Study of Two-Coordinate Electric Drives for Turning Machines

Marin Zhilevski, Mikho Mikhov

Abstract— **The basic requirements for feed drives of turning machines with digital program control are formulated in this paper. The offered methodology for selection of such drives takes into account the specific features of the technological process, the processed material, the tools used, as well as the mechanical gear type. Concrete examples with DC and AC motor drives are presented, illustrating the practical application of this methodology. A number of models for computer simulation of two-coordinate electric drive systems have been developed, allowing study at various reference speeds, positions, and loads applied to the motor shafts. Detailed testing has been carried out by means of computer simulation and experimental research. The results obtained can be used in the design and tuning of such types of two-coordinate drive systems with position control.**

Index Terms— **Turning machines, Feed drives, Position control, Two-coordinate drives, Computer simulation.**

I. INTRODUCTION

Two-coordinate electric drive systems are widely used in turning machines for positioning of the tools. Generally, motions in these systems are formed by the respective trajectories along both coordinate axes. Control algorithms affect the performance, productivity and energy consumption [1], [2].

With respect to modernization of a type of turning machines, some two-coordinate electric drives have been analyzed, allowing the choice of the appropriate type meeting the performance requirements.

Mathematical modeling and computer simulation provide good opportunities to explore different control variants aiming at optimization of motion trajectories [1], [2], [3]. Models of such drives have been developed and used for studying of various control algorithms for the respective dynamic and static regimes at different operation modes.

In this paper, the main requirements for feed drives of a type of turning machines with digital program control are formulated and a methodology for selection of appropriate electric drives is presented. In choosing a suitable feed electric drive, a number of essential factors were taken into account, namely: the technological process features, the processed material, the tools used and the mechanical gear. Concrete examples for selection of feed drives with DC and AC motors are presented, illustrating the practical application of the offered methodology. Models for computer simulation of two-coordinate electric drive systems for turning machines with various algorithms for position control have been developed. Some simulation and experimental results are presented and discussed.

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II. METHODOLOGY FOR FEED DRIVE SELECTION

A. Basic Requirements

Feed drives for turning machines with digital program control should meet the following requirements:

- wide range of speed control;
- good dynamics;
- smooth speed regulation in both directions;
- position accuracy;
- providing the required torque;
- reliability;
- economy and easy maintenance.

The designing process of such drives includes the following basic stages:

1. Development of a methodology for selection of feed drives, taking into account the features of the technological process, the processed material, the tools used, as well as the mechanical gear type.
2. Calculations, corresponding to the respective procedures of the methodology.
3. Technical and economic analysis of the possible options for selection of electric drives, taking into account the catalogue data from the manufacturers.
4. Compiling of a computer simulation model of the respective electric drive.
5. Development of a stand for experimental research.
6. Experimental determination of the parameters required for modeling.
7. Optimization and tuning of the respective control loops.
8. Computer simulation studies with various settings of the control system.
9. Detailed experimental research in the relevant dynamic and static modes of operation to evaluate the actual performance.

B. Features of the Methodology

The simplified block diagram of the methodology algorithm is presented in Fig. 1, where the following notations are used: $D_{mt\max}$ – maximum cutting diameter that can be processed by the machine; D_{gt} – nominal diameter of the mechanical gear made by a ball screw; H_B – Brinell hardness of the processed material; $a_{pt\max t}$ – maximum cutting depth of the tool; $V_{t\max}$ – maximum speed of the drive mechanism; V_{ct} – cutting speed; ω_t – spindle speed; f_{rt} – feed per radian; K_{ct} – specific cutting force, depending on the material type; η – efficiency of the turning machine; $P_{ct\max}$ – maximum power needed to perform cutting, distributed between both feed electric drive and spindle electric drive; $P_{ft\,\max}$ – power required only for the feed electric drive; h_{ti} – nominal steps of the ball screw; ω_{ft_i} – speeds of the motor for different nominal steps of the ball screw; M_{ft_i} – torques of the motor for different nominal steps of the ball screw, $i = 1 \div n$, where n is the number of variants.

