Study of Spindle Drives for Machining Centers with Computer Numerical Control

Marin Zhilevski, Mikho Mikhov

Abstract **— This paper presents the features of spindle drives for machining centers with computer numerical control. Based on formulated requirements, taking into account the possible mechanical operations main drives with DC and AC motors are selected. Mathematical modeling and computer simulation offer effective ways to study the drive systems in different dynamic and static modes of operation, especially when it is not possible or inconvenient to perform such tests in laboratory or industrial conditions. Using the MATLAB/SIMULINK software package, two types of DC drives are studied, namely: a dual-zone electric drive without adaptation and with adaptive control one. An AC drive is implemented which satisfies the necessary requirements. Some experimental results from studies of spindle drives with DC and AC motors are shown and discussed. Practical implementations of spindle drives in different mechanical operations are illustrated. The research held and the results obtained can be used in the development of such electric drives for the studied class of machine tools.**

Index Terms— **machining center, CNC, spindle drive, DC drive, AC drive**

I. Introduction

Machining centers are among the most widely used and well-known in practice machine tools. They are applied mainly for machining prismatic body workpieces by milling surfaces with random contours and for machining holes, such as drilling, boring, countersinking, reaming, threading etc.[1]-[4].

The relatively long period of their application for production of various workpieces makes them a key factor in many production lines. Their options for using a range of different tools in machining, automatic tool change and precision control on all axes, turns them into machines suitable for complex, precise and fast processing of various workpieces. Usually, the term machining center describes almost any drilling and milling machine, the construction of which includes a subsystem for automatic tool change and a workbench for the workpiece. In most cases, these machines are equipped with computer numerical control (CNC), thanks to which the processing of workpieces is controlled by a computer program that performs a number of functions. CNC centers are characterized by higher performance, reliability and accuracy [5]-[7].

A distinctive feature of CNC machining centers is the high degree of process automation. All operations in these machines take place without human intervention.

Marin Zhilevski is with the Faculty of Automatics at Technical University of Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria
(e-mail: mzhilevski@tu-sofia.bg).

Mikho Mikhov is with the Faculty of Automatics at Technical University of Sofia, 8 Kl. Ohridski Blvd, 1000 Sofia, Bulgaria
(e-mail: mikhov@tu-sofia.bg).

The main drive (the spindle drive) is one of the most important working parts in the machine tools. It participates in the process of machining, significantly influencing the quality of the details and the productivity of the whole machine. The spindles are used to transmit the rotational main movement of the cutting tool (at drilling, milling, grinding and other machines) or of the workpiece (at turning machines) and to ensure a certain position of the tool (workpiece) relative to other working parts [8], [9].

The parameters of the spindle drive determine to the highest degree the electric drive choice and the energy consumption in the machine tools [9], [10].

The complete machining of the workpiece performing various mechanical operations with one installation on the machine raises its accuracy and productivity [11].

Achieving the desired accuracy of the machined workpieces is mainly related to the operation of the spindle drive and the conditions in which it works. The different cutting speeds generate different temperatures and forces in the spindle. Another condition for high accuracy is to determine the possible sources of errors in the processing of the part and to eliminate them in advance [9], [11].

The great importance of the spindle also sets the following high requirements that the respective drive must meet [9]: dual-zone speed regulation (at constant torque and at constant power, respectively); high maximum speed; speed reversal; high working accuracy and stability; low friction and wear; oriented braking with high accuracy; protection against pollution; maintainability; low production and repair costs.

This paper describes an approach for selection of spindle drives for a class of machining centers with CNC. Based on the results obtained, DC and AC drives in different working regimes are studied. Some experimental and simulated time diagrams are shown and discussed. The practical applications of the studied class of machining centers are presented with processing of workpieces in different operations.

II. Selection of the Main Drive

The considered class of machines allows for the following mechanical operations: milling, drilling, boring, countersinking, reaming, threading, and processing of keyways. The highest cutting forces (and hence powers) are obtained in the processes of milling, drilling and boring. For this reason, it is necessary to calculate, compare and take into account the highest power value when selecting a spindle drive from catalog data.

