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MULTIOBJECTIVE SYNTHESIS OF TWO DEGREE OF FREEDOM NONLINEAR ROBUST CONTROL BY DISCRETE CONTINUOUS PLANT

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The method of accuracy improving and uncertain plant parameters sensitivity reducing based on multiobjective synthesis of two degree of freedom nonlinear robust control by discrete-continuous plant is developed. Synthesis of nonlinear robust regulators and nonlinear robust observers reduces to Hamilton-Jacobi-Isaacs equations solution. The robust control target vector is choiced by multicriterion nonlinear programming problem solution in which the objective function vectors is direct indexes performance vector that are presented to the system in various modes of its operation. The robust control target vector calculated by synthesized nonlinear robust control system modeling for various modes of system operation with different input signals and for various plant parameters values. The dynamic characteristics modeling end experimental researching results of a synthesized nonlinear electromechanical servo system for system operation various modes with different input signals and for plant parameters various values are given. References 8, figure 1.

Key words: discrete-continuous plant, nonlinear robust control, dynamic characteristics simulation and experimental researches.

Introduction. Large space structures – solar panels and spatially distributed antenna arrays of space vehicles, booms of cranes, hands of anthropomorphic robots, gun barrels are discrete-continuous plants (DCP) [1]. When control such plants, it is necessary to take into account the intrinsic mechanical vibrations caused by the elastic properties of these extended plants, which limits the high accuracy that modern electromechanical systems have with standard regulators [2–4]. For such plants sufficiently stringent requirements are for the index performances set in various modes. Often such plants are mounted on a moving base, on which angles, angular rates and angular accelerations sensors are mounted [1]. To improve the existing systems accuracy two degree of freedom (TDOF) control including closed-loop feed back control and open-loop feed forward control by references and the disturbances are implemented [5]. However, in the existing TDOF control using typical regulators, which limit the further accuracy improving of such system.

The goal of this work is to improve the control accuracy and reduce the plant parameters uncertain sensitivity based on multiobjective synthesis of two degree of freedom nonlinear robust control by discrete-continuous plants.

Problem statement. Consider the DCP mathematical model in solid body and elastic element form. Denote the angle $\varphi(t)$ for solid body and the deviation $y(x, t)$ of the points of the rod from its undeformed state. The torques applied to the solid body equals the actuator torque $T_A(t)$ plus the disturbances torque $T_D(t)$ minus the turnnion friction torque $T_F(t)$. The disturbances torque $T_D(t)$ acts relative to plant as solid body, and the distributed forces $F(x, t)$ acts along the length of the DCP as elastic element.

The equations of plant movement can be written as follows:

$$J\frac{d^2\varphi(t)}{dt^2}(t)-\int_r^{r+l} m_1(x)\frac{\partial^2 y(x,t)}{\partial t^2}dx = T_A(t)+T_D(t)-T_F(t) \tag{1}$$

$$m_1(x)\frac{d^2\varphi(t)}{d^2t}+m(x)\frac{\partial^2 y(x,t)}{\partial t^2}+EI(x)\frac{\partial^4 y(x,t)}{\partial x^4}+\xi EI(x)\frac{\partial^5 y(x,t)}{\partial x^4\partial t}=F(x,t) \tag{2}$$

where J_{0G} is the inertia moment of solid body plant; $m_1(x)$ is the mass of the rod, which is connected with the running weight of the rod $m(x)$ in the ratio $m_1(x) = m(x)(x + r)$, in which r is the distance of the point of at-

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tachment of the rod to the solid body plant, $EI(x)$ and ξ is the DCP distributed rigidity and internal damping coefficient.

We introduce the external disturbances models with the state vectors $x_d(t)$, the components of which are reference and the disturbances torque, that acts on the plant, and them derivatives. We write the mathematical models of external disturbances in the following form:

$$\frac{dx_d(t)}{dt} = f_d\left(x_d(t), \omega_d(t), \eta_d(t)\right), \quad y_d(t) = Y_d\left(x_d(t), \omega_d(t), \eta_d(t)\right); \tag{3}$$

where $\omega_d(t)$, $\eta_d(t)$ are external signal and parametric perturbations vectors [6]; f_d is a nonlinear functions.

