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Experimental study of the dynamic properties of high-precision dual-motor geared servo drives for technological robots

The paper presents the results of an experimental study on the comparative analysis of accuracy of traditional in robotics single-motor and dual-motor geared servo drives, responding to step and sinusoidal input signals. The obtained results of the study indicate higher accuracy of the dual-motor servo drives and allow us to recommend them for construction of technological manipulators with open kinematic chain.

Key words: industrial robots, experimental stand, accuracy of movements, precision position sensor, dual-motor drives, geared drives, combined control.

Introduction

In a number of studies [1-4] devoted to improving accuracy of technological robot movements, it is supposed to construct such manipulators on geared dual-motor servo drives. The structure of such drives is presented in [1, 2] and it consists of five control loops. The current, speed and shaft position control loops of the first motor form an internal servo drive (ISD). The ISD is an integral part of the precision servo drive, which also contains speed and position control loops of the control object. The second motor is part of the torque loader, which is an active controlled backlash eliminator.

The studies [1-3, 5] have concluded that the usage of technological robots with such dual-motor drives contributes to a significant increase in accuracy of tool movements and allows us to talk about the possibility of creating precision and high-performance manipulators designed for such operations as robotic milling. However, such conclusions are made only on the basis of theoretical studies and computer simulation. Therefore, there was a need for an experimental study that could clarify the properties and capabilities of these drives.

The purpose of this study was to determine the dynamic properties of the dual-motor geared servo drives, to compare them with the properties of conventional servo drives, and to compare the results of the theoretical studies to the obtained results of the experimental study. At the same time, it was important to verify in practice that the proposed solution will provide high quality control.

1 Experimental stand for investigation of dynamic properties of dual-motor servo drives.

The first task was to create an experimental stand, which could allow us to study the dynamic properties of such a drive. When developing the stand design, it was taken into account that the energy parameters of the created drive should correspond to the parameters of the drive of the manipulator column, as this drive of the anthropomorphic type robot is one of the most loaded. It is exposed to large dynamic torque, caused by the moment of inertia of the other links of the manipulator. And at the same time this drive is not loaded with a static torque, which eliminates the influence of backlash, unlike the drive of the shoulder link. The arising position errors in this drive lead to larger deviations of the manipulator tool from the desired position.

Figure 1 shows the schematic diagram of the experimental stand (top view) of the study. Two motors are installed on the vertical platform: the motor of the internal servo drive (ISD) and of the torque loader. A resolver, which signal is used to determine speed and position of the internal drive, is installed on the shaft of the first motor. A resolver is also mounted on the shaft of the loader motor. By means of rigid couplings, the shafts of these motors are fitted with pinions which mesh with the main gear wheel. These gears are mechanical transmissions that reduce the rotational frequency of the output shaft of the drive and increase its torque. A precision position sensor is also mounted on this shaft, which is used to close the main position feedback of the dual-motor drive.

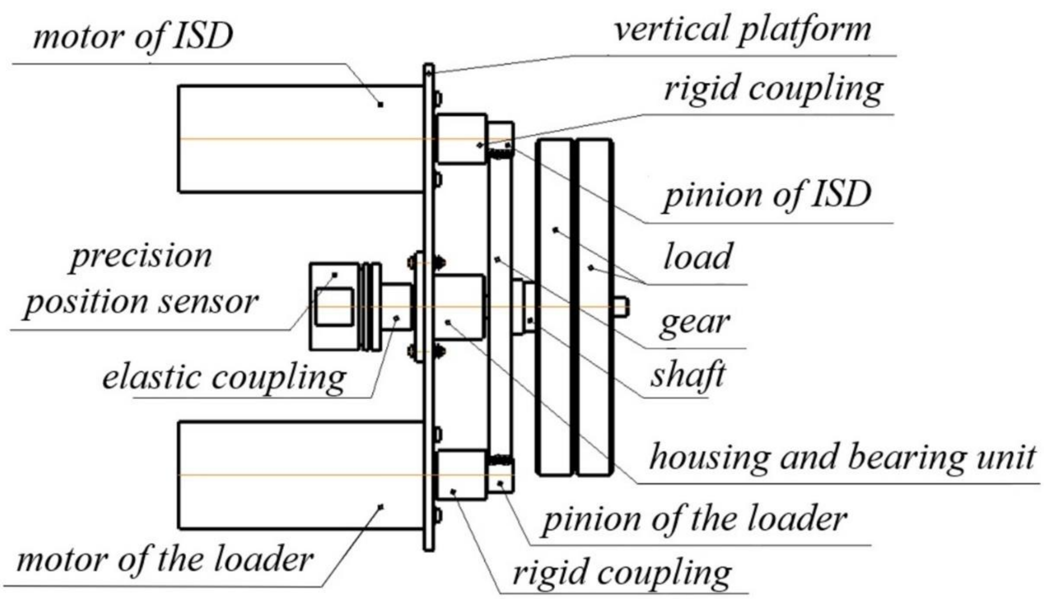

Figure 1 - Schematic diagram of dual-motor drive experimental stand (top view)

As the configuration of the manipulator’s links changes while it’s performing technological operation, the moment of inertia of the moving parts of the drives, including the shoulder link drive, also changes. According to [6], the moment of inertia of the moving parts of the drive in this case can change significantly, in some cases up to 10 times. In order to conduct experiments at different values of the moment of inertia on the stand, the inertia of the manipulator link is simulated using removable plates. Their mass-dimension parameters are selected in such a way that the resulting moment of inertia applied to the ISD motor shaft can be changed from 1 to 4 times when adding or removing this load.

