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ELECTROMECHANICAL SERVO SYSTEM WITH ANISOTROPIC REGULATOR

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Abstract: A method of multiobjective synthesis for nonlinear multi-mass electromechanical servo systems with uncertain plant parameters based on feed-forward robust stochastic anisotropic control to improve the accuracy of such systems is developed. The method is based on the choice of the robust control target vector by solving the corresponding problem of multiobjective nonlinear programming in which the components of the target function vectors are direct quality indicators that are specified to the system in various modes of its operation. The calculation of the target function vector componentrs and the constraints is algorithmic and is related to the synthesis of anisotropic robust regulators and to the modelling of a synthesized nonlinear system for different operating modes of the system, with different input signals and for various values of the plant parameters. The components of the unknown vector are the required weight matrices which form the target vector of robust control. The synthesis of anisotropic regulators is reduced to the solution of a system of four related Riccati equations. The solution to the problem of multiobjective nonlinear programming is based on particle swarm optimization algorithms. The results of theoretical and experimental research into the effectiveness of a two-mass nonlinear robust electromechanical servo system with synthesized anisotropic robust regulators are presented. The comparison of the dynamic characteristics of the synthesized electromechanical servo system showed that the application of synthesized anisotropic robust regulators improves the parameters of accuracy and reduces the sensitivity of the system to changes in the plant parameters compared to the existing system.

Key words: electromechanical servo systems, feed-forward robust stochastic anisotropic regulator, multiobjective synthesis, dynamic characteristics.

1. Introduction

At present, hydraulic systems used in aircrafts, vehicles, guidance and stabilization of tank guns are everywhere replaced by electrical systems [1–2]. Modern literature uses such expressions as "all-electric aircraft" [3–6], "all-electric vehicle" [7], etc. This trend is due to the creation of modern AC motors, in particular synchronous motors with permanent magnets (PMSM), as well as the achievements of modern power electronics, with the use of which frequency converters are implemented. In particular, for the purpose of improving the accuracy of the control of the main armament of the tanks "Leopard" 2A5/6, "Merkava" Mk3, "Abrams" M1, modern AC electric drives are being developed to replace the existing hydraulic ones [8–10]. The scientific and industrial production unit «VNII "Signal"» has developed and experimentally studied 2E58 Electric Drive of Gun and Turret Stabilization System with an AC electric drive based on PMSM and vector control (VC) to replace existing hydraulic drives of main tank armament guidance and stabilization systems [11–15]. Such an AC electric drive can increase speed and acceleration of the tank turret and gun compared to existing hydraulic drives resulting in higher accuracy of the guidance and stabilization system. Experimental studies of such AC electric drives designed for controlling the turret and gun of the T-72 tank made it possible to increase the speed of movement by up to 1.5 times (up to 45 degrees/sec), as well as to iincrease the smoothness of drives at low speeds [12–13].

The American company "HR Textron", the Israeli company "Elbit" based on the developed system for the tank "Merkava" Mk3, the European concern "EADS", and others offer an all-electric guidance and stabilization system of the main armament (Electric Drive of Gun and Turret Stabilization System) to modernize the Ukrainian tanks T-64B (BM "Bulat") [12, 16–19].

Note also that there is a constant increase in the power of electrical systems. In particular, in the first tank gun elevation axis guidance systems, the electric motor power was 0.5 kW, and at present the electric motor power has reached more than 10 kW [13]. In this case, electrical systems have significant advantages over hydraulic systems.

The electromechanical servo systems are required to demonstrate high performance indicators in various modes. Here are some of the requirements that are set for the sytem of guidance and stabilization of the armament of a lightly-armored vehicle [20]: time of response to a given angle of error; time of acceleration to the nominal speed and time of deceleration to full stop; an error of response to a harmonic signal of a specified amplitude and frequency; a stabilization error when driving at the given speed along a normalized path with a random change in profile; maximum speed of guidance; minimum speed of guidance; failure of guidance at minimum speed. Naturally, all these requirements should take into account the limitations of the voltage and current of the anchor chain of the drive motor, as well as the drive motor rate.

But the presence of elastic elements in the electromechanical servo systems between the drive motor and the operating element, the uncertainty of the plant parameters [20–21], the change in mass-inertia characteristics, complex kinematic schemes, unknown external and internal disturbances do not allow us to obtain potentially high dynamic characteristics inherent in modern electromechanical systems with standard regulators [22–23]. The use of state control by complex electromechanical systems containing nonlinear and elastic elements makes it possible to obtain the acceptable quality indicators [24–26]. To reduce the sensitivity of the synthesized systems to changing the parameters and structure of the control object, as well as to external influences, the robust control is used as the state control [27].