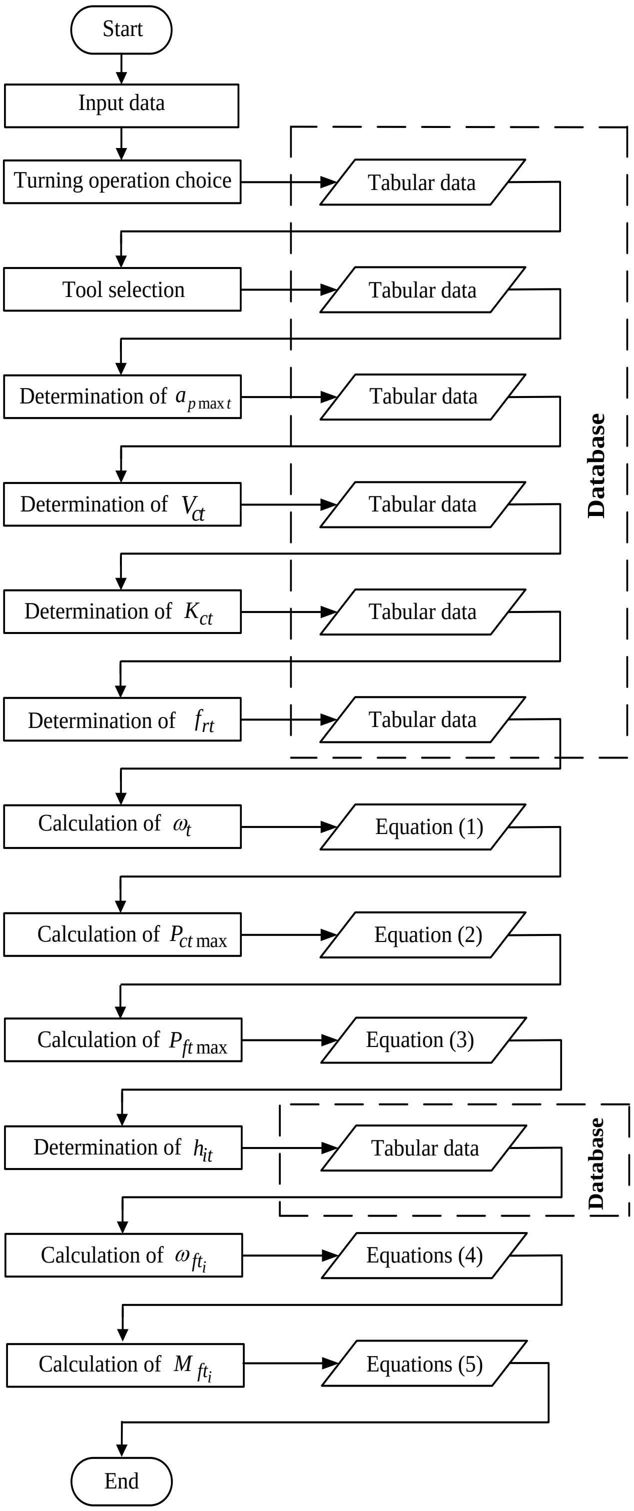


Fig. 1. Block diagram of the algorithm.

In the proposed methodology, a ball screw couple was used as a mechanical gear with a specified screw diameter. The design and calculation of ball screws is described in ISO/DIN standards [4], [5].

The input data are as follows: definition of the heaviest cutting regime; $D_{mt\,\max}$; D_{gt} ; η and $V_{t\,\max}$.

The tabular data used in this methodology are taken from [6] and [7].

The spindle speed is determined by the expression [6]:

$$\omega_t = \frac{V_{ct} \times 2}{D_{mt\,\max}} . \qquad (1)$$

The cutting power that is necessary for the heaviest operating mode of the machine is calculated by the following equation [6]:

$$P_{ct\,\max} = \frac{a_{pt\,\max} \times f_{rt} \times V_{ct} \times K_{ct} \times 10^6 \times 2 \times \pi}{\eta} . \qquad (2)$$

The power required only for the feed electric drive is determined as follows [8]:

$$P_{ft\,\max} = (1 \div 5)\% \times P_{ct\,\max} . \qquad (3)$$

The motor speeds for different nominal steps of the ball screw are calculated by the following expressions [9]:

$$\left.\begin{array}{l} \omega_{ft_1} = \dfrac{V_{t\,\max} \times 2 \times \pi}{h_{t1}} \\ \vdots \\ \omega_{ft_n} = \dfrac{V_{t\,\max} \times 2 \times \pi}{h_{tn}} \end{array}\right\} . \qquad (4)$$

