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Methodology for Selection of Spindle Drives for Milling Machines

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Abstract: ***This paper describes a methodology for selection of spindle electric drives for milling machines with digital program control. The offered algorithm takes into account the technological process features, the tools used, the processed material, and the mechanical gear type. A concrete example has been presented, illustrating the practical application of this methodology. A number of models for computer simulation of electric drive systems with dual-zone speed regulation have been developed, allowing study at various reference speeds and loads applied to the motor shaft. The research held as well as the results obtained can be used in the development of such electric drives for the studied class of machine tools.***

Keywords: Speed control, Dual-zone regulation, Spindle drive, Milling machine.

1. Introduction

Raising the technical level of modern machine tools depends on both the improvement of their control systems, and the functionality of the respective drives.

Compared to other types of drives, the electric ones have some significant advantages and meet high demands such as: wide range of speed regulation; high precision of the respective coordinate control; good dynamics; reliability; economical operation; easy maintenance; good communication abilities, etc. The role of electric drives in machine tools increases and currently they affect even the structures of the driven mechanisms.

In this paper the main requirements to spindle electric drives for a kind of milling machines are analyzed [1], [2]. When choosing a suitable electric drive a number of essential factors have been taken into account, namely: the technological process features, the tools used, the processed material, and the mechanical gear type.

2. Methodology for Spindle Drive Selection

Spindle electric drives must meet the following basic requirements:

- Dual-zone speed regulation (by constant torque and constant power respectively);
- Oriented braking with high accuracy;
- Reversible speed control.

With DC electric drives the speed is regulated at constant magnetic flux in the first zone, while in the second zone the flux is reduced at constant back electromotive force (EMF) voltage or armature voltage. Automatic switching of the two speed areas is realized as a function of one of these variables.

The simplified block diagram of the methodology algorithm is presented in Fig. 1, where the notations are as follows: $D_{c\max}$ – maximal cutting diameter, which can be used by the machine; H_B – Brinell hardness of the processed material; β_c – cutting edge angle of the tool; $a_{p\max}$ – maximal cutting depth of the tool; $a_{e\max}$ – maximal width of cut; $V_{\max}$ – maximal speed of the driven mechanism; z – total number of edges in the tool; V_c – cutting speed; f_z – feed per tooth of the tool; $b_{\max}$ – maximal chip thickness; ω – spindle speed; V_f – feed speed; b_{av} – average chip thickness; k_{c1} – normalized relative cutting force, depending on the type of material; ψ – exponent depending on the material nature; k_c – relative cutting force; $P_{c\max}$ – maximal power needed to perform milling, distributed between both feed electric drive and spindle electric drive; P_{sp} – power required for the spindle electric drive; P_m – power required by the spindle motor after reading the respective efficiency; η – efficiency for the studied milling machine.

The input data are as follows: definition of the heaviest duty cutter; $D_{c\max}$; H_B; β_c; $a_{p\max}$; $a_{e\max}$; $V_{\max}$.

The tabular data used in the methodology are taken from [3] and [4].

The spindle angular speed is calculated by the following equation [3]:

$$\omega = \frac{V_c \times 2}{D_{c\max}} \tag{1}$$

The feed speed in milling is calculated by the next expression [3]:

$$V_f = \frac{f_z \times \omega \times z}{2 \times \pi}. \quad (2)$$

The average chip thickness provided that $\frac{a_{e\max}}{D_{c\max}} < 0.1$ is calculated by the equation [3]:

$$b_{av} = f_z \times \sqrt{\frac{a_{e\max}}{D_{c\max}}}. \quad (3)$$

The average chip thickness, when the ratio $\frac{a_{e\max}}{D_{c\max}} \geq 0.1$ is calculated as follows [3]:

$$b_{av} = \frac{\sin \beta_c \times 180 \times a_{e\max} \times f_z}{\pi \times D_{c\max} \times \arcsin\left(\frac{a_{e\max}}{D_{c\max}}\right)}. \quad (4)$$

