INVESTIGATION OF THE PORTAL-TYPE MACHINE TOOL GEAR-BELT GEARBOX

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Abstract – Many modern technological processes are implemented at high speeds of the machine tool operating bodies relative to the workpieces. With significant dimensions of the processed parts, rack-and-gear drives are used. The design features of the rack-and-gear drive require coordination of the servo drive with the machine operating bodies movement speeds using a gearbox. This paper considers the possibility of creating a gear-belt gearbox for drives of high-speed equipment. The applied gearbox should not cause additional errors in the movement process. The work carried out experimental investigations of a servomotor dynamic characteristics and the qualitative characteristics of measuring encoders, the gearbox influence on the displacement error, machine tool axis movement. The dynamic characteristics of a servomotor without load, assembled with a gearbox and as part of a controlled axis of a portal-type machine have been investigated. It is determined that the delay time of the movement start is no more than 0.002 s for a servomotor without load and as part of a gearbox, and the delay time of the movement start of the gearbox output shaft does not exceed 0.003 s. It has been determined that the maximum possible acceleration of the controlled bodies of the machine during using the considered drive is 8 m/s^2. The dynamic error of the axis movement along a straight trajectory does not exceed 0.023 mm, and along a circular trajectory – 0.035 mm. The error of position determining for the operating body is no more than ±1 discrete. This indicates that the gearbox error is less than the error of the position measurement system used in the investigated machine.

Keywords: High-speed Equipment, Gear-belt Gearbox, Servomotor, Dynamic Characteristics, Portal-type Machine Tool.

1. Introduction

A lot of modern technological processes, such as high-speed machining [1, 2], laser cutting [3, 4], laser welding and cladding [5, 6] are implemented at high speeds of movement of the operating body relative to the workpiece. The implementation of high-speed processing requires the provision of high dynamic characteristics of the controlled bodies of the machine tool [7]. The dynamic capabilities of the controlled axes of machine tool movement of operating bodies have a significant impact on the accuracy and quality of technological processing [8, 9]. Investigations of the *S*-shaped laws of acceleration/deceleration and the influence of motion differential characteristics on the accuracy of trajectory movements confirm the need to increase the dynamic characteristics of the actuators of technological equipment [10].

For the processing of dimensional parts, portal-type schemes of machine tools with a rack-and-gear drive are often used. The design features of such a drive require matching the rotation speed of the drive gear with the required speed characteristics of the moving operating bodies of the machine tool. A significant discrepancy between the required gear rotation speed and the maximum rotation speed of the servomotor arises when using a direct drive of the drive gear [11]. For most rack-and-gear drive sizes, this discrepancy is approximately 1 order of magnitude and increases as the pinion diameter increases. In this regard, it is necessary to use a reduction gear with a gear ratio R = 10…15 [12]. The requirement for a minimum value of backlash or its complete absence is important when selecting a gearbox for the drive of the controlled bodies of the machine tool.

Various types of gearboxes are used in the designs of machine tools: harmonic drive, planetary gear, gear-belt [13, 14]. Harmonic drive gearboxes provide a backlash-free transmission of rotation with a minimum gear ratio R = 75…80. Planetary gearboxes provide the required gear ratio range. There are models of planetary gearboxes with minimum backlash values of the order of several arc seconds, but as the gear wears out, this value increases and cannot be adjusted. In gear-belt gearboxes, the elimination of backlash is provided by the belt tension mechanism and can be eliminated during operation. However, it is almost impossible to obtain the required gear ratio R = 10…15 in a single-stage gear-belt gearbox. And when creating two-stage gearboxes, the number of transmission links increases, and their total error in the transmission of motion may be unacceptable. In this regard, the investigation of the error reflected by a two-stage gear-belt gearbox in the movement of the high-speed technological equipment operating bodies and the resulting dynamic characteristics is an urgent task.

2. Problem Formulation

The investigation of the possibility of using a gear-belt gearbox in a rack-and-gear drive was carried out on the example of a portal-type laser cutting machine with a processing field of 3.5×1.5 m. The maximum feed that must be provided is F = 30 m/min. The longitudinal movement drive uses a 90ST-M04025 servomotor manufactured by Beijing KND CNC Technique Co. LTD, whose main characteristics are shown in Table 1.

