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ANALYSIS OF THE OPTIMAL SPEED-BASED START-UP MODE OF THE TOWER CRANE SWING MECHANISM UNDER CONTROL LIMITATIONS

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A comparative analysis of the optimal starting mode of the tower crane slewing mechanism in terms of speed under asymmetric (task 1) and symmetric (task 2) constraints on optimal control is presented in a scientific article. A two-mass dynamic model was used for the research, whose motion in time is described by a system of two second-order differential equations. In the course of further research, the system of two second-order differential equations was reduced to a single fourth-order differential equation. After performing the appropriate transformations, the fourth-order differential equation was presented in Cauchy form and the initial and final conditions of motion were given, under which the load oscillations will be eliminated after the turning mechanism reaches a steady speed.The optimisation task itself was reduced to the task of unconditional minimisation of a complex integral-terminal functional, where the terminal component is responsible for the fulfilment of the final boundary conditions, and the integral component is responsible for the speed of the mechanism. A series of 54 experimental studies (27 for each of the tasks under investigation) was planned, in which the independent factors were the length of the flexible suspension (which was 10, 15 and 20 metres), the load projection (which was 5, 15 and 20 m), and the load mass (which was 500, 2000 and 5000 kg).During the theoretical studies, the main assessment was carried out according to the following indicators: the duration of the system acceleration to the steady-state speed value; the maximum deviation of the flexible suspension of the load from the vertical; the maximum and root mean square values of the power in the drive and the acceleration of the load.The results of the analysis showed that when using asymmetric constraints for optimal control (task 1), the acceleration time of the studied system to a steady state speed increases compared to symmetric constraints (task 2) in the range from 1.23 to 15. 28 %, and the maximum values of kinematic characteristics decrease from 5.46 to 42.85 % and energy indicators from 0.48 to 27.83 %.

Keywords:tower crane, load, velocity, slewing mechanism, optimal control constraints, Ring-Rot-PSO method.

Introduction. The effective operation of the tower crane slewing mechanism in the practical implementation of the optimal speed-of-operation start-up mode requires that the drive of the studied system operate in the least stressed mode possible. Ensuring such a drive operation mode during the slewing mechanism start-up is possible by using asymmetric constraints on the optimal speed-of-operation control of this system.

The effectiveness of using asymmetric constraints on optimal control in comparison with symmetric constraints is determined by conducting a comparative analysis of the main indicators of system motion under different constraints.

Analysis of publications. In [1], a “suppression-excitation” approach is presented for online trajectory generation of corresponding systems with uncertain motion. In this study, a framework is proposed that allows designing kinematic reference trajectories and detecting flexible modes of uncertain systems during motion in order to improve their tracking efficiency.

In [2], using an artificial neural network, an input signal generation technique is proposed that allows for effective control of tower crane load oscillations with different variations in the length of the flexible suspension. The effectiveness of the proposed method is confirmed by experimental studies using a laboratory tower crane with simultaneous tangential and radial movement.

In the article [3] a method of increasing the efficiency of a robotic manipulator with a corresponding grab grip during the transportation of wood in the woodworking industry is proposed. The efficiency of the manipulator is increased by planning the trajectory of movement, during which the oscillations of the grab grip are damped. The dynamic programming method was used during the calculations.

In [4], it is proposed to control the oscillations of a crane system during underwater load transportation based on a neural network. Neural networks are designed to compensate for unknown parameters in the formulated problem. The corresponding simulation results are presented, allowing to verify the effectiveness and reliability of the proposed control method.

In work [5], using the maximum principle, the problem of determining the control laws of the jib crane slewing mechanism was solved. An algorithm for searching for optimal control of the jib crane productivity was found and substantiated. The optimal mode of motion of the slewing mechanism of the laboratory model of the jib crane was calculated.

The article [6] presents an original microprocessor control system for a bridge crane model based on the Arduino microcontroller. The proposed control system allows for the implementation of control laws that are optimal in terms of speed, which makes it possible to eliminate oscillations of the load fixed on a flexible suspension after the crane stops, as well as to perform its precise positioning in the shortest possible time with a minimum number of control mode switching.

In [7], the methodology for selecting the optimal structure of tower crane mechanisms from a set of possible technical solutions is described. The effectiveness of the optimization is tested in dynamic conditions, taking into account the stiffness of the ropes. Finding a global optimal design solution gives the best combination of the operation of various mechanisms, in which the value of undesirable dynamic indicators is significantly minimized at the stage of designing the metal structure.

In [8], the researchers formalized the dynamics of a ship-to-ship motion system with jib cranes during load transfer from one ship to another. To estimate unknown system disturbances (wave oscillations, ship motion), an appropriate (FISMO) observer was used. A (DEE) mechanism was created that determines the type of disturbances that have an effect on the system (beneficial or harmful). Based on the disturbance estimation, a robust trajectory tracking controller was developed, which allows for accurate load delivery and elimination of residual vibrations of load mounted on a flexible suspension.