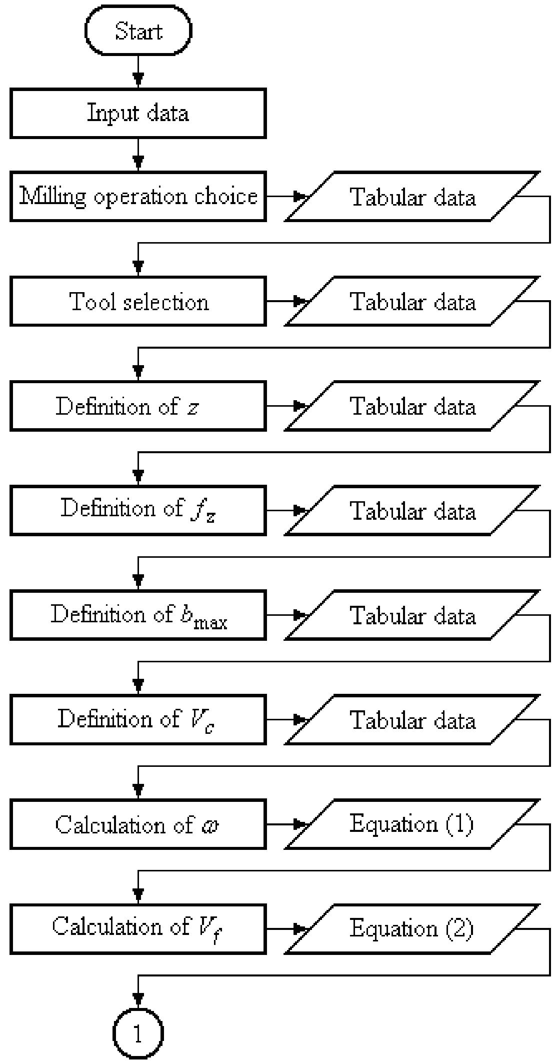

Figure 1: Block diagram of the algorithm

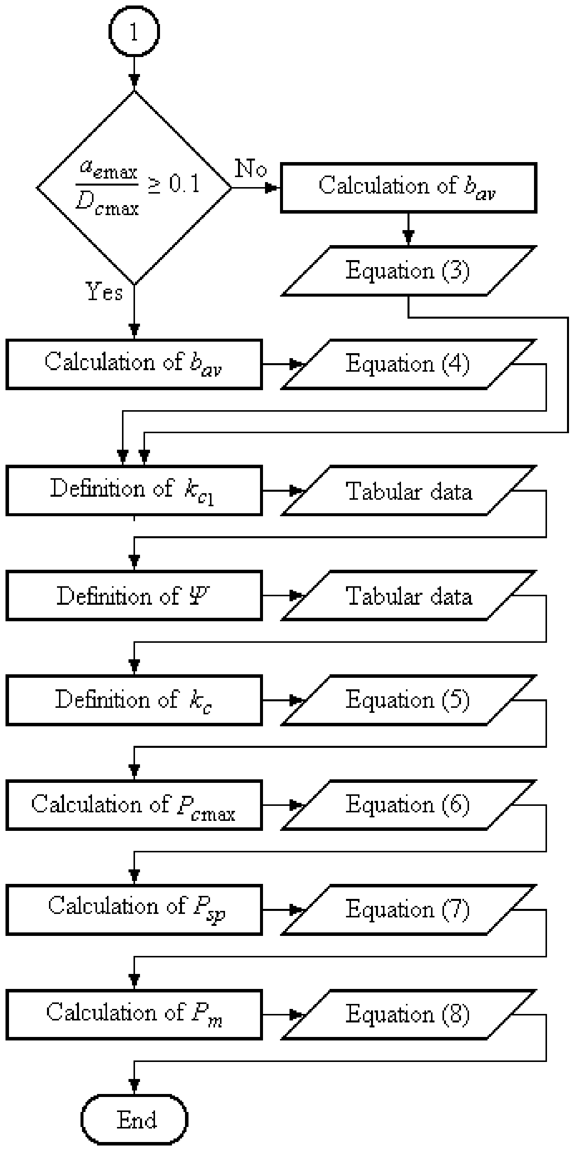

Figure 1: Block diagram of the algorithm (contin.)