Table 1. Characteristics of the servomotor drive 90ST-M04025

Characteristic	Measurement units	Value
Rated power	W	700
Rated torque	N·m	4.0
Short-term maximum torque	N·m	10.0
Rated RPM	rpm	2500
Full speed RPM	rpm	3000

In Fig. 1, *a* shown the torque characteristic of the servomotor. Curve $M_{SM\,nom}$ shows the torque variation in nominal mode. In this mode, the servomotor can operate for an almost unlimited time. Curve $M_{SM\,max}$ shows the value of the maximum allowable torque. Operation in this mode can be carried out for a short time, which corresponds to the acceleration/deceleration sections.

In Fig. 1, *b* shown a diagram of the gearbox reduction ratio coordination with the maximum technological feed (in the example, the feed F = 30 m/min is considered). Curve $n_{SM\,lim}$ shows the required speed of the servomotor at the inlet to the gearbox, at which the given technological feed will be realized. According to this diagram, to obtain a feed of 30 m/min at the nominal speed n_{nom} of the servomotor, a gearbox with a gear ratio R_{nom} = 9.5, and to obtain the same feed of 30 m/min at the maximum speed n_{max} of the servomotor, a gearbox with a gear ratio R_{max} = 11.5 must be used.

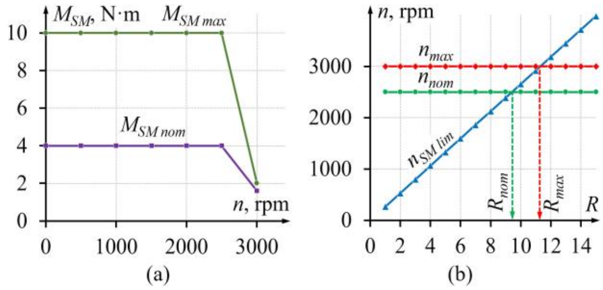

Figure 1: Servomotor characteristics (a) and reduction ratio selection (b)

Accordingly, the used gearbox must have a gear ratio greater than R_{nom}, but not exceeding R_{max}. In this case, the required maximum feed is provided at the servomotor speed not exceeding the maximum. Based on the indicated limitations, the design of a two-stage gearbox with a gear ratio $R = R_1 \cdot R_2 = (72/22) \cdot (72/22) \approx 10.71$ was chosen for the investigation. In Fig. 2 shown the output characteristic of the gearbox torque and the actual acceleration as a function of the reduction ratio.

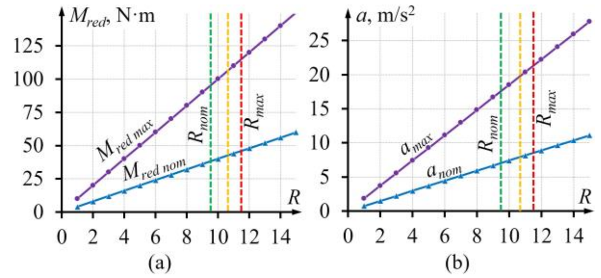

Figure 2: Characteristics of the gearbox torque (a) and the available acceleration (b) depending on the reduction ratio

The 3D model and appearance of the gearbox under investigation are shown in Fig. 3. A feature of the gearbox is that its design provides for the possibility of installing an encoder on the axis of the output shaft, which makes it possible to control the angular movement of the drive gear of the rack-and-gear of the controlled axis.

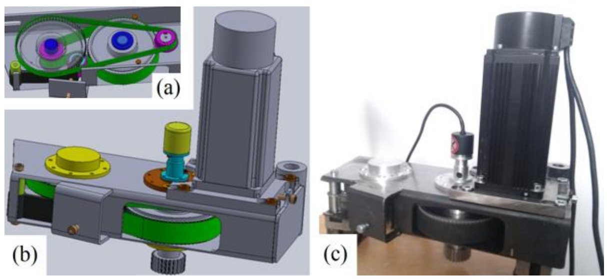

Figure 3: Design layout (a), 3D model (b), and appearance (c) of the proposed gearbox

To determine the effect of the gearbox on the nature of the movement, it is necessary to determine the obtained dynamic characteristics of the controlled bodies of technological equipment and evaluate the errors reflected by the gearbox. In this paper, the following was carried out:

- investigation of a servomotor dynamic characteristics and the qualitative characteristics of measuring encoders;
- investigation of the gearbox influence on the displacement error;
- investigation of machine tool axis movement.

