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CONSTRUCTION OF THE MATHEMATICAL MODEL OF THE STRUCTURE OF THE ACTUATOR AND DESIGN OF CONTROL SYSTEM

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Abstract

This article discusses the problem of constructing a mathematical model of an actuator for specifying the shape of the radio-reflective surface of a large-sized space-based reflector using a cable-stayed structure. For large-sized structures deployment in outer space, an important performance indicator is the ability to minimize the resulting vibrations. So, to configure a radio-reflective net, it is necessary to select an actuator and ensure its reliable control that satisfies the conditions of the task. A DC motor is selected as the actuator. Its mathematical model is presented. A solution to the problem of controlling a DC motor is presented based on an algorithm for optimal correction of the parameters of the control structure. The problem of filtering with optimal adjustment of the shape of the radio-reflecting surface of the frontal network of a transformable reflector has been solved. The results of numerical simulation are presented, showing the possibility of using the proposed optimal control algorithm in real time. Recommendations are given for applying the developed algorithm in real devices.

Keywords: Large-sized transformable reflector; Radio-reflective net; DC motor; Optimal control; Simulation; Modeling.

1. Introduction

One of the actively developing approaches to creating space-based reflectors is the creation of large-sized systems [1], [2]. One of the criteria for their operation is the presence of a simple and reliable structure capable of receiving and transmitting signals in various frequency ranges. This requires [3], [4], [5] the presence of a radio-reflective net, maintaining geometric accuracy during operation, minimizing vibrations of the entire structure as a whole and the radio-reflective net in particular [6].

This construction must have a small volume when stowed in the launch vehicle, withstand the overloads that occur when launching a mission into a given orbit, and at the same time have a large working surface during operation [7], [8], [9]. One of the possible solutions to this problem is the use of a cable-stayed structure [10], [11], [12], [13], [14].

Figure 1 shows the spoke 1, the two main radial cords of the back 3 and front 2 nets and the cable 4 between them. From the right end, the spoke 1 is divided into two parts to set the desired shape of the radio-reflecting surface. In each cable 4 there is an actuator 5, for which a DC motor is accepted in this task. DC electric motors are widely used in various fields, including the space industries [15] due to the simplicity of design, low manufacturing cost, ease of control and maintenance.

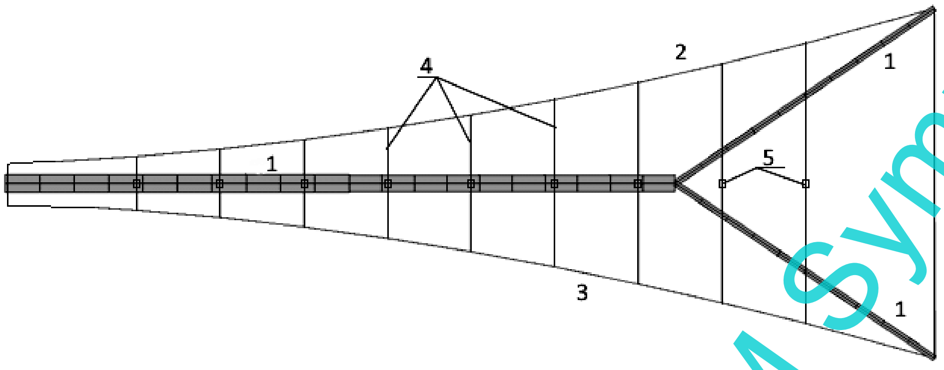

Fig. 1. The scheme of the spokes of the space-based reflector

The following limitations and difficulties should be taken into account when solving the problem of form configuration:

- The energy reserve on a space-based reflector is limited, the question of minimizing energy costs to perform the assigned tasks arises separately
- It is necessary to minimize the vibrations of the entire structure as a whole and of the radio-reflecting net in particular.

The problem solved in this study is to set the shape of the radio-reflecting net, determined by the frontal net 2, by tuning the length of the cables 4 using control of the actuators 5 taking into account minimizing energy costs and minimizing vibration of the structure.

At present, control is carried out according to the proportional-integral-derivative (PID) control structure, which makes it possible to achieve the required parameters in the terminal part. The use of a PID control structure is not optimal for minimizing energy consumption and minimizing design fluctuations.

At the same time, the use of optimal control algorithms will minimize energy costs and minimize fluctuations in the net. This can be achieved by smoothly stopping the engine when using the developed algorithm proposed in this paper.

2. Construction of a mathematical model of the structure of the actuator and modeling of its operation

In order to represent and predict the operation of the actuator used in the development, a mathematical model of the brushless motor included in the MRB-32 [16] assembly was built. The simulation was carried out in the Simulink application package using elements of the SimPowerSystems library. Automatic based on time function was chosen as the control method. A diagram of a model of a DC drive with automatic control by a function of time, in a simple approximation, is presented in Fig 2.

