IOP Conference Series: Materials Science and Engineering

Optimal selection of feed electric drives for boring machines

To cite this article: M Zhilevski and M Mikhov 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **618** 012003

Optimal selection of feed electric drives for boring machines

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Abstract. In this paper are analyzed and formulated the main requirements for the drive systems of a class of modernized boring machines with digital program control. On this basis, a methodology for optimal selection of feed drives is offered. The respective algorithm takes into account the specific features of the technological process, the treated material, the tools used and their wear, the mechanical gears types and the guides. Concrete examples with DC and AC electric drives are presented, illustrating the practical application of the methodology. 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 with digital program control.

1. Introduction

The technical potential of modern machine tools with digital program control depends on both their control systems and the functionality of the respective drive systems.

To meet the constantly growing requirements, modern electric drives should possess a number of features such as: a wide range of speed regulation; high precision of the respective coordinate control; good dynamics; reliability; economic operation; good communication abilities, etc. The role of the drives in machine tools increases constantly and currently they affect even the structures of the driven mechanisms.

Boring machines are used to mill, drill, bore, cut threads or face turn. They can be horizontal and vertical, which refers to the axis orientation of the machine spindle rotation that provides the primary motion [1 - 4].

A drive system for boring machines includes feed drives, spindle drive and auxiliary drives. For modernization of a class of boring machines with digital program control, two additional controlled axes and a device for angular position of the workpieces are introduced. The goal is to extend the capabilities of these machines to process more complex machine parts and to enhance their performance. In this way, the machines under consideration can be attributed to the class of those with multi- coordinate electric driving systems.

Feed electric drives in boring machines are used to position the workpieces and the cutting tools at the desired location and participate in the machining process. For this reason, their positional accuracy and speed significantly influence the quality and performance of the machine tools with digital program control [5 - 8].

In this paper, the main requirements for the respective drives of a type of boring machines are formulated and on this basis, a methodology for selection of appropriate feed electric drives is developed. In choosing suitable feed drives, a number of essential factors were taken into account, namely: the technological process features, the treated materials, the tools used, the mechanical gears and the respective guides. Examples for selection of feed drives with DC and AC motors are shown, illustrating the practical application of the offered methodology. Some experimental results are presented and discussed.

2. Requirements for the drive system

The block diagram of a drive system for these machines is shown in Fig. 1, where the following notations are used: DPC – digital program control device; ED1 - ED10 – electric drives; G1 - G8 – mechanical gears; L1 - L8 – loads. Each of the presented drive subsystems has specific features and requirements that need to be taken into account in the process of design and study.

The feed drives of the *x*, *y, z, a*, and *c* coordinate axes are used for positioning of the tool and the workpiece at the desired locations and they participate in the machining process. The main requirements for them can be formulated as follows: smooth speed regulation in a wide range; good dynamics; high position accuracy; formation of the necessary position cycles; providing the required torque; reversible speed and torque control; compensation of the disturbances; easy maintenance; reliability; economy.

The spindle drive is involved in the machining process and it should meet the following requirements: dual-zone speed regulation (by constant torque and constant power respectively); high maximum speed; sufficient torque; oriented braking with high accuracy; reversible speed control.

The main requirements for the auxiliary drives can be formulated as follows: angular positioning of the workpiece with high precision; instrument subsystem providing choice of the desired tool with high precision; dosing lubrication of the machine coordinate axes; cooling subsystem with possibility of automatic and manual braking and starting from the control panel.

