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ESTIMATION OF BULKY OBJECT MOTION PARAMETERS BY MEANS OF THE LEAST SQUARES METHOD

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Abstract*—The article is dedicated to research of identification procedure efficiency of model parameter and a selection of optimal coefficients values that emerge during the launching and lifting ships. Solving the problems of operational control optimization of such shipbuilding equipment as a slipway is presented.*

Index Terms—Adaptive control system; least squares method; operational control; parameters estimation; slipway; ship lifting complex, process of moving the vessel.

I. INTRODUCTION

The process of moving the vessel at the slipway occurs under the influence of nonstationary external factors, which vary significantly during all way [1]. The main task is to provide evenly motion of a complex object (the ship and special carts) and guaranteed prevention of emergencies.

Ensuring proper safety and reliability of multi-drive system functioning is possible due to further automation of ship lifting complex by implementing a computerized control system [2]. At the operational control of the process of moving the ship on the slipway is necessary to take into account changes in both external and internal factors. For generating a control of electric-drive carts connected by common object (the hull), it is advisable to use adaptive control methods [3].

II. PROBLEM STATEMENT

Factors that affect at the ship lifting complex operation, essentially depends on the location of ship cart on slipway l. The process of moving ship at slipway can divided into several stages, depending on external factors changes (Fig. 1).

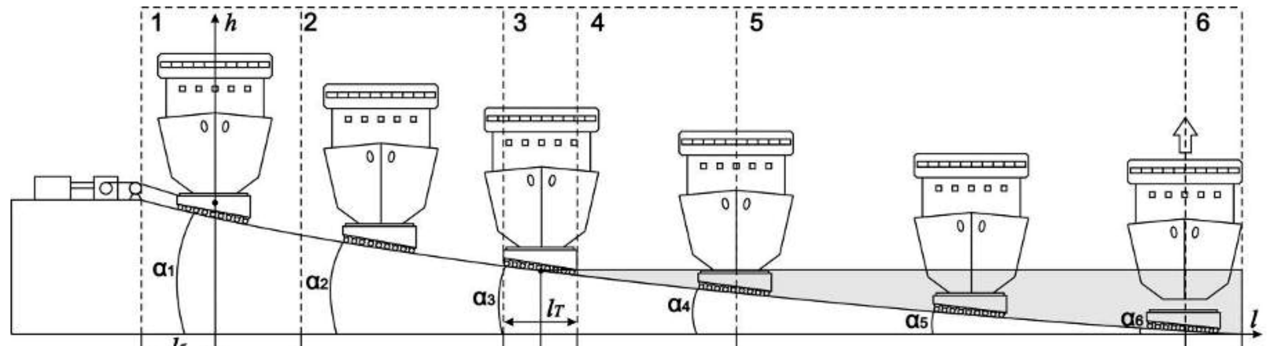

Fig. 1. Stages of ship descent and lifting using the slipway

Stages of ship motion in Fig. 1 are: 1 – movement of the ship cart with acceleration until the required constant speed is reached – $l \in [0, l_1]$; 2 – ship cart movement with constant speed until the entrance into the water – $l \in [l_1, l_2]$; 3 – movement of the ship cart from above water part of slipway into the it's underwater part – $l \in [l_2, l_3]$; 4 – ship cart complete immersion under water – $l \in [l_3, l_4]$; 5 – movement of the ship cart with constant speed in the water until the ship emersion – $l \in [l_4, l_5]$; 6 – ship emersion and carts deceleration until its stop – $l \in [l_5, l_6]$.

The linearized equations of the mathematical model of the ship moving process, as shown in [4], can be written in vector-matrix form

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}, \quad \vec{y} = \mathbf{C}(k) \cdot \vec{x}, \qquad (1)$$

where $\mathbf{x} = (x_1, x_2, x_3, x_4)^{\mathrm{T}}$, $x_1 = l$ is the location of the ship's center of mass; $x_2 = v$ is the translational

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velocity of the center of mass; $x_3 = \varphi$ is the rotation angle of the ship; $x_4 = \omega$ is the rotational speed of the ship.

Matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ have permanent structure, but can change depending on the system operation conditions, and have the form

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ a_{21} & 0 & a_{23} & 0 \\ 0 & 0 & 0 & 1 \\ a_{41} & 0 & a_{43} & 0 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ K_1 & K_1 & \cdots & K_1 \\ 0 & 0 & \cdots & 0 \\ q_1 K_2 & q_2 K_2 & \cdots & q_N K_2 \end{pmatrix}, \quad \mathbf{C}(k) = \begin{pmatrix} 1 & 0 & q_1 & 0 \\ 1 & 0 & q_n & 0 \end{pmatrix}, \quad (2)$$

where $K_1 = -T_m / m$, $K_2 = T_m / J$ are scale factors; $q_i = (k - i)\Delta z + dz$, $i = \overline{1,n}$ is the distance between the point of rotation and the ith carts center; elements of the matrix $\mathbf{C}$ depends to the structure of the measurement system; coefficients a_{21}, a_{23}, a_{41}, a_{43} depend on the values of components x_{1s}, x_{3s} of the object's stable state vector $\mathbf{x}_s = (x_{1s}, \ldots, x_{4s})^{\mathrm{T}}$ and defined as

$$a_{21} = \frac{1}{m}\sum_{i=1}^{N}\left[\left(x_{1s} + q_i x_{3s}\right)\left[\rho g\left(\frac{V_{\text{тm}}\delta_{24} fe_{24}}{(1+fe_{24})^2} + \frac{V_{cm} fe_{45}}{(1+fe_{45})^2}\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right)\right.\right.$$
$$\left.-\left(\frac{(\mu_1-\mu_2)\delta_{23} fe_{23}^{-1}\cos\alpha}{1+fe_{23}^{-1}}\right)\cdot\left((m_{\text{т}} + m_c)g - \rho g\left(\frac{V_{\text{тm}}}{1+fe_{24}} + \frac{V_{cm}}{1+fe_{45}}\right)\right)\right]$$
$$\left.+\left((m_{\text{т}} + m_c)g - \rho g\left(\frac{V_{\text{тm}}}{1+fe_{24}} + \frac{V_{cm}}{1+fe_{45}}\right)\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right)\right],$$

$$a_{23} = \frac{1}{m}\sum_{i=1}^{N} q_i g\left((m_{\text{т}} + m_c) - \rho\left(\frac{V_{\text{тm}}\delta_{24} fe_{24}}{(1+fe_{24})^2} + \frac{V_{cm} fe_{45}}{(1+fe_{45})^2}\right)\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right),$$

$$a_{41} = K_2\sum_{i=1}^{N}\left[\left(x_{1s} + q_i x_{3s}\right)\left[\rho g\left(\frac{V_{\text{тm}}\delta_{24} fe_{24}}{(1+fe_{24})^2} + \frac{V_{cm} fe_{45}}{(1+fe_{45})^2}\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right)\right.\right.$$
$$\left.-\left(\frac{(\mu_1-\mu_2)\delta_{23} fe_{23}^{-1}\cos\alpha}{1+fe_{23}^{-1}}\right)\cdot\left((m_{\text{т}} + m_c)g - \rho g\left(\frac{V_{\text{тm}}}{1+fe_{24}} + \frac{V_{cm}}{1+fe_{45}}\right)\right)\right]$$
$$\left.+\left((m_{\text{т}} + m_c)g - \rho g\left(\frac{V_{\text{тm}}}{1+fe_{24}} + \frac{V_{cm}}{1+fe_{45}}\right)\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right)\right] q_i,$$

$$a_{43} = K_2\sum_{i=1}^{N} q_i^2 g\left((m_{\text{т}} + m_c) - \rho\left(\frac{V_{\text{тm}}\delta_{24} fe_{24}}{(1+fe_{24})^2} + \frac{V_{cm} fe_{45}}{(1+fe_{45})^2}\right)\right)\cdot\left(\sin\alpha - \left(\mu_2 + \frac{(\mu_1-\mu_2)}{1+fe_{23}^{-1}}\right)\cos\alpha\right),$$

where $fe_{ij} = e^{-\delta_{ij}(x_{1s} - l_{ij})}$, $\delta_{ij} = \frac{2}{\Delta_{ij}}\ln\left(\frac{1}{\varepsilon} - 1\right)$ are steepness coefficient transitional areas, $\Delta_{ij} = (l_j - l_i)/2$, ε is the allowable error, $l_{ij} = (l_j + l_i)/2$, $i, j \in \{2, 3, 4, 5\}$.

