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THE MOVEMENT MODE OPTIMIZATION OF THE MANIPULATOR ON THE ELASTIC BASE ACCORDING TO THE CRITERION OF THE MEAN SQUARE VALUE OF THE RATE OF CHANGE OF THE DRIVE TORQUE

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It was established the presence of boom system oscillations in the process of changing the departure into previous studies of the optimization of the movement mode of the manipulator on an elastic base according to the criterion of the root mean square value of the driving moment of the drive. The purpose of the presented article is to solve the problem of reducing these fluctuations to a minimum. In this work, optimization was performed, where as a criterion for optimizing the motion mode of the boom system of the manipulator, it is proposed to use the root mean square value of the speed of change of the driving torque of the drive. Since this amount of power load is the main external factor of the occurrence of oscillations in the elements of the boom system of the manipulator. The driving torque of the drive was find from the dynamic equations of motion of the manipulator. The rate of change of the driving torque it was define as the time derivative of the driving torque expression by the drive. Such a criterion for optimizing the traffic mode is an integral functional. Its minimization it was carry out by methods of variational calculus.

The results of the conducted research made it possible is significantly reduce the oscillations of the elements of the boom system of the manipulator on an elastic basis during the movement in comparison with the criterion of the root mean square moment. As result, to create a drive control system that allows to implement the obtained optimal mode of movement.

Keywords: manipulator on an elastic base, optimization criterion, mean square value of the rate of change of moment, minimization of oscillations.

Introduction. The mobile hydraulic manipulators have gained significant use in construction [1, 2]. The main indicators of the effectiveness of the use of manipulators largely depend on the dynamics of their work.

Manipulator dynamics modeling in many cases is carried out with the assumption that all links of its mechanical system and frame mechanism are solid bodies, and the main support surfaces are horizontal [3-5]. This assumption is valid for stationary systems. However, in mobile machines that work on different types of support surfaces, the mechanical properties of which are not known in advance, there are cases of loss of stability when oscillations occur. For manipulators of mobile systems, it is also important to understand the picture of the dynamic load formation in main support mechanism [6].

In order to reduce dynamic loads on the manipulator support surface, it is needs to minimize fluctuations in the manipulator elements. There are oscillations of the boom system of the manipulator to a large extent depend on the size and character of changes in external loads in particular, the driving moment of the drive mechanism. The character of the change in driving moments is decisively influence by its rate of change in time [7]. Therefore, there is a need to choose a manipulator movement mode that minimizes the effect of the change speed of the drive torque during movement. This characteristic of the action minimization leads to minimization of fluctuations in the system.

Analysis of publications by research topic

The authors in works [8-10] considered the unbalance problem of the jib system a manipulator on an elastic base. However, a qualitative assessment of the impact of the driving force created by the hydraulic drive system on the dynamics of the elastic base mechanism was not consider. In work [9], the method of synthesis of the optimal mode of movement of the manipulator on an elastic base based on kinematic characteristics was consider and in the work [7] is according to the function of the driving torque. Optimization by the speed of change of the driving torque was not consider.

In the work [11], a method of balancing the potential energy of deformation the metal structure of the manipulator elastic boom with the amount of kinetic energy arising from the oscillations of the unbalanced masses of the boom system is proposed. The authors using the Lyapunov function was to consider the stability conditions of the mechanical system.

As an optimization criterion in the study of boom systems of manipulators with flexible links, the function of energy accumulation by an elastic element during the spatial movement of the load is also used [12-14], the value of which proposed to minimize.

The problems of the stability construction lifting and transport machines associated with the deformation of the support surface was shown in the paper [15]where is indicated the limit pressure for various support surfaces, which is in the range from 100 kN/m^2 to 2000 kN/m^2.

In [16], the problem of overloading and overheating of the power drive of the manipulator boom was investigate. This phenomenon occurs because of the action of dynamic loads, which, as is known, it was formed in the process of starting and braking due to the action of oscillations of the elastic parts of the boom and the imbalance of masses [1, 2, and 8].

