Performance Improvement of a Type of Turning Machines

Marin M. Zhilevski and Mikho R. Mikhov

***Abstract*—The basic problems in modernization of a type of turning machines with digital program control are discussed in this paper. The main requirements for the drive system are analyzed and formulated. A number of models for computer simulation with various electric drives have been developed aiming at studying their dynamic and static regimes for the respective control algorithms. Some options for performance improvement of the respective drives are presented. The experimental research carried out confirms good performance of the applied solutions. The results of this study can be used in the design and set up of such driving systems.**

***Index Terms*—Turning machines, Feed drives, Two-coordinate drives, Position control, Spindle drives, Dual-zone drives.**

I. Introduction

Modern machine tools with digital program control have high demands on their precision, performance, reliability, energy consumption, serviceability and more [1]-[3].

The turning machines are of wide-range use and there is a big variety of their types and implementation. Such machines are used for processing by turning rotationally symmetrical details made of external and internal cylindrical, conical, profile and face surfaces. They consist of two feed axes, a spindle and additional auxiliary subsystems.

Various electric drives are analyzed to choose appropriate solutions meeting the static and dynamic characteristics of the respective machine axes and spindle [4]-[9]. A number of electric drives for some coordinate axes and spindles have been studied by means of computer simulation and experimentally [10]-[13].

The coordination of the drive subsystems in machine tools with digital program control is accomplished by appropriate ladder diagrams. Such ladder diagrams for machine tools are developed and described in [14].

In this paper the main requirements for a type of turning machines are formulated and the basic features of the driving system are presented. Some improvements related to the additional auxiliary drives are described. Simulation and experimental results for the feed and spindle drives are presented and discussed. The practical application of a modernized machine of the considered type is illustrated by the production of a specific workpiece.

Published on August 31, 2018.

M. M. Zhilevski, Faculty of Automatics, Technical University of Sofia, Bulgaria, (e-mail: mzhilevski@ tu-sofia.bg).

M. R. Mikhov, Faculty of Automatics, Technical University of Sofia, Bulgaria (e-mail: mikhov@ tu-sofia.bg).

II. Main Requirements

Fig. 1 presents a machine of the class of turning machines with digital program control. The following notations are used: 1 – machine body; 2 – gearbox; 3 – two-coordinate feed drive; 4 – twelve-position turret head; 5 – four-position turret head; 6 – hydraulic tailstock; 7 – a part from spindle clamping device with chuck; 8 – cooling pump; 9 – safety shield; 10 – ball screw; 11 – control panel.

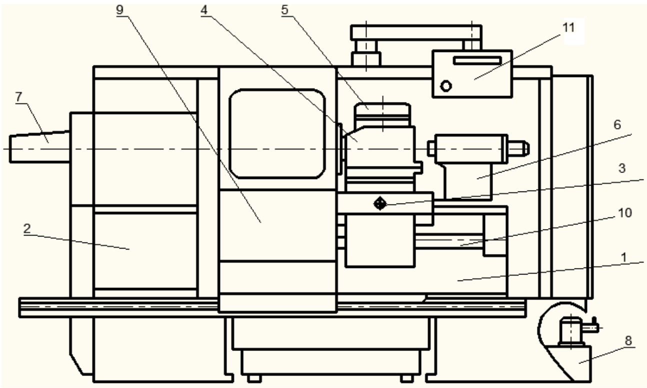


Fig. 1. A machine of the class of turning machines.

The main problems and requirements related to these machines can be formulated as follows:

- selecting suitable electric drives for the coordinate axes and the spindle;
- developing appropriate algorithms for their control;
- creating the necessary software to coordinate the movements along the respective axes and the spindle;
- increasing performance;
- improving control accuracy;
- versatility associated with machining;
- choosing optimal mechanical gears;
- examining tool wear;
- increasing productivity;
- developing appropriate ladder diagrams;
- reducing energy consumption;
- increasing reliability and operational life.

Fig. 2. Control panel of the turning machine.

The developed control panel for this type of turning machines is presented in Fig. 2.

III. Features of the Driving System

The simplified block diagram of the driving system under consideration is shown in Fig. 3, where the following notations are used: DPC – digital program control device; ED1 - ED8 – electric drives; G1 - G4 – mechanical gears; L1 - L6 – loads.