Based on the diagram in Figure 1, an experimental stand was built, shown in Figure 2.

Figure 2 – Experimental stand of the dual-motor drive

To ensure elimination of backlash in such a drive when the control object (CO) is rotated both clockwise and anti-clockwise, the same requirements are imposed on the power and rated torque of the ISD motor and the loader motor. In this case, the dual-motor drive is able to provide torque relevant to half of the motor rated torque value (taking into account gear ratio of the gearboxes), and the parameters of the loader and ISD motors and gearboxes are the same. Therefore, the same PMSM motors B2.SM.000-6200 by KEB are used in the stand for both the ISD and the loader. Parameter values of such motors can be found in [7]. The motors nominal rotational frequency is 6200 rpm, nominal torque - 1 Nm, rotor moment of inertia - $5.7*10^{-5}$ kgm^2, motor EMF coefficient - 0.577 Vs/rad, electromagnetic time constant - 3.2 ms and winding active resistance - 9.2 Ohm. The usage of such motors together with KEB Combivert 05.S4.D30-1270 V1.4 frequency converters, realizing vector control, made it possible to set a PWM frequency value of 16 kHz in the drive power converter.

Cylindrical gears with a gear ratio of 10, stiffness coefficient of 1294000 N*m/rad and backlash of 6 angular minutes are used as gearboxes. Gear wheel and pinions are customized specifically for the stand, they are made of steel 45 with accuracy class 8-D according to GOST 1643-81. Their seating dimensions are made to 7 qualification, and the end runout of teeth is 20 microns for the pinions and 30 microns for the gear wheel. The gear wheel is made with a module 1 with 200 teeth with a dividing diameter of 200 mm. The pinions have 20 teeth and their dividing diameter is 20 mm.

The loader during operation creates a constant torque of 5 Nm on the gear. The loader motor is part of the drive, closed by velocity control loop of its shaft, and it responds to the input reference value of 150 rpm. It is important that such a drive operates in the mode of limiting the developed torque at the level of 0.5 N*m.

To reveal potential accuracy of the dual-motor drive, a LIR-158A precision main position feedback sensor is selected. The sensor has such a resolution that the decimal number corresponding to the code at the output of its quadrature counter, changes by one unit when the CO is rotated by an angle of $6.28*10^{-6}$ rad. Position feedback sensors of the ISD motor shaft and loader motor shaft have resolution of 1024 samples per revolution.

An industrial computer IPC Advantech 610 with ISA bus and running under DOS operating system is used as the drive control device. A 2-channel PCL-833 quadrature counter board is connected to ISA bus, which processes signals from LIR-158A sensor and the ISD motor shaft position sensor. Digital data obtained as a result of processing signals from these sensors are used in the computer to calculate the control voltage in the range of ±10 V, proportional to the desired value of the ISD motor speed, where 10 V corresponds to the speed of 3000 rpm. The calculation is performed by interrupts from the timer at a frequency of 291 Hz, which is due to the period of the system 12-bit timer running at 1193181 Hz (~1.19 MHz). With each interrupt a procedure written in C++ is called, in which the desired control action is calculated taking into account the current sensor values. Then the calculated value is fed as a digital code to the DAC ACL-6126, also connected to the ISA bus, and then the analog value is fed to the frequency converter of the first motor. Thus, current and velocity control loops of the first motor are realized in the frequency converter KEB, and its position control loop is implemented in the industrial computer, as well as speed and position control loops of the control object.

2 Synthesis of the control system of a dual-motor servo drive

To prepare the stand for experiments, the synthesis of its control system as a cascade control system (with several inner control loops) was carried out. The methodology for tuning such a system is given in [8]. According to this technique, first of all, gain coefficients of the PI-controllers of the current and velocity control loops and P-controller of the ISD position control loop are adjusted. While tuning ISD, all the additional load with the inertia moment 0.04 kg*m^2 is installed on the output shaft of the control object, the loader drive is disconnected from the control system. It is present only to increase the moment of inertia of the CO in the form of a passive motor shaft with a reducer. Feedback signals are fed to the control system only from the resolver, installed on the ISD motor shaft. A precision position sensor is used to register the position of the CO without participating in the control process.

When setting the coefficients of the current, velocity and position controllers of the ISD, an important setting criterion is the duration of transients, which must be minimized. Also, an important criterion is overshoot. Thus, in the ISD current control loop the value of the coefficient of the P-component of the controller is chosen to be 700, the value of the I-component - 100. At the same time, the overshooting in the loop should not exceed 5 % while responding to the step reference input. In the velocity control loop of the ISD, the value of the P-component gain of the velocity controller is 640, and the value of the I-component is 280. The overshooting in the velocity control loop does not exceed 50%. In the position control loop, the value of the P-component gain of the ISD is 0.5. The overshooting in this loop also does not exceed 5 %. These coefficient values were selected and used further in the stand.

