Simulation of Crane Trolley Motion Control to Reduce Load Sway

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Abstract. the work aims to develop a method for controlling a crane trolley, providing a decrease in the swinging of the load on the rope at a given positioning accuracy and minimum time for moving the load.

Computer simulation of the trolley controlled movement with a load on a rope was carried out within the "Universal Mechanism" software.

The 2D computer model includes a trolley with a pulley, a rope with a hook, and a load. T-force represents the wind force effect.

The control system (CS) contains three blocks that ensure the movement of the trolley with limited speed and acceleration, the positioning accuracy of the trolley, limiting the deviation and acceleration of a load. List of requirements for the crane CS comprises six issues.

The simulation results illustrate the satisfactory performance of the proposed method. The swing angle and trolley positioning accuracy can be controlled within the acceptable range and the external wind disturbance on the load can be successfully suppressed. The optimal parameters of the proportional-differential corrective control, which ensure the minimum travel time of the trolley with limited oscillation of the load, have been determined. The optimal values of the control parameters depend on the inertial characteristics of the load. The maximum permissible values of speed, acceleration, and positioning errors of the trolley limit from above the optimal values of the control parameters.

1. Introduction

Over the past 20 years, a lot of research has been carried out on the creation of systems and methods for controlling various types of cranes, which ensure a decrease in load swaying, an increase in productivity and positioning accuracy [1]. Many companies have developed systems to damp the vibrations of the load moved by cranes. These systems are aimed at reducing transportation time and reducing the burden on the operator. Thus, SIMOCRANE Sway Control is a control system (CS) from SIEMENS [2]. It uses a mathematical model of load swaying. The model uses signals from optical sensors that determine the height of the load and the angles of deflection of the ropes. The CS reduces the load swaying in one or two directions simultaneously and increases the positioning accuracy.

SIMOCRANE system can also operate without signals from optical sensors as an open-loop CS.

The CS of the KONECRANES Company [3] provides accurate load movement and increases the efficiency of the crane. To reduce the swaying of the load, the CS calculates the optimal acceleration of the crane using information about the movement of the load and the operator's commands. The CS also reduces the likelihood of collision of cargo with walls and surrounding equipment.
The CS includes the following options: swing control and prevention of load impact, hook centering, tracking movement, lifting synchronization, extended set of speeds, microspeed mode.

The Antisway Complete CS developed by SmartCraneLLC [4]. It provides automatic movement of the crane to 25 programmed positions or semi-automatic operation of the crane with limited swaying of the load. CS translates operator commands into carefully planned acceleration versus time dependencies. These dependencies differ slightly from the operator's commands, but they eliminate the swaying of the load.

When developing direct control of the movement of crane mechanisms, the researchers determined the type of control signals that ensure the required movement of the load. A controller with a trajectory design based on S-curve was proposed for trajectory tracking and payload sway decrease of a 2D crane with payload hoisting [5].

The open-loop CSs used for this aim do not take into account random factors of the environment and production processes [6]. An open-loop technique cannot be used for position tracking and disturbance rejection.

Several feedback control methods were also investigated for control of crane systems. These include nonlinear quasi-PID control [7], sliding mode control [8-9], nonlinear control [10-11], robust control [12], adaptive control [13], energy based control [14] and fuzzy logic control [15].

Closed-loop CSs take into account the actual movement of the crane and can implement methods of adaptive control that take into account unplanned force effects and other uncertainties. CS for cranes using PID and PD controllers are considered in [16-17]. The disadvantage of closed-loop CSs is errors and noises generated by feedback sensors.

Combined CSs include direct control of the movement of crane mechanisms and feedback elements that take into account the actual movement of the crane.

To simplify the CSs, a linearized model with partial feedback is considered in [18]. To take into account uncertainties in the operation of crane mechanisms, an adaptive control method was proposed in [19].

To achieve both the precise positioning and low load sway, several combined control techniques have also been studied. These techniques improve the crane performance that could not be obtained by using a single controller. These hybrid controllers include a combined sliding mode control with partial feedback linearization for an overhead crane [20], input shaping via adaptive sliding mode control [21] and with optimal PID control [22]. Input shaping has also been combined with a feedback controller in [23] and with a damper in [24].