Optimal control problem is formulated as the problem of rotational motion stabilization (termination) and retention of uniform translational motion [4]. When solving optimal control problem of complex object moving, represented by the model (2), it is required to achieve the functional purpose of a given state with the least possible cost of control resources. The quality of the motion process control without acceleration (i.e., excluding segments of acceleration and braking) is determined by quadratic criterion as

$$\mathbf{J} = \int_{t_0}^{t_f}\left(\Delta\mathbf{x}^{\mathrm{T}}\mathbf{R}\Delta\mathbf{x} + \mathbf{u}^{\mathrm{T}}\mathbf{Q}\mathbf{u}\right)dt \to \min, \quad (3)$$

where $\Delta\mathbf{x} = \mathbf{x} - \mathbf{x}_э$, $\mathbf{x}_э = (x_1 \quad v_э \quad 0 \quad 0)^{\mathrm{T}}$, the weight matrix **R** and **Q** are symmetrical and positively identified.

Limitations on state are

$$0 \le x_2 \le v_m, \quad |x_3| \le \varphi_m, \tag{4}$$

limitations on control are

$$0 \le u_i \le 1 \text{ or } 0 \le T_i \le T_m \tag{5}$$

and boundary conditions are

$$\mathbf{x}(t_0) = \mathbf{x}_0. \tag{6}$$

The optimal control problem of the slipway complex can be formulated as follows: for a given equations of object (2), limitations on the state (4) and control (5), the boundary conditions (6), it is need to define a control $\mathbf{u}^*(t)$ and a phase trajectory $\mathbf{x}^*(t)$, at which the optimality criterion (3) will have a minimum value.

For criterion (3) the optimal regulator is set by expression

$$\mathbf{u}(t) = -\mathbf{F}(t)\Delta\mathbf{x}(t), \ \mathbf{F}(t) = \mathbf{Q}^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{S}(t), \tag{7}$$

where $\mathbf{S}(t)$ is the symmetric and positive definite matrix, which is determined from the Riccati equation [5].

Formation of optimal control by the expression (7) is based on measurement or evaluation variables of the state vector, which can use the optimal observer of the form

$$\dot{\mathbf{x}} = [\mathbf{A} - \mathbf{KC}]\mathbf{x} + \mathbf{Bu} + \mathbf{Ky}. \tag{8}$$

Synthesis of the observer includes definition of such matrix coefficients $\mathbf{K}$, to which the observer is asymptotically stable [5]. For system with constant parameters, stability depends on the location of the characteristic numbers of the matrix $\mathbf{A} - \mathbf{KC}$ (the poles of the observer) on the complex plane.

Operation of adaptive system is based on timely evaluation of the current state of the object (motion parameters and positions) and prognosis of its possible state at the next period of time. This necessitates the existence of an adequate mathematical model of the object.

III. Aim of the Research

The aim of research is to analyze the possibility of using the least squares method for parameters estimation of the bulky object motion in adaptive control system.

IV. Main part

The block diagram of the adaptive control system with observer and regulator for optimum control of ship moving process at the cross slipway shown in Fig. 2.

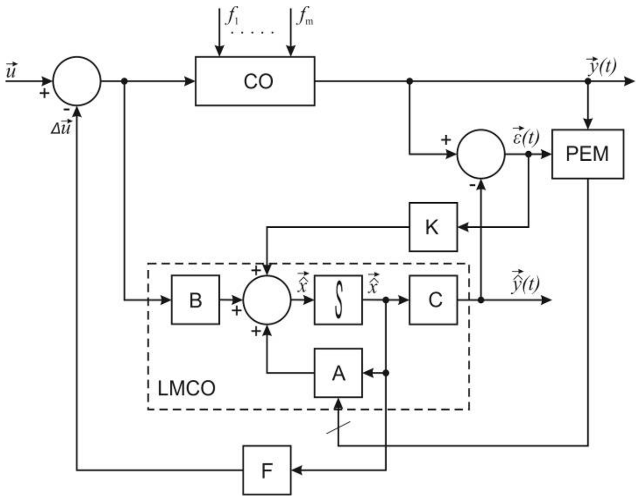

Fig. 2. Block diagram of adaptive control system: CO is the control object; LMCO is the linearized model of control object; PEM are parameters estimation module, which implemented recursive algorithm of matrix **A** identification