Electromechanical servo systems are often installed on a movable hull. These systems employ the classical structure of the feed-forward regulators by means of electric gyroscopic sensors of angles and angle rates that are installed on the gun and on the hullin the elevation and azimuth axes. However, the use of typical regulators does not allow the accuracy of such a feed-forward electromechanical servo system to be improved [20–21].

The characteristic operating modes of such electromechanical servo systems are to respond to random reference inputs and to compensate random perturbation torques of a wide range of frequencies. This is especially true for the servo systems installed on the movable hull. The basis of a combat in modern conditions is firing off at a high speed and maneuvering movement of the machine, so all modern combat vehicles are equipped with weapon stabilizers, which allows the fire on the move. The probability of a target destruction at maximum speeds, high maneuverability and effective evasion of the machine from the enemy's fire damage are largely determined by the accuracy of maintaining a specified direction of the combat module on the target with intense perturbations from the body of the combat vehicle. The main perturbation of the combat module is the unevenness of the road, which is random. Figure 1 shows a fragment of the implementation of the longitudinal profile of the road [21].

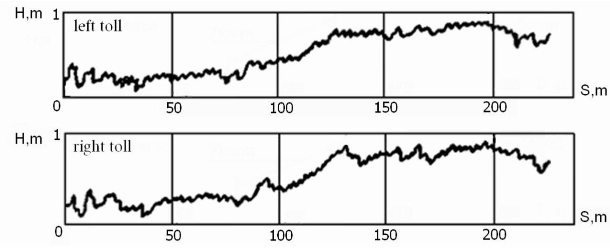


Fig. 1. Longitudinal road profile.

The potential accuracy of such servo systems is determined by the system error from external random disturbances. One type of the robust state control is anisotropic regulator [28]. Such regulators minimize random external influences on the anisotropic norm of the system error.

The purpose of the work is to develop a method of multiobjective synthesis of feed-forward robust stochastic anisotropic control of nonlinear multi-mass electromechanical servo systems with uncertain plant parameters to improve the control accuracy.

2. Problem Statement

Consider the nonlinear model of a discrete system of robust control of a multi-mass electromechanical servo system with a state vector x_k as a difference state equation in the standard form

$$x_{k+1} = f\left(x_k, u_k, \omega_k, \eta_k\right), \quad (1)$$

where u_k is the control, ω_k and η_k are the vectors of external signal and parametric perturbations [28], f is the nonlinear function. The components of the state vector xk are the rates of the drive motor, gearbox and drive mechanism, the elastic forces of high-speed and low-speed shafts [20–21]. The control u_k is represented by the input voltages of drive motors frequency converters.

The components of the vector η_k of the external parametric perturbations are the inertia moments of the control object.

The components of the vector ωk of the external signal perturbations are the perturbation torques acting to the control object, target angles and rates, measurement noises of drive motor current, rate, angle, etc. [20–21].

Mathematical model (1) takes into account the nonlinear dependence of friction on the shafts of the drive motor, rotating parts and working gear element, gaps between teeth gear, constraints of control signals, motor current, motor torque and motor speed.

The main purpose of nonlinear multimass electromechanical servo systems with uncertain parameters of the control object is to maintain its angles and rate at the reference levels.

3. Synthesis Method

For the feed-forward robust stochastic anisotropic control to be synthesized by initial nonlinear system (1), we write the linear mathematical model of a multi-mass electromechanical servo system with a state vector xk as a control object of linear discrete robust control in the standard form of a linear difference equation accepted in the linear theory of robust control:

$$x_{k+1} = Ax_k + B_0\omega_k + B_2u_k + B_1\eta_k , \qquad (2)$$

where A represents the state matrix; B_2 stands for the control matrix; B_0, B_1 are the matrices of external signal and parametric perturbations.

The components of the measurement vector of linear system (2)

$$y_k = C_2x_k + D_{21}\omega_k , \qquad (3)$$

are the directly measured speed of the drive motors angles and speed of the control object (in the form of signals obtained from angular electric gyroscopes and high-speed electric gyroscopes mounted on the gun and hull in horizontal and vertical planes.

An anisotropic regulator is accepted as a linear discrete dynamic system [28] with a state vector ξk, which is given by the difference equation below:

$$\xi_{k+1} = \overline{A}\xi_k + \overline{B}y_k , \qquad (4)$$

$$u_k = \overline{C}\xi_k , \qquad (5)$$

The input of this dynamic system (4) is the measured variables vector yk, and its output is the control vector uk of output system (2), and $\overline{A}$, $\overline{B}$, $\overline{C}$ are the unknown matrices to be determined.

