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Optimization of the Unloading Bridge Working Cycle

Ugljesa Bugaric* - Josif Vukovic - Dusan Petrovic - Zorana Jeli - Zoran Petrovic
University of Belgrade, Faculty of Mechanical Engineering, Serbia

This paper presents one of the possible ways of optimization of unloading bridge working cycle i.e. minimization of: energy consumption, material dissipation during the grab discharging, rope incline angle etc. Optimization procedure of the working cycle is divided into two phases, first optimization of the cargo and grab movement and second determination of the unloading bridge mechanisms movement upon obtained optimum path and parameters of cargo and grab movement. The developed mathematical model enables direct application of optimum control theory methods i.e. optimization of the cargo and grab movement is determined using Pontryagin's maximum principle. All relevant expressions are derived analytically. Repeatable and optimum unloading cycle is necessary for calculation of the real capacity of unloading device which is the base for calculation of energy consumption, exploitation cost, etc.

Keywords: optimization, working cycle, unloading bridge, maximum principle

0 INTRODUCTION

Terminal for bulk cargo unloading presents the organization of different activities, connected with control and handling of material flow from the vessel to the transport or the storage system. The main task of the terminal for bulk cargo unloading is to provide maximum servicing of vessels with minimum of expenses.

Unloading devices present knot points of unloading terminals, and in most cases are the bottle necks, so their functioning is the basic prerequisite for optimum work of the whole unloading system.

Unloading (working) cycle of unloading devices with grab i.e. unloading bridge consist of: material grabbing from the vessel, grab and cargo transfer from the vessel to the receiving hopper, grab discharging and empty grab return transfer from the receiving hopper to the vessel. Full automation of unloading process of the unloading bridge facilities with grab, is possible but it is very expensive. Manual unloading process is not acceptable because crane operator can not repeat the optimum unloading cycle in the longer time period.

The only practical feasible solution is to introduce the half-automatic unloading cycle which consists of the manual part, where the crane operator control the grab moving, and of the automatic part in which the computer controls the grab moving according to the given algorithm.

Manual part of half-automatic unloading cycle consists of the empty grab lowering to the material surface in the vessel, from one of the three points of the end of automatic part of the unloading cycle (Fig. 1.), material grabbing and grab hoisting with cargo to one of the three points of the beginning of automatic part of the unloading cycle. Position of three points, which presents beginning/end of automatic part of half-automatic unloading cycle is virtual and depends on given geometry of system, river water level, material level in the vessel, etc. [3]

Automatic part of half-automatic unloading cycle consists of grab transfer from one of the three points of the beginning of automatic part of the unloading cycle to the receiving hopper, grab discharging and empty grab return transfer from the hopper to the one of the three possible points of the end of automatic part of the unloading cycle.

Main conditions and boundaries which should be taken into consideration in optimization of the half-automatic unloading cycle are: geometrical features of the system (dimensions of the vessel, level of material in the vessel, configuration of the operative coast, geometry of the crane), technical performances of the system (hoisting and travelling velocity and acceleration,

*Corr. Author's Address: University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade 35,Serbia, ubugaric@mas.bg.ac.yu

stress on crane construction), natural phenomena (river water level, wind) etc.

The aim of the work is to obtain optimum half-automatic unloading cycle based on real physical conditions and boundaries. Optimum half-automatic unloading cycle means optimum unloading path (minimum number of oscillations and minimum rope incline angle of the grab and cargo; avoiding of the obstacles i.e. geometric boundaries of the system, positioning of the grab and cargo at the end of the deceleration period, exactly over the hopper for easy grab discharging and in the one of three possible points of the beginning/end of the automatic part of the movement, without swinging), minimum dissipation of material and therefore minimum spending of energy needed for unloading bridge mechanisms movement.

Optimization is done in order to determine feasible unloading capacity of the system (feasible unloading cycle time which can be repeated in time). Cycle time must be plausible and known in advance according to the technical parameters of the system, details given in [1] and [5]. Calculation of the cycle duration for existing system, will be given in the chapter 5.

1 METHODOLOGY

Methodology applied in this paper consists of:

- Mathematical model of the bulk cargo unloading device with grab including defined boundary conditions and control values, based on theoretical and experimental values.
- Optimization of the grab and cargo movement in the automatic part of the half-automatic unloading cycle, of any unloading device using Pontryagin`s maximum principle. It is divided in two parts. First part – optimization of the grab and cargo movement as pendulum, second part – optimum movement of the unloading device mechanisms.
- Obtaining of the half-automatic unloading cycle duration based on shown procedure.