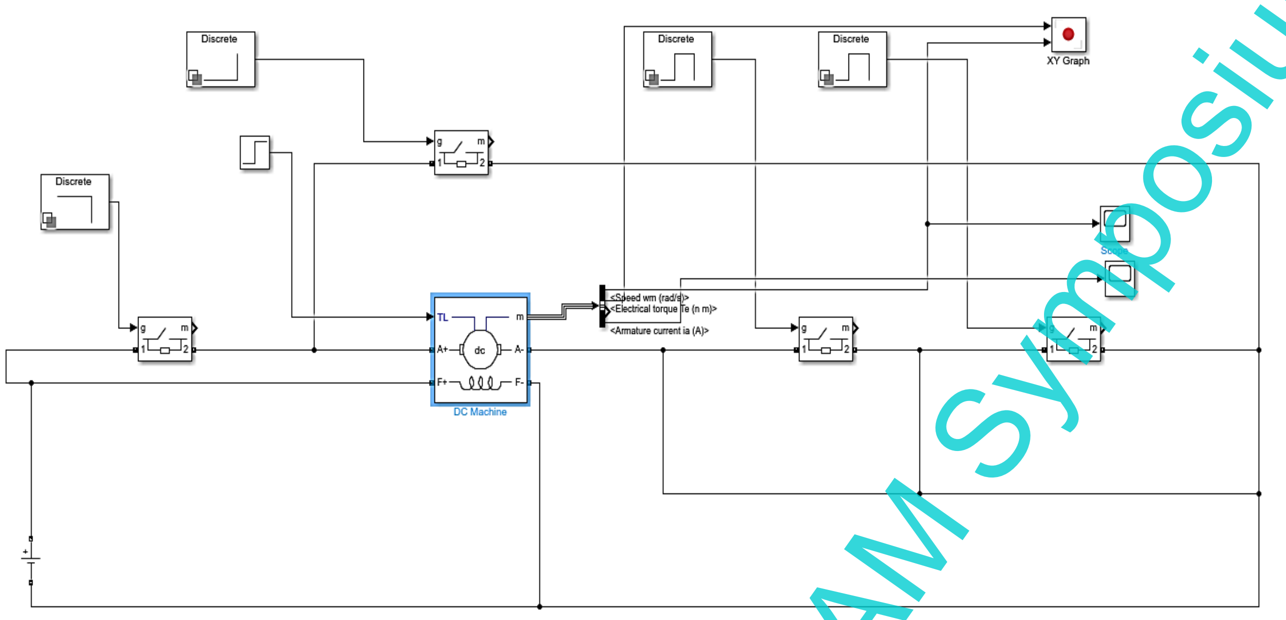

Fig. 2. Diagram of a DC drive model with automatic time control

Ideal switches simulate the operation of contactors, and control occurs using "Stair Generator" blocks, which contain time functions that simulate real control signals. So, for key 1, the mode is as follows: 0...1.5 s – the key is open; 1.5…3.5 s – the key is closed. The "Step" block is needed to create reactance. Scope virtual instruments are installed in the system as tools for visual interpretation of signals and construction of oscillograms. The circuit also contains a power element that simulates the energy source for the system under consideration. The power supply of the field winding and the armature winding of the motor were chosen to be controllable in order to implement reverse functions. Data on the output parameters of the engine is received via a combined bus, which is decomposed into components for further use through the connector module.

Next, Fig. 3-5 shows part of the simulation results using the example of the processes of starting, braking and reversing the used motor, taking into account the setting of the following parameters: supply voltage 24 V; rotor winding resistance 3.45 Ohm; rotor winding inductance 0.0380 H; rotor inertia $17 \cdot 10^{-6}$ kg*m^2. Fig. 3 shows the dependence of the rise and fall of shaft rotation on time.

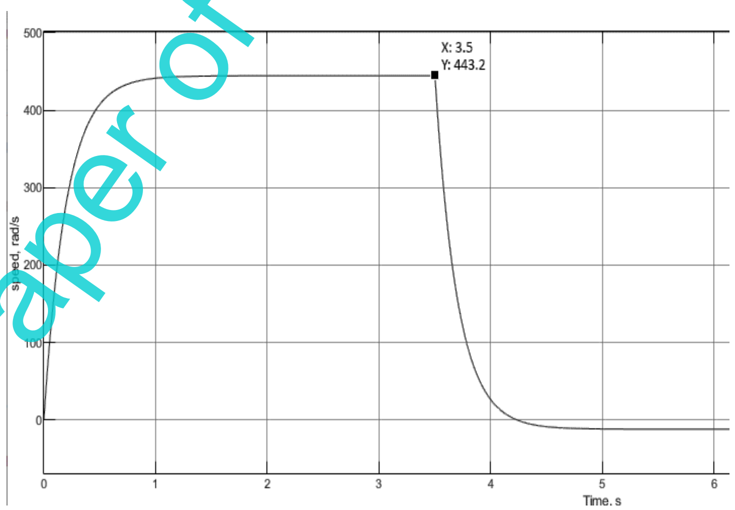

Fig. 3. Dependence of the rise and fall of shaft rotation over time

As can be seen from Fig. 3, the shaft from a state of rest in 0.5 seconds picks up an angular velocity close to 400 rad/s, which in terms of angular frequency is about 3820 rpm and, in general, corresponds to the engine data stated in the technical specification. We can also conclude that the shaft returns to a resting state approximately 1 second after the power is removed. Fig. 4 shows the dependence of the motor armature current on time.