After adjusting the controllers, the ISD responds to the input setpoint of the angular position of the CO equal to 0.1 rad, with a transient duration of 0.12 s, as shown in Figure 3. The transient process (a) and error (b) are shown here. Line 1 corresponds to the signal of the resolver, installed on the shaft of the ISD motor, taking into account the mechanical gear ratio (i.e. the value applied to the output shaft of the CO), and line 2 corresponds to the signal of the precision position sensor of the CO.

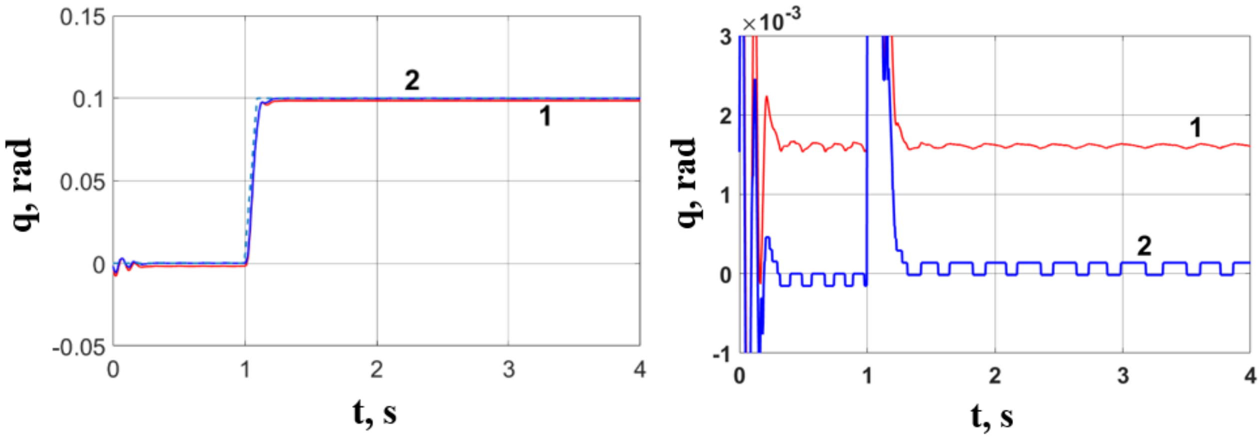

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Figure 3 - Transient process (a) and error (b) at the **ISD** position control when the set reference is 0.1 rad after 1 s (1 - signal of the precision position sensor of the control object, 2 - resolver signal taking into account the mechanical transmission ratio).

Due to the fact that the mechanical transmission of the drive is outside the position control loop, there is a noticeable actual error between the desired and the actual positions of the CO in the figure. For example, the arithmetic mean of the error from the precision encoder signal of the CO position sensor is 1.6 % of the setpoint. If such a drive is used to control position of the shoulder link of a manipulator with a length of 1 m, such an error will lead to deviation of the axis on which the elbow link is mounted by about 1.6 mm, which in many practical applications is unacceptable for a technological robot.

Since the motors and gearboxes of the ISD and the loader are identical, the values of their controller gains after adjustment are also identical, which allows the loader control system to be set up immediately. It is controlled in speed setting mode with a desired value of 150 rpm and a torque limit of 0.5 N*m (half of the motor torque nominal value).

After connecting the loader, the drive consisting only of the ISD and the loader is able to respond to the input setpoints of 0.1 rad with a transient duration of 0.12 s, as shown in Figure 4, where line 1 corresponds to the resolver signal on the ISD motor shaft (taking into account the mechanical transmission ratio), and line 2 corresponds to the signal of the precision position sensor of the control object.

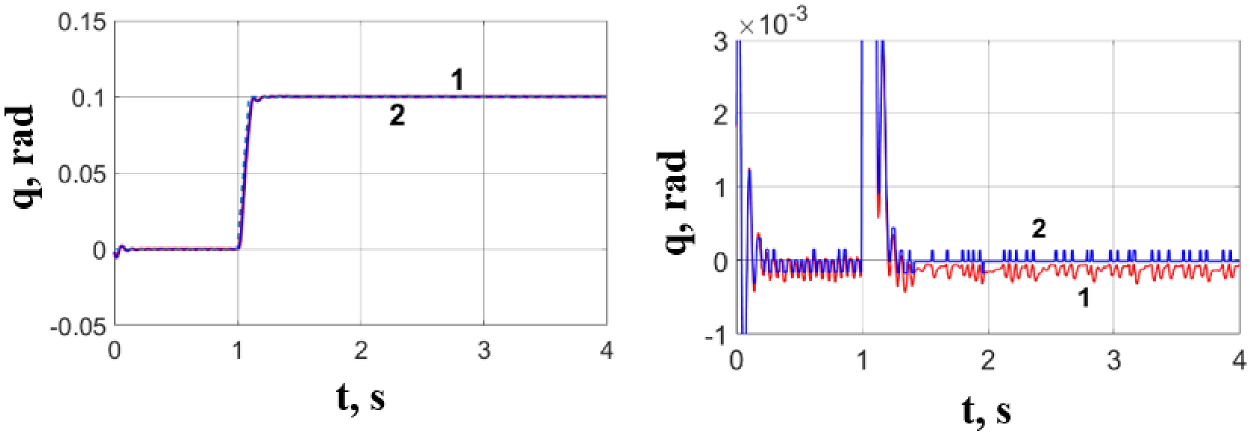

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Figure 4 - Transient process (a) and error (b) during position control of the **ISD with the connected loader** responding to the input setpoint of 0.1 rad after 1 s (1 - signal of the precision position sensor of the control object, 2 - signal of the resolver taking into account the mechanical transmission).