The relative cutting force for the selected material is calculated by the following equation [3]:

$$k_c = k_{c_1} \times b_{av}^{-\Psi}. \quad (5)$$

The cutting power, which is necessary to carry out the milling operation in the heaviest operating mode for the machine is calculated by the expression [3]:

$$P_{c\max} = a_{p\max} \times a_{e\max} \times V_f \times k_c \times 10^6. \quad (6)$$

The power required for the spindle electric drive is calculated as follows [5]:

$$P_{sp} = (95 \div 99)\% \times P_{c\max}. \quad (7)$$

The power required for the spindle motor after reading the machine efficiency η is calculated by this expression [5]:

$$P_m \geq \frac{P_{sp}}{\eta}. \quad (8)$$

3. Practical Implementation

The development of a spindle electric drive includes the following basic stages:

1. Selection of the electric drive type.
2. Synthesis of the control system.
3. Analysis by modeling and computer simulation.
4. Experimental research.

As an example for using of the described methodology, the selection of spindle electric drive for milling machine with face milling is presented. The respective results obtained are given in Tabl. 1.

Table 1: Results from calculations

Step	Operation	Result
1.	Milling operation choice	Face milling
2.	Tool selection	CoroMill 245
3.	Definition of z	8 teeth.
4.	Definition of f_z	$0.00035\,\text{m}$
5.	Definition of $b_{\max}$	$\approx 0.00025\,\text{m}$.
6.	Definition of V_c	≈ 2.75 m/s
7.	Calculation of ω	≈ 68.75 rad/s
8.	Calculation of V_f	≈ 0.031 m/s
9.	Calculation of $a_{e\max} / D_{c\max}$	0.625
10.	Calculation of b_{av}	≈ 0.23 mm
11.	Definition of k_{c_1}	1 700 MPa
12.	Definition of ψ	–0.25
13.	Calculation of k_c	2 454.8 MPa
14.	Calculation of $P_{c\max}$	$\approx 11\ 415$ W
15.	Calculation of P_{sp}	$\approx 10\ 844$ W
16.	Calculation of P_m	$\approx 12\ 757$ W

The input data in this case are as follows: $D_{c\max} = 0.08\,\text{m}$; the heaviest duty cutter – low-alloyed non-hardened; $H_B = 175$; $\beta_c = 45°$; $a_{p\max} = 0.003\,\text{m}$; $a_{e\max} = 0.05\,\text{m}$; $V_{\max} \approx 0.33\,\text{m/s}$.

As a result of the calculations a DC motor MP132L is selected with the following basic parameters: $P_{\text{nom}} = 15\,\text{kW}$, $V_{\text{nom}} = 400\,\text{V}$, $I_a = 46\,\text{A}$, $\omega_{\text{nom}} = 104.67\,\text{rad/s}$.

In synthesis of the respective control systems usually two principal approaches to determination of their structure and parameters are applied. The first one consists in compensation of the controlled object time-constants through nested control loops for the respective state vector constituents. Realization of such an approach is done with the method of subordinate control (cascade control structure) [6], [7]. The second approach consists in setting the root locations of the system characteristic equation through introduction of feedbacks for the controlled object state vector constituents. This method is used in synthesis of systems with optimal modal control [8].

A feature of the dual-zone speed control is that the drive system structure changes along the process of regulation and the optimal coordination of zones creates the main control problem. Mathematical modeling and computer simulation offer effective ways to study the electric drive systems in details, in the respective 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.

Using the MATLAB/SIMULINK software package a number of computer simulation models have been developed of drives with dual-zone speed regulation, allowing study at various reference speeds and loads applied to the motor shaft.