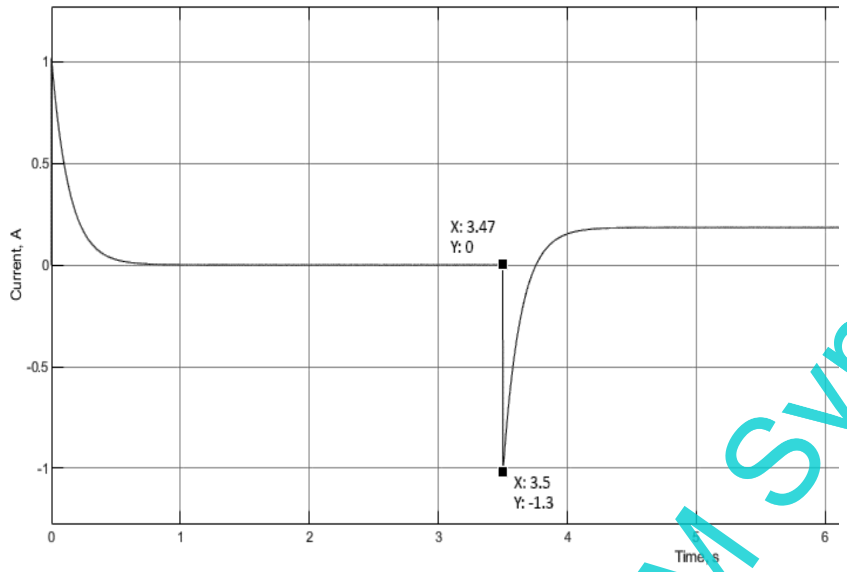

Fig. 4. Dependence of motor armature current on time

The starting current reaches a value of about 1 A and decreases as the engine accelerates to a value close to zero (it should be borne in mind that theoretically the starting process has not yet ended), with a steady angular velocity of 443.2 rad/s. Also shown in Fig. 5 is the dependence of changes in engine torque over time.

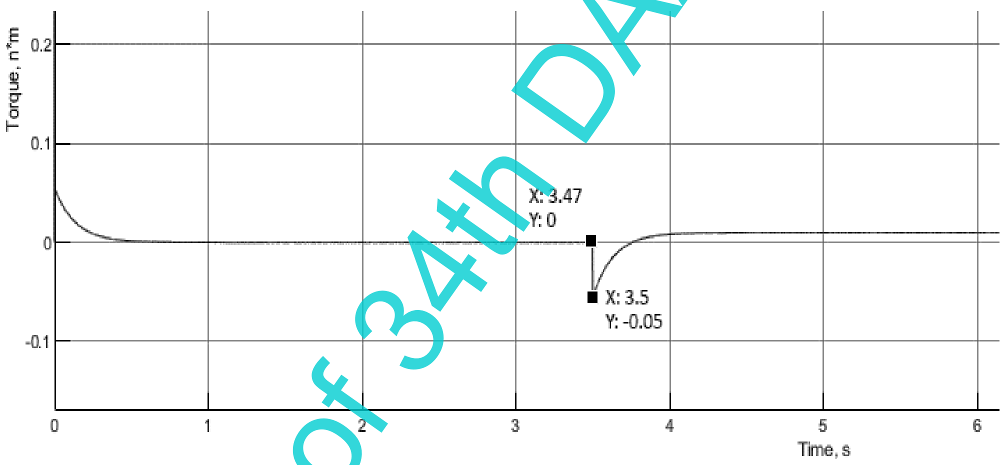

Fig. 5. Dependence of changes in engine torque over time

The resulting model is simplified, however, even in the presented configuration, through proper selection and input of input parameters, it becomes possible to get an idea of the aspects of the operation of the actuator. In order to obtain a much more accurate and high-quality picture of the operation of the drive used, it is planned to significantly supplement this model with gearbox units, additional sensors and other tools that allow for a comprehensive add-on to the actuator system.