Synthesis of anisotropic regulators is related to the minimization of the anisotropic norm of as target vector of robust control

$$z_k = \left(C_1x_k + D_{12}u_k\right), \qquad (6)$$

which is defined by the following expression [28]

$$\overline{A}(G) = -\frac{1}{2}\ln\det\left(\frac{m\sum}{Trace\left(LPL^T + \sum\right)}\right), \qquad (7)$$

where $P \in R^{n\times n}$ is the controllability gramian G which satisfies the Lyapunov equation

$$P = (A + BL)P(A + BL)^T + B\sum B^T ,$$

The matrices $\sum$, $\sum$ are determined by the Riccati equation relative to the matrix $R \in R^{n\times n}$

$$R = A^TRA + qC^TC + L^T\sum L , \qquad (8)$$

where

$$L = \sum\left(B^TRA + qD^TC\right),$$

$$\sum\left(I_m - B^TRB - qD^TD\right)^{-1} .$$

The central idea of the stochastic robust control systems synthesis is related to the minimization of the anisotropic norm of the system by the control vector u_k , but the maximization of the same system norm by the vector of external parametric perturbations . At the same time, due to the introduction of Hamilton's function, the norm of the vector of external influences with the minus sign minimizes the system sensitivity to the change in the parameters of the control object, and, therefore, ensures the robustness of the system.

Such an approach to the optimization problem corresponds to the games approach, when the first player “control” minimizes the target function, and the second player “external parametric perturbations” maximizes the same target function. Moreover, since the source system is described by a system of difference equations – a matrix equation of discrete state, and both players use the same target function, then such a game is called a differential game with zero sum.

The problem of anisotropic regulators synthesis (4)–(5) is reduced to the solution of the system of four related Riccati equations [28]: the first Riccati equation:

$$\tilde{Y} = A_t^T\tilde{Y}A_t + L_t^T\Pi L_t + Q , \qquad (9)$$

where

$$L_t = \Pi^{-1}F_t^T\tilde{Y}A_t ,$$

$$\Pi = \Gamma - F_t^T\tilde{Y}F ,$$

the second Riccati equation

$$R = A_\omega^TRA_\omega + qC_\omega^TC_\omega + L^T\sum L , \qquad (10)$$

where

$$L = \sum\left(B_\omega^TRA_\omega + qD_\omega^TC_\omega\right),$$

$$\sum\left(I_{m1} - B_\omega^TRB_\omega\right)^{-1} ,$$

the third Riccati equation

$$S = \tilde{A}_{11}S\tilde{A}_{11}^T + \tilde{B}_1\tilde{B}_1^T - \Lambda\Theta\Lambda^T , \qquad (11)$$

where

$$\Theta = \tilde{C}_{21}S\tilde{C}_{21}^T + \tilde{D}\tilde{D}^T ,$$

$$\Lambda = \left(\tilde{A}_{11}S\tilde{C}_{21}^T + \tilde{B}_1\tilde{D}^T\right)\Theta^{-1} ,$$

the fourth Riccati equation

$$T = A_u^TTA_u + C_u^TC_u - N^T\Psi N , \qquad (12)$$

where

$$\Psi = B_u^T T B_u + D_{12}^T D_{12},$$

$$N = -\Psi^{-1}\left(B_u^T T A_u + D_{12}^T C_u\right).$$

4. Robust control target vector choice

A synthesized system comprising nonlinear system (1) closed by robust controller (3)–(4) has certain dynamic characteristics that are determined by the model of control system (1), parameters of measuring devices (2), target vector (5).

The most important stage in the formalization of the problem of optimal control is the choice of the quality criterion, determined both by the functional purpose of the unit and by the capabilities of the mathematical apparatus used.

The problem of the reasonable choice of the quality criterion, despite its relevance, is still unresolved. The choice of the quality criterion is a very complex, ambiguous and, often, contradictory task. It is known [24] that any asymptotically stable control system even with unsatisfactory quality of transient processes is optimal in the sense of some criterion of this type.

From the engineering perspective, it seems natural to establish the optimal criteria that take into account the direct quality indicators for the process control, including steady errors, regulation time, overshoot, magnitude of oscillations, etc., which are physically the most clear and have clear limits of permissible values, and are based on a rich experience in the systems design. However, the methods used in the design of control systems more often involve indirect quality indicators, which, are as a rule easier to calculate and are more convenient in analytical research.

With this approach, the strategy that is best for one of the players is at the same time the worst for the other player. This is the so-called saddle point principle, which corresponds to the condition of equilibrium: the minimum guaranteed loss of the first player is equal to the maximum guaranteed win of the second one, so, none of the players is interested in changing the optimal strategy of behaviour.

