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REGRESSION MODEL OF REDUCING OF PENDULUM OSCILLATIONS OF LOAD MOVED BY MEANS OF OVERHEAD CRANE WITH RELAY DRIVE

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ABSTRACT

With the result of conducted research we obtain the dependencies of acceleration and time of accelerated movement of point of suspension load and also deviation angle of overhead crane rope, by which it is necessary to start braking of suspension point, providing complete reducing of pendulum oscillations of load with simultaneous full stop point of suspension from the initial velocity of the point of suspension and the maximum angle of deflection of the hoist rope. We use simulation model of overhead crane and the simplex method of optimization for these dependencies. The obtained dependences are used to do regression model of reducing of pendulum oscillations of load moved by means of overhead crane with relay drive.

Keywords: regression model, overhead crane, drive

1 INTRODUCTION

It is necessary to damp the residual load pendulum oscillations [1-6] to increase the productivity of overhead cranes (OC) with relay drive. Additional start-up motor drive relay OC causes large inrush currents reducing the service period of the electric engine [7].

It is possible to increase the productivity of overhead cranes by reducing of load pendulum oscillations on flexible rope suspension after its delivery to the aim position.

The well-known methods of load residual oscillations damping [2, 3, 4, 5, 6, 8, 9] have general disadvantages in the authors understanding. They are: complication of implemented mathematical methods and models as well as rather big accuracy of linear coordinates of moved load realization. Uncontrolled component part of pendulum oscillations of load is put down partly. As a rule, the time of displacement by oscillation damping is increasing.

In presented work we set the task to show the possibility of making of rather simple regression model of full load flat pendulum oscillation damping. This load is moved by means of overhead crane with relay drive.

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It allows to calculate optimum values of acceleration and braking time of load suspension point in real time regime. Damping of load pendulum oscillations on rope suspension must be implemented for current (measured) values of angle of load rope OC deflection from vertical line and motion speed of suspension point.

2 MATERIALS AND METHODS

In this regard, the experimental researches are carried out using a simulation model OC [10]. Researches are connected with pendulum oscillation of the load along one of the coordinates of three-dimensional space by a single braking suspension point until its complete stop by optimizing the values of the deflection angle of the hoist rope from the vertical q_{bb}, where it is optimal to produce the beginning of the braking (bb) of load suspension point, duration of braking ΔT_{brak} and acceleration of braking, a_{brak}.

The authors accept that that the speedup of acceleration and deceleration of the suspension point are constant and linear speed of the suspension point in the steady state (after completion of acceleration and before braking) is also constant. The settlement scheme of the OC dynamic system and the corresponding simulation model in the notation SimMechanics Second Generation and Simulink are shown in Figure 1.

Using a simulation model OC with load by means of variation of the speedup of acceleration a_{acc} and acceleration time ΔT_{acc} within the limits

$$a_{acc} = (0{,}25{:}0{,}25{:}2{,}5)\ [\text{m/s}^2];\ T_{acc} = (0{,}25{:}0{,}25{:}2{,}5)\ [\text{s}] \quad (1)$$

it was formed two-dimensional arrays of suspension point speed previous the start time of braking $V_s = f(a_{acc}, \Delta T_{acc})$, the maximum angle of deviation of load rope OC from vertical, previous the beginning of the braking time $q_{max}=f(a_{acc}, \Delta T_{acc})$, the optimal value of the angle of deviation of load rope from the vertical q_{bb} during which we have the beginning of braking of suspension point $q_{bb}=f(a_{acc}, \Delta T_{acc})$, optimal duration of braking $\Delta T_{brak}=f(a_{acc},\Delta T_{acc})$ and optimal constant value of the braking acceleration $a_{brak}= f(a_{acc}, \Delta T_{acc})$.