3. Equations of DC motor

When developing the control algorithm for the MRB-32 geared motor, a mathematical model of the electric motor was used, described in [17], [18], [19] in the form

$$\frac{dI(t)}{dt} = \frac{U_a - R \cdot I(t) - k_E \cdot \omega(t)}{L} + \xi_I, \quad (1)$$

$$\frac{d\omega(t)}{dt} = \frac{k_M \cdot I(t) - M_{ex}}{J} + \xi_\omega, \quad (2)$$

$$\frac{d\varphi(t)}{dt} = \omega(t) + \xi_\varphi, \quad (3)$$

where I is motor current, U_a is armature (rotor) voltage, R is armature (rotor) active resistance, L is armature (rotor) winding inductance, k_E is coefficient of proportionality, called back EMF constant, ω is angular velocity of the motor shaft., k_M is motor torque constant, M_{ex} is electromagnetic torque of the motor, J is rotor moment of inertia, φ is the rotation angle, ξ_I, ξ_ω, ξ_φ is noise values corresponding to current, angular velocity and shaft rotation angle of the gearmotor, respectively.

As a first approximation, in the MRB-32 gearmotor, an instrument gearbox with a gear ratio is selected $k_g = 1/i_g$, where i_g = 150 is gear ratio of instrument gearbox.

Due to the need to solve the problem of controlling and filtering noise that arises during the operation of the system for tuning and maintaining the shape of the radio-reflective net of a large reflector, described in Section 1, we will use the generally accepted practice of posing and solving the problem of joint synthesis of optimal control. The formulation of the problem of combined synthesis of optimal control of systems is based on the separation theorem. According to this theorem, an optimal control system consists of a filter that forms estimates of the system's state vector, and an optimal controller that determines control in a deterministic setting under the assumption that the state vector is known exactly. The result of this theorem, proven for linear systems, is quite reasonably transferred to nonlinear systems with small estimation errors [20], [21]. Otherwise, an already complex and time-consuming task becomes dramatically more complicated. In this case, it is possible, for example, due to the duality of optimal control and estimation problems, to apply an approach to combined control synthesis with consideration of the hierarchy of corresponding functionals [22].

The angle of rotation of the shaft φ and the current I of the gearmotor MRB-32 are available for measurement. For this purpose it is supposed to use the 4GNSS sensor OS-213 [23]. For the problem of controlling a geared motor, we consider the observation equations in the form

$$z = h(x,t) + \xi_z. \tag{4}$$

In Equation (4) $z = [z_1 \quad 0 \quad z_3]^T$, $h = [I \quad 0 \quad \varphi]^T$, $z = [\xi_I \quad \xi_\omega \quad \xi_\varphi]^T$ are random processes such as white noise with intensity $B_z = diag(B_{z1}, B_{z2}, B_{z3})$.

In this article, a linearized Kalman filter and an algorithm for optimal correction of control structure parameters are used to construct control [24], [25].

The choice of an algorithm for optimal correction of control structure parameters to solve the control problem is explained by the fact that the use of a classical PID control structure does not take into account the minimization of energy costs, which is extremely important in conditions of energy limitation. The works [16], [17] show that the algorithm for optimal correction of control structure parameters is more stable in terms of convergence compared to classical optimal control methods, such as the Newton and Krylov-Chernousko method.

The control task is to drive the DC shaft of the MRB-32 gearmotor (1) – (3) from the initial position $\mathbf{x}(t_0) = [0,0,0]^T$ to a given end state $\mathbf{x}(t_f) = [0,0,250\pi]^T$ under the control constraint u, which is taken as the external supply voltage $U_{a\,\max}$=±24 V for a given time t_f. This rotation angle φ will provide a change in the length of the cable.

4. Development of a control algorithm of DC motor

In accordance with the separation principle, the control task is preceded by the task of estimating the state vector from incomplete data specified by equation (1) – (3). The optimal estimate can be obtained using the Kalman filter, the equations of which for this problem will take the form of the equations

$$\dot{\hat{I}} = \frac{U_a - R\cdot\hat{I} - k_E\cdot\hat{\omega}}{L} + R_{11}\cdot B_{z_1}^{-1}(z_1 - \hat{I}_z) + R_{13}\cdot B_{z_3}^{-1}(z_3 - \hat{\varphi}), \tag{5}$$

$$\dot{\hat{\omega}} = \frac{k_M\cdot\hat{I} - M_{ex}}{J} + R_{21}\cdot B_{z_1}^{-1}(z_1 - \hat{I}_z) + R_{23}\cdot B_{z_3}^{-1}(z_3 - \hat{\varphi}), \tag{6}$$

$$\dot{\hat{\varphi}} = \hat{\omega} + R_{31}\cdot B_{z_1}^{-1}(z_1 - \hat{I}_z) + R_{33}\cdot B_{z_3}^{-1}(z_3 - \hat{\varphi}), \tag{7}$$

$$\dot{R} = f_x\cdot R + R\cdot f_x^T - R\cdot h_x^T\cdot B_z^{-1}\cdot h_x\cdot R + B_x,\ R(t_0) = R_0. \tag{8}$$

In (5) – (8) $f_x = \frac{\partial f}{\partial x}$, $h_x = \frac{\partial h}{\partial x}$, $h_x = \begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}$, $f_x = \begin{bmatrix}-\frac{R}{L} & -\frac{k_E}{L} & 0\\ \frac{k_M}{J} & 0 & 0\\ 0 & 1 & 0\end{bmatrix}$, $R_{ii}(t_0) = R_0$, $i = \overline{1,n}$, other elements initial covariance matrices of estimation errors were taken equal to zero.

