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Methodology of Synthesizing Digital Regulators in Precision Electric Drives for Orientation and Stabilization Target Tracking System of Mobile Robot's Directional Sensors

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Abstrakt

The article is devoted to the methodology of synthesizing digital regulators in precision electric drives for orientation and stabilization target tracking system of mobile robot's directional sensors. The methodology makes it possible to reduce the transition time in the electric drive rotor angle control channel, to synthesize a quasiinvariant digital automatic control system (DACS) in relation to the external perturbing influence. The methodology recommends distinguishing two modes of electric drive operation: sensor sensitivity axis orientation (reorientation) and its stabilization. The control law structure for both modes remains the same. The regulation algorithm consists of digital proportional-integral-differential regulation algorithms, an algorithm for electric drive dynamic properties correction and an algorithm for the state vector (Luenberger observer or Kalman filter) restoration (evaluation). The information to the observer or filter comes from a digital amp meter. Use of the methodology will allow: to improve electric drive dynamic characteristics with an insignificant increase in energy consumption; to increase reliability and reduce electric drive mass-size parameters.

Keywords

digital automatic control of electric drive, directional sensors, state-space modeling, mobile robots, correction of electric drives dynamic characteristics

1. Introduction

The development of mobile robotics is happening at an accelerating pace [1, 2]. Successfully solving the problem of localizing the robot's mobile base and working body is a necessary condition for its effective use and determines the possibility of its application in general [3-9]. Prospective mobile robots for all environments are mostly intended for autonomous use, i.e. using their own resources during operation [10]. Thus, the speed, accuracy and energy conservativeness, range of navigation system sensors and the working body allow to increase the time of mobile robot effective active operation for its intended purpose [11, 12]. Special requirements for mobile robot sensors arise when robots are used in groups to perform a common task in conditions with unpredictably moving mobile obstacles. Methods for solving such problems assume the presence of sufficiently accurate information about the state vector, absolute and relative speeds of robot and obstacle movement. A possible way to solve the problem of providing primary navigation information to mobile robot navigation systems is to use a large number of heterogeneous omnidirectional sensors.

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However, using an excessive number of omnidirectional sensors in autonomous operation worsens the robot operation technical and economic indicators. Using directional sensors allows solving the problem of obtaining high-precision primary information quickly and efficiently only if there is a of orientation (reorientation) electric drives special system and target tracking stabilization [9-15].

The synthesis of digital regulators that allow making precision electric drives for the orientation and target tracking stabilization system of mobile robot's directional sensors will improve the technical characteristics of individual mobile robots and their groups operation [3]. This fact takes on special significance for group use of mobile robots for military purposes [16].

Methodology of synthesizing digital regulators in precision electric drives for orientation and stabilization target tracking system of mobile robot's directional sensors develops the engineering methodological apparatus for synthesizing digital regulators.

2. Problem Statement

Currently, digital control of mechatronic devices electric drives that are actually used in practice is carried out, at best, by digital PID regulators [17]. These DPID regulators are parametrically tuned to deterministic mathematical models that are only suitable for tuning in orientation (reorientation) mode [18, 19]. Then, at best, parametric fine-tuning is performed during field tests or maintenance work during normal operation [20, 21]. Algorithmic correction of electric drive dynamic characteristics is not performed. The electric drive rotor speed and (or) its rotation angle are measured by special mechanical sensors (primary information sensors) that do not have sufficient reliability and, at the same time, increase the mass and electric drive energy consumption [22, 23]. Chaotic movements of mobile obstacles in the tactical and mobile robot operational areas worsen the efficiency of its operation. To fully identify (determinate) the obstacle properties and the danger emanating from it, it is necessary to perform very frequent directional sensor sensitivity axis orientation (reorientation) operations and to stabilize the sensitivity axis in a given direction for some time with precision. At the same time it is necessary to suppress the so-called "chattering" as much as possible [24, 25, 26].

Thus, the task of developing an engineering methodology for the precision electric drives digital regulators synthesis for the orientation and stabilization of mobile robots directional sensors target tracking system is relevant. Object of the research is digital automatic control process of directional sensor orientation system electric drive. Subject of the research are digital automatic control algorithms of directional sensor orientation system electric drive. The proposed engineering technique is limited to application for the control objects, whose mathematical models can be considered linear and stationary.Problem statement (scientific problem to be solved) is to satisfy two contradictory requirements (criteria) through digital electric drive algorithmic modernization (control algorithm improvement): directional sensor fast reorientation and accuracy of its stabilization in a given position.

In the presented methodology, the scientific problem is decomposed into two sub-problems: the first sub-problem consists in upgrading the reorientation algorithm; the second sub-problem consists in upgrading the stabilization algorithm. It is proposed to solve the first sub-problem in the deterministic formulation, and to solve the second sub-problem in the stochastic formulation. In this case, only the control algorithms change parameters, while their structure remains unchanged as a result of solving both sub-problems. Thus, the methodology allows synthesizing an algorithm of digital automatic control in the directional sensor electric drive orientation and stabilization system adaptive to a particular mode of operation.