Connection of the loader in this case, even without position feedback of the control object, reduced the arithmetic mean value of the CO position error to 0.15 % of the reference value. As can be seen in the figure 4, the red line almost coincides with the blue line, which indicates a significant reduction in the error between the set and actual positions of the control object due to reducing the influence of backlash and elasticity of mechanical gears.

In [2], it was demonstrated using computer simulation that in such a drive, weakly damped oscillations can occur in the mechanical subsystem consisting of mechanical gear and a shaft with additional load, especially when using wave gearboxes common in robotics with much lower value of the stiffness coefficient, for example, $3.2*10^4$ N*m/rad. In this case in the stand, the stiffness coefficient of the mechanical transmission is large enough, so such oscillations are not noticeable in Figure 4. However, according to the principle of impedance control presented in [2, 8, 9], the introduction of velocity feedback loop of the control object makes it possible to significantly increase gain of the position P-controller of the ISD and eliminate the possibility of such oscillations. Figure 5 shows the graphs of position error both with and without velocity feedback control loop of the control object at the increased value of the position P-controller gain of the ISD from the value 0.5 to the value 0.9.

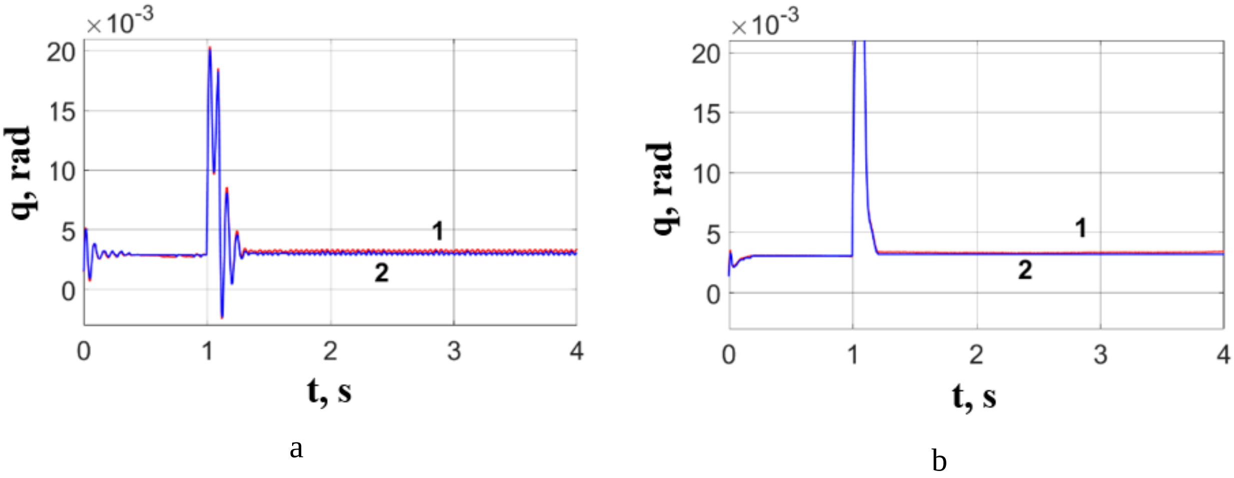
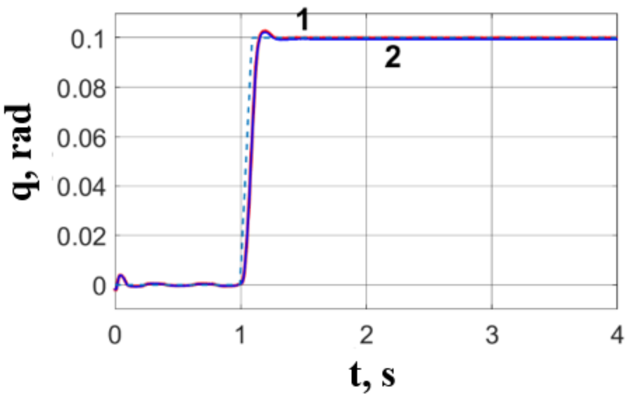


Figure 5 – Error of the **ISD** position **with the connected loader** without **velocity feedback control loop of the control object** (a) and **with** it (b) at responding to input setpoint 0.1 rad after 1 s (1 - signal of the precision position sensor of the control object, 2 - signal of the resolver taking into account the mechanical transmission).

As a result of increasing gain of the position P-controller of the ISD, low-frequency oscillations appeared, as shown in Figure 5(a). As can be seen in Figure 5(b), the velocity feedback control loop can damp such oscillations. However, the arithmetic mean value of the position error of the control object (according to precision position sensor) increased and amounted to 3.4 % of the set value.

In [1] it is shown that to eliminate such an error it is necessary to close the main position feedback control loop of the control object of precision drive, and in the direct control loop to use an integral controller. At the value of the gain of drive position I-controller equal to 1.1, the overshooting is minimized and becomes less than 5% of the reference value, and the transients are as shown in Figure 6.



