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Optimization of Bridge Crane Movement Control

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Abstract. Transient modes of bridge cranes movement determine their energy, dynamic and electrical performance, as well as productivity and durability of work. An optimal control problem of its movement has been solved while making an analysis of indicators for efficient performance of a bridge crane. Terminal and integral criteria have been selected as optimization criteria. They represent undesirable dynamic properties of the crane. Legendre method has been used to determine the possibility for achieving minimum of the optimization criterion. An analysis of the Euler-Poisson equation, which is a necessary condition for the minimum of the integral criterion, has shown that it is impossible to find a solution for the optimization problem in an analytical form. A method of differential evolution has been used in order to find an approximate solution to the optimization problem. The approximate (suboptimal) solution has been found in the complex domain, which is a limited domain conjunction of dynamic parameters and phase coordinates of the system. Limitation in the domain of the system phase coordinates (a polynomial basis function has been used in the paper) provides the possibility to attain absolute minimums of terminal problem criteria. A simulation of the bridge crane motion has been carried out in order to establish an efficiency for implementation of the suboptimal control. During this process dynamic mechanical characteristics of its electric drive have been taken into account. While carrying out the simulation, a frequency and an amplitude of the electric drive voltage in the crane movement mechanism have been changed (frequency scalar method for speed changing of an asynchronous electric drive has been used). A comparative analysis of the dynamic, kinematic, electrical and energy performance indicators of the bridge crane under suboptimal and S-curved (standard) laws of frequency and voltage variations in the crane electric drive has made it possible to establish an improvement in the efficiency of its operation under suboptimal control.

Keywords: bridge crane, optimal control, integral and terminal criteria, simulation, oscillations, dynamic loads, differential evolution

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Оптимизация управления движением мостового крана

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Реферат. Переходные режимы движения мостовых кранов определяют их энергетические, динамические и электрические показатели, а также производительность и долговечность работы. На основе анализа показателей эффективности работы мостового крана решена задача оптимального управления его передвижением. В качестве критериев оптимизации выбраны терминальные и интегральный критерии, отображающие нежелательные динамические свойства крана. С помощью метода Лежандра установлена возможность достижения минимума интегрального критерия. Анализ уравнения Эйлера – Пуассона, которое является необходимым условием минимума интегрального критерия, показал, что аналитическое нахождение решения оптимизационной задачи невозможно. Для нахождения приближенного решения оптимизационной задачи использован метод дифференциальной эволюции. Приближенное (субопти-

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мальное) решение было найдено в комплексной области, которая является конъюнкцией ограниченных областей динамических параметров и фазовых координат системы. Ограничение области фазовых координат системы (в статье использована полиномиальная базисная функция) дало возможность достичь абсолютных минимумов терминальных критериев задачи. Для установления эффективности реализации субоптимального управления проведено моделирование движения мостового крана с учетом динамической механической характеристики его электропривода. В процессе моделирования изменению подвергались частота и амплитуда питающего напряжения электропривода механизма передвижения крана (использован частотный скалярный метод изменения скорости асинхронного электропривода). Сравнительный анализ динамических, кинематических, электрических и энергетических показателей работы мостового крана при субоптимальном и *S*-образном (стандартном) законах изменения частоты и напряжения питания электропривода крана дал возможность установить улучшение эффективности его работы при субоптимальном управлении.

Ключевые слова: мостовой кран, оптимальное управление, интегральный и терминальный критерии, моделирование, колебания, динамические нагрузки, дифференциальная эволюция

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Introduction

Bridge cranes are used in many processing of the state-of-the-art technology. The efficiency of crane operation has an impact on the productivity process of production. In order to state the ways of increasing crane effectiveness, the study of crane process has to be done.

In the first scientific researches of bridge cranes dynamics the simple models of the systems and external forces were used [1–4]. The two- and three-mass models have been used. The drive force was assumed constant. The results of these works allowed calculate dynamical loads with analytical expressions at a first approximation. In the works [5–8] assumed that drive force is a function of time or speed of a system drive. The compilation of the models allowed find an analytical expressions for dynamical loads calculation.