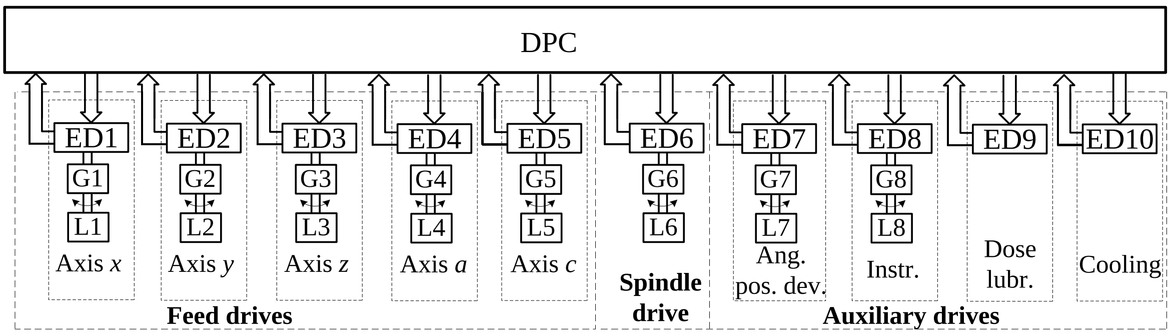


Figure 1. Block diagram of the drive system.

The choice of appropriate feed electric drives for the studied class of machines includes selection of motors, power converters, controllers, sensors and mechanical gears. This problem is extremely important in terms of performance, techno-economic parameters, reliability, etc.

3. Selection of feed drives

A unified approach for the designing process of feed drives for boring machines is applied, including the following basic stages: development of a methodology for optimal choice of these drives; calculations, according to the respective procedures of the methodology; technical and economic analysis of the possible variants of electric drives; modeling and computer simulation of the relevant dynamic and static modes of operation; experimental study to evaluate the actual performance of the drive system.

3.1. Features of the methodology

When choosing an electric drive, it is essential to define the heaviest processing mode of operation, the mass of the coordinate axis and the guides of the machine to optimize the power and the price.

Fig. 2 shows the simplified block diagram of the developed algorithm for selection of feed drives. The following notations are used in this section: D_{gb} – nominal diameter of a ball screw; a_b – acceleration of the ball screw; $D_{mb\max}$ – maximum diameter of the boring machine; $D_{cb\max}$ – maximum diameter of boring instrument; H_B – Brinell hardness of the processed material; $m_{m\max}$ –

maximum mass of the driven mechanism; $V_{b\max}$ – maximum speed of the driven mechanism; V_{cb} – cutting speed; ω_b – spindle speed; V_{fb} – feed speed; f_{rb} – feed per radian; a_{pb} – cutting depth, which is the difference between the uncut and the cut hole radius; K_{cfzb} – specific cutting force, when feeding the tool tooth; η_b – efficiency of the boring machine; $P_{cb\max}$, P_{cbw} – maximum powers needed to perform cutting distributed between feed and spindle drives, respectively without and with taking into account the tool wear; P_{fb} – power required only for the feed drive; F_{fb} – force required only for the feed drive; F_g – force required for the guides; μ_g – friction coefficient of the guides; P_{fbgc} – power required for the feed drive with the required friction power; $P_{fbg\max}$ – maximum power required for the feed drive in maximum cutting speed of the mechanism; h_{bi} – nominal steps of the ball screw; ω_{fbi} – speeds of the motor for different nominal steps of the ball screw; M_{fbi} – motor torques for different nominal steps of the ball screw; $i = 1 \div n$, where n is the variant number.