Measured external disturbances models output vector are references plant angular position, angular rate and angular acceleration are measured by sensors mounted on measuring systems, as well as the angles, angular rates and angular accelerations are measured by moving base mounted sensors.

Method of synthesis. We introduce the extended system with the state vector $x(t)$ of the extended system, including the plant state vector $x_p(t)$ and the disturbances state vector $x_d(t)$. Then we write the extended system state equation and output equation in the standard form

$$\frac{dx(t)}{dt} = f\left(x(t), u(t), \omega(t), \eta(t)\right), \; y(t) = Y\left(x(t), \omega(t), u(t)\right), \tag{4}$$

where $\omega_{dG}(t)$, $\eta_{dG}(t)$ are the vectors of the external signal and parametric perturbations [6]; f_{dG}, is a nonlinear functions. Initial plant model includes DCP model taking into account the finite number of elastic oscillation forms in (1)–(2) and drive motors model [1], moving base suspension effects. Measured output vector of the initial system is formed by different sensors which measured the plant angular, rate and acceleration [1].

Then the task of nonlinear TDOF robust regulator synthesis is the determination of such regulator [6] which, based on the measured output (4) are formed the control u(t) by the dynamic system is described by the difference state equation and output equation

$$\frac{d\chi(t)}{dt} = G\left(\chi(t), u(t), \omega(t), \eta(t), y(t)\right); \qquad u(t) = R\left(\chi(t), y(t)\right), \tag{5}$$

where G and R are nonlinear functions.

We introduce the robust control target vector

$$z\left(x(t), u(t), \eta(t)\right) = Z\left(x(t), u(t), \eta(t)\right), \tag{6}$$

where Z is nonlinear function.

Then the synthesis of the nonlinear robust regulator is reduced to determining the nonlinear functions R by minimizing target vector norm (6) on control vector $u(t)$ and maximization of the same norm on plant uncertain vector $\eta(t)$ for the worst case disturbance. Nonlinear functions G and R are determined from of the Hamilton-Jacobi-Isaacs equations solutions [6, 7].

Dynamic characteristics of synthesized system including a nonlinear plant (4) is closed by a nonlinear robust controller and nonlinear robust observer (5) are determined by the control system model of the system, the measuring devices parameters and the target vector (6). For the correct definition of the target vector (6), we introduce the unknown parameters vector which is nonlinear target vector function (6) parameterization matrices. We introduce the objective function vector are direct index performance vector that are presented to the system [1]. The index performance vector calculated by modeling of the initial nonlinear system (4), is closed by synthesized nonlinear regulator (5) in various operation modes with different input signals and for plant parameters values various [1]. This multiobjective nonlinear programming problem is solved based on multi-swarm stochastic multi-agent optimization algorithms from Pareto optimal solutions [8].

In such TDOF nonlinear robust control by DCP closed loop feed back control is calculated based on plant state vector, but open-loop feed forward control is calculated based on reference and disturbance models state vector. Moreover, nonlinear robust feed back and feed forward control are calculated simultaneously based on the Hamilton-Jacobi-Isaacs equations solutions [6, 7].

Implementation example. As an example of the implementation of synthesized robust control by DCP we consider T-64BM tank 2A46-2 gun stabilization system. This system is designed to guide for given angular positions and contains from two angular position servo systems in elevation and azimuth axis [1]. The system is mounted on the moving base. Closed -loop feed back control is implemented using electric gyroscopic sensors are mounted on the plant in elevation and azimuth axis. This sensors are measured plant angular positions, plant angular rate and plant angular acceleration in elevation and azimuth axis. So the output vector (3) components are the plant angles, angular rates and angular acceleration in elevation and azimuth axis are measured by electric gyroscopic sensors are mounted on plant in elevation and azimuth axis.

To improve the servo system accuracy two degree of freedom control [5] is implemented. Open-loop feed forward control by reference is realized by means of electric gyroscopic sensors are mounted on measuring systems in elevation and azimuth axis. Open -loop control by disturbance is realized by electric gyroscopic sensors are mounted on the moving base in three planes.