The parameters of the linearized model (2) of ship movement, depending on the location point on the slip, take different values due to variability of disturbing factors. Therefore there is a need for timely estimation of the matrix **A** components. Changes in the values of matrix **A** components leads to the need to find new coefficients values of the observer matrix **K** and regulator **F** and then, accordingly, – a new solution of Riccati equation.

The main task in the design of adaptive control systems is the task of configuration the PEM work, as the effectiveness of its work depends on the efficiency of the adaptive control system as a whole throughout the entire process of the ship's moving.

We could write the equations (1) in sampled (finite-difference) form as

$$\begin{cases} x_1[k] = x_1[k-1] + x_2[k-1]\Delta t, \\ x_2[k] = x_2[k-1] + \Delta t\big(a_{21}x_1[k-1] \\ \qquad\qquad + a_{23}x_3[k-1]\big) + b_1[k-1]\Delta t, \\ x_3[k] = x_3[k-1] + x_4[k-1]\Delta t, \\ x_4[k] = x_4[k-1] + \Delta t\big(a_{41}x_1[k-1] \\ \qquad\qquad + a_{43}x_3[k-1]\big) + b_2[k-1]\Delta t, \end{cases} \tag{9}$$

where $b_1[k] = K_1\sum_{i=1}^{N} u_i[k]$ and $b_2[k] = K_2\sum_{i=1}^{N} q_i u_i[k]$ characterize the impact of controls at the step k

(number of iterations which is corresponding to time moment $t_k = k\Delta t$); Δt is the sampling interval; a_{21}, a_{23}, a_{41}, a_{43} are matrix **A** coefficients, which must be found.

The method of least squares can be used to find them [6]:

$$s = \sum \left(x_i^M[k] - x_i^o[k] \right)^2 \to \min, \quad i = \overline{1,4}. \qquad (10)$$

By substituting the equations (9) to (10) and taking the derivative a systems of linear algebraic equations for the unknown coefficients was obtained:

– for a_{21} and a_{23}:

$$\begin{cases} a_{21}\sum_{k=1}^{N}\Delta t^2 x_1^2[k-1] + a_{23}\sum_{k=1}^{N}\Delta t^2 x_1[k-1]x_3[k-1] = \sum_{k=1}^{N}\left(x_2^o[k]-x_2[k-1]\right)\Delta t\, x_1[k-1] - \sum_{k=1}^{N}\Delta t^2 b_1[k-1]x_1[k-1], \\ a_{21}\sum_{k=1}^{N}\Delta t^2 x_1[k-1]x_3[k-1] + a_{23}\sum_{k=1}^{N}\Delta t^2 x_3^2[k-1] = \sum_{k=1}^{N}\left(x_2^o[k]-x_2[k-1]\right)\Delta t\, x_3[k-1] - \sum_{k=1}^{N}\Delta t^2 b_1[k-1]x_3[k-1], \end{cases} \qquad (11)$$

– for a_{41} and a_{43}:

$$\begin{cases} a_{41}\sum_{k=1}^{N}\Delta t^2 x_1^2[k-1] + a_{43}\sum_{k=1}^{N}\Delta t^2 x_1[k-1]x_3[k-1] = \sum_{k=1}^{N}\left(x_4^o[k]-x_4[k-1]\right)\Delta t\, x_1[k-1] - \sum_{k=1}^{N}\Delta t^2 b_2[k-1]x_1[k-1], \\ a_{41}\sum_{k=1}^{N}\Delta t^2 x_1[k-1]x_3[k-1] + a_{43}\sum_{k=1}^{N}\Delta t^2 x_3^2[k-1] = \sum_{k=1}^{N}\left(x_4^o[k]-x_4[k-1]\right)\Delta t\, x_3[k-1] - \sum_{k=1}^{N}\Delta t^2 b_2[k-1]x_3[k-1]. \end{cases} \qquad (12)$$

The procedure of identification can be finished under the conditions

$$\Delta a_{ij}[N] = \left(a_{ij}[N] - a_{ij}[N-1]\right) < \sigma, \quad i = \{2,4\}, \; j = \{1,3\}, \qquad (13)$$

where σ – small value.