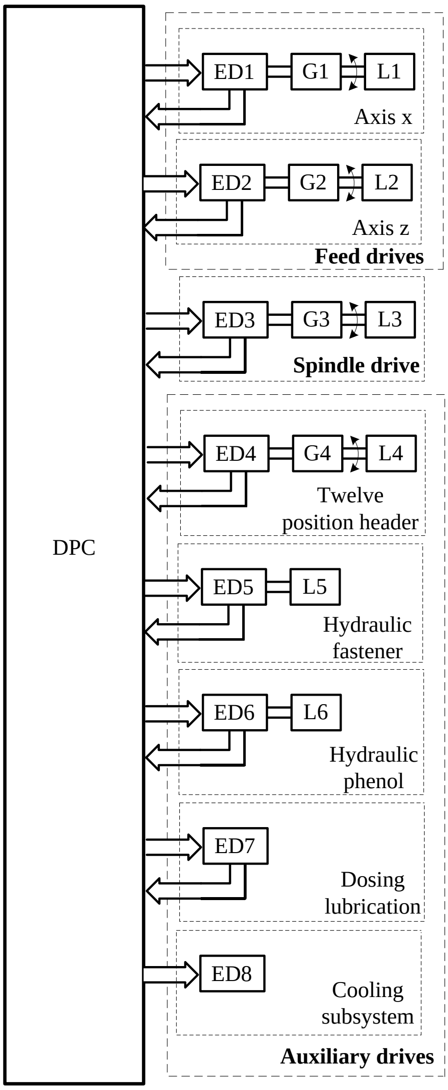


Fig. 3. Block diagram of the driving system.

Each of the presented drive subsystems has specific features and requirements that need to be taken into account in the process of design, study and application.

The designing process of a drive system for turning machines includes the following basic stages:

1. Development of methodologies for selection of feed and spindle 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. Compilation 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.

A. *Two-coordinate x-z feed drive*

The main requirements for the feed drives of turning machines can be formulated as follows:

- smooth speed regulation in a wide range;
- good dynamics;
- positioning accuracy;
- formation of the necessary position cycles;
- maximum starting torque to ensure good dynamics;
- reversible speed and torque control;
- compensation of the disturbances;
- safety;
- economy.

A methodology for selection of feed drives for turning machines is presented in [15]. On the basis of this methodology, two-coordinate DC and AC electric drives are chosen.

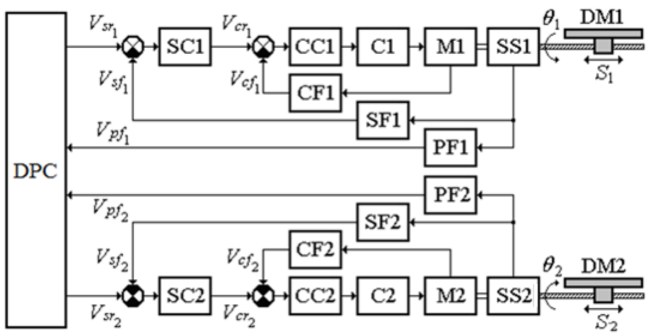


Fig. 4. Block diagram of a two-coordinate drive system.

The simplified block diagram of a two-coordinate electric drive system with DC motors is presented in Fig. 4, where the notations are as follows: 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.

This two-coordinate drive has cascade structure with subordinate regulation of currents, speeds and positions. Control loop optimization and tuning of the respective controllers have been done sequentially, starting from the innermost one [16].

DOI: http://dx.doi.org/10.24018/ejers.2018.3.8.871

The transfer functions of the current controllers assume the following form:

$$G_{cc}(s)=\frac{R_{a_\Sigma}\left(\tau_{a_\Sigma}s+1\right)}{a_c K_c K_{cf}\tau_{\mu c}s}, \qquad (1)$$

where: R_{a_Σ} is summary armature circuit resistance; a_c – coefficient influencing the current loop dynamic characteristics; K_{cf} – gain of the armature current feedback; $\tau_{\mu c}$ – summary small time-constant of the current loop, not subject to compensation.

