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RESULTS OF RESEARCH ON BACKLASH COMPENSATION IN A POWER ELECTRIC DRIVE BY LOW-POWER ELECTRONIC DEVICE

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Abstract. This article considers the feasibility of restoring and maintaining the kinematic accuracy of the support-rotary device drives by introducing a backlash compensation device into the control system. The power electromechanical drives of support-rotary device considered in this article contain two motors, the summation of the torques of which is carried out on a common output shaft. It is shown that the restoration of the required kinematic accuracy of the drives can be achieved by introducing one of two variants of an electronic device for backlash compensation into the control system. In the first variant, equal and opposite displacement signals are introduced into the control signals of the motors. The second variant introduces an electronic cross-connections backlash compensation scheme was into the control system. The study of the operation of the support-rotary device drive system with two backlash compensation devices carried out by a simulation method showed that the use of a cross-connection scheme is the most preferable and effective.

As a result of the research, it was shown that the introduction of an electronic backlash compensation device into the control system makes it possible to ensure the operability of the power electromechanical drives of a support-rotary device with initial kinematic accuracy.

Keywords: Backlash, backlash compensation device, multi-motor drive, tandem control.

1. Introduction

The long-time presence of a large-sized support-rotary device (SRD) in an open atmosphere leads, as a result of corrosion, to the appearance of additional gaps in the gearboxes, and this impairs the kinematic accuracy of electromechanical drives. It was found that after the 30 years of SRD being in the open air, the gears of the drive systems were corrosive, as a result of which the loss of the metal layer occurred, which in turn led to the appearance of backlash (gaps) and a decrease in the kinematic accuracy of the drive system [1]. The restoration of the kinematic accuracy of the electromechanical drive of a large-sized SRD after a long stay in an open atmosphere is of a great practical importance, and the way to restore it is an actual scientific task.

There are known ways to compensate for backlash in mechanical transmissions of electromechanical drives, described in [2–10], based on the following principles:

a) using mechanical spring devices to compensate for backlash [2];

b) frequency correction and system bandwidth degradation [4, 5];

c) the use of a backlash and elastic deformation sensor [5, 6];

d) converting signals from speed and torque sensors to determine the amount of backlash and elastic deformations [4, 7];

e) introducing a nonlinear corrective element "dead zone" into the error signal circuit [6].

Since the drive systems of SRD consist of two drives operating with the same load (Figure 1), it is possible to restore the kinematic accuracy by using special drive channels control circuits to compensate the backlash and improve the operation in dynamic tracking modes.

The greatest development in the multi-motor electric drive was made using two ways of backlash compensation. The first way of backlash compensation is similar to the operation of an "electromechanical spring", based on the creation of, opposite in sign, but equal in magnitude, torques that compensate for the gap, which is implemented by introducing constant displacements of a constant value into the control signals of the motors of the drive. Methods to implement this way are described in [11–17]. Another way is "tandem control", based on phase displacement of control signals for individual electric motors, depending on the calculated coordinates [18–24]. A feature of this way is the need to carry out a large amount of calculations and build a complex digital control system using microprocessors for its implementation.

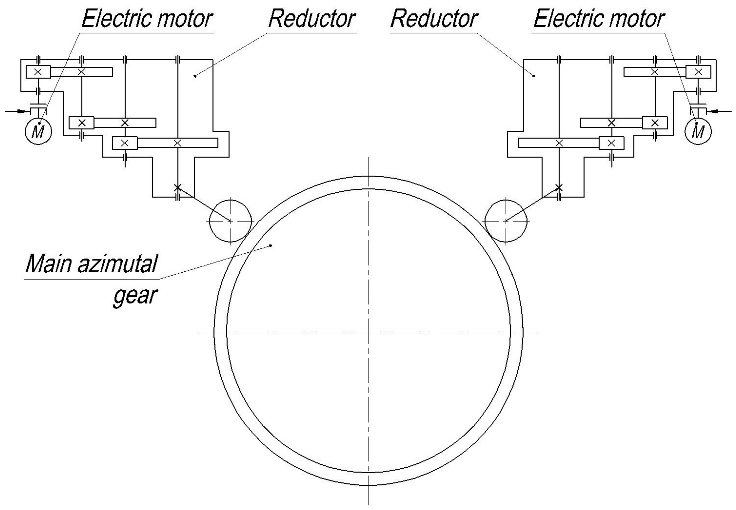


Figure 1. Kinematic diagram of support-rotary device drive.