Length of a hoist rope accepted value l=10 [m], mass of load m_l=100 [kg], damping coefficient on angular coordinate b=100 [N·m/(rad/s)]. Each element of the array $q_{bb} = f(a_{acc}, \Delta T_{acc})$, $\Delta T_{brak}=f(a_{acc}, \Delta T_{acc})$, $a_{brak} = f(a_{acc}, T_{acc})$ was formed as a result of solving the problem of optimizing the values of the parameters defining the braking process (q_{bb}, ΔT_{brak}, a_{brak}) by means of simplex method by the criterion of minimization of indicator

$$y = \dot{q}_{res} + V_{sres} + \Delta y, \quad (2)$$

where the $\dot{q}_{res}$ – maximum residual velocity of angle changing of deflection of hoist rope from the vertical after the moment of ceasing of braking; V_{sres} – maximum residual velocity of the point of load suspension after the moment of ceasing of braking; Δy – penalty function.

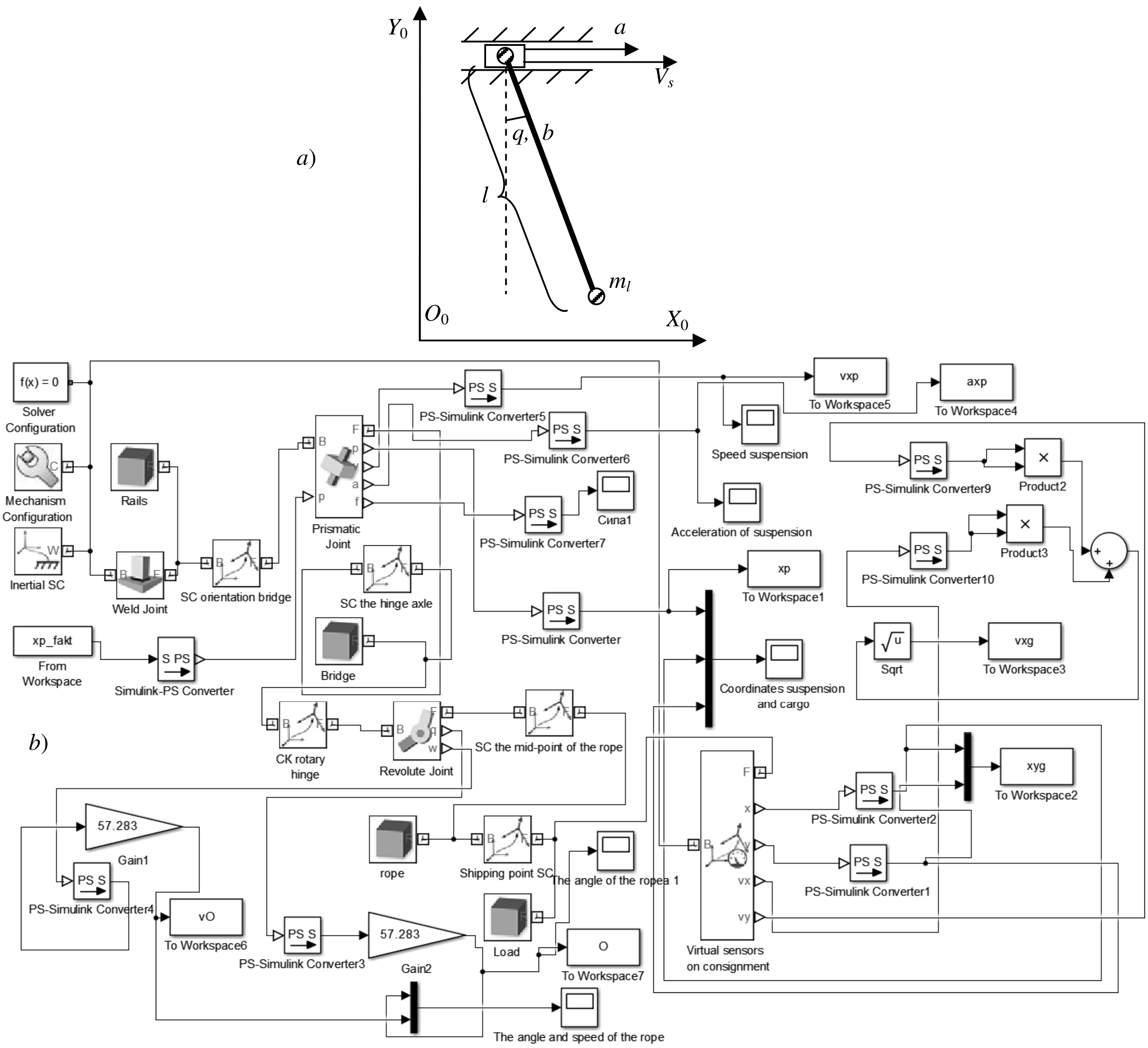

Figure 1 Settlement scheme of the OC dynamic system (a) and the corresponding simulation model in SimMechanics Second Generation and Simulink notation (b).

Given in (2) indicators are determined by means of signal processing of virtual meters in simulation model OC. We use method of adding penalty function [11, 12] to the basic function (2) to mix the problem of imputation optimization to the problem of implicit optimization whose solution we apply the simplex method:

$\Delta y=0$ at $T_{q\max} \geq T_{brak}$;

$\Delta y=k\cdot|(T_{q\max}-T_{brak})|$ at $T_{q\max}<T_{brak}$,

where $T_{q\max}$ – the nearest to the present time past time of reaching q_{max}; T_{brak} – time of braking beginning; k = 100 – empiric penalty coefficient.

3 RESULTS

The results of computational experiments on the simulation model can be presented in graphical form of relations of different parameters from each other (Figure 2).

