AN EXPERIMENTAL STUDY OF THE EFFICIENCY OF OPTIMAL CONTROL FOR LIFTING MACHINES

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The article is devoted to the synthesis of optimal speed performance control, in which the Pontryagin maximum principle and the phase-plane method are used to search for switching points of the relay control function. A crane trolley model and computer control system, able to implement the automatic movement of the trolley according to the optimal laws, were developed. The conducted experimental study allowed us to establish that the operating cycle of the traveling mechanism can be reduced by 1.5-3.1 times using optimal speed performance control.

Keywords: optimal control, lifting machines, crane, speed performance, traveling mechanism

1. Introduction and problem statement

Lifting machines are an important link in logistics chains and industrial processes. Therefore, they must have high performance and operational accuracy. Automated operation of traveling mechanisms is an effective way to increase the performance of cranes. Despite numerous publications in the field of study and a wide range of machine types considered therein, the issue is still quite topical, and a number of problems still remain unresolved.

In [1], a dynamic model of a jib rotary crane was obtained. In [2] and [3], models of gantry crane trolleys with a suspended load and their control systems are presented. An overview of dynamic models of overhead crane trolleys is given in [4]. More complicated models are also known. For example, in [5], the possibility of changing the length of load suspension was taken into account. A

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dynamic model in [6] takes into account the shape of the suspended load, which is represented as a double pendulum.

It is known that horizontal movement of a crane and load trolley causes swinging of a load suspended on flexible ropes. Therefore, automation is impossible without controlling the motion trajectory of the "trolley-load" system to eliminate completely load swings at the end of the transfer cycle. In order to achieve the maximum increase in the productivity, automatic microcontroller control systems must implement the optimal speed performance laws of motion. The synthesis of the optimal control laws is based on dynamic models. The above publications refer to the models that are most commonly used to solve optimal speed performance problems.

Numerous studies are devoted to the methods of synthesis of laws of motion of crane mechanisms. For this purpose, both traditional optimization methods and new approaches can be applied. In [7], the Bezier curve and particle swarm optimization method are used to plan the movement of the trolley-load system. In [8], the synthesis of the control law is based on the controllability function method. In [9], a study of a quasi-optimal speed performance control is described.

Studies of the optimal speed performance control of cranes and the publications reviewed above focus on the synthesis of the laws of motion and underlying mathematical methods. Thus, the ability to move the load to a given point within the shortest time and complete swing damping at the end of the transfer cycle is justified. However, operating cycles of crane mechanisms can vary greatly. For traveling mechanisms, one of the key parameters is the path traveled, because it predetermines whether the mechanism can accelerate to the rated speed, whether there is a distance reserve to fulfill the planned damping algorithm for load swings, etc. In addition, in some cases an experienced crane operator with adequate skills can achieve greater speed than a master controller running the programmed law of motion. The issue of comparative evaluation of manual and automatic optimal speed performance control has not been studied sufficiently yet. Regularities that enable to quantify the effectiveness of the implementation of automatic optimal speed performance control of lifting machines have not been adequately investigated yet.

2. Purpose and objective of the study

The purpose of the study is evaluation of the decrease in the duration of the operating cycle and the number of engines starting of the traveling mechanism with manual and optimal speed performance control.

The following problems should be solved to achieve the purpose:
- mathematical description of the trolley-load system and development of

an algorithm for the optimal speed performance control;

- creating a crane trolley model and automatic control software that can implement the optimal speed performance laws of motion;

- conducting an experimental study of manual and optimal speed performance control;

- determining the regularities of change of the characteristics, such as the ratio of numbers of engine startings, the relative duration of load swing damping, the ratio of durations of operating cycles with manual and optimal speed performance control depending on the length of the path traveled.