3. Methodology for synthesis of digital regulators of precision electric drives for orientation and target tracking stabilization system of directional sensors of mobile robots

3.1. Methodology steps

Step 1. Finding the control law structure that is common to solving the problems of target tracking and stabilization.

Sub-step 1.1. Select the control object (type of electric drive) and build its mathematical model.

Sub-step 1.2. Selecting the control law structure.

Step 2. Deterministic parametric optimization of orientation control law.

Sub-step 2.1. Drive dynamic properties (characteristics) algorithmic correction (calculation of internal correction circuit regulator parameters rational values), under the condition that all the drive state vector components are measured absolutely accurately.

Sub-step 2.2. External circuit regulator Parametric optimization, assuming that all drive state vector components are measured absolutely accurately.

Sub-step 2.3. Luenberger observer synthesis and its connection to the DACS external and internal circuits by an electric drive.

Sub-step 2.4. A computer experiment to assess the DACS operation quality with a Luenberger observer.

Step 3. Control law stochastic parametric optimization for stabilizing target tracking.

Sub-step 3.1. State evaluation algorithm (Kalman filter) synthesis and its connection to the DACS external and internal circuits by the electric drive.

Sub-step 3.2. External circuit regulator parameters stochastic optimization, which was built in Sub-step 2.2. of methodology, and a computer experiment to assess the quality of stochastic DACS operation with a Kalman filter.

Step 4. Conclusions.

3.2. Methodology steps execution

Step 1.

Sub-step 1.1. The control object is a specific type of electric drive, which, by its technical characteristics, is best suited to the overall design of orientation and stabilization system [27]. Let us assume that this is a direct current motor (DCM).

The DCM mathematical model is represented in a multidimensional state space with two inputs and two outputs [28]. One of the inputs is the input that supplies the control voltage to the DCM armature, and the other is the perturbation. The first output is the DCM armature $i(t)$current, and the second is the angular velocity of its rotor $w(t)$. There is a linear stationary relationship between the input and the output. Thus, the control object mathematical model can be classified as a multidimensional linear invariant model (MIMO LTI model) [27, 28].

Sub-step 1.2. The digital regulator algorithm of digital automatic control system (DACS) for the DCM rotor (armature) angular velocity consists of three algorithms: two regulator algorithms and a state observer algorithm [19]. The regulators are serial and parallel links that correct the DCM dynamic properties. As a sequential correcting link, we choose a digital proportional-integral-differential regulator (DPID regulator), which gives the DACS the property of quasi-adaptability [27]. As a parallel corrective link, we use linear feedback on the DCM state vector with a matrix gain. To calculate this matrix gain, we will further use three methods of state regulation: the method of state regulation with the desired (specified) characteristic equation; the method of modal state regulation; and the method of linear quadratic state regulation. These methods are most often used in engineering practice to correct the dynamic properties of control objects with MIMO LTI by operation mathematical models [27]. The methodology provides for simulation modeling, based on the results of which it is proposed to select the best matrix feedback coefficient calculated by these methods. The coefficient is selected depending on the mode (orientation or target tracking stabilization) according to the criteria set for the respective operating modes.

The criteria for setting the regulators parameters and the state observer depend on the mode of DACS operation.

The problem of reorienting the sensor sensitivity axis is considered in a deterministic formulation. In this problem, it is necessary to choose the parameters in such a way as to minimize the transient time, overshoot, oscillation, and additional energy consumption for reorientation (if the sensor has an autonomous power supply).

The problem of stabilizing the sensor sensitivity axis in the tracking mode is considered in a stochastic formulation. In this problem, the parameters are selected subject to minimizing the error variance of keeping the sensor sensitivity axis in a given position and minimizing additional energy consumption by the sensor autonomous power supply.

We draw attention to the methods of setting up the DACS, which are the same for both modes of its operation. If the DCM mathematical models parameters and perturbations are known, then the regulator parameters and the state observer can be set in advance using these models, i.e., before the sensor is used. If there is no such information, then, of course, it is necessary to perform the mathematical models parameters operational identification and the DCM operational adjustment to a specific situation, i.e., to make the DCM adaptive (quasi-adaptive).

In the deterministic formulation, the state observer uses an algorithm called the Luenberger observer, and in the stochastic formulation – Kalman filter.

Conclusion: as a result of methodology first step, we obtain the DACS mathematical model structure in the form shown in Fig. 1.

The continuous and DCM discrete MIMO LTI mathematical models were used for simulation modeling (algorithmic calculation of optimization criteria values) and regulators parametric synthesis, the Luenberger observer, and the Kalman filter [19].

