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Optimisation of start-up power mode of rotation mechanism of manipulator crane with a cylindrical articulated load suspension

Abstract. The study deals with the problem of improving the efficiency of the manipulator crane by selecting the driving modes of the rotary mechanism drive during the start-up process. When manipulator cranes operate in areas of transients, significant dynamic loads occur, which lead to swinging of the load on the articulated suspension. This leads to a decrease in the productivity and reliability of the crane manipulator and an increase in the energy consumption of the rotary mechanism drive. It is proposed to reduce dynamic loads during the operation of the turning mechanism in the areas of transients (starting, braking) of the manipulator crane by optimising the driving mode of the drive mechanism. In this case, the manipulator crane is presented in the form of a two-mass dynamic model, where the first mass is the rotary part of the manipulator crane with a drive mechanism, and the second mass is a load on a cylindrical hinge suspension. The purpose of the study is to improve the efficiency of the crane manipulator by optimising the starting mode of the turning mechanism. The methodology is optimal driving modes of crane mechanisms, which minimise the effect of dynamic loads, and provide for optimisation criteria based on the RMS values of the driving forces of the drives. The developed dynamic model allowed constructing a mathematical model described by a system of nonlinear differential equations. Optimisation of the movement mode of the crane manipulator rotation mechanism is carried out by minimising the integral dynamic criterion, which is the RMS value of the driving torque of the drive during the transition process. As a result of the optimisation carried out, the starting mode of the crane manipulator rotation mechanism is found, which minimises power loads and load fluctuations on the articulated suspension in the radial direction. The resulting optimal starting mode of the turning mechanism allowed increasing the productivity and reliability of the manipulator crane, and reducing the energy costs of the drive

Keywords: tower crane, turning mechanism, optimal control, cylindrical hinge suspension, load oscillation

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INTRODUCTION

During the operation of the manipulator crane rotation mechanism, dynamic loads occur in the drive elements, which lead to the rocking of the load on the hinge suspension and, as a result, reduce the productivity and reliability of the manipulator, and increase energy costs. These loads are especially dangerous during the transition processes of starting and braking the turning mechanism, when the driving or braking forces rarely increase or decrease. At this time, both high-frequency vibrations of the drive elements and low-frequency vibrations of the load on the articulated suspension are generated.

It is possible to reduce dynamic loads in the drive elements and the manipulator structure by selecting a favourable mode of movement of the drive rotation mechanism during transients. The most effective method for choosing a favourable mode of movement of the crane manipulator rotation mechanism is methods for optimising driving modes and, in particular, variational methods. Therefore, it is advisable to optimise the rotation mode of the manipulator crane according to the selected criterion. Since power loads are the most dangerous for a manipulator crane, the optimisation criterion should reflect these

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loads. This criterion can be the RMS value of the driving torque of the turning mechanism during start-up or braking. Minimising the selected criterion would reveal the mode of movement of the manipulator crane rotation mechanism in the start-up and braking areas, which reduces the power loads on the elements of the manipulator crane.

The efficiency of using manipulator cranes is determined by their performance, reliability, and safety of operation. The main factor determining these characteristics of the manipulator crane is the dynamic loads that occur in its links and drive mechanisms [1]. These loads become especially dangerous during transients (start-up, braking) [2; 3]. Dynamic loads largely depend on the control system of the drive mechanisms of the manipulator crane [4; 5]. Dynamic loads significantly increase when combining the working movements of the manipulator crane mechanisms [6; 7]. Especially dangerous is the combination of movements of the rotation mechanism and the movement of the boom system links in the process of changing the departure, where loads increase by two or more times [8]. In [9], it was found that a slight decrease in dynamic loads during the passage of transients significantly improves the reliability indicators of manipulator cranes. In addition, dynamic loads have a significant impact on the accuracy of load positioning [10]. Dynamic loads can be reduced by using the fundamental principles of mechanics, based on which methods for optimising manipulators are built [11]. To find the optimal laws of motion of crane mechanisms, mathematical methods were used, where extreme values of control criteria were found [10; 12]. Optimal driving modes of crane mechanisms, which minimise the effect of dynamic loads, are given in [12; 13], where the RMS values of the driving forces of the drives were selected as optimisation criteria. An example of optimising the modes of joint movement of crane mechanisms is found in study [14], which considers the movement of the departure and turn movement mechanism. When solving problems of optimising the mode of movement of the rotation mechanism, deviations from the vertical suspension of the load in the radial direction (plane of departure change) occur, which are ignored in the studies [14; 15]. At the same time, these suspension deviations have a certain impact on the dynamics of turning the manipulator crane and they must be considered when optimising the power mode of turning. Optimal modes of movement of crane mechanisms should be adapted to the operating conditions of cranes [16; 17].