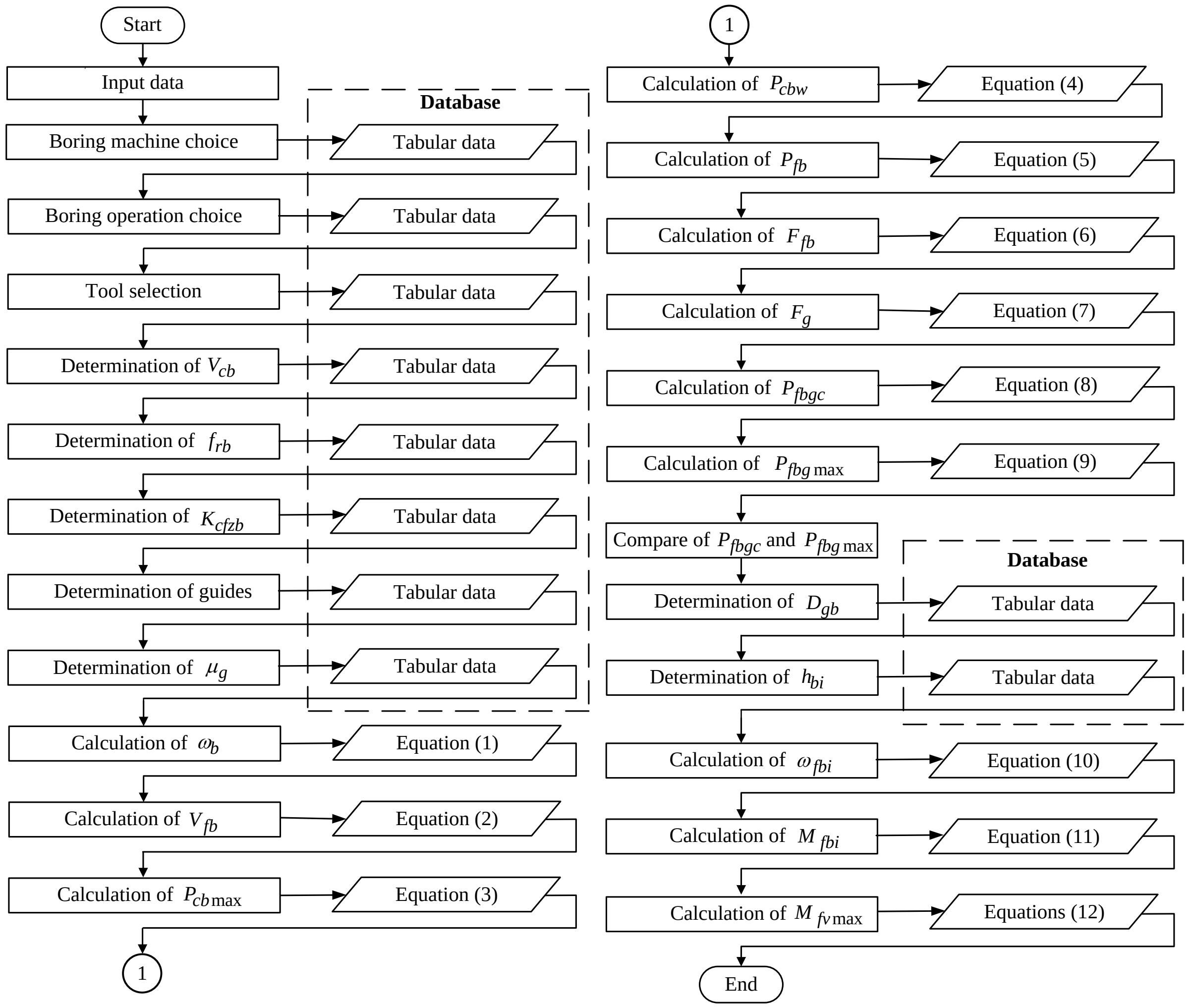


Figure 2. Block diagram of the algorithm for drive selection.

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 [9 - 11].

The tabular data used in this methodology are taken from [9] and [12 - 14]. The choice of boring tools goes through the following several stages: definition of the operation type; selection of a boring system; definition of the boring diameter and hole requirements; choosing of the entering angle; selection of an adaptor and inserts for the tools.

The input data are as follows: the heaviest cutting regime, H_B, $D_{cb\max}$, $D_{mb\max}$, $a_{pb\max}$, $m_{m\max}$, $a_{b\max}$, η_b and $V_{b\max}$.

The spindle speed in the boring process is determined by the expression [12]:

$$\omega_b = \frac{V_{cb} \times 2}{D_{mb\max}} \tag{1}$$

The boring feed speed is calculated using the following equation [12]:

$$V_{fb} = f_{rb} \times \omega_b \tag{2}$$

The maximum power needed to perform cutting, distributed between both feed drive and spindle drive without taking into account the tool wear, is calculated by the next expression [12]:

$$P_{cb\max} = \frac{V_{cb} \times a_{pb\max} \times f_{rb} \times K_{cfzb} \times 2\pi \times 10^6}{\eta_b} \times (1 - \frac{a_{pb\max}}{D_{cb\max}}) \tag{3}$$

