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OPTIMIZATION OF THE MODE OF MOVEMENT OF THE BOOM SYSTEM OF THE LOADER CRANE

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The article presents a method of solving the problem of elimination of oscillations of the load on a knuckle joint suspension while simultaneously moving two links of the boom system. The problem is solved by two optimization criteria, namely, the root-mean-square values of the generalized power and power of the drive mechanisms. The solution to the optimization problem is presented in a discrete form. The multi-epoch particle swarm optimization (ME-PSO) method has been used for that purpose. This helped to obtain the discrete values of the kinematic and power characteristics of the boom system of the loader crane. The resultant optimal mode moving of the boom system improved the loader crane in terms of performance, reliability and energy efficiency.
Keywords: mathematical model, changing the boom, combination of movements, manipulator, Lagrange equation of the second kind, dynamic loads, load oscillations.

Introduction

In the process of moving the load by the loader crane, dynamic loads occur in the elements of the metalware and drive mechanisms. These loads are especially dangerous during the transient processes of the movement of the boom system (starting and braking). At this moment in time, one of the main causes occur of dynamic loads is the oscillation of the load on a knuckle joint suspension. In turn, the oscillations of the load depending on the nature of the change in the driving forces in the drive mechanisms (hydraulic cylinders) [1]. The consequence is a decrease in the reliability and performance of loading and unloading operations. The task of research is to obtain such laws of change of driving forces at which fluctuations of load on a knuckle joint would be the smallest. It is proposed that to eliminate the load oscillations and to reduce the dynamical forces, the starting process should be optimized. For this purpose, it is advisable to use an integral criterion that takes into account the action of dynamic forces in the hydraulic cylinders and their speed of movement. When solving the optimization problem, there is a problem of minimizing the complex nonlinear integral criterion. One of the ways to solve the above problem is to use the ME-PSO method [11, 12] or other similar methods. The solution of this problem will make it possible to apply the optimization methods for the motion modes of nonlinear mechanical systems.

Analysis of publications

The analysis of study [1-2] on the dynamics of motion of manipulators shows that the scientific and technical problem was solved before, but to the full extent to eliminate the fluctuations of the load failed.

In the studys [3-5], a dynamic analysis of the joint trolley movement and hoisting mechanism in the tower crane hoist is considered and a method is Drive power minimization of outreach change mechanism of tower crane during steady-state slewing mode.

In the study [6-8], the results of recent research, development and implementation of applied optimization methods, issues of formalization, classification and evaluation of complexity of computational optimization problems are obtained. It is confirmed that optimization methods can be used to solve a wide range of applied problems that arise in science, technology, biology, economics, production, etc. Optimization by natural methods is widespread in various fields of human activity.

One of the methods used to solve this problem is the particle swarm optimization (PSO) method [8]. The authors of analyzed the genetic algorithm of PSO and the neuro-genetic method of solving the problem.

The PSO method is used to calculate different control problems, design artificial neural networks, process signals, etc. [8-15].

The authors of [14-15] propose a new method based on particle swarm optimization technology. The basic idea is to restore a swarm of low-performing intelligence. The use of technologies, the PSO method, or other similar methods and their modifications makes it possible to use methods of optimizing the modes of motion of nonlinear mechanical systems. The task of eliminating cargo fluctuations due to the choice of laws of change of motive effort in hydraulic cylinders is new and contains elements of scientific novelty.

Purpose and research task statement

Elimination of the oscillations of the load fixed on the knuckle joint suspension by optimizing the mode of change of driving effort in the hydraulic cylinder during starting and horizontal movement of the load.

Research results

To achieve this goal, we used a loader crane consist of the main boom and a jib with a telescopic extension system to which the load is mounted on a knuckle joint suspension. In the process of moving the load by loader crane, we will assume that the main boom is stationary and the load movement the going on only by lowering the jib and the movement telescopic boom. In this, consider the case of moving the boom system of the loader crane, in which the load moving horizontally. This mode of movement of the boom system provides significant savings in the energy costs of the drive mechanisms of movement of the jib and the telescopic extension system. This mode of movement of the boom system of the loader crane is achieved by coordinated simultaneous operation of the mechanisms of movement of the jib and the telescopic extension system.

For this case, the loader crane is presented as a holonomic mechanical system consisting of absolutely rigid links, except for load that oscillate in the plane of moving. The dynamic model of such a system has two degrees of freedom and is presented in (Fig. 1). For the generalized coordinates of the accepted model, the linear coordinates of the centre of mass of the load z and the horizontal coordinate of the point A of the telescopic extension system x are used. In this case, the vertical coordinate of point A of the telescopic extension system always remains constant, ie $yA=h$=const. This is a kinematic condition that imposes additional attachment on the loader crane in the process boom system moves.

In Fig. 1 accepted the following designations: α – the angle of the main boom to the horizon; a – the length of the hydraulic cylinder motion of the jib; b – length of the jib; d – length of the telescopic extension system; l – length of the knuckle joint suspension; β, v – is the angular coordinates of rotation of the jib and the deflection of the load; x, x_1, x_2, y, y_1, y_2 – coordinates of the centre of mass; U_1, U – lengths of hydraulic cylinders.

To compile the equations of motion of change of departure of the boom system of the loader crane shown in Fig. 1, we use the second-order Lagrange equation [1]:

$$\begin{cases} \frac{d}{dt}\frac{\partial T}{\partial \dot{x}} - \frac{\partial T}{\partial x} = Q_x - \frac{\partial V}{\partial x}; \\ \frac{d}{dt}\frac{\partial T}{\partial \dot{z}} - \frac{\partial T}{\partial z} = -\frac{\partial V}{\partial z}, \end{cases} \quad (1)$$

where: T, V is respectively the kinetic and potential energy of the system; Q_x – is a potential component of the generalized force corresponding to the generalized coordinate x.

