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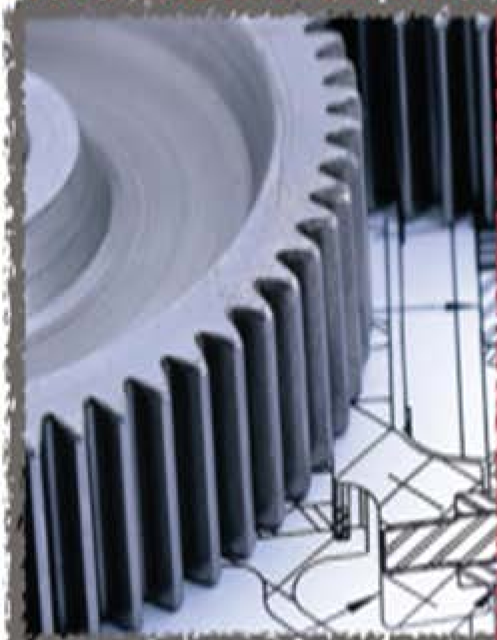

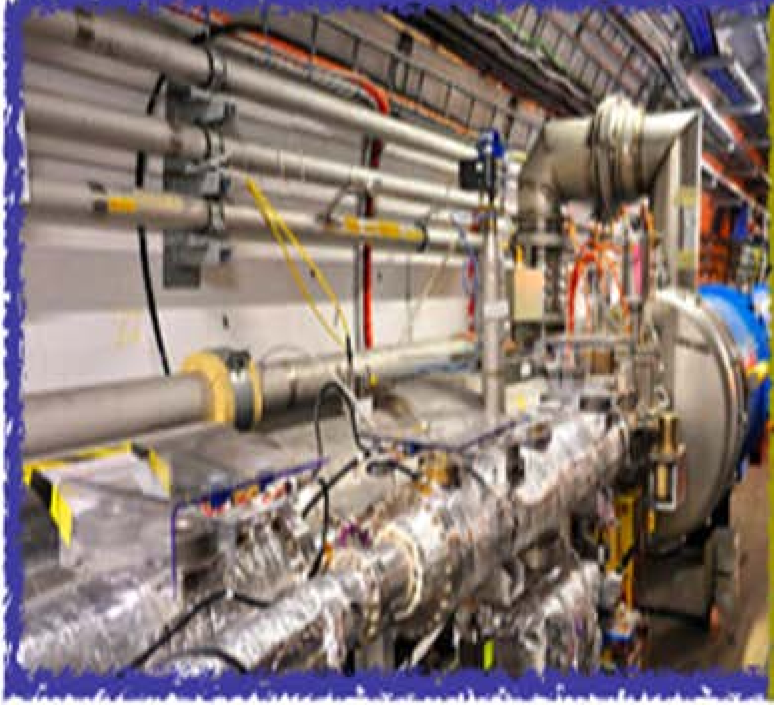

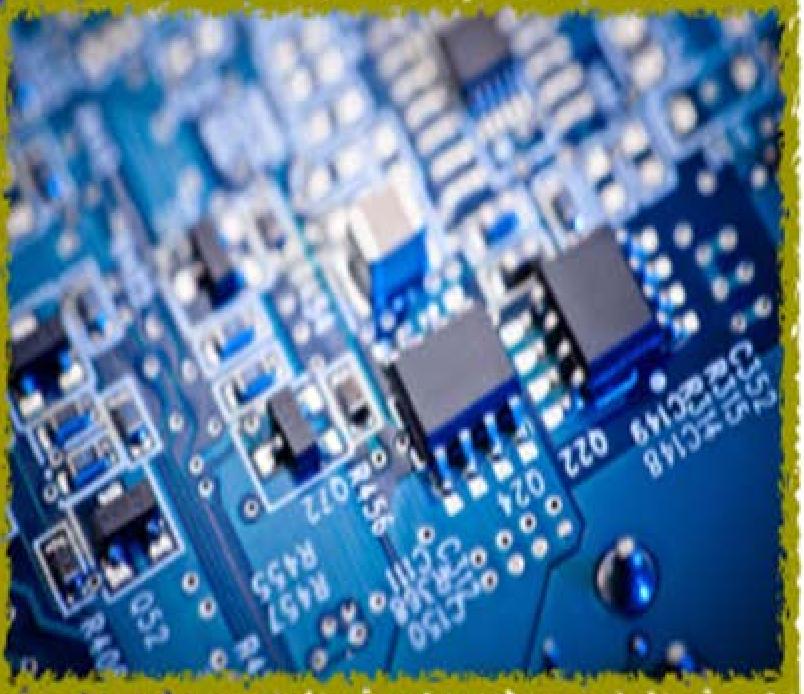

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Study of Electric Drives for Rotary Table of Milling Machines

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***Abstract*—This paper describes a methodology for selection of electric drives for rotary table of milling machines with digital program control. The offered algorithm takes into account the technological process features, the tools used, the processed material, as well as the mechanical gear type. Actual examples have been presented illustrating the practical implementation of the offered methodology. An improved structure of rotary table has been developed. The research carried out and the results obtained can be used in the development of such electric drives for the studied class of machine tools.**

***Keywords*—milling machine; rotary table; electric drive; position control**

I. INTRODUCTION

For modernization of a type of milling machines two additional controlled axes have been applied, namely a table rotation as axis 4 and rotary table tilting as axis 5. 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 those with multi-coordinate electric drive systems [1].

The corresponding electric drives in this case are as follows: 1 – for *x* coordinate axis; 2 – for *y* coordinate axis; 3 – for *z* coordinate axis; 4 – for table rotation; 5 – for table tilting; 6 – for spindle.

