Investigation of efficiency of electric drive control system of excavator traction mechanism based on feedback on load

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Abstract. The article presents the results of a study of the efficiency of the electric drive control system of the traction mechanism of a dragline based on the use of feedback on load in the traction cable. The investigations were carried out using a refined electromechanical model of the traction mechanism, which took into account not only the elastic elements of the gearbox, the backlashes in it and the changes in the kinematic parameters of the mechanism during operation, but also the mechanical characteristics of the electric drive and the features of its control system. By mathematical modeling of the transient processes of the electromechanical system, it is shown that the introduction of feedback on the load in the elastic element allows one to reduce the dynamic loads in the traction mechanism and to limit the elastic oscillations of the actuating mechanism in comparison with the standard control system. Fixed as a general decrease in the dynamic load of the nodes of traction mechanism in the modes of loading and latching of the bucket, and a decrease the operating time of the mechanism at maximum load. At the same time, undesirable phenomena in the operation of the electric drive were also associated with the increase in the recovery time of the steady-state value of the speed of the actuating mechanism under certain operating conditions, which can lead to a decrease in the reliability of the mechanical part and the productivity of the traction mechanism.

1. Introduction
An increase in the speeds of movement and loads of modern excavators and the presence in the kinematic chain of traction mechanisms of elements with pronounced elastic properties lead to the appearance of significant dynamic loads, elastic deformations of the links and oscillation of the actuating mechanism in transient operating modes, which in turn increase the duration of transient processes, reduce the productivity and reliability of excavators [1-3]. An effective means of limiting dynamic loads and reducing the level of oscillational movements in digging and lifting mechanisms is to use the capabilities of the modern electric drive and its control system, which allow one to form a given character of motion and control the torque in a wide range of disturbance frequencies [4-11]. At present, the main way to limit dynamic loads in the excavator's actuating mechanisms by means of an electric drive is to use feedbacks on the load in the elastic element [12, 13]. Studies of the effectiveness of feedbacks on the load in these research were carried out on the basis of a simplified
two-mass model of the mechanical system of the traction mechanism of the excavator. A refined mathematical model of the traction mechanism of the walking excavator ESh 20.90 was proposed in work [14] in the form of a four-mass electromechanical system that took into account not only the elastic elements of the gearbox, the backlashes in it and the changes in the kinematic parameters of the mechanism during operation, but also the mechanical characteristics of the drive and the features its control system. In this article, we present the results of a study of the efficiency of the electric drive control system of the traction mechanism of a walking excavator with feedback on the load in the traction cable based on the refined electromechanical model of the mechanism.

2. Object and methods of research

In drawing up the dynamic model of the traction mechanism, the following assumptions were adopted [14]: the masses of the main elements of the traction mechanism are concentrated; elastic elements are the connecting shafts of the gearbox and the rope, which was presented in the form of a weightless elastic system with variable stiffness and viscous friction coefficients; there are backlashes in the first and second stages of the gearbox and internal friction of the moving masses; the moment of inertia of the bucket depends on the degree of its filling as a function of the path traveled. In the dynamic model of the traction mechanism, the mechanical characteristic formed by the electric drive and limiting the maximum acceleration at start-up were also taken into account. Under the assumed assumptions, the design scheme of the mechanism was presented in the form of a four-mass electromechanical system. The control of elastic oscillations in the mechanical system was carried out with an electric drive with a standard two loop subordinate control system of the thyristor converter- DC-motor, using flexible and rigid feedback on the load in the elastic element, which was connected to the input of the speed controller, what allows one to keep the current limitation to form a mechanical characteristic. The combined structural scheme of the refined electromechanical model with flexible and rigid feedbacks on the load in the elastic element is shown in figure 1.