When developing spindle drives, it is necessary to take into account a number of important factors, such as: the features of the technological process, the type of processed materials, the parameters of the tools used and the selected mechanical gears.

https://doi.org/10.47978/TUS.2021.71.03.008

The power required for the spindle drive in boring operation is determined by the next expression [12], [13]:

$$P_{spb} = (0.95 \div 0.99) \times (1.1 \div 1.3) \times \times \frac{V_{cb} \times a_{pb\max} \times f_{rb} \times K_{cfzb} \times 2\pi \times 10^6}{\eta} \times \times (1 - \frac{a_{pb\max}}{D_{cb\max}}) \quad (1)$$

Minimum speed, which is selected for the spindle motor:

$$\omega_{bm} = \frac{V_{cb} \times 2}{D_{mb\max}} \times K_{spg} . \quad (2)$$

The following notations are used in this section: $D_{cb\max}$ – maximum diameter of boring tool; V_{cb} – cutting speed; ω_b – spindle speed in the cutting process; f_{rb} – feed per radian; $a_{pb\max}$ – maximum cutting depth; K_{cfzb} – specific cutting force; η – efficiency of the machine; ω_{bm} – minimum speed, which is selected for spindle motor from catalogue data; K_{spg} – mechanical gear ratio of the spindle drive.

The power required for the spindle drive in drilling process is calculated by the expression [12]-[14]:

$$P_{spd} = (0.95 \div 0.99) \times (1.1 \div 1.3) \times \times \frac{D_{cd\max} \times f_{rd} \times V_{cd} \times K_{cfzd} \times \pi \times 10^6}{2\eta} . \quad (3)$$

The minimum speed, which is selected for the spindle motor in drilling operation:

$$\omega_{dm} = \frac{V_{cd} \times 2}{D_{cd\max}} \times K_{spg} . \quad (4)$$

The notations used are as follows: $D_{cd\max}$ – maximum drill diameter that can be used by the machine; V_{cd} – cutting speed; ω_d – spindle speed in drilling process; f_{rd} – feed per radian; K_{cfzd} – specific cutting force, when feeding the tool tooth; P_{spd} – power required only for the spindle drive; ω_{dm} – minimum speed, which is selected for spindle motor from catalogue data.

The cutting power, which is necessary to carry out the milling in the heaviest operating mode for the machine is calculated by the expression [12]-[14]:

$$P_{spm} = (0.95 \div 0.99) \times \frac{a_{p\max} \times a_{e\max} \times V_f \times k_c \times 10^6}{\eta} . \quad (5)$$

The minimum speed, which is selected for the spindle motor in drilling operation:

$$\omega_{mm} = \frac{V_{cm} \times 2}{D_{cm\max}} \times K_{spg} . \quad (6)$$

The notations used are as follows: $D_{c\max}$ – maximal cutting diameter, which can be used by the machine; $a_{p\max}$ – maximal cutting depth of the tool; $a_{e\max}$ – maximal width of cut; ω_{mm} – spindle speed; V_f – feed speed; b_{av} – average chip thickness; k_c – relative cutting force.

After taking into account the heaviest modes of the different mechanical operations, two spindle electric drives are selected with the following motors [15]-[17]:

- DC spindle motor MP112MA with nominal data: $P_{sp} = 13$ kW , $\omega_{sp} = 238.6$ rad/s ;
- AC motor DH with the nominal data: $P_{sp} = 7.2$ kW , $\omega_{sp} = 523.4$ rad/s .

III. DC AND AC DRIVE SYSTEMS

Based on the obtained selection results, the drive systems with DC and AC motors are studied in different operation modes.

Mathematical modeling and computer simulation offer effective ways to study the electric drive systems in details, in various dynamic and static working regimes, especially when it is not possible or it is inconvenient to carry out such tests in laboratory or industrial environments.

The spindle drive should be four-quadrant with both armature current and speed reversion. Fig. 1 shows speed/torque characteristics of such electric drive, where $\omega_{\max}$ is the upper bound of the speed regulation range and $T_{\max}$ is the maximum motor torque. At $\omega_r > \omega_b$ field cuttent in steady state regime is $I_2 < I_{2\text{rat}}$, while the admissible armature current is limited below the $I_{1\max}$ value.

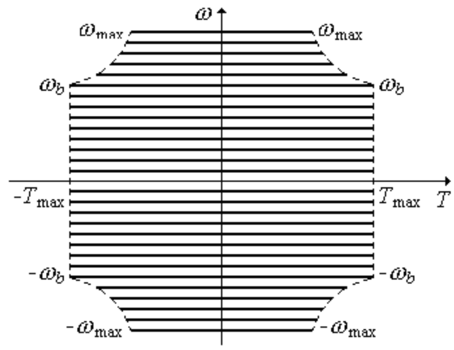


Fig. 1. Speed/torque curves of the four-quadrant drive system

A. DC drives

The studied spindle DC electric drives are as follows:

- implemented dual-zone drive without adaptation;
- computer simulated dual-zone drive with adaptive control.

