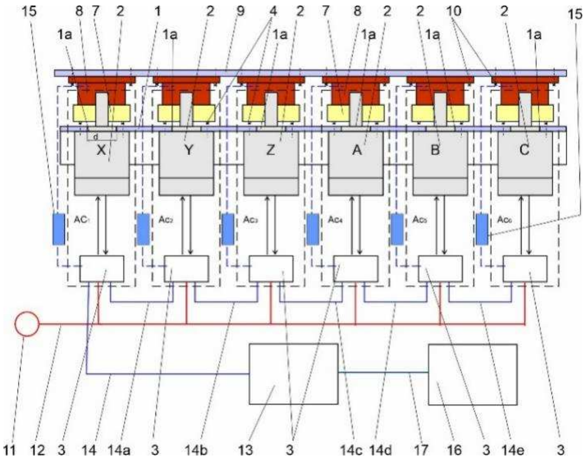


Fig. 1. Test bench diagram

Each kinematic axis ACi that is mounted on the bench consists of an electric motor 2 and the drive 3, with the role of actuation and control.

The bench in figure 1 has six kinematic axes AC_i, i=1...6, (three translation axes X, Y, Z and three rotation axes A, B, C), but the number of axes can be expanded or reduced.

Drives 3 are powered from an electric grid 11, through cables 12. The axes are controlled using the CNC controller 13 which communicates with drives 3 through a bus 14 using the EtherCAT protocol.

A PC 16 that is connected to the CNC controller 13 through a network cable 17 and communicates via the Ethernet protocol (LAN), is used to control the machine.

In order to test the AC_i axes as close as possible to their operation within 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 discs 7 are sized for each kinematic axis to give a moment of inertia Ie that produces a torque equivalent to that which occurs in the operation of the axis in the machine assembly. The electromagnetic brakes 8 produce a braking force proportional to the supply current.

An application provided by the CNC controller manufacturer is installed on the PC 16. The application allows the writing of CNC instructions / programs and the manual operation of the machine.

2. ESTABLISHING THE AXIS LOAD

Figure 2 shows the generalized diagram of a kinematic axis. The motor M acts through the transmission Tr with transfer ratio u on the final effector E_f. Depending on the type of axis, linear or rotary, the effector E_f is acted upon by the forces and moments of inertia (F_i, T_i) and the forces and moments of the machining process (F_s, T_s).

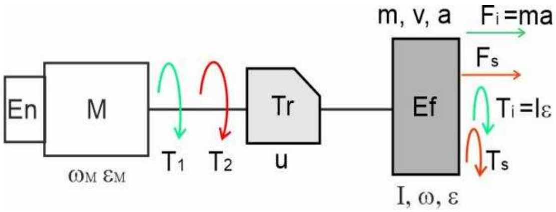
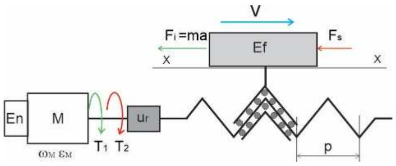
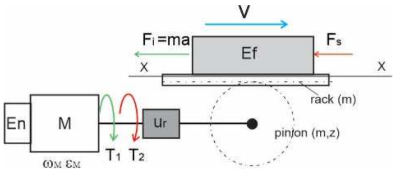
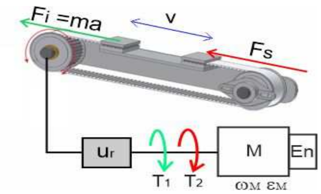
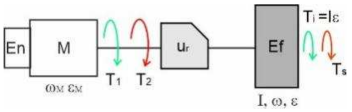
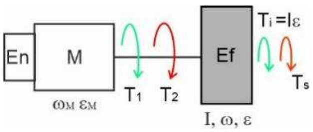


Fig. 2. The general diagram of a kinematic axis

During the first stage the equivalent moments at the motor axis for each kinematic axis are determined, based on the technical design of the machine, the kinematic and the constructive parameters of the axes and the forces in the machining process:

Table 1

Different types of kinematic axes

Axis type	Mechanism	Diagram	Transfer rate u	T1 [Nm] T2 [Nm]
Linear	Ballscrew and nut		$u = \frac{v}{\omega_M} = \frac{p}{2000\pi} \cdot u_r$ p=pitch [mm]	$T_1 = F_i \cdot u$ $T_2 = F_s \cdot u$
	Rack and pinion		$u = \frac{v}{\omega_M} = \frac{m \cdot z}{2000} \cdot u_r$ m=gear module [mm] z=gear tooth	$T_1 = F_i \cdot u$ $T_2 = F_s \cdot u$
	Synchronous belt		$u = \frac{v}{\omega_M} = \frac{p_b \cdot z}{2000\pi} \cdot u_r$ p_b=pitch [mm] z=gear tooth	$T_1 = F_i \cdot u$ $T_2 = F_s \cdot u$
Rotary	With transmission		$u = \frac{\omega}{\omega_M} = u_r$	$T_1 = T_i \cdot u$ $T_2 = T_s \cdot u$
	Direct drive		$u = 1$	$T_1 = T_i \cdot u$ $T_2 = T_s \cdot u$

- moment T_1 produced by the forces and moments of inertia resulting from the operation of the axis within the machine;

- moment T_2 which represents the resistive torque produced by the cutting forces.

Table 1 presents the kinematic diagram, the transfer ratios and the calculation relations for the main types of kinematic axes.

During the second stage the equivalent load of each kinematic axis mounted on the bench is determined. The equivalent axis of the real axis contains motor 2 which is the motor of the kinematic axis itself, disk 7 which provides a moment of inertia Ie equivalent to that produced by the moving elements of the axis and brake 8 which represents the resistive loads in the process.

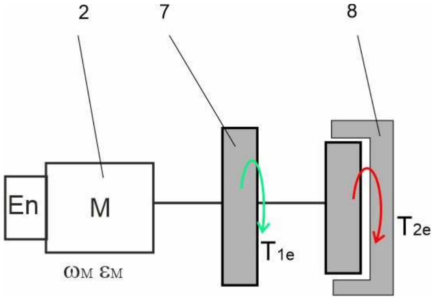


Fig. 3. Equivalent diagram

For the equivalent axis in figure 3, the resisting moments at the shaft of motor 2 are determined:

$$T_{1e} = T_1 = I_e \cdot \varepsilon \qquad (1)$$

$$T_{2e} = T_{21} = k_e \cdot T_F \qquad (2).$$

From equation (1) the moment of inertia Ie is determined so that disk 7 can be dimensioned:

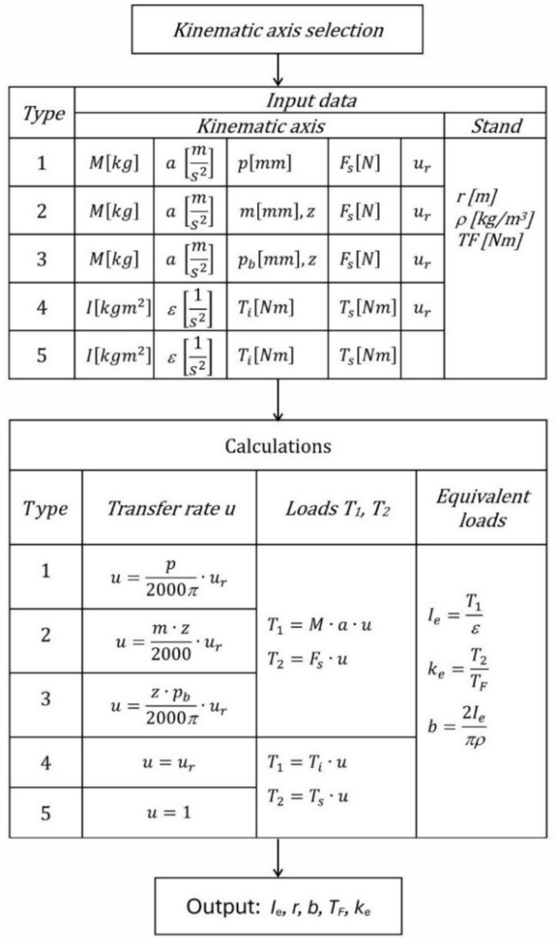
$$I_e = \frac{1}{2} M_d \cdot r_d^2 \qquad (3).$$

If a certain radius r is chosen for disk 7 and the density of the material is known, equation 3 can be used to calculate its width.

From equation (2) the correction coefficient k_e is obtained. Electromagnetic brakes 8 are chosen to produce a braking moment T_F above the maximum load of the kinematic axis. To produce the braking moment T_{2e}, the electromagnetic brake 8 will be supplied with a current proportional to the correction factor k_e. The correspondence between the supply current and the correction factor k is made through a calibration process.