The torques of the motor for different nominal steps of the ball screw are determined by the following equations [9]:

$$\left.\begin{array}{l} M_{ft_1} = \dfrac{P_{ft\,\max}}{\omega_{ft_1}} \\ \vdots \\ M_{ft_n} = \dfrac{P_{ft\,\max}}{\omega_{ft_n}} \end{array}\right\} . \qquad (5)$$

C. Practical Implementation

The practical implementation of this methodology takes into account the specific features of the concrete machine, such as technological process, processed materials, tools and gears.

Fig. 2 shows a diagram, illustrating the used elements of a feed electric drive for one coordinate axis. The notations used are as follows: DPC – digital program control; 1 – position sensor; 2 – driven mechanism; 3 – guides; 4 – ball screw; 5 – coupling between the motor and the ball screw; D_{gt} – nominal diameter of the mechanical gear made by a ball screw; h_t – nominal steps of the ball screw; V_t – maximum speed of the drive mechanism.

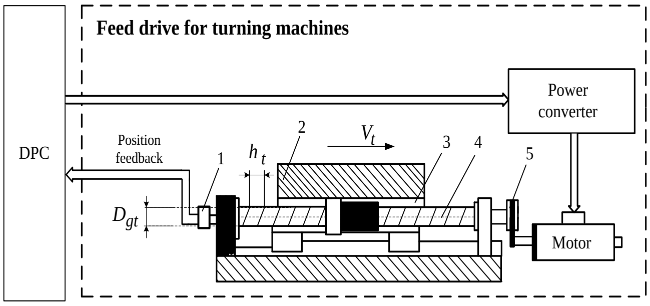


Fig. 2. Block diagram of a feed electric drive.

Some examples of using this methodology in selection of feed electric drives for a turning machine for cutting materials with different hardness are presented below.

Table 1: Results from the calculations.

Step	Operation	Grey cast iron	Aluminium alloys
1.	Determination of H_B	220	60
2.	Turning operation choice.	Roughing	Roughing
3.	Tool selection.	CoroTurn	CoroTurn
4.	Determination of $a_{pt\max t}$.	0.003 m	0.003 m
5.	Determination of V_{ct} .	≈ 4 m/s	≈ 11.67 m/s
6.	Determination of K_{ct} .	1290	500
7.	Determination of f_{rt} .	$\approx 4.7\times10^{-5}$ m/s	$\approx 4.7\times10^{-5}$ m/s
8.	Calculation of ω_t .	≈ 16 rad/s	≈ 46.7 rad/s
9.	Calculation of $P_{ct\max}$.	≈ 5375.4 W	≈ 6078.6 W
10.	Calculation of $P_{ft\max}$.	≈ 268.8 W	≈ 303.9 W
11.	Determination of h_{ti} ($i=1\div4$).	$h_1=0.005$ m $h_2=0.01$ m $h_3=0.02$ m $h_4=0.04$ m	$h_1=0.005$ m $h_2=0.01$ m $h_3=0.02$ m $h_4=0.04$ m
12.	Calculation of ω_{ft_i} ($i=1\div4$).	$\omega_{ft_1}\approx 314$ rad/s $\omega_{ft_2}\approx 157$ rad/s $\omega_{ft_3}\approx 78.5$ rad/s $\omega_{ft_4}\approx 39.3$ rad/s	$\omega_{ft_1}\approx 314$ rad/s $\omega_{ft_2}\approx 157$ rad/s $\omega_{ft_3}\approx 78.5$ rad/s $\omega_{ft_4}\approx 39.3$ rad/s
13.	Calculation of M_{ft_i} ($i=1\div4$).	$M_{ft_1}\approx 0.85$ Nm $M_{ft2}\approx 1.71$ Nm $M_{ft_3}\approx 3.42$ Nm $M_{ft4}\approx 6.85$ Nm	$M_{ft_1}\approx 0.97$ Nm $M_{ft2}\approx 1.94$ Nm $M_{ft_3}\approx 3.87$ Nm $M_{ft4}\approx 7.74$ Nm

The input data in this case are as follows:

- the heaviest cutting regime i.e. with grey cast iron and aluminium alloys;
- $D_{mt\max}$ =0.5 m;
- $D_{gt}=0.04$ m ;
- $\eta=0.85$;
- $V_{t\max}\approx 0.25$ m/s .