Increase the efficiency of the crane manipulator by optimising the start mode of the rotation mechanism. To achieve this goal, it is necessary to develop a mathematical model of the dynamics of the rotation mechanism of the manipulator crane, choose a criterion for optimising the dynamics of the rotation mechanism, optimise the start mode, and analyse the optimisation results obtained.

RESULTS AND DISCUSSION

To optimise the movement mode of the manipulator crane rotation mechanism, a dynamic model has been developed, which is shown in Figure 1. In this figure, the following designations are used: 1 – rotary part of the manipulator with

a drive mechanism; 2 – articulated boom system; 3 – cylindrical hinged cargo suspension; 4 – load. When the boom system of the manipulator is rotated, all links rotate around the fixed axis of the rotary part, and the suspension 3 and load 4 additionally deviate from the vertical in the plane of change of departure (radial direction). Based on the design of the cylindrical hinge A of the load suspension, the latter can deviate from the vertical only in the radial direction when turning the manipulator crane. There are no deviations from the vertical of suspension 3 and load 4 in the plane of rotation of manipulator, since they are blocked by hinge A. When constructing a dynamic model, it is assumed that all the links of the crane manipulator are absolutely solid bodies, and there are no gaps in kinematic pairs. Rotation of the manipulator crane is carried out by a drive mechanism with a driving torque M .

Based on the above, it can be stated that the presented dynamic model of the crane manipulator has two

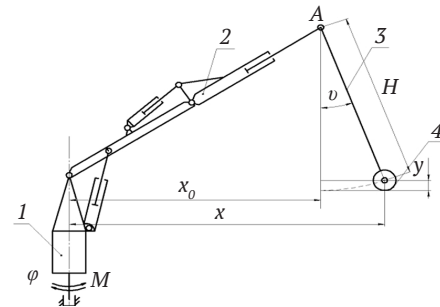


Figure 1. Dynamic model of turning a manipulator crane with cylindrical articulated load suspension

degrees of freedom: rotation of the entire system around a fixed vertical axis and deviation from the vertical of the hinge suspension with a load in the radial direction (plane of change in the departure of the load). The angular coordinate φ of the rotation mechanism and the linear horizontal coordinate of the centre of mass of the load in the radial direction X are selected as the generalised coordinates of the dynamic model when turning the manipulator crane.

To construct a mathematical model of the dynamics of rotation of a manipulator crane with a dynamic model (Fig. 1), the Lagrange equation of the second kind is used:

$$\begin{cases} \frac{d}{dt} \frac{\partial T}{\partial \dot{\varphi}} - \frac{\partial T}{\partial \varphi} = M - \frac{\partial \Pi}{\partial \varphi}; \\ \frac{d}{dt} \frac{\partial T}{\partial \dot{x}} - \frac{\partial T}{\partial x} = - \frac{\partial \Pi}{\partial x}; \end{cases} \quad (1)$$

where: t – time; T, P – kinetic and potential energy of the system, respectively; M – driving moment of the rotation mechanism drive reduced to the axis of the rotary part of the manipulator.

The expression of the kinetic energy of the system, ignoring the weight of the load suspension, has the following form:

$$T = \frac{1}{2} I_o \dot{\varphi}^2 + \frac{1}{2} m (\dot{x}^2 + \varphi^2 x^2), \quad (2)$$

where: I_0 – moment of inertia of the rotary part of the manipulator relative to its own axis of rotation; m – weight of the load with the gripper.