![Figure 1. Structural scheme of electromechanical model with feedbacks on load.](image)

The speed of the drive was set in block $U_{ref}$ and the shape of the mechanical characteristic, the cutoff and stopping torque – in the Mech_character subsystem. The $U_{scop}$ unit limited the mismatch at the input of the current controller, which allows forming the required acceleration (deceleration) of the drive during start (reverse). The dynamic characteristics of the gearbox were modeled by the Gearbox unit. The changes in the rope's stiffness, the viscous friction in it and the moment of inertia of the working element, depending on the path traveled by the bucket, were taken into account by the Cable_bucket unit. Calculation of parameters of the feedback on load in the traction element was carried out according to the procedure described in work [12].

In accordance with the notation of the structural scheme adopted in [14], the calculated values of the model parameters were as follows: $U_{scop} = -10...1.3; U_{ref} = 0...10; K_{SS} = 0.151; K_{1} = 10; K_{2} = 8; K_{SR} = 8; K_{CS} = 0.00313; K_{CR}(P) = 0.341; T_{CR}(I) = 4; K_{p} = 120; T_{b} = 0.01 sec; C_{e} = 17.37; K_{a} = 33; T_{u}$
=0.082 sec; \( J_1 = 301; J_2 = 215; J_3 = 63.5; J_0 = 30 \text{ kg} \cdot \text{m}^2; \ c_{12} = 349650; \ c_{23} = 58173 \frac{N \cdot m}{\text{rad}}; \ b_1 = 1000; \ b_2 = 500 \frac{N \cdot s}{m}; \ a_1 = a_2 = a_3 = 20; \ \varepsilon_1 = 0.03 \text{rad}; \ \varepsilon_2 = 0.2 \text{rad}; \ E_k = 12300000000 \text{ Pa}; \ F_k = 0.00188 \text{ m}^2; \ L_{\text{max}} = 100 \text{ m}; \ K_z = 2; \ K_{\text{on}} = 0.000251; \ K_{\text{on}} T_{\text{on}} = 0.000002342.

The traction mechanism of the excavator operates in intensive short-time modes with frequent start-up, revers, significant oscillation loads during digging and latching bucket in almost every cycle of excavation. Since the load is insignificant during the start-up of the mechanism, since the empty bucket is just beginning to go deeper into the rock, the study of the load-step modes and the latching bucket is of the greatest interest. Investigations have been carried out for the load-step mode \( M_c = 1.5 M_{\text{nom}} \) when the mechanism is operating at rated speed \( \omega_{\text{nom}} \) with preload \( M_c = 0.5 M_{\text{nom}} \) and with subsequent latching bucket \( M_c = 3 M_{\text{nom}} \). Assessment of loads in the transmission in the transient modes was carried out on the following quantitative characteristics: the maximum torque in the \( i \)-th element of the transmission (\( M_{i_{\text{max}}} \)); the integral load in this element (\( M_{i_{\text{int}}} = \frac{1}{T} \int_0^T M_i dt \)) and the integral square-law load (\( M_{i_{\text{int}}}^2 = \frac{1}{T} \int_0^T (M_i)^2 dt \)) in it.

To evaluate the effectiveness of the influence of feedbacks on dynamic loads and elastic oscillations of the traction mechanism of the excavator in the transient operating modes, a numerical simulation of the electromechanical system in the Matlab Simulink (shown in figure 1) was carried out.

3. Research and discussion of results

The following parameters of the electromechanical model of the traction mechanism of the excavator were monitored during the simulation: motor torque \( M_{dv} \); the torque in the first stage gear, \( M_{12} \); the torque in the second stage gear, \( M_{23} \), and the load on actuating mechanism \( M_{34} \). The obtained values of the investigated parameters for the standard system (ST) and the feedback system (F&R) are given in table 1.