The transfer functions of the speed controllers is as follows:

$$G_{sc}(s)=\frac{K_{cf}\tau_{m_\Sigma}}{a_s K_m K_{sf} R_{a_\Sigma}\tau_{\mu s}}, \qquad (2)$$

where a_s is a coefficient influencing the speed loop dynamic characteristics; K_{sf} – gain of the speed feedback; $\tau_{\mu s}$ – summary small time-constant of this loop, not subject to compensation.

The transfer functions of the position controllers is expressed by the following equation:

$$G_{pc}(s)=\frac{2K_{sf}\varepsilon_{d\max}}{K_{pf}\omega_{\text{rat}}}, \qquad (3)$$

where $\varepsilon_{d\max}$ is maximum deceleration; K_{pf} – gain of the position feedback; ω_{rat} – rated speed.

Mathematical modeling and computer simulation provide good opportunities to explore different control variants aiming at optimization of motion trajectories. Models of drives with DC motors have been developed and used for studying of various control algorithms for the respective dynamic and static regimes at different operation modes.

The vector-matrix model of the DC electric drive used is as follows:

$$\begin{bmatrix}\frac{d\theta_i}{dt}\\ \frac{d\omega_i}{dt}\\ \frac{di_{a_i}}{dt}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & -\frac{K_{t_i}}{J_i}\\ 0 & -\frac{K_{e_i}}{L_{a_i}} & -\frac{R_{a_i}}{L_{a_i}}\end{bmatrix}\begin{bmatrix}\theta_i\\ \omega_i\\ i_{a_i}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \frac{K_{c_i}}{L_{a_i}}\end{bmatrix}v_i+\begin{bmatrix}0\\ -\frac{1}{J_i}\\ 0\end{bmatrix}i_{l_i}, \qquad (4)$$

where: θ_i is angular position for the respective i axis; ω_i – angular 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 power converter; J_i – total inertia referred to the motor shaft; i_{l_i} – armature current which is determined by the respective load torque; $i=1,2$ – index for the coordinate axis *x* or *z*.

In general, when two-coordinate drives with position control are used, the motion trajectories are formed by the respective displacements along both axes. Such trajectories are shown in Fig. 5, where the notations used are as follows: S_i – linear position for the respective i axis; S_{if} – linear final position for the respective i axis.

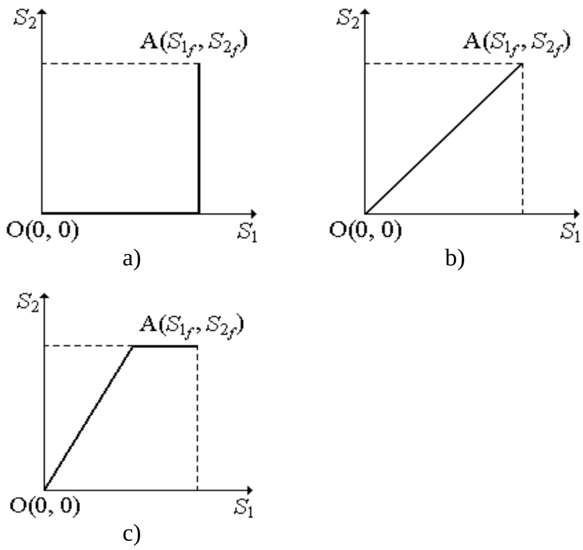


Fig. 5. Motion trajectories for two-coordinate position control: a) consecutive motion along the coordinate axes; b) simultaneous motion along the coordinate axes; c) combined motion along the coordinate axes.

Fig. 5a shows a trajectory obtained by successive movement along the coordinate axes.

The total time for positioning is as follows:

$$t_p=t_{p_1}+t_{p_2}, \qquad (5)$$

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

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

$$t_p=t_{p_1}=t_{p_2}, \qquad (6)$$

Fig. 5c 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:

$$t_p=t_{p_1}, \qquad (7)$$

A stand for experimental research of electric drives was developed, equipped with the necessary measuring and visualization devices. Studies were carried out for different versions of controllers and operation regimes.