The dynamics problem the manipulator, taking into account the elastic characteristics of the links and support surfaces, is relevant because this is considered by a some authors in different variations, however, such studies are still insufficient to solve this problem [17, 18]. In particular, it don’t known how the operating mode of the drive of the boom system of the manipulator will affect the dynamic loads in the structural elements and how is it possible to implement the movement of the manipulator boom with minimal power consumption of the drive.

In this work, it is propose to consider the optimization problem according to the criterion of the minimum root mean square value of the driving torque of the drive for a simplified scheme of a manipulator with an elastic support link, which characterizes the flexibility not only of the support surface, but also of the metal structure of the machine.

The purpose this research is to minimize the oscillations of the manipulator links on an elastic basis by optimizing the movement mode of the drive mechanism in the process of changing the departure of the cargo.

Presentation of the main material

It will use a simplified dynamic model of the boom system of the manipulator with the load, which was built in the plane of the departure change to carry out research (Fig. 1) [7].

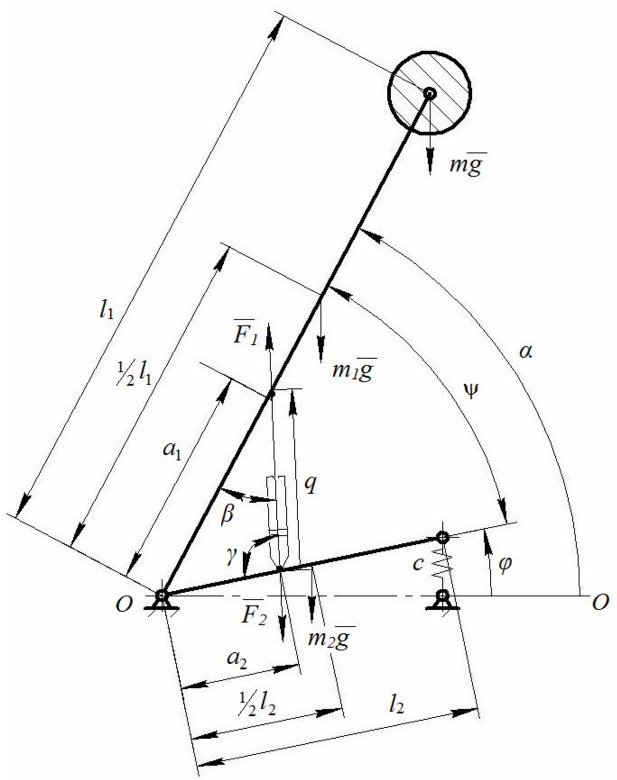

Fig. 1. The dynamic model of the manipulator boom system
with a hydraulic drive mounted on an elastic base

The adopted dynamic model consists of rigid boom links with a length of l_1 and a support frame with a length of l_2. The link of the support frame has two support points, one of which is share with the support joint of the boom and is assumecompletely rigid, and other is a replace by a movable link that reflects the elastic properties of the deformed support mechanism and the support surface. The movable elastic support have a characterized summary coefficient of elasticity c. The drive mechanism in the form of a hydraulic cylinder is placed between the boom and the support frame and is attached to the boom at a distance of a_1 and to the support frame at a distance of a_2, which are measured from the rigid support of the boom (point of rotation of the boom).

The dynamic model involves the following assumptions:

- the load with a concentrated mass m is rigidly attached to the end of the boom of the manipulator;
- the centers of mass of the boom m_1 and the support frame m_2 are located in the middle of the corresponding elements and, regardless of the geometry of the specified parts, are located at distances $\frac{1}{2}l_1$ and $\frac{1}{2}l_2$ from the rigid support hinge of the boom;
- the friction and play in kinematic pairs it was not taken into account;
- the mechanical system of the boom is placed on the horizontal support surface.