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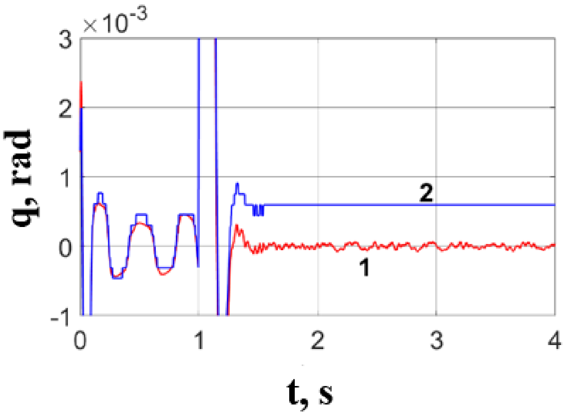

b

Figure 6 - Transient process (a) and error (b) during position control of a **dual-motor drive** responding to the input reference 0.1 rad after 1 s (1 - signal of the precision position sensor of the control object, 2 - signal of the resolver taking into account the ratio of the mechanical transmission).

If we do not introduce the corrective velocity feedback of the CO, and immediately close the main feedback loop of the precision drive, self-oscillations may appear, as shown in Figure 7. Reducing the gain coefficients of the ISD position controllers and the entire drive would lead to a reduction in the cut-off frequency of the drive, which is already quite limited. As a result of the synthesis of the control system of the dual-motor drive, the estimate of the cut-off frequency of its open position loop was 27 rad/s. Thus, conducting corrective feedback on the CO velocity makes it possible to simultaneously increase the cut-off frequency of the drive and prevent the occurrence of self-oscillations.

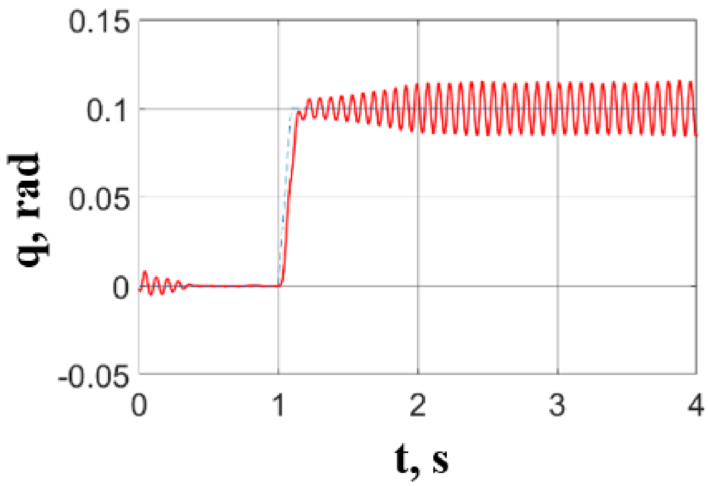

Figure 7 - Transient process during position control of a **dual-motor drive** without feedback loop of CO velocity when the setpoint is 0.1 rad after 1 s (calculated from the signal of a precision position sensor of the CO).

As a result, the drive is capable of handling a reference input of 0.1 rad with a transient time of 0.135 s. The arithmetic mean value of the error is close to 0 ($3.7*10^{-8}$ rad), and the maximum error in the steady-state mode is 0.0001 rad, which, when using such a drive to control the position of the shoulder link of a 1 m long manipulator, would lead to a deviation of the axis of the elbow link by about 100 μm. Such a value is considerably smaller than that presented in Figure 3(a), but for technological operations such as robotic milling it is still quite large. Figure 6(b) shows oscillations occurring in steady state with an amplitude of approximately 0.00005 rad and a frequency of 4.4 s^{-1}.

During computer simulation of the dual-motor drive it was found that such oscillations occur due to insufficient resolution of the position sensor installed on the shaft of the ISD motor. Thus, a sensor with a resolution of 1024 discretes per revolution is used in the test bench. The results of computer simulation confirm that when the resolution of the sensor is increased up to 5000 pulses per revolution, the maximum amplitude of such oscillations decreases almost by 10 times. That is, when using such a drive to control the position of the shoulder link of a 1 m long manipulator, the deviation of the tool center point would be approximately 10 μm. Hence, it follows that when building a dual-motor drive, the ISD position sensor should have a resolution of at least 5000 pulses per revolution.

Additionally, Figure 6(b) shows that in steady-state mode, the error value of the resolver signal, referred to the output shaft of the control object, is 0.0006 rad. Such a large error proves that accuracy of the drive without a main closed position feedback loop of the CO would be at least 6 times lower than the accuracy of the dual-motor drive with loader and such position feedback control loop.

3 Comparison of the dynamic properties of a dual-motor geared servo drive and a conventional single-motor drive

Since the purpose of this study was to compare the dynamic properties of a dual-motor drive with conventional drives, the control system of a single-motor drive was also synthesized. For this case the synthesized ISD with connected additional load was taken as a basis. The position of the control object was monitored using a LIR-158A precision encoder, but the main position control loop was closed by the ISD resolver signal. The gain coefficient of the position P-controller was adjusted to the value of 0.5 and the transient process was obtained, as shown in Figure 8, where the solid blue line is the signal corresponding to the position of the motor shaft taking into account the gear ratio, the solid red line is the signal corresponding to the position of the control object.