3. Investigation of a Servomotor Dynamic Characteristics and the Qualitative Characteristics of Measuring Encoders

The determination of the dynamic characteristics and qualitative characteristics of the measuring encoders was carried out on an experimental stand, the scheme and appearance of which are shown in Fig. 4. The stand provides the ability to determine the dynamics of the servomotor rotor movement using duplicated measurement of the rotor position. For this purpose, the internal encoder E1 of the servomotor and an additional encoder E2 mounted on the shaft of the motor are used. The resolution of the internal encoder of the servomotor is $Z_1 = 2500$ discrete/rev and the external encoder is $Z_2 = 3000$ discrete/rev. Servomotor control, registration, and processing of experimental data is carried out using a software and hardware complex (SHC) [15, 16].

The control cycle frequency is 1 kHz.

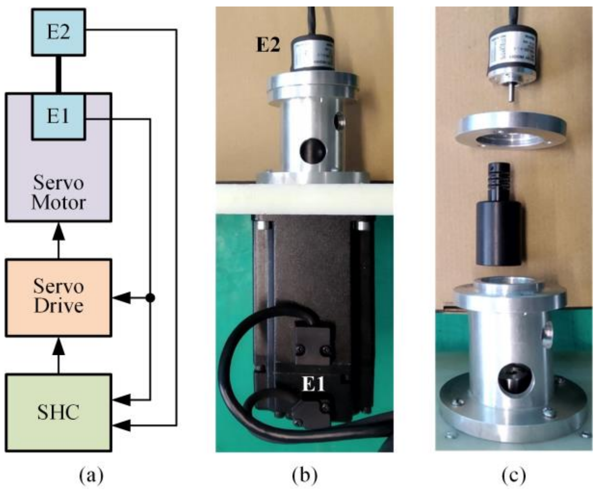

Figure 4: Scheme (a) and appearance of the stand for the investigation of the servomotor (b) and encoder (c)

The transient process of servomotor acceleration was investigated with a step variation in the control set V_{set} from 0 to 10% and 100% of the maximum no-load value V_{max}. The actual rotation speed was recorded according to the readings of the external encoder V_{enc2}. The resulting graphs are shown in Fig. 5. In both cases, the delay time for the start of the rotor movement is 0.002 s. The value of speed overshoot when setting the maximum control voltage does not exceed 5.5%.

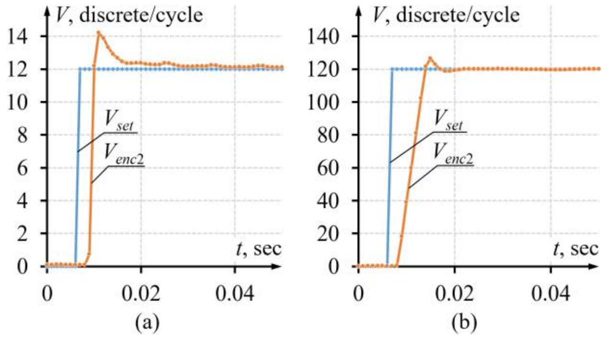

Figure 5: The transient process with a step variation in the control set to the level of 10% (a), and 100% (b)