From an engineering point of view, the main task that arises during filter synthesis is to define mathematical models of noise. According to [15], system noise can be specified in the form of white noise with a power spectral density equal to unity. We use the maximum principle to search for optimal control, taking into account the formulation of the problem of minimizing energy problems over the entire control time. As a target, we consider the Boltz functional:

$$J = \boldsymbol{V}_f(\boldsymbol{x}, t_f) + \int_{t_0}^{t_f} f_0(\boldsymbol{x}, u, t)dt, \quad (9)$$

where $\boldsymbol{V}_f = 0{,}5[\boldsymbol{x}(t_f) - \boldsymbol{x}_f]^{\mathrm{T}} \rho [\boldsymbol{x}(t_f) - \boldsymbol{x}_f]$; $f_0 = 0{,}5 k_u U_a{}^2/R^2$; $\rho = \mathrm{diag}(\rho_1, \rho_2, \rho_3)$; k_u, ρ_1, ρ_2, ρ_3 are given coefficients; $\boldsymbol{x}_f = (I_f \ \boldsymbol{\omega}_f \ \boldsymbol{\varphi}_f)^{\mathrm{T}}$ is given final values of the corresponding variables in (1) – (3). Since the task was set to minimize energy costs, the expression for the consumed supply voltage $U_a$over the entire modeling interval was taken as the function f_0.

Solving this problem using the maximum principle using classical methods allows us to identify the structure of optimal control. Using the moment of time $\tau_i$of switching the control structure as parameters, we represent the control structure in the form

$$u(t) = u_1(t) + \Delta \mathbf{u}_i^{\mathrm{T}}(t) \boldsymbol{l}(t, \tau_i), \quad (10)$$

where $i = \overline{1, r}$, i is control structure section number, r is number of control switchings in the structure $\boldsymbol{l}^{\mathrm{T}}(t, \tau_i) = [l(t, \tau_1) \ l(t, \tau_2) \dots l(t, \tau_r)]$, $\Delta \mathbf{u}_i^{\mathrm{T}} = [-u_i + u_{i+1}, \dots, -u_{i-1} + u_r]$, $u_i(t) = u_1(t)$ for $t<\tau_1$. Here u_1, u_{i+1} are control in the previous and subsequent sections of this structure relative to τ_1; $l(t, \tau_1)$ are Heaviside functions.

To use the algorithm for correcting the parameters of the control structure, the equations are added to the original system (1) – (3) $\dot{\boldsymbol{\tau}} = \mathbf{w}$, where $\boldsymbol{\tau} = (\tau_1 \ \tau_2 \dots \tau_r)^{\mathrm{T}}$; $\mathbf{w} = (w_1 \ w_2 \dots w_r)^{\mathrm{T}}$ are vectors of new variables taken as controls. Then the equations for the generalized state vector will be written as

$$\dot{\mathbf{x}} = \boldsymbol{f}(\mathbf{x}, u, t); \ \dot{\boldsymbol{\tau}} = \mathbf{w}. \quad (11)$$

This problem can be solved by minimizing the new criterion

$$J_1 = J + \frac{1}{2} \int_{t_0}^{t_f} \mathbf{w}^{\mathrm{T}} \mathbf{k}^{-2} \mathbf{w} dt + \frac{1}{2} \int_{t_0}^{t_f} \mathbf{w}_0^{\mathrm{T}} \mathbf{k}^{-2} \mathbf{w}_0 dt \ , \quad (12)$$

where $\mathbf{k}$ is diagonal matrix of given coefficients, $\mathbf{w}_0$ is optimal value $\mathbf{w}$.

By introducing a new control vector **w**, the original optimization problem by defining u is solved indirectly through finding this vector **w**.

5. Results of testing the proposed control algorithm of DC Motor

To assess the influence of disturbances on the system, it is necessary to determine the magnitude of external disturbances and measurement noise. In addition to external disturbances, a change in the initial and final states can be observed, caused by impacts on the structure when delivering the reflector into orbit.

Let us assume that the filtered measurement noise does not exceed the errors of the measuring sensors. External disturbances (the influence of load, ambient temperature, solar pressure, radiation, etc.) affect the entire vector of state variables. As a rule, external disturbances are random, uncorrelated and uniformly distributed over a given range. In outer space, the external influence exerted on the reflector is quite long-lasting and slowly growing, so over the considered time interval (no more than 10 s) it can be considered quasi-stationary. Let us take the disturbances to be equal to ±1% of the maximum values of the corresponding variables. In general, the magnitude of disturbances from emergency situations is difficult to predict.