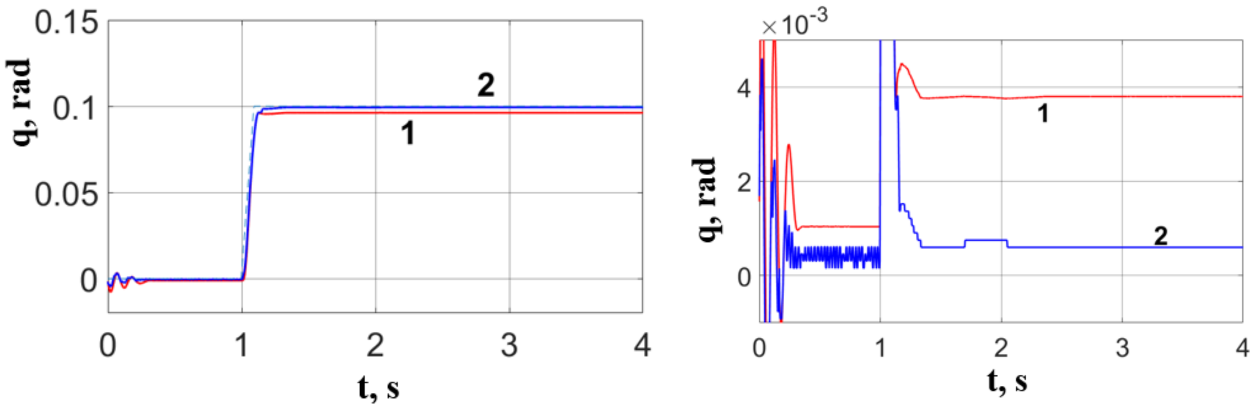

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Figure 8 - Transient process (a) and error (b) at position control of **single-motor drive** responding to the input setpoint 0.1 rad after 1 s (1 - signal of the precision sensor of the position of the control object, 2 - signal of the resolver taking into account the ratio of the mechanical transmission).

As a result of this tuning, the cut-off frequency estimate of the open-loop single-motor drive was 46 rad/s, which is higher than the cut-off frequency estimate of the dual-motor drive. The drive is capable of handling a reference input of 0.1 rad with a transient time of 0.12 s. In this case, the average value of the deviation of the CO from the reference position in steady state is 0.004 rad, although the resolver signal shows a deviation of 0.0006 rad. When using such a drive for position control of the shoulder link of the manipulator with a length of 1 m, it would lead to a deviation of the tool center point by about 4 mm, which is absolutely unacceptable for such technological operations as robotic milling.

In general, the obtained results, as, for example, in Figure 6, testify to the high accuracy of the dual-motor drive. For example, the drive responded to a reference input of 0.1 rad 40 times more accurately (taking into account the average and maximum values of the error).

In order to compare the dynamic properties of the dual-motor servo drive to the traditional single-motor one, a number of experiments were also carried out in which a sinusoidal input signal $\beta(t)=\sin(\omega t)$ with amplitude 0.1 rad and frequency ω equal to 0.1, 0.5 and 1 rad/s was set as the reference position value of the drive. Figure 9 shows the transient process (a) and the error (b) when a dual-motor drive is driven by a harmonic input signal with an amplitude 0.1 rad and frequency 0.5 rad/sec.

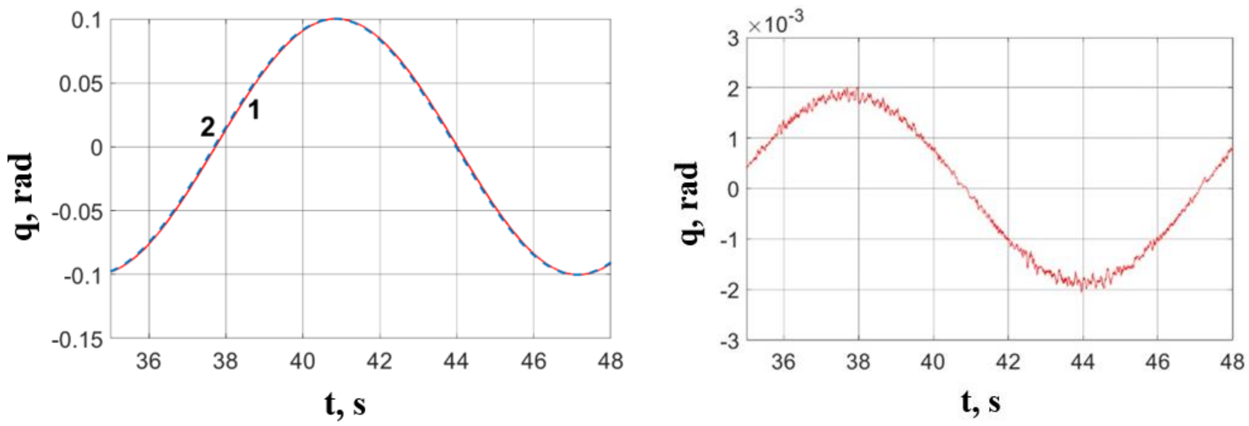

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Figure 9 - Transient process (a) and error (b) when a **dual-motor drive** with auxiliary load responds to harmonic input signal with amplitude 0.1 rad and frequency 0.5 rad/s (1 - signal of the precision position sensor of the control unit, 2 - desired position of the CO).