Proposed methodology is applied for the optimization of the bridge crane unloading cycle at the existing unloading terminal in Prahovo port on Danube river, Serbia. All relevant technical data needed for modeling of the bridge crane are obtained from the existing devices. Empirical data, gained from the real system (existing unloading terminal) are introduced in the result section of the paper [1] and [7].

1.1. Mathematical Model of the Unloading Bridge

Analyzed unloading bridge is in fact a gantry crane with cantilever on both sides. Crane construction consists of two box girders with rails for single trolley on top.

Simplified scheme of the unloading bridge is shown on Figure 1.

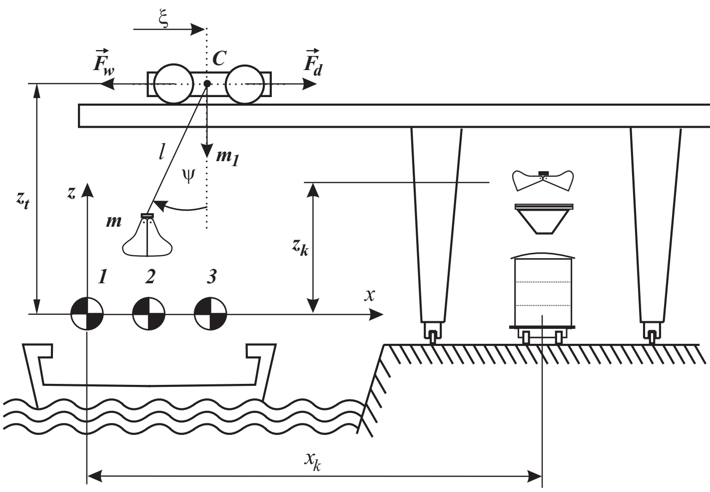

Fig. 1. *Simplified scheme of the unloading bridge*

Generalized coordinate is: ξ - instantaneous center of gravity (C) position of the crane trolley. Review of indications used in the mathematical model: ψ - rope angle, g - gravity acceleration, m - grab and cargo mass, x_k - distance between vessel and hopper, z_k - height distance between beginning/end point of automatic part of half-automatic unloading cycle and discharging point of the grab, z_t - height distance between beginning/end point of automatic part of half-automatic unloading cycle and rope suspension point, m_1 - mass of the crane trolley, l - instantaneous rope length, F_d – driving force of trolley, F - force in the rope, F_w - resistance force of motion [5]:

$$F_w = (F\cos\psi + m_1 g)\cdot(2f + \mu d)\cdot\beta / D_w ,$$

where: d - the journal diameter, D_w - diameter of the trolley wheel, μ - coefficient of friction for the wheel bearing refereed to the axle journal, f - coefficient of rolling friction, β - flange friction factor (caused by trolley skewing).

Differential equation which describes movement of unloading bridge trolley is:

$$m_1\ddot{\xi} = F_d - F_w - F\sin\psi , \tag{1}$$

where:

$$\xi = x + l\cdot\sin\psi ,$$

$$l = (z_t - z)/\cos\psi \quad \text{i.e.} \quad \xi = x + (z_t - z)\cdot tg\psi$$

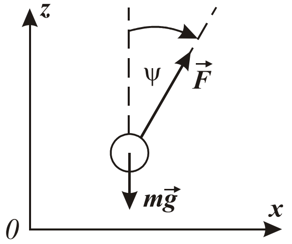

Fig. 2. *Forces which act on the grab and cargo*

Movement of the grab and cargo is suitable to analyze in the coordinate system x-z (Fig. 2). At the beginning of the movement grab and cargo are at point 0. In that case differential equations which describe movement of grab and cargo are:

$$m\ddot{x} = F\sin\psi,\; m\ddot{z} = F\cos\psi - mg,\; \frac{F}{m} = S,$$
$$\ddot{x} = S\sin\psi,\; \ddot{z} = S\cos\psi - g, \tag{2}$$

Grab and cargo, for time interval known in advance [0, t_c], from initial state:

$$t = 0,\; x(0) = 0;\; \dot{x}(0) = 0;$$
$$z(0) = 0;\; \dot{z}(0) = 0; \tag{3}$$

should came to ending state:

$$t = t_c,\quad x(t_c) = x_k;\quad \dot{x}(t_c) = 0;$$
$$z(t_c) = z_k;\quad \dot{z}(t_c) = 0; \tag{4}$$

with limitation that grab and cargo should pass through point ($x_k/2$, z_k), defined by system geometry (generally position in x – direction is arbitrary), and after that continue to move horizontaly i.e.

$$x(\tau) = x_k/2;\quad z(\tau) = z_k;\quad z(\tau \le t \le t_c) = z_k , \tag{5}$$

where moment of time τ is not known in advance.