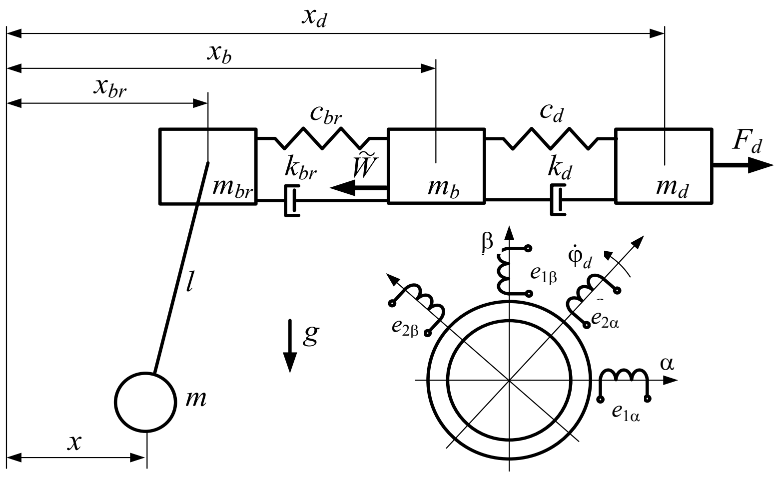
The new approaches to dynamic loads calculation comprise the dynamic mechanical characteristic of the system's drive [7, 9], non-linear effects [10–15] etc.

The problems of rationalization of the bridge crane movement were studied in the works [16, 17]. Another approach to increase bridge crane efficiency is to obtain the optimal law of its movement. One of the major conditions that have been met in many works is to eliminate cargo oscillations. The major factor in such approach is optimization criterion. Minimization of transition regimes duration [18–25] is attended by increasing of dynamical loads. The integral criterion which includes dynamical and energetic functions [9, 26, 27] allows to increase productivity, reliability and energy efficiency. Because of a system processing depends on the external forces and system parameters [28, 29], the solution of optimization problems if crane dynamics has to be found in domains of movement regimes and system parameters.

In spite of rigorous research in the area of crane dynamics and its optimal control, the unsolved scientific problems still remain: 1) optimization of the bridge crane regimes has done only in relation to one criterion (time, energy, force etc.). This problem statement is limited; 2) the implementation of the optimal laws of crane motion with frequency-controlled drive did not study properly; 3) the capability of using a particular techniques in optimization problems has been studied improperly; 4) the analysis of the solved optimal problem, carried out upon not all indications and so on.

For this reason the goal of the article is to obtain optimal movement regime of the bridge crane and its dynamic parameters, which allows to increase the efficiency processing of the crane upon such indications: productivity, reliability, energy efficiency, etc. In order to achieve the goal the following tasks, it is necessary to solve next issues: 1) to state an optimization regime's problem for bridge crane; 2) to find the solution of the stated problem; 3) to carry out a comparison study of the obtained results and to estimate the effect of the optimization.

Main part. In order to provide a research we have chosen a dynamics model of the bridge crane and the scheme of its asynchronous drive (fig. 1) [9, 17].