The electric drive without adaptation is presented in [18]. Some results from studies for different operation modes and speeds are shown in the following paragraph.

Using the MATLAB/SIMULINK software package some simulation models have been developed for drives with dual-zone speed regulation to verify the respective control algorithms [19], [20].

For the drive with adaptive control, the transfer function of the armature current controller is as follows [20]:

$$G_{c_1c}(s)=\frac{R_{1_\Sigma}\left(\tau_{1_\Sigma}s+1\right)}{a_{c_1}K_{p_1}K_{c_1f}\tau_{\mu c_1}s} \tag{7}$$

where a_{c_1} is a coefficient influencing the armature current loop dynamic characteristics; $\tau_{\mu c_1}=\tau_{p_1}+\tau_{c_1f}$ – summary small time-constant of this loop, not subject to compensation; $\tau_{1\Sigma}=L_{1_\Sigma}/R_{1_\Sigma}$ – armature circuit time-constant; L_{1_Σ} – armature inductance.

The applied optimization approach leads to the following transfer function of the respective speed controller:

$$\begin{aligned} G_{sc}(s)&=\frac{J_\Sigma K_{c_1f}}{a_sK_{sf}\tau_{\mu s}K_e}\left(1+\frac{1}{a_s^2\tau_{\mu s}s}\right)= \\ &=K_{sc}\left(1+\frac{1}{\tau_{sc}s}\right)=f(\Phi), \end{aligned} \tag{8}$$

where: a_s is a coefficient influencing the speed loop dynamic characteristics; $\tau_{\mu s}=a_{c_1}\tau_{\mu c_1}+\tau_{sf}$ – summary small time-constant of this loop, not subject to compensation; $K_e=c\Phi$ – back EMF voltage coefficient; K_{sc} and τ_{sc} – gain and time-constant of the speed controller.

In the second speed zone the magnetic flux changes and to improve the electric drive performance an adaptive speed controller with switchable structure has been synthesized. 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.

Block diagram of the adaptive speed controller is shown in Fig. 2. The structure shift is realized through a signal from the respective switching block SB.

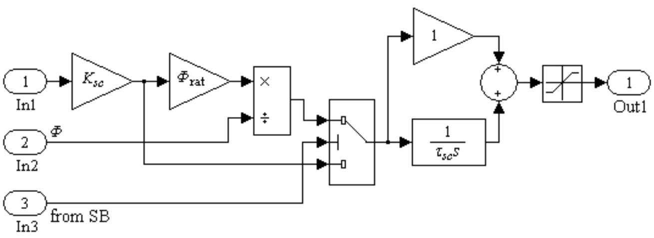


Fig. 2. Model of the adaptive speed controller with current limiter

The transfer function of the field current controller is described by the following equation:

$$G_{c_2c}(s)=\frac{R_{2_\Sigma}\left(\tau_{2_\Sigma}s+1\right)}{a_{c_2}K_{p_2}K_{c_2f}\tau_{\mu c_2}s}\,. \tag{9}$$

where a_{c_2} is a coefficient influencing the field current loop dynamic characteristics; $\tau_{\mu c_2}=\tau_{p_2}+\tau_{c_2f}$ – summary small time-constant of this loop, not subject to compensation; $\tau_{2\Sigma}=L_{2_\Sigma}/R_{2_\Sigma}$ – field circuit time-constant; L_{2_Σ} – field inductance.

B. AC drive

The implemented AC drive with induction motor has been developed by AMK company. Its functional scheme is presented in [16], [17].

Due to the use of significantly more powerful motors for the main drives (compared to the feed drives), in this case a system with a controllable rectifier is chosen, in which there is a possibility to return energy to the AC power supply. The control is entirely digital, carried out by setting the necessary parameters from a database. The type of motor used and the respective converter, input/output components are indicated and on this basis the necessary adjustment for the specific system is performed.

The selected AC motor is from the DH series of the AMK company with a built-in encoder, type resolver for feedback. These are highly dynamic three-phase motors that are particularly suitable for main electric drives of machine tools. The advantages of the induction motor used are the following: easy maintenance; built-in cooling fan; high overload capacity; capabilities for speed, position and synchronized control.

Fig. 3 presents the respective characteristics of this AC electric drive, where the notations used are the following: 1 - power curve; 2 - torque curve.