Fig. 2 shows a model of DC electric drive system with dual-zone speed regulation, where control shift is a function of the motor back EMF voltage. The notations used are as follows: $G_{sc}(s)$ – transfer function of the speed controller; $G_{c_1c}(s)$ – transfer function of the armature current controller; K_{p_1} and τ_{p_1} – gain and delay of the armature voltage power converter; $R_{1\Sigma}$ – armature circuit resistance; $\tau_{1\Sigma}$ – armature circuit time-constant; K_{c_1f} and τ_{c_1f} – gain and time-constant of the armature current feedback; K_{sf} and τ_{sf} – gain and time-constant of the speed feedback; $G_{ec}(s)$ – transfer function of the back EMF voltage controller; $G_{c_2c}(s)$ – transfer function of the excitation current controller; K_{p_2} and τ_{p_2} – gain and delay of the excitation voltage power converter; $R_{2\Sigma}$ – excitation circuit resistance; $\tau_{2\Sigma}$ – excitation circuit time-constant; K_{c_2f} and τ_{c_2f} – gain and time-constant of the excitation current feedback; K_{ef} and τ_{ef} – gain and time-constant of the back EMF voltage feedback; AVB – absolute value block; K_Φ – coefficient of the magnetic flux curve gradient; c – motor coefficient; 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_1 – armature voltage; I_1 – armature current; T – motor torque; T_l – load torque applied to the motor shaft; J_Σ – total inertia referred to the motor shaft; ω – angular motor speed; V_{er} – back EMF voltage reference signal; V_{ef} – back EMF voltage feedback signal; V_{c_2r} – excitation current reference signal; V_{c_2f} – excitation current feedback signal; V_2 – excitation voltage; I_2 – excitation current; Φ – magnetic flux. The power converter for armature voltage is of reversive type, while the power converter for the field voltage is non-reversive.

The electric drive system consists of two interrelated subsystems:

- Dual-loop subsystem for speed regulation, which includes an external speed loop and a subordinated armature current loop;
- Dual-loop subsystem for back EMF voltage regulation, including external back EMF voltage loop and subordinated excitation current loop.

Control loops opitimization is carried out following the resepctive criteria, providing for the necessary performnce. Controllers tuning is done sequentially, starting from the innermost loops. The armature current is limited to the maximal admissible value of $I_{1\max}$, which provides a maximal motor torque.

If motor speed direction changes, the feedback signal sign of V_{ef} changes also, but the V_{er} signal remains with the same sign. For that reason, to avoid the V_{ef} sign influence, in four-quadrant drive systems an absolute value block AVB is included.

Speed regulation until the value of $\omega \le \omega_{\text{nom}}$ is carried out