The angle φ of rotation of the support frame and the angle α of rotation of the boom relative to the horizontal surface it was take as generalized independent coordinates. The angle of rotation of the support frame depends on the elastic deformation of the support frame and the movement of the rod of the drive hydraulic cylinder determines the change in the angle of rotation of the boom. Changing the departure of the cargo is carry out by the manipulator in an unchanged space and will be determinate by the angle α of rotation of the boom manipulator relative to the horizontal surface. It was determinate by the joint movement of the considered system due to the vibrations of the support frame and the rotation of the boom manipulator relative to the support frame:

$$\alpha = \psi + \varphi . \tag{1}$$

Works [18-20] show that the use of D'Alembert's principle for Lagrange equations allows obtaining mathematical models in an explicit form. These equations reflect the effect of rotational and translational motion of the elements of the boom system of the manipulator of a complex structure on its dynamics and are best suited for solving control tasks. Within the framework of the Newtonian theory, a mathematical model of the considered holonomic boom system it was define using the Lagrange equations of the second kind, which is written in the form of a system of recurrent differential equations [7]

$$\begin{cases} (J_1 + ml_1^2)\ddot{\alpha} = M - (m + \dfrac{m_1}{2})gl_1 \cos\alpha; \\ J_2\ddot{\varphi} = -M - m_2 g l_2 \cos\varphi - cl_2^2(\varphi - \varphi_0), \end{cases} \tag{2}$$

where $J_1 = m_1 l_1^2/3$ and $J_2 = m_2 l_2^2/3$ – moments of inertia of the boom and the support frame relative to their pivot points; $\ddot{\alpha}$ and $\ddot{\varphi}$ – angular accelerations of the boom and the support surfaces; M – external driving moment of the drive; φ_0 – the initial deviation of the support link (subsequently accepted $\varphi_0 = 0$).

The first and second equations of system (2) have connected by a moment determined by the following next dependence

$$M = F_1 a_1 a_2 \frac{\sin(\alpha - \varphi)}{\sqrt{a_1^2 + a_2^2 - 2a_1 a_2 \cos(\alpha - \varphi)}}, \tag{3}$$

where F_1 – the force on the rod of the hydraulic cylinder.

From the first equation of system (2), we express the driving moment M, which depends on the coordinate α and has the next form

$$M = (J_1 + ml_1^2)\ddot{\alpha} + (m + \frac{m_1}{2}) g l_1 \cos\alpha . \tag{4}$$

Since the purpose of this work is to reduce the manipulator system oscillations, which largely depends on the rate of change in time of the external driving moment, then it will be determine this value by taking the time derivative of expression (4)

$$\frac{dM}{dt} = \dot{M} = (J_1 + ml_1^2)\dddot{\alpha} - (m + \frac{m_1}{2}) g l_1 \dot{\alpha} \sin\alpha . \tag{5}$$

As a criterion for optimizing the mode of change of departure of the boom system of the manipulator, we will choose the mean square value of the speed of change in time of the driving torque. Because this component has a main effect on the vibrations of the mechanical system of the manipulator on the supporting base:

$$\dot{M}_{ck} = \sqrt{\int_0^{t_1} \dot{M}^2 dt} \to \min \tag{6}$$

or

$$\dot{M}_{ck} = \frac{1}{(J_1 + ml_1^2)} \sqrt{\int_0^{t_1} \left(\dddot{\alpha} - \frac{(m + (m_1/2)) g l_1}{(J_1 + ml_1^2)} \dot{\alpha} \sin\alpha \right)^2 dt} \to \min. \tag{7}$$

From equation (7), it is obvious that the minimum value of the function will be providewhen the integrand acquires the minimum value.

Let's mark

$$f = \left(\dddot{\alpha} - k^2 \dot{\alpha} \sin\alpha \right)^2, \tag{8}$$

де $k = \sqrt{\dfrac{(m + \frac{m_1}{2}) g l_1}{(J_1 + ml_1^2)}}$.

The given task is equivalent to the minimization of the functional

$$\int_0^{t_1} f dt \to \min , \tag{9}$$

with next boundary conditions of movement:

$$t = 0 : \alpha = \alpha_0, \dot{\alpha} = 0, \ddot{\alpha} = 0;$$
$$t = t_1 : \alpha = \alpha_к, \dot{\alpha} = 0, \ddot{\alpha} = 0. \tag{10}$$

It was solve the given variational problem (9) by numerical methods.