3. Mathematical model of the trolley-load system and synthesis of optimal speed performance control laws

The calculation of the control laws of traveling mechanisms is based on a dual-mass model of the trolley-load system (Fig. 1).
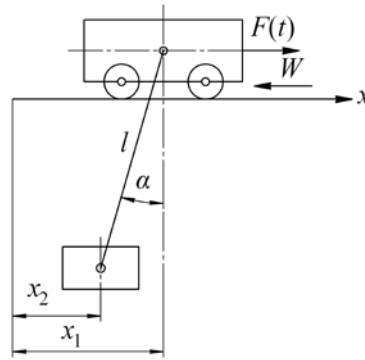

Fig. 1. Dynamic model of the movement of a trolley with a load on a flexible suspension
m_1 is the trolley weight, m_2 is the load weight, $F(t)$ is the driving force, W is the force of static resistance to movement, l is the length of the load suspension, x_1 is the path traveled by the trolley, x_2 is the path traveled by the load

The movement of the trolley-load system is described by the system of differential equations 1. These equations are obtained on the basis of the dynamic equilibrium condition underlying the d'Alembert's principle.

$$\begin{cases} m_1\ddot{x}_1 = F(t) - W\operatorname{sign}\dot{x}_1 - \dfrac{m_2 g}{l}\cdot(x_1 - x_2); \\ m_2\ddot{x}_2 = -\dfrac{m_2 g}{l}\cdot(x_1 - x_2). \end{cases} \tag{1}$$

The system order had to be reduced so that the numerical integration methods could be used. The following substitution of variables are introduced for this purpose: $y_1 = x_1$; $y_2 = \dot{x}$; $y_3 = x_2$; $y_4 = \dot{x}_2$. After substitutions, the system of equations (1) is written as:

$$\begin{cases} \dot{y}_1 = y_2; \\ \dot{y}_2 = (y_3 - y_1) \cdot m_2 \cdot g / (m_1 \cdot l) + U(t); \\ \dot{y}_3 = y_4; \\ \dot{y}_4 = (y_1 - y_3) \cdot \dfrac{g}{l}, \end{cases} \tag{2}$$

where: $U(t) = (F(t) - W \operatorname{sign} \dot{y}_2) / m_1$.

The driving force $F(t)$ is the control parameter, but for the sake of convenience, function $U(t)$, which is proportional to $F(t)$, is considered to be the control parameter. Pontryagin's maximum principle is used to determine the form of optimal function $U(t)$. According to the maximum principle, optimal speed performance control $U(t)$ is achieved when the Hamilton function H has a maximum:

$$H = \sum_{i=1}^{4} \psi_i \cdot \dot{y}_i = \psi_1 y_2 - \psi_2 \cdot (y_1 - y_3) \cdot m_2 g / (m_1 l) + \\ + \psi_2 U(t) + \psi_3 y_4 + \psi_4 \cdot (y_1 - y_3) \cdot g / l \tag{3}$$

where: $\dot{\psi}_i$ – variables of the conjugate system of equations necessary to formulate the Pontryagin's maximum principle:

$$\dot{\psi}_i = -\sum_{n=1}^{4} \frac{\partial y_n}{\partial y_i} \cdot \psi_n , \quad i = 1, \ldots \ldots , 4 . \tag{4}$$

Analysis of the Hamilton function shows that it reaches maximum when the control mode has the form of the relay function:

$$U(t) = |U_0| \cdot sign \cdot \left[C_1 + C_2 t + C_3 \sin \cdot (\lambda t + \alpha) \right] \tag{5}$$

$$\text{where } U_0 = \begin{cases} \left(K - W sign\, y_2\right)/m_1 \text{ during acceleration;} \\ -\left(N + W sign\, y_2\right)/m_1 \text{ during braking;} \end{cases} \tag{6}$$

K, N – maximum allowed forces, moving and braking, respectively.

Function (5) is the optimal control law which ensures maximum speed of the trolley with a load on the flexible suspension.

Since in the case under consideration, switching points of the control function cannot be determined using the maximum principle because of the presence of a discontinuous function sign y_2 in the expression for U_0, the phase plane method is advisable.