The DCM continuous MIMO LTI mathematical model (On Fig. 1. model is represented by the State Space block and the Bn suppressor) has the following parameter values: A=[-25 -7.5;7.5 0]; B=[1 0;0 -1]; Bn=[5 0;0 -5]; C=[1 0;0 1]; D=[0 0;0 0]. The continuous MIMO LTI input signals of DCM mathematical model (block 6, Fig. 1) are: the voltage applied to the DCM armature (armature circuit control), which is fed from the DPID regulator output - the first control input (block 4.1, Fig. 1), and the braking control torque, which is fed from block 3, Fig. 1 - the second control input. Note that in the physical sense of electric drive control problem, both inputs can be perturbed (block 1, fig. 1). The output signals of block 6, fig.1 are: armature current $i(t)$and the DCM $w(t)$ armature (rotor) angular velocity.

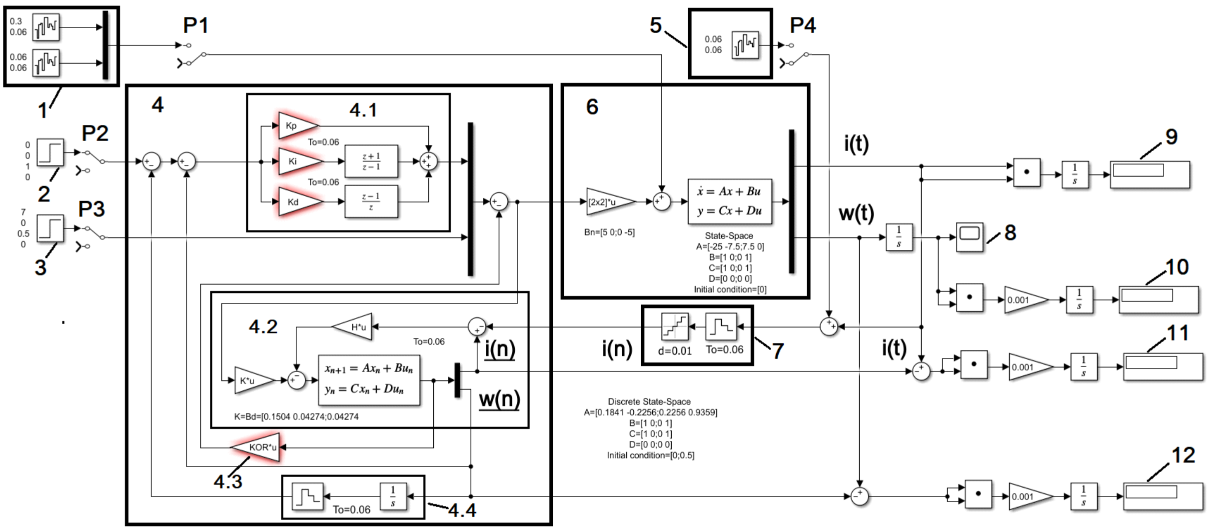

Figure 1: Structure of DACS computer mathematical model by precision electric drive for orientation and target tracking stabilization system of mobile robots directional sensors

A DCM discrete MIMO LTI mathematical model was built for a sampling interval of To=0.06 s using the c2d function of MATLAB+Simulink computer mathematics system [29]:

$$x(n+1) = Ad \cdot x(n) + Bd \cdot u(n), \quad (1)$$

$$y(n) = Cd \cdot x(n) + Dd \cdot u(n), \quad (2)$$

where Ad = [0.1841 -0.2256; 0.2256 0.9359], Bd = [0.1504 0.04274; 0.04274 -0.2928], Cd = [1 0;0 1], Dd = [0 0; 0 0].

Note that the notation Cd = [1 0;0 1] means that the digital sensors measure the primary information of both DCM output signals. This paper proposes to use a digital amp meter to measure the DCM armature current and then algorithmically calculate the DCM rotor (armature) angular velocity using a Luenberger observer or Kalman filter (depending on the electric drive operating mode). In this case Cd = [1 0].

On Fig.1 designated: 1, 5 - simulation blocks of external stochastic perturbations of band-type white noise with a variance equal to Noise power/Sample time, where the values of Noise power are indicated in the diagram in relative units and are set in the parameter block of corresponding blocks Band-Limited White Noise 1 and 5; Sample time=0. 06 s (perturbations 1 and 5 act respectively at the DCM input and at the input of DCM digital meter (sensor) armature current); 2, 3 - blocks of control action simulation by the DCM rotor rotation angle and braking action respectively; 4 - digital DCM control algorithm, which consists of 4.1 - DPID - regulator algorithm, 4.2 - Luenberger observer (orientation mode) or Kalman filter (target tracking stabilization mode), 4. 3 - an algorithm for correcting the DCM dynamic characteristics, 4. 4 - algorithm for calculating the DCM rotor threshold angle; 6, 7 – DCM computer mathematical models and digital sensor of primary information (sensor) current in the DCM armature circuit, respectively; 8 - oscilloscope to observe changes in the DCM rotor angle in time; 9, 10, 11,12 - displays for receiving information about the value of proportional energy consumption by electric drive, target tracking errors variance, evaluation by Kalman filter of armature current true value and DCM angular velocity; P1-P4 - switches for external influences connection.