The coefficients of the respective mechanical gears for feed drives are as follows:

$$K_{g_1} = 5 \text{ mm/rev} \approx 0.8\text{x}10^{-3} \text{ m/rad};$$
$$K_{g_2} = 10 \text{ mm/rev} \approx 1.6\text{x}10^{-3} \text{ m/rad}. \quad (8)$$

Fig. 6 shows the developed two-coordinate electric drive for a machine of the considered class. The data of the used DC motors are as follows:

- for axis *x:* $T_{xnom} = 5.4$ Nm $\omega_{xnom} = 209.34$ rad/s;
- for axis *z*: $T_{znom} = 17.6$ Nm $\omega_{znom} = 157$ rad/s.

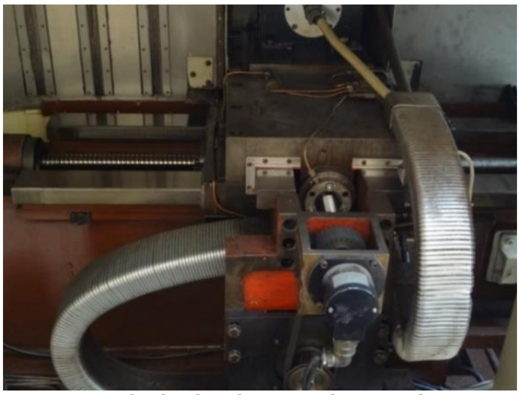


Fig. 6. The developed two-coordinate *x-z* drive.

Some experimentally obtained trajectories with the two-coordinate DC motor drive are shown in Fig. 7.

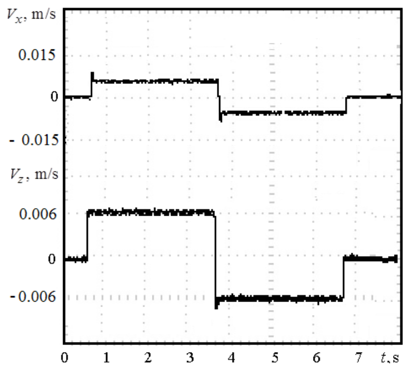


Fig. 7. Time-diagrams of motions along the *x* and *z* axes.

B. Spindle drive

The main requirements for the spindle drives for turning machines are as follows:

- dual-zone speed regulation (by constant torque and constant power respectively);
- high maximum speed;
- oriented braking with high accuracy;
- reversible speed control.

In these electric drives speed regulation is carried out at constant motor torque until a basic speed is reached. After that, it is realized at constant power. The rated motor speed is most often regarded as boundary level and switching over of zones is carried out automatically.

A methodology for selection of spindle drives for turning machines is presented in [17]. On the basis of this methodology, DC and AC electric drives are chosen.

The block diagram of a DC motor spindle drive is presented in Fig. 8, where the following notations are used: CD – control device; SC – speed controller; CC1 – armature current controller; CS1 – armature current sensor; CF1 – armature current feedback block; SS – speed sensor; SF – speed feedback block; C1 – armature voltage power converter; CC2 – field current controller; CS2 – field current sensor; CF2 – field current feedback block; AVF – armature voltage feedback block; AVB – absolute value block; SB – switching block; C2 – field voltage power converter; M – separately excited DC motor; LM – field winding; V_{sr} – speed reference signal; V_{sf} – speed feedback signal; V_{c_1r} – armature current reference signal; V_{c_1f} – armature current feedback signal; $|V_{v_1f}|$ – armature voltage feedback signal; $V_{\varphi r}$ – magnetic flux reference signal; V_{c_2f} – field current feedback signal; V_1 – armature voltage; V_2 – field voltage; I_1 – armature current; I_2 – field current; ω – motor speed.

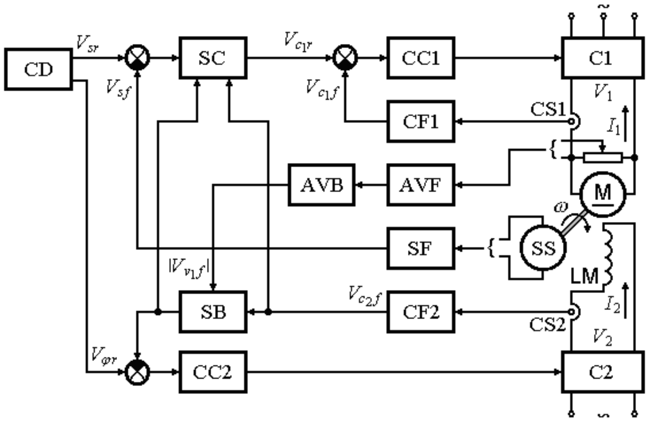


Fig. 8. Block diagram of a dual-zone drive system.