As can be seen in Figure 9(a), the drive has a velocity error, to eliminate which, both in the dual-motor and conventional drives, it is possible to use a combined control loop with an additional component, proportional to the rate of change of the reference input. In addition to the input signal β(t), the input signal $Q(t)$, determined by formula (1), is fed to the input of the position controller of both single- and dual-motor drives.

$$Q(t) = \frac{d\beta(t)}{dt}\frac{1}{\omega_{cp}}, \tag{1}$$

where ω_{cp} – an estimate of the open loop cut-off frequency of the drive position. Thus $\frac{d\beta(t)}{dt} = \omega \cdot \cos(\omega t)$ – is the rate of change of the input setpoint β(t), which allows not to use a differentiating device. As a result of application of the combined control, the graphs presented in Figures 10 and 11 are obtained.

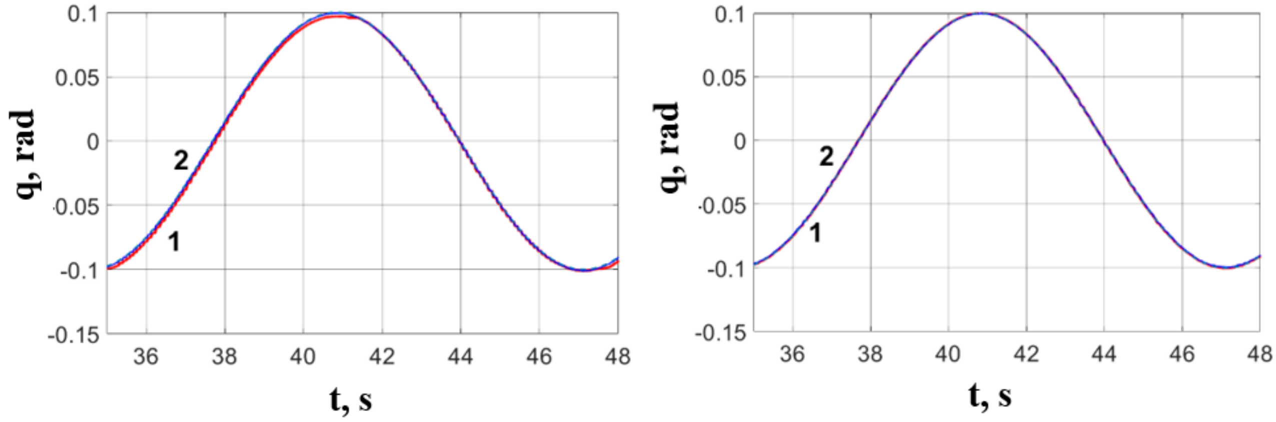

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Figure 10 – Response on harmonic input signal with amplitude 0.1 rad and frequency 0.5 rad/s of a **single-motor** (a) and **dual-motor** (b) drive with additional load (solid blue line - resolver signal (taking into account the mechanical transmission ratio), solid red line - the signal of a precision position sensor of the CO).

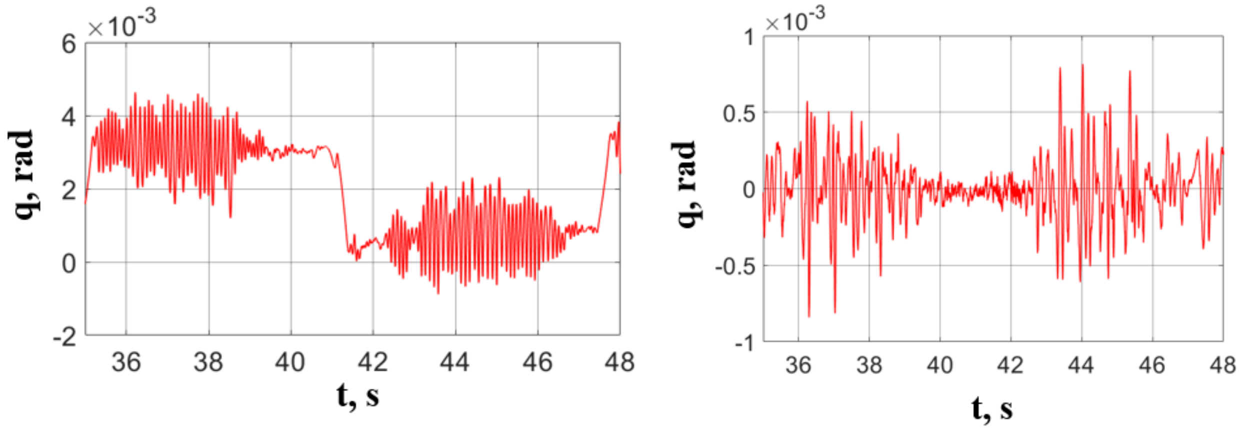

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Figure 11 - Error of **single-motor** (a) and **dual-motor** (b) drive with additional load responding to harmonic input signal with amplitude of 0.1 rad and frequency of 0.5 rad/s (signal of precision position sensor).