The respective results obtained are presented in Table 1.

The calculations performed according to the presented methodology have the same input data for materials of different hardness, in order to compare and analyze the obtained results.

The required nominal values of the motor torque in processing of the two materials are determined as follows:

- for machining of grey cast iron:

$$\begin{cases} M_{ft1nom}\approx 1.1\times M_{ft_1}\approx 0.935 \text{ Nm}; \\ M_{ft2nom}\approx 1.1\times M_{ft_2}\approx 1.88 \text{ Nm}; \\ M_{ft3nom}\approx 1.1\times M_{ft_3}\approx 3.76 \text{ Nm}; \\ M_{ft4nom}\approx 1.1\times M_{ft_3}\approx 7.535 \text{ Nm}. \end{cases} \quad (6)$$

- for machining of aluminium alloys:

$$\begin{cases} M_{ft1nom}\approx 1.1\times M_{ft_1}\approx 1.067 \text{ Nm}; \\ M_{ft2nom}\approx 1.1\times M_{ft_2}\approx 2.134 \text{ Nm}; \\ M_{ft3nom}\approx 1.1\times M_{ft_3}\approx 4.257 \text{ Nm}; \\ M_{ft4nom}\approx 1.1\times M_{ft_3}\approx 8.514 \text{ Nm}. \end{cases} \quad (7)$$

The selected motors must have nominal power of about 10% greater than the calculated one, in order to compensate for the allowable wear over time. The power values obtained are used for the motor selection from the respective technical catalogues.

Table 2: Basic data of the selected drives.

In machining of grey cast iron, a DC electric drive with the following parameters is selected [9], [11], [12]: - ball screw with diameter 0.04 m and step $h=0.01$ m ; - DC motor 3PI12.12 with nominal data: $M_{fnom}=3.5$ Nm , $\omega_{fnom}=209.34$ rad/s ; - encoder model 7 L with resolution 2500 pulses/rev.; - power converter SA-12.
In machining of aluminium alloys, an AC electric drive with following parameters is selected [9] ,[13], [14]: - ball screw with diameter 0.04 m and step $h=0.005$ m ; - AC motor DT5-3-10 with nominal data: $M_{fnom}=2.4$ Nm , $\omega_{fnom}=418.68$ rad/s with resolver for feedback; - power converter KW2.

As a result of the calculations made for these two materials, appropriate DC and AC electric drives were chosen. Some of their basic parameters are presented in Table 2.

III. Two-coordinate Drive System

A. Basic Features

The simplified block diagram of a two-coordinate electric drive system for turning machines is presented in Fig. 3, where the notations are as follows: DPC – digital program control; SC1 and SC2 – speed controllers; CC1 and CC2 –

current controllers; C1 and C2 – power converters; M1 and M2 – DC motors; SS1 and SS2 – speed sensors; DM1 and DM2 – driven mechanisms; CF1 and CF2 – current feedback blocks; SF1 and SF2 – speed feedback blocks; PF1 and PF2 – position feedback blocks; V_{sr_1} and V_{sr_2} – speed reference signals; V_{cr_1} and V_{cr_2} – current reference signals; V_{pf_1} and V_{pf_2} – position feedback signals; V_{sf_1} and V_{sf_2} – speed feedback signals; V_{cf_1} and V_{cf_2} – current feedback signals; θ_1 and θ_2 – angular positions; S_1 and S_2 – linear displacements.

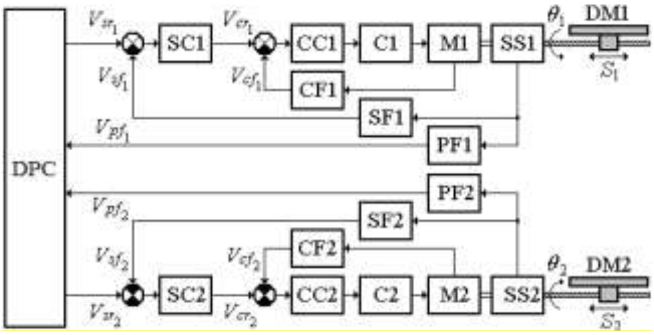


Fig. 3. Block diagram of a two-coordinate drive system.