According to the modern concept of a guaranteed result, a mathematical model of uncertainty has been developed on the basis of the hypothesis of the "worst" behaviour of perturbing factors [27]. The essence of this hypothesis, overcoming the uncertainty in the problem of control, consists in interpreting uncontrolled perturbing factors as some hypothetical deterministic perturbation, of which only the ranges of its change are known. This perturbation is introduced into the dynamics model of the control object with the assumption of its most unfavorable (extreme) effect on the control process. In other words, it is considered that those values are realized in the apriori given range of perturbation change, resulting in the lowest quality of the control process.

It should be noted that the perturbation introduced into the study admits a very broad interpretation and is not a physical, but an abstract mathematical concept, symbolizing the influence of disturbing factors. Thus, not only the "external" perturbations applied to the object from the side of the environment, but also all sorts of "internal" perturbations (for example, noise, and measurement errors) can be attributed to it. It is also possible to include here uncertain factors related to the inaccuracy of a mathematical description of the object: unknown parameters of the object, unaccounted inertial and nonlinear links, errors in linearization and discretization of the object model.

For target vector (7) to be correctly defined, we introduce the vector of unknown parameters $\chi = \{C_1, D_{12}\}$, the components of which are the required weight matrices (C_1, D_{12}), which form the target vector $z_k$of robust control (7). The vector target function takes the following form

$$F(\chi) = \left[F_1(\chi), F_2(\chi) ... F_m(\chi)\right]^T, \qquad (13)$$

in which the components of the target function vector $F_i(\chi)$ are direct quality indicators that are presented to the system in various modes of its operation. These are time of the first matching, time of regulation, overshooting, etc. [20–21]. To calculate the target function vector (10) and constraints on state variables and control, initial nonlinear system (1)–(2) is modelled by a closed synthesized anisotropic regulator (3)–(4) in various operating modes, with different input signals and for various values of the object parameters [20–21].

5. Solution algorithm

This multiobjective problem of nonlinear programming (13) is solved on the basis of the multiswarm algorithm of particle swam optimization (PSO) [29–30] from Pareto optimal solutions [38] taking into account the preference relations [31].

We used the PSO algorithm, in which the number of swarms m is equal to the number of components of target function vector (13).

The motion of *i*-th particle of *j*-th swarm is described by the following expressions

$$\begin{aligned} v_{ij}(t+1) &= w_j v_{ij}(t) + c_{1j} r_{1j}(t) * \ldots \\ \ldots * &H(p_{1ij}(t) - \varepsilon_{1ij}(t))[y_{ij}(t) - \ldots \\ \ldots - &x_{ij}(t)] + c_{2j} r_{2j}(t) H(p_{2ij}(t) - \ldots \\ \ldots - &\varepsilon_{2ij}(t))[y_j(t) - x_{ij}(t)] \end{aligned}, \quad (14)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1), \quad (15)$$

where $x_{ij}(t)$ and $v_{ij}(t)$ are the position and velocity of i-th particle of j-th swarm.

In (14), $y_{ij}(t)$ and y_j are the best local and global positions of the i–th particle, found respectively by only one i–th particle and all the particles of the j-th swarm.

Two independent random numbers $r_{1j}(t)$, $r_{2j}(t)$ are in the range of [0,1.0], which determine the stochastic components of the particles' velocity.

Positive constants c_{1j} and c_{2j} determine cognitive and social weights of the particles' velocity components. The values of these constants c_{1j} and c_{2j} are chosen taking into account the possible range of unknown parameters of the vector χ.

To fasten te process of finding a solution with small increments of the change in the unknown parameters vector χ, the nonlinear search algoritm Cuckoo Search of PSO [32] was used in (14).

The Heaviside function H is used as a function of swithching particle's motion to the local $y_{ij}(t)$ and global $y_j(t)$ optimum, respectively.

Switching the parameters of the cognitive p_{1ij} and social p_{2ij} components of the particle's velocity to the local and global optimum is accepted in the form of increments of changes in the unknown parameters of the vector χ, when moving to local and global optimum, respectively.

The andom numbers $\varepsilon_{1ij}(t)$ and $\varepsilon_{2ij}(t)$ determine the parameters of switching the particle motion to local and global optimum, respectively. If $p_{1ij} < \varepsilon_{1ij}(t)$ and $p_{2ij} < \varepsilon_{2ij}(t)$, then the velocity component $v_{ij}(t)$ of this i-th particle of the j-th swarm at the step t does not change, and the particle moves in the same direction as at the previous optimization step.

To improve the quality of the solution finding process, the inertia coefficients w_{1j} are used in the range of (0.5–0.9).