Within the entire range, the motor speed is set up by the control signal V_{sr}, while through the signal $V_{\varphi r}$ the respective excitation current is defined. This electric drive is of four-quadrant type with both current and speed reversion. The power converter for the armature voltage is reversible, while the power converter for the excitation voltage is non-reversible. To avoid the V_{v_1f} sign influence, an absolute value block is included.

The transfer function of the speed controller is described as follows:

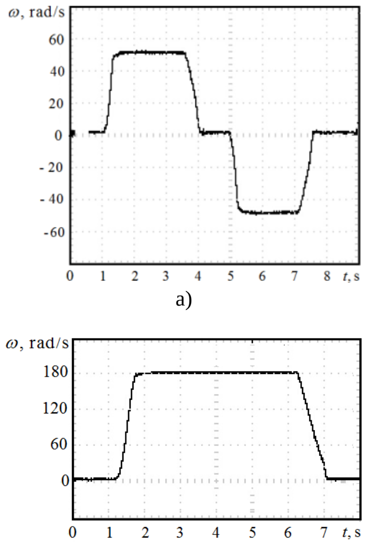
$$G_{sc}(s) = \frac{J_{\Sigma} K_{c_1f}}{a_s K_{sf} \tau_{\mu s} c\Phi} \left(1 + \frac{1}{a_s^2 \tau_{\mu s}}\right), \quad (9)$$

where: J_{Σ} is total inertia referred to the motor shaft; K_{c_1f} – gain of the armature current feedback; a_s – coefficient influencing the speed loop dynamic characteristics; K_{sf} – gain of the speed feedback; $\tau_{\mu s}$ – summary small time-constant of this loop, not subject to compensation; c – motor coefficient; Φ – magnetic flux.

In the second zone the magnetic flux changes, and to improve the electric drive performance, an adaptive speed controller with switchable structure has been applied. In this zone the controller parameters adapt to the decreasing magnetic flux. Adaptation to flux change starts after the zone switching, which takes place at the specified base value of the armature voltage.

Fig. 9 presents speed oscillograms of the DC spindle drive obtained experimentally for both zones of regulation. The data of the used DC motor are as follows: $P_{nom} = 7.5$ kW, $\omega_{nom} = 104.67$ rad/s.

The implemented DC drive has good tuning qualities and provides the specified static and dynamic characteristics. A disadvantage is the presence of a brush collector.



b)

Fig. 9. Speed oscillograms of the DC spindle drive.

Electric drives with AC motors have easier operational maintenance but their price is relatively higher. They are an appropriate option for turning machines. An AC spindle drive was implemented with the following parameters of the motor: $P_{nom} = 5,5$ kW, $\omega_{nom} = 628$ rad/s.

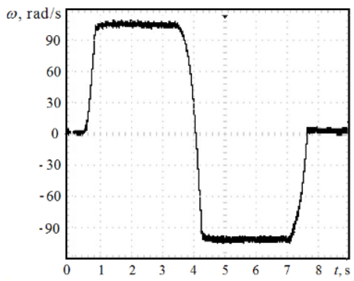


Fig. 10. Speed time diagram of AC spindle drive.

Fig. 10 shows a speed time diagram obtained experimentally.

C. Auxiliary drives

The main requirements for the auxiliary drives can be formulated as follows:

- twelve-position turret head providing choice of the desired tool with high precision;
- hydraulic clamping device with chuck and hydraulic tailstock ensuring precise clamping of the workpiece during the entire working period;
- dosing lubrication of the machine coordinate axes;
- cooling subsystem with possibility of automatic and manual braking and starting from the control panel in order to reduce energy consumption.

A number of constructive corrections were introduced to improve the performance and service life of these auxiliary drives.

The coordination of all the drive subsystems in the turning machine is accomplished by the developed appropriate ladder diagrams.

IV. Practical Application

The practical application of a modernized machine of the considered type is illustrated by the production of a specific workpiece.

