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B.I. Kuznetsov, T.B. Nikitina, V.V. Kolomiets, I.V. Bovdui

IMPROVING OF ELECTROMECHANICAL SERVO SYSTEMS ACCURACY

Aim. ***Improving of accuracy parameters and reducing of sensitivity to changes of plant parameters of nonlinear robust electromechanical servo systems of guidance and stabilization of lightly armored vehicle weapons based on multiobjective synthesis. Methodology. The method of multicriterion synthesis of nonlinear robust controllers for controlling by nonlinear multimass electromechanical servo systems with parametric uncertainty based on the choice of the target vector of robust control by solving the corresponding multicriterion nonlinear programming problem in which the calculation of the vectors of the objective function and constraints is algorithmic and associated with synthesis of nonlinear robust controllers and modeling of the synthesized system for various modes of operation of the system, with different input signals and for various values of the plant parameters. Synthesis of nonlinear robust controllers and non-linear robust observers reduces to solving the system of Hamilton-Jacobi-Isaacs equations. Results. The results of the synthesis of a nonlinear robust electromechanical servo system for the guidance and stabilization of lightly armored vehicle weapons are presented. Comparison of the dynamic characteristics of the synthesized servo electromechanical system showed that the use of synthesized nonlinear robust controllers allowed to improve the accuracy parameters and reduce the sensitivity of the system to changes of plant parameters in comparison with the existing system. Originality. For the first time carried out the multiobjective synthesis of nonlinear robust electromechanical servo systems of guidance and stabilization of lightly armored vehicle weapons. Practical value. Practical recommendations are given on reasonable choice of the gain matrix for the nonlinear feedbacks of the regulator and the nonlinear observer of the servo electromechanical system, which allows improving the dynamic characteristics and reducing the sensitivity of the system to plant parameters changing in comparison with the existing system.*** References 12, figures 1.

Key words: **electromechanical servo systems of guidance and stabilization of lightly armored vehicle weapon, nonlinear robust system, multiobjective synthesis, dynamic characteristics.**

Цель. Повышение параметров точности и уменьшение чувствительности системы к изменениям параметров объекта управления нелинейной робастной электромеханической следящей системы наведения и стабилизации вооружения легкобронированной машины на основе многокритериального синтеза. Методология. Метод многокритериального синтеза нелинейных робастных регуляторов для управления нелинейными многомассовыми электромеханическими следящими системами с параметрической неопределенностью основан на выборе вектора цели робастного управления путем решения соответствующей задачи многокритериального нелинейного программирования, в которой вычисление векторов целевой функции и ограничений носит алгоритмический характер и связано с синтезом нелинейных робастных регуляторов и моделированием синтезированной системы для различных режимов работы системы, при различных входных сигналах и для различных значений параметров объекта управления. Синтез нелинейных робастных регуляторов и нелинейных робастных наблюдателей сводится к решению системы уравнений Гамильтона – Якоби – Айзекса. Результаты. Приводятся результаты синтеза нелинейной робастной электромеханической следящей системы наведения и стабилизации вооружения легкобронированной машины. Сравнение динамических характеристик синтезированной следящей электромеханической системы показало, что применение синтезированных нелинейных робастных регуляторов позволяет повысить параметры точности и снизить чувствительность системы к изменению параметров объекта управления по сравнению с существующей системой. Оригинальность. Впервые проведен многокритериальный синтез нелинейной робастной электромеханической следящей системы наведения и стабилизации вооружения легкобронированной машины. Практическая ценность. Приводятся практические рекомендации по обоснованному выбору матриц коэффициентов усиления нелинейных обратных связей регулятора и нелинейного наблюдателя следящей электромеханической системы, что позволяет улучшить динамические характеристики и снизить чувствительность системы к изменению параметров объекта управления по сравнению с существующей системой. Библ. 12, рис. 1.