The difference in the measurements of the motion process by the internal and external encoder was evaluated at a steady mode. In Fig. 6 shown the differences in the rotor speed obtained from the measurements by the internal and external encoder and reduced to the discreteness of the internal encoder:

$$\Delta V_{enc} = V_{enc1} - V_{enc2}(Z_1/Z_2).$$

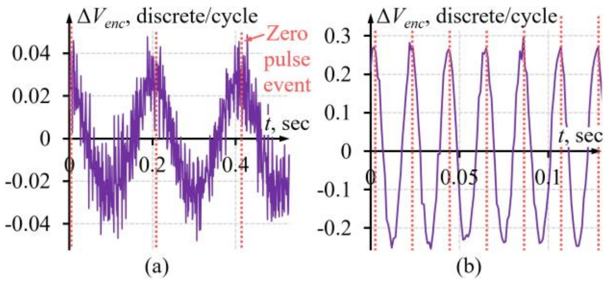

Figure 6: The error in speed determining at 10% (a), and 100% (b) of the maximum moving speed

Differences in the registered speed (Fig. 6, *a*) when moving with a control set at 10% is about ±0.05 discrete/cycle. The period of this value variation coincides with the period of passing the zero-pulse mark of the sensor. The difference between the recorded speed readings when moving in the mode of maximum control set (Fig. 6, *b*) is about ±0.3 discrete/cycle, which corresponds to a value of ±2.2′ of the angular position per control cycle. The period of the value variation is calculated from the period of the passage of the zero-pulse mark of the sensor. This indicates that there is a difference between the internal and external encoder in the arrangement of the measuring divisions on the sensor mirror, or there is a displacement of the sensor rotation axis relative to the geometric axis of the applied measuring divisions of the sensor.

In Fig. 7 shown the results of comparing the angular position of the servomotor rotor recorded by two encoders at different speeds. The discrepancy in the recorded angular position readings is ±1.1 discrete. The nature of the error variation depends on the angular position of the rotor, as evidenced by the position of the graph of the variation in the mismatch of the readings relative to the zero-pulse mark of the sensor. The difference in the readings of the registered angular position does not depend on the rotational speed of the servomotor rotor and is about ±7.9′.

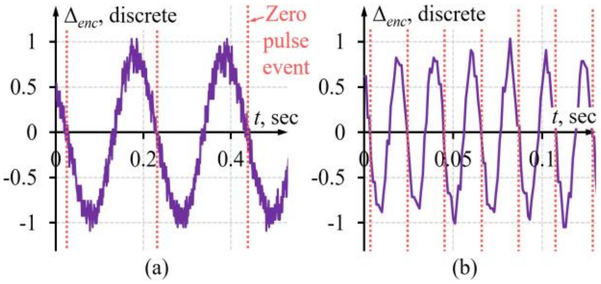

Figure 7: Position determination error at 10% set (a), and at 100% set (b)

A detailed analysis of the experimental data made it possible to determine that the scale of the external encoder gives an error in the unevenness of the arrangement of measuring divisions of the order of 1 discrete. The problem of sensor manufacturing errors and the influence of these errors on the measured motion parameters is widely studied by specialists in various fields of technology [17, 18]. A large number of investigations are devoted to the development of methods and algorithms for processing encoder measuring signals and error compensation for the most accurate measurement of the technical systems elements movement parameters [17, 19–21]. The presence of distortion of the encoder scale necessitates the use of algorithms for correcting the measured position, but this problem is not considered in this paper. It should be noted that the observed errors in the servomotor rotor movement can also be caused by the processes taking place in electrical machines, manufactured with some deviations from the nominal parameters. To determine the effect of such deviations in the design, it is necessary to carry out mathematical modeling of electrical machines, as shown in [22, 23].

Thus, it has been determined that the dynamic characteristics of the servomotor ensure the delay time of the start of the rotor movement no more than 0.002 s. The value of speed overshoot when setting the maximum control voltage does not exceed 5.5%. In the investigation of the qualitative characteristics of the measuring encoders, it was determined that the inconsistency of measurements between the used encoders provides information about the rotation speed with an accuracy of 2.2′ per cycle and measurement of the position with an accuracy of ±7.9′.

4. Investigation of the Gearbox Influence on the Displacement Error

The investigation of the influence of the gearbox on the displacement error was carried out according to the scheme shown in Fig. 8. The error of the final link movement, which is the sum of errors introduced by the servomotor and the gearbox, was estimated. Servomotor error is determined by both design errors and control errors reflected by the servo drive and E1 encoder. Gearbox error is due to errors in gears, belts, bearings and shafts. In addition, the measurement of the motion of the gearbox original link is carried out with an error determined by the errors of the encoder E2 and the recording system of the SHC [15, 16].