Step 2.

Sub-step 2.1. The DCM discrete deterministic MIMO LTI mathematical model (1), (2) is used for calculations at this step of methodology.

Let's correct the DCM dynamic properties (build an internal corrective circuit with a matrix of corrective feedback coefficients KOR (block 4.3, Fig. 1)) using the three most commonly used engineering methods of regulation (electric drives dynamic properties correction) [27]. The theoretical provisions related to these methods, as well as detailed methods and examples of regulators synthesis using these methods, are presented in [28]. Using these methods, we obtain the following results.

1. Correction of DCM dynamic properties by the method of state regulation with the desired (specified) characteristic equation.

Correction problem statement: by using the internal feedback circuit, to provide the specified values of characteristic equation coefficients for the DACS DCM internal circuit mathematical model (i.e., the DACS DCM internal circuit mathematical model should have the desired (specified) characteristic equation). Let's assume that the desired characteristic equation has the same roots equal to 0.5).

As a result of solving the correction problem, we obtain a matrix of feedback coefficients KOR=KOR1=[0.1915 2.1337;0 0].

2. Correction of DCM dynamic properties by the method of modal state regulation.

Correction problem statement: by using the internal feedback circuit, to provide the specified values of characteristic equation roots for the DACS DCM internal circuit mathematical model. Let's assume (as in section 2.1) that the desired characteristic equation has the same roots, which are equal to 0.5).

As a result of solving the correction problem, we obtain a matrix of feedback coefficients KOR=KOR2=[-1.8068 -1.0343;-1.0344 -1.6399].

3. Correction of DCM dynamic properties by the method of linear quadratic state regulation

Correction problem statement: by using an internal feedback circuit, to perform such a control object dynamic properties correction by the method of linear quadratic state regulation, at which the quadratic quality criteria.

$$J = x^T(N) \cdot Q \cdot x(N) + \sum_{n=0}^{N-1} (x^T(n) \cdot Q \cdot x(n) + u^T(n) \cdot R \cdot u(n))$$

reaches its lowest value when the system (1) is transferred from the initial state x(0) to the final state x(N), where the matrices Q, R, – are symmetric and, respectively, positive-semidefinite and positive definite.

As a result of solving the correction problem, we obtain a matrix of feedback coefficients KOR=KOR3= [0.0731 0.0623; -0.2964 -1.1854], under the condition that
Q=[1 0;0 1], R=[0.7 0;0 0.3].

Sub-step 2.2. The tuning of DPID regulator (search for values of its parameters close to the optimal ones) can be performed using any of numerical optimization methods. In the proposed methodology, at this step and in the future, the following was done: the transition time process duration to be minimized was chosen as the optimization criteria; a numerical optimization method called the Hooke-Jeeves method [30] was applied, where the optimization criteria values were calculated using a computer mathematical model; the first approximation to the PID regulator parameters optimal values was found using the Ziegler–Nichols method [27, 28].

As a result, the following DPID regulator parameters values were obtained (block 4.1, Fig. 1) for each of DCM dynamic properties correction variants:

1. The lack of DCM dynamic properties correction (KOR=KOR0 = [0 0;0 0], block 4.3, fig.1): Kp=Kp0=1, Ki=Ki0=0.08, Kd=Kd0=1.47;
2. DCM dynamic properties correction by the method of state regulation method with the desired (specified) characteristic equation (KOR= KOR1, block 4.3, Fig. 1): Kp=Kp1=5; Ki=Ki1=0.8; Kd=Kd1=2.47 ;
3. DCM dynamic properties correction by the method of modal state regulation(KOR= KOR2, block 4.3, Fig. 1): Kp=Kp2=18; Ki=Ki2=5.5; Kd=Kd2=2.25;
4. Control object dynamic properties correction using the method of linear quadratic state regulation (KOR= KOR3=[0.0731 0.0623; -0.2964 -1.1854], block 4.3, fig.1): Kp=Kp3=18; Ki=Ki3=5; Kd=Kd3=5.62.

Sub-step 2.3. The term Luenberger observer is understood as a special algorithm for processing the output signal vector of a control object $y(n)$ given by equation (2) and allowing to obtain an control object state vector evaluation in the form [27, 28]:

$$\hat{x}(n+1) = Ad \cdot \hat{x}(n) + Bd \cdot u(n) + H \cdot (\hat{y}(n) - y(n)) \quad (3)$$

In the Luenberger observer theory, it is assumed that the signal $y(n)$ is measured absolutely accurately. The search for the matrix elements H values can be performed using the acker function of MATLAB computer mathematics system [29]. If the matrices Ad, Cd and the characteristic equation roots desired values

$$det\left(z \cdot I - (A^T + C^T \cdot H^T)\right) = 0 \quad (4)$$

are given, then the acker function solves this characteristic equation with respect to the matrix H unknown elements.