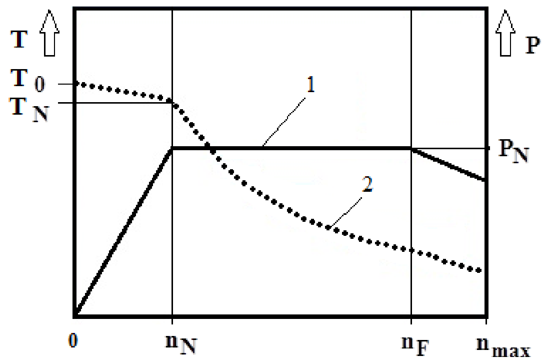


Fig. 3. Characteristics of the electric drive with AC motor

The following section presents some results of the implemented spindle drive.

As a comparison between the two drive systems, it can be summarized that the respective dynamic and static indicators of the studied AC electric drive are high and fully comparable with those of the DC electric drive. At the same time, it should be noted the much easier operational maintenance of this drive, due to the lack of a collector-brush device. As a disadvantage, at this stage can be indicated its higher price.

IV. Experimental Studies

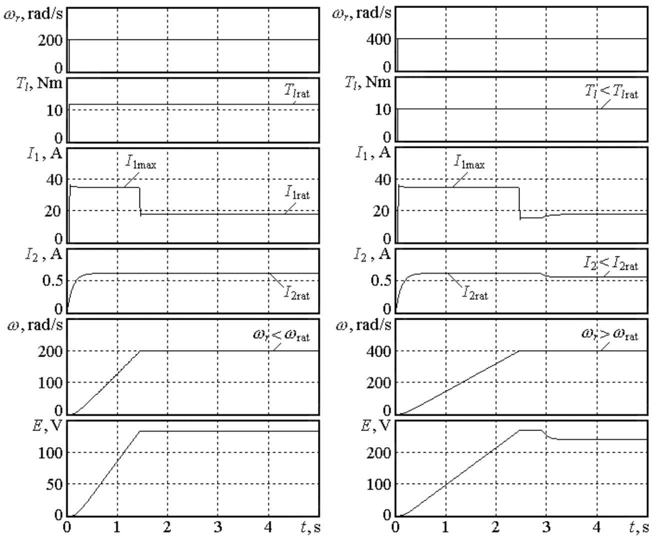
The next figures illustrate some experimental studies from the simulations and the implemented spindle drives in different speeds, loads and operation modes.

Fig. 4 presents results from the computer simulation in MATLAB/SIMULINK for the both zones of the speed regulation.

Fig. 4a shows some time-diagrams for the first zone of speed regulation. The start process is presented, as well as operation at steady state regime with rated load applied to the motor shaft.

Fig. 4b illustrates the drive performance in the zone with flux weakening. The presented characteristics are as follows:

speed reference $\omega_r(t)$; load torque $T_l(t)$, armature current $I_1(t)$, field current $I_2(t)$, motor speed $\omega(t)$ and back EMF voltage $E(t)$.



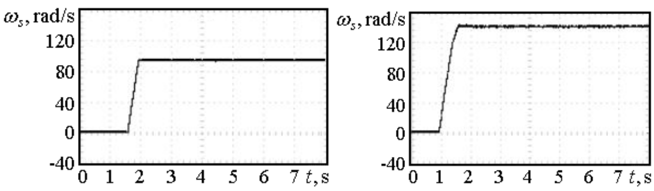
a) b)

Fig. 4. Time-diagrams of speed regulation

Fig. 5 shows experimental results from the study of implemented DC drive in a machining center from the considered class.

The trajectory presented in Fig. 5a is obtained when operating below the basic spindle speed. The set speed is 100 rad/s and is located in the first zone.

Figure 5b shows a trajectory at a given speed of 140 rad/s, which in this case corresponds to work in the second zone.



a) b)