The requirements for the drive system can be formulated as follows:

- forming of the necessary motion trajectories;
- maximum starting torque to ensure good dynamics;
- reversible speed and torque control;
- compensation of the disturbances.

Both drive subsystems have identical cascade structures with subordinate regulation of currents, speeds and positions. Control loops optimization and tuning of the respective controllers were done sequentially, starting from the innermost ones [10].

B. Computer Simulation

Using the MATLAB/SIMULINK software package, some computer simulation models of two-coordinate drive systems with different types of electric motors were developed. They allow for detailed studies of the respective static and dynamic regimes and analyses of their performance.

A simplified block diagram of one of the models is presented in Fig. 4.

The vector-matrix model of the DC motor drive under consideration is as follows:

$$\begin{bmatrix} \frac{d\theta_i}{dt} \\ \frac{d\omega_i}{dt} \\ \frac{di_{a_i}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & \frac{K_{t_i}}{J_{\Sigma_i}} \\ 0 & -\frac{K_{e_i}}{L_{a_i}} & -\frac{R_{a_i}}{L_{a_i}} \end{bmatrix} \begin{bmatrix} \theta_i \\ \omega_i \\ i_{a_i} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{K_{c_i}}{L_{a_i}} \end{bmatrix} v_i + \begin{bmatrix} 0 \\ -\frac{1}{J_{\Sigma_i}} \\ 0 \end{bmatrix} i_{l_i}, \quad (8)$$

where: θ_i is angular position; ω_i – motor speed; i_{a_i} – armature current; K_{e_i} – back EMF voltage coefficient; K_{t_i} – torque coefficient; R_{a_i} – armature circuit resistance; L_{a_i} – armature inductance; K_{c_i} – amplifier gain of the power converter; v_i – input control signal of the converter; J_{Σ_i} – total inertia referred to the motor shaft; i_{l_i} – armature current which is determined by the respective load torque; $i = 1,2$ – number of the coordinate axes (*x* and *z*, respectively).

The maximum operating speed of the motors for the respective coordinate axis is chosen to be equal to the nominal value:

$$\omega_{\max_i} \le \omega_{\text{nom}_i}. \quad (9)$$

For the corresponding mechanical gears, the linear speed and linear position can be determined as follows:

$$V_i = \omega_i / K_{gi}; \; S_i = \theta_i / K_{gi}, \quad (10)$$

where K_{gi} is the respective gear coefficient.

In general, when two-coordinate drives with position control are used, the motion trajectories are formed by the respective displacements along both axes.

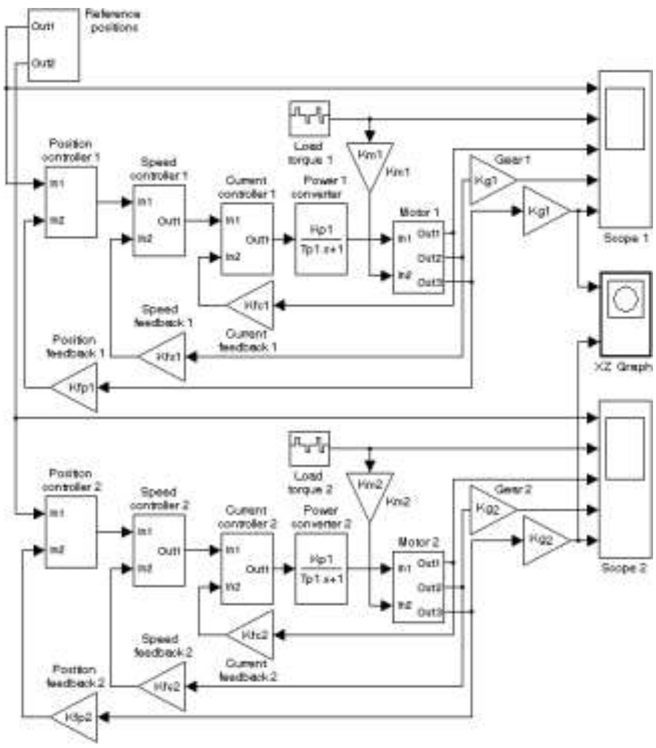


Fig. 4. Model of the two-coordinate DC drive system.