When combined control is used for a single-motor drive, the value of ω_{cp} is assumed to be 46 rad/s, for a dual-motor drive it is 27 rad/s. When increasing or decreasing the values of the cut-off frequency, the arithmetic mean and maximum values of the error are increasing, which confirms the correctness of estimation of cut-off frequencies. It is reasonable to consider the average values of the absolute value of the drive error $|\delta_T|_{cp}$ and the maximum values of the error $\Delta|\delta_T|_{\max}$ deviation from $|\delta_T|_{cp}$, determined by formulas (2) and (3), as indicators of drive's accuracy.

$$|\delta_T|_{cp} = \frac{1}{T}\int_0^T |\delta_T(t)|\,dt, \quad (2)$$

$$\Delta|\delta_T|_{\max} = \max\left|(|\delta_T(t)| - |\delta_T|_{cp})\right|, \quad (3)$$

Table 1 - Error values determined during the experiment.

	average value of the absolute value of the error, $\lvert\delta_T\rvert_{cp}$, rad				maximum deviation of the error from the average absolute error, $\Delta\lvert\delta_T\rvert_{\max}$, rad			
	with additional load		without additional load		with additional load		without additional load	
The input signal freq., rad/s	1-motor drive	2-motor drive	1-motor drive	2-motor drive	1-motor drive	2-motor drive	1-motor drive	2-motor drive
0.1	$15*10^{-4}$	$0.605*10^{-4}$	$12*10^{-4}$	$0.453*10^{-4}$	$6.8*10^{-3}$	$4*10^{-3}$	$5.1*10^{-3}$	$3*10^{-3}$
0.5	$20*10^{-4}$	$1.406*10^{-4}$	$16*10^{-4}$	$0.608*10^{-4}$	$6.4*10^{-3}$	$3.4*10^{-3}$	$4.5*10^{-3}$	$3.1*10^{-3}$
1	$23*10^{-4}$	$1.211*10^{-4}$	$21*10^{-4}$	$0.933*10^{-4}$	$7.1*10^{-3}$	$4.1*10^{-3}$	$5.1*10^{-3}$	$3*10^{-3}$

As a result of the experiment, the error values for single- and dual-motor drive are obtained and presented in Table 1. Figure 10 shows the response to a sinusoidal input signal with an amplitude 0.1 rad and frequency 0.5 rad/s by a conventional single-motor and dual-motor servo drive with an installed additional load. The backlash of the mechanical transmission of the single-motor drive is especially noticeable when the direction of rotation of the motor shaft is changed. The average value of the absolute value of the error in this case was $20*10^{-4}$ rad. In the dual-motor drive the backlash of the mechanical transmission is eliminated, so the average value of the absolute value of the error in this case was $1.406*10^{-4}$ rad.

At all the presented frequencies, both without and with additional load, the average value of absolute value of the error of the dual-motor drive is 14-26 times less than that of the single-motor drive. The maximum deviation of the error from the mean value of the absolute error is 1.7 to 1.8 times smaller for a dual-motor drive than for a single-motor drive. A more important indicator of drive's accuracy may be the maximum error value, shown in Figure 11. For the single-motor drive it is $4.6*10^{-3}$ rad and for the dual-motor drive it is $0.84*10^{-3}$ rad, indicating that the dual-motor drive is 5.5 times more accurate. By using a more accurate position sensor on the motor shaft of the internal servo drive, as mentioned earlier, the maximum error value can be further reduced.

Also, at reduction of the moment of inertia of the CO the average value of the absolute error of a dual-motor drive is 22-26 times less than that of a single-motor drive. As a result, in all considered cases the error of the dual-motor drive is noticeably smaller than that of the single-motor drive.

Conclusions

The results of the experimental study confirmed high accuracy of the dual-motor servo drive, which main feature is the presence of the main position feedback control loop of the control object and the absence of self-oscillations due to the usage of a controlled active torque loader and a cascaded five-loop control structure.

The drive used in the experiments has the following dynamic properties. The duration of the transient process when responding to a step reference input 0.1 rad is 0.135 s; the average value of the error in the steady state does not exceed $3.7*10^{-8}$ rad, and the maximum error in the steady state is equal to $1*10^{-4}$ rad. This shows that the investigated dual-motor servo drive is 40 times more accurate than the single-motor servo drive of the traditional structure, closed by the position control loop of the motor shaft. The experimental study also showed that the dual-motor servo drive works out a harmonic reference input signal with amplitude 0.1 rad and frequency 0.5 rad/s with a maximum value of $8.4*10^{-4}$ rad error, which is 5.5 times more accurate than the single-motor servo drive.

It was also found that the relatively low resolution of the encoder on the motor shaft is an obstacle to further improve the dynamic properties of the dual-motor drive. The results of computer simulation show that it is reasonable to use position encoder on the motor shaft of the internal servo drive with higher resolution. In particular, when using an encoder that generates 5000 pulses per revolution, the accuracy of a dual-motor servo drive will be 400 times higher than the accuracy of a single-motor servo drive.

When the moment of inertia of the control object is increased by 4 times, the presented accuracy improvement with a dual-motor drive is also maintained. However, when the moment of inertia changes more significantly, it is advisable to adaptively adjust the value of the ISD velocity controller gain and the velocity feedback coefficient of the control object in order to maintain high dynamic properties of the drive.

The experimental results confirm the results of theoretical studies comparing the accuracy of traditional single- and dual-motor servo drives presented in [2, 3] and [10, 11].

Thus, the dual-motor servo drives considered in this paper, have high dynamic accuracy. They are recommended for building technological robots with manipulation mechanisms with an open kinematic chain, when they are analytically programmed, and intended for technological operations requiring increased accuracy of movements, for example, for robotic milling or laser marking.

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