To assess the effectiveness of the proposed methods and CSs, researchers mainly use analytical models of the movement of cranes, including those implemented in the Matlab/Simulink environment. This article presents a methodology for evaluating the effectiveness and determining the parameters of the crane movement control method using the "Universal Mechanism" (UM) software.

The aim of the work is to develop a method for controlling a crane trolley, providing a decrease in the swinging of the load on the rope at a given positioning accuracy and minimum time for moving the load.

The method of carrying out the work is computer simulation of the controlled movement of a trolley with a load on a rope using the UM software.

The novelty of the work is in the use of a computer dynamic model of a crane trolley instead of an analytical one; in the formulation of a set of requirements for a crane CS; in the development of the 3-block method for the trolley movement control; in determining the optimal values of control parameters by means of a computational experiment.

2. Requirements for the CS of the crane

The CS of the crane when moving the load must ensure the following restrictions:

- Trolley positioning accuracy does not exceed $\pm \Delta t$ for a limited time.
- Trolley speed does not exceed $V_{\text{cart}}$.
- Acceleration of the trolley does not exceed $a_{\text{cart}}$. 


Horizontal displacement of the center of mass (CM) of the load relative to the trolley \( \delta_1 \) does not exceed \( \Delta_1 \) during movement.

Horizontal displacement of the CM of the load relative to the given position \( \delta_2 \) does not exceed \( \Delta_2 \) after stopping the trolley. Instead of restrictions \( \delta_1 \) and \( \delta_2 \), it is possible to use restrictions on the angle of deviation of the ropes from the vertical \( \Theta_1 \) during movement and \( \Theta_2 \) after stopping the trolley (\( \Theta_1 \geq \Theta_2 \)).

Horizontal component of the load acceleration does not exceed \( a_{\text{load}} \).

Time of load movement is minimal.

3. Description of the computer model
To simulate the movement of a trolley with a load, a 2D computer model was created in the UM environment (Fig. 1).

![Computer model of a trolley with a load](image)

**Figure 1.** Computer model of a trolley with a load.

The computer model includes a trolley with a pulley, a rope with a hook, and a load. Model bodies move in the vertical \( YZ \) plane. Forces and displacements of bodies in the direction of the \( X \) axis are not considered.

The trolley moves along the \( Y \) axis under the action of the traction force \( F_h \). The force of resistance to the movement of the trolley is given by the formula

\[
F_{\text{cart}} = -(m_{\text{cart}} + m_{\text{hook}} + m_{\text{load}})(\beta_0 \text{sgn}(v_y) + \beta_1 v_y).
\]

Here \( m_{\text{cart}}, m_{\text{hook}}, \) and \( m_{\text{load}} \) are the masses of the trolley, a hook and a load. \( \beta_0 \) and \( \beta_1 \) are the resistance coefficients to the trolley movement, \( v_y \) is the projection of the trolley speed on the \( Y \) axis.

The model of the block pulley mechanism for lifting the load [25] includes a block with a hook suspension, rotational and translational hinges. The change in the height of the load is given by the hinge coordinate. The load is suspended on the hook with two slings.

The moment of resistance to the rotation of the rope with relative to the pulley is given by the formula

\[
M_{\text{pol}} = -(m_{\text{hook}} + m_{\text{load}})\beta_2 \omega_p.
\]

Here \( \omega_p \) is the angular velocity of the rope deflection from the vertical, \( \beta_2 \) is the drag coefficient.

The force effect of the wind on the load is represented in the model by the \( T \)-force.

A computer model in the UM environment allows a more detailed description of crane mechanisms in comparison with analytical models.
4. Trolley motion control method
In accordance with the listed requirements, the CS contains three blocks that ensure the movement of the trolley with limited speed and acceleration, the positioning accuracy of the trolley, limiting the deviation and acceleration of CM of the load.

Block 1. For smooth movement of the load, one- and multi-stage dependences of the preset trolley speed \( V \) on time \( t \) are used. For example, with a one-stage dependence
\[
V = V_m \sin(\pi t / T_0),
\]
where \( V_m \) is the maximum preset speed of the trolley, \( T_0 \) is the estimated time of movement of the trolley.