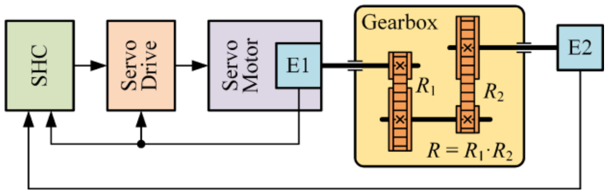

Figure 8: Gearbox investigation scheme

In Fig. 9 shown a diagram of the acceleration of the input and output shafts of the gearbox with a step setting of the control signal to the level corresponding to the maximum rotation speed. The graphs of variations in the control signal V_{set}, the rotational speed of the servomotor rotor V_{enc1}, the rotational speed of the gearbox output shaft V_{enc2}.

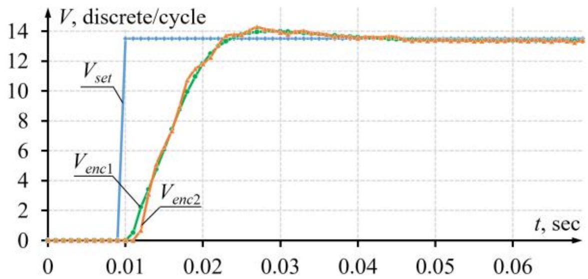

Figure 9: Acceleration diagram for step control action

In Fig. 10 shown the nature of the variation of servomotor rotor acceleration and the output shaft in the acceleration section with a stepwise setting of the control signal. The presence of oscillations of the output shaft in the absence of such oscillations in the movement of the servomotor indicates the elastic deformation of the drive belts.

The dynamic characteristics of the gearbox are shown in Table 2. In Fig. 11 shown the graphs of variation in the error of the servomotor rotation speed and the gearbox output shaft. The speed of the servomotor is maintained by the electric drive with an accuracy of ±0.25 discrete/cycle. The error in the speed of rotation of the gearbox output shaft also does not exceed ±0.25 discrete/cycle.

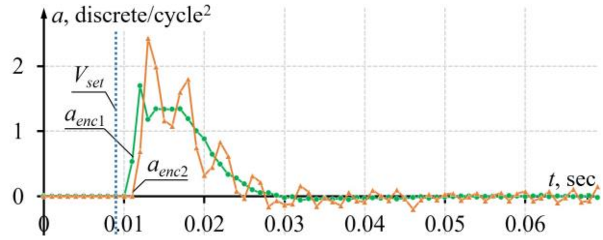

Figure 10: The nature of the speed and acceleration variation in the acceleration section

Table 2. Dynamic characteristics of the gearbox

Parameter	Measure-ment units	Value for the servo-motor rotor	Value for the gearbox output shaft
Steady-state movement speed, V	discrete/ cycle	119.1	13.34
	rpm	2857.8	266.8
Maximum acceleration, a	discrete/ cycle^2	15.135	2.68
	rev/s^2	6054	893.3
Time of the movement start delay, τ	s	0.002	0.003
The transient time constant, T	s	0.014	0.015
Overshooting, σ_{max}	%	5.04	6.93
Time T_R of reaching a stable speed, not exceeding the tolerance σ = 1 discrete/cycle	s	0.040	0.041

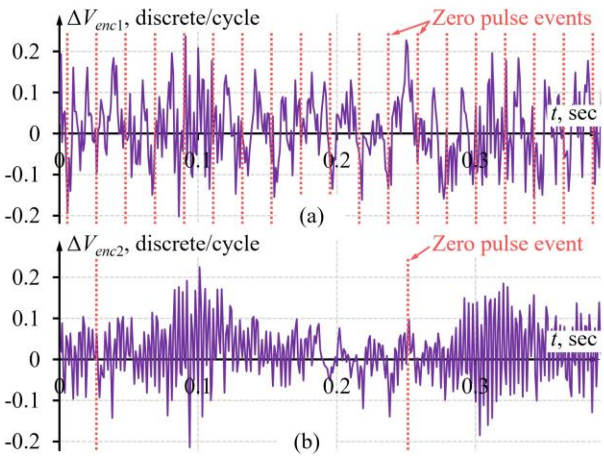

Figure 11: Servomotor (a) and gearbox output shaft (b) speed error

In Fig. 11 shown the graphs of variation in the error of the servomotor rotation speed and the gearbox output shaft. The speed of the servomotor is maintained by the electric drive with an accuracy of ±0.25 discrete/cycle. The error in the speed of rotation of the gearbox output shaft also does not exceed ±0.25 discrete/cycle.