If such functions $\psi(t)$, $S(t) > 0$ can be found, together with following conditions:

$$\psi(0) = 0;\quad \dot{\psi}(0) = 0;\quad S(0) = g$$
$$\psi(t_c) = 0;\quad \dot{\psi}(t_c) = 0;\quad S(t_c) = g, \tag{6}$$

in a way that appropriate solutions of equations (2) fulfills conditions (3), (4) and (5), the whole system can be controlled.

By increasing the order of differential equations (2) those equations can be written as:

$$\dddot{x} = \dot{S}\sin\psi + S\dot{\psi}\cos\psi$$
$$\dddot{z} = \dot{S}\cos\psi - S\dot{\psi}\sin\psi \tag{7}$$

and conditions (6) can be written as:

$$\ddot{x}(0) = 0;\quad \dddot{x}(0) = 0;\quad \ddot{z}(0) = 0;$$
$$\ddot{x}(t_c) = 0;\quad \dddot{x}(t_c) = 0;\quad \ddot{z}(t_c) = 0. \tag{8}$$

In that way task of controlled movement of the grab and cargo can be stated in a following form:

$$x^{IV} = u_x,\quad z^{IV} = u_z \tag{9}$$

$$x(0)=0;\quad \dot{x}(0)=0;\quad \ddot{x}(0)=0;\quad \dddot{x}(0)=0;$$
$$z(0)=0;\quad \dot{z}(0)=0;\quad \ddot{z}(0)=0;$$
$$x(t_c)=x_k;\quad \dot{x}(t_c)=0;\quad \ddot{x}(t_c)=0;\quad \dddot{x}(t_c)=0;$$
$$z(t_c)=z_k;\quad \dot{z}(t_c)=0;\quad \ddot{z}(t_c)=0;$$
$$x(\tau)=x_k/2;\quad z(\tau)=z_k;\quad z(\tau \le t \le t_c)=z_k \tag{10}$$

where u_X and u_Z are allowed values of control which belongs to open set.

Initial condition for $\dddot{z}$ is not set in order to ensure movement in z - direction at the beginning of the movement, while final condition for $\dddot{z}$ is automatically fulfilled due to transverse condition.

According to (2) and (7) equations (9) and conditions (10) are equivalent with equations (2) and conditions (3), (4), (5) and (6).

Optimization of the unloading bridge working cycle is divided in two parts. First part –

optimization of the grab and cargo movement as pendulum, second part – optimum movement of the unloading device mechanisms.

1.2 First Part of Optimization - Optimization of the Grab and Cargo Movement

First part of optimization assumes optimization of the grab and cargo movement (i.e. pendulum), automatic part of the half-automatic unloading cycle, independently from unloading device (bridge crane) mechanisms with respect to equations (9) and conditions (10).

By introducing new variables y_i (i=1 to 8) system (9) and conditions (10) can be written in the following form:

$$\dot{y}_1 = y_2;\ \dot{y}_2 = y_3;\ \dot{y}_3 = y_4;\ \dot{y}_4 = u_x;$$
$$\dot{y}_5 = y_6;\ \dot{y}_6 = y_7;\ \dot{y}_7 = y_8;\ \dot{y}_8 = u_z \tag{11}$$

$$\begin{aligned}&y_1(0)=0; \quad y_2(0)=0; \quad y_3(0)=0; \quad y_4(0)=0;\\ &y_5(0)=0; \quad y_6(0)=0; \quad y_7(0)=0;\\ &y_1(t_c)=x_k; \quad y_2(t_c)=0; \quad y_3(t_c)=0; \quad y_4(t_c)=0;\\ &y_5(t_c)=z_k; \quad y_6(t_c)=0; \quad y_7(t_c)=0;\\ &y_1(\tau)=x_k/2; \quad y_5(\tau)=z_k; \quad y_5(\tau\le t\le t_c)=z_k;\end{aligned} \tag{12}$$

which allowed direct application of Pontryagin's maximum principle. Values u_x and u_z are control values in x and z direction [2], [4] and [7].