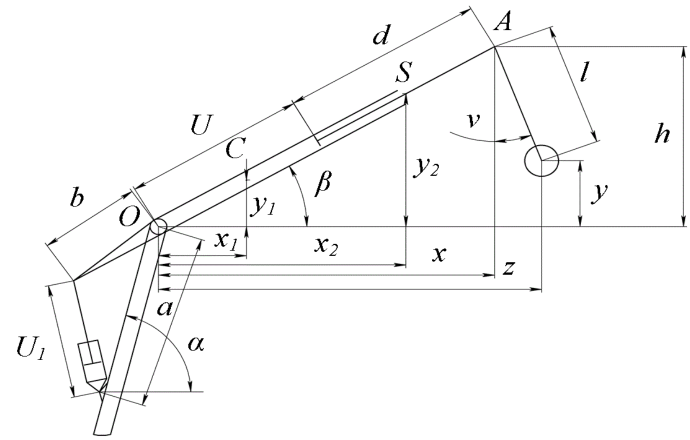

Fig. 1. Dynamic model of the movement of the boom system of the loader crane

The kinetic and potential energy of the system is determined by the following dependencies:

$$T = \frac{1}{2}(J_1 + J_2)\dot{\beta}^2 + \frac{1}{2}m_2\dot{S}^2 + \frac{1}{2}m\dot{z}^2; \quad (2)$$

$$V = (m_1 y_1 + m_2 y_2 + my)g, \quad (3)$$

where: J_1, J_2 is respectively the moments of inertia of the jib and the telescopic boom; m_1, m_2, m_3 – respectively the weight of the jib, the telescopic boom and the load; S – is the coordinate of the centre of mass of the telescopic boom in the direction of its movement; g – acceleration of gravity.

Not a potential component of generalized force which corresponds to the coordinate x, determine from the condition of equality of elementary works:

$$Q_x \delta x = F_1 \cdot \delta U_1 + F \cdot \delta U, \quad (4)$$

where: F_1, F – respectively the force in the hydraulic cylinders; δU_1, δU – elemental displacements of the rods of hydraulic cylinders, which are determined by the following dependencies:

$$\delta U_1 = \frac{\partial U_1}{\partial x}\delta x; \qquad \delta U = \frac{\partial U}{\partial x}\delta x. \quad (5)$$

After substituting expressions (5) in equation (4) we obtain:

$$Q_x = F_1\frac{\partial U_1}{\partial x} + F\frac{\partial U}{\partial x}. \quad (6)$$

Take the necessary derivatives of expressions (2) and (3), and as a result, we have:

$$\frac{\partial T}{\partial x} = (J_1 + J_2)\dot{\beta}\frac{\partial \dot{\beta}}{\partial x} + \frac{1}{2}\frac{\partial J_2}{\partial x}\dot{\beta}^2 + m_2\dot{S}\frac{\partial \dot{S}}{\partial x}; \qquad \frac{\partial T}{\partial z} = 0; \quad (7)$$

$$\frac{\partial T}{\partial \dot{x}} = (J_1 + J_2)\dot{\beta}\frac{\partial \beta}{\partial x} + m_2\dot{S}\frac{\partial S}{\partial x}; \quad \frac{\partial T}{\partial \dot{z}} = m\dot{z}; \quad (8)$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{x}}=\left(J_1+J_2\right)\left(\ddot{\beta}\frac{\partial\beta}{\partial x}+\dot{\beta}\frac{\partial\dot{\beta}}{\partial x}\right)+\dot{x}\frac{\partial J_2}{\partial x}\dot{\beta}\frac{\partial\beta}{\partial x}+m_2\left(\ddot{S}\frac{\partial S}{\partial x}+\dot{S}\frac{\partial\dot{S}}{\partial x}\right); \tag{9}$$

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{z}}=m\ddot{z}; \tag{10}$$

$$\frac{\partial V}{\partial x}=\left(m_1\frac{\partial y_1}{\partial x}+m_2\frac{\partial y_2}{\partial x}+m\frac{\partial y}{\partial x}\right)g;\quad \frac{\partial V}{\partial z}=mg\frac{\partial y}{\partial z}. \tag{11}$$

After substituting expressions (6-11) in equation (1) we obtain:

$$\begin{cases}\left(J_1+J_2\right)\left(\ddot{\beta}\frac{\partial\beta}{\partial x}+\dot{\beta}\frac{\partial\dot{\beta}}{\partial x}\right)+\frac{\partial J_2}{\partial x}\dot{\beta}^2+m_2\left(\ddot{S}\frac{\partial S}{\partial x}+\dot{S}\frac{\partial\dot{S}}{\partial x}\right)-\left(J_1+J_2\right)\dot{\beta}\frac{\partial\dot{\beta}}{\partial x}-\frac{1}{2}\frac{\partial J_2}{\partial x}\dot{\beta}^2-\\ -m_2\dot{S}\frac{\partial\dot{S}}{\partial x}=F_1\frac{\partial U_1}{\partial x}+F\frac{\partial U}{\partial x}-\left(m_1\frac{\partial y_1}{\partial x}+m_2\frac{\partial y_2}{\partial x}+m\frac{\partial y}{\partial x}\right)g;\\ m\ddot{z}=-mg\frac{\partial y}{\partial z}.\end{cases} \tag{12}$$