The optimal speed performance operating cycle of the traveling mechanism of the trolley under such conditions includes a few phases. One of the possible optimal speed performance motion schemes of the trolley is shown in Fig. 2:

Phase 1: duration t_1 - acceleration of the trolley to the rated speed;
Phase 2: duration t_2 - movement of the trolley at the rated speed;
Phase 3: duration t_3 - braking of the trolley to the complete stop;
Phase 4: duration t_4 – zero speed of the trolley, free oscillations of the load;
Phase 5: duration t_5 - acceleration of the trolley to the rated speed;
Phase 6: duration t_6 - movement of the trolley at the rated speed;
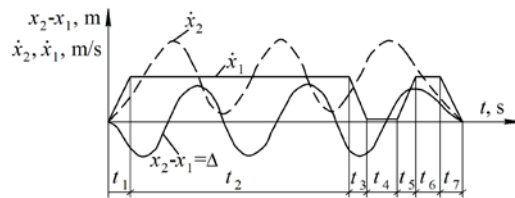Phase 7: duration t_7 - braking of the trolley to the complete stop.

Fig. 2. Phases of the optimal speed performance operating cycle of the traveling mechanism of the trolley

x_1, x_2 – travel of the trolley and the load, respectively, $\dot{x}_1$, $\dot{x}_2$ – speed of the trolley and the load, respectively, Δ – vertical deviation of the load, $t_1...t_7$ – duration of the movement phases

According to Figure 2, the speed of the trolley, the speed of the load and the vertical deviation of the load are zero at the end of the movement. Thus, the movement of load to a given point (positioning) is achieved with full swing damping within the shortest time of the operating cycle and the smallest number of engine startings.

Experimental bench and studies of the manual and optimal control

An overhead crane trolley model with a suspended load was used to conduct experimental studies of the operating cycle of the traveling mechanism

with manual and optimal speed performance control. The basic part of the bench is an electric hoist with a load carrying capacity of 0.5 tons, equipped with a variable frequency mechanism drive. A microprocessor control system and special software were developed to enable implementation of the control in automatic mode.

The basic part of the control system hardware (Fig. 3) is a personal computer 1 with a high calculated power and a convenient interface.

Computer 1 located in the control station (Fig. 4) is connected to the microcontroller which controls the voltage inverter of the frequency converter 3. The control station enables to implement both manual and optimal control.
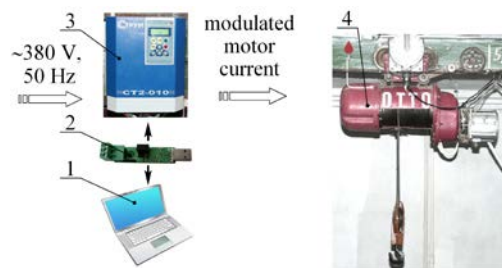

Fig. 3. Structure of the microprocessor control system
1 – PC; 2 – USB/RS485 interface converter; 3 – frequency converter; 4 – electric hoist

Fig. 4. Control and data acquisition station of the experimental bench based on the electric hoist with a capacity of 0.5 t
1 – hook suspension of the electric hoist, 2 – power supply unit speed and the rope deviation angle sensors of the electric hoist, 3 – frequency converter, 4 – PC, 5 – relay-contact equipment cabinet, 6 – analog-to-digital sensor signal converter, 7 – manual control panel

The software part of the control system consists of an application for the synthesis of the optimal control laws, an application for the automatic control of the frequency converter, and low-level firmware of the microprocessor of the frequency converter.

The experiment on the study of manual control was conducted as follows. The trolley with the load was adjusted for each mode of movement in accordance with the plan of the experiment. Since the manual control is characterized by multiple random errors that depend on a particular operator, these studies require numerous repetitions and a change of operators. Consequently, certain regularities can be deducted using the methods of experiment processing and statistics. Therefore, a group of 10 participants was invited to the control panel. Each participant controlled manually the movement of the trolley. During the experiment, the change with time of the trolley speed and the deviation angle of

the load rope during the operating cycle of the traveling mechanism was recorded. The obtained oscillograms were used to determine duration of each operating cycle, number of drive engine startings of the traveling mechanism and duration of its operation. The distance from the point of the beginning of movement to the point of positioning the load (path traveled) was also determined for each operating cycle. In a series of 10 measurements, each next control was carried out by another person. Since the primary objective of the experiment was estimating the reduction of duration of the operating cycle of the traveling mechanism, the task of each participant was moving the trolley with a load to a specified distance within the shortest time. It was desirable that after the trolley stops at the end point, the load has the smallest possible swinging amplitude, and the number of drive engine startings is as small as possible.