| Characteristic | \( M_c = 1.5 M_{\text{nom}} \) | \( M_c = 3 M_{\text{nom}} \) | \( M_c = 1.5 M_{\text{nom}} \) | \( M_c = 3 M_{\text{nom}} \) |
|---------------|-----------------|-----------------|-----------------|-----------------|
| max \( M_{dv} \) | 1.65 | 2.14 | -1.14…1.82 | -0.89…2.4 |
| \( M_{dv_{\text{int}}} \) | 1.408 | 1.9 | 1.16 | 1.68 |
| \( M_{dv_{\text{int}}}^2 \) | 1.44 | 1.9 | 1.45 | 1.81 |
| max \( M_{12} \) | 1.87 | 2.88 | -0.17…1.8 | 3.3 |
| \( M_{12_{\text{int}}} \) | 1.426 | 2.303 | 1.29 | 2.076 |
| \( M_{12_{\text{int}}}^2 \) | 1.42 | 2.33 | 1.4 | 2.15 |
| max \( M_{23} \) | 1.96 | 3.4 | 1.7 | 3.36 |
| \( M_{23_{\text{int}}} \) | 1.428 | 2.586 | 1.375 | 2.435 |
| \( M_{23_{\text{int}}}^2 \) | 1.46 | 2.64 | 1.414 | 2.48 |
| max \( M_{34} \) | 1.9 | 3.48 | 1.64 | 3.17 |
| \( M_{34_{\text{int}}} \) | 1.402 | 2.658 | 1.382 | 2.628 |
| \( M_{34_{\text{int}}}^2 \) | 1.44 | 2.71 | 1.41 | 2.66 |
As an illustration, figure 2a shows the oscillograms of the transient processes of motor torque $M_{dv}$ and torque $M_{12}$ in the first stage of the gearbox in the load-step mode, and in figure 2b oscillograms of moment $M_{12}$ during the opening of the backlash during the formation of a significant braking torque of the motor (see zone 3 in figure 2a).

The oscillograms of the elastic torque in the second stage gear $M_{23}$ of the gearbox and on actuating mechanism $M_{34}$, as well as the speed of motor $\omega_1$ and actuating mechanism $\omega_4$, are shown in figure 3. The analysis of these oscillograms shows that the motion control by forming the required torque of the drive allows limiting the oscillations of the load torque in the transmission elements, but at the same time the speed of the actuating mechanism in the load-step mode decreases, which leads to a decrease in the productivity of the digging mechanism. The opening of backlash in the first stage of the gearbox in the load-step mode increases the loading of the gearbox and, as a result, can lead to a decrease in the fatigue life of the gears and shafts due to frequent changes in the direction of the load moment.

![Figure 2](image1.png)

**Figure 2.** Motor torque $M_{dv}$ and the torque in first stage of gearbox $M_{12}$ in case of a load-step mode (a) for ST (1) and F&R (2) and at the moment of opening backlash in the first stage of gearbox (b).

![Figure 3](image2.png)

**Figure 3.** The torques in the second stage of gearbox $M_{23}$, on actuating mechanism $M_{34}$; the speed of motor $\omega_1$ and actuating mechanism $\omega_4$ for ST(1) and F&R (2).

Executed studies of the effectiveness of the influence of feedbacks on dynamic loads and elastic oscillations of the traction mechanism of the excavator in the transient operating modes make it possible to draw the following conclusions.

1. The change in the torque of electric motor $M_{dv}$ in the load-step and latching mode has an alternating character with oscillation amplitudes $-1.1...2.2M_{nom}$ (figure 2a). The value of the braking torque of the motor depends on the value of the load on the actuating mechanism and the speed of its increase. For load-step mode, the integral torque of motor $M_{dv, int}$ is reduced by 18% for the F&R...
system, and the value of square-law moment $M_{dv\text{int} 2}$ remains practically unchanged. In the latching mode for the system with F&R, values $M_{dv\text{int}}$ and $M_{dv\text{int} 2}$ are respectively lower by 12% and 5%, compared with the standard control system.