Calculations of **A** matrix coefficients were carried out by the following algorithm:

1) Setting initial values of the matrix $\mathbf{A}[0]$.

2) Reading of the experimental values of the object vector states $\mathbf{x}_o[k]$ and the control vector $\mathbf{u}[k]$.

3) Setting initial values of the components of the model vector states $\mathbf{x}_m[0] = \mathbf{x}_o[0]$.

4) Determination of the values of the components of the model vector state $\mathbf{x}_m[k]$ for $k = 1,2,3,\ldots N$ according to (9).

5) Calculation of the **A** matrix components by equations systems (11), (12).

6) Condition check-up (13). If the condition is not satisfied then return to step 2°.

7) End of identification procedure. Transferring of the **A** matrix components into LMCO block.

Modeling of the parameters identification procedure of ship's moving process model was carried out with the following initial data: length of slipway inclined railway lines – 70 m; inclination angle of slipway – 7°; quantity of railway lines with special carts – $n = 10$ units; distance between the centers of ship carts – 8 m; mass of ship – m_c=2000 t; mass of cart – $m_T = 13$ t; total mass of the object – $m = 2130$ t; cable maximum tension – T_m= 320 kN; inertia moment of a complex object "ship and carts" – $J = 1{,}435\cdot 10^9$ kg·m^2; center of mass location – Δz =37.8 m; number for the nearest cart on the left side from the center of rotation – $k = 5$; distance between cart k and the center of rotation– dz = 5.8 m.

Results of the matrix **A** coefficient estimates at different sampling intervals Δt are shown in Fig. 3.

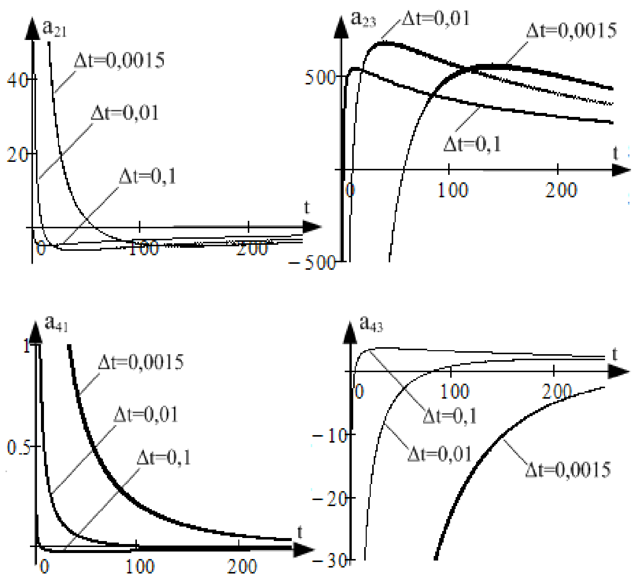

Fig. 3. Dynamics of configuration of the matrix **A** coefficients

The graphs of the dynamics of the components of the system states with $\Delta t = 0.01$ s (line 1) and with

$\Delta t = 0.1$ s (line 2) are shown in Fig. 4. A values obtained by the model with $\Delta t = 0.01$ s are practically identical with the experimental values.

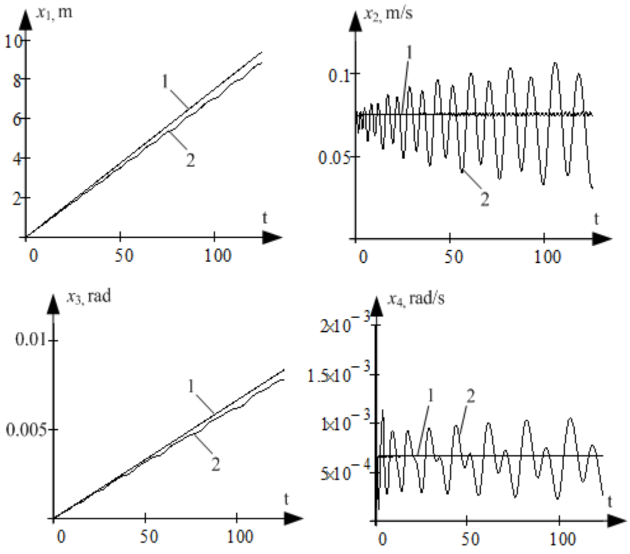

Fig. 4. Graphs of dynamics of the states vector components

Calculations were made with change of Δt in the range 0.001...1, the error (deviation of the calculated values from experimental) was estimated as