a b

Fig. 1. Four-mass dynamics model of the bridge crane (a) and scheme of the bridge crane asynchronous drive (b): $\tilde{W}$ – variable resistance of the bridge crane movement; l – length of flexible suspension of a cargo; g – acceleration of gravity; x, x_b, x_{br}, x_d – generalized coordinates of the cargo, an end beams, the crane bridge and the drive respectively; m, m_b, m_{br}, m_d – reduced masses of the cargo, the end beams, the crane bridge and the drive respectively; c_{br}, c_d – reduced coefficients of stiffness of the crane bridge and the transmission respectively; k_{br}, k_d – reduced dissipation factor of the crane bridge and the transmission respectively; F_d – drive force which is reduced to forward movement (it depends on electromagnetic torque of the crane drive); $u_{1\alpha}$, $u_{1\beta}$ – generalized vector projections of voltage stator to coordinate axes α and β $\left(u_{1\alpha}=U_{\max}\cos\left(2\pi\int_0^t f dt\right),\ u_{1\beta}=U_{\max}\sin\left(2\pi\int_0^t f dt\right)\right)$; $U_{\max}$ – phase voltage amplitude of the drive; f – frequency of drive voltage; $e_{2\beta}$, $e_{2\alpha}$ – EMF, which was inducing by flux linkage of rotor to axes α and β respectively; ($e_{2\alpha}=p\omega_{дв}(L_2 i_{2\beta}+L_{12}i_{1\beta})+i_{2\alpha}R_2$), $e_{2\beta}=p\omega_{дв}(L_2 i_{2\alpha}+L_{12}i_{1\alpha})+i_{2\beta}R_2$)); p – number of the crane electric drive pairs of poles; R_1 – active resistance of the stator winding; R_2 – reduced to the stator active resistance of the rotor winding; δ – dispersion coefficient ($\delta = 1-(1+X_1(2\pi f L_{12})^{-1}(1+X_2(2\pi f L_{12})^{-1})^{-1})$; X_1 – inductive reactance of the stator winding; X_2 – reduced to the stator inductive reactance of the stator winding; L_1, L_2 – inductance of the stator and the rotor windings respectively; L_{12} – coefficient of the mutual induction; k_r, k_s – magnetic coupling ratio of the rotor and the stator respectively ($k_r=L_{12}L_2^{-1}$; $k_s=L_{12}L_1^{-1}$); $\omega_{дв}$ – angular speed of the drive; $i_{1\alpha}$, $i_{1\beta}$ and $i_{2\alpha}$, $i_{2\beta}$ – projections of generalized vector of current of the stator and rotor to coordinates axes α and β

Mathematical model of the crane is the system of the non-linear homogeneous differential equations of second order:

$$\begin{cases}
\dfrac{di_{1\alpha}}{dt}=\dfrac{1}{\delta L_1}(u_{1\alpha}-i_{1\alpha}R_1+k_r e_{2\alpha});\\
\dfrac{di_{1\beta}}{dt}=\dfrac{1}{\delta L_1}(u_{1\beta}-i_{1\beta}R_1-k_r e_{2\beta});\\
\dfrac{di_{2\alpha}}{dt}=-\dfrac{1}{\delta L_2}((u_{1\alpha}-i_{1\alpha}R_1)k_s+e_{2\alpha});\\
\dfrac{di_{2\beta}}{dt}=-\dfrac{1}{\delta L_2}((u_{1\beta}-i_{1\beta}R_1)k_s-e_{2\beta});\\
3pL_{12}(i_{1\beta}i_{2\alpha}-i_{1\alpha}i_{2\beta})\dfrac{u\eta_{dr}}{r_w}=m_d\dfrac{d^2x_d}{dt^2}+c_d(x_d-x_b)+k_d\left(\dfrac{dx_d}{dt}-\dfrac{dx_b}{dt}\right);\\
m_b\dfrac{d^2x_b}{dt^2}=c_d(x_d-x_b)+k_d\left(\dfrac{dx_d}{dt}-\dfrac{dx_b}{dt}\right)-c_b(x_b-x_{br})-k_b\left(\dfrac{dx_b}{dt}-\dfrac{dx_{br}}{dt}\right)-\tilde{W};\\
m_{br}\dfrac{d^2x_{br}}{dt^2}=c_b(x_b-x_{br})+k_b\left(\dfrac{dx_b}{dt}-\dfrac{dx_{br}}{dt}\right)-\dfrac{mg}{l}(x_{br}-x);\\
\dfrac{d^2x}{dt^2}=\dfrac{g}{l}(x_{br}-x),
\end{cases} \tag{1}$$

where u – gear ratio of the drive; η_{dr} – efficiency of the transmission; r_w – radius of a wheel of the crane movement mechanism. Variable resistance of the bridge crane movement $\tilde{W}$ determined as follow:

$$\tilde{W}=\begin{cases} c_d x_d + k_d \dfrac{dx_d}{dt}, \ \text{if } c_d x_d + k_d \dfrac{dx_d}{dt} < (0{,}012 \ldots 0{,}02)(m_b + m_{br} + m)g; \\ (0{,}012 \ldots 0{,}02)(m_k + m_m + m_b)g, \ \ if \ c_d x_d + k_d \dfrac{dx_d}{dt} \geq (0{,}012 \ldots 0{,}02)(m_b + m_{br} + m)g. \end{cases} \tag{2}$$

The chosen mathematical model includes mechanical and electrical values. Thus, in the research we took into account complicate electrical-mechanical processes and its interinfluence.

One of the ways to increase a crane operation is to optimize its transition regimes of motion and its parameters. In the framework of this study a complex (terminal-integral) criterion has been chosen, which can be presented as follows:

$$Cr = Ter + Int = \left(\delta_1^{Ter} F_d^2(0) + \delta_2^{Ter} F_d^2(T)\right)^{0,5} =$$
$$= \left(T^{-1} \int_0^T (\delta_1^{Int} F_d^2 + \delta_2^{Int} R_d^2 + \right. \tag{3}$$
$$\left. + \delta_3^{Int} R_{br}^2 + \delta_4^{Int} \Omega_0^4 m^2 \Delta x^2) dt \right)^{0,5} \to \min,$$

where Ter and Int – terminal and integral parts of complex criteria Cr respectively; T – duration of the transition process (acceleration or deceleration of a crane); R_{br} and R_d – dynamical loads in the crane bridge and the drive (transmission) respectively; Δx – lack of perpendicularity of the cargo, which determines low-frequency dynamic loads in the crane bridge; Ω_0 – free frequency of a load on a flexible suspension; δ_1^{Ter} and δ_2^{Ter} – weight coefficients for terminal part of Cr; δ_1^{Int}, δ_2^{Int}, δ_3^{Int} and δ_4^{Int} – weight coefficients for integral part of Cr. Weight coefficients for both parts of criterion (2) are dimensionless, their sum is equal to one. The values of weight coefficients stated the importance of respective factors, i. e. how important to decrease one or the other factor.

Minimization of criterion Cr (2) allows to increase life duration of the crane elements (bridge, couplings, gears, shafts etc.), crane's productivity and energy efficiency.

Without consideration of electromagnetic transition processes in the crane drive and dissipation of the energy in mechanical elements, the criterion Cr (2) could be presented in the following form:

$$Cr = \left(\delta_1^{Ter} \left(\tilde{W}(0) + \sum_{u=1}^{4} A_u \frac{d^{2u}x}{dt^{2u}}(0) \right)^2 + \delta_2^{Ter} \left(\tilde{W}(T) + \sum_{h=1}^{4} A_h \frac{d^{2h}x}{dt^{2h}}(T) \right)^2 \right)^{0,5} = \left(T^{-1} \int_0^T \Bigg(\delta_1^{Int} \times \right.$$
$$\left. \times \left(\tilde{W} + \sum_{i=1}^{4} A_i \frac{d^{2i}x}{dt^{2i}} \right)^2 + \delta_2^{Int} \left(\tilde{W} + \sum_{j=1}^{3} B_j \frac{d^{2j}x}{dt^{2j}} \right) + \delta_3^{Int} \left(\sum_{q=1}^{2} C_q \frac{d^{2q}x}{dt^{2q}} \right)^2 + \delta_4^{Int} m^2 \left(\frac{d^2x}{dt^2} \right)^2 \Bigg) dt \right)^{0,5} \to \min, \tag{4}$$

where A_i, B_j, C_q – coefficients, which are determined by the following expressions:

$$A_1 = m + m_{br} + m_b + m_d;$$

$$A_2 = \frac{(m_{br} + m)(m_d + m_b)}{c_{br}} + \frac{m_d (m_{br} + m + m_b)}{c_d} + \left(m_{br} + m_b + m_d\right)\Omega_0^{-2};$$