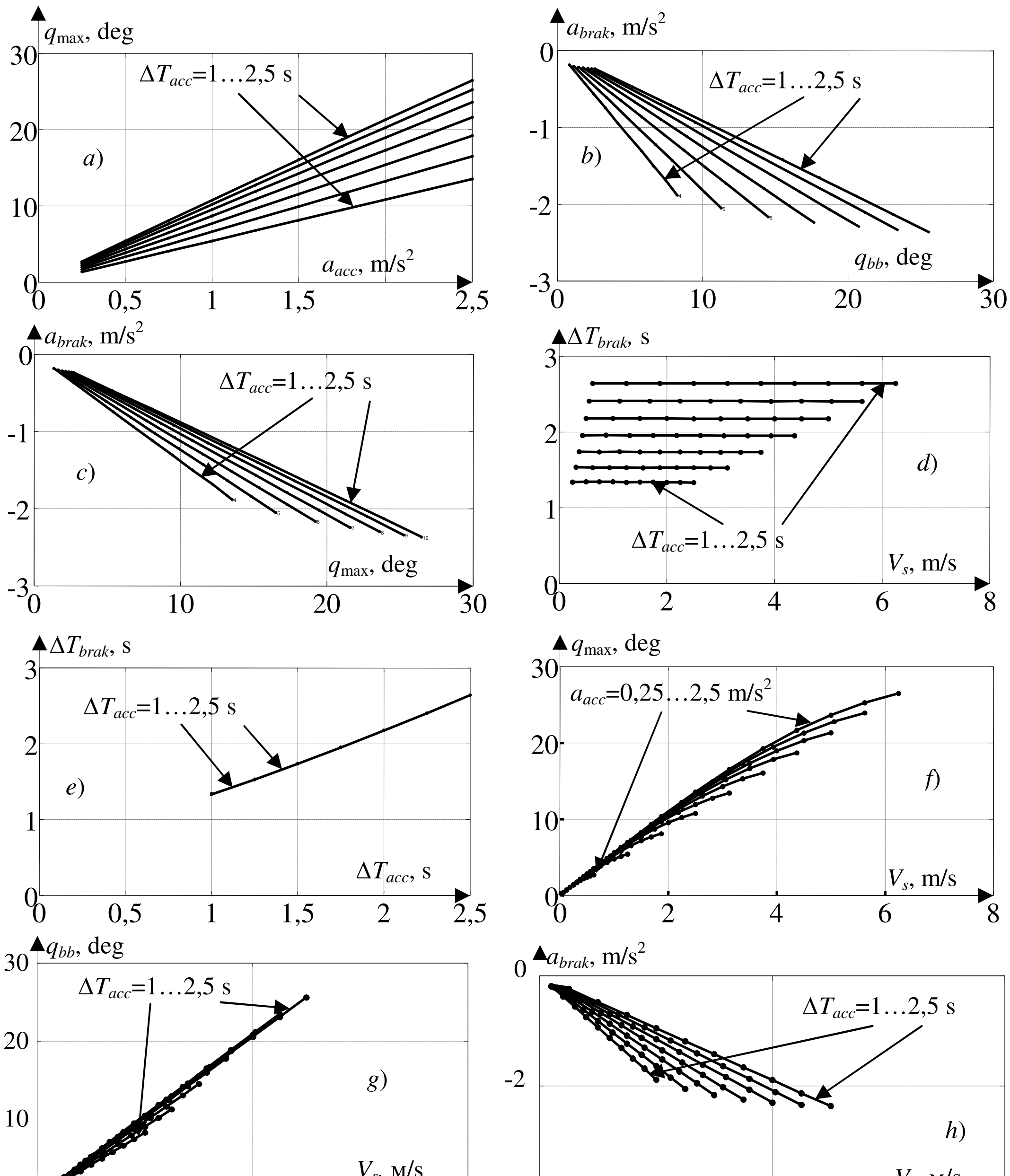

Figure 2 Obtained functional dependencies received during the computational experiments with optimization: a) $q_{\max}$ from a_{acc}; b) a_{brak} from q_{bb}; c) a_{acc} by q_{max}; d) ΔT_{brak} from V_s; d) ΔT_{brak} from ΔT_{acc}; e) $q_{\max}$ from V_s; g) q_{bb} from V_s; h) a_{brak} from V_s.

Table I - The denotations of coefficients bi (i∈ [1,36]) of regression equation of the deflection angle from the vertical hoist rope qbb at which it is optimal to produce the beginning of braking of point suspension load, changing Vs and qmax

Coefficient	b_1	b_2	b_3	b_4	b_5	b_6
Denotation	-0,25207	-0,51995	-2,50149	-0,35418	-0,09879	0,002282
Coefficient	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}
Denotation	8,305368	22,72767	5,290067	1,984357	0,006708	-0,00157
Coefficient	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}
Denotation	-56,0639	-21,9505	-12,8091	-0,78185	0,029136	0,000121
Coefficient	b_{19}	b_{20}	b_{21}	b_{22}	b_{23}	b_{24}
Denotation	29,69254	23,63402	6,383197	-0,08011	-0,00633	6,53E-05
Coefficient	b_{25}	b_{26}	b_{27}	b_{28}	b_{29}	b_{30}
Denotation	8,464829	-11,9735	-0,88149	0,067979	-0,00103	4,4E-06
Coefficient	b_{31}	b_{32}	b_{33}	b_{34}	b_{35}	b_{36}
Denotation	-9,25646	3,478413	-0,18614	0,00331	-2,1E-05	2,07E-08

Table II - The denotations of coefficients b_i ($i \in [1, 36]$) of the regression equation of duration of braking ΔT_{brak}, changing V_s and q_{max}