During the study, the path traveled by the trolley (the distance to the positioning point) and the control method (manual or automatic) changed, which allowed determining their influence on the parameters being studied. The length of the suspension and the mass of the load remain constant. The length of the suspension is taken as the maximum for this experimental bench. This is necessary to achieve the maximum amplitude of swing and complicate the positioning of the load.

The study of the optimal speed performance control was conducted as a series of experiments, which represented the implementation of the laws of optimal motion by the model. The change of the speed of the trolley and the deflection angle of the load rope during the working cycle of the traveling mechanism over time were also recorded in the form of oscillograms.

The experimental data obtained from the oscillograms are presented as single-factor paired measurements x_j, y_j, divided into series according to the length of the path of the trolley, where x_j is the path traveled by the trolley, y_j is the number of starts of the motor of the traveling mechanism or the duration of its operation or the duration of the operating cycle. Mean values, arithmetic mean values of standard deviations, and variation coefficients are calculated for each series of measurements. The actual confidence limits of the results of the j th measurement are determined by taking into account the table value of the Student criterion for given confidence probability $P = 0,9$. The measurements with the maximum deviation were checked for compliance with the Romanovsky criterion, in order to rule out gross errors.

The determination of the regularities of changes of the measured values as regression equations is based on the assumption that they depend linearly on the path traveled and is performed using the least squares method. Pearson coefficients were found to verify the validity of this assumption. This verification confirmed a high degree of linear correlation in pairs: "the duration of the

overload cycle – the path traveled by the trolley", "the operation time of the drive motor – the path traveled by the trolley". The lower values of the Pearson coefficient were obtained in the pair "the number of starts of the drive motor – the path traveled by the trolley"; however, in this study, the functional dependency for this pair was also found in a linear form.

The results statistical evaluation of the experiment results is shown in Fig. 5. In the graphs, the dependent variables are plotted on the vertical axis, namely, the measured values are number of engine startings n, times (5, a), duration of engine operating $t_{operating}$, s (5, b), duration of the operating cycle t_{cycle}, s (5, c). An independent variable is plotted on the horizontal axis – path traveled l, m. Each graph shows the regression equations and their graphs.
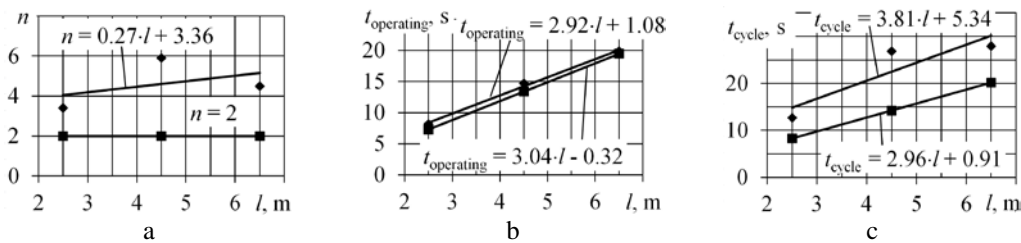

Fig. 5. Analysis of the results of an experimental study of the manual and optimal speed performance trolley control

♦ – manual control, ■ – automatic control

a – number of drive engine startings during the operating cycle; b – duration of operation of the drive engine during the operating cycle; c – duration of the operating cycle of the trolley traveling mechanism

The obtained regression equations are functional dependencies of the measured values on the path traveled. They were taken as the basis for determining regularities of changes in the ratio of the number of engine startings, relative duration of load swing damping, the ratio of durations of operating cycles with the manual and optimal speed performance control depending on the length of the path traveled and quantifying the effectiveness of automatic control for different operating cycles.