By reducing similar terms in equations (12) and using dependencies: $\dot{\beta}=\dot{x}\frac{\partial\beta}{\partial x}$; $\ddot{\beta}=\ddot{x}\frac{\partial\beta}{\partial x}+\dot{x}^2\frac{\partial^2\beta}{\partial x^2}$; $\dot{S}=\dot{x}\frac{\partial S}{\partial x}$; $\ddot{S}=\ddot{x}\frac{\partial S}{\partial x}+\dot{x}^2\frac{\partial^2 S}{\partial x^2}$, we obtain the system of differential equations of motion of the boom system of the loader crane with the load:

$$\begin{cases}\left(J_1+J_2\right)\left(\ddot{x}\frac{\partial\beta}{\partial x}+\dot{x}^2\frac{\partial^2\beta}{\partial x^2}\right)+\frac{\partial\beta}{\partial x}+\frac{1}{2}\frac{\partial J_2}{\partial x}\dot{x}^2\left(\frac{\partial\beta}{\partial x}\right)^2+\left(J_1+J_2\right)\times\\ \times\dot{\beta}\frac{\partial\dot{\beta}}{\partial x}-m_2\left(\ddot{x}\frac{\partial S}{\partial x}+\dot{x}^2\frac{\partial^2 S}{\partial x^2}\right)\frac{\partial S}{\partial x}=F_1\frac{\partial U_1}{\partial x}+F\frac{\partial U}{\partial x}-\left(m_1\frac{\partial y_1}{\partial x}+m_2\frac{\partial y_2}{\partial x}+m\frac{\partial y}{\partial x}\right)g;\\ \ddot{z}=-g\frac{\partial y}{\partial z}.\end{cases} \tag{13}$$

We express the coordinate's *β, S,* y_1, y_2, *y,* U_1, *U* through the generalized coordinates *x* and *z*:

$$y=h\left(1-\cos\frac{x-z}{h}\right);\quad y_x=\frac{\partial y}{\partial x}=\sin\frac{x-z}{h};\; y_z=\frac{\partial y}{\partial z}=-\sin\frac{x-z}{h}; \tag{14}$$

$$S=\sqrt{h^2+x^2}-\frac{d}{2};\; S_x=\frac{\partial S}{\partial x}=\left[1+\left(x/h\right)^2\right]^{-1/2};\; S_{xx}=\frac{\partial^2 S}{\partial x^2}=\frac{1}{h}\left[1+\left(x/h\right)^2\right]^{-3/2}; \tag{15}$$

$$y_1=\frac{h-\left(c-b\right)}{2\sqrt{h^2+x^2}};\quad y_{1x}=\frac{\partial y_1}{\partial x}=-\frac{c-b}{2h^2}\cdot\frac{x}{\left[1+\left(x/h\right)^2\right]^{3/2}}; \tag{16}$$

$$y_2=h\left(1-\frac{d}{2\sqrt{h^2+x^2}}\right);\quad y_{2x}=\frac{\partial y}{\partial x}=\frac{d}{2h^2}\cdot\frac{x}{\left[1+\left(x/h\right)^2\right]^{3/2}}; \tag{17}$$

$$\beta=\arctan\left(x/h\right);\; \beta_x=\frac{\partial\beta}{\partial x}=-\frac{1}{h\left[1+\left(x/h\right)^2\right]};\; \beta_{xx}=\frac{\partial^2\beta}{\partial x^2}=-\frac{2x}{h^3\left[1+\left(x/h\right)^2\right]^2}; \tag{18}$$

$$U=\sqrt{h^2+x^2}-d;\quad U_x=\frac{\partial U}{\partial x}=\frac{1}{\sqrt{1+\left(h/x\right)^2}}; \tag{19}$$

$$U_1=\sqrt{a^2+b^2-2ab\cos(\alpha-\beta)};\;\; U_{1x}=\frac{\partial U_1}{\partial x}=-\frac{ab}{U_1}\frac{\partial\beta}{\partial x}\sin(\alpha-\beta). \tag{20}$$

Define the moments of inertia of the links of the boom system:

$$J_1=m_1\left(c^2-cb+b^2\right);\; J_2=m_2\left(\frac{d^2}{3}+dU+U^2\right);\; J_{2x}=\frac{\partial J_2}{\partial x}m_2U_x(d+2U). \tag{21}$$

In the last equation of system (13) we substitute the expression (14), as a result of which we have:

$$\ddot{z}=g\frac{x-z}{h}. \tag{22}$$

Where do we find:

$$x=z+\frac{h}{g}\ddot{z};$$
$$\dot{x}=\dot{z}+\frac{h}{g}\dddot{z};$$
$$\ddot{x}=\ddot{z}+\frac{h}{g}z^{IV}. \tag{23}$$

Using expressions (23), we replace the system of equations (13) with one differential equation, which is represented in the following form:

$$\left(\ddot{z}+\frac{h}{g}z^{IV}\right)\left[(J_1+J_2)\beta_x^2+m_2S_x^2\right]+\left(\dot{z}+\frac{h}{g}\dddot{z}\right)^2\Big[(J_1+J_2)\beta_x\beta_{xx}+$$
$$+m_2S_xS_{xx}+\frac{J_{2x}\beta_x^2}{2}\Big]+(my_x+m_1y_{1x}+m_2y_{2x})g=Q_x. \tag{24}$$

According to the criterion of optimization of the mode of change of departure of the boom system of the loader crane, we will choose the root-mean-square values of the generalized force Q_x, which has the form:

$$Q_{xc}=Q_{xc}=\left[\frac{1}{t_1}\int_0^{t_n}Q_x^2dt\right]^{1/2}=\left\{\left\{\frac{1}{t_n}\int_0^{t_n}\left(\ddot{z}+\frac{h}{g}z^{IV}\right)\left[(J_1+J_2)\beta_x^2+m_2S_x^2\right]+\left(\dot{z}+\frac{h}{g}\dddot{z}\right)^2\times\right.\right.$$
$$\times\left[(J_1+J_2)\beta_x\beta_{xx}+m_2S_xS_{xx}+\frac{J_{2x}\beta_x^2}{2}\right]+m\ddot{z}+(my_x+m_1y_{1x}+m_2y_{2x})g\Big\}^2dt\Big\}^{1/2}, \tag{25}$$

where: t – is the time; t_n – is the duration of the startup process of the loader crane.

