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Methodology for Selection of Spindle Drives for Turning Machines

Marin Zhilevski[1], Mikho Mikhov[2]
[1,2]Faculty of Automatics, Technical University of Sofia, Bulgaria
Corresponding Author: Mikho Mikhov

ABSTRACT: This paper presents an approach to selection of spindle electric drives for a class of turning 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. Concrete examples for selection of spindle drives with DC and AC motors are presented, illustrating a practical application of the developed methodology. The research carried out as well as the results obtained can be used in the development of such electric drives with dual-zone speed regulation for the studied class of machine tools.
KEYWORDS: Turning machines, Spindle drive, Speed control, Dual-zone regulation, Selection of spindle drive.

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I INTRODUCTION

The technical potential of modern machine tools depends on both their control systems and the functionality of the respective drives. The role of the electric drives in machine tools increases constantly and currently they affect even the structures of the driven mechanisms. The spindle electric drives are involved in the machining process, significantly affecting the quality of the parts and their productivity.

Compared to other types of drives, the electric ones have a number of 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.

In spindle electric drives 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 distinctive feature of the dual-zone speed regulation is that the system structure changes along the process of regulation. Optimal coordination of speed zones makes a major control problem.

For spindle electric drives with dual-zone speed control both with DC and AC motors are used.

With DC electric drives the armature voltage is regulated at constant magnetic flux in the first zone, while in the second zone the flux is reduced at constant armature voltage or back electromotive force voltage [1], [3], [6], [7]. In synthesis of the respective controllers 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) [1], [3], [6], [8]. 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 modal control [2], [4]. Using an appropriate vector-matrix description of the controlled object, in [7] an optimal modal speed controller for the first zone is synthesized, as well as an adaptive optimal modal controller of the back electromotive force voltage for the second zone.

With the MATLAB/SIMULINK software package a number of 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 [6], [7], [8].

Recently, dual-zone speed regulation systems with AC motors are used applying vector control [9], [10]. The main advantages of such electric drives relate to the easier maintenance of the AC motors.

In this paper the main requirements to spindle drives for a type of turning machines with digital program control are formulated and a methodology for selection of appropriate electric drives is presented. When choosing a suitable spindle 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. Some dual-zone spindle drives with DC and AC motors are presented, illustrating the practical application of the offered approach.

II METODOLOGY FOR SPINDLE DRIVES SELECTION

A. Basic requirements to the spindle drives

Spindle drives must meet the following main requirements:

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

Fig. 1 shows speed/torque characteristics of the four-quadrant electric drive system with dual-zone speed regulation, where $\omega_{\max}$ is the upper bound of the speed range and $T_{\max}$ is the maximum motor torque.

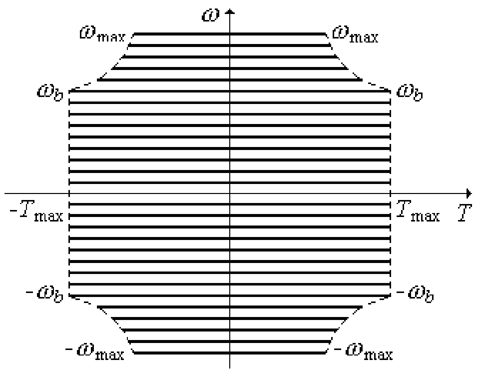


Fig.1: Speed/torque curves of the four-quadrant drive system.

The respective torque/speed and power/speed diagrams are presented in Fig. 2. Speed control is realized at constant motor torque (T = const) until the basic speed level ω_b is reached. After that, it is carried out at constant power (P = const).

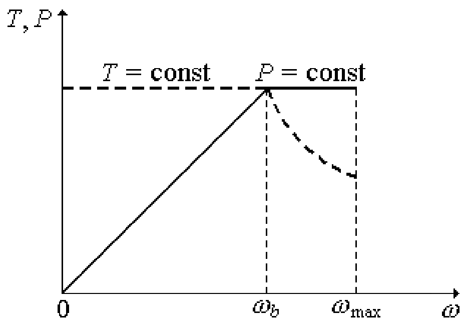


Fig. 2: Torque/speed and power/speed diagrams.

The design of a spindle electric drive for turning machines includes the following basic stages:

1. Development of methodology for selection of a spindle drive rendering an account of the specific features of the technological process, the processed material, as well as the type of the mechanical gear used.
2. Performing calculations corresponding the respective procedures on the methodology.
3. Performing technical and economic analysis of the possible options for selection of electric drives, taking into account the catalog 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 control loops.
8. Carrying out computer simulation studies with various settings of the control loops.
9. Detailed experimental studies 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. 3, where the following notations are used: $D_{mt\max}$ – maximum cutting diameter, which can be worked by the machine; H_B – Brinell hardness of the processed material; $a_{pt\max t}$ – maximum cutting depth of the tool; 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_{spt} – power required only for the spindle electric drive.