Various electric drives are analyzed to choose appropriate solutions meeting the static and dynamic characteristics of the respective machine coordinates, [2], [3], [4], [5], [6].

Electric drives for some coordinate axes have been studied by means of computer simulation and experimental research in [7], [8], [9], [10].

In this paper the main requirements to the necessary electric drives for rotary table are formulated and a methodology for selection is presented. Comparative analysis of different versions has been carried out aiming at performance improvement. Experimental results are presented and discussed.

II. METODOLOGY FOR ELECTRIC DRIVES SELECTION

A simplified block diagram of the multi-coordinate driving system under consideration is shown in Fig. 1. The notations are as follows: DPC – digital program control device; ED1 - ED6 – electric drives for the respective coordinate axes; G1 - G6 – mechanical gears; L1 - L6 – loads.

The development of electric drives for rotary table includes the following basic stages:

1. Formulation of the requirements.
2. Selection of electric drives for rotation and tilting.
3. Synthesis of the control system.
4. Analysis by modeling and computer simulation.
5. Experimental research.

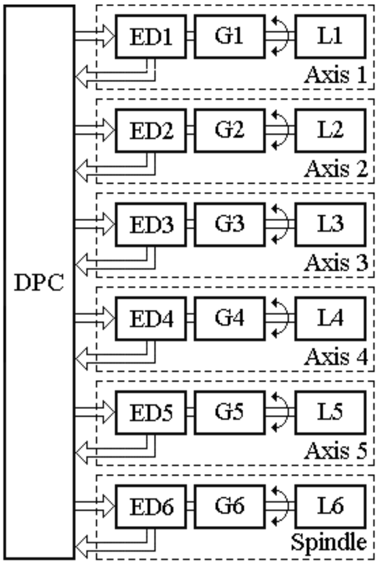


Fig. 1. *Block diagram of the multi-coordinate drive system.*

The main requirements to the electric drives concerning rotary table can be formulated as follows:

- formation of the necessary motion trajectories;
- acquiring maximum starting torque to ensure good dynamics;
- providing reversible speed control;
- compensation of disturbances.