Ключевые слова: **электромеханическая следящая система наведения и стабилизации вооружения легкобронированной машины, нелинейная робастная система, многокритериальный синтез, динамические характеристики.**

Introduction. Lightly armored wheeled and tracked vehicles produced in Ukraine have high tactical and technical characteristics and successfully compete with foreign weapons [1]. The basis of combat in modern conditions is firing off at a high speed and maneuvering movement of the machine, so all modern lightly armored vehicles in the world equipped with weapons stabilizers, allowing to guide the target fire on the move. The probability of fire engagement of the target at maximum speeds, high maneuverability and effective evasion of the machine against the enemy's fire damage is largely determined by the accuracy of maintaining the specified direction of the combat module on the target with intense perturbations on the machine's side. Increasing the accuracy has an important economic component. For example, the practice of using the Protector combat module in Kongsberg's Crows II version based on actual operation data in 2007 made it possible to reduce the consumption of 12.7-mm cartridges by 70 % due to a sharp increase in the accuracy of the hit from the first shot. Therefore, the issues of further improving the accuracy of weapons stabilization are an urgent problem, both in the development of new weapons systems and in the modernization of existing systems in service.

To systems of guidance and stabilization of lightly armored vehicles weapons, sufficiently stringent requirements are set for the performance indicators in various modes. We bring a part of such requirements for the light-armored vehicle presented to the guidance and stabilization system [1]: time of working out of a given angle of error; acceleration time to rated speed and deceleration time to full stop; an error in working out a harmonic signal of a specified amplitude and frequency; stabilization error when moving along a normalized path with a random profile change with a given speed; maximum speed of guidance; minimum speed of guidance; failure of guidance at minimum speed. Naturally, this should take into account the voltage and current limitations of the anchor chain of the drive motor, as well as the speed of rotation of the drive motor.

The goal of this work is to improve of the accuracy parameters and reduce of sensitivity to changes of plant parameters for electromechanical servo system guidance and stabilization of lightly armored vehicle weapons based on multiobjective synthesis of nonlinear robust control.

Problem statement. Stabilizers of armored vehicles weapons in a vertical and horizontal plane are built according to the same type of scheme [1-4]. With the help of an optical sight, the sight mirror is mounted in the direction of the target, respectively in the horizontal and vertical planes. The specified direction is compared with the actual direction of the armament block and the voltages proportional to the discrepancy signals between the specified directions of the shot lines and the axis of the bore channel are fed to the inputs of the turret drives in the horizontal guidance channel and the arming unit in the vertical guidance channel. In addition, the absolute speed of rotation of the turret in the horizontal plane and the combat module in the vertical plane are measured with the aid of gyroscopic angular velocity sensors mounted on the arms block and used to develop control.

The turret in the horizontal plane and the combat module in the vertical plane are driven by DC motors driven from permanent magnets, whose armature circuits are powered by pulse-width converters. The rotational speed of the motors that drive the turret and the combat module is measured using tachogenerators. The currents of the motor armature anchors are measured by shunts included in the motor armature circuits, converted and also used for control purposes

The presence in the electromechanical servo systems of elastic elements between the drive motor and the operating element, the uncertainty of the parameters of the control objects, the change in mass-inertial characteristics, complex cinematic schemes, unknown external and internal disturbances do not allow to obtain potentially high dynamic characteristics inherent in modern electromechanical systems with standard regulators [2, 3]. The use of state control by complex electromechanical systems containing nonlinear and elastic elements allows obtaining acceptable quality indicators. To reduce the sensitivity of synthesized systems to changing the parameters and structure of the control object and external influences, robust control is used as the state control. Consider the design of such system.

Let us consider the nonlinear model of a discrete plant of robust control of a multimass system with a state vector x_k in the form of a difference state equation in the standard form

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

where u_k is the control vector, ω_k and η_k are the vectors of the external signal and parametric perturbations [5, 6], f is a nonlinear function.