2. The torque oscillations in the first stage of gearbox $M_{12}$ change the sign with amplitude $-0.17...1.8M_{\text{nom}}$ when the load is up, which lead to a double re-conjugation of the first stage of the gearbox (figure 2b). The values of the integral $M_{12\text{int}}$ and square-law $M_{12\text{int} 2}$ moments are reduced by 10% and 2% in the load-step mode and by 10% and 8% when the bucket is latched, respectively. The amplitude of oscillation $M_{12}$ during latching bucket increases by 14% in comparison with the standard control system, however, there is a decrease in the average load of the stage gear in the case of a load-step and when the actuating mechanism is latched. The logarithmic decrement of oscillations in the load-step mode does not change, and the transient time decreases from 2.0 seconds ($ST$) to 1.3 seconds (F&R). In the latching mode, the oscillation decrement increases from $\chi = 0.102$ ($ST$) to $\chi = 0.223$ (F&R), the stopping time is reduced from 1.1 sec ($ST$) to 0.7 sec (F&R).

3. The torque oscillations in the second stage gear $M_{23}$ of the gearbox do not change sign when the load is up and the latching mode; therefore, there is no opening of the backlash in this gear. The maximum value of torque $M_{23}$ is reduced by 14% in case of a load-step and by 2% - at a latching. The values of the integral $M_{23\text{int}}$ and square-law $M_{23\text{int} 2}$ moments are reduced by 4% and 3% in the load-step mode and by 6% and 7% - by the latching of the actuating mechanism, respectively. The logarithmic decrement of oscillations in the load-step mode decreases from $\chi = 0.12$ ($ST$) to $\chi = 0.0606$ (F&R). In the mode of latching the actuating mechanism, the decrement of the oscillations does not change; the stopping time is reduced from 1.1 sec ($ST$) to 0.7 sec (F&R). It should be noted that the increase in inertia of the mechanical part, as far as the distance from the source of the driving torque, leads to a decrease in the intensity of the decrease in the dynamic loading of the transmission elements.

4. The amplitude of torque oscillations in rope $M_{3k}$ in the load-step mode and latching when using feedbacks is reduced by 14% and 9%, respectively. The values of the integral $M_{23\text{int}}$ and square-law $M_{23\text{int} 2}$ torque are reduced by 2% in the mode of load-step and by 1% and 2% - with the latching of actuating mechanism, in comparison with the standard control system. The time of complete stopping of the actuating mechanism in the latching mode for these control systems is practically the same and is 0.8 sec. However, the stopping time of the motor in the latching mode for the feedback system is 0.7 sec, which is 0.4 sec less than with the standard control system, what reduces the operating time of the mechanism under the action of maximum loads. At the same time, there is a significant increase in the duration of recovery of the speed $\omega_2$ to a steady-state value in comparison with the standard control system, which can lead to a decrease in the performance of the traction mechanism.

In the course of the study, it was found that a decrease in the coefficient of rigid feedback on load $K_{on}$ with control of the amplitude value of the braking torque of the motor makes it possible to get rid of the negative effect of opening the backlash in the first stage of the gearbox. For example, having $K_{on} = 0.0002$ and the value of braking moment $M_{dv} < -M_{\text{nom}}$ opening the backlash in the kinematic chain of the reducer was not observed. The amplitude values of the moments in the elements of the reducer are increased by 2-3%, without a significant change in the nature of the transient processes and the loading of the transmission elements in the load-step and latching modes of the bucket. A decrease in coefficient $K_{on}$ leads to an increase in the amplitude of the oscillations of the speed of the actuating mechanism by 3%, while the logarithmic decrement of oscillations from $\chi = 0.046$ ($K_{on} = 0.000251$) to $\chi = 0.057$ ($K_{on} = 0.0002$) increases.

The analysis of the loading of the gear unit elements indicates a general reduction the load in the load-step and latching mode of the actuating mechanism for the feedback control system. However, in
the latching mode of actuating mechanism, the amplitude of the torque oscillations in the first stage of the gearbox is increased due to the alternating nature of the torque of the electric drive. The use of rigid and flexible feedbacks is most effective in digging mode when there is no complete stopping of the actuating mechanism and the load value does not reach the limit value.