Block 2: If, after the estimated time \( T_0 \), the required accuracy of the trolley position is not reached, then the trolley will continue to move under the action of a corrective force
\[
F_{corr} = \gamma_0 \sin(L_0 - y) + \gamma_2(L_0 - y) \text{ if } y < L_0 - \Delta_c \text{ or } y > L_0 + \Delta_c, F_{corr} = 0 \text{ otherwise}.
\]
Here \( \gamma_0 \) is the constant component of the corrective force, \( \gamma_2 \) is the coefficient of proportionality, \( L_0 \) is the calculated displacement of the trolley, \( y \) is the coordinate of the trolley.

Block 3. It is possible to reduce the load swaying on the rope by adjusting the preset trolley speed. To do this, the CS includes a proportional-differential controller (PD-controller) that calculates the speed of regulation
\[
v_{PD} = \tilde{\zeta} |\Theta| + \tilde{\varphi} [\Theta'],
\]
where \( \tilde{\zeta} \) and \( \tilde{\varphi} \) are the regulation coefficients, \( \Theta \) is the angle of deviation of the hoist ropes from the vertical, \( \Theta_p = d\Theta / dt \), \( [\Theta] \) and \( [\Theta'] \) are the regulation parameters.

To move the trolley at a given speed \( V \), the force of the trolley movement mechanism \( F_h \) is given by the formula
\[
F_h = \gamma_0 + \gamma_1 (V - v_y - v_{PD}), \tag{1}
\]
where \( \gamma_0 \) is the component of the force \( F_h \), \( \gamma_1 \) is the proportionality coefficient.

The current speed of the trolley can exceed the specified speed if \( \gamma_0 > F_c \), where \( F_c \) is the projection of the main vector of resistance and inertia forces of the trolley with a load on the \( Y \) axis. The current speed can be less than the specified speed if \( \gamma_0 < F_c \). In this case, the time for moving the load increases.

The component \( \gamma_0 \) has the form:
\[
\gamma_0 = F_{h0} \sin(\pi / 2t_0) \text{ for } t \in [0, t_0), \quad \gamma_0 = F_{h0} + (F_{hl} - F_{h0})v / T_0 \text{ for } t \in [t_0, T_0], \quad \gamma_0 = 0 \text{ for } t > T_0.
\]
Here \( F_{h0} \) and \( F_{hl} \) are the values of the force \( F_h \) required for the movement of the trolley at \( t = t_0 \) and \( t = T_0 \); \( t_0 \) is the duration of the soft start, that is, the duration of the increase in the force \( F_h \) from 0 to \( F_{h0} \).

Equation (1) corresponds to PD-control, since it takes into account the actual speed of the trolley, the sway angle and the sway angular velocity.

The movement of the load is considered complete if the trolley has reached a given position \( y \in [L_0 - \Delta_c, L_0 + \Delta_c] \), the horizontal deviations of the CM of the load \( \delta \) do not exceed \( \Delta_2 \) and the projection of the CM speed of the load on the \( Y \) axis does not exceed \( \Delta' \). The time corresponding to these conditions is designated as the actual time of movement of the load \( T_\lambda \).

The CS model of a crane trolley, which implements the described control method, was created using the UM structural diagram editor.
5. Optimization of control parameters

The actual travel time of the load $T_R$ depends on the unplanned force effects on the trolley and the load. For example, the increase in the trolley movement resistance when the ambient temperature drops and the wind disturbance.

The purpose of optimization is to determine the values of the control parameters that provide the minimum time for moving the load, i.e. $\min(T_R)$.

Let us determine the optimal values of the control parameters $\varphi_1$, $\varphi_2$, $[\Theta]$, $[\Theta']$, $y_{20}$, $y_2$ under the constraints indicated above by scanning the space of admissible values of the parameters $\varphi_1 \in [0, 10]$, $\varphi_2 \in [0, 10]$, $[\Theta] \in [0, \Theta_1]$, $[\Theta'] \in [0, \alpha_{\max}]$, $y_{20} \in [0, F_{c0}]$, $y_2 \in [0, F_{c1}]$. Here $\alpha_{\max} = \Theta_1 \sqrt{9/g} / T_p$, $g$ is the acceleration of gravity. $l_p$ is the minimum length of the rope for the problem under consideration.

If for $y = L_0 + \Delta_c$ $v_y = V_{cart}$ and $F_{corr} \approx F_{cart}$, then we assume $F_{c0} = (m_{cart} + m_{hook} + m_{load}) \beta_0$ and $F_{c1} = (m_{cart} + m_{hook} + m_{load}) \beta_1 V_{cart} / \Delta_c$.