The required derivatives of expression (2) are used for the system of equations (1):

$$\begin{aligned} \frac{\partial T}{\partial \varphi} &= 0; \quad \frac{\partial T}{\partial \dot{\varphi}} = m\dot{\varphi}^2 x; \\ \frac{\partial T}{\partial \varphi} &= (I_0 + mx^2)\dot{\varphi}; \quad \frac{\partial T}{\partial \dot{\varphi}} = mx; \end{aligned} \quad (3)$$

$$\frac{d}{dt} \frac{\partial T}{\partial \dot{\varphi}} = (I_0 + mx^2)\ddot{\varphi} + 2m\dot{x}\dot{\varphi}; \quad \frac{d}{dt} \frac{\partial T}{\partial \dot{x}} = mx. \quad (4)$$

The dependence of the potential energy of the system is found

$$\Pi = mgy = mgH(1 - \cos\vartheta), \quad (5)$$

where: g – acceleration of gravity; H – height of the position of the centre of mass of the load relative to the boom joint; Y – angular coordinate of the suspension deviation from the vertical in the plane of departure change, determined by the following dependence:

$$\vartheta = (x - x_0)/H. \quad (6)$$

where: x_0 – initial coordinate of the position of the centre of mass of the load.

The partial derivatives of expression (5) is taken from the generalised coordinates φ and X , considering that $\sin\vartheta \approx \vartheta$ and $\cos\vartheta \approx 1$, as a result:

$$\frac{\partial \Pi}{\partial \varphi} = 0; \quad \frac{\partial \Pi}{\partial x} = mgH \frac{\partial \vartheta}{\partial x} \sin\vartheta \approx mgH \vartheta \approx \frac{mg}{H}(x - x_0). \quad (7)$$

Substituting dependencies (3), (4), and (7) in system (1), a mathematical model of the dynamics of rotation of a crane manipulator with a load is obtained, which has the following form:

$$\begin{cases} (I_0 + mx^2)\ddot{\varphi} + 2m\dot{x}\dot{\varphi} = M; \\ mx - \ddot{m}x\dot{\varphi}^2 = \frac{mg}{H}(x - x_0). \end{cases} \quad (8)$$

A system of two second-order differential equations (8) is reduced to one fourth-order differential equation. To do this, from the second equation of system (8), the angular velocity of the rotating part of the manipulator is expressed in terms of the horizontal coordinates of the load and its time derivatives:

$$\dot{\varphi} = \sqrt{\frac{g}{H} + \frac{1}{x} \left(\ddot{x} - \frac{g}{H}x_0 \right)} \quad (9)$$

Taking the time derivative of expression (9), the angular acceleration of the rotary part of the manipulator is found

$$\ddot{\varphi} = \frac{1}{2} \frac{\dot{x}\ddot{x} - \dot{x}(\ddot{x} - g/H)}{x^2 \dot{\varphi}} \quad (10)$$

Substituting expressions (9) and (10) into the first equation of system (8), the dependence of the driving moment of the rotation mechanism drive on the coordinate of the centre of mass of the load and its time derivatives are obtained

$$\begin{aligned} M &= \frac{1}{2} (I_0 + mx^2) \frac{\dot{x}\ddot{x} - \dot{x} \left(\ddot{x} - \frac{g}{H}x_0 \right)}{x^2 \sqrt{\frac{g}{H} + \frac{1}{x} \left(\ddot{x} - \frac{g}{H}x_0 \right)}} + \\ &+ 2m\dot{x} \sqrt{\frac{g}{H} + \frac{1}{x} \left(\ddot{x} - \frac{g}{H}x_0 \right)} \end{aligned} \quad (11)$$