The authors of [9] developed an optimal fuzzy adaptive-robust controller for systems with an insufficient number of actuators. The basic structure of the controller is built on “feedback linearization”, which allows making a nonlinear system more linear for control. The effectiveness of the proposed controller was tested on a fourth-order inverted pendulum model, which is a classical nonlinear unstable system. By using adaptive logic (through a fuzzy system), the controller can dynamically adjust its parameters to changing conditions and uncertainties, while maintaining stability.

In the article [10], the researchers propose to eliminate the oscillations of a tower crane mounted on a flexible suspension during the combined movement mode of the trolley movement and boom rotation mechanisms. The authors propose to use a hybrid control strategy that combines two approaches. The first of which is “feed-forward”, which allows you to form a command for movement in such a way as to minimize the excitation of the load oscillations. The other is “feedback”, which consists in hierarchical control with a variable structure, which makes it possible to carry out a stable and stable minimization of load oscillations and control the position of the load trolley.

In [11], a dynamic analysis of a self-propelled jib crane (DEK 251) was performed with the combined operation of the lifting, turning and load-out mechanisms. Based on the results of the dynamic analysis, it was proposed to optimize the motion modes at the moments of starting and stopping the above mechanisms. This will increase the productivity of the self-propelled jib crane.

The authors of the article [12] present the formulation of the optimal control problem for the dynamic system "crane-load". The main attention is paid to the acceleration period, which satisfies the condition of minimum duration and elimination of oscillations of the load fixed on a flexible suspension. An objective function is developed that ensures the fulfillment of the final boundary conditions and an analysis is carried out from the point of view of its topological features.

The article [13] proposes a method for suppressing load oscillations in a knuckle-joint suspension during the simultaneous motion of two links of a boom system. The control problem is stated as a multi-criteria optimization one based on minimizing the RMS values of the generalized power and the drive-mechanism power. The application of ME-PSO enables efficient exploration of the solution space across multiple epochs, leading to robust convergence toward optimal motion profiles. As a result, discrete optimal values of the kinematic and power characteristics of the loader-crane boom system are obtained. The optimized motion mode derived through the ME-PSO-based framework significantly enhances the loader crane's operational performance, reliability, and energy efficiency, while effectively reducing load oscillations.

From the analysis of literary sources, it was found that the main problems are minimizing vibrations and determining the optimal trajectory of movement of a load mounted on a flexible suspension, to which a significant number of works are devoted.However, the issue of analyzing the main characteristics under symmetric and asymmetric constraints on the optimal speed control of the tower crane slewing mechanism has not been given attention. Therefore, the proposed work is devoted to this issue.

Purpose of the paper. The purpose of this work is to conduct a comparative analysis of the main characteristics of the optimal speed-of-motion mode of the tower crane slewing mechanism under asymmetric and symmetric constraints on the control of this system.

To achieve the goal, it is necessary to solve the following tasks:

1) formulate the optimal control problem for the system under study;
2) plan theoretical (experimental) research;
3) solve the optimization problem when varying the system parameters;
4) analyze the results obtained;
5) draw conclusions from the research based on the analysis.

Research results. The dynamic model of the tower crane slewing mechanism, shown in Fig. 1, was used to perform the research [14].

The motion of the researched system (Fig. 1) in time is described by the following system of differential equations [14]:

$$\begin{cases} J_1 \cdot \ddot{\varphi}_1 + m \cdot R^2 \cdot (g/L) \cdot (\varphi_1 - \varphi_2) = M - M_0 \cdot sign(\dot{\varphi}_1); \\ \ddot{\varphi}_2 = (g/L) \cdot (\varphi_1 - \varphi_2). \end{cases} \tag{1}$$

The system of differential equations (1) is reduced to a single fourth-order differential equation, resulting in:

$$\overset{IV}{\varphi}_2 + \ddot{\varphi}_2 \cdot (\Omega_0^2 + \Omega^2) = \frac{M - M_0}{J_1} \cdot \Omega_0^2, \tag{2}$$

where Ω and Ω_0 – frequencies of natural oscillations of a pendulum with movable and fixed suspension points, respectively. The given values are determined according to the following dependencies [15]:

$$\Omega = \sqrt{\frac{m \cdot R^2}{J_1} \cdot \frac{g}{L}} \tag{3}$$

and

$$\Omega_0 = \sqrt{g/L}\ . \tag{4}$$

After introducing the appropriate transformations: $\tilde{\Omega} = \Omega_0^2 + \Omega^2$, $U = M - M_0/J_1$ та $y_1 = \dot{\varphi}_2$, the differential equation (2) is represented in the form of Cauchy [15]:

$$\begin{cases} \dot{y}_1 = y_2; \\ \dot{y}_2 = y_3; \\ \dot{y}_3 = U \cdot \Omega_0^2 - y_2 \cdot \tilde{\Omega}. \end{cases} \tag{5}$$