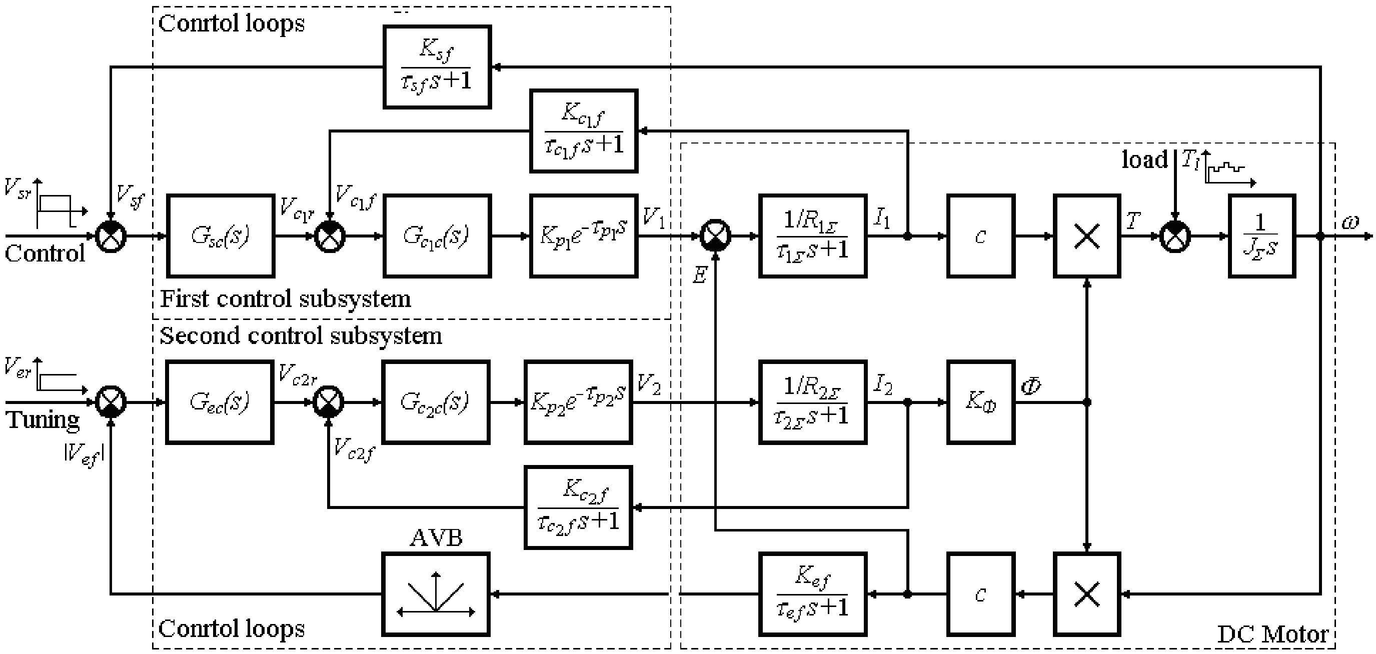

Figure 2: Model of a drive system when the control shift is a function of the motor back EMF voltage

at nominal magnetic flux $(\Phi = \Phi_{\text{nom}})$, at the expense of the armature voltage change. At $\omega > \omega_{\text{nom}}$ the regulation is done through the flux reduction $(\Phi < \Phi_{\text{nom}})$.

Within the entire range, speed is set up by the control signal V_{sr}, while through the tuning signal V_{er} a back EMF voltage, determining the basic speed is defined.

A simplified model of a dual-zone drive system where the control shift is a function of the armature voltage is illustrated in Fig. 3, where the next notations are used: V_{sr} – speed reference signal; V_{sf} – speed feedback signal; $G_{sc}(s)$ – transfer functions of the speed controller; K_{sf} and τ_{sf} – gain and time-constant of the speed feedback; CLB – current limitation block; V_{c_1r} – armature current reference signal; V_{c_1f} – armature current feedback signal; $G_{c_1c}(s)$ – transfer function of the armature current controller; K_{p_1} and τ_{p_1} – gain and time-constant of the armature voltage power converter; K_{c_1f} and τ_{c_1f} – gain and time-constant of the armature current feedback; R_{1_Σ} – armature circuit resistance; τ_{1_Σ} – armature circuit time-constant; c – motor coefficient; E - back EMF voltage; $V_{\varphi r}$ – magnetic flux reference signal; $G_{c_2c}(s)$ – transfer function of the field current controller; SB – switching block; $|V_{v_1f}|$ – armature voltage feedback signal; V_{c_2f} – field current feedback signal; K_{p_2} and τ_{p_2} – gain