The criterion obtained should be minimized because it reflects the costs of the reduced effort of the drive mechanisms of the jib and the telescopic boom. However, it is not possible to analytically minimize criterion (25) and choose laws of change of coordinate $z = z\ (t)$ and its derivatives under the boundary conditions of the process of starting the loader crane:

$$\begin{cases} t=0: x=z=z_0,\ \dot{x}=\dot{z}=0; \\ t=t_n: x=z=\dfrac{V_st_n}{2},\ \dot{x}=\dot{z}=V_s, \end{cases} \tag{26}$$

where: V_s – speed of steady load movement; z_0 – the initial value of the z coordinate. We reduce the system of boundary conditions (26) to the coordinate z and its derivatives in time. To do this, we use dependencies (23), resulting in:

$$\begin{cases} t=0:\ \ z=z_0,\ \ \dot{z}=0,\ \ \ddot{z}=0,\ \ \dddot{z}=0; \\ t=t_n:\ \ z=z_0+\dfrac{V_st_n}{2},\ \ \dot{z}=V,\ \ \ddot{z}=0,\ \ \dddot{z}=0. \end{cases} \tag{27}$$

To find an approximate solution the optimization problem (25), (27) we use an approach whose essence is to define a class of multivariable functions that satisfy the boundary conditions (27) and to determine the minimum value of criterion (25).

The class of multivariable functions on which we will find the approximate solution of the optimization problem is given as the solution of the boundary value problem:

$$\begin{cases} L(z)=0; \\ \begin{cases} t=0: z=z_0,\ \dot{z}=0,\ \ddot{z}=0,\ \dddot{z}=0; \\ t=\dfrac{t_n}{2}: z=z_{t_n/2},\ \dot{z}=\dot{z}_{t_n/2}; \\ t=t_n: z=z_0+\dfrac{V_s t_n}{2},\ \dot{z}=V_s,\ \ddot{z}=0,\ \dddot{z}=0, \end{cases} \end{cases} \tag{28}$$

where L – is an operator acting on the function $z(t)$.

The boundary-value solution (28) contains two unknown parameters $z_{t_n/2}$ and $\dot{z}_{t_n/2}$ In this study, we take operator $L(z)$ as a tenth-order differential equation $L(z)=\overset{x}{z}(t)$. However, in the general case, this operator may be different. Its rationale is beyond the scope of this paper.

Let us solve the boundary value problem (28). Then we form an expression of the functional (25):

$$Cr=Cr(z_{t_n/2},\ \dot{z}_{t_n/2},\ t_n), \tag{29}$$

Which seems to be a nonlinear function of its arguments. In order to effectively find such values and at which the functional (25) obtains a minimum, a modification of the ME-PSO meta-heuristic swarm method was used [15]. Its application doesn't require the continuity and differentiation of the criterion (29) and does not impose on the optimization problem rigid requirements. As soon as we were able to build functional dependency (29) we can use the ME-PSO method and find the optimal values for unknown parameters $z_{t_n/2}$ and $\dot{z}_{t_n/2}$. The following parameters of the method are used in the work: acceptable rate of decrease of criterion AR = 0,005; number of lobules (swarm population) – 50; the number of iterations is 40. These parameters make it quite efficient to use computing resources to solve the problem. All calculations were made for the boom system of the loader crane with the following parameters: m=155 kg; m_1=65 kg; m_2=500 kg; h=1,9 m; z_0=1,1 m; V=0,5 m/s; a=1,65 m; b=0,5 m; c=2,2 m; d=1,8 m; t_0=0 s; t_n=1 s; g=9,81 m/s^2.

As a result of using the method, the following values were obtained: $z_{t_n/2}=1{,}15\,\text{m}$ and $\dot{z}_{t_n/2}=0{,}25\,\text{m/s}$.

A similar approach is also used to minimize the power of the root-mean-square value of the drive mechanisms. The expression that describes this criterion is represented by the following dependency under boundary conditions (27):

$$P_{xck}=\left[\frac{1}{t_1}\int_0^{t_n}P_x^2dt\right]^{1/2}=\left\{\frac{1}{t_n}\int_0^{t_n}\left\{\left(\ddot{z}+\frac{h}{g}z^{IV}\right)\left(\left(\ddot{z}+\frac{h}{g}z^{IV}\right)\left((J_1+J_2)+\beta_x^2+m_2S_x^2\right)+\left(\dot{z}+\frac{h}{g}\dddot{z}\right)^2+\right.\right.\right.$$

$$\left.\left.\left.+\left((J_1+J_2)\beta_x\beta_{xx}-m_2S_xS_{xx}+\frac{J_{2x}\beta_x^2}{2}\right)+m\ddot{z}+\left(my_x+m_1y_{1x}+m_2y_{2x}\right)g\right\}^2dt\right\}^{1/2}. \tag{30}$$

The multi-parameter function, which seeks the approximate minimum of criterion (30), is the solution of the boundary value problem (28). The following parameter values were obtained for this task: $z_{t_n/2}=1{,}15\,\text{m}$ and $\dot{z}_{t_n/2}=0{,}26\,\text{m/s}$.