The call to the acker function is as follows acker(AdT,CdT,[zb1 zb2]) under the condition that we consider a DCM two-dimensional discrete mathematical model (1), (2) and z_{b1}, z_{b2} - desired values of characteristic equation roots (4).

Let's build a Luenberger observer for the DCM under the condition that the DCM current armature is measured using a special digital sensor (digital primary information sensor (DPIS)).

The Luenberger observer construction is performed using the mathematical model (1), (2):
Ad = [0.1841 -0.2256; 0.2256 0.9359], Cd=[1 0].

Set the same values for the characteristic equation roots: Zb1=0.5, Zb2=0.5.

We calculate the quantitative values of Luenberger observer feedback matrix elements
H=(acker(A', C', [Zb1 Zb2]))'
H = [0.1200; -0.6166].

Sub-step 2.4. During the deterministic computer experiment (step 2 of methodology), the switches P1 and P4 are disabled, and P2 and P3 are connected. This allows, in the process of performing a computer experiment, to supply the algorithm model input (block 4, Fig. 1) with a stepped action (block 2, Fig. 1) that controls the DCM rotor rotation angle and a controlling (or perturbing) braking action (block 3, Fig. 1). The input of Luenberger observer (block 4.2, Fig. 1) is supplied with a DCM $i(n)$ armature current digital value from the current sensor output (block 7, Fig. 1). At the output of Luenberger observer, we obtain the DCM armature current $i(n)$ calculated values and its angular velocity $w(n)$. After integrating $w(n)$ in block 4.4, Fig. 1, the signal is fed into the feedback channel by the angle of DCM rotor rotation (Fig. 2).

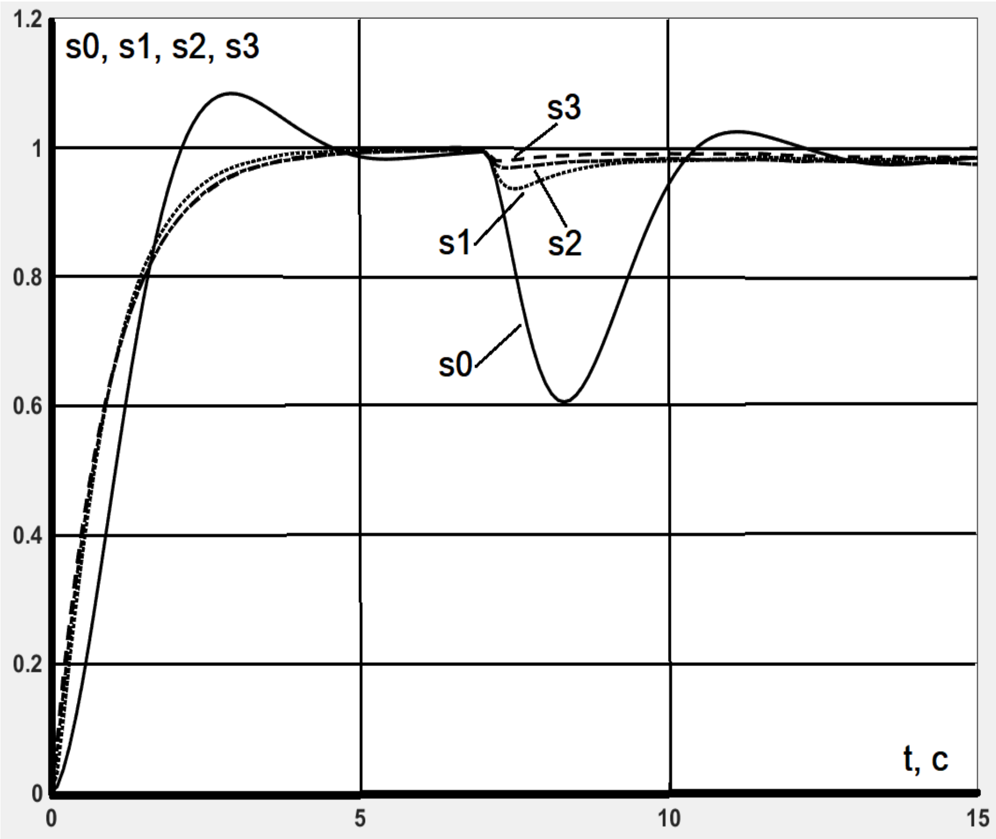

Figure 2: Graphs of time changes in the angle of DCM rotor rotation (measured in relative units) for different variants of DCM dynamic characteristics correction: s0, s1, s2, s3 - correspond to sets of regulator parameters values presented in Sub-step 2.2: 1), 2), 3), 4), respectively

Step 3.