As the constraints in this problem, first of all, we took into account the constraints on the motor voltage and current. These limitations are due to technical possibilities of the motor. In addition, there were set some restrictions on the maximum particle's velocities $v_{ij}(t)$ to achieve the desired accuracy of obtaining the corresponding components of the vector solution, as well as to improve the solution convergence.

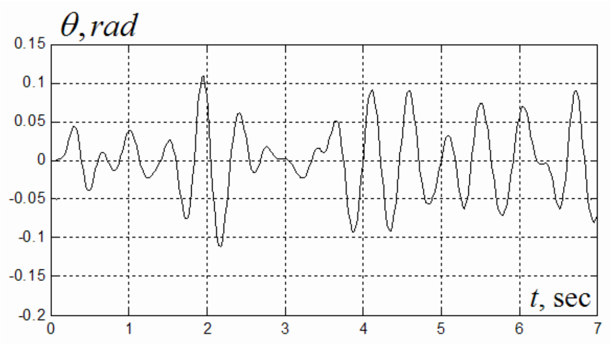
To find a global solution to the original multiobjective problem of nonlinear programming (13) while searching the optimal solutions of the local ones, individual swarms exchange information among themselves. In this case, to calculate the velocity of the particles in one swarm, information on the global optimum obtained by the particles of another swarm is used. This makes it possible to isolate all potential Pareto optimal solutions.

In this case, using the global solution $X_j(t)$ obtained by the j-th swarm as a global optimal solution $X_k(t)$ of the k-th swarm is more preferable on the basis of the preference relation [31].

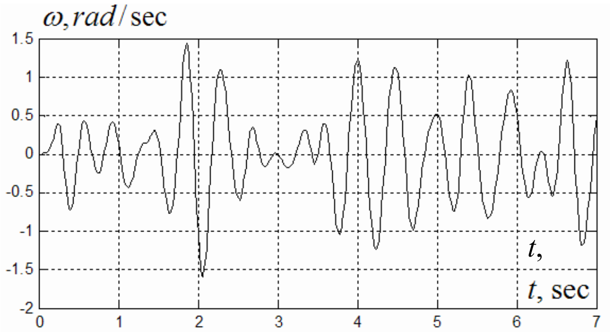
In fact, with this approach the basic idea of the method of successive narrowing the field of compromise solutions is realized: from the initial set of possible solutions, based on information about the relative importance of local solutions, all Pareto optimal solutions that can not be selected according to the available information on the pre-reverence relation. Removal is carried out until the global optimal solution is obtained. As a result of applying this approach, no potentially optimal solution will be removed at each step of the contraction. Note that the PSO algorithms using art is the informed choice of their settings [30].

6. Computer simulation

Consider the research into dynamic characteristics of a two-mass nonlinear electromechanical servo system [21] with synthesized anisotropic regulators and its sensitivity to object parameters change. Let us consider the state variables of this two-mass electromechanical servo system with synthesized anisotropic regulators at a random change in the purturbation torques. Fig. 2 shows the realization of random processes of changing the state variables of the: a) angle and b) the rate with random purturbation torques. It is shown that using the synthesized anisotropic regulators allows a 1.5–2.5 times reduction in the error of compensation of random external perturbation in comparison with the existing system with typical regulators.



a



b

Fig. 2. Realization of random processes of the state variables chanching with random disturbances torques: a – angle$ b – rate.

In fact, the control system has nonlinear elements. This, first and foremost, concerns the availability of dry friction both in the propulsion motor and in the object of control. In addition, the system has nonlinear characteristics of the elements of elasticity between the motor and control object. Consider the influence of these elements on the dynamic characteristics of the system. In this case, we will consider the dynamic characteristics of the system for the three values of the moments of inertia of the working mechanism – the nominal and the moment of inertia, which are twice as great and little as the nominal value. One of the tense criteria for synthesis of a electromechanical servo system is the time of the transient process in the mode of response to small angles. As an example, Fig. 3 shows transient processes of: the object angle in the mode of response to small angles.

As can be seen from Fig. 3, the transient processes do not change significantly when changing the moment of inertia of the working mechanism and satisfy the technical requirements of the system.

As a second example, consider the transient processes of the state variables of this two-mass electromechanical servo system with synthesized anisotropic controllers when working out the system of the given inconsistency of 0.1 *rad*. between the actual and the given angular positions of the control object. In Fig. 4 shows the transient processes of the angle a) and the angle rate b) when working out the electromechanical system of inconsistency 0,1 *rad*. Thus, employing the synthesized anisotropic controllers resulted in 1,5–2 times reduction in the time of transient processes as compared to the existing system with typical regulators.