To optimise the driving mode during the start-up of the turning mechanism, the RMS value of the driving moment is chosen as a criterion, which is presented in the form of intelligent functionality

$$M_{\text{ck}} = \left[\frac{1}{t_1} \int_0^{t_1} M^2 dt \right]^{1/2} \quad (12)$$

which must be minimised when ensuring the following boundary traffic conditions:

$$\begin{cases} t = 0: x = x_0, \dot{x} = 0, \dot{\varphi} = 0, \ddot{\varphi} = 0; \\ t = t_1: \dot{x} = 0, \ddot{x} = 0, \dot{\varphi} = \omega, \ddot{\varphi} = 0. \end{cases} \quad (13)$$

where: t_1 – duration of the process of starting the rotation mechanism of the crane manipulator; ω – steady-state angular velocity of the rotation mechanism.

Using dependencies (9) and (10), the boundary conditions (13) is reduced to the coordinate of the mass centre of the cargo X and its time derivatives. After that:

$$\begin{cases} t = 0: x = x_0, \dot{x} = 0, \ddot{x} = 0, \ddot{\varphi} = 0; \\ t = t_1: x = \frac{x_0}{\left(1 - \frac{\omega^2 H}{g}\right)}, \dot{x} = 0, \ddot{x} = 0, \ddot{\varphi} = 0. \end{cases} \quad (14)$$

The obtained optimisation problem (12) and (14) cannot be solved analytically, since the integrative expression of the functional (12) is a nonlinear function of the coordinate, velocity, acceleration, and jerk of the load movement in the plane of departure change. Therefore, an approximate method can be used for solving the optimisation problem of determining the power mode of starting the rotation mechanism of the manipulator crane.

The essence of this method [18] is that the solution of the optimisation problem is sought on a class of multiparametric functions that satisfy the given boundary conditions and provide a minimum of the criterion represented as an integral functional. In this form, the solution of the optimisation problem is represented as the solution of the following boundary value problem

$$\begin{cases} L(x) = 0 \\ \left\{ \begin{aligned} t = 0: x = x_0, \dot{x} = 0, \ddot{x} = 0, \ddot{\varphi} = 0; \\ t = t_1/2: x = x(t_1/2), \dot{x} = \dot{x}(t_1/2); \\ t = t_1: x = \frac{x_0}{(1 - \omega^2 H/g)}, \dot{x} = 0, \ddot{x} = 0, \ddot{\varphi} = 0. \end{aligned} \right. \end{cases} \quad (15)$$

Where $L(x)$ – operator that depends on the function $x(t)$. The solution of the above problem (15) has two unknown parameters $x(t_1/2)$ and $\dot{x}(t_1/2)$. In the given boundary value problem, the operator $L(x)$ can be represented by a differential equation of different orders. The operator is used as an ordinary tenth-order differential equation $L(x)$.

As a result of solving the boundary value problem (15), an expression of criterion (12) is developed in the form of a functional that does not depend linearly on the parameters $x(t_1/2)$ and $\dot{x}(t_1/2)$ and it seems to be such a functional dependency:

$$C_r = Cr(x(t_1/2), \dot{x}(t_1/2), t_1) \quad (16)$$

Values of parameters $x(t_1/2)$ and $\dot{x}(t_1/2)$ are found, for which criterion (12) takes the smallest value when providing the boundary conditions (14). To solve this problem, a modified metaheuristic method for swarming ME-PSO particles

was used [19]. This method does not require continuity and differentiation of the functions on which criterion (12) depends, and also does not impose additional conditions on the optimisation problem. After constructing the functional dependency (16), the Me-PSO method can be used to find the optimal values of unknown parameters $x(t_1/2)$ and $\dot{x}(t_1/2)$. When solving this problem, the following parameters of the ME-PSO method are accepted: the permissible rate of reduction of the AR=0.005 criterion; the swarm population – 50; the number of iterations – 40 (Fig. 2). The given parameters of the method allowed effectively using computational resources to obtain a solution to the optimisation problem.