The convergence of the ME-PSO method, which is illustrated by the graphs in Fig. 2, indicates that for both problems such values were found and under which criteria (25) and (30) obtain absolute minimums under boundary conditions (27).

As a result of the solution of the set optimization problem kinematic characteristics of the links of the loader crane are obtained $x(t)$, $z(t)$, $U(t)$, $U_1(t)$, $\beta(t)$ and their partial and full-time derivatives, as well as the generalized force Q_x, which includes the effort in the cylinders related to the ratio:

$$Q_x = F\frac{\partial U}{\partial x} + F_1\frac{\partial U_1}{\partial x}. \tag{31}$$

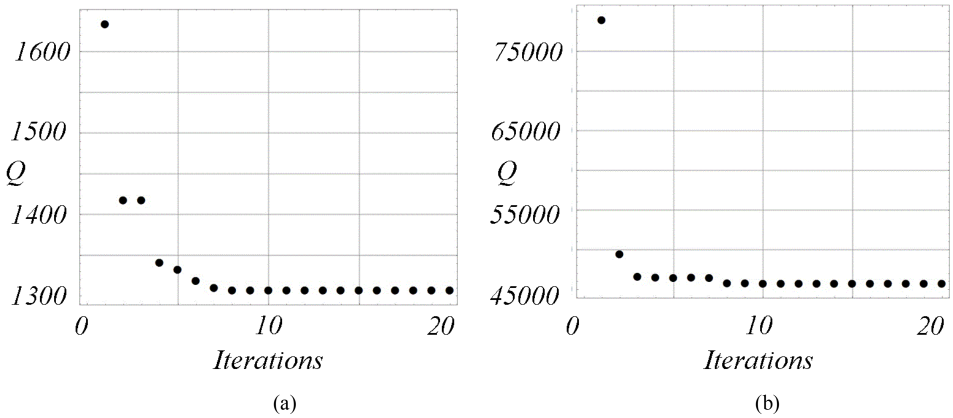

Fig. 2. Graph of convergence of the optimization criterion to a minimum: (a) criterion of the root mean square value of the generalized force; (b) the root mean square criterion of the power of the drive mechanisms

Now let's determine the force in the hydraulic cylinders of the telescopic boom F and the jib F_1. To do this, let's solve the first task of dynamics. We will assume that all links of the manipulator follow the laws determined by the solution of the optimization problem. This system has three degrees of freedom. For the generalized coordinates, we use the linear coordinate of the telescopic boom U, the angular coordinate of the movement of the jib β and the angular coordinate of the deviation of the load. For such a mechanical system, the equations of motion will look like:

$$\begin{cases} \left[J_1+J_2(U)\right]\ddot{\beta}+m_2(d+2U)\dot{\beta}\dot{U}-m\ddot{z}(U+d)\sin\beta=F_1\dfrac{\partial U_1}{\partial\beta}- \\ \qquad -\left[m_1\dfrac{c}{2}+m_2\left(U+\dfrac{d}{2}\right)+m(U+d)\right]g\cdot\cos\beta; \\ m_2\ddot{U}-\dfrac{1}{2}m_2\dot{\beta}\dot{U}(d+2U)+m\ddot{z}\cos\beta=F-(m_2+m)g\cdot\sin\beta; \\ \ddot{z}=-g\cdot\tan\nu, \end{cases} \tag{32}$$

From the first two equations of the obtained system we find the driving forces in the hydraulic cylinders:

$$\begin{aligned} F_1 = \Big\{&\left[J_1+J_2\right]\ddot{\beta}+m_2(d+2U)\dot{\beta}\dot{U}-m\ddot{z}(U+d)S\sin\beta+ \\ &+\left[m_1\frac{c}{2}+m_2\left(U+\frac{d}{2}\right)+m(U+d)\right]g\cos\beta\Big\}\Big/\frac{\partial U_1}{\partial\beta}; \end{aligned} \tag{33}$$

$$F = m_2\ddot{U}-\frac{1}{2}m_2\dot{\beta}\dot{U}(d+2U)+m\ddot{z}\cos\beta+(m_2+m)g\sin\beta. \tag{34}$$

With $\dfrac{\partial U_1}{\partial \beta}$ determined by the dependence:

$$\frac{\partial U_1}{\partial \beta} = -\frac{ab\sin(\alpha - \beta)}{U_1}. \qquad (35)$$

As a result of the solution of the set optimization problems, phase portraits of the crane loader crane movement were constructed (Fig. 3), as well as: schedules of speeds and acceleration of cargo (Fig. 4 and Fig. 5), graphs of the power of moving the jib (Fig. 6) and moving the telescopic boom (Fig. 7), and graphs of efforts in hydraulic cylinders (Fig. 8 and Fig. 9).

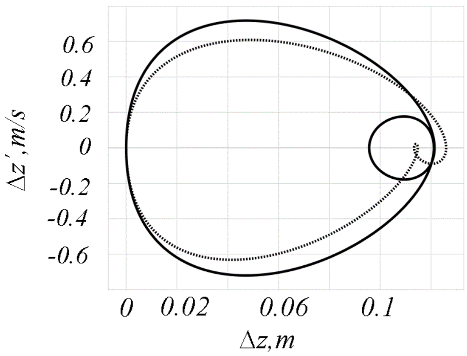

Fig. 3. Phase portrait of load deflection

Analyzing the phase portraits (Fig. 3) of the load oscillations, we can note the following.

In the process of starting the manipulator, when changing the departure of the boom system of the manipulator under different optimal modes of movement, there are slight deviations of the load, which almost attenuate when entering the steady movement.