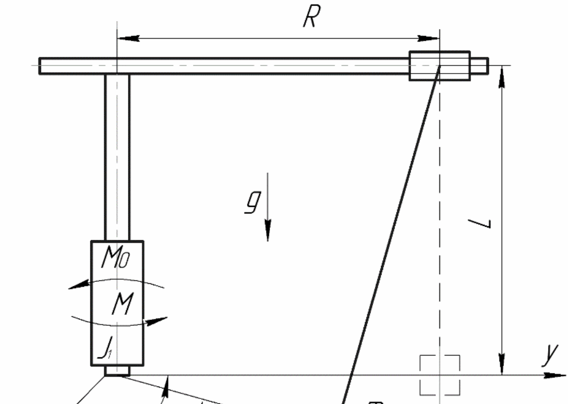


Fig. 1. Dynamic model of the tower crane slewing mechanism
Note: φ_1 – angular coordinate of rotation of tower, jib and drive elements reduced to the crane rotation axis; φ_2 – angular coordinate of rotation of the load fixed on the flexible suspension; M, M_0 – driving moment of the drive and moment of static resistance forces of the crane rotation reduced to the crane rotation axis, respectively; J_1 – moment of inertia of the drive, tower and boom elements reduced to the crane rotation axis; g – acceleration of free fall; L and R – length of the flexible suspension and outstretched load, respectively [14]

Acceleration of the researched system to the value of the steady angular velocity, taking into account the system of equations (5), occurs under the following boundary conditions of motion [15]:

$$\begin{cases} y_1(0) = y_2(0) = y_3(0) = 0; \\ y_1(T) = \omega_T\,;\; y_2(T) = y_3(T) = 0, \end{cases} \tag{6}$$

where ω_T – the steady angular velocity of the crane's slewing mechanism; T – the total acceleration time of the system to the steady angular velocity of the crane's slewing mechanism. Satisfying boundary conditions (6) allows achieving the steady angular velocity of the system ω_T at time T with elimination of load oscillations on a flexible suspension. Minimising the value of T allows for an increase in the productivity of the crane's slewing mechanism.

Considering the above, it is proposed to use a comprehensive integral-terminal criterion as an optimisation criterion, which is presented in the form of the following functional [15]:

$$Cr^{COMPLEX} = T + TER \cdot \psi \to \min. \tag{7}$$

In expression (7), the integral component of the criterion allows minimising the value of T, while the terminal component allows achieving the final boundary conditions of the system's motion (6). $\psi = 10^6 \cdot \omega_T^{-1}$ is a weighting coefficient that reflects the need to ensure the final conditions of motion (6) and reduces the dimension of the TER criterion to the dimension of T.

At the same time, the integral functional of the complex optimisation criterion (7) has the form:

$$\int_0^T dt = T = \sum_{i=1}^{3} t_i \to \min, \tag{8}$$

and the terminal criterion is determined by the following dependence:

$$TER = \left\|\Delta\right\|_2 = \sqrt{(y_1(T) - \omega_T)^2 + y_2(T)^2 \cdot \Omega^{-2} + y_3(T)^2 \cdot \Omega^{-4}}, \tag{9}$$

where Δ_2 is the vector of deviation of phase coordinates from their final (desired) values (6).

Optimal control must meet the following conditions in order to take into account the overload capacity of the drive of the system under investigation: [15]:

$$U_{MIN} \le U_{i\text{–}\breve{u}Type} \le U_{MAX}\,\cdot \tag{10}$$

Here U_{MIN} and U_{MAX} – the lower and higher limits of optimal control change, respectively.

This research proposes to consider two types of constraints on optimal control. The first type is characterised by asymmetric constraints on optimal control, while the second type is characterised by symmetric constraints.

Asymmetric constraints on optimal system control are as follows:

$$U_{TYPE1} = \begin{cases} U_{MAX} = \dfrac{M_{MAX} - M_0}{J_1}; \\ U_{MIN} = \dfrac{-M_0}{J_1}, \end{cases} \tag{11}$$

where M_{MAX} – maximum torque acting on the rotating part of the crane. The U_{MIN} value corresponds to the operation of the system when the electric drive is switched off (movement occurs solely due to the action of the static resistance torque of the M_0 system).

Symmetrical constraints on optimal system control are described by the following expression:

$$U_{TYPE2} = \begin{cases} U_{MAX} = \dfrac{M_{MAX} - M_0}{J_1}; \\ U_{MIN} = \dfrac{-M_{MAX} - M_0}{J_1}. \end{cases} \tag{12}$$

The solution of optimisation problems 1 (11) and 2 (12) was performed according to the main parameters of the system under study, which are listed in Table 1.

The length of the load offset change (R, m), the length of the flexible load suspension (L, m) and the reduced mass of the load on the flexible suspension (m, kg) are proposed to be used as parameters that vary when solving optimisation problems 1 (11) and 2 (12). The levels of variation of the proposed parameters are summarised in Table 2.