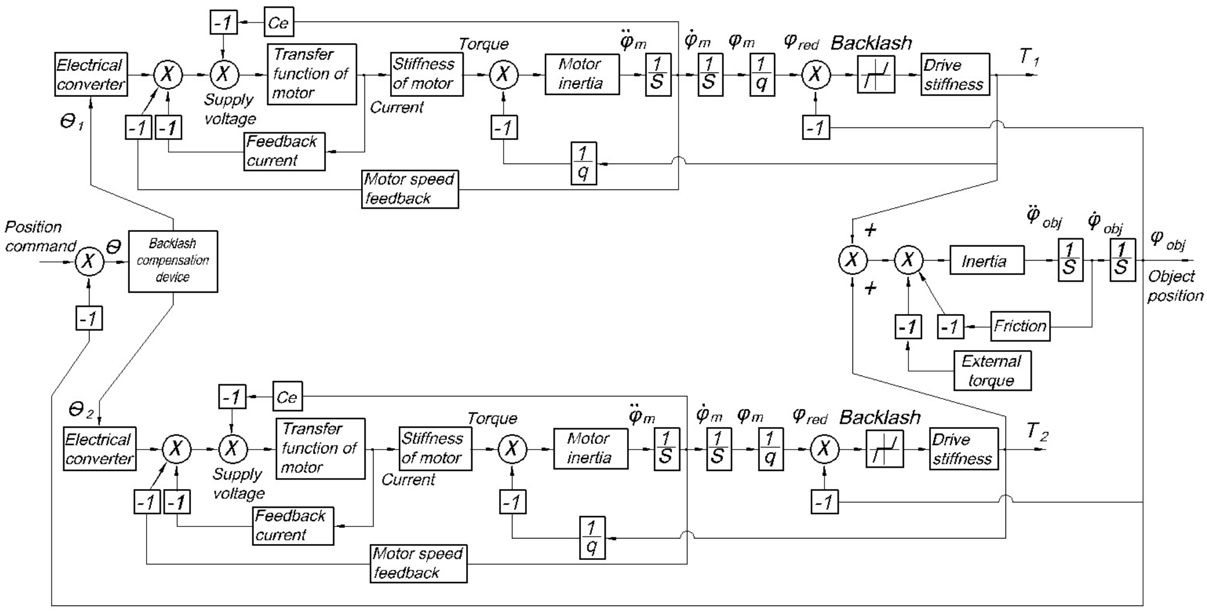


Figure 2. Block diagram of a system with non-linearity of backlash.

2. Methods

The article discusses two ways to compensate for the backlash of a multi-motor electric drive gears, based on the transformation of a dynamic error signal: the well-known method of backlash compensating with the introduction of displacement signals (electromechanical spring) [11–17], and a newly developed method with a delay of the dynamic error signal [25]. Each of the methods is implemented by a special electronic device introduced into the dynamic error channel of the electro drive.

A comparison of the schemes was carried out by mathematical modelling. The simulation was carried out in the MatLab Simulink software environment, a mathematical model of the investigated drive system was compiled, consisting of two motors operating on a common load and the backlash model in the form of a dead zone coupled with transmission stiffness. The block diagram of the developed model is shown in Figure 2. The parameters of the SRD drives are considered using the example of the signal $\varphi(t) = A sin\ (\omega t)$. The following parameter values are used in the model: electric motor armature voltage – 440 V; armature current – 115 A; rated power of the electric motor – 45 kW; rated speed – 750 rpm; the moment of inertia of the rotor – 2.575 kgm^2; gear ratio of the gearbox – 400; backlash of mechanical transmissions – 0.017 deg.

Initially, the operation of an idealized drive without any backlash was simulated, as a result, the reference characteristics of the drive with the guidance signal was obtained. Then backlash was introduced into the model and the results of its impact were considered. Then, one of the electronic devices for backlash compensation was introduced into the control system of the drives and the parameters were synthesized until

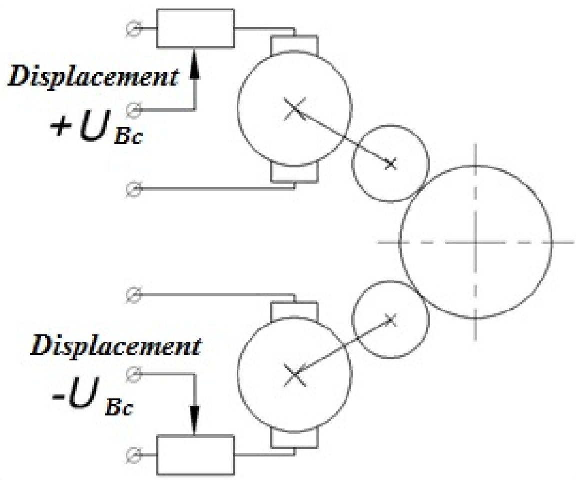


Figure 3. Backlash compensation with connecting additional supply voltages.

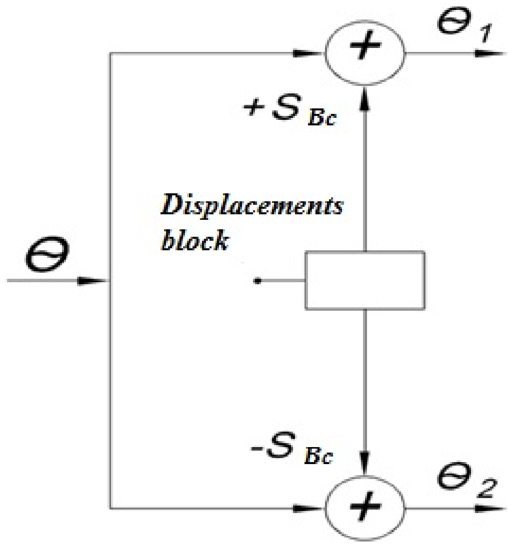


Figure 4. Backlash compensation device scheme on input of displacement signals.

the reference characteristics of the SRD drives corresponding to the idealized model without backlash was obtained.

3. Backlash compensation device with input of displacement signals

In the well-known scheme with an input of displacement control channels (electromechanical spring scheme), a certain constant displacement signal is supplied to each channel, equal in magnitude and different in sign. This creates an expansion of two gears relative to the common wheel. In the first known works [2], the thrust torques were created by additional supply voltages to the electric motors (Figure 3).

Later, to create thrust torques, instead of supplying voltages to the motors, an electronic device was used, which introduces displacements into the dynamic error signal (Figure 4), which is created by the preliminary displacement block [3]. This ensures opposite torques of the motors at zero value of the control signal, similar to the action of a spring.