The specialized SprutCAM 11 software [18] was used to prepare the geometric model of the workpiece, to configure the class and to define the parameters of the turning machine. Fig. 10 shows the resulting geometric shape of the workpiece.

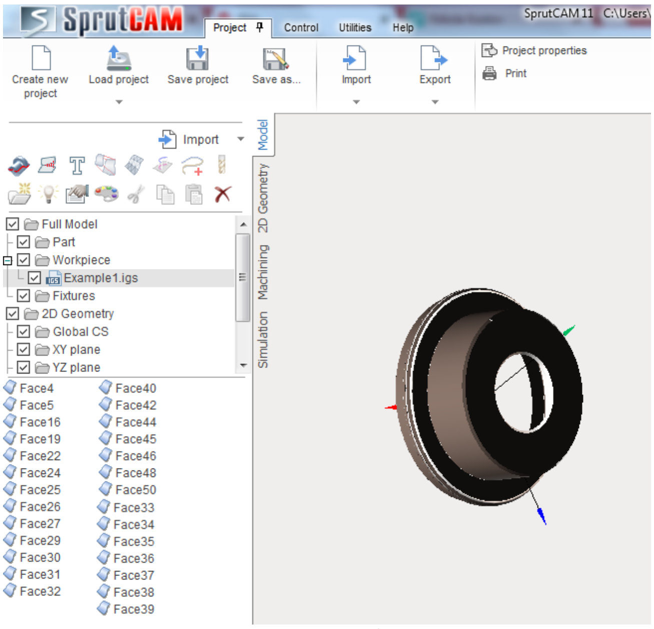


Fig. 10. Geometric shape of the workpiece.

Using the specialized software, the generated program is entered into the memory of the machine tool. A part of the program is shown in Fig. 11.

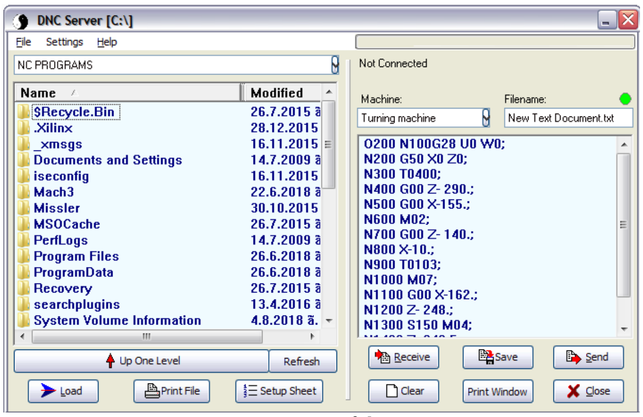


Fig. 11. A part of the program.

Fig. 12 illustrates the process of machining of a workpiece.

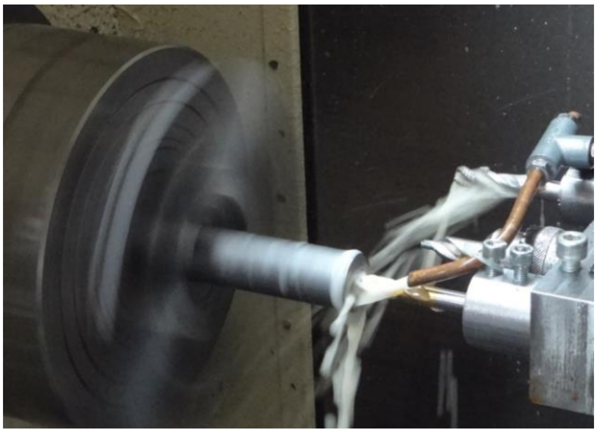


Fig.12. Machining process.

The processed workpiece is shown in Fig. 13.

Fig. 13. The processed workpiece

V. CONCLUSION

The main requirements for the modernized machine tools of the studied class of turning machines and their drive systems are formulated and analyzed.

Models for computer simulation of two-coordinate and spindle electric drives were developed, allowing study at various reference speeds, positions, and loads applied to the motor shafts.

Comparative analysis of different solutions with DC and AC motors was carried out aiming at performance improvement. A number of constructive corrections were introduced to improve the characteristics and service life of the auxiliary drives.

The practical application of a modernized turning machine of the considered type is illustrated by the production of a specific workpiece.