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

The tabular data used in this methodology are taken from [11] and [12].

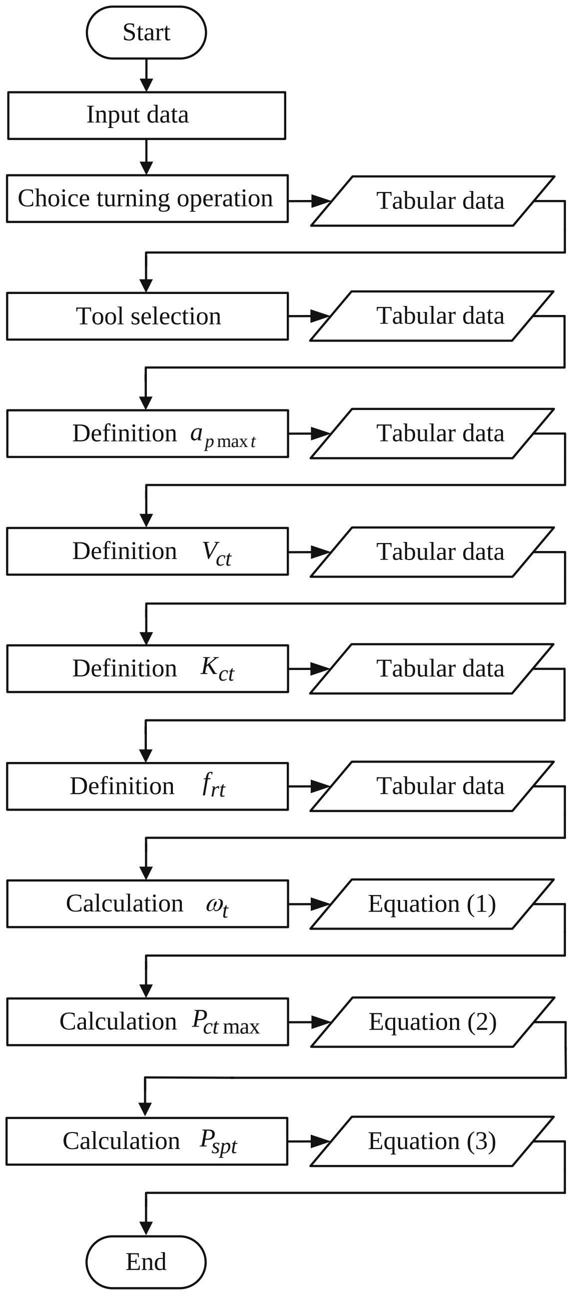


Fig. 3: Block diagram of the algorithm.

The spindle speed is calculated by the following expression [11]:

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

The cutting power, which is necessary for the heaviest operating mode of the machine is calculated by the next equation [11]:

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

Power required for the electric spindle drive is calculated by the expression [5]:

$$P_{sp} = (95 \div 99)\% \times P_{ct\max}. \qquad (3)$$

III PRACTICAL IMPLEMENTATION

The practical implementation of the described methodology renders an account of the specific features of the concrete machine, such as technological process, tools and processed materials.

As examples for using of this methodology, selection of spindle electric drives for a turning machine at cutting of materials with different hardness are presented.

The input data in this case are as follows: the heaviest cutting regime i.e. at low-alloyed steel and aluminium alloys; $D_{mt\max}$ =0.3 m; $\eta = 0.85$. The respective results obtained are presented in Table 1.

After calculation by the developed methodology, the selected motor must have a nominal power of about 10% greater than obtained to compensate for the allowable wear over time.

Table 1: Results from the calculations.

Step	Operation	Low alloyed steel	Aluminium alloys
1.	Determination of H_B	180	60
2.	Turning operation choice	Roughing	Roughing
3.	Tool selection	CoroTurn	CoroTurn
4.	Definition of $a_{pt\max t}$	0.0025 m	0.0025 m
5.	Definition of V_{ct}	4.25 m/s	$\approx$ 11.67 m/s
6.	Definition of K_{ct}	2570	500
7.	Definition of f_{rt}	$\approx 4.7 \times 10^{-5}$ m/s	$\approx 4.7 \times 10^{-5}$ m/s
8.	Calculation of ω_t	$\approx$ 28.33 rad/s	$\approx$ 77.33 rad/s
9.	Calculation of $P_{ct\max}$	$\approx$ 8059.71 W	$\approx$ 4279.8 W
10.	Calculation of P_{spt}	$\approx$ 7656.72 W	$\approx$ 4065.81 W

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.