$$A_3 = \frac{(m_{br} + m) m_d m_b}{c_d c_{br}} + \left(\frac{m_d (m_{br} + m_b)}{c_d} + \frac{m_{br}(m_d + m_b)}{c_{br}} \right) \Omega_0^{-2};$$

$$A_4 = \frac{m_{br} m_d m_b}{c_d c_{br}} \Omega_0^{-2}; \ B_1 = m + m_{br} + m_b;$$

$$B_2 = (m_{br} + m_b)\Omega_0^{-2} + \frac{m_b}{c_{br}}(m_{br} + m); \ B_3 = \frac{m_b m_{br}}{c_{br}} \Omega_0^{-2};$$

$$C_1 = m + m_{br}; \ \ C_2 = m_{br} \Omega_0^{-2}.$$

The boundary conditions for the reduced masses are followed:

$$\begin{cases} \begin{cases} x(0) = \dfrac{dx}{dt}(0) = 0; \\ x_{br}(0) = \dfrac{dx_{br}}{dt}(0) = 0; \\ x_b(0) = \dfrac{dx_b}{dt}(0) = 0; \\ x_d(0) = \dfrac{dx_d}{dt}(0) = 0 \end{cases} \\ \begin{cases} x(T) = s;\ \dfrac{dx}{dt}(T) = v; \\ x(T) - x_{br}(T) = x_{br}(T) - x_b(T) = x_b(T) - x_d(T) = 0; \\ \dfrac{dx}{dt}(T) - \dfrac{dx_{br}}{dt}(T) = \dfrac{dx_{br}}{dt}(T) - \dfrac{dx_b}{dt}(T) = \dfrac{dx_b}{dt}(T) - \dfrac{dx_d}{dt}(T) = 0, \end{cases} \end{cases} \tag{5}$$

Boundary conditions (5) could be rewritten in following form:

$$\begin{cases} \dfrac{d^i x}{dt^i}(0) = 0,\ i = \overline{(0,\ 7)}; \\ x(T) = s,\ \dfrac{dx}{dt}(T) = v,\ \dfrac{d^j x}{dt^j}(T) = 0,\ \ j = \overline{(2,\ 7)}. \end{cases} \tag{6}$$

Note, that augmentation to boundary conditions (6) extra conditions:

$$\begin{cases} \dfrac{d^8 x}{dt^8}(0) = 0; \\ \dfrac{d^8 x}{dt^8}(T) = 0 \end{cases} \tag{7}$$

could allow hitting the global minimum of the terminal criteria *Ter* (3).

The study of the integral criterion *Int* with Legendre condition [30] shows that it could be minimized. Indeed, the strong of the Legendre condition occurs:

$$\frac{\partial^2 I}{\partial\left(\dfrac{d^8 x}{dt^8}\right)^2} = 2\delta_1^{Int} A_4^2 > 0, \tag{8}$$

where I – integrand of the functional *Int*.

The first part of the expression (2) does not cause a significant effect. So, during optimal control problem solving, let us assume $\widetilde{W}$ is constant and equal to $0{,}015(m_b + m_{br} + m)g$. This assumption greatly simplifies the solving of the problem.

Let us try to use the variation calculus [30] to find solution to the problem. For this purpose it is necessary to obtain the extremum necessary criterion of the *Cr* – the Euler-Poisson equation. It could be presented as follow:

$$L(x) = \sum_{z=0}^{n} (-1)^z \frac{d^z}{dt^z} \frac{\partial I}{\partial \overset{z}{x}} = 0, \tag{8}$$

where L – differential functional, which forms the Euler-Poisson equation. The expanded form of the expression (8) has the following form:

$$L(x) = \sum_{z=2}^{8} D_z \frac{d^{2z} x}{dt^{2z}} = 0, \tag{9}$$

where D_z – coefficients, which are depend on already known coefficients A_i, B_j and C_q.