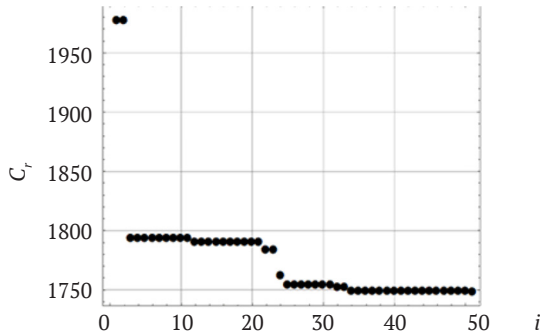


Figure 2. Graph of changes in the C_r criterion during the optimisation procedure (depending on the i -th iteration number)

Calculations were made for the rotation mechanism of the manipulator crane with the following parameters: $m=500$ kg; $I_0=3,200$ kg·m²; $x_0=5.5$ m; $H=1.5$ m; $g=9.81$ m/s²; $t_1=2.0$ s; $\omega=0.42$ deg/s.

Figure 3-Figure 9 show the graphical dependences of the kinematic, power, and energy characteristics of the optimal power mode of rotation of the manipulator crane.

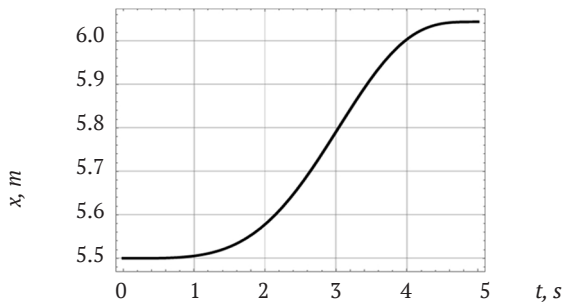


Figure 3. Graph of movement of the centre of mass of the load in the radial direction

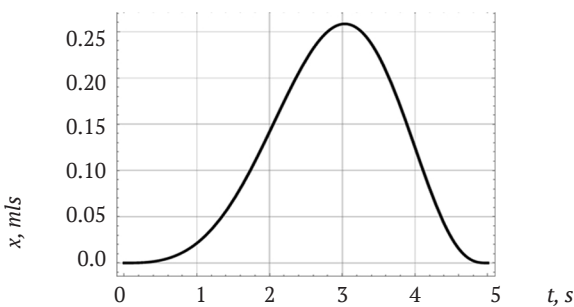


Figure 4. Graph of the velocity of the centre of mass of the load in the radial direction

Figure 3-Figure 5 show graphs of the kinematic characteristics of the movement of the centre of mass of the load in the radial direction. The movement of the centre of mass of the load (Fig. 3) has a smooth change character without fluctuations, which is close to the S-shaped law of motion. At the same time, at the beginning of the movement for one second, the movement of the centre of mass of the load in the radial direction was practically absent, and then it began to grow smoothly. The greatest increase in movement is observed in the section from two to four seconds, and then it begins to gradually decrease and at the end of the movement for 0.5 seconds remains almost unchanged.

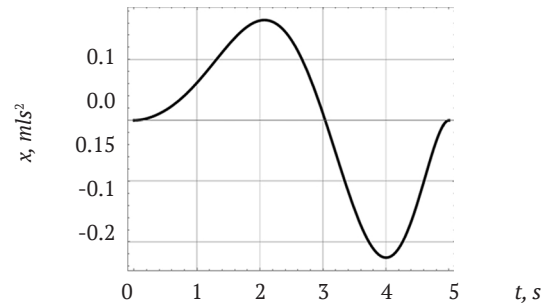


Figure 5. Graph of acceleration of the centre of mass of the load in the radial direction

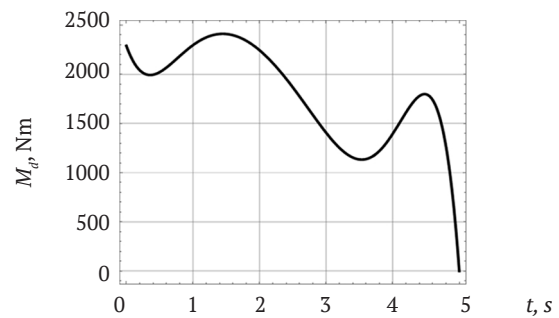


Figure 6. Graph of acceleration of the centre of mass of the load in the radial direction