The error reflected by the gearbox was estimated as the difference between the error of the output shaft and the error of servomotor rotation, taking into account the transmission ratio of the gearbox and the ratio of resolving encoders:

$$\Delta_{gearbox} = \Delta_{shaft} - \Delta_{SM} \cdot (Z_2/Z_1)/R\,. \qquad (1)$$

An estimate of the output shaft rotation speed error caused by the gearbox is shown in Fig. 12. The results of the investigation showed that the component of the output shaft rotation speed error caused by the gearbox, in absolute value does not exceed ±0.25 discrete or 1.8′ of the angular position per cycle, which is an acceptable value for this problem.

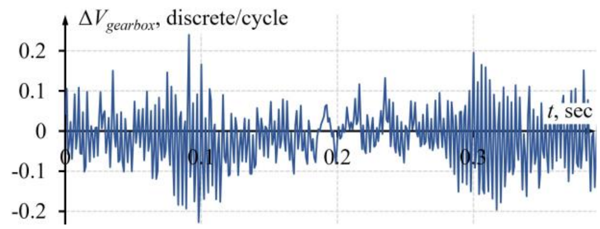

Figure 12: Error component of the output shaft rotation speed due to the gearbox

An estimate of the output shaft angular position error obtained by equation (1), is shown in Fig. 13. The nature of the error variation corresponds to the nature of the encoder E2 error (Fig. 7) with distortions caused by the errors reflected by the gearbox. The magnitude of the error reflected by the gearbox is estimated by the distortion of the amplitude and does not exceed ±1 discrete, which is 7.2′ of the angular position of the original shaft.

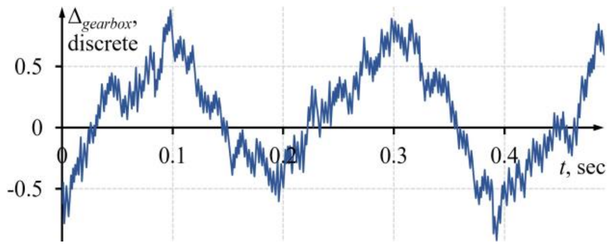

Figure 13: Periodic position error gearbox output shaft

Thus, it was determined that the dynamic characteristics of the servo drive ensure the delay time of the gearbox output shaft movement starts no more than 0.003 s. The value of speed overshoot when setting the maximum control voltage does not exceed 6.93%. The error of the gearbox output shaft rotational speed in absolute value does not exceed ±0.25 discrete or 1.8′ angular position per cycle. This indicates that the gearbox error is less than the error caused by the distortion of the encoder scale. The magnitude of the angular position error caused by the gearbox does not exceed ±1 discrete, or 7.2′ of the output shaft angular position of the, which is equivalent to the error of the encoders. Thus, the error of the investigated gearbox is much less than the error of the measuring system.

5. Investigation of Machine Tool Axis Movement

The investigation of the controlled axis movement was carried out on the example of the axis of a portal-type machine driven by a rack-and-gear transmission using the proposed design of a gear-belt gearbox with a servo drive. In Fig. 14 shown the design layout of the longitudinal displacement unit of the portal part of the machine and the appearance of the unit on the test bench.