The research as well as the results obtained can be used in the development of such drive systems for the studied class of machine tools.

ACKNOWLEDGMENT

This work is supported by the Technical University of Sofia, Bulgaria under Research Project No. 181PR000308 /2018.

REFERENCES

[1] Popov G., *Machine tools, part I: Applicability, device and control*, Second book, Technical of University of Sofia, Sofia, 2010, ISBN 978-954-438-766-2.
[2] Tata McGraw-Hill Education, *Manufacturing Technology: Metal cutting and machine tools*, Vol. 2, 2013, ISBN 9781259029561.
[3] Youssef, H. A., H. El-Hofy, *Machining Technology: Machine Tools and Operations*, CRC Press, 2008, ISBN 9781420043402.
[4] Acarnley P., *Stepping Motors: a Guide to Theory and Practice*. London, IEE, 2002, ISBN 978-085-296-029-5.
[5] Bose B. K., *Power electronics and motor drives: advances and trends*. London, Academic Press, 2006, ISBN 978-0-12-088405-6.
[6] Hanselman D., *Brushless Permanent Magnet Motor Design*, Orono, University of Maine, 2006, ISBN 1-881855-15-5.
[7] Keuchel U., R. M. Stephan, *Microcomputer-based adaptive control applied to thyristor-driven DC motors*, London, Springer-Verlag, 1994, ISBN 978-038-719-855-5.
[8] SERVOMOTORS, *Gama Motors Catalogue*, 2014.
[9] AMKASYN, *AC Servo- and Main Spindle Motors*, AMK Catalogue, 2014.
[10] Mikhov M., 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, 2012, ISBN 978-619-167-002-4.
[11] Mikhov M., M. Zhilevski, A. Spiridonov, Modeling and Performance Analysis of a Spindle Electric Drive with Adaptive Speed Control, *Journal Proceedings in Manufacturing Systems*, Vol. 7, No. 3, pp. 153-158; 2012, ISSN 2067-9238.
[12] Mikhov M., B. Balev, Modeling and Optimization of an Electric Drive System with Dual-Zone Speed Regulation, *Proceedings of the International Scientific Conference on Information, Communication and Energy Systems and Technologies*, Nish, Serbia and Montenegro, 2005, Vol. 2, pp. 575-578, ISBN 86-85195-26-8.
[13] Mikhov M., Ts. Georgiev, An Approach to Synthesis of a Class of Electric Drives with Dual-Zone Speed Control, *Advances in Electrical and Computer Engineering,* Vol. 10, No. 4 pp. 87-94, 2010, ISSN 1582-7445.
[14] Zhilevska M., Modernization of the class of milling machines, *Dissertation*, Gabrovo, 2017.
[15] Zhilevski M., M. Mikhov, Study of Two-Coordinate Electric Drives of Turning Machines, *International Journal of Engineering and Applied Sciences*, Vol. 5, Issue 6, pp. 29-34, 2018, ISSN: 2394-3661.
[16] Mikhov M., *Electric Drives Control Systems*, Technical University of Sofia, Sofia, 2009, ISBN 978-954-438-628-3.
[17] Zhilevski M., M. Mikhov M., Methodology for Selection of Spindle Drives for Turning Machines, *International Journal of Engineering Research and Development,* Vol. 14, Issue 5, pp. 42-48, 2018, ISSN:2278-800X.
[18] http://www.aertia.com/docs/sprut/SprutCAM40_Eng_Pdf.pdf.

Marin M. Zhilevski was born in 1986 in Gabrovo, Bulgaria. He is an Assistant Professor at the Technical of University of Sofia, Faculty of Automatics, Department of Electrical Motion Automation Systems. He received his PhD in Electric Drives in 2015. His interests are related to Control of Electric Drive Systems, Machine Tools, Programmable Logic Devices and Systems, Automatics, Robotics, etc.

Mikho R. Mikhov was born in 1948. He received his MSc degree in Electrical Engineering in 1972 and his PhD in Industry Automation in 1983 from the Technical University of Sofia, Bulgaria. He is Professor at the Faculty of Automatics, Technical University of Sofia. He is interested in Electric Drives, Control of Electromecanical Systems, Industry Automation, Wireless Monitoring and Control, and Computer Simulation.