Fig. 5. Spindle speed oscillograms

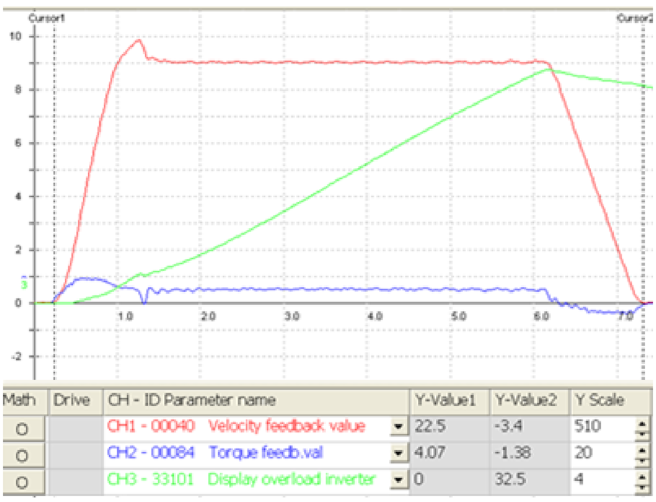


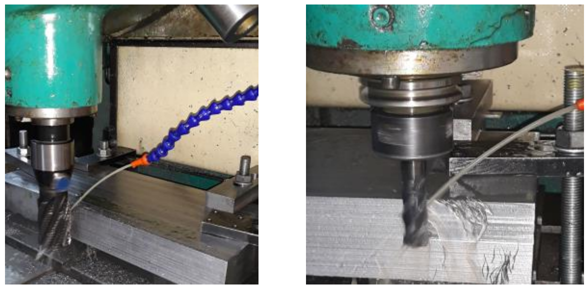
Fig. 6. Study of the implemented AC spindle drive

Fig. 6 shows a time diagram for the implemented AC drive of the AMK company, obtained by rotating the spindle in one direction. For registration of the relevant characteristics, the software product AIPEX PRO was used, which is strictly specialized and allows for detailed research with high quality results. The abscissa axis shows the time for performing the examinations in seconds, and the ordinate - the corresponding signals, as the scale is in volts. A red line illustrates the speed of rotation, a blue line - the torque, and a green line - the inverter load. In this study, the set speed is 53.41 rad/s.

V. Practical Applications

The following figures present practical applications of the modernized machining centers with CNC in different mechanical operations.

Fig. 7a and Fig. 7b illustrate the processes in rough and fine milling of the workpiece respectively. The diameters of the tool used are 0.063m (processing depth - 0.002m) and 0.016 m (processing depth - 0.0005m).



a) b)

Fig. 7. Rough and fine milling processes

Fig. 8 demonstrates the spindle operation in drilling processes of different diameters and workpieces.

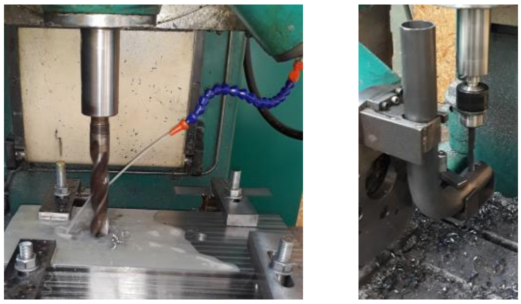
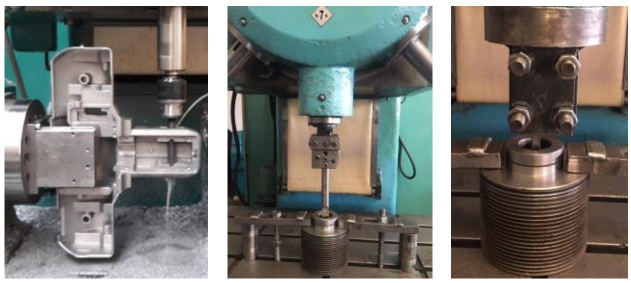


Fig. 8. Drilling processes of workpieces

Fig. 9 presents other mechanical operations for the studied machining center. Fig. 9a, 9b, and 9c show the processes of reaming, boring and machining of spline channels. respectively.



a) b) c)

Fig. 9. Different mechanical operations.

In figure 10 are shown some machined workpieces from the machining center in different operations.

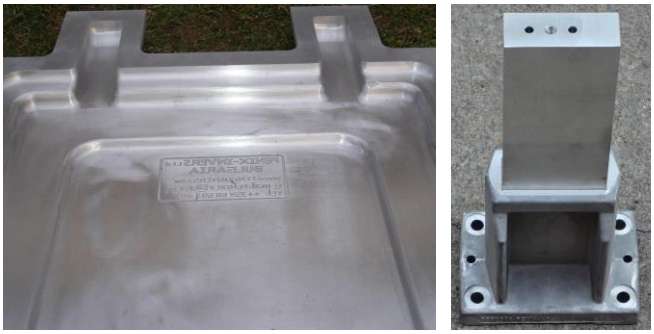


Fig. 10. Machined workpieces

VI. CONCLUSION

The features of the spindle drives for a type of machining centers with CNC are presented in this paper. Based on the set requirements are selected the main drives with DC and AC motors taking into account the possible mechanical operations in the studied class of machines. Practical applications of the machining centers are shown in different mechanical operations and processed workpieces.

The main results from the research held could be formulated as follows: expanding the possibilities for processing more complex workpieces; shortening the time for the respective operations; increasing the energy efficiency of the studied machines.

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