Coefficient	b_1	b_2	b_3	b_4	b_5	b_6
Denotations	0,705817	-4,70412	-0,17287	-0,20991	-0,02189	0,00133
Coefficient	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}
Denotations	31,05741	7,592292	1,719708	0,75559	-0,02932	-0,00028
Coefficient	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}
Denotations	-53,3078	-2,40926	-5,97321	-0,02038	0,014598	-0,00011
Coefficient	b_{19}	b_{20}	b_{21}	b_{22}	b_{23}	b_{24}
Denotations	23,11647	9,422257	2,162298	-0,11461	-0,00058	2,92E-05
Coefficient	b_{25}	b_{26}	b_{27}	b_{28}	b_{29}	b_{30}
Denotations	-2,15499	-4,46324	-0,16366	0,028677	-0,00065	3,66E-06
Coefficient	b_{31}	b_{32}	b_{33}	b_{34}	b_{35}	b_{36}
Denotations	-2,43068	1,172566	-0,07864	0,001549	-4,7E-06	-7,5E-08

Table III - The denotations of coefficients b_i ($i \in [1, 36]$) of the regression equation of braking acceleration a_{brak}, changing V_s and q_{max}

Coefficient	b_1	b_2	b_3	b_4	b_5	b_6
Denotations	-0,0629	-0,24769	-0,4082	-0,16261	-0,03813	-0,00018
Coefficient	b_7	b_8	b_9	b_{10}	b_{11}	b_{12}
Denotations	1,13742	3,488527	2,084317	0,750042	0,027261	-0,00049
Coefficient	b_{13}	b_{14}	b_{15}	b_{16}	b_{17}	b_{18}
Denotations	-8,51162	-7,4824	-4,70546	-0,48964	0,006204	0,000105
Coefficient	b_{19}	b_{20}	b_{21}	b_{22}	b_{23}	b_{24}
Denotations	7,674561	8,548148	2,949286	0,021757	-0,00316	2,41E-05
Coefficient	b_{25}	b_{26}	b_{27}	b_{28}	b_{29}	b_{30}
Denotations	3,078755	-4,87594	-0,51471	0,027577	-0,00035	1,35E-06
Coefficient	b_{31}	b_{32}	b_{33}	b_{34}	b_{35}	b_{36}
Denotations	-3,57426	1,487305	-0,06915	0,001098	-6,6E-06	6,89E-09

Table IV - The denotations of indicators of the the regression (3) of the angle of load rope deviation from the vertical q_{bb} when it is optimal to produce braking beginning of the load suspension point from parameters V_s and q_{max}

Indicator	Denotation
Coefficient of determination R^2	0,999999
Corrected coefficient of determination $\overline{R}^2$	0,999998
Fisher criterion F	1106150
Sum of squared residuals RSS	0,00237
Standard error of the regression equation SEE	0,00835
Maximum relative inaccuracy of approximation $\delta_{\max}$, %	0,063

Table V - The denotations of the quality of the regression (3) of the braking duration ΔT_{brak} from parameters V_s and q_{max}

Indicator	Denotation
Coefficient of determination R^2	0,999843
Corrected coefficient of determination $\overline{R}^2$	0,999682
Fisher criterion F	6205
Sum of squared residuals RSS	0,002
Standard error of the regression equation SEE	0,00782
Maximum relative inaccuracy of approximation $\delta_{\max}$, %	0,77

Table VI - The denotations of indicators of the regression (3) of accelerating braking a_{brak} from parameters V_s and q_{max}

Indicator	Denotation
Coefficient of determination	0,999987
Corrected coefficient of determination $\overline{R}^2$	0,999975
Fisher criterion F	79243
Sum of squared residuals RSS	0,000349
Standard error of the regression equation SEE	0,0032
Maximum relative inaccuracy of approximation $\delta_{\max}$, %	0,26