3. PROGRAM PRESENTATION

The program for calculating the elements that ensure the loading of the motors of each kinematic axis is based on the algorithm presented in fig. 4. The program requires data specific to each kinematic axis and those related to the test bench as input. Following the calculations, the program provides the data necessary for the manufacturing of inertia disk 7 (r, b) and the correction factor k_e of the braking torque T_F.



Type	Input data					
	Kinematic axis					Stand
1	$M[kg]$	$a\left[\frac{m}{s^2}\right]$	$p[mm]$	$F_s[N]$	u_r	r [m] ρ [kg/m³] TF [Nm]
2	$M[kg]$	$a\left[\frac{m}{s^2}\right]$	$m[mm], z$	$F_s[N]$	u_r	
3	$M[kg]$	$a\left[\frac{m}{s^2}\right]$	$p_b[mm], z$	$F_s[N]$	u_r	
4	$I[kgm^2]$	$\varepsilon\left[\frac{1}{s^2}\right]$	$T_i[Nm]$	$T_s[Nm]$	u_r	
5	$I[kgm^2]$	$\varepsilon\left[\frac{1}{s^2}\right]$	$T_i[Nm]$	$T_s[Nm]$		

Calculations			
Type	Transfer rate u	Loads T_1, T_2	Equivalent loads
1	$u = \frac{p}{2000\pi} \cdot u_r$	$T_1 = M \cdot a \cdot u$ $T_2 = F_s \cdot u$	$I_e = \frac{T_1}{\varepsilon}$ $k_e = \frac{T_2}{T_F}$ $b = \frac{2I_e}{\pi\rho}$
2	$u = \frac{m \cdot z}{2000} \cdot u_r$		
3	$u = \frac{z \cdot p_b}{2000\pi} \cdot u_r$		
4	$u = u_r$	$T_1 = T_i \cdot u$ $T_2 = T_s \cdot u$	
5	$u = 1$		

Output: I_e, r, b, T_F, k_e

Fig. 4. Program flowchart

4. RESULTS

The program was used to simulate the motor load for a 5-axis CNC machine, with three linear axes (X, Y, Z) and two rotary axes (A, C). Table 2 presents the input data and the results obtained.

Axis	Type	Input data	Output data
X	1	M=150kg, a=30m/s^2, p=5 mm, F_S=500 N, Is=6x10^{-5} kgm^2, r_d=30mm, T_F=4 Nm	Md=0.347 kg b=16 mm ke=0.199
Y	1	M=100kg, a=30m/s^2, p=5 mm, F_S=500 N,	Md=0.277 kg b=13 mm ke=0.199

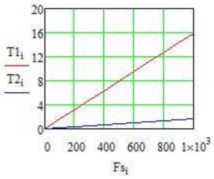
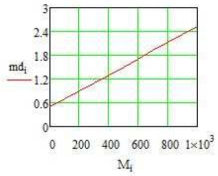
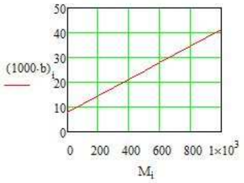
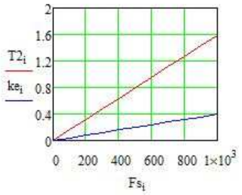
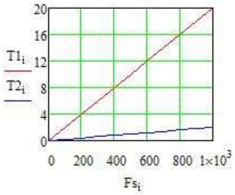
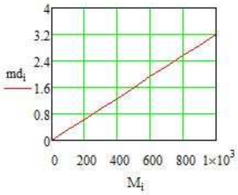
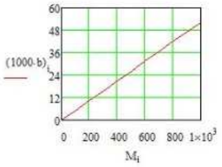
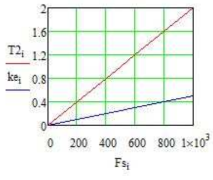
		$I_S=6x10^{-5}$ kgm², r_d=30mm, T_F=4 Nm	
Z	1	M=35kg, a=30m/s², p=5 mm, F_S=500 N, $I_S=6x10^{-5}$ kgm², r_d=30mm, T_F=4 Nm	Md=0.185 kg b=8.5 mm ke=0.199
A	4	I=0.404 kgm², ε=100 s⁻², T_F=30 Nm, u_R=1:80, r_d=62.5 mm	Md=2.606 kg b=27 mm ke=0.417
C	4	I=0.054 kgm², ε=100 s⁻², T_F=30 Nm, u_R=1:80, r_d=50 mm	Md=0.572 kg b=9.4 mm ke=0.417

The program also allows optimizations by introducing variable input data. Table 3 presents the simulation results for a kinematic axis with a ball screw having the variable parameters the mass of the mobile assembly (M=100-1000 Kg) and the force in the machining process (Fs=100-1000N). For the kinematic axis with a rack and pinion, two cases were simulated:

- M and Fs are variable;
- M and Fs are constant and ur variable.