Table 1

Values of the main parameters of the tower crane slewing system

Parametername	Unitofmeasurement	Symbol	Numericalvalue
Maximumtorque	Nm	MMAX	149,3·103
Combinedmomentofstaticforceresistance	Nm	M0	12,6·103
Combinedmomentofinertia	kg · m2	J1	1,5·106
Steadyangularvelocity	rad/s	ωT	0,089

Table 2

Levels of variation in the parameters of the slewing mechanism

Parameter	Value								
Load overhang (*R*, m)	5								
Length of flexible load suspension (*L*, m)	10			15			20		
Total load mass (*m*, kg)	500	2000	5000	500	2000	5000	500	2000	5000
Experiment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Load overhang (*R*, m)	15								
Length of flexible load suspension (*L*, m)	10			15			20		
Total load mass (*m*, kg)	500	2000	5000	500	2000	5000	500	2000	5000
Experiment number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Load overhang (*R*, m)	20								
Length of flexible load suspension (*L*, m)	10			15			20		
Total load mass (*m*, kg)	500	2000	5000	500	2000	5000	500	2000	5000
Experiment number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**

In total, it is proposed to solve the optimisation problem 54 times, 27 times for each of the types studied.

The indicators proposed for assessing the acceleration of the turning mechanism to a steady speed are as follows:

- The duration of the mechanism's acceleration to a steady speed;
- The maximum deviation of the load from the vertical;
- Maximum power in the mechanism drive;
- Root mean square power in the mechanism drive;
- Maximum acceleration of the load;
- Root mean square acceleration of the load.

The RING-ROT-PSO optimisation method [16] was used to determine the optimal control in terms of speed for the optimisation problems under study. The values of the parameters used to solve the problem are listed in Table 3.

Table 3

Values of the RING-ROT-PSO optimisation method parameters and the range of target function arguments

No	Parameters	Dimensionality	Numerical value
1	t_1, t_2, t_3	s	from 0.1 to 6.0
2	Total number of particles in the swarm	pieces	50
3	Total number of iterations		200

Research results

As a result of a multi-stage solution of optimisation problems (7), (11) and (12), the values of the researched indicators for each experiment were determined. For problem 1, the values of the researched indicators are summarised in Table 4. For problem 2, the values of the studied indicators are presented in Table 5.

A slight increase in the duration of the system acceleration to the steady-state speed under asymmetric constraints on optimal control (task 1) compared to symmetric constraints (task 2) is observed when comparing the results presented in Table 4 and Table 5. The values for the remaining indicators increase under symmetric constraints.

Table 4

Values of the research indicators for problem 1

Parameter	Value								
Experiment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
System acceleration time to steady state speed (T, s)	3.47	3.42	3.41	4.07	4.05	4.02	4.58	4.56	4.52
Maximum deviation from the vertical of the flexible load suspension (θ, град)	2.73	2.66	2.87	3.45	3.47	3.52	4.06	4.06	4.12
Maximum power in the system drive (P, kW)	13.20	12.53	13.12	13.19	13.18	13.15	13.21	13.13	13.12
Maximum load acceleration (m/s^2)	0.070	0.069	0.076	0.068	0.069	0.070	0.067	0.068	0.069
Root mean square power in the drive (P, kW)	3.77	3.56	3.87	3.61	3.63	3.66	3.52	3.50	3.54
Root mean square acceleration of the load (m/s^2)	0.023	0.022	0.025	0.021	0.022	0.022	0.021	0.021	0.021
Experiment number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
System acceleration time to steady state speed (T, s)	3.45	3.35	3.24	4.05	4.05	3.77	4.53	4.37	4.17
Maximum deviation from the vertical of the flexible load suspension (θ, град)	2.80	3.01	3.26	3.53	3.53	4.15	4.14	4.38	4.83
Maximum power in the system drive (P, kW)	13.24	13.32	13.19	13.36	13.36	13.34	13.21	13.11	13.07
Maximum load acceleration (m/s^2)	0.073	0.082	0.096	0.071	0.071	0.095	0.069	0.095	0.093
Root mean square power in the drive (P, kW)	3.82	3.98	4.11	3.71	3.71	4.16	3.56	3.71	4.06
Root mean square acceleration of the load (m/s^2)	0.024	0.026	0.029	0.022	0.022	0.028	0.021	0.027	0.027
Experiment number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
System acceleration time to steady state speed (T, s)	3.43	3.29	3.25	4.00	3.82	3.69	4.47	4.25	4.06
Maximum deviation from the vertical of the flexible load suspension (θ, град)	2.88	3.16	3.46	3.57	3.95	4.43	4.18	4.64	5.27
Maximum power in the system drive (P, kW)	13.36	13.29	13.22	13.25	13.24	13.17	12.97	13.13	13.79
Maximum load acceleration (m/s^2)	0.076	0.090	0.104	0.072	0.087	0.107	0.071	0.086	0.108
Root mean square power in the drive (P, kW)	3.90	4.07	3.73	3.72	3.99	4.43	3.54	3.90	4.53
Root mean square acceleration of the load (m/s^2)	0.024	0.028	0.031	0.023	0.026	0.030	0.022	0.026	0.030