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{\left(x_i^{M} - x_i^{o}\right)^2}{\left(x_i^{o}\right)^2}}. \qquad (14)$$

The graphs of the error δ depending on the sampling interval Δt shown in Fig. 5.

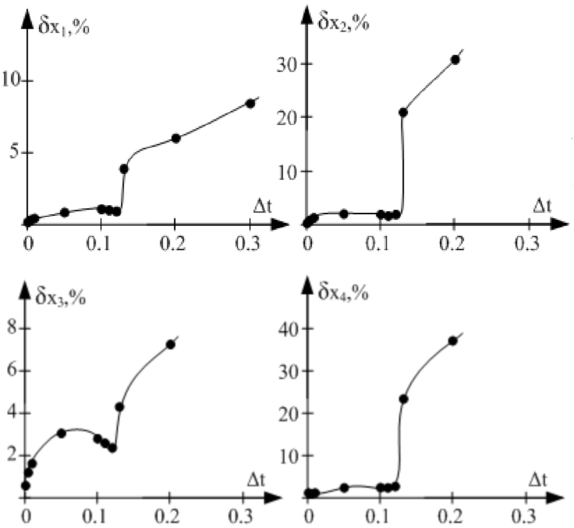

Fig. 5. The graphs of the error depending on the sampling interval

For this example, as seen from the graphs in the Fig. 3, the duration of the identification phase increases significantly by reducing the sampling interval Δt, however, by increasing the $\Delta t > 0.13$ s we can see a dramatic increase of error $\delta > 5\%$ (see Fig. 5). For this example it is advisable to choose a sampling interval $\Delta t = 0{,}1$ s, in this case identification time will be $t_{id} = 80$ s.

If the external conditions of large size object's moving are changed, the identification process must be activated again for the matrix **A** coefficients correction. The condition of identification phase activation is

$$\left|x_i^{M}[k] - x_i^{o}[k]\right| > \varepsilon,\ i = \overline{1,4}. \qquad (15)$$

Determination of time intervals for identification procedure of the model parameters and the choice of optimal values for configuration algorithm coefficients must be made by pre-modeling of adaptive control system of ship's moving process at the slipway based on the specific type of the ship and ship-raising facilities.

V. CONCLUSIONS

Using of least squares method allows getting an adequate estimation of both motion parameters and the model coefficients in real time. The timely identification of the process of moving bulky object is a necessary condition for the effective functioning of the adaptive control system of ship's moving at the slipway. Adaptive control methods allow synthesizing system control whose motion trajectory approaches to a given.

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Г. В. Рудакова, О. В. Поливода, А. А. Омельчук. Оцінювання параметрів руху великогабаритного об'єкту методом найменших квадратів

Досліджено ефективність процедури ідентифікації параметрів і вибору оптимальних значень коефіцієнтів моделі процесу спуску і підйому судна. Наведено вирішення завдання оптимізації оперативного керування суднопідіймальним комплексом типу сліп.

Ключові слова: адаптивна система керування; метод найменших квадратів; оперативне керування; оцінювання параметрів; сліп; суднопідіймальний комплекс; процес переміщення судна.

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А. В. Рудакова, О. В. Поливода, А. А. Омельчук. Оценивание параметров движения крупногабаритного объекта методом наименьших квадратов

Исследована эффективность процедуры идентификации параметров и выбора оптимальных значений коэффициентов модели процесса спуска и подъема судна. Приведено решение задачи оптимизации оперативного управления судоподъёмным комплексом типа слип.

Ключевые слова: адаптивная система управления; метод наименьших квадратов; оперативное управление; оценка параметров; слип; судоподъемный комплекс; процесс перемещения судна.

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