During the grab and cargo transfer from vessel to hopper and vice versa minimum rope incline angle as well as no more than one oscillation of the grab and cargo are required. Beside that, changes in rope load as a result of grab and cargo transfer should be reduced to a minimum. In that sense condition of optimality (13) presents good enough measure of behavior of those values.

$$J = \int_0^{t_c} \frac{1}{2}\left(y_3^2 + y_4^2 + u_x^2 + y_8^2\right)dt \to \infty \tag{13}$$

Differential equations (11) and conditions (12) together with condition of optimality (13) presents the task of optimum control.

In another words, on the basis of equation system (2), it can be concluded that rope inclination and angular velocity of rope have greater influence on movement in ***x***–direction i.e. on values y_3, y_4, and u_x while change of rope load has greater influence on movement in z - direction i.e. on value y_8. So, minimum value of (13) fulfills required demands and represents optimality criterion for discussed problem and it provides that the values of control and rope incline angle not become so big, minimum number of oscillations, continuousness of the force in rope, uniform work, etc.

The problem defined by the relations (11), (12) and (13) is reduced to the form which makes possible the direct application of maximum principle. For these reasons, considering (11) and (13) the function is established:

$$\begin{aligned}H = &-\frac{1}{2}\left(y_3^2 + y_4^2 + u_x^2 + y_8^2\right) +\\ &+ \lambda_1 y_2 + \lambda_2 y_3 + \lambda_3 y_4 + \lambda_4 u_x +\\ &+ \lambda_5 y_6 + \lambda_6 y_7 + \lambda_7 y_8 + \lambda_8 u_z\end{aligned} \tag{14}$$

where the values λ_i satisfied the differential equations system:

$$\dot{\lambda}_i = -\frac{\partial H}{\partial y_i}\ (i = 1 \text{ to } 8),$$

$$\dot{\lambda}_1 = 0;\ \dot{\lambda}_2 = -\lambda_1;\ \dot{\lambda}_3 = y_3 - \lambda_2;\ \dot{\lambda}_4 = y_4 - \lambda_3;$$
$$\dot{\lambda}_5 = 0;\ \dot{\lambda}_6 = -\lambda_5;\ \dot{\lambda}_7 = -\lambda_6;\ \dot{\lambda}_8 = y_8 - \lambda_7. \tag{15}$$

According to the theorem of the principle of maximum, function (14) for the optimum solution has the maximum value. According to the needed condition of extreme:

$$\frac{\partial H}{\partial u_x} = 0 \text{ and } \frac{\partial H}{\partial u_z} = 0, \tag{16}$$

the controls in x and z direction are obtained:

$$-u_x + \lambda_4 = 0 \quad \to u_x = \lambda_4;$$
$$\lambda_8 = 0 \quad \to \dot{\lambda}_8 = 0 \quad \to y_8 = \lambda_7. \tag{17}$$

Following transverse conditions should be added to conditions (12):

$$\lambda_8(0) = 0; \qquad \lambda_8(t_c) = 0,$$

what is trivially fulfilled in (17).

Structure of differential equation systems (11) and (15) shows that optimization of grab and cargo movement in x and z direction can be done separately. System of differential equations for optimization grab and cargo movement in x direction has the following form:

$$\begin{aligned}&\dot{y}_1 = y_2; \quad \dot{y}_2 = y_3;\\ &\dot{y}_3 = y_4; \quad \dot{y}_4 = \lambda_4;\\ &\dot{\lambda}_1 = 0; \quad \dot{\lambda}_2 = -\lambda_1;\\ &\dot{\lambda}_3 = y_3 - \lambda_2; \quad \dot{\lambda}_4 = y_4 - \lambda_3.\end{aligned} \tag{18}$$

Boundary conditions are:

$$t = 0,$$
$$y_1(0) = 0 \;;\; y_2(0) = 0 \;;$$
$$y_3(0) = 0 \;;\; y_4(0) = 0 \;;$$
$$t = t_c,$$
$$y_1(t_c) = x_k \;;\; y_2(t_c) = 0 \;;$$
$$y_3(t_c) = 0 \;;\; y_4(t_c) = 0. \qquad (19)$$

System of differential equations for optimization grab and cargo movement in z direction has the following form:

$$\dot{y}_5 = y_6;\; \dot{y}_6 = y_7;\; \dot{y}_7 = y_8;\; \dot{y}_8 = -\lambda_6;$$
$$\dot{\lambda}_5 = 0 \;;\; \dot{\lambda}_6 = -\lambda_5;\; \dot{\lambda}_7 = -\lambda_6;\; \dot{\lambda}_8 = 0. \qquad (20)$$