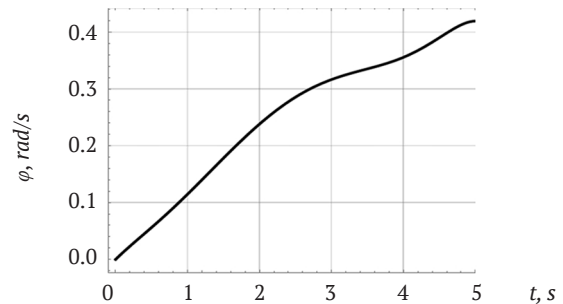


Figure 7. Graph of the angular velocity of the rotary part of the manipulator crane

This mode of moving the load in the radial direction is the most appropriate, since when entering the steady-state mode of movement, there will be no fluctuations of the load in the radial direction.

The change in the load velocity in the radial direction (Fig. 4) also has a smooth change character without

fluctuations. Here, the speed of movement of the load gradually increases to the maximum value, which is provided at the third second of movement, and then gradually decreases to zero. The presence at the end of the start-up of a stable value of cargo movement and zero speed confirms the absence of fluctuations in the load in the radial direction during the steady-state mode of rotation of the manipulator crane. The acceleration of the load in the radial direction (Fig. 5) also changes smoothly, increasing from zero to the maximum, and then decreasing to the minimum negative value and gradually increasing from it to zero.

The dynamic component of the driving torque of the manipulator rotation mechanism (Fig. 6) changes from the initial, almost maximum, to the final zero value in the presence of vibrations in the middle of the start-up section. This mode of changing the dynamic component of the driving torque indicates the presence of variable dynamic loads in the drive of the turning mechanism during start-up. The graph of angular acceleration of the crane manipulator rotation mechanism (Fig. 7) is practically a copy of the graph of changes in the dynamic component of the driving torque of the drive. This is conditioned by the fact that the dynamic component of the driving moment is the product of a slightly variable moment of inertia of the rotary part of the manipulator crane and its angular acceleration. The graph of the angular velocity of the rotary part of the manipulator crane (Fig. 8) increases from zero in the first half of the start-up almost according to a linear law, and in the second part of the start-up, this increase slows down with a slight fluctuation in the turn speed.

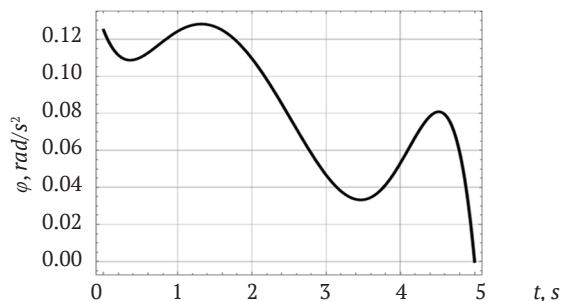


Figure 8. Graph of the angular velocity of the rotary part of the manipulator crane

The dynamic component of the drive power of the manipulator crane rotation mechanism (Fig. 9) increases from zero to the maximum value in the presence of power fluctuations, and then sharply decreases to zero within 0.5 seconds. Fluctuations in the dynamic component of the drive power of the turning mechanism are caused by the nature of changes in the driving torque, which also has an oscillatory character.

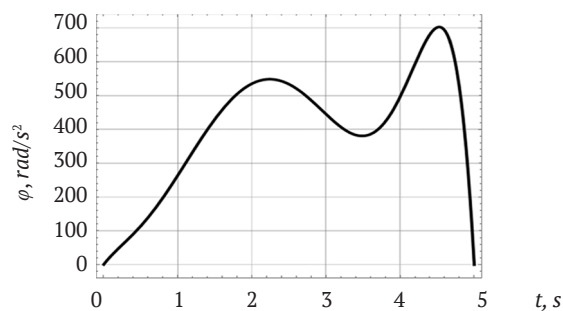


Figure 9. Graph of the dynamic power component of the drive mechanism of the manipulator crane rotation

The obtained optimal modes of movement of crane manipulator mechanisms should be used in real drive designs [20]. For this purpose, control systems are used [21]. It is possible to estimate the influence of optimal driving modes on the strength characteristics of structures by performing calculations for strength and reliability [22]. To assess the impact of optimal movement modes of mechanisms on the efficiency of manipulator cranes, it is necessary to monitor them.