The graph of change in the ratio of the number of engine startings $n* = n_{handle} / n_{optimal}$ during the operating cycle of the traveling mechanism and the optimal control is shown in Fig. 6, where n_{handle} is the number of engine startings with the manual control, $n_{optimal}$ is the number of engine startings with the optimal control.
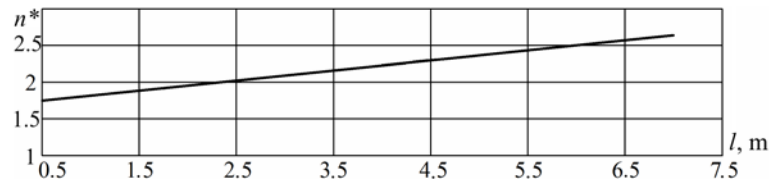
Fig. 6. The dependence of the change in the ratio of the number of starts of the drive engine of the traveling mechanism in case of manual and optimal speed performance control during the operating cycle of the traveling mechanism on the length of the path traveled by the trolley l

The graphs of change of relative duration of load swing damping $t^* = t_{\text{damping}} / t_{\text{cycle}}$ with regard to the path traveled by the trolley l are shown in Fig. 7, where t_{damping} is the time spent for load swing damping, t_{cycle} is the complete operating cycle time.
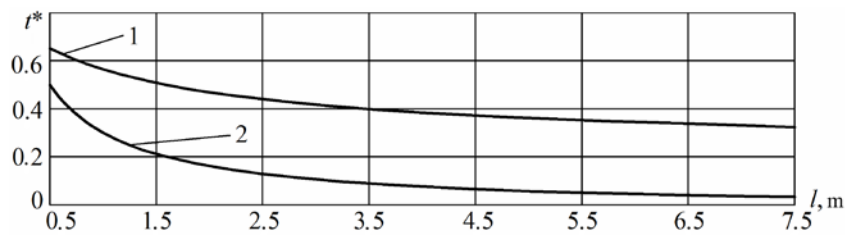

Fig. 7. Dependence of the relative duration of load swing damping t^* on the length of the path traveled by the trolley l

1 – manual control; 2 – time- optimal control

The graph of change of ratios of operating cycle durations $j_t = t_{\text{cycle}}^{\text{handle}} / t_{\text{cycle}}^{\text{optimal}}$ with the manual and optimal speed performance control on the path traveled l by the trolley is shown in Fig. 8, where $t_{\text{cycle}}^{\text{handle}}$ and $t_{\text{cycle}}^{\text{optimal}}$ are operating cycle duration of the traveling mechanism with the optimal and manual control, respectively.
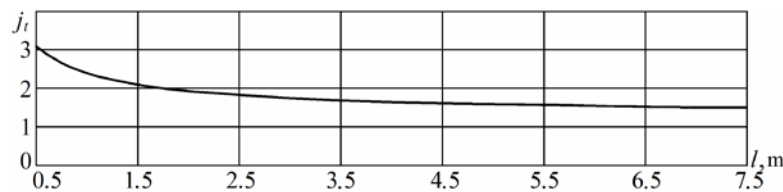

Fig. 8. Dependence of ratios of operating cycle duration j_t on the length of the path traveled l by the trolley

4. Discussion of the results of the study

The analysis of graphs in Fig. 5b and 5c shows that the operating cycle duration of the traveling mechanism is longer than that of the engine operation.

This difference is caused by the necessity to wait for the proper swing phase when alternating acceleration and deceleration commands for load swing damping. Comparison of graphs 5b and 5c shows that the average operating cycle duration of the traveling mechanism is longer than the duration of operation of the drive engine by almost the same value for different lengths of the path traveled by the trolley. This suggests that the duration of load swing damping almost does not vary at different paths traveled by the trolley. Thus, with short paths traveled, the relative duration of load swing damping will be longer.