4. Conclusion
The introduction of rigid and flexible feedbacks on the load in the elastic element in the traction control system of the excavator makes it possible to reduce the loading of the transmission elements, the values of which depend on the value of the load on the actuating mechanism and the rate of its change. Load parameters were reduced for all elements of the mechanism in the load-step mode; however, when the actuating mechanism was latched, a significant increase in load was observed in the first stage of the gearbox due to the excavator shape of the mechanical characteristic of the motor. There was an effect of opening the gear of the first stage of the gearbox with a load-step mode on the actuating mechanism, which is associated with the formation of a braking torque with a value of more than $-M_{nom}$. It is shown that a decrease in the coefficient of rigid feedback, provided that the braking torque of the motor is limited in magnitude $M_{br} < -M_{nom}$, allows one to get rid of the effect of opening the backlash in the kinematic chain of the gearbox, but leads to a slight increase in the amplitude of the torque oscillations in the elastic elements of the gearbox. In the course of modeling, it is established that in certain operating modes the use of feedbacks on the load in the elastic element can lead to an increase in the recovery time of the steady-state speed of the actuating mechanism and a decrease in the productivity of the traction mechanism and the reliability of its operation.

References
[1] Stepanov A G, Kornyakov M V 2014 Machine Dynamics (Irkutsk: Irkutsk State Technical University) p 412
[2] Kozyaruk A E, Taranov S I, Samolazov A V 2014 Directions for increasing the efficiency of operation of excavator-car complexes in open-cast mining. Mining equipment and electromechanics. 16–11
[3] Kuznetsov N K, Makhno D E, Iov, I A 2017 Damping elastic oscillations of digging mechanism, IOP Conference Series: Earth and Environmental Science Vol. 87(2) p 6
[4] Malafeev S I, Novgorodov A A, Serebrennikov N A 2012 The new excavator ECG-18R: a system of DC drives with pulse-width control. Mining equipment and electromechanics. 6 21–25
[5] Joint Power Company 2012 Research of the work of the main drives of the excavator ECG-18R. Moscow
[6] Ganin A R, Donchenko T V, Shibanov D A 2013 Practical results of introduction of excavators of new product line of «IZ-Karteks named after P G Korobkov» at the Russian mines. Mining industry 2(108) 1–6
[7] Malafeev S I, Anuchin A V, Serebrennikov A N 2013 Excavator ES-11/75 with a new control system for mining equipment. Mining equipment and electromechanics 2 6–14
[8] Leonenko A S 2010 Methods and technical solutions to increase the efficiency of operation of mining machines in cold area: monograph (Irkutsk: Irkutsk State Technical University) p 280
[9] Samoylenko A M 2013 System automatics regulation tension of elevating and traction ropes excavating machine at digging. Mining equipment and electromechanics 9 45–48
[10] Mazunin V P, Dvonyikov D A 2012 Improving response in control of adjustable electric drives of mechanisms with elastic links. Russian Electrical Engineering 83(10) 556–561
[11] Datskovskii L Kh, Rogovoi V I, Kuznetsov I S 2010 Electric drive of mine-lifting machines. Russian Electrical Engineering 81(1) 15–30
[12] Lyakhomskiy A V, Fashilenko V N 2004 Control of electromechanical mining machine systems (Moscow: Moscow State Mining University) p 294
[13] Khatagov A C, Soin A M, Khatagov Z A 2008 Evaluation of the modernization efficiency of the rotation drive of mine shovel. Mining information and analytical bulletin 11 80–85
[14] Kuznetsov N K, Iov I A, Iov A A 2017 Developing electromechanical model of walking dragline traction mechanism. Proceedings of Irkutsk State Technical University. 21(11) 53–66