The control signal θ in a system with the main position feedback is a dynamic error signal. When a control signal arrives, for example, a positive one, the signal value in the corresponding channel is added to the offset signal, and in the opposite channel, the offset signal is subtracted from the control signal. If the values of the control signals are lesser than the offset value, it creates a thrust torque to compensate for backlash in the system. When the value of the control signal exceeds the offset value, the signal in the second channel will change sign, and both motors will create torques in the same direction.

4. Backlash compensation device with cross connections

The disadvantage of the known method of backlash compensation, based on the introduction of displacement signals, is the low efficiency of the electric drive due to the high mutual loading of the electric motors. In the process of research, in order to compensate for the influence of backlash in gears, to ensure the summation of the dynamic capabilities of the channels in the steady-state motion mode, as well as to decrease the mutual torques and increase the efficiency, a control scheme for the drive channels with the introduction of cross-connections has been developed. The scheme implements a method for backlash compensation by introducing a delay into the dynamic error signal of one of the drive channels. The developed scheme of the backlash compensation device will be called a cross-connections scheme (Figure 5).

This scheme can be considered as a special type of tandem control, in which the phase shift is carried out not by calculating the coordinates of individual electric motors, but by converting the error signal by introducing a dynamic delay that depends on the value of backlash.

The backlash compensation device consists of two splitters, two switches, two aperiodic links with time constants T_1, T_2, a signal module extraction block, four multiplying blocks, and two summing blocks. The input of the backlash compensation device is branched with a splitter to three outputs. Two outputs are connected to corresponding switches. One output of the switch is connected to the first input of the summator through the first product block, and the second through the aperiodic link. The second product block forms a cross-connection line to the second input to the second summator. Switches are configured for positive and negative dynamic error signal. The outputs of the switches are signals (0, 1) and (-1, 0), respectively. After the switch, one of the branches includes a signal module extraction block, which is necessary to match the signs of signals at the outputs of the products blocks, the second inputs of the four product

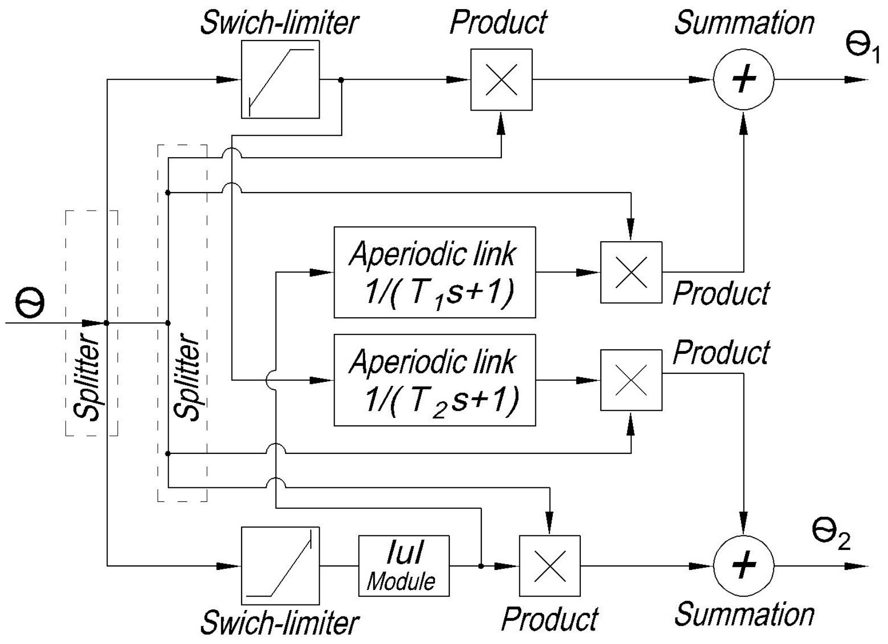


Figure 5. Scheme of backlash compensation device with cross-connections.

blocks are connected to the remaining outputs of the input signal splitter. The signals from the outputs of the summation blocks are the output signals of the backlash compensation device θ_1, θ_2.

The principle of operation of a cross-connections scheme is based on the phase shift of the signal in the second channel, the value of which is selected depending on the amount of backlash. For this purpose, aperiodic links with time constants T_1, T_2 are used. Initially, the values of the time constants are equal to $T_1 = T_2$, then the value – $T_{1,2}$ is selected depending on the individual parameters of a separate channel.

It is known that the backlash has the greatest influence in the tracking system when the direction of movement is changed; in that moment, there is a change in the working surfaces (sides) of the gear teeth, and for the time of this switching, the system appears to be open. Changing the direction of movement of the control object requires switching channels. Switches are used to prevent the backlash from opening when the direction of movement is changed. For this purpose, switching filters and cross-connections are used.

In the mode of steady motion, after the end of the transient processes, the signal in the second channel is close to the signal in the first channel, therefore, both channels operate in the same direction, in this mode of movement, the drive torques are summed up.

The backlash in mechanical transmissions causes amplitude limiting and phase displacement during the guidance signal processing. If the selected time constants T_1, T_2 provide a displacement in the second channel greater than the displacement produced by the action of the backlash, then in the electric drive consisting of two motors connected by a common mechanical transmission, there will be thrust torques for backlash compensation.