Boundary conditions are:

$$t = 0,\; y_5(0) = 0 \;;\; y_6(0) = 0 \;;$$
$$y_7(0) = 0 \;;\; \lambda_8(0) = 0 \;;$$
$$t = \tau,\; y_5(\tau) = z_k;\; y_6(\tau) = 0 \;;$$
$$y_7(\tau) = 0 \;;\; \lambda_8(\tau) = 0;$$
$$\tau \le t \le t_c \;\; y_5(\tau) = z_k;\; y_6(t) = 0 \;;$$
$$y_7(t) = 0 \;;\; \lambda_8(t) = 0 \,. \qquad (21)$$

Each of differential equations systems (18) and (20) defined on this way, with condition (19) and (21) presents the two-point boundary value problem. Due to configuration of the differential equation systems (18) and (20) each of them can be solved analytically [4].

1.2.1 Analytical Solutions

According to differential equation systems (11) and (18) following relations can be established: (movement in x - direction)

$$u_x = \lambda_4, \quad \lambda_1 = L_1,$$
$$\lambda_2 = -L_1 t + L_2,$$
$$\lambda_3 = y_2 + \frac{1}{2} L_1 t^2 - L_2 t + L_3,$$

$$\lambda_4 = y_3 - y_1 - \frac{1}{6} L_1 t^3 + \frac{1}{2} L_2 t^2 - L_3 t + L_4,$$
$$\dot{y}_4 = \dot{y}_2 - y_1 = -\frac{1}{6} L_1 t^3 + \frac{1}{2} L_2 t^2 - L_3 t + L_4 \,.$$

Finally, differential equation system (18) can be reduced to one fourth order differential equation:

$$y_1^{IV} - \ddot{y}_1 + y_1 = -\frac{1}{6} L_1 t^3 + \frac{1}{2} L_2 t^2 - L_3 t + L_4 \,, \qquad (22)$$

where L_1 to L_4 are arbitrary constants.

Solution of above differential equation has the following form:

$$y_1 = x = (A_1 e^{\sqrt{3}t/2} + B_1 e^{-\sqrt{3}t/2})\cos(t/2) + (C_1 e^{\sqrt{3}t/2} + D_1 e^{-\sqrt{3}t/2})\sin(t/2) + E_1 t^3 + F_1 t^2 + G_1 t + H_1 \;, \qquad (23)$$

Differentiating previous expression per t expressions for y_2 to y_4 are obtained as:

$$y_2 = \dot{x} = 0.5\Big[\sqrt{3}(-B_1 + A_1 e^{\sqrt{3}t})\cos(t/2) + (D_1 + C_1 e^{\sqrt{3}t})\cos(t/2) - (B_1 + A_1 e^{\sqrt{3}t})\sin(t/2) + \sqrt{3}(-D_1 + C_1 e^{\sqrt{3}t})\sin(t/2)\Big] e^{-\sqrt{3}t/2} + 3E_1 t^2 + 2F_1 t + G_1 \,, \qquad (24)$$

$$y_3 = \ddot{x} = 0.5\Big[(B_1 + A_1 e^{\sqrt{3}t})\cos(t/2) + \sqrt{3}(-D_1 + C_1 e^{\sqrt{3}t})\cos(t/2) + \sqrt{3}(B_1 - A_1 e^{\sqrt{3}t})\sin(t/2) + (D_1 + C_1 e^{\sqrt{3}t})\sin(t/2)\Big] e^{-\sqrt{3}t/2} + 6E_1 t + 2F_1 \qquad (25)$$

$$y_4 = \dddot{x} = \Big[D_1 \cos(t/2) + C_1 e^{\sqrt{3}t}\cos(t/2) - A_1 e^{\sqrt{3}t}\sin(t/2) - B_1 \sin(t/2)\Big] e^{-\sqrt{3}t/2} + 6E_1 \qquad (26)$$

$$\dot{y}_4 = x^{IV} = u_x = 0.5\Big[-(B_1 + A_1 e^{\sqrt{3}t})\cos(t/2) + \sqrt{3}(-D_1 + C_1 e^{\sqrt{3}t})\cos(t/2) + \sqrt{3}(B_1 - A_1 e^{\sqrt{3}t})\sin(t/2) - (D_1 + C_1 e^{\sqrt{3}t})\sin(t/2)\Big] e^{-\sqrt{3}t/2} \qquad (27)$$

where A_1, B_1, C_1, D_1, E_1, F_1, G_1, H_1 are constants which are determined upon boundary conditions (3) and (4).