According to the criterion of optimization of the root mean square value of the generalized force, the maximum value of the load-deflection is 0,12 m. The maximum value of the deflection velocity is 0,7 m/s.

According to the criterion of optimization of the root mean square value of the power of the drive mechanisms, the maximum value of the load deviation is slightly increased and is 0,13 m. This case, the speed of deflection of the cargo is less and its maximum value is 0,6 m/s.

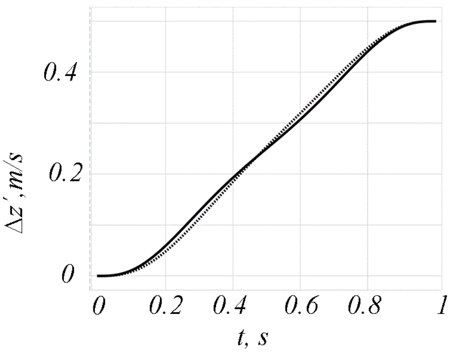

Fig. 4. Graphical dependence of the speed of movement of load

Comparing the graphical dependencies of the speed of cargo movement (Fig. 4), it can be noted that the two optimization criteria are quite close to each other. In both cases of optimization, the steady-state velocity is 0,5 m/s and the steady-state approach takes approximately 1 s. According to the criterion of optimization of the root mean square value of power, the speed at the beginning and the end of the movement changes according to the parabolic law, and in the middle of the section of motion, it has a pronounced linear nature of change. With Root mean square value of effort optimization, gives a load velocity mode close to two s-shaped motion laws.

Analyzing the graphical dependencies of load acceleration (Fig. 5), it can be noted that the two dependency optimization criteria are also similar.

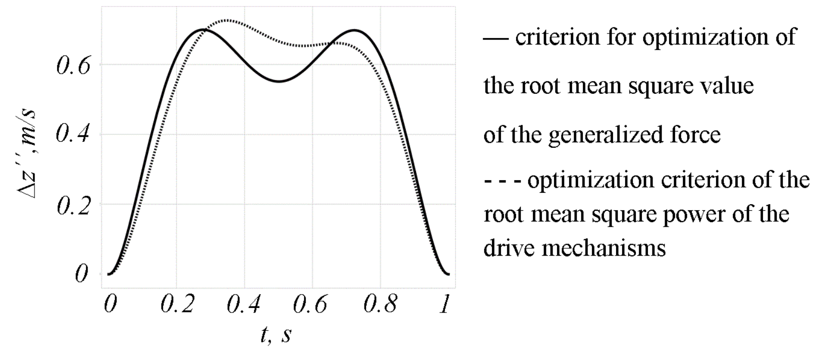

Fig. 5. Graphic dependence of acceleration of movement of load

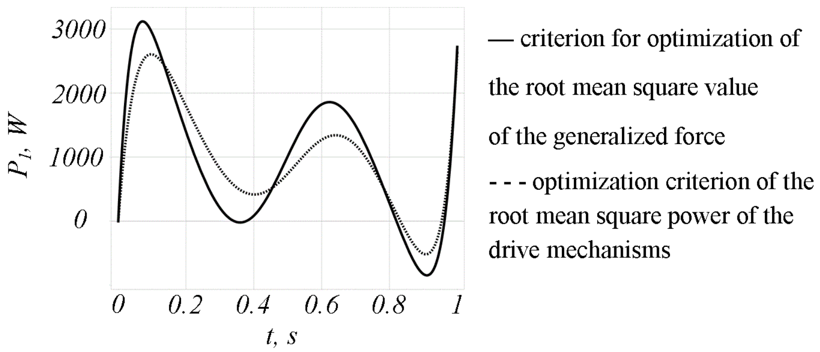

Fig. 6. Graphical dependence of the power consumed to move the jib

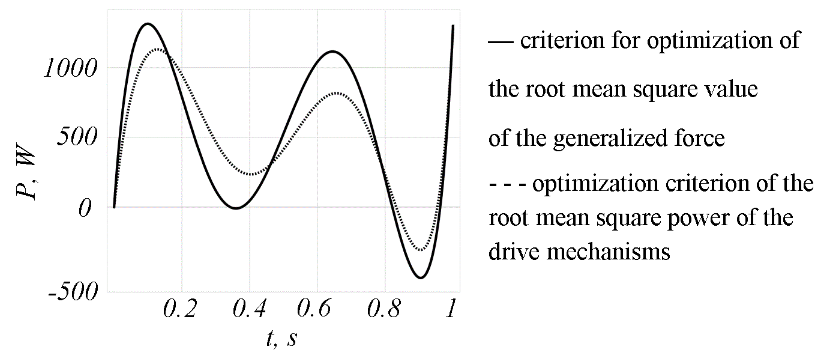

Fig. 7. Graphical dependence of the power consumed to move the telescopic boom

According to the criterion of optimization of the root mean square value of the generalized force, the maximum value of load acceleration is 0,7 m/s^2, at the time t = 0,28 s. At the time t = 0,5 s, the acceleration is 0,55 m/s^2, which caused by the load oscillations.