The simplified block diagram of the methodology algorithm is presented in Fig. 2 and Fig. 3 where the notations are as follows: g_{rt} – gear coefficient; $D_{c\,\max}$ – maximum cutting diameter, which can be used by the machine; $D_{rt\max}$ – maximum diameter of the working area of rotary table; H_B – Brinell hardness of the processed material; β_c – cutting edge angle of the tool; $a_{p\max}$ – maximum cutting depth of the tool; $a_{e\max}$ – maximum width of cut; $\omega_{rt\max}$ – maximum speed of the driven mechanism; z – number of edges in the tool; f_z – feed per tooth of the tool; $b_{\max}$ – maximum chip thickness; V_c – cutting speed; ω – spindle speed; ω_{frt} – table feed of drive mechanism in milling operation; b_{av} – average chip thickness; k_{c1} – normalized relative cutting force, depending on the material nature; ψ – exponent depending on the material nature; k_c – relative cutting force; $P_{crt\max}$ – maximum power needed to perform milling, distributed between both rotary feed electric drive and spindle electric drive; P_{frt} – power required for the rotary feed electric drive; ω_{mrt} – speed of the search motor at set rate of mechanical gear; M_{mrt} – torque of the search motor at set rate of mechanical gear.

The input data in this case are as follows: direct coupling between motor and worm gear with the gear coefficient g_{rt}; maximum cutting diameter $D_{c\max}$; heaviest regime of cut machining; parameters $D_{rt\max}$, H_B, β_c, $a_{p\max}$, $a_{e\max}$ и $\omega_{rt\max}$.

The tabular data used in this methodology are taken from [11], [12] , [13].

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

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

The feed speed of the rotary table driving mechanism is calculated as follows [11]:

$$\omega_{frt} = \frac{f_z \times \omega \times z}{\pi \times D_{rt}} \tag{2}$$

The average chip thickness, provided that $\frac{a_{e\max}}{D_{c\max}} < 0.1$, is calculated by next equation [11]:

$$b_{av} = f_z \times \sqrt{\frac{a_{e\max}}{D_{c\max}}} \tag{3}$$

The average chip thickness, when the ratio $\frac{a_{e\max}}{D_{c\max}} \geq 0.1$ is calculated as follows [11]:

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

The relative cutting force for the selected material is calculated by the following equation [11]:

$$k_c = k_{c_1} \times b_{av}{}^{-\Psi} \tag{5}$$

The cutting power which is necessary to carry out milling in the heaviest operating mode is calculated by the next expression [11]:

$$P_{crt\max} = \frac{a_{p\max} \times a_{e\max} \times \omega_{frt} \times D_{rt} \times k_c \times 10^6}{2} \tag{6}$$

This power is distributed between both rotary feed electric drive and spindle electric drive.

The power required for the rotary feed electric drive is calculated by the equation [14]:

$$P_{frt} = (1 \div 5)\% \times P_{c\max} \tag{7}$$

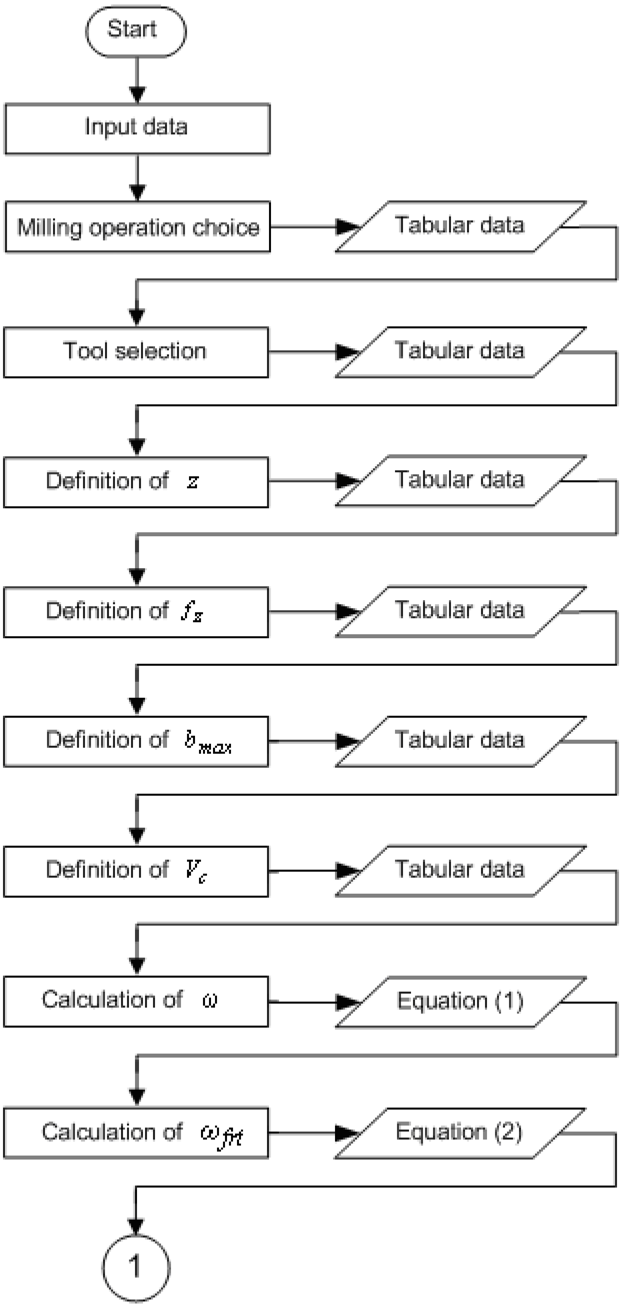


Fig. 2. *Block diagram of the algorithm.*

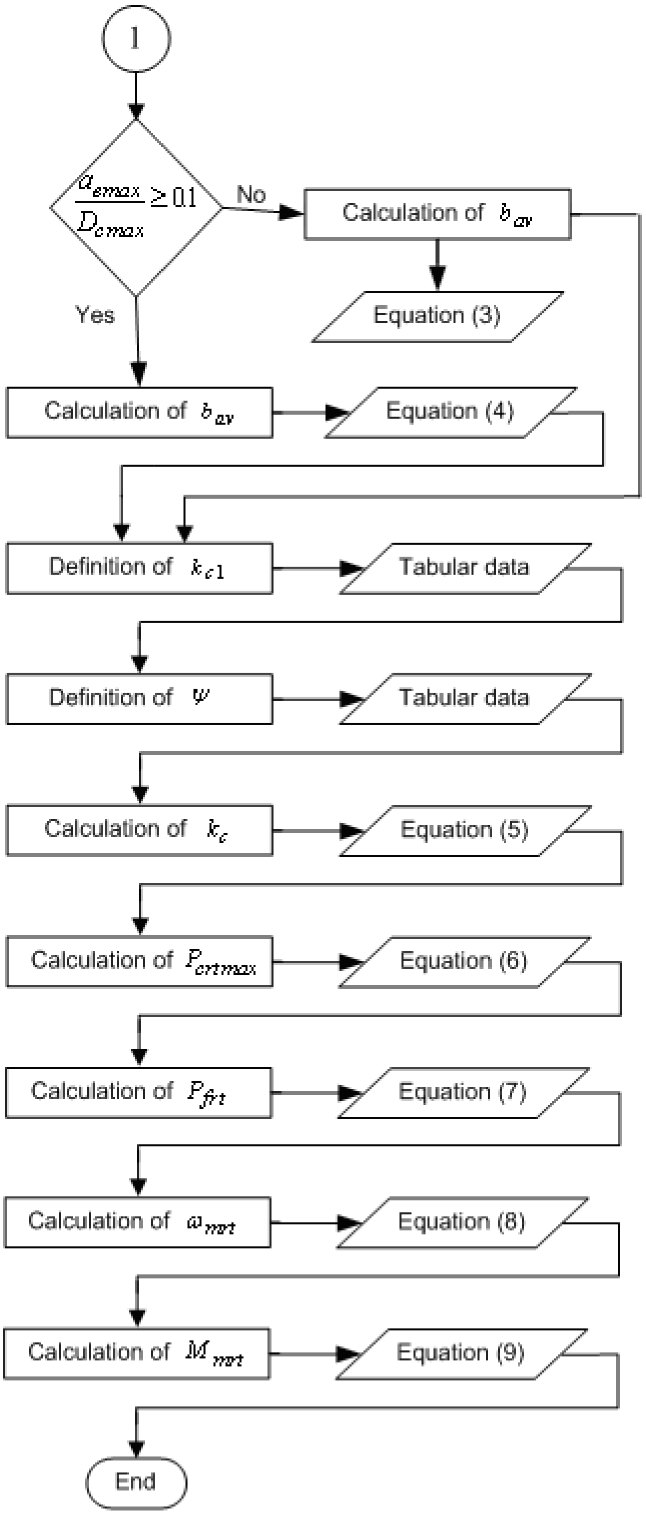


Fig. 3. *Block diagram of the algorithm (contin.).*

The following equation determines the motor speed at a set gear coefficient [13]:

$$\omega_{mrt} = \frac{\omega_{rt\max}}{g_{rt}} \tag{8}$$

The motor torque at this speed value is calculated by the expression [13]:

$$M_{mrt} = \frac{P_{frt}}{\omega_{rtm}} \tag{9}$$

The so determined motor torque can be increased by about 10% for greater reliability of the respective electric drive.

III. PRACTICAL IMPLEMENTATION

The practical application of the offered methodology is illustrated by examples of selection of electric drives for the two coordinate axes while processing of materials of different hardness. The respective calculation results are presented in Table I and Table II.

The input data for the fourth axis are as follows: direct coupling motor and worm gear with coefficient $g_{rt4} = 2^0/\text{rev} \approx 0.00556$; $D_{c\max} = 0.08\,\text{m}$; heaviest regime of cut machining for aluminum alloy and low-alloyed steel; $D_{rt\max} = 0.4\,\text{m}$; $a_{p\max} = 0.002\,\text{m}$; $a_{e\max} = 0.05\,\text{m}$; $\omega_{rt\max 4} \approx 1.05\,\text{rad/s}$.

TABLE I. RESULTS FOR AXIS 4.

№	Operation	Aluminum alloy	Low-alloyed steel
1.	Definition of H_B	130	175
2.	Milling operation choice	Face milling	Square shoulder face milling