For movement in z - direction according to differential equation systems (11) and (20) following relations can be established:

$$u_z = -\lambda_6, \quad \lambda_5 = L_5,$$
$$\lambda_6 = -L_5 t + L_6, \quad \dot{y}_8 = \dot{\lambda}_7,$$
$$\dot{y}_8 = -\lambda_6 \;, \quad \dot{y}_8 = L_5 t - L_6$$

where L_5 and L_6 are arbitrary constants.

Substituting (L_5, $-L_6$) with (A_2, B_2) the required expressions for movement in z –direction are obtained as:

$$\dot{y}_8 = z^{IV} = u_z = A_2 t + B_2 \tag{28}$$

$$y_8 = \dddot{z} = \frac{1}{2} A_2 t^2 + B_2 t + C_2 \tag{29}$$

$$y_7 = \ddot{z} = \frac{1}{6} A_2 t^3 + \frac{1}{2} B_2 t^2 + C_2 t + D_2$$

$$y_6 = \dot{z} = \frac{1}{24} A_2 t^4 + \frac{1}{6} B_2 t^3 + \frac{1}{2} C_2 t^2 + D_2 t + E_2 \tag{30}$$

$$y_5 = z = \frac{1}{120} A_2 t^5 + \frac{1}{24} B_2 t^4 + \frac{1}{6} C_2 t^3 + + \frac{1}{2} D_2 t^2 + E_2 t + F_2 \tag{31}$$

where A_2, B_2, C_2, D_2, E_2, F_2 are constants which are determined upon boundary conditions (12).

Directly from differential equation system (2) expressions for Ψ and S are obtained as:

$$\psi = arctg \frac{\ddot{x}}{\ddot{z} + g}, \quad S = \sqrt{\ddot{x}^2 + (\ddot{z} + g)^2}\ . \tag{32}$$

1.3. Optimum Movement of the Unloading Bridge Mechanisms (Trolley)

Driving force F_d, needed for trolley movement, due to relatively less complex construction of unloading bridge, can be determined directly from differential equation (1) on the basis of obtained optimum grab and cargo movement given by expressions (23´to (32) as a direct task of dynamics from following expression:

$$F_d = m_1 \cdot \frac{d^2}{dt^2} \left[x + (z_t - z) \cdot \frac{\ddot{x}}{\ddot{z} + g} \right] + + F_w + F \cdot \sin\psi \tag{33}$$

2 RESULTS

Results of the derived mathematical model are differential equations of unloading bridge trolley motion, along with boundary conditions and controlled values. Results of the first part of the optimization are optimum motion of the grab and cargo during automatic part of the cycle, represented by velocity, acceleration, jerk and control values (in x and z direction), inclination angle, angular velocity. Output values from first part of optimization are input values for second part of optimization. Results of the second part of the optimization is needed driving force for obtaining optimum unloading bridge trolley motion and change of the rope length per time. All obtained results are presented on Fig. 3 to 5.

Figure 3 show results of grab and cargo optimization process per time. Those results are: change of coordinates x and z per time (Fig. 3a), change of grab and cargo velocity in x and z direction per time ($\dot{x}$, $\dot{z}$ Fig. 3b), change of grab and cargo acceleration in x and z direction per time ($\ddot{x}$, $\ddot{z}$ Fig. 3c), change of grab and cargo jerk in x and z direction per time ($\dddot{x}$, $\dddot{z}$ Fig. 3d), change of grab and cargo control in x and z direction per time ($x^{IV} = u_x$, $z^{IV} = u_z$ Fig. 3e), change of rope incline angle ψ and angular velocity $\dot{\psi}$ of grab and cargo per time (fig. 3f); change of force in the rope F/m i.e. S per time (Fig. 3g); and optimum path of grab and cargo $z = F(x)$ (Fig. 3h).

Values, upon which results shown on figure 3 are obtained, are: distance between vessel and hopper in x - direction $x_k = 9m$, distance between vessel and hopper in z - direction $z_k = 8m$, $t_c = 20s$ - time, known in advance, needed for obtaining one half of automatic part of half–automatic unloading cycle i.e. grab transfer from vessel to hopper or vice versa, t_c is determined upon maximum allowed velocities and accelerations in x and z direction [1] and $\tau = x^{-1}(x_k/2)$ - time needed for grab and cargo transfer to one half of distance between vessel and hopper i.e. $z(\tau \le t \le t_c) = z_k$.