The maximum power needed to perform cutting, distributed between both feed drive and spindle drive with taking into account the tool wear, is determined by the equation [12]:

$$P_{cbw} = (1.1 \div 1.3) \times P_{cb\max} \tag{4}$$

The power required only for the feed drive is determined as follows [15]:

$$P_{fb} = (1 \div 5)\% \times P_{cbw} \tag{5}$$

The force required for the feed drive is determined as follows [16]:

$$F_{fb} = \frac{P_{fb}}{V_{fb}} \tag{6}$$

The force required for guides of the feed drive is determined by the expression [9]:

$$F_g = m_{m\max} a_{b\max} \mu_b \tag{7}$$

The power required for the feed drive taking into the guides, is determined as follows [16]:

$$P_{fbgc} = (F_g + F_{fb}) V_{fb} \tag{8}$$

The power required for the feed drive in rapid travel for positioning, is determined as follows [16]:

$$P_{fbg\max} = F_g V_{fb\max} \tag{9}$$

The motor speeds for different nominal steps of the ball screw are calculated as follows [16]:

$$\omega_{fbi} = \frac{V_{fb\max} \times 2 \times \pi}{h_{bi}} \tag{10}$$

The torques of the motor for different nominal steps of the ball screw in the cutting process are determined by the following equation [16]:

$$M_{fbi} = \frac{P_{fbgc}}{\omega_{fbi}} \tag{11}$$

The torques of the motor for different nominal steps of the ball screw in maximum feed speed are determined by the following equation [16]:

$$M_{fv\max i} = \frac{P_{fbg\max}}{\omega_{fbi}} \tag{12}$$

3.2. Practical application

The offered methodology for drives selection takes into account the specific features of the technological processes, the processed materials, the tools used and their wear, the guides, as well as the mechanical gear types. It gives opportunity for choice of motors, power converters, mechanical gears and sensors.

Fig. 3 shows a diagram, illustrating the elements used for spindle and axis z drives of the studied machine. The notations used are as follows: DPC – digital program control device; 1 – position sensor for z axis; 2 – motor for z axis; 3 – coupling between the motor and the ball screw for z axis; 4 – ball screw for z axis; 5 – guides for z axis; 6 – speed sensor for the spindle drive; 7 – spindle motor; 8 – coupling between the spindle motor and gearbox; 9 – gearbox for the spindle drive; 10 – boring instrument; 11 – driven mechanism (work desk for the workpiece); 12 – processed workpiece; h_{bz} – nominal steps of the ball screw for z axis; D_{gbz} – nominal diameter of the mechanical gear made by a ball screw for z axis; V_{bz} – speed of the z axis; F_{gz} – force required for the guides of the z axis; F_{fbz} – force for the feed drive in the cutting process of z axis.

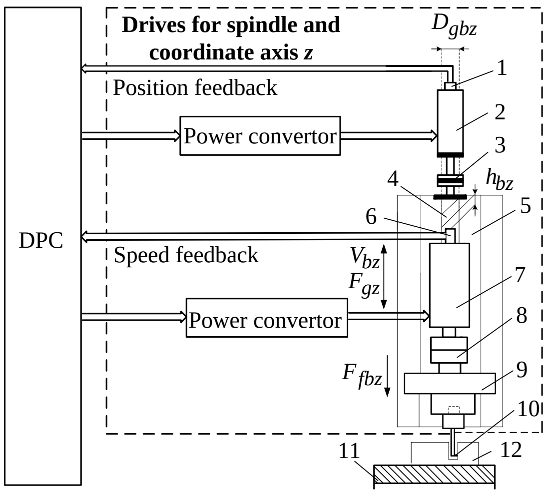


Figure 3. Diagram of the elements used for spindle and axis z drives.

Some examples of using this methodology for selection of feed electric drive for cutting materials with different hardness are presented below.

The input data are as follows: the heaviest cutting regime of operation – at unalloyed steel with $H_B = 170$ and cast iron with $H_B = 130$; $D_{mb\max} = 0.05$ m, $D_{cb\max} = 0.04$ m, $a_{pb\max} = 0.002$ m, $m_{m\max} = 500$ kg, $a_{b\max} = 10$ m/s, $\eta_b = 0.85$ and $V_{b\max} = 0.5$ m/s. The results are given in Table 1.