3.	Definition of β_c	45°	90°
4.	Tool selection	CoroMill 245	CoroMill 290
5.	Definition of Z	6 teeth	6 teeth
6.	Definition of f_z	0.0002 m	0.00025 m
7.	Definition of $b_{\max}$	0.00014 m	0.00025 m
8.	Definition of V_c	4.58 m/s	2.75 m/s
9.	Calculation of ω	1145 rad/s	68.75 rad/s
10.	Calculation of ω_{frt}	0.11 rad/s	0.082 rad/s
11.	Calculation of $a_{e\max}/D_{c\max}$	0.625	0.625
12.	Calculation of b_{av}	0.18 mm	0.23 mm
13.	Definition of k_{c_1}	700 MPa	1700 MPa
14.	Definition of ψ	0.25	0.25
15.	Calculation of k_c	1067.1 MPa	2451 MPa
16.	Calculation of $P_{crt\max}$	2334 W	4023 W
17.	Calculation of P_{frt}	116.68 W	201.14 W
18.	Calculation of ω_{mrt}	188.85 rad/s	188.85 rad/s
19.	Calculation of M_{mrt}	0.62 Nm	1.1 Nm

After calculations for the fourth coordinate axis the motor torques are recalculated for both processed materials, given in the input data:

- for machining of aluminum alloy:

$$M_{mrtnom} \approx 1.1 \times M_{mrt} \approx 0.682\ \text{Nm} \tag{10}$$

- for machining of low-alloyed steel:

$$M_{mrtnom} \approx 1.1 \times M_{mrt} \approx 1.21\ \text{Nm} \tag{11}$$

The input data for the fifth axis are as follows: direct coupling between motor and worm gear with coefficient $g_{rt5} = 3^0/\text{rev} \approx 0.00833$; $D_{c\max} = 0.08\,\text{m}$; heaviest regime of cut machining for aluminum alloy and gray cast iron; $D_{rt\max} = 0.4\,\text{m}$; $a_{p\max} = 0.002\,\text{m}$; $a_{e\max} = 0.05\,\text{m}$; $\omega_{rt\max 5} \approx 0.90\,\text{rad/s}$.