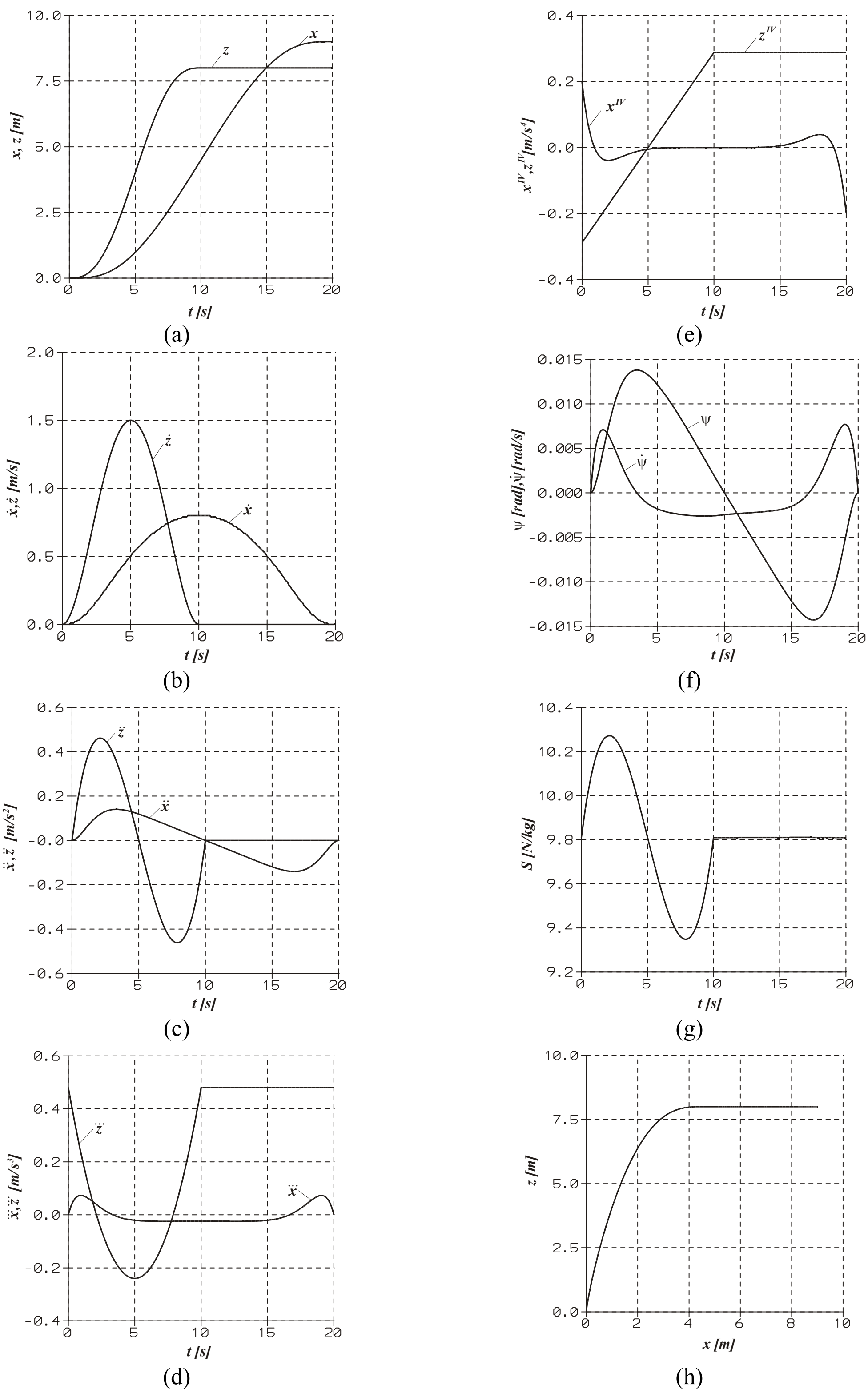

Fig. 3. *Change of the optimised values*

Numerical values needed for calculation of the driving force F_d from expression (33) are following: diameter of the trolley wheel, D_w = 0.4m, the journal diameter d = 0.1m, coefficient of friction for the wheel bearing refereed to the axle journal $\mu = 0.012$, coefficient of rolling friction f = 0.05cm, flange friction factor β = 2.3, height distance between beginning/end point of automatic part of half-automatic unloading cycle and rope suspension point z_t = 17m, mass of the crane trolley m_1 =15000kg, mass of the grab and cargo m = 12500 kg. Result is shown on the Figure 4, while change of the rope length is shown on the Figure 5.