The mathematical model (1) takes into account the nonlinear frictional dependencies on the shafts of the drive motor, the rotating parts of the reducer and the operating element, the play between the teeth of the driving and driven gears, the control constraints, current, torque and engine speed, as well as the moment of inertia of the plant.

Method of synthesis. The task of synthesis is the determination of such a regulator [7, 8] which, based on the measured output of the initial system

$$y_k = Y(x_k, \omega_k, u_k) \quad (2)$$

forming control u_k using a dynamic system described by the difference state equation and output

$$\xi_{k+1} = f(\xi_k, u_k, \omega_k, \eta_k) + \sum_{i=1}^{3} G_i (y_k - \dots - Y(\xi_k, \omega_k, u_k)); \quad (3)$$

$$u_k = \sum_{i=1}^{3} U_i(\xi_k, y_k), \quad (4)$$

where i is the order of the forms G_i and U_i.

The synthesis of the regulator (4) is reduced to determining the matrix of the forms of the regulator gain U_i by minimizing the norm of the target vector

$$z(x_k, u_k, \eta_k) = \sum_{i=2}^{4} Z_i(x_k, u_k, \eta_k) \quad (5)$$

on control vector of $\boldsymbol{u}_k$ and maximization of the same norm on a of plant uncertain vector $\boldsymbol{\eta}_k$ for the worst case disturbance.

The synthesis of the observer (3) is reduced to determining the observer gain coefficients G_i by minimization of the error vector of the recovery of the state vector $\boldsymbol{x}_k$ of the initial system and maximization of the same norm of the error vector along the plant uncertainty vector $\boldsymbol{\eta}_k$ and the vector of external signal influences $\boldsymbol{\omega}_k$, which also corresponds to the worst case disturbance.

Matrices of the regulator U_i and observer G_i gain coefficients are found from approximate solutions of the Hamilton-Jacobi-Isaacs equations [7, 8], in which the matrices of linear forms being found from the four Riccati equations solutions. This approach corresponds to the standard 4-Riccati approach to the synthesis of linear robust or anisotropic regulators [9].

To determine the regulator (4) for plant (1) with target vector (5) consider Hamiltonian function

$$H(x_k, u_k, \eta_k) = z(x_k, u_k, \eta_k) + V_x^T(x_k, u_k, \eta_k) f(x_k, u_k, \eta_k), \quad (6)$$

where V_x are partial derivatives with respect to the state vector $\boldsymbol{x}_k$ of the infinite-horizon performance functional (Lyapunov function)

$$V(x_k, u_k, \eta_k) = \sum_{i=k}^{\infty} z(x_i, u_i, \eta_i). \qquad (7)$$

To determine the robust regulator (4) it is necessary to find the minimum norm of the target vector (5) along the control vector $\boldsymbol{u}_k$ and the maximum of this norm in the external perturbations vector $\boldsymbol{\eta}_k$, which reduces to solving the minimax extremal problem of Hamiltonian function [7]

$$H^*(x_k) = \min_{u_k} \max_{d_k} \{H(x_k, u_k, \eta_k)\}. \qquad (8)$$

The necessary conditions for the extremum of the Hamiltonian function (8) both in the control vector $\boldsymbol{u}_k$ and in the external perturbation vector $\boldsymbol{\eta}_k$ are these equations

$$H_u\left(x_k, u^*(x_k), \eta^*(x_k)\right) = 0\,; \qquad (9)$$

$$H_\eta\left(x_k, u^*(x_k), \eta^*(x_k)\right) = 0\,, \qquad (10)$$

which are Hamilton-Jacobi-Isaacs equations. Here H_u and H_η are the partial derivatives of the Hamiltonian function with respect to the control vector $\boldsymbol{u}_k$ and with respect to the external perturbations vector $\boldsymbol{\eta}_k$.

Note that these equations (9) – (10) are also necessary conditions for optimizing a dynamic game, in which the first player –the regulator which minimizes the target vector, and the second player – external disturbances which maximizes the same target vector.