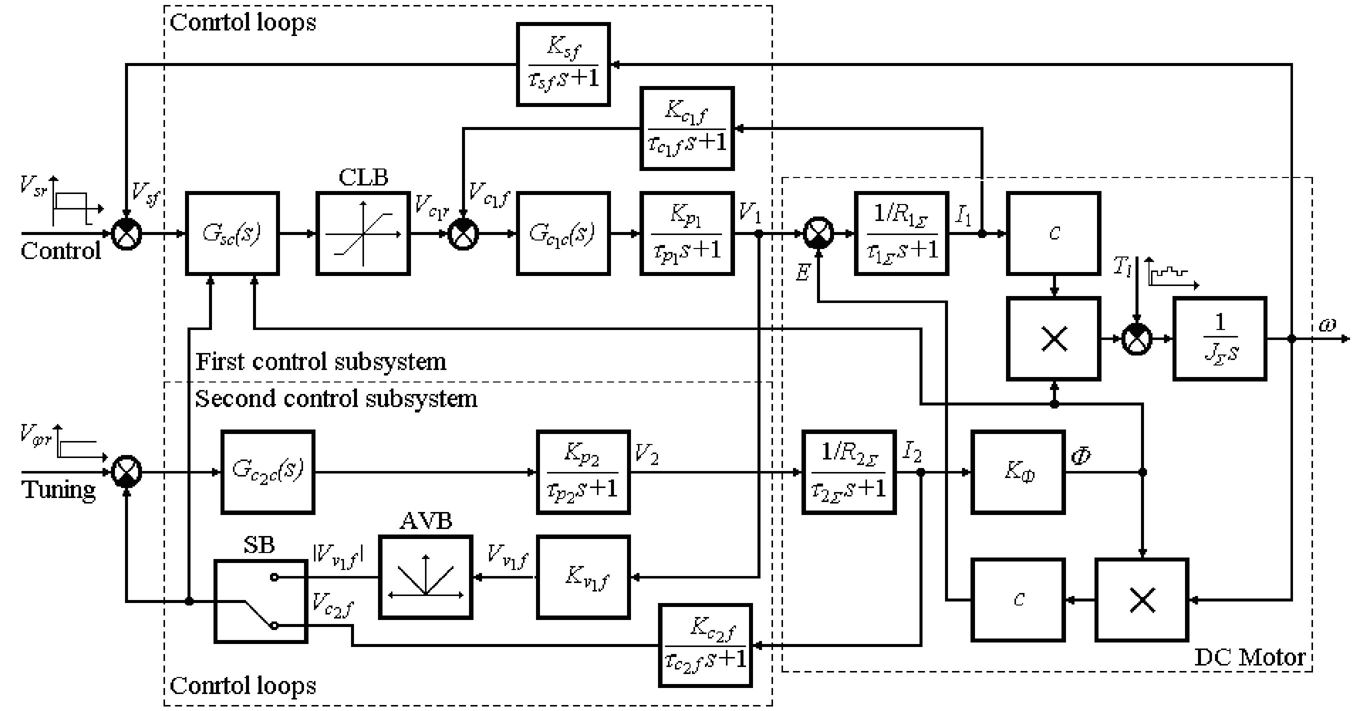

Figure 3: Model of a drive system when the control shift is a function of the armature voltage

and time-constant of the field voltage power converter; AVB – absolute value block; $K_{v_1 f}$ – gain of the armature voltage feedback; R_{2_Σ} – field circuit resistance; τ_{2_Σ} – field circuit time-constant; $K_{c_2 f}$ and $\tau_{c_2 f}$ – gain and time-constant of the field current feedback; K_Φ – coefficient of the magnetic flux curve gradient; Φ – magnetic flux; T – motor torque; T_l – load torque applied to the motor shaft; J_Σ – total inertia referred to the motor shaft.

To improve the electric drive performance in this case an adaptive speed controller with switchable structure is developed. In the second 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 $V_1 = V_{1b}$. Such an approach provides for better static and dynamic characteristics of the driving system.

Motor speed regulation until the voltage value of $V_1 \le V_b$ is carried out at nominal magnetic flux $(\Phi = \Phi_{nom})$, at the expense of the armature voltage change. At $V_1 > V_b$ the regulation is done through the flux reduction $(\Phi < \Phi_{nom})$. Within the entire range, speed is set up by the control signal V_{sr}.

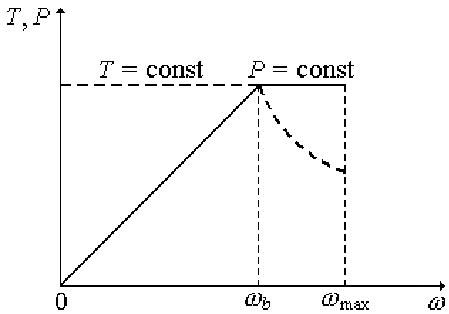

Figure 4: Torque/speed and power/speed diagrams

The respective torque/speed and power/speed diagrams are presented in Fig. 4. As evident, speed control is realized at constant motor torque until the basic speed level ω_b (normally ω_{nom}) is reached. After that, it is carried out at constant power.