Sub-step 3.1. In the target tracking stabilization mode, a discrete Kalman filter (an optimal discrete linear observer of stochastic system state vector, whose parameters are calculated using the known equations, which are obtained as a result of solving a linear quadratic Gaussian problem [27]) is proposed to evaluate the DCM state vector values. The Kalman filter matrix gain is proposed to be calculated for the steady-state mode.

The DCM state equation and the observation equation are in the form of a stochastic MIMO LTI mathematical model. This means that the state and observation equations (1) and (2) include additive terms in the form of discrete white noise $w(n)$ and $v(n)$, respectively:

$$x(n+1) = A \cdot x(n) + B \cdot u(n) + w(n); \quad (4)$$

$$y(n) = C \cdot x(n) + D \cdot u(n) + v(n), \quad (5)$$

where $w(n)$, $v(n)$ – normally distributed mutually uncorrelated discrete white noise such that $E[w(n)]=0$; $E[v(n)]=0$; $E\left[\begin{bmatrix} w(i) \\ v(i) \end{bmatrix}\begin{bmatrix} w(j) & v(j) \end{bmatrix}\right] = \begin{bmatrix} W \cdot \delta(i-j) & 0 \\ 0 & V \cdot \delta(i-j) \end{bmatrix}$; $W \geq 0; V > 0$ - this means that the written matrices are positively semidefinite and positively definite, respectively; $E[v(i)vT(j)]=V\delta(i\text{-}j)$; V - is the matrix of variances and observation noise mutual variances $\delta(i\text{-}j)$ - is a discrete impulse function; $w(n)$ and $v(n)$ – are independent of $x(n)$; $x(0)$ – is an initial condition that satisfies the requirements: $E\left[x(0)\right] = 0$; $E\left[x(0) \cdot x^T(0)\right] = X_0 \geq 0$ (X_0 – additive semi-definite matrix); $E[\dots]$ - operation of calculating mathematical expectation.

The discrete Kalman filter structure completely coincides with equation (3), which describes the discrete Luenberger observer structure (algorithm of action) [27, 28]. The Kalman filter steady-state gain is calculated by solving a well-known system of matrix algebraic equations [19, 27].

$$H = A \cdot S \cdot C^T \cdot (V + C \cdot S \cdot C^T)^{-1}; \tag{6}$$

$$S = (A - H \cdot C) \cdot S \cdot A^T + W, \tag{7}$$

where the matrices A, C are the same as in equations (1), (2) and (3), the intensity matrices elements are set in relative units W=[0.3 0;0 0.06], V=[0.06] (the matrix V consists of only one element because only the DCM armature current is measured). We note that when performing sub-steps 3.2 and 3.3 of methodology in blocks 1 and 5 (Fig. 1), the Noise power parameter was set to the same value as that used to calculate the Kalman filter gain steady-state value.

To solve systems (6), (7), it is possible to use special functions of computer mathematics system MATLAB+Simulink [29].

As a result of calculating the Kalman filter matrix gain, we obtain H =[0.0461;-0.0426].

Sub-step 3.2. Stochastic optimization of outer circuit regulator parameters (DCM regulator parameters stochastic optimization) is proposed to be performed by numerical methods [29]. In this particular case, the Hooke-Jeeves method was used.

As an optimization (minimization) criteria, we used an variance evaluation of sensor sensitivity axis stabilization error when it tracks the target in a steady-state dynamic mode (display readings 10, Fig. 1).

That is, the criteria numerical value was determined algorithmically using a computer mathematical model (Fig. 1), in which the switches had the following positions: P2 and P3 - open; P1 and P4 - closed.

The simulation time was 1000 s, and as a first approximation to the optimal value, we chose the DPID regulator parameters values, which were obtained in sub-step 2.2 of methodology. The the internal corrective circuit regulator parameters of were equal to the values calculated in sub-step 2.1 of methodology. Stochastic optimization of these parameters was not performed.

The results of outer circuit regulator parameters stochastic optimization and the computer experiment to assess the stochastic DACS operation quality are presented in Tables 1, 2, 3, 4.

Table 1
The results of stochastic optimization and computer experiment under the condition that the DCM dynamic properties correction was not performed.

Modeling parameters			
Display readings (Fig. 1)	DPID is a regulator (see Sub-step 2.2, 1)) and a Luenberger observer	DPID is a regulator (see Sub-step 2.2, 1)) and a Kalman filter	Stochastically optimal DPID regulator (Kp=2.1, Ki=0.83, Kd=3.05) and a Kalman filter
Block 9 (energy consumption for regulation, Q)	61.92	5.899	9.479
Block 10 (evaluation of tracking angle stabilization variance, Ds)	0.1118	0.01069	0.006931
Block 11 (evaluation of DCM armature current variance, Di)	0.1166	0.006864	0.006961
Block 12 (evaluation of DCM armature (rotor) angular velocity variance, Dw)	0.8765	0.02363	0.02361

Table 2
The results of stochastic optimization and computer experiment under the condition that the DCM dynamic properties correction is performed by the method of state regulation with the desired (specified) characteristic equation.