The difficulty of obtaining a nonlinear discrete control law is due to the fact that the difference Hamilton-Jacobi-Isaacs equations (9) – (10) is a nonlinear algebraic equation, while the Hamilton-Jacobi-Isaacs equations for a continuous system is a partial differential equation. Therefore, the difference Hamilton-Jacobi-Isaacs equations is not a quadratic equations in the control and perturbation.

In this paper we use an approximate solution of the Hamilton-Jacobi-Isaacs equation (9) – (10) assuming the analytical dependences of the nonlinearities of the original system (1), (2), (5) in the form of the corresponding series [8]. Then the linear approximation of the Hamilton-Jacobi-Isaac equation (9), (10) are the algebraic Riccati equations

$$P = A^T PA + R - \begin{bmatrix} A^T PB & A^T PE \end{bmatrix} \ldots$$

$$\ldots \begin{bmatrix} I + B^T PB & B^T PE \\ E^T PA & E^T PE - \gamma^2 I \end{bmatrix}^{-1} \begin{bmatrix} B^T PA \\ E^T PA \end{bmatrix}. \qquad (11)$$

Here, the matrices A and B in (11) are the corresponding matrices of the linear system obtained by linearizing the original nonlinear system (1), (2), (5).

Similarly matrices of the observer G_i gain coefficients (3) are found from approximate solutions of the Hamilton-Jacobi-Isaacs equations type (9) – (10).

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, so that none of the players is interested in changing the optimal strategy of behavior.

According to the modern concept of guaranteed result, a mathematical model of uncertainty is constructed on the basis of the hypothesis of the «worst» behavior of perturbing factors. The essence of this hypothesis, overcoming the uncertainty in the control problem, 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 model of the dynamics of the control object with the assumption of its most unfavorable (extreme) effect on the control process. In other words, it is considered that in the a priori a given range of perturbation change, those values are realized that ensure the lowest quality of the control process.

It should be noted that the perturbation introduced into the study admits a very broad interpretation and does not appear as a physical, but as 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» disturbances (for example, noise and measurement errors) can be attributed to it. It is also possible to include here also uncertain factors related to the inaccuracy of the mathematical description of the object: unknown parameters of the object, unaccounted inertial and nonlinear links, errors in linearization and discretization of the object model.

Robust control target vector choice. A synthesized system including a nonlinear plant (1) that is closed by a robust controller (3) – (4) has certain dynamic characteristics that are determined by the control system model of the system (1), the parameters of the measuring devices (2), the 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 control object and by the capabilities of the mathematical apparatus used.

The problem of a 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 [7] 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 point of view, it seems natural to construct optimal criteria that directly take into account the direct indicators of the quality of the management process, such as steady errors, regulation time, overshoot, magnitude of oscillations, etc., which are physically most clear and have clear limits of permissible values, based on a rich experience in the design of systems. However, in methods of designing control systems, indirect quality indicators are more widely used, which, as a rule, are easier to calculate and more convenient in analytical research.

For the correct definition of the target vector (7), we introduce the vector of the unknown parameters $\chi = \{Z_i(x_k, u_k, \eta_k)\}$, the components of which are the required weight matrices of the norm $Z_i(x_k, u_k, \eta_k)$. We introduce the vector target function