Table 2: Basic data of the selected drives.

In machining of low alloyed steel is selected DC electric drive with parameters [13]: - DC motor MP132M with nominal data: $P_{nom} = 11$ kW, $\omega_{nom} = 104.67$ rad/s, $V_{nom} = 400$ V, $I_a = 34$ A; - thyristor converter 8EOA 3.
In machining of aluminium alloys is selected AC electric drive with parameters [9] ,[10]: - AC motor DH 10-40 with nominal data: $P_{nom} = 6.3$ kW, $\omega_{nom} = 157$ rad/s, $V_{nom} = 350$ V, $I_{nom} = 15$ A; - power converter KW8.

The required nominal values of the motor power for the presented two materials in the input data are determined as follows:

- for machining of low alloyed steel:

$$P_{tnom} \approx 1.1 \times P_{spt} \approx 8422.37 \text{ W}. \quad (4)$$

- for machining of aluminium alloys:

$$P_{tnom} \approx 1.1 \times P_m \approx 4472.39 \text{ W}. \quad (5)$$

The power values obtained are used for the motor selection from the respective technical catalogues. As a result from the calculations made for these two materials, appropriate DC and AC spindle electric drives were selected. Some of their basic data are presented in Table. 2.

IV EXPERIMENTAL STUDY

A stand for experimental research of electric drives for machine tools was developed, equipped with the necessary measuring and visualization devices (Fig. 4).

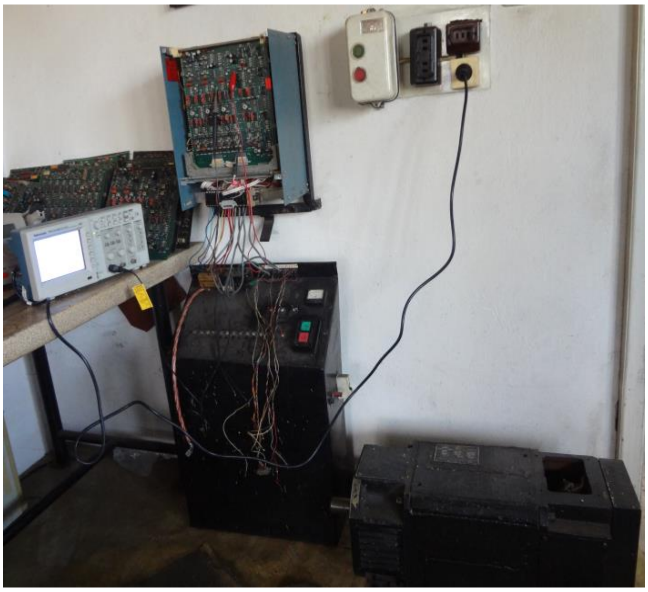
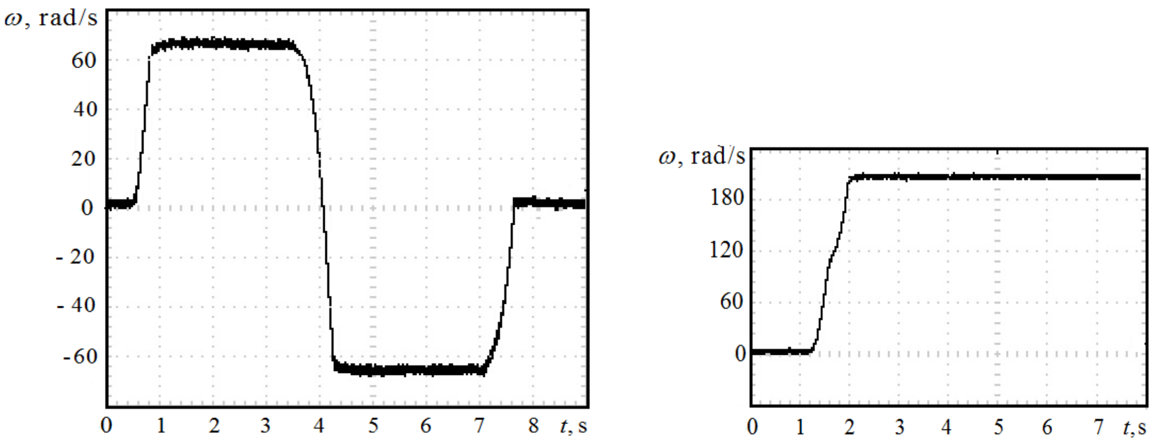


Fig. 4: Experimental study of a spindle electric drive.

On the basis of the formulated requirements, the developed methodology, the selected DC and AC electric drives for a machine of the considered class, detailed experimental study was carried out at different settings of the controllers and operating modes. The following figures presents some of the oscillograms obtained.