The increase in the duration of the system acceleration under asymmetric constraints (task 1) is due to the fact that during the second (intermediate) stage of motion t_2, the drive is switched off and the system moves due to the moment of static resistance force M_0. For an adequate assessment of the results obtained, the values of the discrepancy in the acceleration time of the system for a series of all theoretical studies are summarised in Table 6.

The increase in the values of the other studied indicators (maximum deviation from the vertical of the flexible suspension of the load, maximum and root mean square values of power in the drive, maximum and root mean square acceleration of the load) under symmetrical control constraints is due to the fact that such constraints are characterised by a more intense mode of operation of the drive of the mechanism of the researched rotation mechanism system.

Table 5

Values of the research indicators for problem 2

Parameter	Value								
Experiment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
System acceleration time to steady state speed (T, s)	3.08	3.09	3.09	3.48	3.47	3.47	3.88	3.89	3.89
Maximum deviation from the vertical of the flexible load suspension (θ, град)	3.69	3.71	3.72	4.67	4.64	4.65	5.79	5.83	5.84
Maximum power in the system drive (P, kW)	14.02	14.09	14.09	15.35	15.29	15.31	16.93	17.00	17.02
Maximum load acceleration (m/s^2)	0.122	0.123	0.123	0.125	0.124	0.124	0.132	0.133	0.133
Root mean square power in the drive (P, kW)	4.08	4.11	4.11	4.42	4.40	4.41	4.82	4.85	4.85
Root mean square acceleration of the load (m/s^2)	0.035	0.035	0.035	0.034	0.034	0.034	0.035	0.035	0.035
Experiment number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
System acceleration time to steady state speed (T, s)	3.10	3.10	3.14	3.54	3.54	3.57	3.90	3.89	3.90
Maximum deviation from the vertical of the flexible load suspension (θ, град)	3.72	3.74	3.76	4.84	4.88	4.94	5.85	5.90	5.95
Maximum power in the system drive (P, kW)	14.11	14.11	13.73	15.71	15.77	15.58	17.04	17.12	16.96
Maximum load acceleration (m/s^2)	0.123	0.124	0.121	0.128	0.129	0.127	0.133	0.134	0.133
Root mean square power in the drive (P, kW)	4.12	4.14	4.13	4.54	4.58	4.61	4.85	4.90	4.92
Root mean square acceleration of the load (m/s^2)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.036	0.035
Experiment number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
System acceleration time to steady state speed (T, s)	3.01	3.13	3.21	3.53	3.55	3.62	3.88	3.89	3.98
Maximum deviation from the vertical of the flexible load suspension (θ, град)	3.67	3.78	3.66	4.83	4.94	4.88	5.85	5.93	5.98
Maximum power in the system drive (P, kW)	13.97	14.02	13.34	15.70	15.77	14.46	17.03	17.08	16.15
Maximum load acceleration (m/s^2)	0.122	0.124	0.109	0.128	0.129	0.118	0.133	0.134	0.126
Root mean square power in the drive (P, kW)	4.03	4.15	4.20	4.55	4.61	4.52	4.86	4.91	4.91
Root mean square acceleration of the load (m/s^2)	0.035	0.035	0.034	0.035	0.035	0.034	0.035	0.035	0.034

Table 6

Values of the discrepancy in the system acceleration time, %

Name	Value, %								
Experiment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Duration of system acceleration to steady	11.23	9.64	9.38	14.49	14.32	13.68	15.28	14.69	13.93
Experiment number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Duration of system acceleration to steady	10.14	7.46	3.08	12.59	12.59	5.30	13.90	10.98	6.47
Experiment number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Duration of system acceleration to steady	12.24	4.86	1.23	11.75	7.06	1.89	13.19	8.47	1.97

The value of the discrepancy in the acceleration time of the mechanism to a steady velocity (Table 6) ranges from 1.23% (experiment 21) to 15.28% (experiment 7).

The values of discrepancies for a series of all theoretical research are entered in Table 7.