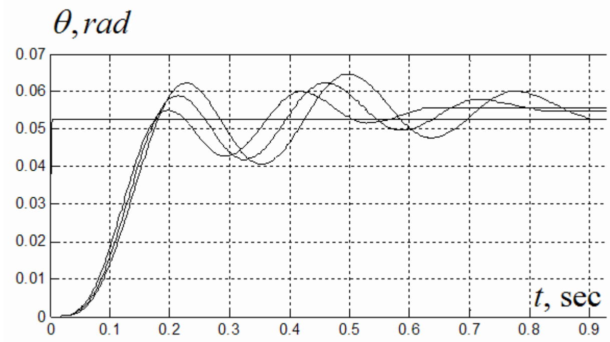
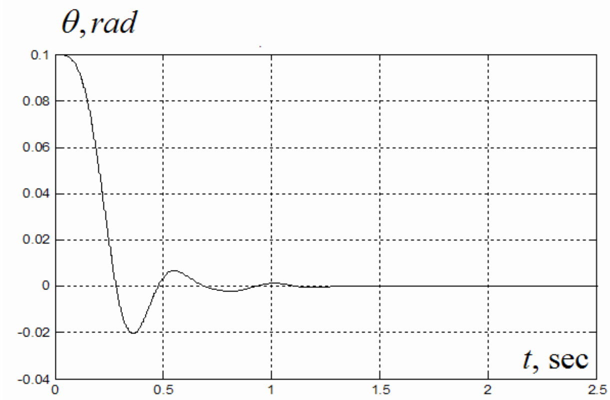


Fig. 3. Transient processes of the object angle in the mode of response to small angles with an anisotropic regulator.



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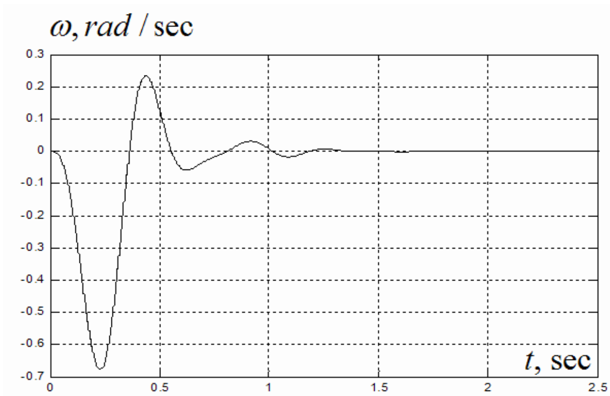


b

Fig. 4. Transient processes of electromechanical system response to inconsistency of 0,1 rad: a) the angle, b) the angle rate.

In this way the comparison of the dynamic characteristics of this two-mass electromechanical servo system with synthesized anisotropic controllers showed that the use of synthesized anisotropic regulators allowed a 1.5-2.5 times reduction in the error of compensation of random external perturbation, a reduction in the time of regulation, and the sensitivity of the system to parameters change in comparison with the existing system with typical regulators.

7. Experimental Researches

For the experimental researche to be carried out in different operating modes, we have developed a model of two-mass electromechanical servo system. Figure 5 shows the model of a two-mass electromechanical servo system.

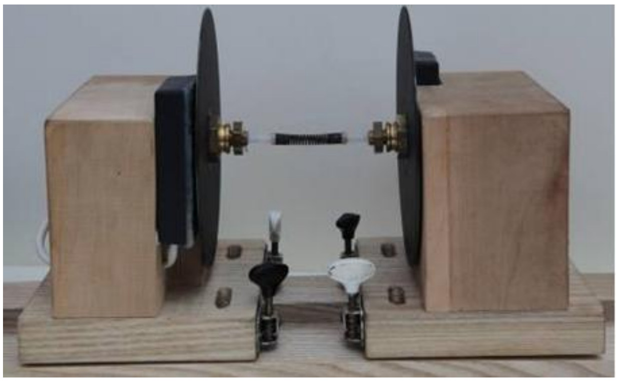


Fig. 5. Two-mass electromechanical servo system model.

The model consists of two electric machines, the shafts of which are connected by an elastic element whose parameters are chosen so that the natural frequencies of the mechanical elastic vibrations of the layout coincide with the experimentally obtained oscillations of the real system.

The block-diagram of a two-mass electromechanical system model is shown in Fig. 6.