6. Simulation results

Simulation of the compact load movement is carried out under the wind force acting on the load and the following initial data: $m_{cart} = 200$, $m_{hook} = 0$, $m_{load} = 600$, $V_m = 0.3$, speed of lifting the load $v_{load} = 0.1$, the initial length of the rope $l_{ro} = 4$, $T_0 = 10$, $m_0 = 0.5$, $L_0 = 1.9099$, $y_2 = 1.015$, $F_{ho} = 100$, $F_{hl} = 80$, $F_{c0} = 80$, $F_{c1} = 9000$, $\beta_0 = 0.1$, $\beta_1 = 0.015$, $\beta_2 = 0.01$. Wind impulse in the time interval $t \in [5, 6.5]$ equals 100. Compact load lifted directly by the hook without slings.

Variable constraints include values: $V_{cart} = 0.36$, $a_{cart} = 0.3$, $a_{load} = 0.26$, $\Delta_c = 0.02$, $\Delta_l = 0.1$, $\Delta_2 = 0.045$, $\Delta' = 0.03$. Its correspond to the angles of deflection of the ropes from the vertical $\Theta_1 = 0.025$ and $\Theta_2 = 0.015$ at a distance from the axis of the rope pulley to the CM of the load of 4 ... 3 m.

Numerical values of all quantities are given in units of the international system.

Simulation shows that minimum value $T_R = 15.84$ s corresponds to the parameter values $\varphi_1 = 1.5$, $\varphi_2 = 1.5$, $[\Theta] = 0$, $[\Theta'] = 0$, $y_{20} = 50$, $y_2 = 9000$. Close to the minimum, values $T_R = 16.73 ... 16.24$ s take place when $\varphi_1 = 2$, $\varphi_2 = 1.5 ... 2$, $[\Theta] = 0$, $[\Theta'] = 0$, $y_{20} = 50$, $y_2 = 7000 ... 9000$.

Fig. 2 shows the dependences of the angle of ropes $\Theta$ on time $t$ with and without wind force acting on the load and without regulation ($\varphi_1 = \varphi_2 = y_{20} = y_2 = 0$) in both cases.

![Figure 2](image)

**Figure 2.** Dependences of $\Theta$ on $t$ under the action of the wind force on the load (blue marked line) and without the wind force (bard unmarked line) in the absence of regulation.

An impulse of wind force of 100 Ns increased the amplitude of the angle $\Theta$ by 3.16 times from 0.011 to 0.0348 rad at $t > 10$ s.

Fig. 3 shows the dependences of the angle of ropes $\Theta$ on the time $t$ when the wind force acts on the load and optimal regulation, as well as in the absence of regulation but the presence of a correcting force ($\varphi_1 = \varphi_2 = 0$, $y_{20} = 50$, $y_2 = 9000$).

Without the use of a PD-controller, the amplitude of the sway angle $\Theta$ is 0.035 rad at $t \in [10, 20]$. The PD-controller with optimal parameters reduced the amplitude of the angle $\Theta$ from 0.02 rad at $t = 6.8$ s to 0.004 rad at $t = 18.8$ s. The use of the optimal PD-controller reduced the maximum amplitude of the angle $\Theta$ by 1.6 times at $t \in [0, 10]$ and by 8.75 times at $t \in [18, 20]$. 
Modeling has shown that an increase in the values of $V_1$ and $V_2$ reduces the load swaying. The upper permissible values of $V_1$ and $V_2$ are generally determined by the restrictions listed in the part 2. For the considered example, the upper limits of $V_1$ and $V_2$ are determined by the values $V_{\text{cart}}$, $a_{\text{cart}}$, and $\Delta_c$.

The optimal values of the parameters $[\Theta]$ and $[\Theta']$, which determine the moment of switching on the speed of regulation $v_{PD}$, are equal to zero, since at $[\Theta]>0$ and $[\Theta']>0$ jerks appear in the movement of the trolley.

Simulation the movement of a large-sized cargo is carried out with cylindrical hollow body with a diameter of 0.7 m and a length of 2 m. The cargo lifted by two slings with a length of 1.47 m, connected to a hook.