According to the graph in Fig. 5 a, the average number of engine starting during the operating cycle of the traveling mechanism is 3 to 6 and almost does not depend on the length of the path traveled by the trolley.

The wide variation range of durations of the operating cycle of the traveling mechanism and the number of engine starting shows greater probability of errors in case of manual control.

The dimension of the coordinates of the horizontal axis of the graphs in Fig. 5 is chosen so that the regression equation has the form of a straight line equation. The duration of the operating cycle of the traveling mechanism and the duration of operation of the drive engine will have a linear dependence on the path traveled because, as shown above, the duration of the swing damping period is a constant and the duration of the movement at steady speed also linearly depends on the path traveled.

The analysis of the graphs in Fig. 6 suggests that the number of starts of the drive engine is 1.8-2.6 times fewer with optimal control than with manual control.

The graphs of Fig. 7 show that both with manual and optimal control, the share of time spent on load swing damping increases as the path traveled decreases. In case of manual control, the duration of swing damping can take up to 65% of the total cycle duration.

The calculated regularities of the optimal speed performance movement of the traveling mechanism are implemented using a microprocessor-based automatic control system and allow damping the load swings within the shortest possible time. At the same time, the longest relative duration of load swing damping was 50% of the duration of the operating cycle of the mechanism. With manual control, the relative duration of load swing damping can take up to 65% of the duration of the working cycle.

With an increase in the length of the path traveled, the relative duration of load swing damping decreases sharply and asymptotically approximates to the steady-state value. This value can be 35% or 5% of the duration of the working cycle with manual and optimal speed performance control, respectively.

The graph in Fig. 8 shows that using optimal speed performance control can reduce the duration of the working cycle of the traveling mechanism by 1.5-3.1 times. The ratio of the duration of the working cycles will differ because of the need to damp the load swings and depends on the length of the path traveled.

In the papers referred to in the literature review, the optimal control is considered from the point of view of the algorithm for synthesizing laws of motion and control systems, and the laws of motion are given without comparison with alternative control modes. In this study, regularities are determined allowing evaluating the ratios of durations of working cycles, duration of swing damping and the number of engine startings per cycle of the traveling mechanism with manual and automatic optimal speed performance control. These dependences enable evaluating the effectiveness of optimal control and determining rational areas of its application.

It should be noted that the presented graphs are plotted on the basis of functional dependencies obtained as a result of experimental studies, which were conducted using a trolley model. The recalculation coefficients for the length of the path traveled should be determined using the theory of similarity to apply the experiment results to a real crane. Knowing the coefficient of similarity, it can be established what path traveled by a real crane or a crane trolley will correspond to the path traveled by the model.

Further studies of this issue can be focused on conducting experiments with real cranes and increasing the number of influencing factors.

6. Conclusions

A mathematical model of the trolley-load system has been developed. It was used as a basis for developing an algorithm for the synthesis of the optimal speed performance control using the Pontryagin's maximum principle and the phase-plane method to search for switching points of the relay control function.

A crane trolley model and computer control system, able to implement the automatic movement of the trolley according to the optimal laws, have been created.

The experimental study of manual and optimal control has been conducted. The collected data have been recorded and processed using the experiment planning and statistical evaluation methods. Average values and areas of confidence intervals have been determined. The regression analysis of the collected data has been conducted.

The regularities have been determined which allow to evaluate the reduction of the duration of the working cycle and the number of engine startings of the traveling mechanism with manual and optimal speed performance control. The ratio of numbers of starts of the drive engine with optimal control to those with manual control is 1.8-2.6 depending on the length of the path traveled. The relative duration of the load swing damping increases as the path traveled decreases and can take up to 65% of the total duration of the working cycle of the mechanism with manual control and up to 50% with the optimal control. With an increase of the length of the path traveled, the share of time spent for swing damping decreases. With manual control, this value can be 7 times greater than with automatic. The ratio of the duration of working cycles with manual and optimal control has different values depending on the length of the path traveled. Based on the obtained regularities, it has been established that with the optimal speed performance control, the working cycle of the mechanism can be reduced by 1.5-3.1 times.

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