Table 7

Significance of differences in the researched indicators, %

Name	Value								
Experiment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Maximum deviation from the vertical of the flexible suspension of the load	26.01	28.30	22.84	26.12	25.21	24.30	29.87	30.36	29.45
Maximum power in the system drive	5.84	11.07	6.88	14.07	13.79	14.10	21.97	22.76	22.91
Maximum acceleration of the load	42.62	43.90	38.21	45.60	44.35	43.54	49.24	48.87	48.12
Root mean square power in the drive	7.59	13.38	5.83	18.32	17.50	17.00	26.97	27.83	27.01
Root mean square acceleration of the load	34.58	37.14	28.57	38.53	35.29	35.29	40.00	40.00	40.00
Experiment number	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Maximum deviation from the vertical of the flexible suspension of the load	24.73	19.51	13.29	27.06	27.66	15.99	29.23	25.76	26.38
Maximum power in the system drive	6.16	5.95	3.93	14.95	15.28	14.50	22.47	23.42	22.93
Maximum acceleration of the load	40.65	33.87	20.66	44.53	44.96	25.19	48.12	29.10	30.07
Root mean square power in the drive	7.28	3.86	0.48	18.28	18.99	9.76	26.59	24.28	17.47
Root mean square acceleration of the load	31.42	25.71	17.14	37.14	37.14	20.00	40.00	25.00	22.85
Experiment number	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
Maximum deviation from the vertical of the flexible suspension of the load	21.52	42.85	5.46	26.08	20.04	29.71	28.54	21.75	11.87
Maximum power in the system drive	4.36	5.20	0.89	15.60	16.04	8.92	23.84	23.12	14.61
Maximum acceleration of the load	37.70	27.41	4.58	43.75	32.55	9.32	46.61	35.84	14.28
Root mean square power in the drive	3.22	1.92	11.19	18.24	13.44	1.99	27.16	20.57	7.73
Root mean square acceleration of the load	31.42	20.00	8.82	34.28	25.71	11.76	37.14	25.71	11.76

The range of discrepancies in the researched system indicators (Table 7) is:

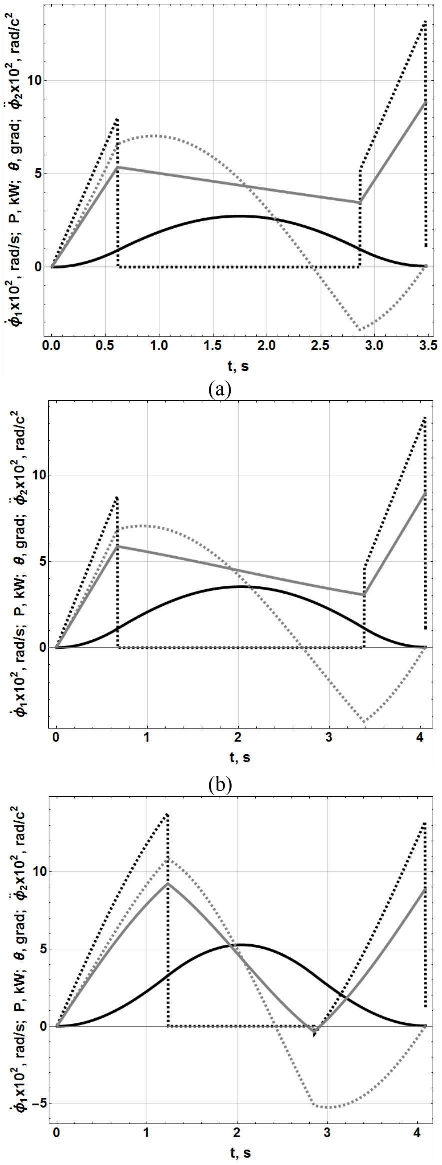
- for the maximum deflection of the load fixed on a flexible suspension from 5.46% (experiment 21) to 42.85% (experiment 20);
- for the maximum power value from 0.89% (experiment 21) to 23.84% (experiment 25). The root mean square value of power from 0.48 (experiment 12) to 27.83 (experiment 8);
- for maximum load acceleration from 4.58% (experiment 21) to 49.24% (experiment 7). The root mean square acceleration of the load ranged from 8.82% (experiment 21) to 40.0% (experiments 7–9 and 16) respectively.

The corresponding graphical dependencies of the researched indicators were constructed for some experiments. For asymmetric constraints on optimal control (task 1), the corresponding graphical dependencies are presented in Fig. 2.

At the same time, the corresponding graphical dependencies for symmetric constraints on optimal control (task 2) are shown in Fig. 3.

Conclusions. A comparative analysis of the optimal starting mode of the tower crane slewing mechanism in terms of velocity under asymmetric and symmetric constraints on optimal control has been performed. A series of 54 full-factor experiments (27 for each of the studied tasks) was planned for comparative analysis.

The independent factors were: the length of the flexible suspension (10, 15 and 20 m), the mass (500, 2000 and 5000 kg) and the outreach (5, 15 and 20 m) of the load. The evaluation indicators were: the time required for the system to accelerate to a steady state velocity; the maximum deviation of the flexible suspension load from the vertical; the maximum and root mean square values of the drive power; and the maximum and root mean square values of the acceleration of the load attached to the flexible suspension.