Table 1. Results from the calculations.

Step	Operation	Unalloyed steel	Cast iron
1.	Boring machine choice	Vertical	Vertical
2.	Boring operation choice	Roughing	Roughing
3.	Tool selection	Core 820	Core 820

Table 1. Results from the calculations (Cont.).

4. Determination of V_{cb} [m/s]	≈ 3.17	≈ 5
5. Determination of f_{rb} [m/rad]	3.1×10^{-5}	6.3×10^{-5}
6. Determination of K_{cfzb} [MPa]	2200	940
7. Determination of guides	Rolling	Rolling
8. Determination of μ_g	0.003	0.003
9. Calculation of ω_b [rad/s]	126.8	200
10. Calculation of V_{fb} [m/s]	3.93×10^{-3}	12.6×10^{-3}
11. Calculation of $P_{cb\max}$ [W]	3034.86	4156.55
12. Calculation of P_{cbw} [W]	3338.34	4572.2
13. Calculation of P_{fb} [W]	166.9	228.6
14. Calculation of F_{fb} [N]	42472.5	18142.9
15. Calculation of F_g [N]	15	15
16. Calculation of P_{fbgc} [W]	166.98	228.8
17. Calculation of $P_{fbg\max}$ [W]	7.5	7.5
18. Compare of P_{fbgc} and $P_{fbg\max}$	$P_{fbgc} > P_{fbg\max}$	$P_{fbgc} > P_{fbg\max}$
19. Determination of D_{gb} [m]	0.04	0.025
20. Determination of h_{bi} [m]	$h_{b1}=0.005$ $h_{b2}=0.01$ $h_{b3}=0.02$ $h_{b4}=0.04$	$h_{b1}=0.005$ $h_{b2}=0.01$ $h_{b3}=0.02$
21. Calculation of ω_{fb_i} [rad/s]	$\omega_{fb_1}\approx 628$; $\omega_{fb_2}\approx 314$; $\omega_{fb3}\approx 157$; $\omega_{fb4}\approx 78.5$	$\omega_{fb_1}\approx 628$; $\omega_{fb_2}\approx 314$; $\omega_{fb3}\approx 157$
22. Calculation of M_{fb_i} [Nm]	$M_{fb_1}\approx 0.27$; $M_{fb_2}\approx 0.53$; $M_{fb_3}\approx 1.06$; $M_{fb_4}\approx 2.12$	$M_{fb_1}\approx 0.36$; $M_{fb_2}\approx 0.72$; $M_{fb_3}\approx 1.53$
23. Calculation of $M_{fv\max_i}$ [Nm]	$M_{fv\max_1}\approx 0.01$; $M_{fv\max_2}\approx 0.02$; $M_{fv\max_3}\approx 0.05$; $M_{fv\max_4}\approx 0.01$	$M_{fv\max_1}\approx 0.01$; $M_{fv\max_2}\approx 0.02$; $M_{fv\max_3}\approx 0.05$

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

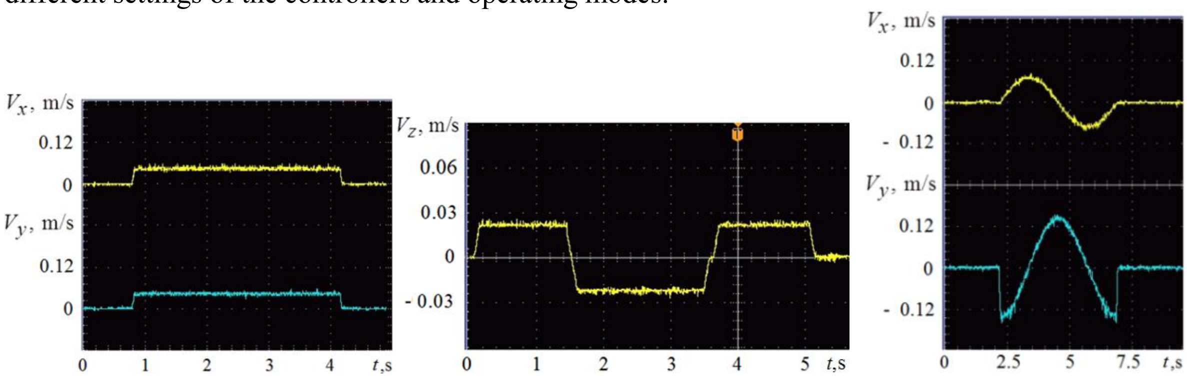
Table 2. Data of the selected feed drives.