Have been find the solution of the variational problem in the section of the arrow's movement from 45° to 85° for a duration of movement of 3 s. The parameters of the mechanical system were adopted as next: $m_1 = 300$ kg; $m_2 = 100$ kg; m=900 kg; l_1 =4 m; l_2 =2 m; c = 500 000 N/m^2; α_0= 0,8 rad. (45°); α_k = 1,45rad. (85°).

It will be present the numerical solutions of the given variational problem in the form of a polynomial, which consists of two terms

$$\alpha(t) = \alpha_1(t) + \alpha_2(t), \ 0 \le t \le t_1. \tag{11}$$

The first term $\alpha_1(t)$ is a polynomial chosen from the condition of ensuring the boundary conditions of motion, and the second term $\alpha_2(t)$ is a polynomial that determines the free coefficients and satisfies such boundary conditions

$$\alpha_2(0) = 0, \ \ \dot{\alpha}_2(0) = 0, \ \ \ddot{\alpha}_2(0) = 0;$$
$$\alpha_2(t_1) = 0, \ \ \dot{\alpha}_2(t_1) = 0, \ \ \ddot{\alpha}_2(t_1) = 0. \tag{12}$$

The term $\alpha_1(t)$ was take in the form of a 5th-degree polynomial to ensure conditions (10):

$$\alpha_1(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 + C_4 t^4 + C_5 t^5, \ 0 \le t \le t_1. \tag{13}$$

Let's take the first and second derivatives of this expression:

$$\dot{\alpha}_1(t) = C_1 + 2C_2 t + 3C_3 t^2 + 4C_4 t^3 + 5C_5 t^4, \tag{14}$$

$$\ddot{\alpha}_1(t) = 2C_2 + 6C_3 t + 12C_4 t^2 + 20C_5 t^3. \tag{15}$$

It was find the constant coefficients after substituting the initial conditions at t = 0 from expression (10) in equations (14) and (15):

$$C_0 = \alpha_0, \ C_1 = 0, \ C_2 = 0. \tag{16}$$

As a result of substituting the final conditions at $t = t_1$ from equality (10) and constant integrations (16) in the dependence (14) and (15), we obtain a system of linear equations

$$C_3 + C_4 t_1 + C_5 t_1^2 = \frac{\alpha_к - \alpha_0}{t_1^3};$$

$$3C_3 + 4C_4 t_1 + 5C_5 t_1^2 = 0;$$

$$6C_3 + 12C_4 t_1 + 20C_5 t_1^2 = 0. \tag{17}$$

The solution of the system of equations (17) gives the following values of constant coefficients

$$C_3 = 10\frac{\alpha_k - \alpha_0}{t_1^3}, \ C_4 = -15\frac{\alpha_k - \alpha_0}{t_1^4}, \ C_5 = 6\frac{\alpha_k - \alpha_0}{t_1^5}. \tag{18}$$

The polynomial is $\alpha_2(t)$ to must provide a minimum of the integral functional (7), so it was propose to use it in the following form:

$$\alpha_2(t) = t^3(t-t_1)^3(A_0 + A_1 t + A_2 t^2 + \ldots + A_n t^n),\ 0 \le t \le t_1. \quad (19)$$

The multiplier is $t^3(t-t_1)^3$ in expression (19) guarantees the fulfillment of the target boundary conditions for any coefficients $A_0, \ldots A_n$. These coefficients are free and it used to search for the minimum of the functional (7).

In this research, two versions of the polynomial $\alpha_2(t)$ was analyze to: third and fifth order. For the first option, four unknown coefficients were searched, and for the second, six. A modified particle swarm method was use to find solutions [21]. The results of the calculations show in the table 1.