In order to solve differential equation to find the auxiliary equation is necessary:

$$\sum_{z=2}^{8} D_z r^{2z} = 0. \tag{10}$$

Taking out a factor r^4 and substituting r^2 to y we obtain the next equation:

$$y^2 \sum_{z=0}^{6} D_{z+2} y^z = 0. \tag{11}$$

It is impossible to find the solution of the sixth-degree algebraic equation. Consequently, to find the solution of the optimal control problem is also impossible. It may be shown; that analytical solution could not be found with Pontryagin's maximum principle or dynamic programming method neither.

Hence, we could use an approximate approach. In order to find the approximate solution of the problem let use direct variation method [31]. The basis function is a polynomial of the n-th order:

$$\tilde{\alpha} = \sum_{b=0}^{17} G_b t^b + \sum_{e=18}^{n} G_e t^e, \qquad (12)$$

where G_e – unknown coefficients; n – the highest degree of among extra members of the polynomial, which will be used in order to minimize integral criterion *Int*.

The unknown coefficients G_b must be found in such a way that function (12) met boundary conditions:

$$\begin{cases} \dfrac{d^i\tilde{\alpha}}{dt^i}(0) = 0, \; i = \overline{(0,\ 8)}; \\ \tilde{\alpha}(T) = s, \; \dfrac{d\tilde{\alpha}}{dt}(T) = v, \; \dfrac{d^j\tilde{\alpha}}{dt^j}(T) = 0, \; j = \overline{(2,\ 8)}. \end{cases} \qquad (13)$$

So, the polynomial expression (12) is the function of n-18 unknown coefficients G_e. We can find the expression:

$$\left(T^{-1}\int_0^T \left(\delta_1^{Int}\left(\tilde{W} + \sum_{i=1}^{4} A_i \frac{d^{2i}\tilde{\alpha}}{dt^{2i}}\right)^2 + \right.\right.$$
$$+\delta_2^{Int}\left(\tilde{W} + \sum_{j=1}^{3} B_j \frac{d^{2j}\tilde{\alpha}}{dt^{2j}}\right) + \delta_3^{Int}\left(\sum_{q=1}^{2} C_q \frac{d^{2q}\tilde{\alpha}}{dt^{2q}}\right)^2 + \qquad (14)$$
$$\left.\left. + \delta_4^{Int} m^2 \left(\frac{d^2\tilde{\alpha}}{dt^2}\right)^2 \right) dt \right)^{0,5} = f(G_e,\ A_i,\ B_j,\ C_q,\ s,\ T).$$

Note, the system parameters m_d, m_b, m_{br}, m are unchangeable (based on meeting of the crane design conditions). Parameters T, v could be changed, but they were defined by the technological conditions of the crane processing. Accept that, they are unchangeable. Parameters c_{br}, l are changeable but only in limited domains. We might obtain the values of c_{br}, l, in their limited domains such, that expression (14) attains the minimum. The same is true for regime parameter s.

In order to minimize the expression (14) the stated optimal control problem has been reduced to the linear programming problem [32]:

$$\begin{aligned} & f(G_e,\ c_d,\ l,\ s) \to \min; \\ & c_{d.\min} \le c_d \le c_{d.\max}; \\ & l_{\min} \le l \le l_{\max}, \end{aligned} \qquad (15)$$

where $c_{d.\min}$ and $c_{d.\max}$ – lower and higher border of parameter c_d domain respectively; $l_{\min}$ and $l_{\max}$ – lower and higher border of parameter l domain respectively.

In the context of the used application n has been chosen equal to 5. It is the rational value – the compromise between a computational compilation and an accuracy of problem solution.

The stated linear programming problem has been solved with the differential evolution method [33] for tabulated parameters (tabl. 1).