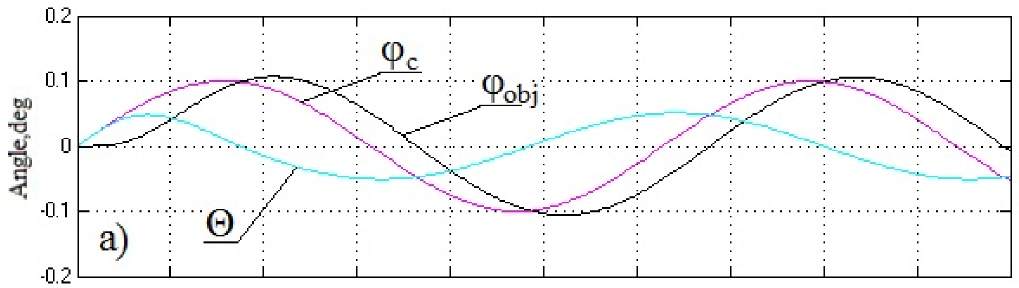
5. Experiment results

The study of the electric drive operation with a backlash was carried out by simulating in Simulink using the example of a harmonic guidance signal. The results of the operation of the drive under study with the known scheme of the backlash compensation device based on the introduction of displacement signals are shown in Figure 6. It follows from the graphs that the dynamics of the drive is close to the dynamics of an idealized model without any backlash. The smoothness of the change in the coordinates of the electric drive is ensured in the entire range of development (Figure 6a). Figure 6b shows significant thrust torques exceeding the required total torque.

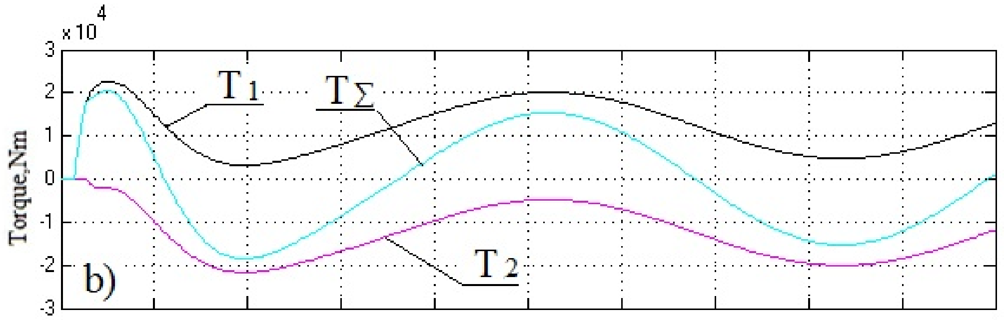
A significant amount of energy is spent on mutual torques of the motors, which leads to a decrease in the efficiency of the electric drive, which does not exceed 30 % in the steady-state motion mode (Figure 6c).

The simulation results show that the use of a backlash compensation device with an input of displacement signals makes it possible to compensate for the effect of backlash caused by corrosion and ensure the required accuracy of operation. The operating parameters, in terms of processing the control signal, are as close as possible to the parameters of the drive without backlash, however, the high thrust torque leads to high energy costs and a decrease in efficiency.

The results of the operation of the drive with a cross-connection backlash compensation device when small values of T_1,$T_2 = 0.2$ s are selected (the displacement in the second channel is lower than the displacement produced by the backlash) and when a harmonic guidance signal arrives are shown in Figure 7. The simula-



(A).



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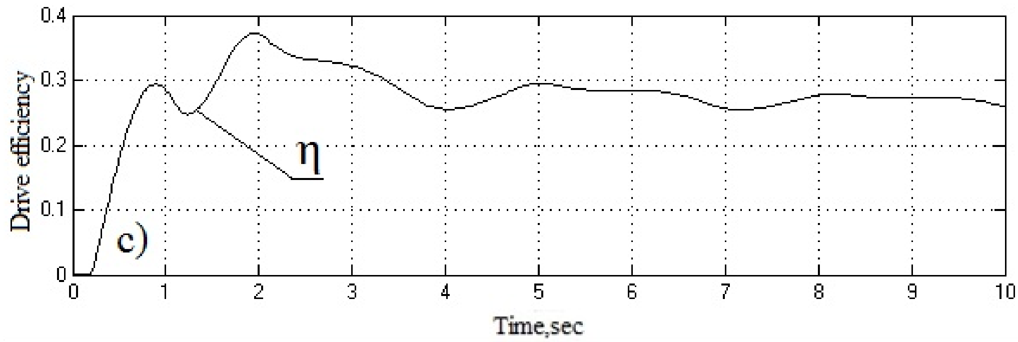


(C).

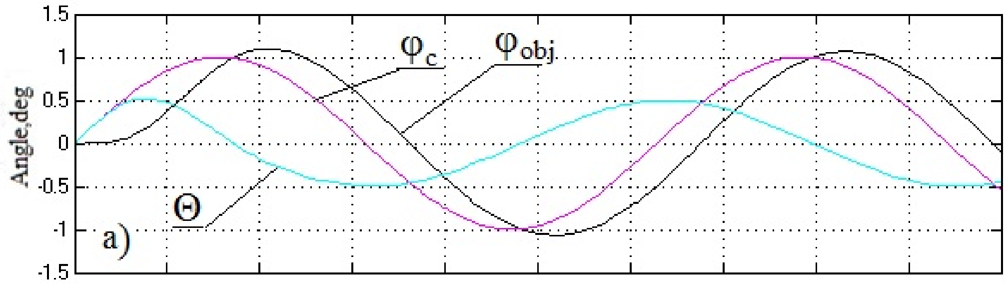
FIGURE 6. The operation of the drive with a backlash compensation device with input of displacement signals with harmonic guidance signal: a) guidance signal – φ_c, execution of the guidance signal by the drive – φ_{obj}, and dynamic system error signal θ; b) torques developed by motors and total drive torque; c) efficiency of the electric drive.

tion showed the drive execution to the guidance signal; when the sign of the dynamic error signal changes, a shift in the amplitudes of the torques of individual motors is observed (Figure 7b), which compensates for the backlash effect. A feature of the work is the absence of thrust torques. Figure 7c shows the change in the efficiency of the electric drive, which in the steady state motion mode, approaches 80 %.