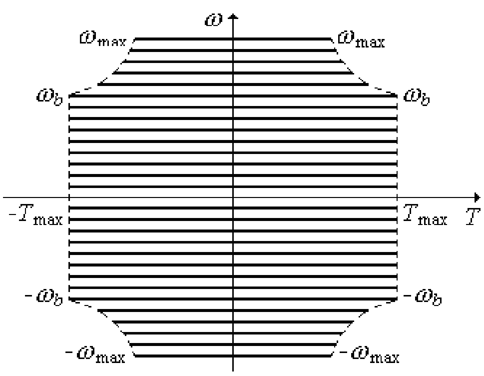

Figure 5: Speed/torque curves of the drive system

Fig. 5 shows speed/torque characteristics of the four-quadrant electric drive system, where ω_{max} is the upper bound of the speed regulation range and T_{max} is the maximal motor torque.

To provide the nessesary experimental studies a laboratory stand for drive loading and measurment of tne controlled variables has been developed. Fig. 6 presents some time diagrams obtained experimentally for both zones of speed regulation at different reference speeds and tuning of the control loops.

The respective reference speeds are as follows: 96 rad/s (Fig. 6(a), 120 rad/s (Fig. 6(b), and 144 rad/s/ (Fig. 6(c).

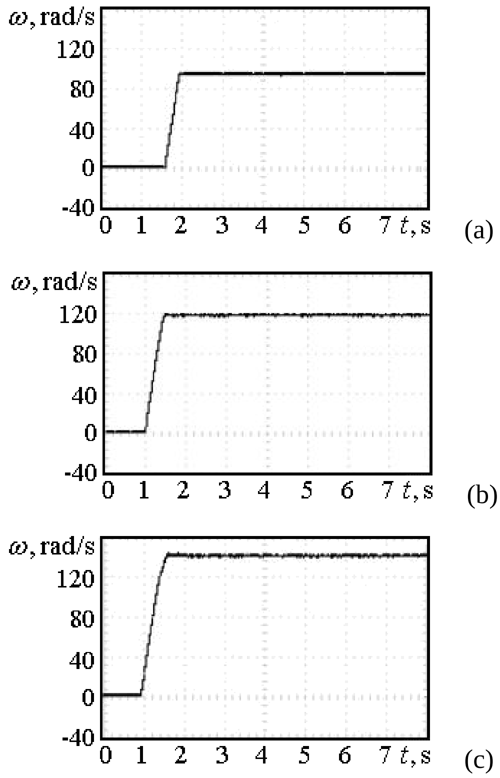

Figure 6: Some experimentally obtained time diagrams

4. Conclusions

The basic requirements for spindle electric drives of a class of milling machines with digital program control are formulated and analyzed.

A methodology for selection of spindle electric drives for these machines is offered. The presented algorithm takes into account the technological process features, the tools used, the processed material, and the mechanical gear type. A concrete example has been presented, illustrating the practical application of this methodology.

Computer simulation models of electric drive systems with dual-zone speed regulation have been developed, allowing studies at various reference speeds and loads applied to the motor shaft.

The research carried out as well as the results obtained can be used in the development of such spindle electric drives for the studied class of machine tools.

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References

[1] M. Mikhov, M. Zhilevski, "Performance Improvement of a Type of Milling Machines", In Proceedings of the International Conference "Research and Development in Mechanical Industry", Vol. 1, pp. 218-227, Kopaonik,

Serbia, 2013, ISBN 978-86-6075-042-8.

[2] M. Mikhov, M. Zhilevski, “Analysis of a Multi-Coordinate Drive System Aiming at Performance Impro-vement”, In Proceedings of the International Conference “Research and Development in Mechanical Industry,” Vol. 2, pp. 1102-1107, Vrnjacka Banja, Serbia, 2012, ISBN 978-86-6075-037-4.

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

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

[5] I. Andonov, Cutting of Metals, Softtrade, Sofia, 2001, ISBN 954-9725-52-9 (In Bulgarian).

[6] M. Mikhov, B. Balev, “Modeling and Optimization of an Electric Drive System with Dual-Zone Speed Regulation,” In Proceedings of the International Scientific Conference on Information, Communication and Energy Systems and Technologies, Vol. 2, pp. 575-578, Nish, Serbia and Montenegro, 2005, ISBN 86-85195-25-X.

[7] M. Mikhov, 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.

[8] M. Mikhov, 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.