Having analyzed the control structure obtained in [17], [18], we can describe function (10) taking into account restrictions in the form

$$U_a(t) = U_{a\,\max} \mathrm{sign}(P_I) - 2U_{a\,\max} l(t, \tau_1) + U_{a\,\max} l(t, \tau_2), \quad (13)$$

where P_I is conjugate variable in I arising from the solution of the optimal control problem.

Based on (12), two structure changes were chosen at time τ_1 and τ_2, respectively. Numerical modeling of the transition of the system from the initial state $\mathbf{x}(0) = (0\ 0\ 0)^{\mathrm{T}}$ to the final state $\mathbf{x}(t_f) = (0\ 0\ 250\pi)^{\mathrm{T}}$ while minimizing the energy $P_e = U_a \cdot I$ in time $t_f = 3$ seconds was carried out by the Euler method with a step $\Delta t = 0.001$ seconds.

In Fig. 6 presents the results of the simulation: graphs of the dependences $\varphi(t)$ and $\omega(t)$. It can be seen that it was possible to solve the task, rotate the shaft of the MRB-32 gearmotor to a given angle $\varphi = 250\pi$ rad. Moreover, for all modeling cases, the error in the shaft rotation angle φ at the final moment of time did not exceed 0.1 rad.

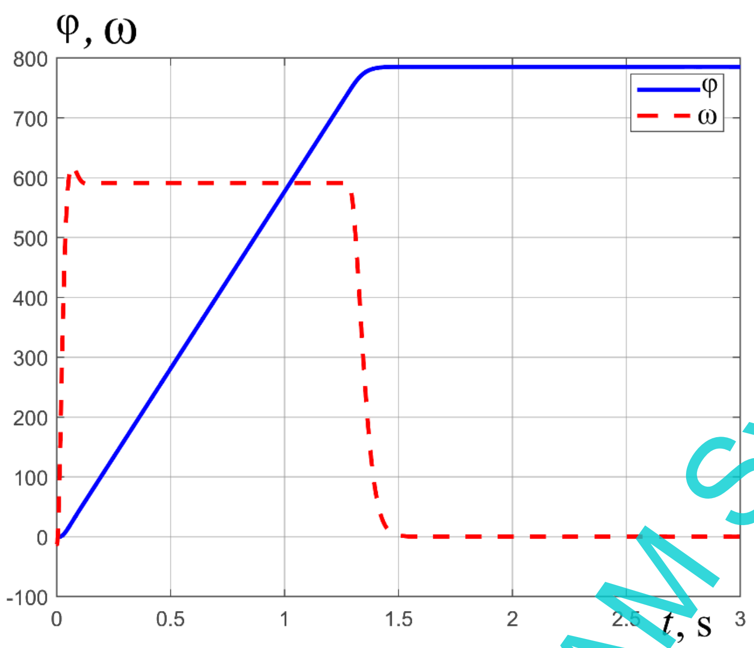

Fig. 6. Dependence φ(t) and ω(t)

For selected disturbances and measurement noise, optimal filtering and control algorithms successfully solve the problem. A feature of this algorithm is the good convergence of the structure change time τ_1 and τ_2 to the optimal value when choosing these variables in the modeling interval t=[0, 3] and subject to the conditions $\tau_1(0)$< and $\tau_2(0)$. In Fig. 7 shows graphs of the control of the switching moments τ_1 and τ_2 versus time, clearly demonstrating that the moment τ_1 converges to the optimal value, and τ_2 tends to t_f.