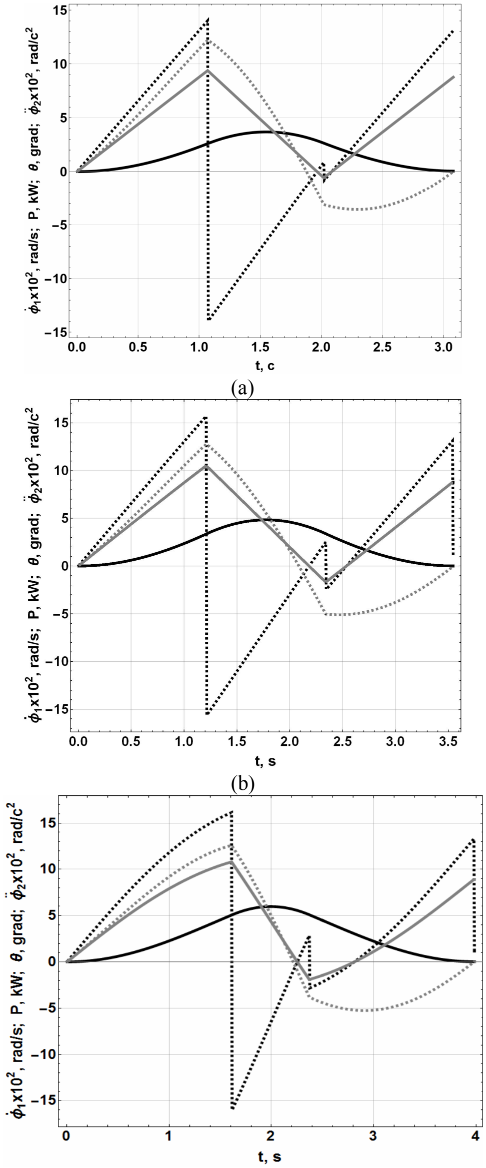


(a)

(b)

(c)

Fig. 1. Graphical dependencies of the researched indicators for the corresponding experiments with asymmetric control constraints (task 1): Note: (a) – experiment No. 1; (b) – experiment No. 13; (c) – experiment No. 27; deviation from the vertical of the flexible suspension of the load (black solid curve); angular velocity of rotation of coordinate φ_1 (grey solid curve); power in the drive (black dashed curve); acceleration of the fixed load (grey dashed curve)



(a)

(b)

(c)

Fig. 3. Graphical dependencies of the researched indicators for the corresponding experiments with symmetrical control constraints (task 2): Note: (a) – experiment No. 1; (b) – experiment No. 13; (c) – experiment No. 27; deviation from the vertical of the flexible suspension of the load (black solid curve); angular velocity of rotation of coordinate φ_1 (grey solid curve); power in the drive (black dashed curve); acceleration of the fixed load (grey dashed curve)

The calculations showed that with asymmetric constraints on optimal control (task 1), compared to symmetric constraints (task 2), the system acceleration time increases from 1.23 to 15. 28%, and the maximum deviations of the load from the flexible suspension point decrease from 5.46 to 42.85%. The range of the maximum and root mean square values of the power in the system drive is from 0.89 to

23.84% and from 0.48 to 27.83%, respectively, and the maximum and root mean square values of load acceleration range from 4.58 to 49.24% and from 8.82 to 40.0%, respectively.

The increase in the duration of the system acceleration to a steady velocity under asymmetric constraints is due to the fact that at the intermediate stage of acceleration, the drive is switched off and the system moves only under the action of the static resistance torque. The decrease in the rest of the researched indicators is due to the fact that asymmetric restrictions are characterised by a less intense drive start-up mode of the researched system. Therefore, for optimal velocity modes, it is advisable to use asymmetric restrictions for optimal control.

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АНАЛІЗ ОПТИМАЛЬНОГО ЗА ШВИДКОДІЄЮ РЕЖИМУ ПУСКУ МЕХАНІЗМУ ПОВОРОТУ БАШТОВОГОКРАНА ПРИ ОБМЕЖЕННЯХ НА КЕРУВАННЯ