$$F(\chi) = [F_1(\chi), F_2(\chi)...F_m(\chi)]^T \qquad (10)$$

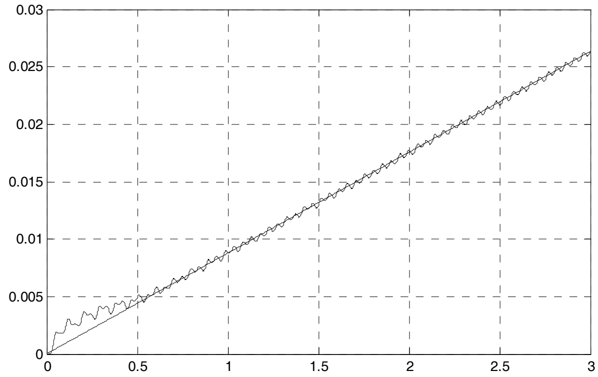
in which the components of the vector target function $F_i(\chi)$ are direct quality indicators that are presented to the system in various modes of its operation such as the time of the first matching, the time of regulation, overshooting, etc. To calculate the vectors objective function (10) and constraints on state variables and control, the initial nonlinear system (1), (2) is modeled by a closed synthesized nonlinear regulator (3), (4) in various modes of operation, with different input signals and for various values of the plant parameters [10, 11]. This multiobjective nonlinear programming problem is solved on the basis of multi-swarm stochastic multi-agent optimization algorithms [12].

Computer simulation results. We present the results of research of dynamic characteristics and sensitivity to the plant parameters change of a nonlinear two-mass electromechanical servo system of lightly armored vehicle weapons [1] with synthesized nonlinear robust regulators. In the existing system, PD regulators are used, which are realized with the aid of a gyroscopic angle sensor and a gyroscopic angular velocity sensor. The introduction of the integral control law leads to the emergence of undamped oscillations in the mode of working out the given angles of the combat module position, due to the presence of dry friction on the shafts of the drive motor and the working member. With the help of robust controllers it was possible to ensure a stable operation of the system taking into account all the essential nonlinearities inherent in the elements of this system when two integrating links are introduced into the control loop.

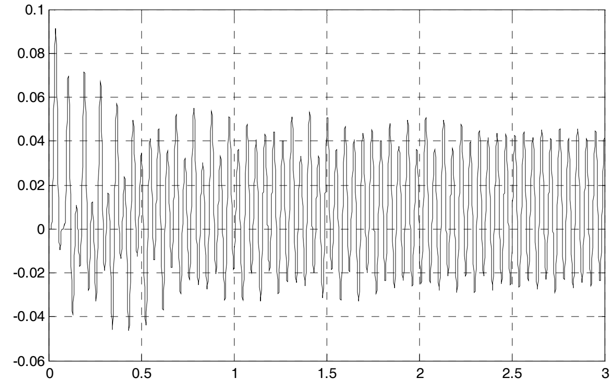
As an example, Fig.1 shows the transient processes of state variables: *a*) the combat module angle; *b*) the combat module speed; *c*) the elasticity moment and *d*) motor speed in the guidance mode with a low speed 0.5 grad/s in the synthesized system. As can be seen from Fig.1,*b* and Fig.1,*d*, the drive motor and the combat module are moving in a «stick-slip» mode. As can be seen from Fig.1,*a*, the established error in the processing of the linearly changing driving force of the gun barrel angle of the combat module of a lightly armored machine is practically zero.

Such system with second-order astatism, taking into account all the non-linearities and the moment of inertia of the working element that changes during operation, made it possible to improve the smoothness of the motion of the control object by more than 3.7 times when hovering at low speeds. We note that this indicator largely determines the potential accuracy of the operation of the electromechanical servo system in one of the most important modes of its operation.

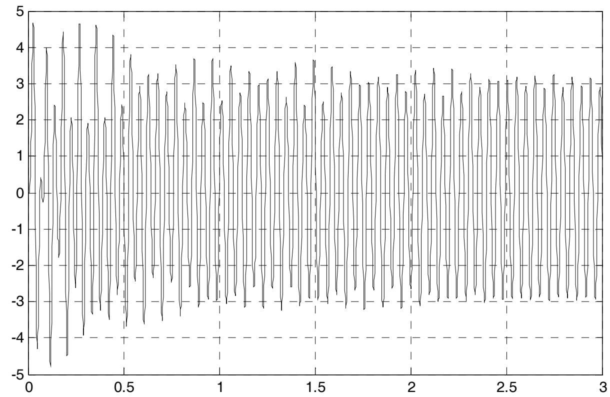
The use of synthesized nonlinear robust controllers has also made it possible to reduce the time of transient processes in the regime of working out small angles by more than 5.3 times in comparison with the existing system. Moreover, when the moment of inertia of the working mechanism changes within the given limits, the transient processes change insignificantly and satisfy the technical requirements imposed on the system.