In Fig. 5, some motion trajectories to the same final position are presented. They were obtained for different movement algorithms.

Fig. 5a shows a trajectory obtained by successive movement along the coordinate axes. The total time for positioning is as follows:

$$t_p = t_{p_1} + t_{p_2}, \quad (11)$$

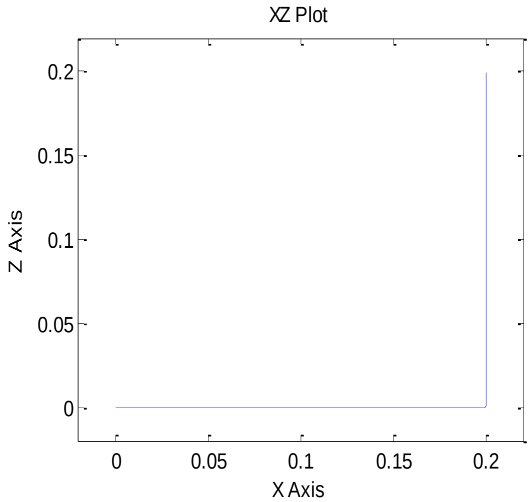
where: t_{p_1} is the motion time along the *x* axis; t_{p_2} – the motion time along the *z* axis.

Fig. 5b presents a trajectory obtained for combined motion along the coordinate axes. If both drives operate at the same speed, the total time of positioning is equal to the time necessary for the drive with longer displacement time:

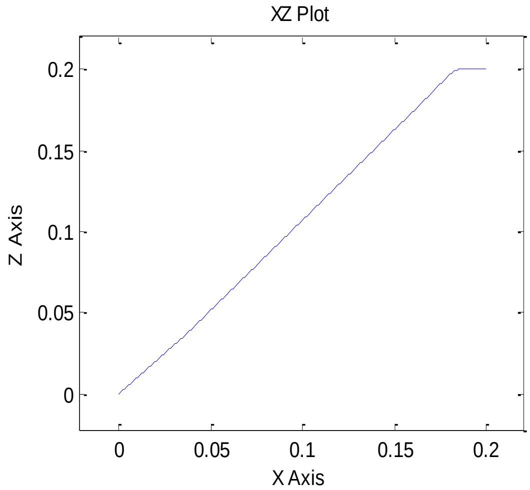
$$t_p = t_{p_1} . \tag{12}$$

Fig 5c shows a trajectory obtained by simultaneous movement along both coordinate axes. In this case the positioning time is:

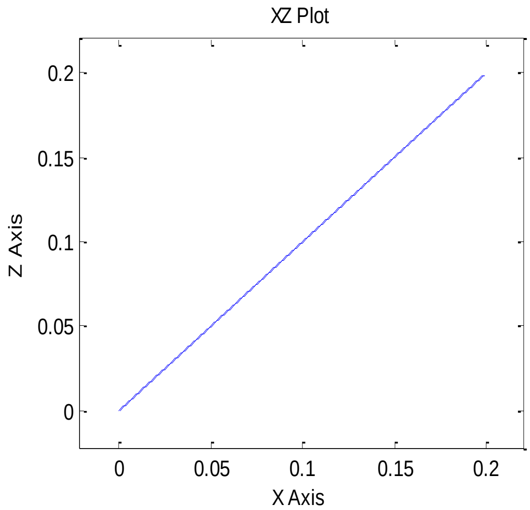
$$t_p = t_{p_1} = t_{p_2} . \tag{13}$$



a)



b)



c)

Fig. 5. Trajectories for two-coordinate position control.