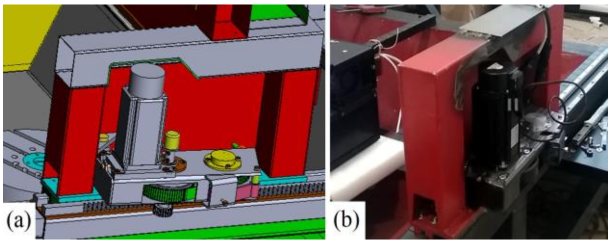

Figure 14: Installation of the gearbox on the machine portal support: 3D-model (a) and external view of the gearbox mounted on a support (b)

Determination of the controlled axis boundary dynamic characteristics was carried out in the investigation of the transient process when setting the step control action to the level corresponding to the maximum feed. In Fig. 15 shown the graphs of the transient process in terms of the servomotor rotor rotation speed V_{enc1} and the gearbox output shaft V_{enc2}.

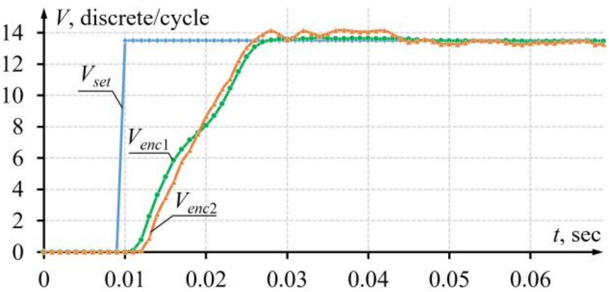

Figure 15: Transient process of the portal-type machine axis acceleration

Table 3 shows the main dynamic characteristics obtained from the results of processing experimental data. From tests follows that the maximum speed of the axis movement exceeds 30 m/min, and the acceleration can be up to 8 m/s². The non-linearity of the servomotor rotor acceleration section (V_{enc1} in Fig. 15) and the corresponding variation of the rotor acceleration (a_{enc1} in Fig. 16) corresponding to this non-linearity is explained by the flexibility of the gear belts. This phenomenon indicates the need to build a control loop with an encoder installed on the gearbox output shaft.

Table 3. Dynamic characteristics of the gearbox

Parameter	Measure-ment units	Value for the servo-motor rotor	Value for the gearbox output shaft
Steady-state movement speed, V	discrete/cycle	120.325	13.475
	rpm	2887.9	269.6
	m/min	–	30.47
Maximum acceleration, a	discrete/cycle²	13.375	1.55
	rev/s²	5350	516.6
	m/s²	–	8.0
Time of the movement start delay, τ	s	0.002	0.003
The transient time constant, T	s	0.015	0.016
Overshooting, σ_{max}	%	1.61	5.23
Time T_R of reaching a stable speed, not exceeding the tolerance $\sigma = 1$ discrete/cycle	s	0.037	0.034

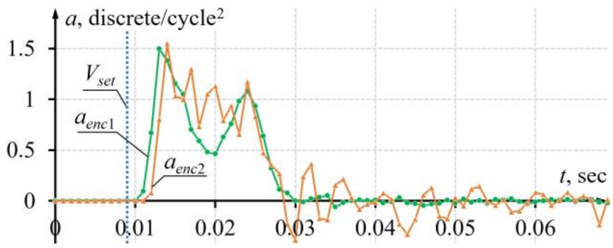

Figure 16: Transient process in the acceleration parameter during the portal-type machine axis acceleration

The estimation of the displacement error of the machine axis was carried out with the program setting of rectilinear and circular trajectories. In Fig. 17 shown an example of an axis reciprocal movement along a straight path. Acceleration/deceleration was carried out with an acceleration of 5.2 m/s² to a speed of 21.2 m/min with a full reverse motion at the extreme points of the trajectory. In this case, the axis dynamic positioning error did not exceed 0.023 mm.

In Fig. 18 shown the graphs of the machine axis parameters variation during moving the tool along a circular path. During the tool moving along an arc of a circle with a radius of 50 mm at a feed of 18.2 m/min, the maximum acceleration reached 3.5 m/s², and the axis dynamic positioning error did not exceed 0.019 mm (Fig. 18, *a*). During the tool moving along an arc of a circle with a radius of 12 mm at a feed rate of 15.1 m/min, the maximum acceleration reached 6.1 m/s², and the axis dynamic positioning error did not exceed 0.035 mm (Fig. 18, *b*). The increase in the error with a decrease in the radius of the circular trajectory is due to the influence on the variation of the movement differential characteristics, such as acceleration and jerk, which significantly increase as the radius of curvature decreases. The possibility of compensating for the influence of the movement differential characteristics on the movement accuracy has been shown in a number of works and requires more in-depth research.