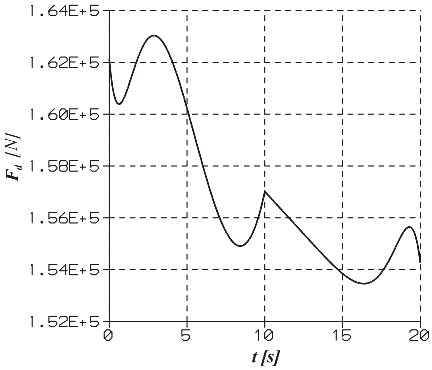

Fig. 4. *Driving force needed for optimum unloading bridge trolley movement*

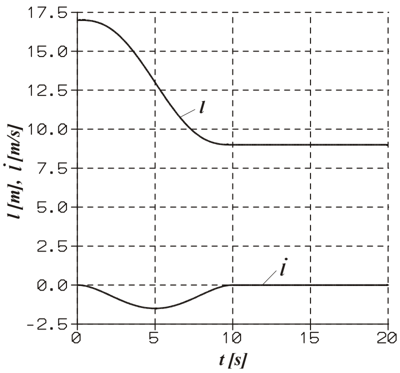

Fig. 5. *Change of the rope length per time*

3 DISCUSSION

Using all obtained results from previous chapters, together with empirical data obtained from real system, makes possible to define duration of the working cycle. All obtained results (velocity, acceleration and jerk) are real and in the range of the suggested values for this type of unloading devices. [6]

3.1. Working Cycle Duration

Duration of half-automatic working (unloading) cycle consist of following times needed for complete certain operations: [1]

– automatic part of half automatic unloading cycle:

$$t_{ac} = 2\,t_c + t_{gd} = 2 \cdot 20 + 8 = 48\,s$$

where t_{gd} = 8s is time needed for grab discharging.

– manual part of half-automatic unloading cycle:

$$\begin{aligned} t_{mc} &= t_{gl} + t_{gc} + t_{gh} + t_e = \\ &= (1.2 \div 7.2) + 15 + (1.2 \div 7.2) + 5 = \\ &= (22.4 \div 34.4)\,s \end{aligned}$$

where:

t_{gl} = (1.2 to 7.2)s - time for grab lowering from one of three possible points of ending of automatic part of unloading cycle to material in the vessel with velocity 50 m/min. Lowering distance depends on water level and vary between 1 and 6m,

t_{gc} = 15s - time needed for grab closing,

t_{gl} = (1.2 to 7.2)s - time for grab hoisting from material in the vessel to one of three possible points of beginning of automatic part of unloading cycle with velocity 50 m/min. Hoisting distance depends on water level and vary between 1 and 6m,

t_e = 5s - extra time needed for crane operator to locate the most suitable place for grabbing.

Finally duration of working cycle is:

$$\begin{aligned} t_{uc} &= t_{ac} + t_{mc} = \\ &= 48 + (22.4 \div 34.4) = \\ &= (70.4 \div 82.4)\,s. \end{aligned}$$

Repeatable and optimum unloading cycle (in the sense explained in Chapter 1) is necessary for calculation of the real capacity of unloading device which is the base for calculation of energy consumption, exploitation cost, etc.

4 CONCLUSIONS

The characteristic of bulk cargo is the fact that the transport expenses, manipulation and waiting present the important part of their values. Unloading bulk cargo terminal works 24 hours seven days a week during the sailing period. Presented optimized working cycle of unloading bridge reduces rope inclination angle, force in a rope and therefore needed energy for performing such kind of motion.

Application of the obtained results is in introducing of the half automatic unloading cycle during the bulk cargo material unloading. In that case it is possible to achieve the optimum unloading cycle, dissipation of material during the grab discharging can be reduced to the minimum, dynamic stress of cranes can be smaller and it is also possible to eliminate influence of the human factor in unloading process (training of operator, weather conditions, night work, etc.).

It is important to underline that developed optimization procedure for grab and cargo movement has universal application i.e. results of optimization process can be applied on any transport device which can perform such kind of motion (harbor cranes, overhead cranes etc.).

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