IV. Experimental Studies and Analysis

Detailed experimental studies were carried out for different versions of controller tunings and operating regimes. Some time-diagrams are presented in Fig. 6. It shows speed trajectories along the *x* and *z* axes, obtained experimentally. The selected mechanical gears are of ball-screw type with the following coefficients:

$$K_{gx} = 5 \text{ mm/rev} \approx 0.8\text{x}10^{-3} \text{ m/rad} ;$$

$$K_{gz} = 10 \text{ mm/rev} \approx 1.6\text{x}10^{-3} \text{ m/rad} .$$

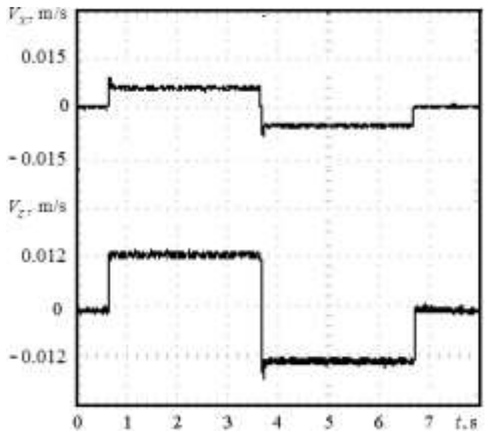


Fig. 6. Time-diagram of motions along the *x* and *z* axes.

The behavior analysis shows that the presented position control algorithms provide good performance, suitable for a number of practical applications. Time shortening of the transient regimes at positioning is essential for mass production of parts, because it increases the respective machine effectiveness.

V. Conclusion

The basic requirements for feed drives of a type of turning machines with digital program control are formulated and analyzed. A methodology for selection of such electric drives for these machines is offered. The presented algorithm takes into account the technological features, the processed material, the tools used and the mechanical gear type. Concrete examples for selection of electric drives with DC and AC motors are presented, illustrating the practical application of this methodology.

Models for computer simulation of two-coordinate electric drive systems with various algorithms for position control have been developed. The presented algorithms for position control were analyzed on the basis of computer simulations and experimental studies.

This research and the results obtained can be used in the design and tuning up of such two-coordinate systems of electric drives.

Acknowledgment

This work is supported by the Technical University of Sofia, Bulgaria under Research Project No. 181PR0003-08-/2018.

References

[1] M. Mikhov, I. Tatarov, Analysis of a Two-Coordinate Driving System Aiming at Performance Improvement. *Bulletin of the PGU*, Vol. 61, No. 3, pp. 105-110, Ploiesti, Romania, 2009.

[2] M. Mikhov, G. Mitrinski, Analysis of Some Algorithms for Positioning Control of Two-Coordinate Driving Systems, *Proceedings of the International Conference on Research and Development in Mechanical Industry*, Vol. 1, pp. 638-643, Donji Milanovac, Serbia, 2010.

[3] M. Mikhov, M. Zhilevski, Computer Simulation and Analysis of Two-coordinate Position Electric Drive System, *Proceedings of the International Scientific Conference on Information, Communication and Energy Systems and Technologies*, pp. 251-254, V. Tarnovo, Bulgaria, 2012.

[4] DIN 69051-3: *Werkzeugmaschinen; Kugelgewindetriebe; Abnahme-bedingungen und Abnahmeprüfungen*, 1998.

[5] DIN 69051-4: *Kugelgewindetriebe–Berechnung der statischen und dynamischen Tragzahl sowie der Lebensdauer*, Entwurf April 1989.

[6] Sandvik Coromant, *Metalcutting Technical Guide: Turning, Milling, Drilling, Boring, Toolholding*, Sandvik, 2005.

[7] Sandvik Coromant, *Tool Selection Guide, Selected Assortment in Turning-Milling-Drilling*, Sandvik, 1997.

[8] I. Andonov, *Cutting of Metals*, Softtrade, Sofia, 2001 (In Bulgarian).

[9] *Precision Ball Screw Assemblies*, Rexroth Bosch Group, Catalogue, 2009.

[10] M. Mikhov, *Control Systems of Electric Drives*, Technical University of Sofia, Sofia, 2009 (In Bulgarian).

[11] SERVOMOTORS, *Gama Motors Catalogue*, 2014.

[12] http://www.zgpu-group.com/archives/category/sensors.

[13] AMKASYN, *Servo Drives KE/KW*, AMK Catalogue, 2014.

[14] DYNASYN, *Servo Motors DT and DP*, AMK Catalogue, 2014.

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