The angular positions references are determined by the separate optical or radio technical measuring systems in elevation and azimuth axis. This measuring systems are mounted on a gyro-stabilized platform. In addition to the references plant angular positions, these measuring systems also are measured the angular rate and angular acceleration of changes in the references plant angular position by electric gyroscopic sensors are mounted on these measuring systems. The output vector components (3) are the references plant angular position, the angular rate and angular acceleration of changes in the references plant angular position are measured by electric gyroscopic sensors are mounted on this measuring systems.

On the moving base are mounted electric gyroscopic sensors of angles, angular rates and angular accelerations in three base rotation axis. The output vector (3) components are the angles, angular rates and angular acceleration in three base rotation axis are measured by electric gyroscopic sensors are mounted on moving base. In addition, linear accelerometers are measured the acceleration of the moving base in three axes also are mounted on the moving base. These accelerometers are used to evaluate the distributed forces $F(x, t)$ in (1) are acted along the length of the plant as elastic element in elevation and azimuth axes.

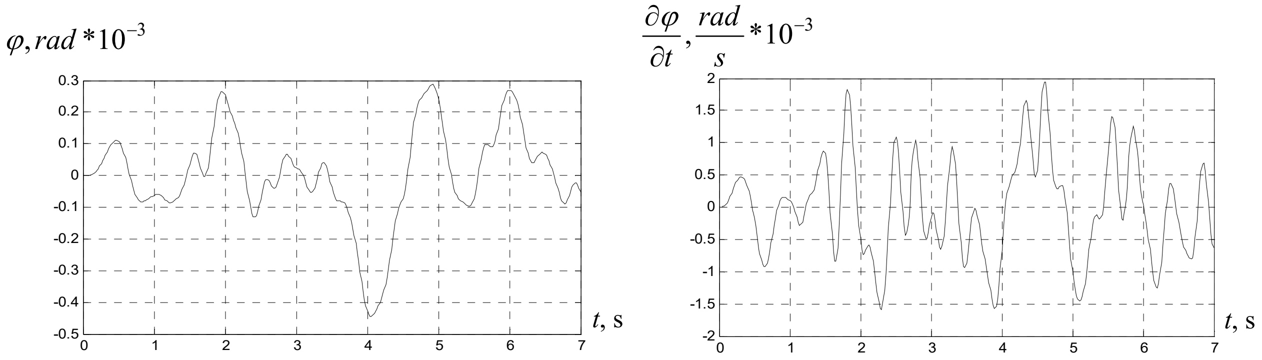
The control $u(t)$ in (3) is the input of the drive motors frequency converters are powered by a synchronous motors with permanent magnets and with direct actuator torques $TA(t)$ control in (1) in elevation and azimuth axis.

Computer simulation results. Comprehensive research of dynamic characteristics and sensitivity to the plant parameters change of the electromechanical system with DCP for T-64BM tank 2A46-2 gun stabilization system with synthesized nonlinear robust regulators are developed. The basis of combat in modern conditions is firing off at a high speed and maneuvering movement of the tank. This operation mode determines potential accuracy of the tank weapon stabilization systems while firing on the move. On Figure are shown state variables random processes implementation of the synthesized electromechanical tank gun stabilization systems in the azimuth axis when the tank is moved at a speed of 8 $m*s^{-1}$ along the standard tank route. On Figure are shown: a) the of plant and the given direction deviation angle $\varphi(t)$ and b) its derivative $d\varphi(t)/dt$. As can be seen from this figure, the error of stabilization of a given angle of a tank gun is about 0.3 mrad, which is about 1.7 times less than the error of a system with a typical proportional-differential controller [1] and iscorresponded to the modern tank weapons stabilization system accuracy.

During the simulation of the dynamic characteristics of the synthesized electromechanical tank armament stabilization systems, it was found that the use of nonlinear robust control made it possible to reduce more then 1.8 times the time spent on working out the initial angular mismatch of 0.1 *rad* between gun and targets directions. When the plant inertia moment was changed by 30 %, the mining time was changed by less than 10 % while maintaining the level of overregulation, while in the system with a typical regulator, the mining time was changed to 30 % with a significant change in the system overshoot. Thus, the use of nonlinear robust controllers also made it possible to reduce the sensitivity of the system to plant parameters changes as compared to the existing system.