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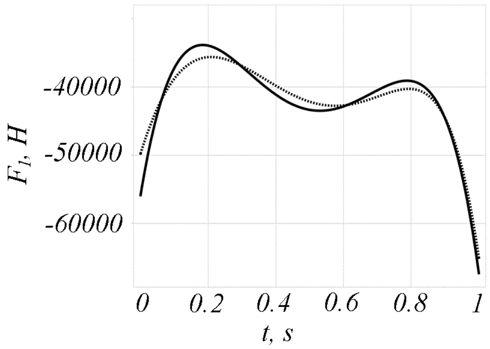
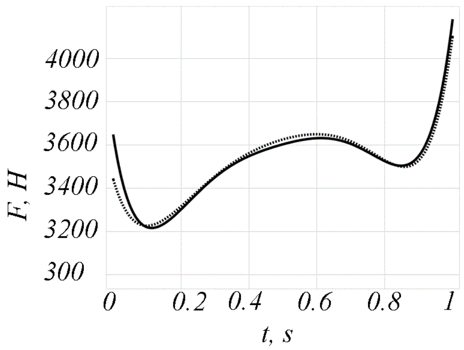


— criterion for optimization of the root mean square value of the generalized force
- - - optimization criterion of the root mean square power of the drive mechanisms

Fig. 8. Graphic dependence of the effort that develops the hydraulic cylinder of jib



— criterion for optimization of the root mean square value of the generalized force
- - - optimization criterion of the root mean square power of the drive mechanisms

Fig. 9. Graphic dependence of the effort which develops the hydraulic cylinder of telescopic boom

According to the criterion of optimization of the root mean square value power of the drive mechanisms, the maximum value of load acceleration is slightly increased and is 0,77 m/s^2, at the time t = 0,35 s. In the future, the acceleration gradually decreases to zero.

From the graphical dependences of the change of power for moving the jib (Fig. 6) and the telescopic boom (Fig. 7), it can be noted that the nature of the change in power over time by both criteria is similar. However, when optimized by the criterion of the root mean square of the generalized effort, the maximum power value is slightly higher than the optimization criterion for the root mean square power of the drive mechanisms. In this case, the maximum value of the power of the hydraulic cylinder for moving of the jib (Fig. 6) is 3100 W, at the time t = 0,08 s, and minimum – 800 W, at the time t = 0,9 s. For the hydraulic cylinder of moving of the telescopic boom (Fig. 7), the maximum power value is 1300 W, at the time t = 0,1 s, and the minimum – 500 W, at the time t = 0,9 s.

According to the criterion of optimization of the root mean square value of the efforts of the drive mechanisms, the maximum value of the power of the hydraulic cylinder of movement of the jib (Fig. 6) is 2600 W, at the time t = 0,15 s, minimum – 450 W, at the time t = 0,9 s. For the cylinder of displacement of the telescopic boom (Fig. 7), the maximum power value is 1150 W, at the time t = 0,1 s, and the minimum – 300 W, at the time t = 0,9 s.

With further displacement, power is an oscillatory character. This is caused by oscillation in the load. The negative values of the power of the hydraulic cylinder for moving the jib (Fig. 6) and the hydraulic cylinder for moving the telescopic boom (Fig. 7) are caused by the oscillation of the load in the direction of movement of the hydraulic cylinders.

Analyzing the graphical dependencies of the efforts that develop the hydraulic cylinders of the jib (Fig. 8) and the telescopic boom (Fig. 9), it can be noted that the nature of the change in effort by the two criteria is similar.

Analyzing the graphical dependencies of the efforts that develop the hydraulic cylinders of the jib (Fig. 8) and the telescopic boom (Fig. 9), it can be noted that the nature of the change in effort by the two criteria is similar.

According to the criterion of optimization of the root mean square value of the generalized force at the beginning of the movement for the hydraulic cylinder of the jib (Fig. 8), the force is equal to 56000 N. At the time t = 0,15 s, the effort becomes a minimum value and is equal to 46000 N. The maximum effort value becomes at the time t = 1 s and is equals to 48000 N.

For the hydraulic cylinder of the telescopic boom (Fig. 9) at the beginning of the effort movement is 3650 N. At the time t = 0,1 s, the effort becomes minimal and equals 3200 N. The maximum effort value becomes at the time t = 1 s and equals 4190 N.

According to the criterion of optimization of the root mean square power of the drive mechanisms at the beginning of the movement for the hydraulic cylinder of the jib (Fig. 8), the effort is equal to 50000 N. At the time t = 0,15 s, the effort becomes a minimum value and equals 44000 N. The maximum effort value becomes at the time t = 1 s and equals 65000 N. For the hydraulic cylinder, of the telescopic boom (Fig. 9) at the beginning movement of the effort is equals 3450 N. At the time t = 0,1 s, the effort acquires a minimum value and equals 3200 N. The maximum value of the effort acquires at the time t = 1 s and equals 4100 N.

Conclusions. As a result of the study, two optimization problems were solved with the aim of reducing the load oscillations while the simultaneous movement of two links of the boom system.

The complex integral dynamic criterion for optimization of the root mean square value of the generalized force, which is presented as a nonlinear integral functional, is substantiated. The criterion obtained reflects the undesirable properties of the boom system, so its value was minimized.

The complex integral dynamic criterion of the root mean square value of the power of the drive mechanisms, which is presented as a nonlinear integral functional, is substantiated. The criterion obtained reflects the undesirable properties of the drive mechanisms of the boom system, so its value was also minimized.

To solve these problems, the continuous functions z_0, z_1, z_2, …, z_{n-1}, z_n were replaced by unknown discrete values. They were obtained as the input algorithm of ME-PSO and these values are related to the criteria (25, 30). Such results were provided by a strategy of finding the global extremum by a swarm of particles.

The obtained optimal mode of movement of the boom system allowed to minimize dynamic loads in the drive mechanisms and metalware of the loader crane. With the received modes of movement of the boom system, elimination of load oscillations is achieved. This mode of movement improves the performance of the loader crane and its efficiency as a whole.