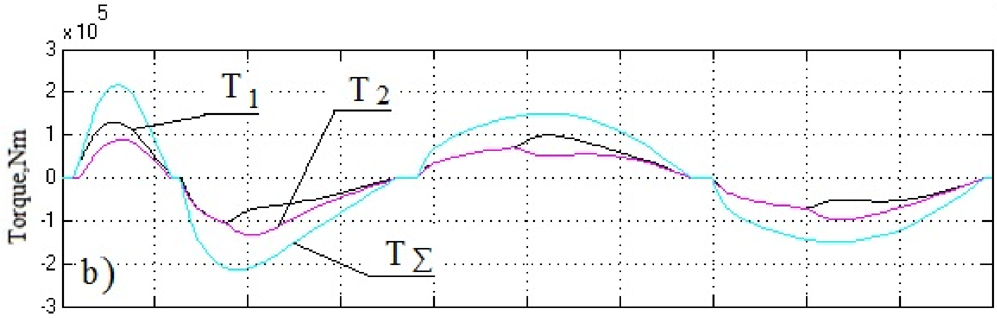
Figure 8 shows the harmonic guidance signal processing by the drive when high values of the time constants T_1, $T_2 = 1.0$ s are selected. In Figure 8b, you can see that an increase in the time constants led to the appearance of thrust torques, which function in almost the entire operating range. Thus, when choosing high values of the time constants T_1, T_2, the backlash is compensated by creating thrust torques by an electric drive, similar to the action of the known device with the input of displacement signals. The disadvantage of this mode, as in the case of the known device, is the decrease in efficiency of the electric drive (Figure 8c), which in the mode of steady motion is in the range of 30–40 %.

The dependence of the efficiency of the electric drive on the selected values of the time constants T_1, T_2 is shown in Figure 9. The graph was obtained by simulating the processing of a harmonic guidance signal with an amplitude of 1^0 by an electric drive. The figure shows that an increase in the time constants T_1, T_2 leads to a decrease in efficiency, since thrust torques begin to appear in the system, which leads to energy losses.

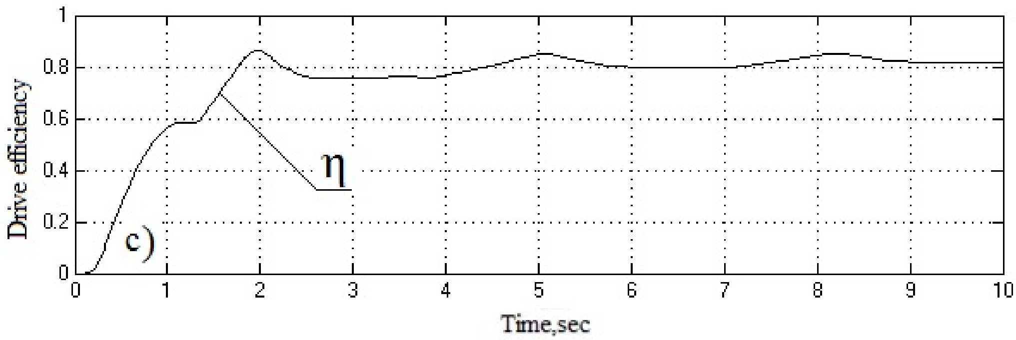
By simulation, it was found that for the selected guidance signal and the amount of backlash, there is such a value of the time constant – T_1, $T_2 = 0.65$ s, at which the phase displacement in the second channel is close to the displacement produced by the backlash. Relative to this point, a combined graph of the dependence of the efficiency of the electric drive and



(A).



(B).



(C).

FIGURE 7. Operation of the drive with a cross-connection backlash compensation device with a harmonic guidance signal when small values of the time constants T_1, T_2 are selected: a) guidance signal – φ_c, execution of the guidance signal by the drive – φ_{obj}, and dynamic system error signal θ; b) the torques developed by the motors and total drive torque; c) the efficiency of the electric drive.

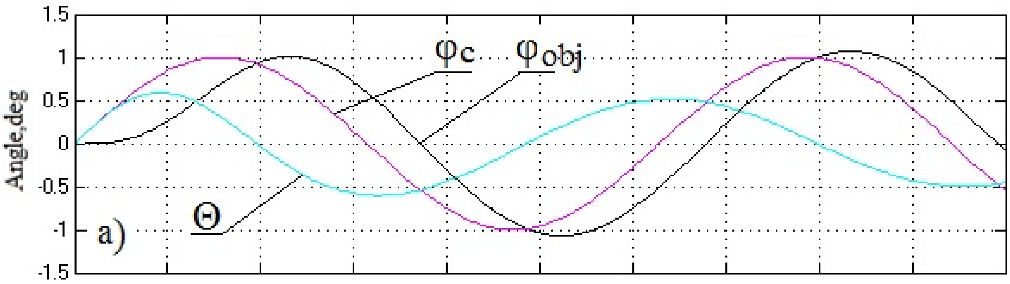
the torques of individual motors on the value T (Figure 10) is plotted. For convenience, this point will be called the transition point. When choosing values – T_1, T_2 to the left of the transition point, the electric drive will operate without thrust torques, to the right – there will be thrust torques in the system. An increase in the values of T_1, T_2 significantly to the right of the transition point will lead to a decrease in the participation of the second channel in joint work, up to the transformation of the drive into a single-channel drive with a passive load.