Elements	In machining of unalloyed steel	In machining of cast iron
Ball screw	diameter 0.04 m with step 0.02 m	diameter 0.025 m with step 0.01 m
Motor	DC motor PI10.06: $M_{nom}=1.6$ Nm $\omega_{nom}=314$ rad/s	AC motor DS4: $M_{nom}=1.6$ Nm, $\omega_{nom}=439.64$ rad/s
Power convertor	model SA-12	model KW2
Position sensor	encoder	resolver

As a result of the calculations made for these two materials, appropriate DC and AC electric drives were chosen from [17 - 21]. Some of their basic parameters are presented in Table 2.

4. Experimental studies

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



a) *b)* *c)*

Fig. 4. Time diagrams for feed drives with DC motors.

Some experimentally obtained oscillograms with feed DC and AC electric drives are presented respectively in Fig. 4 and Fig. 5.

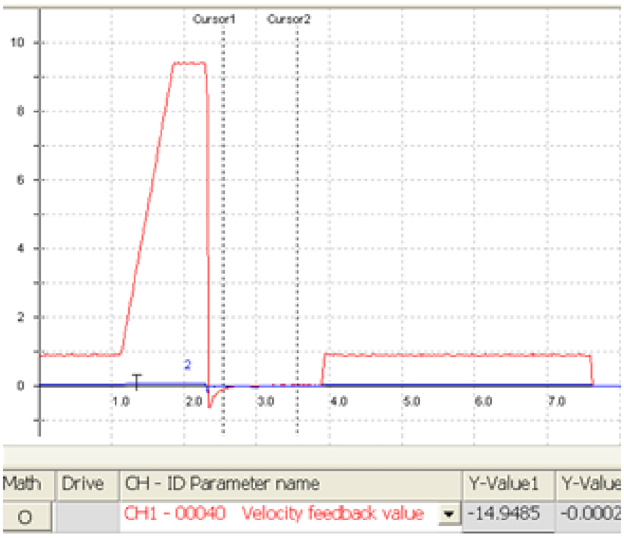


Figure 5. Experimentally obtained time diagram for an implemented feed electric drive with AC motor.

Fig. 4*a* and 4*b* show speed trajectories along the two-coordinate drive *x-y* and the axis z. Fig. 4*c* presents circular interpolation with the two-coordinate drive *x-y*. The selected mechanical gears are of ball-screw type with the following coefficients: $K_{gx} = K_{gy} = K_{gz} = 10$ mm/rev $\approx 1.6\text{x}10^{-3}$ m/rad.

Fig. 5 presents a time diagram, obtained experimentally for an implemented feed AC electric drive with vector control. In this case the respective velocity feedback signal [V] is displayed as a function of the time [s].

Based on the studies carried out with DC and AC electric drives the following practical inferences can be drawn: the implemented DC drives have good tuning qualities and provide the necessary static and dynamic characteristics, however a disadvantage is the presence of the brush collector; electric drives with AC motors have easier operational maintenance but their price is relatively higher.

5. Conclusion

The basic requirements for the drive systems of a class of boring machines with digital program control are formulated. A methodology for optimal selection of feed drives is offered and some examples with DC and AC electric drives are described.

The developed algorithm takes into account the technological process, the tools used, the mechanical gears and the guides.

Experimental results with implemented feed electric drives are presented and analyzed.

The research held and the results obtained can be used in the choice of such drives for the studied class of machine tools.

Acknowledgments

This work is supported by the Technical University of Sofia, Bulgaria under Research Project No. 191PR0002-08/2019.

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