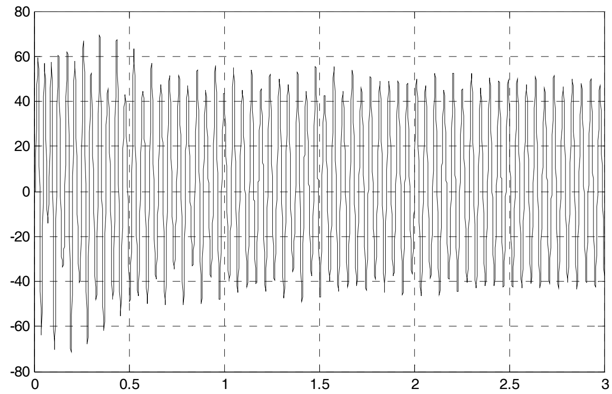
a



b



c



d

Fig. 1. Transient processes of state variables:
a) the combat module angle and *b*) combat module speed;
c) elasticity moment and *d*) the motor rotation speed in the guidance mode at a rate of 0.5 grad/s

The synthesized system also allowed to increase the accuracy of working out harmonic influences of a given range of frequencies in 2.7 – 3.3 times, which increased the efficiency of the system installed on a mobile base moving along an uneven road at a given speed and given parameters of road irregularities.

Experimental researches results. For carrying out of experimental researches the model of a two-mass electromechanical system is developed. The layout 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. Experimental research of model of electromechanical servo system confirmed the correctness of computer simulation results and experimental research.

Conclusions.

1. For the first time the multiobjective synthesis of nonlinear robust regulators for controlling by non-linear multi-mass electromechanical servo systems of lightly armored vehicles weapons with parametric uncertainty based on the choice of the target vector of robust control by solving the corresponding multiobjective nonlinear programming problem. Calculation of the vectors of the objective function and constraints of nonlinear programming problem are algorithmic character and are connected with synthesis of nonlinear robust controllers and modeling of the synthesized system for various operating modes of the system, with different input signals and for different values of the plant parameters is given.
2. Synthesis of nonlinear robust regulators and nonlinear robust observers reduces to solving the system of Hamilton-Jacobi-Isaacs equations.
3. Based on the analysis of the dynamic characteristics of the synthesized servo electromechanical system of lightly armored vehicles weapons have shown that the use of synthesized nonlinear robust controllers has allowed to improve the accuracy parameters and to reduce the sensitivity to plant parameters changes in comparison with the existing system.
4. Further increase of accuracy can be obtained by restoring, with the observer of plant parametric uncertainty vector and of external signal disturbances vector and basis on their design of feed forward control system. In addition, to further improve accuracy, it is expedient to replace the DC drive motor with a high-torque motor and realize a gearless drive with separate stabilization of the aiming and aiming lines.

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B.I. Kuznetsov[1], *Doctor of Technical Science, Professor,*
T.B. Nikitina[2], *Doctor of Technical Science, Professor,*
V.V. Kolomiets[2], *Candidate of Technical Science,*
I.V. Bovdui[1], *Candidate of Technical Science,*
[1] State Institution «Institute of Technical Problems of Magnetism of the NAS of Ukraine»,
19, Industrialna Str., Kharkiv, 61106, Ukraine,
phone +380 50 5766900,
e-mail: kuznetsov.boris.i@gmail.com
[2] Kharkov National Automobile and Highway University,
25, Yaroslava Mudroho Str., Kharkov, 61002, Ukraine,
e-mail: tatjana55555@gmail.com

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