Table 1

The values of the coefficients of the polynomials $\alpha_2(t)$, which provide the minimization of the criterion (7)

Values of coefficients	The number of unknown coefficients of the polynomial	
	4	6
A_0	$-2.88816 \cdot 10^{-3}$	$-2.90753 \cdot 10^{-3}$
A_1	$1.78445 \cdot 10^{-3}$	$1.85215 \cdot 10^{-3}$
A_2	$1.22972 \cdot 10^{-4}$	$-2.26934 \cdot 10^{-4}$
A_3	$5.64945 \cdot 10^{-5}$	$1.310341 \cdot 10^{-4}$
A_4	-	$-2.41385 \cdot 10^{-5}$
A_5	-	$2.85788 \cdot 10^{-6}$

The Fig. 2 shows graphical dependencies illustrating the application of the numerical optimization method.

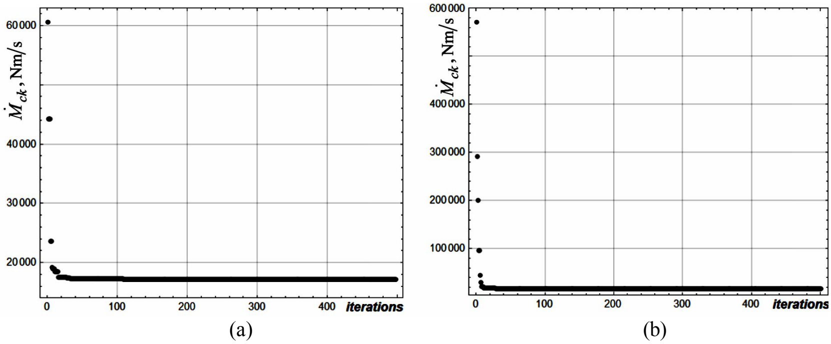

Fig. 2. Graphs of convergence of values of criterion (7) during optimization:
(a) for the variant with four unknown coefficients; (b) for the option with six unknown coefficients

From Fig. 2, it can be seen that in both cases the minimum of criterion (7) is quickly localized (approximately until the thirtieth iteration) and subsequent iterations pass without a significant change in the value of the optimization criterion.

For both cases, the value of the optimization criterion is equal to 17210 Nm/s. It is quite close to the value of the criterion, which corresponds only to the component $\alpha_1(t)$. The latter is equal to 17424 Nm/s, which is only 1.23% more than the criterion value achieved for the polynomial $\alpha(t)$. This indicates that the polynomial $\alpha_1(t)$ plays a dominant role in the criterion (7). Moreover, one can hypothesize, that these values of the boundary conditions and their number that provide this value of the criterion. However, the development of this hypothesis is beyond the scope of this work and is the subject of further research.

Since the values of the criteria are practically the same, then we will show the corresponding graphic dependences only for the variant of the polynomial with six calculated coefficients (see Fig. 3).