Table 3

Loads for different kinematic axis !

<table>
<tr><td colspan="4">Type 1- Ball screw: M=100… 1000 kg; F_S=100…1000 N, p=10 mm, T_F=4 Nm, Is=6,2x10⁻⁴ Kgm², r_d =50 mm</td></tr>
<tr>
<td> </td>
<td> </td>
<td> </td>
<td> </td>
</tr>
<tr><td colspan="4">Type 2- Pinion-rack: M=100… 1000 kg; F_S=1000 N, m=2 mm, z=20, T_F=4 Nm, r_d =50 mm, u_r=1:10</td></tr>
<tr>
<td> </td>
<td> </td>
<td> </td>
<td> </td>
</tr>
<tr><td colspan="4">Type 2- Pinion-rack: M=1000 kg; F_S=1000 N, m=2 mm, z=20, T_F=4 Nm, r_d =50 mm, u_r=1/50 … 1</td></tr>
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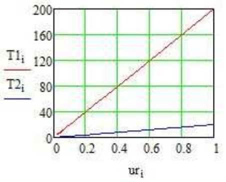
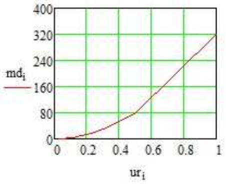
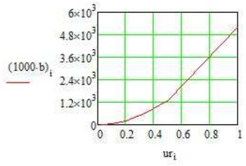
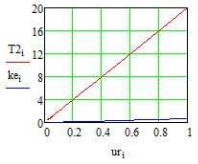
<td> </td>
<td> </td>
<td> </td>
<td> </td>
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5. CONCLUSION

The test bench presented in the paper allows testing a kinematic axis system before actually building the machine. In order to highlight any possible design errors a program was created to determine what loads the axis motors must be subjected to in order to obtain equivalent loads to those in the operation of the machine.

The input data for the program are obtained from the machine tool design. The 3D model of the machine, having assigned the materials from which the component parts are made, offers us the possibility of evaluating the masses and moments of inertia necessary in the program. Other input data result from the technical characteristics and the kinematic diagram of the machine.

The main results provided by the program are the dimensions of disk 7 that gives the inertial load and the correction factor k_e, of the braking torque.

The program was tested for a five-axis CNC machine-tool. The machine was designed by the authors of the paper and the structural elements are made of mineral casting, a type of polymer concrete.

Using the bench and program described in the paper, for the above mentioned machine, the following tests can be performed:

- accuracy and repeatability of positioning of numerically controlled axes with equivalent loads;
- linear, circular and helical interpolation tests.

6. ACKNOWLEDGMENT

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Stand si program pentru simularea functionarii si preciziei axelor cinematice CNC

Lucrarea prezinta un stand pentru testarea si incercarea unui sistem de axe cinematice care intra in componenta unor echipamente tehnologice. Este descrisa componenta standului și algoritmul de calcul pentru incarcare a axelor cinematice cu sarcini echivalente cu cele la care sunt supuse in timpul functionarii in masina reala. Standul este alcatuit dintr-un support in care sunt montate toate motoarele axelor cinematice ale masinii si o masa care sustine celelalte elemente ale sistemului de comanda. Pe axul motoarelor se monteaza discuri si frane electromagnetice care asigura solicitari echivalente cu cele din timpul functionarii masinii. Incarcarea motoarelor cu sarcini inertiale si sarcini statice se face prin dimensionarea corespunzatoare a discurilor inertiale si a factorului de franare, elemente care rezulta din program. Pentru optimizarea masinii, programul permite obtinerea incarcarii pentru date de intrare variabile. Standul a fost realizat practic si echipat pentru testarea axelor cinematice a unei masini-unelte CNC cu cinci axe în scopul testarii masinii pentru cateva programe de interpolare. Avantajele cercetarii efectuate sunt redate sintetic in lucrare.

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