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Ловейкін В.С., Ромасевич Ю.О., Сподоба О.О., Ловейкін А.В., Почка К.І.
ОПТИМІЗАЦІЯ РЕЖИМУ РУХУ СТРІЛОВОЇ СИСТЕМИ КРАНА МАНІПУЛЯТОРА

У статті представлено метод вирішення проблеми усунення коливань вантажу, який закріплено на жорсткому шарнірному підвісі в момент одночасного переміщення двох ланок стрілової системи. Суть методу полягає в оптимізації режиму одночасного переміщення двох ланок стрілової системи крана маніпулятора при горизонтальному переміщені вантажу в період пуску. Задача розв'язана за двома критеріями оптимізації, а саме: за критерієм оптимізації середньоквадратичного значення узагальненої сили та критерієм оптимізації середньоквадратичного значення потужності приводних механізмів. Розроблені критерії відображають небажані властивості ланок стрілової системи та механізмів приводу, тому їх значення зводилися до мінімуму.

Розв'язок задачі оптимізації представлено у дискретному вигляді. Для цієї мети був використаний метод оптимізації рою частинок (ME-PSO). Це допомогло отримати дискретні значення кінематичних та силових характеристик стрілової системи крана маніпулятора.

Оскільки критерій оптимізації є інтегральним функціоналом, то для його оптимізації використані методи варіаційного числення. Рішення варіаційної задачі оптимізації представлено у вигляді багато параметричних функцій, які задовольняють крайові умови руху та мінімізують отримані безрозмірні критерії. Для цієї мети був використаний метод оптимізації рою частинок (ME-PSO). Це дало можливість отримати залежності оптимальних енергетичних та силових характеристик стрілової системи та механізмів приводу крана маніпулятора. Отриманий в результаті оптимізації режим переміщення ланок стрілової системи покращив силові та енергетичні характеристики крана маніпулятора, що дало можливість підвищити його надійність та продуктивність.

Ключові слова: математична модель, зміна вильоту, суміщення рухів, маніпулятор, рівняння Лагранжа другого роду, динамічні навантаження, коливання вантажу.

Loveikin V.S., Romasevich Yu.O., Spodoba O.O., Loveykin A.V., Pochka K.I.
OPTIMIZATION OF THE MODE OF MOVEMENT OF THE BOOM SYSTEM OF THE LOADER CRANE

The article presents a method for solving the problem of eliminating vibrations of the load, which is fixed on a rigid articulated suspension at the time of simultaneous movement of two links of the boom system. The essence of the method is to optimize the mode of simultaneous movement of two links of the boom system of the loader crane with horizontal movement of the load during the start-up period. The problem is solved according to two optimization criteria, namely: according to the optimization criterion of the root-mean-square value of the generalized force and the optimization criterion of the root-mean-square value of the power of drive mechanisms. The developed criteria reflect the undesirable properties of the links of the boom system and drive mechanisms, so their value was minimized.

The solution of the optimization problem is presented in a discrete form. For this purpose, the particle swarm optimization (ME-PSO) method was used. This helped to obtain discrete values of the kinematic and power characteristics of the boom system of the loader crane.

Since the optimization criterion is an integral functional, the methods of the calculus of variations are used for its optimization. The solution of the variational optimization problem is presented in the form of many parametric functions that satisfy the boundary conditions of motion and minimize the obtained dimensionless criteria. For this purpose, the particle swarm optimization (ME-PSO) method was used. This made it possible to obtain the dependence of the optimal energy and power characteristics of the boom system and the drive mechanisms of the loader crane. The mode of movement of the boom system links obtained as a result of optimization improved the power and energy characteristics of the loader crane, which made it possible to increase its reliability and productivity.

Keywords: mathematical model, changing the boom, combination of movements, manipulator, Lagrange equation of the second kind, dynamic loads, load oscillations.

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Ловейкін В.С., Ромасевич Ю.О., Сподоба О.О., Ловейкін А.В., Почка К.І. **Оптимізація режиму руху стрілової системи крана маніпулятора** // Опір матеріалів і теорія споруд: наук.-тех. збірник – К.: КНУБА, 2023. – Вип. 111. – С. 223-236.
Розв'язано задачу оптимізації, режиму одночасного переміщення двох ланок стрілової системи крана маніпулятора при горизонтальному переміщені вантажу в період пуску. Задача розв'язана за двома критеріями оптимізації, а саме: за критерієм оптимізації середньоквадратичного значення узагальненої сили та критерієм оптимізації середньоквадратичного значення потужності приводних механізмів. Для розв'язку поставленої задачі був використаний метод оптимізації рою частинок (ME-PSO). Це допомогло отримати дискретні значення кінематичних та силових характеристик стрілової системи крана маніпулятора. Отриманий в результаті оптимізації режим переміщення ланок стрілової системи покращив силові та енергетичні характеристики крана маніпулятора, що дало можливість підвищити його надійність та продуктивність.
Іл. 9. Бібліогр. 15 назв.

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Loveikin V.S., Romasevich Yu.O., Spodoba O.O., Loveykin A.V., Pochka K.I. **Optimization of the mode of movement of the boom system of the loader crane** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles- K.: KNUBA, 2023. – Issue 111. - P. 223-236.
The optimization problem has been solved for the mode of simultaneous movement of two links of the boom system of the loader crane with horizontal movement of the load during the start-up period. The problem is solved according to two optimization criteria, namely: according to the optimization criterion of the root-mean-square value of the generalized force and the optimization criterion of the root-mean-square value of the power of drive mechanisms. To solve the problem, the particle swarm optimization method (ME-PSO) was used. This helped to obtain discrete values of the kinematic and power characteristics of the boom system of the loader crane. The mode of movement of the boom system links obtained as a result of optimization improved the power and energy characteristics of the loader crane, which made it possible to increase its reliability and productivity.
Fig. 9. Ref. 15.

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