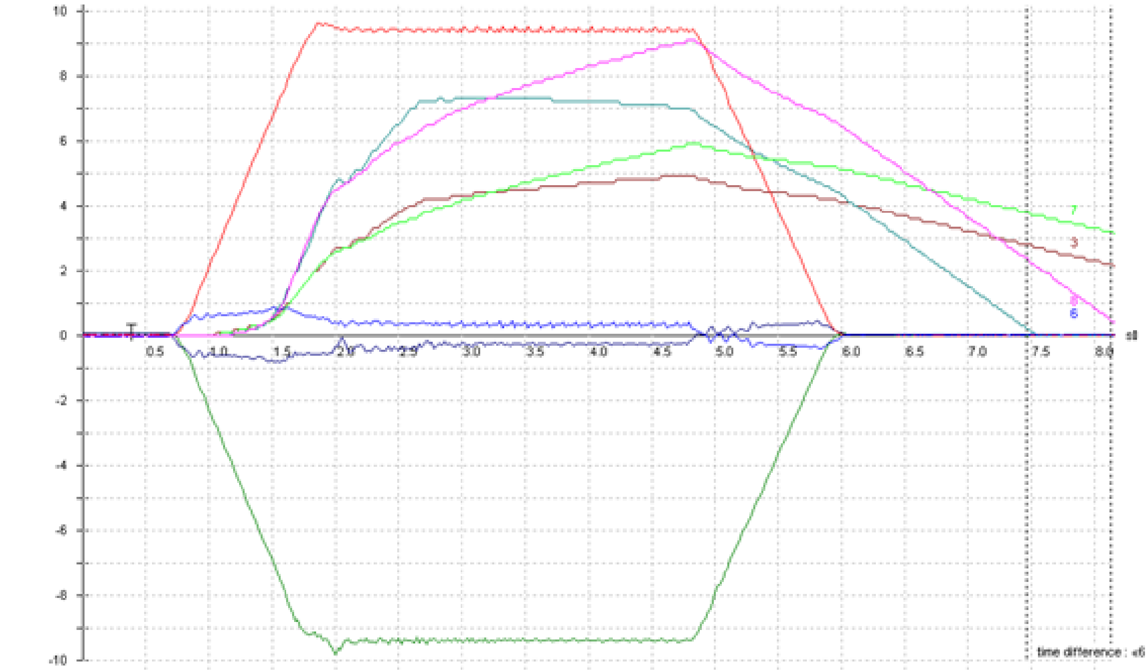


a) **b)**

Fig. 5: Experimentally obtained time diagrams for spindle drive with DC motor.

Fig. 5 shows time diagrams obtained experimentally for both zones of speed regulation at different reference speeds and tuning of the control loops. Fig. 5a presents a time diagram for the first speed zone with direct reverse. The reference speeds are 62.83 rad/s and -62.83 rad/s, respectively. Fig. 5b shows a time diagram for the second zone. In this case the reference speed is 209.44 rad/s.

Fig. 6 presents some time diagrams, obtained experimentally for an AC spindle drive with vector control. The forward and reverse speeds are outlined in red and green respectively. The torque is shown with dark blue line, and the load of the inverter – with light blue line. The set speeds are 53.43 rad/s for each direction of rotation.



	Math	Drive	CH - ID Parameter name	Y-Value1	Y-Value2	Y Scale	Y-Offset	Unit	Hold
✓	O	1 - Drive ...	CH1 - 00040 Velocity feedback value	0.2	-0.2	510	0	1/min	HOLD
✓	O	1 - Drive ...	CH2 - 00084 Torque feedb.val	-0.04	-0.04	20	0	Nm	HOLD
✓	O	1 - Drive ...	CH3 - 33102 Display overload motor	2.2	2.8	1	0	%	HOLD
✓	O	1 - Drive ...	CH4 - 33101 Display overload inverter	0	0.2	1	0	%	HOLD
✓	O	2	CH1 - 00040 Velocity feedback value	0.4	0.3	510	0	1/min	HOLD

Fig. 6: Experimentally obtained time diagrams for spindle drive with AC motor.

Based on the studies realized with various DC and AC electric drives the following practical inferences can be drawn:

- the implemented DC motors have good tuning qualities and provide the specified static and dynamic characteristics for spindle drives. A disadvantage is the presence of the brush collector.
- electric drive systems with AC motors have easier operational maintenance but their price is relatively higher.

V CONCLUSIONS

The basic requirements for spindle drives of a class of turning 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. Concrete examples for selection of spindle drives with DC and AC motors have been presented, illustrating the practical application of this methodology.

The research held as well as the results obtained can be used in the development of such dual-zone electric drives for the studied class of machine tools.

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