Analysis of the results allow us to hypothesize that the optimal parameters of braking (q_{bb}, ΔT_{brak}, a_{brak}) depend only on two parameters characterizing the process of motion of a dynamic system OC before braking: on constant velocity of point suspension load motion V_s before braking and on the maximum deviation of the hoist rope OC from vertical prior to the time of braking $q_{\max}$. This hypothesis was confirmed experimentally in imitation model. By the results of computational experiments (using the Levenberg-Markvardt algoritm [13-15]) authors obtained regression dependences of the braking parameters (q_{bb}, ΔT_{brak}, a_{brak}) by V_s and $q_{\max}$, representing symmetric polynomials from two variables predictors V_s and q_{max} in degrees [0; 1; 2; 3; 4; 5] in all possible combinations of degrees of the argument:

$$
\begin{aligned}
q_{\mathrm{bb}}, \Delta T_{brak}, a_{brak} = {} & b_1 \cdot v_\Pi^5 \cdot q_{\max}^5 + b_2 \cdot v_\Pi^5 \cdot q_{\max}^4 + \\
& + b_3 \cdot v_\Pi^5 \cdot q_{\max}^3 + b_4 \cdot v_\Pi^5 \cdot q_{\max}^2 + b_5 \cdot v_\Pi^5 \cdot q_{\max} + b_6 \cdot v_\Pi^5 + \\
& + b_7 \cdot v_\Pi^4 \cdot q_{\max}^5 + b_8 \cdot v_\Pi^4 \cdot q_{\max}^4 + b_9 \cdot v_\Pi^4 \cdot q_{\max}^3 + b_{10} \cdot v_\Pi^4 \cdot q_{\max}^2 + \\
& + b_{11} \cdot v_\Pi^4 \cdot q_{\max} + b_{12} \cdot v_\Pi^4 + b_{13} \cdot v_\Pi^3 \cdot q_{\max}^5 + b_{14} \cdot v_\Pi^3 \cdot q_{\max}^4 + \\
& + b_{15} \cdot v_\Pi^3 \cdot q_{\max}^3 + b_{16} \cdot v_\Pi^3 \cdot q_{\max}^2 + b_{17} \cdot v_\Pi^3 \cdot q_{\max} + b_{18} \cdot v_\Pi^3 + \\
& + b_{19} \cdot v_\Pi^2 \cdot q_{\max}^5 + b_{20} \cdot v_\Pi^2 \cdot q_{\max}^4 + b_{21} \cdot v_\Pi^2 \cdot q_{\max}^3 + \\
& b_{22} \cdot v_\Pi^2 \cdot q_{\max}^2 + b_{23} \cdot v_\Pi^2 \cdot q_{\max} + b_{24} \cdot v_\Pi^2 + b_{25} \cdot v_\Pi \cdot q_{\max}^5 + \\
& + b_{26} \cdot v_\Pi \cdot q_{\max}^4 + b_{27} \cdot v_\Pi \cdot q_{\max}^3 + b_{28} \cdot v_\Pi \cdot q_{\max}^2 + b_{29} \cdot v_\Pi \cdot q_{\max} + \\
& + b_{30} \cdot v_\Pi + b_{31} \cdot q_{\max}^5 + b_{32} \cdot q_{\max}^4 + b_{33} \cdot q_{\max}^3 + b_{34} \cdot q_{\max}^2 + \\
& + b_{35} \cdot q_{\max} + b_{36}.
\end{aligned}
\qquad (3)
$$

The coefficients denotations of the regression equation (3) are shown in Table I-III.

Analysis of indicators of the quality of multiple non-linear regression equation (2) (Table IV-VI) shows us that the regression equation of this type gives the best results in terms of accuracy (minimum inaccuracy $\delta_{\max}$). All the coefficients of the regression equation are significant according to the Student's t-statistics. The maximum relative inaccuracy of approximation $\delta_{\max}$ is less than 0,77 % for the duration of braking ΔT_{brak} throughout the considered range of predictors.

Testing of regression equations for damping load show their efficiency (Fig. 3). In the example shown in Fig. 3, acceleration of speed up a_{acc} and duration of speed up ΔT_{acc} are taken equal a_{acc} = 2 [m/s^2], ΔT_{acc} = 2 [s].