This example differs from the previous one by the inertial characteristics of the load being moved $m_{\text{hook}} = 76$, $m_{\text{load}} = 524$, moments of inertia of the load relative to the central axes $J_{xx} = J_{zz} = 374.6$, $J_{yy} = 220.2$. That is, the mass of the load with

\begin{equation}
\begin{aligned}
\text{Fig. 3. Dependences of } \Theta \text{ on } t \text{ under the action of wind force on the load and optimal regulation (blue unmarked line), as well as in the absence of regulation, but the presence of a corrective force (blue marked line).}
\end{aligned}
\end{equation}

The hook, the distance from the axis of the rope pulley to the CM of the load remained the same.

Simulation shows that minimum value $T_R = 15.7$ s corresponds to the values of the parameters $\varsigma_1 = 1.5$, $\varsigma_2 = 1.0$, $[\Theta] = 0$, $[\Theta'] = 0$, $g_2 = 9000$. Values close to the minimum $T_R = 16.51...16.26$ s take place at $\varsigma_1 = 2$, $\varsigma_2 = 1.0$, $[\Theta] = 0$, $[\Theta'] = 0$, $g_2 = 7000 ... 9000$. The actual travel time of a large-sized cargo is longer than that of a compact cargo with the same restrictions.

Fig. 4 shows the dependences of the angle of ropes $\Theta$ on time $t$ when moving compact and large-sized loads with load hoisting, wind disturbance and optimal regulation. At $t > 6$ s, the amplitude of the sway angle $\Theta$ for a compact load is $1.051 ... 1.054$ times greater than that of a large-sized one.

Fig. 5 shows the dependences of the large-sized cargo CM displacement relative to the trolley $\delta_1$, the displacement of the trolley relative to the given position $\delta_{\text{cart}}$ versus time $t$ when the wind force acts on the load and optimal regulation. $\delta_{\text{cart}} = y - L_0$.

Comparison of the $\delta_1$ values in Fig. 5 at the moments of time $t = 10.5$ s and $t = 18.7$ s shows that the PD-control reduced the load swaying amplitude by 3.59 times due $8.26$ s. The oscillation period of $\delta_1$ is $4.13$ s, the oscillation decrement of $\delta_1$ is $1.43$.

\begin{equation}
\begin{aligned}
\text{Fig. 4. Dependences of } \Theta \text{ on } t \text{ when moving compact load (blue marked line) and large-sized (bard unmarked line) cargo under the influence of wind force and optimal regulation.}
\end{aligned}
\end{equation}
Figure 5. Dependences of the relative displacement of a large-sized cargo $\delta_1$ (blue line), the displacement of the trolley relative to the given position $\delta_{\text{cart}}$ (brown line) on time $t$ under the action of wind force and optimal regulation.

The proposed technique for evaluating the effectiveness of the crane trolley control includes:

- Creation of a computer dynamic model of the crane in the environment of the UM, MSC ADAMS, etc.
- Formulation of requirements for the CS, for the movement of the crane and load.
- Creation of a CS model representing the investigated method of crane movement control, planning and conducting a computational experiment to determine the criteria for the effectiveness of the control method.
- Determination of optimal or recommended values of control parameters based on the results of a computational experiment.

This technique can be used for all mechanisms and types of cranes.

7. Conclusion

A computer model of the crane trolley controlled movement has been developed, including a multi-mass dynamic model and a control module. A combined control of the trolley movement sets the trolley movement speed as a function of time and corrective control, taking into account the actual position of the trolley and the load.

Requirements for the controlled movement of the crane trolley are formulated, taking into account the permissible speed and acceleration of the trolley, the positioning accuracy of the trolley, the limitation of the deviation and acceleration of the CM of the load.

The simulation results illustrate the satisfactory performance of the proposed method. The swing angle and trolley positioning accuracy can be controlled within the acceptable range and the external wind disturbance on the load can be successfully suppressed. The optimal parameters of the proportional-differential corrective control, which ensure the minimum travel time of the trolley with limited oscillation of the load, have been determined. It is shown that the optimal values of the control parameters depend on the inertial characteristics of the load. The maximum permissible values of speed, acceleration and positioning errors of the trolley limit from above the optimal values of the control coefficients $\zeta_1$ and $\zeta_2$.

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