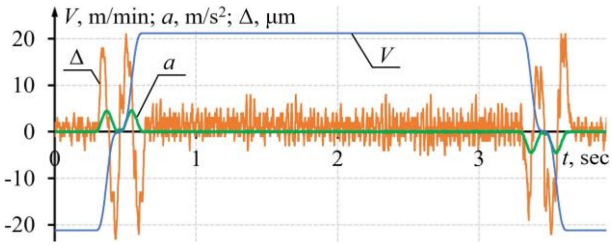

Figure 17: Straight-line movement of the machine axis at a feed rate of 21.2 m/min

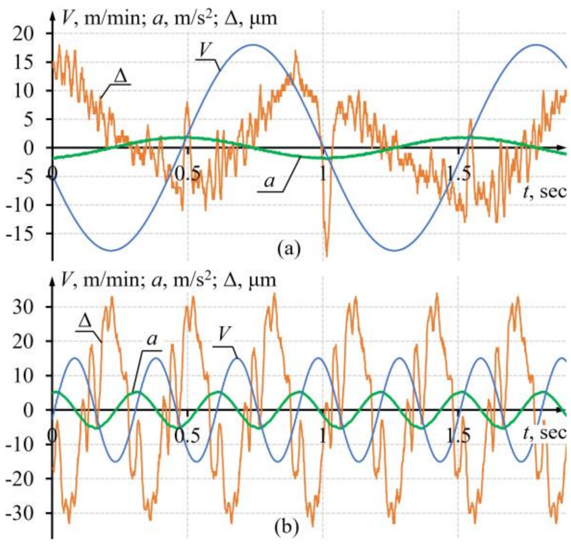

Figure 18: Parameters of the axis movement during the tool moving along an arc of a circle with a radius of 50 mm at a feed rate of 18.2 m/min (a), during the tool moving along an arc of a circle with a radius of 12 mm at a feed rate of 15.1 m/min (b)

Consequently, the maximum speed of the axis movement exceeds 30 m/min, and the acceleration reaches 8 m/s². The dynamic error of the axis movement along a straight trajectory does not exceed 0.023 mm, and along a circular trajectory – 0.035 mm. Thus, the use of a gear-belt gearbox in the high-speed technological equipment moving bodies drive provides acceptable accuracy and the necessary dynamics of movement.

6. Conclusions

In the presented paper, the possibility of using a two-stage gear-belt gearbox in a rack-and-gear drive for moving bodies of high-speed technological equipment is experimentally investigated. The dynamic characteristics of a servomotor without load, assembled with a gearbox and as part of a controlled axis of a portal-type machine have been investigated. It is determined that the delay time of the movement start is no more than 0.002 s for a servomotor without load and as part of a gearbox, and the delay time of the movement start of the gearbox output shaft does not exceed 0.003 s. It has been determined that the maximum possible acceleration of the controlled bodies of the machine during using the considered drive is 8 m/s².

An investigation of the qualitative characteristics of measuring encoders revealed the presence of an error of the applied encoders relative to each other of the order of 1 discrete. The use of two encoders to determine the motion parameters of the gearbox input and output shafts made it possible to determine the fraction of the error caused by the gearbox. The error of position determining for the operating body is no more than ±1 discrete. This indicates that the gearbox error is less than the error of the position measurement system used in the investigated machine.

The investigation of the machine tool bodies movement showed that the use of a gear-belt gearbox in the drive for moving high-speed technological equipment bodies provides acceptable accuracy and the necessary dynamics of movement. The dynamic error of the axis movement along a straight trajectory does not exceed 0.023 mm, and along a circular trajectory – 0.035 mm.

During the investigation, manifestations of belts compliance were revealed, but the influence of this effect on the processing accuracy has not been investigated. It should be noted that, in addition to the need to study the compliance of the belts, it was identified the need for research on the correction of the measured position by encoders to eliminate the negative effect of the distortion of the encoder scale.

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