Residual denotations of velocities change of the deflection angle of the rope $\dot{q}_{res}$ after braking obtained in example for solving the optimizing problem by means of simplex method and using regression equations are 0,088 and 0,108 [deg/s] correspondingly. The residual value of the linear velocity of the point of suspension after braking V_{sres}, obtained in the example for solving the optimization problem by means of simplex method and using the regression equation are 0,0197 and 0,0219 [m/s] correspondingly.

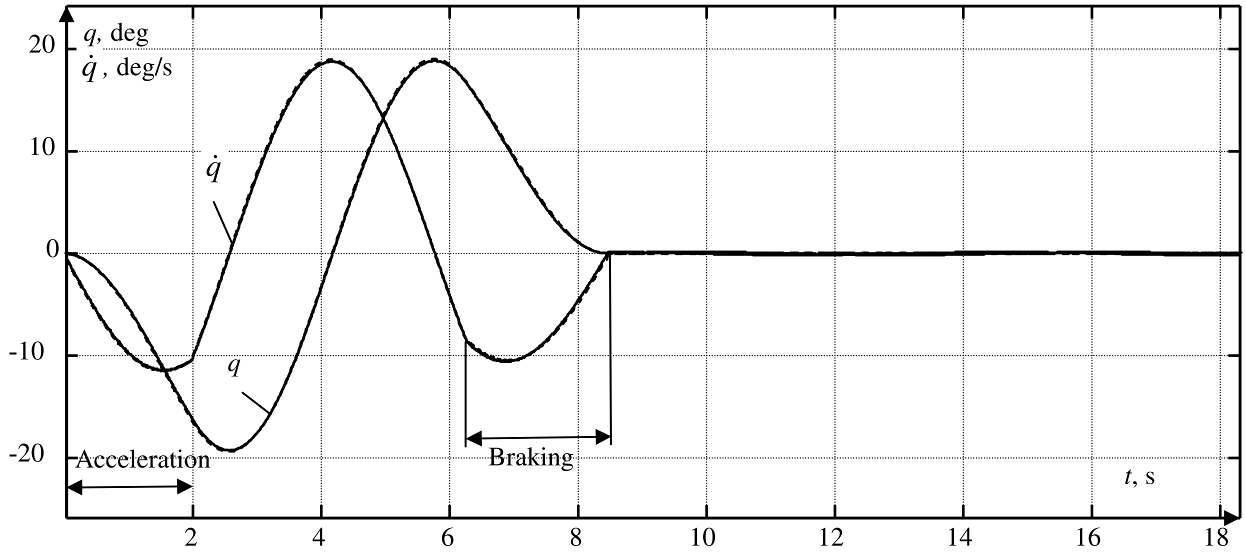

Figure 3 Examples of time dependences of the deflection angle of the hoist rope and rate of change of the deflection angle: solid line - obtained by solving the optimization problem by means of simplex method using a penalty functions; dashed line - obtained by parameters denotations (q_{bb}, ΔT_{brak}, a_{brak}), calculated by regression (3).

As a rule, load OC displacement is carried out not in the one plane (only by bridge movement and trolley movement). It is carried out in combination of two regulated movements, i.e. on space trajectory.

However, space load oscillations for small angles values (less than 5 in most cases of displacement) can be with comparatively little accuracy and be presented as superposition of displacements in two mutually perpendicular planes. I.e. worked out equations of regression can be used for residual load pendulum oscillations damping by its space displacement.

4 CONCLUSIONS

Using imitation model OC we get equations of regression of load pendulum oscillations, moved by overhead crane with relay drive. Application of these equations of regression gives the possibility of the synthesis of acceleration values and braking time in real-time regime. It allows to damp load pendulum oscillations on rope suspension for present (measured) angle values of load rope deviation from vertical line and movement speed of suspension point. Herewith, we do not use imitation modeling which takes a lot of time. The synthesis is carried out by regression equations. Regression models, which are analogous to presented, can be in real-time regime and can be used in the systems of automatic direction OC.

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