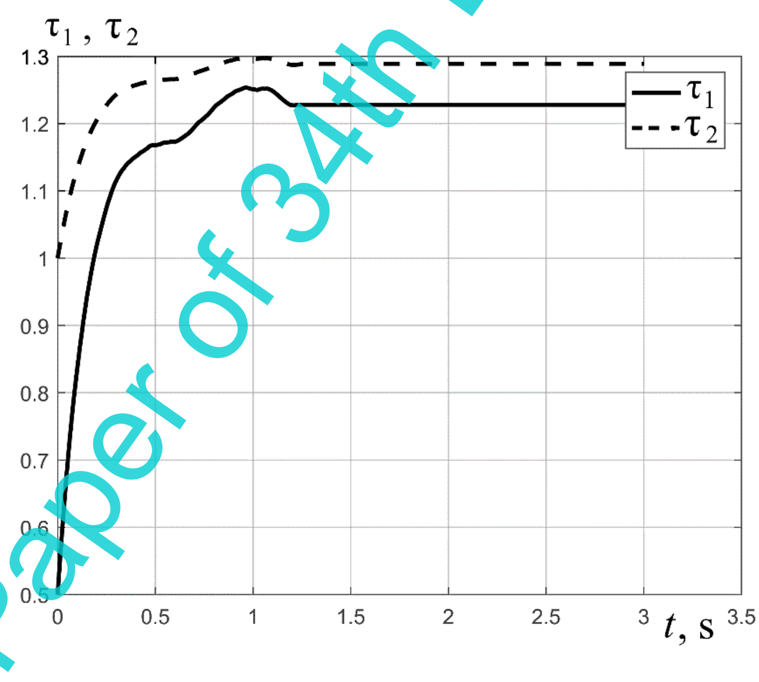

Fig. 7. Structure change time graphs $\tau_1(t)$ and $\tau_2(t)$

As can be seen from the presented graphs, τ_2 is located quite close to τ_1. In some cases, due to the presence of disturbances, their intersection occurs. Based on this, it is advisable to determine the condition $|\tau_2-\tau_1|<\varepsilon$, where ε is a given small value, at which only one switching remains. Time τ_1 allows one to successfully work out the disturbances exerted on the system before the moment of structure change occurs. After reaching time τ_2, the algorithm does not have a control effect on system (1)-(3), which leads to failure of the terminal conditions. To solve this problem, it is necessary to control the final simulation time t_f, that is, determine $\tau_2 = t_f$. Next, it is necessary to apply a stabilization algorithm, for example, in the form of a PID (proportional-integral-differentiating) structure. Due to the proximity of the state vector **x** to the specified final conditions, one adjustment of the PID controller will be required without changing its coefficients, regardless of the operating mode, which greatly simplifies its use.

In Fig. 8 shows the diagonal elements of the covariance matrix at $R_{11}(0) = 0.00055$; $R_{22}(0) = 1.9$; $R_{33}(0) = 0.0004$. Quite quickly they come to steady-state values. Simulation was carried out with different initial values of the diagonal elements of the covariance matrix and different intensity of measurement noise, the Kalman filter successfully worked out all options.

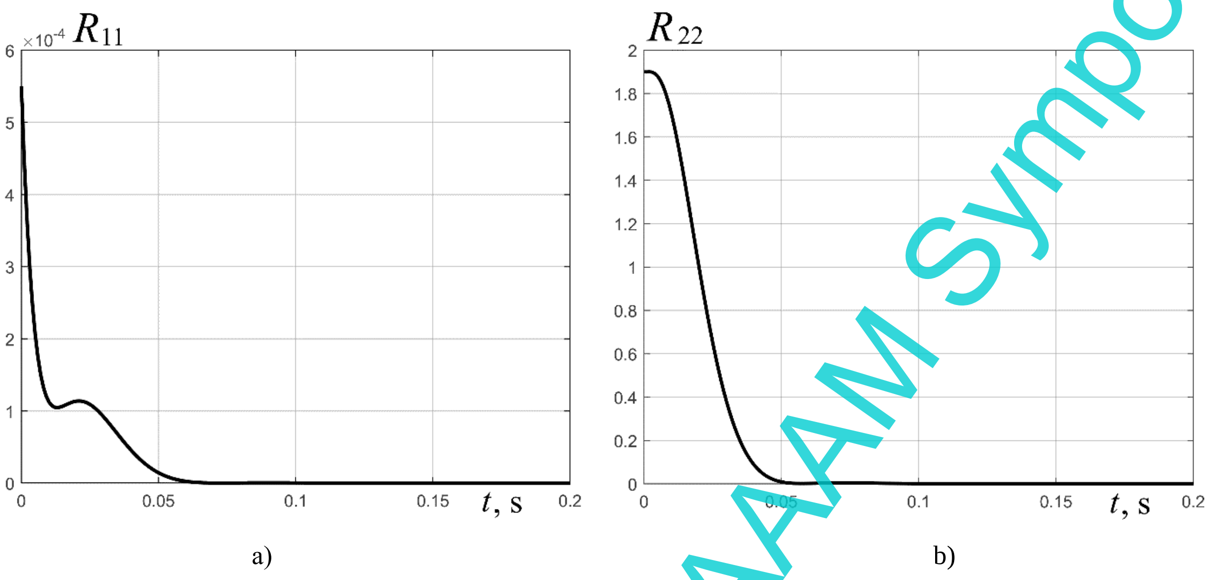

Fig. 8. Graphs a) R_{11} (t); b) R_{22} (t)

When the intensity of disturbances increases to values $\mathbf{B}_x = diag(0.005, 0.1, 0.5)$, vibrations of the structure and the operation of the control algorithm become noticeable. In Fig. 9 and fig. 10 shows the graphs $\varphi(t)$ and $U_a(t)$, respectively.