CONCLUSIONS

1. A dynamic model of the rotation mechanism of the manipulator crane is constructed, which considers the main movement of the rotation mechanism and the oscillatory movement of the load on a cylindrical hinge suspension in the radial direction (the plane of change in the departure of the load).
2. Based on the dynamic model, a mathematical model of the dynamics of the movement of the crane-manipulator rotation mechanism is compiled, which is described by a system of nonlinear second-order differential equations.
3. For such a mathematical model, an optimisation problem is set and solved to determine the rotation mode of the manipulator crane, which provides the minimum RMS value of the driving torque of the drive mechanism when the boundary conditions of movement are met. The boundary driving conditions are selected from the condition for eliminating load vibrations in the radial direction when entering the steady-state mode of rotation of the manipulator crane.
4. As a result of solving the optimisation problem, the law of motion of the turning mechanism is determined, which minimises the optimisation criterion and provides the necessary boundary conditions for movement. At the same time, there are some fluctuations in the kinematic characteristics of the turning mechanism with a fairly smooth mode of cargo movement in the radial direction. There are also fluctuations in the driving torque and dynamic power component of the drive mechanism of the manipulator crane rotation.

5. To eliminate these shortcomings of the obtained optimal driving mode, it is necessary to use complex optimisation criteria, which would include other individual criteria that allow eliminating fluctuations in the kinematic, power, and energy characteristics of the crane rotation mechanism.

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Оптимізація силового режиму пуску механізму повороту крана-маніпулятора з циліндричним шарнірним підвісом вантажу

Анотація. В статті розглядається проблема підвищення ефективності роботи крана-маніпулятора за рахунок вибору режимів руху приводу механізму повороту під час процесу пуску. При роботі кранів маніпуляторів на ділянках перехідних процесів виникають значні динамічні навантаження, які призводять до розгойдування вантажу на шарнірному підвісі. Це призводить до зменшення продуктивності та надійності крана-маніпулятора, а також підвищення енергетичних витрат приводу механізму повороту. Зменшити динамічні навантаження при роботі механізму повороту на ділянках перехідних процесів (пуск, гальмування) крана-маніпулятора запропоновано шляхом проведення оптимізації режиму руху приводного механізму. При цьому кран-маніпулятор представлено у вигляді двомасової динамічної моделі, де першою масою виступає поворотна частина крана-маніпулятора з приводним механізмом, а другою масою є вантаж на циліндричному шарнірному підвісі. Мета дослідження – підвищення ефективності крана-маніпулятора шляхом оптимізації режиму пуску механізму повороту. Методологією є оптимальні режими руху кранових механізмів, які до мінімуму зводять дію динамічних навантажень, передбачають наявність критеріїв оптимізації за середньоквадратичними значеннями рушійних сил приводів. Розроблена динамічна модель дозволила побудувати математичну модель, що описується системою нелінійних диференціальних рівнянь. Оптимізацію режиму руху механізму повороту крана-маніпулятора здійснено шляхом мінімізації інтегрального динамічного критерію, який представляє собою середньоквадратичне значення рушійного моменту приводу за час проходження перехідного процесу. В результаті проведеної оптимізації знайдено режим пуску механізму повороту крана-маніпулятора, який до мінімуму зводять силові навантаження та коливання вантажу на шарнірному підвісі в радіальному напрямку. Отриманий оптимальний режим пуску механізму повороту дозволив підвищити продуктивність та надійність роботи крана-маніпулятора, а також зменшити енергетичні витрати приводу

Ключові слова: баштовий кран, механізм повороту, оптимальне керування, циліндричний шарнірний підвіс, коливання вантажу