Table 1

Values of system parameters, which have been used in calculations

Parameter	Unit of measurement	Value
m_d	kg	$3{,}50 \cdot 10^3$
m_b		$2{,}05 \cdot 10^4$
m_{br}		$2{,}60 \cdot 10^4$
m		$2{,}00 \cdot 10^4$
T	s	$4{,}00 \cdot 10^0$
$P_{d.nom}$	Wt	$2\times1{,}50 \cdot 10^4$
$l_{\min}$	m	$1{,}50 \cdot 10^0$
$l_{\min}$		$8{,}00 \cdot 10^0$
v	m/s	$2{,}10 \cdot 10^0$
c_{br}	H/m	$6{,}90 \cdot 10^6$
$c_{d.\min}$		$4{,}80 \cdot 10^6$
$c_{d.\max}$		$1{,}92 \cdot 10^7$

The optimal value parameter c_d is the domain boundary $c_{d.\min}$. The best values for parameters l and s are 2,15 m and 4,2 m respectively. In order to show the advantages of the obtained suboptimal regime of the bridge crane processing the comparative analysis have been carried out. The suboptimal regime of the crane movement was comparing with S-curve law of the crane motion. Such law took in comparing because it is standard curve in variable-frequency crane drive [34]. The comparing was carried out with indicators: maximum of load deflection angle $\varphi_{\max}$ during the crane movement; maximum of load deflection angle $\varphi_{\max.T}$ after the crane stop; maximum of force in the crane bridge $R_{br.\max}$; maximum of force in the crane transmission $R_{d.\max}$; maximum of the crane drive torque $M_{d.\max}$; root-mean-square force in the crane bridge $R_{br.\mathrm{RMS}}$; root-mean-square force in the crane transmission $R_{d.\mathrm{RMS}}$; root-mean-square of the crane drive torque $M_{d.\mathrm{RMS}}$; relative maximum of the crane drive power $\tilde{P}_{\max}$ (in fractions of nominal value); relative maximum of the crane drive current $\tilde{I}_{\max}$ (in fractions of nominal value). The indicators that have been calculated for all cycle of motion "acceleration-steady movement-deceleration" are tabulated in tabl. 2.

Duration of the steady movement of the crane is equal to 3 s. Analysis of the tabl. 2 data shows that suboptimal control of the crane movement reduced root-mean-square forces and torques, but maximums of the dynamical loads slightly increased.

The reason why root-mean-square forces and torques have decreased is the oscillation of the load on the flexible suspension became much lesser and dynamical loads, which have been caused by oscillation, have decreased. The residual oscillation (after the crane stop) of the cargo during suboptimal control practically non-exists. It allows to increase the crane productivity. Also, the intensity of cranes operator's work became much lesser.

In order to show quality of implementation, the curves have been plotted (fig. 2).

Gray curve on the fig 2 presents preset speed of the crane. Analysis of the curves shows that frequency-controlled crane drive able to implement the suboptimal law at high quality. Plots, which are presented in fig. 2, shows, that the determine factor of the crane working process is the shape of the acceleration and deceleration curves.

Table 2

Values of indicators

Indicators	Unit of measurement	Regime of motion		Reduction
		S-curved	Suboptimal	
$\varphi_{\max}$	grad	$1{,}10 \cdot 10^1$	$7{,}56 \cdot 10^0$	45,5 %
$\varphi_{\max.T}$		$1{,}10 \cdot 10^1$	$2{,}50 \cdot 10^{-1}$	44 times
$R_{br.\max}$	H	$4{,}67 \cdot 10^4$	$4{,}88 \cdot 10^4$	–4,3 %
$R_{d.\max}$		$1{,}49 \cdot 10^3$	$1{,}75 \cdot 10^3$	–14,8 %
$R_{br.\mathrm{RMS}}$		$1{,}25 \cdot 10^4$	$1{,}06 \cdot 10^4$	17,9 %
$R_{d.\mathrm{RMS}}$		$3{,}53 \cdot 10^2$	$3{,}36 \cdot 10^2$	5,1 %
$M_{d.\max}$	Hm	$9{,}77 \cdot 10^2$	$9{,}98 \cdot 10^2$	–2,1 %
$M_{d.\mathrm{RMS}}$		$2{,}24 \cdot 10^2$	$2{,}16 \cdot 10^2$	3,7 %
$\tilde{P}_{\max}$	–	$3{,}70 \cdot 10^0$	$3{,}52 \cdot 10^0$	5,1 %
$\tilde{I}_{\max}$	–	$4{,}47 \cdot 10^0$	$3{,}91 \cdot 10^0$	14,3 %