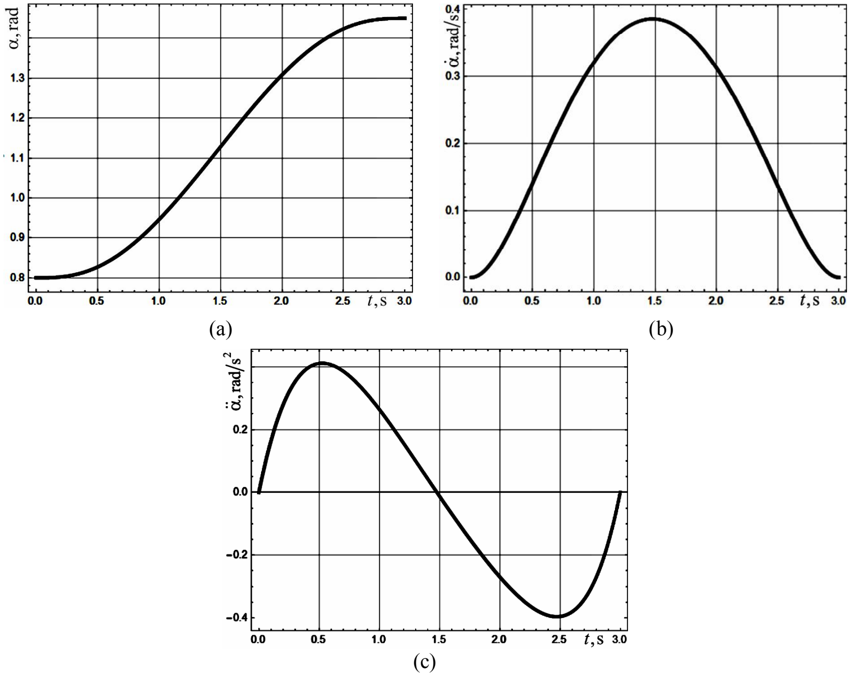

Fig. 3. Graphs that illustrate the change in kinematic and dynamic characteristics of the system over time: the function $\alpha(t)$ (a), its first (b) and second (c) derivatives

The results of the numerical solution (11) found, taking into account equations (13) and (19), are substituted into system (2), from which the dependences of the change in the angle $\varphi(t)$ of the rotation of the manipulator support frame relative to the horizontal surface and the function of the drive torque (4) are found (see Fig. 4).

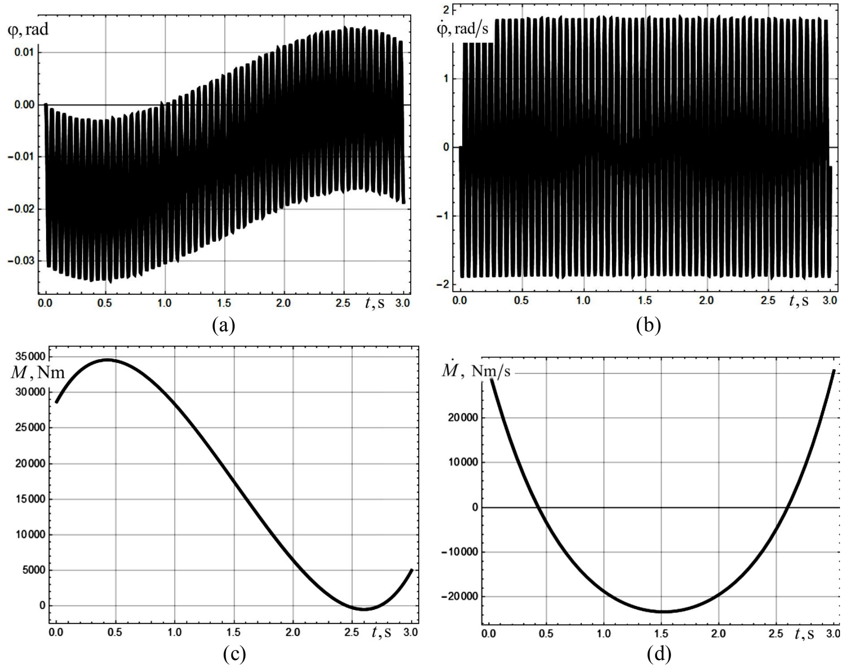

Fig. 4. Graphs that illustrate the change in the function of the angle φ(*t*) (a), the rate of change of the angle φ(*t*) (b), the function of the driving moment *M*(*t*) (c) and the rate of change of moment over time (d)

A comparison of oscillations of the support mechanism of the manipulator, determined according to the criteria of the minimum root mean square values of the driving torque [7] and the speed of change in time of the driving torque of the drive (Fig. 5). That the amplitude of oscillations in the mode according to the criterion of the root mean square value of the speed of change of the driving torque is almost always smaller than the amplitude of oscillations in the mode according to the criterion of the mean square value of the driving torque of the drive. It can have be seen from the graphical dependences shown in Fig. 5. At the same time, the amplitude of oscillations for the obtained optimal mode of movement is 45% for the maximum value and 60% for the average values of the amplitude of oscillations, determined by the criterion of the root mean square value of the drive torque. This indicates the advantages of using the criterion of the mean square value of the rate of change of the driving torque of the drive mechanism for the optimization of the motion mode of oscillating systems.