TABLE II. RESULTS FOR AXIS 5.

№	Operation	Aluminum alloy	Gray cast iron
1.	Definition of H_B	130	245
2.	Milling operation choice	Face milling	Square shoulder face milling
3.	Definition of β_c	45°	90°
4.	Tool selection	CoroMill 245	CoroMill 290
5.	Definition of z	6 teeth	6 teeth
6.	Definition of f_z	0.0002 m	0.00025 m
7.	Definition of $b_{\max}$	0.00014 m	0.00025 m
8.	Definition of V_c	4.58 m/s	2.58 m/s
9.	Calculation of ω	114.5 rad/s	64.50 rad/s
10.	Calculation of ω_{frt}	0.11 rad/s	0.077 rad/s
11.	Calculation of $a_{e\max}/D_{c\max}$	0.625	0.625
12.	Calculation of b_{av}	0.18 mm	0.23 mm
13.	Definition of k_{c_1}	700M Pa	1100 MPa
14.	Definition of ψ	0.25	0.28
15.	Calculation of k_c	1067.1 MPa	1657.1 MPa
16.	Calculation of $P_{crt\max}$	2333.6 W	2551.7 W
17.	Calculation of P_{frt}	116.68 W	127.58 W
18.	Calculation of ω_{mrt}	108.04 rad/s	108.04 rad/s
19.	Calculation of M_{mrt}	0.93 Nm	1.2 Nm

After calculations for the fifth coordinate axis the motor torques are recalculated for the respective processed materials:

- for aluminum alloy:

$$M_{mrtnom} \approx 1.1 \times M_{mrt} \approx 1.02\ \text{Nm} \qquad (12)$$

- for gray cast iron:

$$M_{mrtnom} \approx 1.1 \times M_{mrt} \approx 1.32\ \text{Nm} \qquad (13)$$

After the calculations performed, appropriate electric drives for both additional coordinate axes are selected. The respective calculation results are presented in Table III [15], [16], [17], [18].

IV. IMPROVED CONSTRUCTION OF ROTARY TABLE

The rotary table is an operating device, which can be involved directly or indirectly in the machining process, depending on the workpiece geometry and the described trajectory of the tool. In the first case the workpiece placed on the table work area is rotated during the milling operation. In the second case it is positioned at the selected angle and remains stationary.

TABLE III. SELECTED DRIVES.

For axis 4 (rotation)
For processing of aluminum alloy a synchronous electric drive with the following parameters is selected: - worm gear with coefficient: $g_{rt4} = 2^0/\text{rev} \approx 0.00556$; - synchronous motor - model DT4-1-10 with the following nominal data: $M_{nom} = 1\,\text{Nm}$, $\omega_{nom} = 418.68\,\text{rad/s}$ with integrated encoder – type of resolver; - power converter – model KW2 of AMK.
For processing of low alloy steel a DC electric drive with the following parameters is selected: - worm gear with coefficient: $g_{rt4} = 2^0/\text{rev} \approx 0.00556$; - DC motor - model PI 10.06 with nominal data: $M_{nom} = 1.6\,\text{Nm}$, $\omega_{nom} = 314\,\text{rad/s}$; - power converter - model SA -12; - encoder – model 7L.
For axis 5 (tilting)
For processing of aluminum alloy a DC electric drive with the following parameters is selected: - worm gear with coefficient: $g_{rt5} = 3^0/\text{rev} \approx 0.00833$; - DC motor - model PI 10.08 with nominal data: $M_{nom} = 2\,\text{Nm}$, $\omega_{nom} = 314\,\text{rad/s}$; - power converter - model SA -12; - encoder – model 7L.
For processing of gray cast iron a stepping electric drive with the following parameters is selected: - worm gear with coefficient: $g_{rt5} = 3^0/\text{rev} \approx 0.00833$; - stepper motor - model EzM-86M-A with nominal data: $M_{nom} = 4\,\text{Nm}$, $\omega_{nom} = 314\,\text{rad/s}$; - power converter - model Ezi- Servo ; - encoder – resolution of 10 000 imp./rev..