Modeling parameters			
Display readings (Fig.1)	DPID is a regulator (see Sub-step 2.2, 2)) and a Luenberger observer	DPID is a regulator (see Sub-step 2.2, 2)) and a Kalman filter	Stochastically optimal DPID regulator (Kp=6.1, Ki=2.3, Kd=4.2) and a Kalman filter
Block 9 (energy consumption for regulation, Q)	1369	10.93	16.83
Block 10 (evaluation of tracking angle stabilization variance, Ds)	0.1053	0.00691	0.006338
Block 11 (evaluation of DCM armature current variance, Di)	1.0200	0.008742	0.01273
Block 12 (evaluation of DCM armature (rotor) angular velocity variance, Dw)	1.093	0.02272	0.02281

Table 3
The results of stochastic optimization and computer experiment under the condition that the DCM dynamic properties correction is performed by the method of modal state regulation.

Modeling parameters			
Display readings (Fig.1)	DPID is a regulator (see Sub-step 2.2, 3)) and a Luenberger observer	DPID is a regulator (see Sub-step 2.2, 3)) and a Kalman filter	Stochastically optimal DPID - regulator (Kp=23.6, Ki=6.2, Kd=3.4) and Kalman filter
Block 9 (energy consumption for regulation, Q)	5786	107.2	116.4
Block 10 (evaluation of tracking angle stabilization variance, Ds)	0.07995	0.005521	0.00514
Block 11 (evaluation of DCM armature current variance, Di)	5.595	0.0268	0.09231
Block 12 (evaluation of DCM armature (rotor) angular velocity variance, Dw)	1.28	0.02088	0.02245

Table 4
The results of stochastic optimization and computer experiment under the condition that the DCM dynamic properties correction is performed by the method of linear quadratic state regulation

Modeling parameters			
Display readings (Fig.1)	DPID is a regulator (see Sub-step 2.2, 4)) and a Luenberger observer	DPID is a regulator (see Sub-step 2.2, 4)) and a Kalman filter	Stochastically optimal DPID regulator (Kp=22.1, Ki=7.5, Kd=6.8) and a Kalman filter
Block 9 (energy consumption for regulation, Q)	7246	45.1	73.19
Block 10 (evaluation of tracking angle stabilization variance, Ds)	0.07867	0.005398	0.005102
Block 11 (evaluation of DCM armature current variance, Di)	12.69	0.06397	0.1422
Block 12 (evaluation of DCM armature (rotor) angular velocity variance, Dw)	1.351	0.0214	0.02179

4. Results and discussions

Due to the use of a Luenberger observer or Kalman filter, it was possible to refuse to use DCM rotor angular velocity mechanical sensors and its rotation angle . Algorithmic measurement of these physical quantities using information from a digital amp meter connected to the DCM armature circuit allows to improve the reliability and DCM operation energy efficiency by the electric drive. Sensors with moving parts are known to have worse performance (weight and energy) than sensors without moving parts [20, 22].

4.1 Deterministic mathematical model (switches P1, P4 are opened, and P2, P3 are closed)

The graphs shown in Fig. 2 (observed using oscilloscope 8, Fig. 1) allow us to compare the transients qualitative nature in the investigated DACS and to establish a quantitative ratio between the numerical characteristics of these processes. As we can see, in the DACS, with any of three options considered in sub-step 2. 1 for correcting the DCM dynamic properties, the transient duration is about 5 s (in the DACS without correction, this time is about 7 s), there is no overstaying in the DACS with correction at all (i.e., all corrected DACS are aperiodic), and the corrected DACS are quasi-invariant to the external perturbation action (see Fig. 2, , the perturbation is given from block 3 at the seventh second). As we can see, the burst of deviation from the set position is reduced for the graph s1 by a factor of 10, and for the graphs s2 and s3 by a factor of almost 20 compared to the graph s0

The comparison of regulators energy characteristics in the orientation (reorientation) mode was carried out with the use of the indicator $Q = \int_0^T i(t)^2 dt$, where $i(t)$ is the current at the DCM armature circuit (measured in the number of units). The quantitative value of this parameter is proportional to the energy amount released at the DCM armature circuit active at the simulation interval equal to T s. In deterministic modeling, T=15 s. Comparing the results of simulation by energy criteria Q (shown on the display 9 Q0=0.9298, Q1=1.013, Q2=15.77, Q3=2.48, where the number indicates the energy performance correspondence to the corresponding graph s0, s1, s2, s3 on Fig. 1), we can conclude about the DACS parameters options energy efficiency, which are indicated by numbers 1 and 3.