This graph is only valid for a specific backlash value and guidance signal parameters. When the values T_1, $T_2 = 0$ are selected, the drive will operate without displacements and the signals in the channels will be equal.

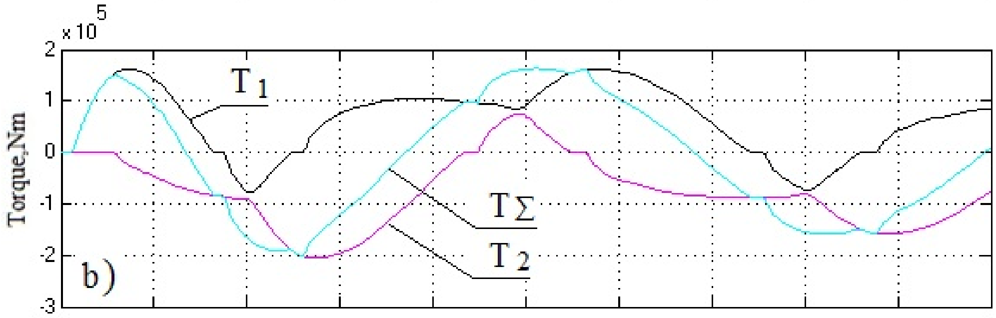
An increase in backlash will lead to a shift of the transition point to the right, a decrease in backlash – to the left. Specific values – T_1, T_2 depend on the speed parameters of electric motors and power amplifiers, therefore, the choice of values must be made individually, based on a combination of parameters.

When considering the operation of the cross-connections backlash compensation device, it was found that the electric drive can operate with the device in two modes of operation: with thrust torques and without thrust torques. The thrust torques mode (Figure 8) occurs when the control signal in the second channel (reversible) has a displacement greater than the displacement caused by the backlash.

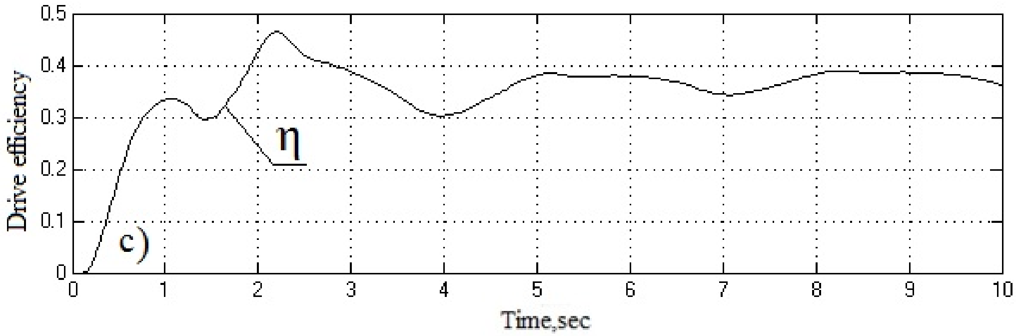
Without thrust torques (Figure 7), the indicated displacement is lesser than the displacement produced by the backlash, and in this mode, the electric drive operates more efficiently. If the drive operates only with certain, previously known guidance signals, then it is possible to fine-tune the operating modes of the cross-connections backlash compensation device (with or without thrust torques). When the drive is operating



(a).



(b).



(c).

Figure 8. Operation of the drive with a cross-connection backlash compensation device with a harmonic guidance signal when large values of the time constants T_1, T_2 are selected: a) guidance signal – φ_c, execution of the guidance signal by the drive – φ_{obj}, and dynamic system error signal θ; b) the torques developed by the motors and total drive torque; c) the efficiency of the electric drive.

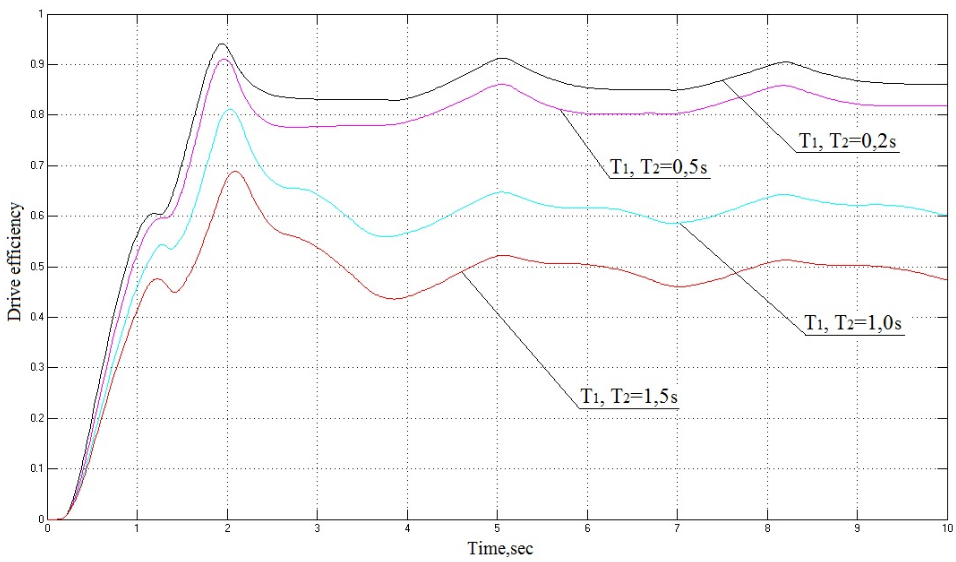


Figure 9. The dependence of the efficiency of the electric drive on the selected values of the time constants T_1, T_2.