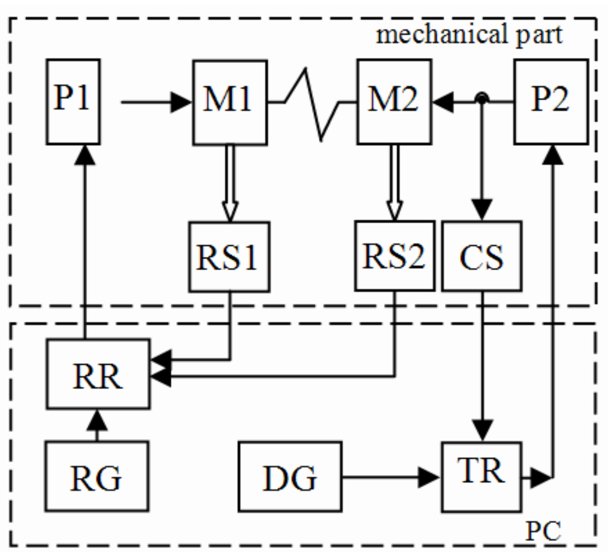
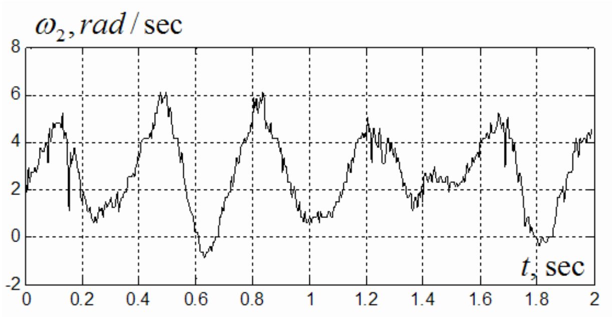


Fig. 6. Block-diagram of two-mass electromechanical servo system model.

The mechanical part of the stand is made on the basis of two identical motors of M1 and M2 types. The M1 motor convertes electrical energy into mechanical, and the M2 motor forms a load for M1. The shafts of the motors are connected by an elastic transmission. The system contains reference generators (RG) and disturbances generators (DG). The external perturbation torques are produced by the M2 motor.

The torques control system of the M2 contains a torque regulator (TR), which generates a perturbation torque. The TR contains feedback on the M2's current, which is measured with a current sensor (CS).



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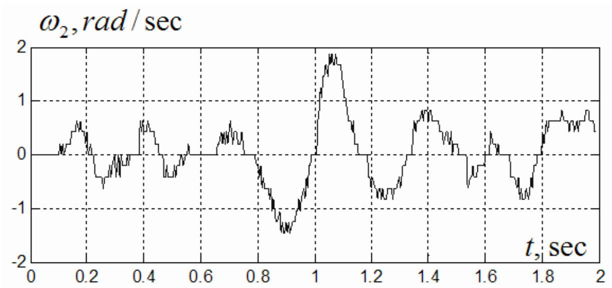


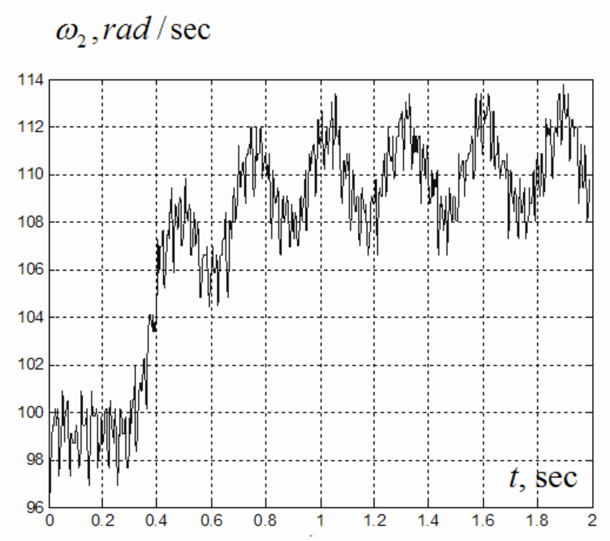
b

Fig. 7. Experimental random processes of the M2 rate at random external disturbance torques:
a – with typical regulators; b – with anisotropic regulators.

In a guidance mode, when the system responds to a reference rate of the control object, the M1 is controlled from the converter R1 by means of the rate regulator (RR) from the rate sensors RS1 or RS2, which measure M1's rate or M2's rate.

Consider the experimental research into the dynamic characteristics of such a two-mass electromechanical servo system model with synthesized anisotropic regulators. Fig. 7 shows the experimental random processes of the M2's rate with a) typical and b) anisotropic regulators at random torques of external disturbances.

As can be seen from these Figures, the maximum rate of M2 with a typical regulator is 4 sec^{-1}, whereas an anisotropic regulator provides the maximum rate of 1.8 sec^{-1}. Thus, the use of an anisotropic regulator can provide more than 2 times reduction in the control error.