According to the physical sense of the processes occurring in the electric drive, it is clear that to achieve a decrease in the control object transition time from one state to another is possible only at the expense of additional energy consumption. A comparative analysis of the value Q for the algorithmic correction investigated variants of DCM dynamic characteristics confirms this fact.

4.2 **Stochastic mathematical model** (switches P1, P4 are closed, and P2, P3 are opened)

A energy comparative evaluation and DACS accuracy characteristics with a Luenberger observer or Kalman filter and different variants of DACS dynamic characteristics correction and without correction was performed using the criteria Q, D_s, D_i, D_w, which were observed on displays 9, 10, 11, 12, respectively (all measurements were performed in relative units, all criteria preferably minimized).

The value $Q = \int_0^{1000} i(t)^2 dt$, where $i(t)$ is the current in the DCM armature circuit, is proportional to the energy amount released in the active resistance of DCM armature circuit during the simulation interval equal to 1000 s.

The value $D_s = 0.001 \cdot \int_0^{1000} s(t)^2 dt$ is a tracking variance evaluation of directional sensor sensitivity axis for a given direction.

The values $D_i = 0.001 \cdot \int_0^{1000} (i(t) - i(n))^2 dt$,

$D_w = 0.001 \cdot \int_0^{1000} (w(t) - w(n))^2 dt$, respectively, are variance evaluations of evaluation error by the Luenberger observer or Kalman filter of the current in the DCM armature circuit or its angular velocity.

As a result of applying the additive convolution method [31] for variants multi-criteria comparison presented in Tables 1-4, we conclude that the best regulator for the stabilization mode of tracking the directional sensor sensitivity axis is the regulator with parameters corresponding to Table 2 (DCM dynamic properties correction is done by the method of state regulation with the desired (specified) characteristic equation). In this case, the regulator receives information about the DCM state vector from the Kalman filter. Moreover, the table shows that DPID regulator parameters stochastic optimization in comparison to the criteria values obtained for the first approximation (calculated during step 21 of methodology) is inexpedient, since it does not significantly improve the accuracy, but significantly worsens the energy performance.

5. Conclusions

Luenberger observer connection to the DPID algorithm in the DACS regulator by the electric drive of directional sensor sensitivity axis orientation does not affect the transient process quality process in the DACS and its response to a stepped perturbation. Transient process duration is kept equal to about 5 s for DACS with correction of DCM dynamic characteristics by any of three methods: method of state regulation with a desired (specified) characteristic equation; method of modal state regulation; method of linear quadratic state regulation.

It is positive that the DCM rotor angular velocity algorithmic measurement using a Luenberger observer or Kalman filter can reduce the weight and DACS dimensions and improve its reliability. The improvement is due to the elimination of the mechanical tachogenerator and rotary angle meter in the DACS feedback circuit. It is proposed to use a small-sized digital sensor to measure current in the DCM armature circuit.

The most energetically advantageous target tracking algorithm is the DPID regulation algorithm without correction of electric drive dynamic characteristics. The most accurate target tracking algorithm is the DPID-regulation algorithm used in conjunction with the algorithm for correcting the electric drive dynamic characteristics, which is synthesized by the linear quadratic regulation state method.

The best compromise variant of target tracking algorithm, which allows to reduce the target tracking error variance by 30% and only doubles the power consumption, is the DPID regulation algorithm used together with the algorithm of correction of electric drive dynamic characteristics, which is synthesized by the method of state regulation with a desired (specified) characteristic equation.

All algorithms in the target tracking stabilization mode use information about the electric drive state vector, which is fed from the Kalman filter output.

In DACS with correction of DCM dynamic characteristics it is possible to reduce the transient time by 40% and reduce by a factor of ten the amplitude of output signal surge under the stepped braking perturbation action in comparison with DACS - without DCM dynamic characteristics correction.

The recommendation for the practical application of the research results presented in this article is as follows. In the process of directed-action sensor operation there are two modes: sensor sensitivity axis orientation (reorientation) and its stabilization. In the orientation (reorientation) mode use DACS with connection of Luenberger observer to the PID regulator algorithms and correction of dynamic drive characteristics. In the mode of stabilizing the sensor sensitivity axis position, use the Kalman filter instead of the Luenberger observer. In both modes, you can use the state regulation method to correct the control object dynamic properties with the desired (specified) characteristic equation.

The use of proposed recommendations will allow to achieve the objectives set in the article: to improve the electric drive dynamic characteristics with a slight increase in energy consumption; to improve reliability and reduce the electric drive mass-size parameters.

The restriction on the stationarity of the mathematical model of the control object can be replaced by quasi-stationarity. In this case the algorithm of the operational identification of the parameters of control object is added to the general algorithm for processing information of control object.

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