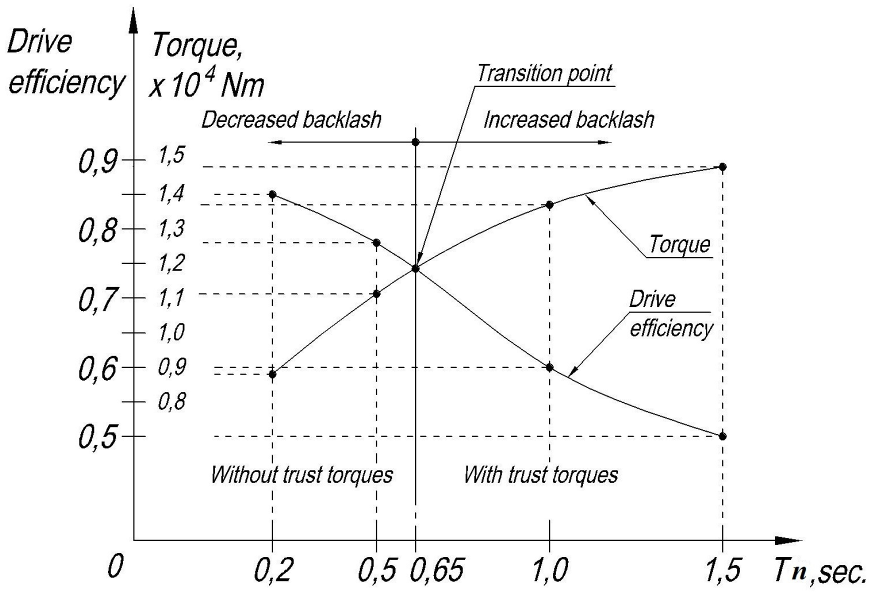


Figure 10. A combined graph of the dependence of the drive efficiency and the torques of individual motors on the value – T.

with arbitrary (random) guidance signals, a variable operation of the electric drive with backlash in gears in two modes is possible: with and without thrust torques.

6. Comparison results

The comparison of the schemes of the backlash compensation devices shows that the device based on the introduction of the displacement signal is the simplest to implement and gives an effect similar to the effect of a mechanical spring. The simulation results shown, when choosing the smallest value of the error signal displacements according to the condition of the absence of self-oscillations, one of the channels develops a torque that is almost twice the required one (Figure 6b), while excess energy is expended to create thrust torques. The effect of backlash compensation in the dynamics is achieved by significant energy losses for the mutual torques of the channels. The efficiency of a drive with a device with an input of displacement signals with a harmonic guidance signal does not exceed 40 %.

The cross-connection scheme shows that, when a small value of the time constant of the aperiodic block is selected due to the absence of self-oscillations in the steady-state mode of motion, the summation of the torques of individual motors is provided; the backlash is compensated by shifting the control signals in individual channels. The dynamics of the main movement is close to the dynamics of the ideal model without any backlash. The efficiency of the electric drive approaches 80 % when processing the harmonic guidance signal.

An increase in the time constants T_1, T_2 of the aperiodic links leads to a change of the operation of the electric drive. The thrust torques of the electric drive appear (Figure 8b), which increases the energy consumption and leads to a decrease in efficiency (Figure 8c), similar to the device with an input of displacement signals.

The use of a backlash compensation device for a drive containing two control channels will ensure the required kinematic accuracy of drive systems during the operation and will not require any additional effort to restore accuracy.

The simulation showed that the developed device for backlash compensation with cross-connections allows ensuring the accuracy of an electromechanical drive with backlash in mechanical transmissions, and compensating for the gap caused by prolonged idling periods so that when the dynamic error signal changes, it creates a shift in control signals in individual channels, providing a compensation for backlash, and in the mode of steady motion, it creates the summation of the torques of the channels.

When choosing large values of the time constants T_1, T_2 of a cross-connection device, the backlash is compensated by creating thrust torques, similar to a device with an input of displacement signals; in this case, the efficiency does not exceed 40 %. The choice of small values of the time constants T_1, T_2 of the aperiodic links of the backlash compensation device provides high-speed performance, an increase in the accuracy of operation (the value of the dynamic error is lower (Figure 7a)) and an increase in efficiency of up to 85 %.

An analysis of the operating parameters of a drive with various schemes for constructing backlash compensation devices testifies that it is advisable to use a circuit with cross-connections.

7. Conclusions

(1.) The conducted research on compensation of backlash in mechanical transmissions of a power electromechanical drive by introducing various devices for backlash compensation shows that the devices provide the required dynamic characteristics with different energy efficiency.

(2.) The proposed electronic device for backlash compensation allows, due to the transformation of the signal of the dynamic error of the system in low-power electrical control circuits, to create a shift of signals in each channel so that when the sign of the signal of the dynamic error changes, it compensates for the backlash, and when the motion is steady, the torques of the individual motors are summed up.

(3.) It is shown that the proposed cross-connection backlash compensation scheme provides a kinematic accuracy with increased efficiency, which is two times higher than the efficiency of the circuit with the input of displacement signals.

References

[1] S. L. Samsonovich, R. V. Goryunov. Research of the influence of atmospheric corrosion on the kinematic accuracy of the drive of a large-sized supporting and rotating device. *Handbook An engineering journal* (2):16–22, 2019. https://doi.org/10.14489/hb.2019.02.pp.016-022.