The proposed improved structure of rotary table is illustrated in Fig. 4, where the notations are as follows: 1 – electromagnet; 2 – springs; 3 – pressure disc; 4 – clutch disc; 5 – position sensor; 6 – electrical motor; 7 – worm wheel; 8 – coupling between motor and worm wheel; 9 – worm screw; 10 – shaft; 11 – work area of the rotary table.

A feature of the presented mechanism is that all elements, namely electromagnet, pressure and clutch discs, worm wheel, as well as the working area of the rotary table, are located on one shaft.

This construction can be used at processing with direct or indirect involvement of the rotary table.

The main advantages of the proposed improved construction can be formulated as follows:

- better stability of the entire coordinate axis during mechanical processing;
- higher reliability;

- positioning with higher accuracy;
- longer of service life;
- easier control of the improved mechanism;
- reduced influence of the electric drive used.

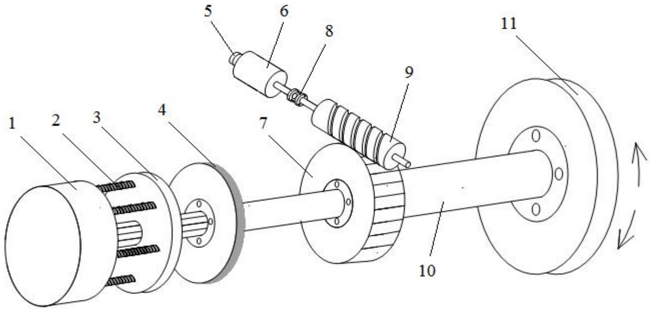
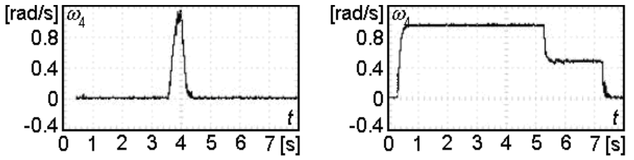


Fig. 4. *Improved construction of the rotary table.*

The mechanical part for the fifth coordinate axis is similar to the described one and it can be subject to the same improvement.

V. EXPERIMENTAL RESULTS

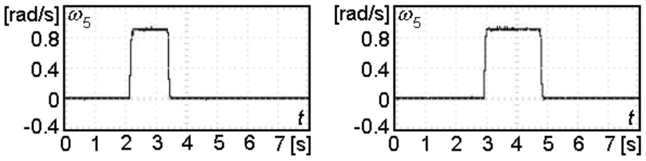
Some experimentally obtained oscillograms for axis 4 and axis 5 are shown in Fig. 5 and Fig. 6.



a) *b)*

Fig. 5. *Experimentaly obtained oscillograms for axis 4.*

Fig. 5 presents time-diagrams for rotation of the table. In Fig. 5a an angular speed trajectory is shown, including acceleration and deceleration when a small displacement is performed. Fig. 5b shows switching from high to low speed value.



a) *b)*

Fig. 6. *Experimentaly obtained oscillograms for axis 5.*

Speed trajectories illustrating tilting of the rotary table are shown in Fig. 6. The reference angles are $+60^0$ (a) and $+90^0$ (b), respectively.

VI. CONCLUSION

A methodology for selection of electric drives for rotary table of milling machines with digital program control is offered. The presented algorithm takes into account the technological process features, the tools used, the processed material, as well as the mechanical gear type. Some examples have been presented illustrating the practical implementation of this methodology.

An improved construction of rotary table for milling machines is offered.

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

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