Conclusions

Optimizing the motion mode of the manipulator according to the criterion of the mean-square value of the speed of change of the driving torque allows achieving a smooth mode of motion of the manipulator boom, as evidenced by the figures shown in fig. 4 graphical dependencies. The change in the angular coordinate of the rotation of the support mechanism of the manipulator for the obtained mode of movement will be carry out with micro-oscillations of small amplitude.

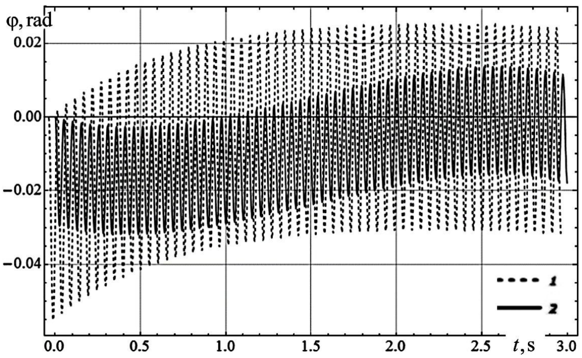

Fig. 5. Oscillation graphs of the support mechanism of the manipulator for the minimum mean square value of the driving torque of the drive (1) and the mean square speed of change of the driving torque of the drive (2) optimal by the criterion

The graphical dependences of the vibrations of the support frame of the manipulator mounted on an elastic base for cases of implementation of optimal modes of movement determined by the criteria of the minimum root mean square values of the driving torque and the rate of change of the driving torque shown in Fig. 5 show significant advantages of using the last criterion.

It was also establish, that the conditions for ensuring the boundary conditions of the movement play a dominant role in the minimization of the integral criterion. Moreover, it is possible to hypothesize that it is the values of the boundary conditions and their number that provide the value of the optimization criterion.

Note that the application of motion modes obtained on the basis of the derivative of the driving moment allows to increase the smoothness of the movement of the boom system of the manipulator, and therefore to reduce the amplitude of oscillations of the manipulator's support mechanism.

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Метою представленого дослідження є вирішення задачі зменшення до мінімуму коливаньстрілової системи маніпулятора на пружній основі. Для цього в якості критерію оптимізації режиму руху стрілової системи маніпулятора запропоновано використати середньоквадратичне значення швидкості зміни рушійного моменту приводу, оскільки ця величина силового навантаження є основним зовнішнім фактором виникнення коливань в елементах стрілової системи маніпулятора. Запропоновано застосувати цільову функцію оптимізації режиму руху у вигляді середньоквадратичного значення швидкості зміни рушійного моменту приводу. Рушійний момент приводу знайдено з динамічних рівнянь руху маніпулятора. Швидкість зміни рушійного моменту визначено, як похідну за часом від виразу рушійного моменту приводу. Такий критерій оптимізації режиму руху являє собою інтегральний функціонал, мінімізація якого здійснена методами варіаційного числення.
Табл. 1. Іл. 4. Бібліогр. 21 назв.

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Loveikin V.S., Mishchuk D.O., Romasevych Yu.O. **The movement mode optimization of the manipulator on the elastic base according to the criterion of the mean square value of the rate of change of the drive torque** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2023. – Issue 110. – P. 457-468.
The purpose this main research is to solve the problem of reducing to a minimum the oscillations of the manipulator boom system on an elastic base. For optimization, it was propose to use the root mean square value of the speed of change of the driving torque of the drive as a criterion for the movement mode of the boom system of the manipulator. This amount of power load is the main external factor causing oscillations in the elements of the boom system of the manipulator. It was propose to apply the objective function of the optimization of the driving mode in the form of the mean square value of the speed of change of the drive driving torque. The driving torque of the drive was find from the dynamic equations of motion of the manipulator. The rate of change of the driving torque was define as the time derivative of the expression of the driving torque of the drive. Such a criterion for the optimization of the motion mode is an integral functional, the minimization of which is carried out by the methods of variational calculus.
Table 1. Fig. 4.Ref. 21.

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