[2] P. V. Belyanskiy, B. G. Sergeev. *Control of terrestrial antennas and radio telescopes [in Russian]*. Sovet radio publishing house, Moscow, 1980.

[3] A. A. Kirillov, V. G. Stebletsov. *Bases of the electric drive of aircraft. Tutorial*. Biblio-Globus publishing house, Moscow, 2013. [2020-03-05], https://rucont.ru/efd/260901.

[4] M. Nordin, P.-O. Gutman. Controlling mechanical systems with backlash – a survey. *Automatica* **38**(10):1633–1649, 2002. https://doi.org/10.1016/S0005-1098(02)00047-X.

[5] R. M. R. Bruns, J. F. P. B. Diepstraten, X. G. P. Schuurbiers, J. A. G. Wouters. Motion control of systems with backlash, 2006. DCT rapporten; Vol. 2006.075 [2020-02-16], https://pure.tue.nl/ws/files/4295876/633392.pdf.

[6] B. K. Chemodanov. *Servo drives [in Russian]*. Bauman MSTU publishing house, Moscow, 1999. ISBN 5-7038-1383-2.

[7] L. Márton. Adaptive friction compensation in the presence of backlash. *Control engineering and applied informatics* **11**(1):3–9, 2009.

[8] R. R. Selmic, F. L. Lewis. Neural net backlash compensation with Hebbian tuning using dynamic inversion. *Automatica* **37**(8):1269–1277, 2001. https://doi.org/10.1016/S0005-1098(01)00066-8.

[9] G. Tao, F. L. Lewis. *Adaptive control of nonsmooth dynamic systems*. Springer-Verlag, London, 2001. ISBN 978-1-84996-869-0, https://doi.org/10.1007/978-1-4471-3687-3.

[10] S. Suraneni, I. N. Kar, O. V. Ramana Murthy, R. K. P. Bhatt. Adaptive stick-slip friction and backlash compensation using dynamic fuzzy logic system. *Applied Soft Computing* **6**(1):26–37, 2005. https://doi.org//10.1016/j.asoc.2004.10.005.

[11] V. V. Yavorsky. Backlash compensation device in a two-motor electric drive, 1980. Patent SU746399, Bull. No. 25.

[12] Y. Postnikov, et al. DC twin-motor driver, 1984. Patent SU1075360A, Bull. No. 7.

[13] Y. Oho, K. Iijima. Motor control device and motor control method, 2019. Patent US 2019/0079487 A1.

[14] T. Uchida, A. Ito, N. Furuya, T. Oshima. 3D14 positioning system based on twin motor cooperative control with gear backlash compensation. *The Proceedings of the Symposium on the Motion and Vibration Control* pp. 3D14–1–3D14–12, 2010. https://doi.org/10.1299/jsmemovic.2010._3D14-1_.

[15] W. Zhao, X. Ren. Adaptive robust control for four-motor driving servo system with uncertain nonlinearities. *Control Theory and Technology* **15**(1):45–57, 2017. https://doi.org/10.1007/s11768-017-5120-7.

[16] F. Xu, H. Wang. Clearance elimination method with two motors based on fuzzy control for turntable. In *Proceedings of the Seventh Asia International Symposium on Mechatronics*, pp. 702–710. Springer Singapore, Singapore, 2020. https://doi.org/10.1007/978-981-32-9437-0_72.

[17] M. Deng. *Operator-based nonlinear control systems: design and applications*. Wiley–IEEE Press, Piscataway, 2014. ISBN 978-1-118-13122-0.

[18] T. Uchida, A. Ito, T. Kitamura, N. Furuya. Positioning system with backlash compensation by twin motor cooperative control (Evaluation of rectilinear motion mechanism installed planetary gear speed reducer). *Transactions of the JSME (in Japanese)* **80**(814):DR0162, 2014. https://doi.org/10.1299/transjsme.2014dr0162.

[19] W. Gawronski, J. J. Beech-Brandt, H. G. Ahlstrom, E. Maneri. Torque-bias profile for improved tracking of the Deep Space Network antennas. *IEEE Antennas and Propagation Magazine* **42**(6):35–45, 2000. https://doi.org/10.1109/74.894180.

[20] Z. Haider, F. Habib, M. H. Mukhtar, K. Munawar. Design, control and implementation of 2-DOF motion tracking platform using drive-anti drive mechanism for compensation of backlash. In *2007 International Workshop on Robotic and Sensors Environments*. 2007. https://doi.org/10.1109/ROSE.2007.4373968.

[21] S. G. Robertz, L. Halt, S. Kelkar, et al. Precise robot motions using dual motor control. In *2010 IEEE International Conference on Robotics and Automation*. 2010. https://doi.org/10.1109/ROBOT.2010.5509384.

[22] Y. Toyozawa, K. Maeda, N. Sonoda. Tandem control method based on a digital servo mechanism, 1997. Patent US005646495A.

[23] S. Tararykin, et al. Method for controlling interconnected electric motors (variants), 2008. Patent RU2316886C1, Bull. No. 18.

[24] I. Polyushchenkov, et al. Method of the interconnected electric drives coordinates adjustment, 2018. Patent RU2655723C1, Bull. No. 16.

[25] S. L. Samsonovich, B. K. Fedotov, R. V. Goryunov. Method and device for selection of backlash in kinematic transmission of support-rotary device with two interconnected electric drives, 2020. Patent RU2726951C1, Bull. No. 20.