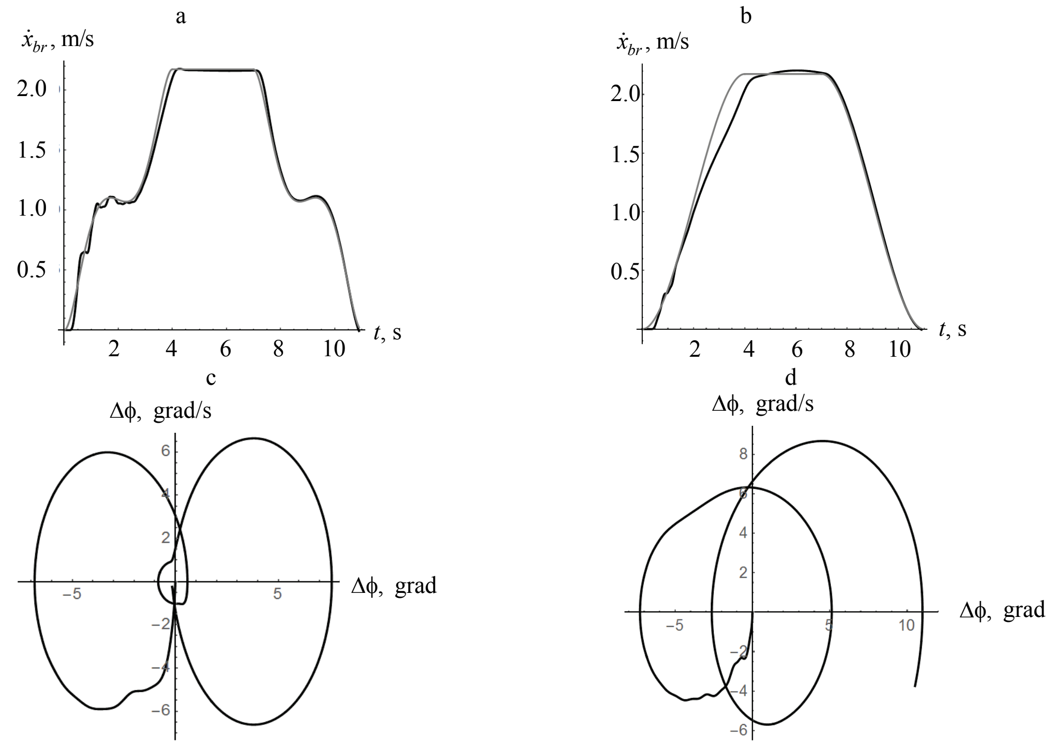


Fig. 2. Curves of crane speed during suboptimal (a) and S-curve (b) control; phase trajectory of the cargo oscillation during suboptimal (c) and S-curve (d) control

CONCLUSIONS

The major scientific results, obtained in the article are:

1) it is impossible to find the exact solution of the optimal control problem for four-mass dynamical model of the crane. An efficient method which reduces the optimal control problem to the linear programming problem is direct variational techniques. It is desirable to seek the solution of the problem in limited domains of phase coordinates and dynamical parameters of a system;

2) obtained in the work suboptimal control of the crane movement could be implemented with the frequency-controlled drive. The optimal values of the stiffness coefficients of the crane transmission and a length of flexible suspension might be used in improvement of crane processing;

3) one of the determine factor of the crane working process is the shape of the acceleration and deceleration curves. During suboptimal control of the crane movement root-mean-square forces and torques are decreasing, but maximum dynamic loads are increasing slightly.

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