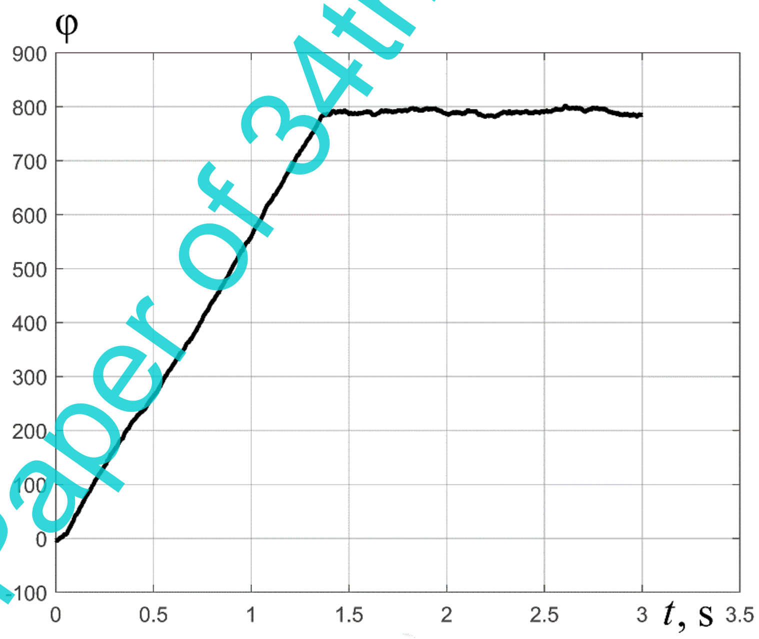

Fig. 9. Graph (*t*) under the influence of disturbances

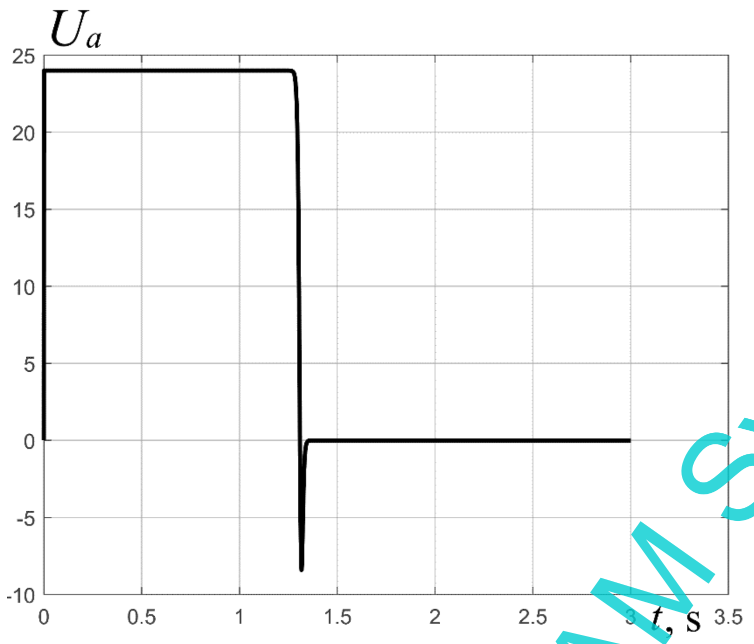

Fig. 10. Graph U_a (t)

In this case, the control U_a does not have time to completely change the structure, but reaches a level of ~ -9 V and returns to the final value of 0 V. This is due to the choice of the continuous function $\boldsymbol{l}(t, \tau_i)$. The transition between control levels in (12) does not occur by relay switching, but rather smoothly. This allows you to customize the control algorithm for a real system with a given delay.

6. Conclusion

As a result of the work done, the mathematical model of the selected DC motor MRB-32 was confirmed. A solution to the problem of optimal control of a stochastic DC motor model using incomplete data using the separation principle is presented. The use of an algorithm for optimal correction of control structure parameters with the obtained data evaluated using a Kalman filter made it possible to solve the problem posed for various intensities of disturbances and measurement noise.

To use the algorithm for optimal correction of control structure parameters in real time, it is recommended to switch to the PID control structure when approaching the final simulation time. This will allow us to solve the problem of optimal control of the actuator, as well as solve the problem of stabilization. In this case, due to small deviations of the state vector at the final moment of time from the specified terminal ones, only one adjustment of the PID controller parameters will be required.

Taking into account the disturbances and noises of the proposed sensors acting on the system under study leads to complex problems of processing the measurement results and their planning. It is expedient to use the algorithm of correcting the control structure parameters studied in the article in more complex solutions using measurement processing and optimization of observation intervals.

The results of these studies can be used to calculate energy costs, select the actuator and power plant of the space-based reflector. The application of the developed optimal control algorithm requires significant computational costs, which must be taken into account when designing on-board equipment. With further research, it is planned to conduct an additional analysis of possible electronic components (microcontrollers, FPGAs, etc.), as well as conducting prototype tests of the actuator and confirm the effectiveness of the developed algorithm on the layout.

7. Acknowledgments

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