У науковій статті представлено порівняльний аналіз оптимального за швидкодією режиму пуску механізму повороту баштовий крана при несиметричних (задача 1) та симетричних (задача 2) обмеженнях на оптимальне керування. Для проведення досліджень використана двомасова динамічна модель, рух якої в часі описується системою із двох диференційних рівнянь другого порядку. У ході подальшого дослідження, систему із двох диференційні рівнянь другого порядку було зведено до одного диференційного рівняння четвертого порядку. Після проведення відповідних перетворень, диференційне рівняння четвертого порядку, було представлено у формі Коші та наведено початкові і кінцеві умови руху при виконанні, яких коливання вантажу будуть усуватися після виходу механізму повороту до значення усталеної швидкості.Саму оптимізаційну задачу було зведено до задачі безумовної мінімізації комплексного інтегрально-термінального функціоналу де термінальна складова відповідає за виконання кінцевих крайових умов, а інтегральна складова за швидкодію механізму. Сплановано серію із 54 експериментальних досліджень (по 27 для кожної із досліджуваних задач), в яких незалежними чинниками виступали довжина гнучкого підвісу (яка становила 10, 15 та 20 метрів), виліт вантажу (що становив 5, 15 та 20 м), а також та маса вантажу (вона складала 500, 2000 та 5000 кг). Під час проведення теоретичних досліджень основна оцінка проводилася за наступними показниками, а саме: тривалість розгону системи до значення величини усталеної швидкості; максимальне відхилення від вертикалі гнучкого підвісу вантажу; максимальне та середньоквадратичні значення потужності в приводі та пришвидшення вантажу.За результатами проведеного аналізу встановлено, що при використанні несиметричних обмежень на оптимальне керування (задача 1) збільшується тривалість розгону досліджуваної системи до значення усталеної швидкості при порівнянні порівнянні із симетричними обмеженнями (задача 2) в діапазоні від 1.23 до 15.28 %, а також зменшуються максимальні значення кінематичних характеристик від 5.46 до 42.85 % та енергетичних показників у межах від 0.48 до 27.83 %.

Ключові слова: баштовий кран, вантаж, швидкодія, механізм повороту, обмеження на оптимальне керування, метод Ring-Rot-PSO.

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ANALYSIS OF THE OPTIMAL SPEED-BASED START-UP MODE OF THE TOWER CRANE SWING MECHANISM UNDER CONTROL LIMITATIONS

A comparative analysis of the optimal starting mode of the tower crane slewing mechanism in terms of speed under asymmetric (task 1) and symmetric (task 2) constraints on optimal control is presented in a scientific article. A two-mass dynamic model was used for the research, whose motion in time is described by a system of two second-order differential equations. In the course of further research, the system of two second-order differential equations was reduced to a single fourth-order differential equation. After performing the appropriate transformations, the fourth-order differential equation was presented in Cauchy form and the initial and final conditions of motion were given, under which the load oscillations will be eliminated after the turning mechanism reaches a steady speed.The optimisation task itself was reduced to the task of unconditional minimisation of a complex integral-terminal functional, where the terminal component is responsible for the fulfilment of the final boundary conditions, and the integral component is responsible for the speed of the mechanism. A series of 54 experimental studies (27 for each of the tasks under investigation) was planned, in which the independent factors were the length of the flexible suspension (which was 10, 15 and 20 metres), the load projection (which was 5, 15 and 20 m), and the load mass (which was 500, 2000 and 5000 kg).During the theoretical studies, the main assessment was carried out according to the following indicators: the duration of the system acceleration to the steady-state speed value; the maximum deviation of the flexible suspension of the load from the vertical; the maximum and root mean square values of the power in the drive and the acceleration of the load.The results of the analysis showed that when using asymmetric constraints for optimal control (task 1), the acceleration time of the studied system to a steady state speed increases compared to symmetric constraints (task 2) in the range from 1.23 to 15. 28 %, and the maximum values of kinematic characteristics decrease from 5.46 to 42.85 % and energy indicators from 0.48 to 27.83 %.

Keywords: tower crane, load,velocity, slewing mechanism, optimal control constraints, Ring-Rot-PSO method.

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Ловейкін В.С., Ромасевич Ю.О., Почка К.І., Стехно О.В., Ляшко А.П. **Аналіз оптимального за швидкодією режиму пуску механізму повороту баштового крана при обмеженнях на керування**// Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2026. – Вип. 116. – С. 251-262. – Англ.

У статті наведено порівняльний аналіз оптимального за швидкодією режиму пуску механізму повороту баштового крана за несиметричних і симетричних обмежень керування. Дослідження виконано на основі двомасової динамічної моделі, зведеної до диференційного рівняння четвертого порядку з крайовими умовами усунення коливань вантажу. Проведено 54 експерименти з варіюванням довжини підвісу, вильоту та маси вантажу. Встановлено, що несиметричні обмеження збільшують тривалість розгону, проте зменшують максимальні кінематичні та енергетичні показники системи.

Іл. 3. Бібліогр. 16 назв.

UDC621.87
Loveikin V.S., Romasevych Yu.O., Pochka K.I., Stekhno O.V., Liashko A.P. **Analysis of the optimal speed-based start-up mode of the tower crane swing mechanism under control limitations** // Strength of materials and theory of structures: scientific and technical collection - Kyiv: KNUBA, 2026. - Issue 116. - P. 251-262.

The paper presents a comparative analysis of the time-optimal start-up mode of a tower crane slewing mechanism under asymmetric and symmetric control constraints. The study is based on a two-mass dynamic model reduced to a fourth-order differential equation with boundary conditions ensuring load oscillations up pression. A total of 54 experiments were conducted by varying the suspension length, out reach, and load mass. The results show that asymmetric constraints increase acceleration time but reduce maximum kinematic and energy per formance indicators of the system.

Fig. 3. Ref. 16.

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