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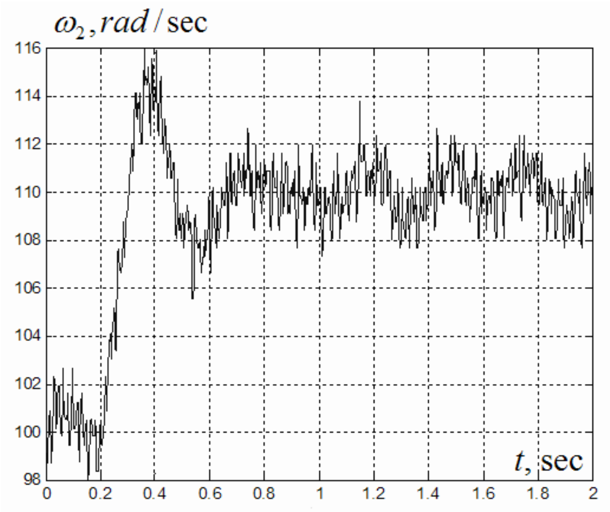

b

Fig. 8. Transient processes of M2's rate:
a – with typical regulators; b – with anisotropic regulators.

Fig. 8 shows experimental transient processes of the M2 rate: a) with a typical regulator and b) with an anisotropic regulator.

The comparison of these transient processes shows that synthesized anisotropic regulators enabled us to shorten the time of the first matching of the transient process of a two-mass electromechanical servo system model from 0.5 *sec* for a system with typical regulators to 0.25 *sec* for a system with anisotropic regulators at almost the same values of overregulation, that improves the rate control system accuracy by 2 times.

8. Conclusions

1. It is the first time when a method of multiobjective synthesis of feed-forward robust anisotropic control by nonlinear multimass electromechanical servo systems with parametric uncertainty is developed. The method is based on the solution of the multiobjective problem of nonlinear programming, in which the vector's components of the target function are direct quality indicators of the system in various modes of its operation.

2. The calculation of the vectors of the target function and constraints is algorithmic and is associated with synthesis of anisotropic robust regulators and modelling of the synthesized nonlinear system for its various operating modes, with different input signals and for various values of the object parameters. The synthesis of anisotropic robust regulators and anisotropic robust observers is reduced to the solution of the system of four related Riccati equations.

3. The computer and experimental results of the analysis of dynamic characteristics of a synthesized two-mass electromechanical servo system showed that the use of synthesized nonlinear robust regulators resulted in a 1.7 times' reduction in the error of stabilization of a given angular position of a plant, a 1,8-2 times reduction in the time of response to the initial angular misalignment of 0.1 rad between the gun and target directions, a 20 % reduction in the system sensitivity to the parameters changes in comparison with the existing system with a standard proportional-differential regulator.

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ЕЛЕКТРОМЕХАНІЧНА СЛІДКУЮЧА СИСТЕМА ІЗ АНІЗОТРОПІЙНИМ РЕГУЛЯТОРОМ

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Розроблено метод багатокритеріального синтезу нелінійних багатомасових електромеханічних слідкуючих систем із параметричною невизначеністю на основі комбінованого робастного стохастичного анізотропійного управління для підвищення точності таких систем. Метод заснований на виборі вектора мети робастного управління шляхом вирішення відповідної задачі багатокритеріального нелінійного програмування, в якій компонентами вектора цільової функції є прямі показники якості, такі як час першого узгодження, час регулювання, перерегулювання перехідних процесів, дисперсія помилки слідкування або стабілізації при відпрацюванні випадкових задаючих, або компенсації випадкових збурюючих впливів і т.д. Причому, ці вимоги пред'являються при роботі системи в різних режимах і в умовах зміни параметрів, а можливо і структури її об'єкта управління. Обчислення компонент вектора цільової функції і обмежень має алгоритмічний характер і пов'язане з синтезом анізотропних регуляторів і моделюванням синтезованої нелінійної системи для різних режимів роботи системи, при різних вхідних сигналах і для різних значень параметрів об'єкта управління. Компонентами вектора невідомих параметрів є шукані вагові матриці, за допомогою яких формується вектор мети робастного управління. Синтез анізотропійних регуляторів зводиться до вирішення системи чотирьох пов'язаних рівнянь Риккати для мінімізації анізотропійної норми вектора мети стохастичного робастного управління. Рішення завдання багатокритеріального нелінійного програмування засноване на алгоритмах оптимізації роєм часток. Наведено результати теоретичних і експериментальних досліджень нелінійної робастної двох масової електромеханічної слідкуючої системи з синтезованими анізотропійними регуляторами. Показано, що застосування синтезованих анізотропійних регуляторів двох масової електромеханічної слідкуючої системи дає змогу зменшити помилку компенсації випадкового зовнішнього збурення в 1,5–2 рази, зменшити час регулювання в 5 разів та знизити чутливість системи до зміни параметрів об'єкта управління порівняно із існуючою системою з типовими регуляторами.

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