Experimental researches results. Experimental researches of T-64BM tank 2A46-2 gun electromechanical servo system as DCP with TDOF nonlinear robust controller in different operating modes are developed. At the beginning the experimental researches of the dynamic characteristics of gun as DCP of robust control are carried out. To measure the deformations of the tank gun barrel caused by elastic vibrations of the barrel strain gages are glued to the barrel of the tank gun at a distance of 0.8 m, 2.3 m and 3.8 m from the gun trunnions axis. Based on these experimental researches, the mathematical model of gun as DCP of robust control (1)-(2) was refined. In particular the experimentally determined resonant frequency of the T-64BM tank 2A46-2 gun barrel elastic vibrations is 10.14 Hz. Experimental research of gun electromechanical servo system confirmed the correctness of computer simulation results.

Based on the analysis of experimental researches and computer simulation results of dynamic characteristics of the synthesized electromechanical tank armament stabilization systems as a DCP are shown that the use of synthesized nonlinear robust regulators made it possible to reduce by 1.7 times the error of stabilization of a given angular position of a tank gun when the tank is moved along the standard tank route, reduce by 1.8–2 times the time spent working off the initial angular misalignment of 0.1 rad between the gun and target directions, reduce by 20 % the system sensitivity to plant parameters changes in comparison with the existing system with standard proportional-differential regulator.



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It is shown that experimental and calculated dynamic characteristics does not exceed on 20 %.

Conclusions. For the first time the method of multiobjective synthesis of two degree of freedom nonlinear robust control by discrete-continuous plant to accuracy improving and to uncertain plant parameters sensitivity reducing is developed.

The multiobjective synthesis of two degree of freedom nonlinear robust control by discrete-continuous plant is reduced to Hamilton-Jacobi-Isaacs equations solution. The robust control target vector is choice by multicriterion nonlinear programming problem solution. The objective function vectors are direct indexes performance vector that are presented to the system in various modes of its operation. The calculation of the robust control target vector associated to synthesized nonlinear system modeling for system operation various modes with different input signals and for the plant parameters various values.

As a result of synthesis of two degree of freedom nonlinear robust control by discrete-continuous plant are showed that the use of synthesized controllers allowed to improve the control accuracy and to reduce the sensitivity of the system to plant parameters changes in comparison with the existing systems.

Field experimental researches of two degree of freedom nonlinear robust control by electromechanical servo system are shown that experimental and calculated dynamic characteristics does not exceed on 20 %.

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БАГАТОКРИТЕРІАЛЬНИЙ СИНТЕЗ НЕЛІНІЙНОГО РОБАСТНОГО КЕРУВАННЯ З ДВОМА СТУПЕНЯМИ СВОБОДИ ДИСКРЕТНО-КОНТИНУАЛЬНИМ ОБ'ЄКТОМ

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Розроблено метод підвищення точності та зменшення чутливості до невизначеності параметрів об'єкту керування на основі багатокритеріального синтезу нелінійного робастного керування з двома ступенями свободи дискретно-континуальним об'єктом керування. Синтез нелінійних робастних регуляторів та нелінійних робастних спостерігачів зводиться до розв'язання рівнянь Гамільтона-Якобі-Айзекса. Вектор мети робастного керування визначається на основі рішення завдання багатокритеріального нелінійного програмування, вектором цільової функції якої є прямі показники якості, що пред'являються до системи у різних режимах її роботи. Ця векторна цільова функція обчислюється під час моделювання синтезованої системи в різних режимах роботи з різними вхідними сигналами та для різних значень параметрів об'єкту керування. Наведено результати моделювання та експериментальних досліджень вказаної системи. Бібл. 8, рис. 1.

Ключові слова: дискретно-континуальний об'єкт керування, нелінійне робастне керування, моделювання динамічних характеристик, експериментальні дослідження динамічних характеристик.

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МНОГОКРИТЕРИАЛЬНЫЙ СИНТЕЗ НЕЛИНЕЙНОГО РОБАСТНОГО УПРАВЛЕНИЯ С ДВУМЯ СТЕПЕНЯМИ СВОБОДЫ ДИСКРЕТНО-КОНТИНУАЛЬНЫМ ОБЪЕКТОМ

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Разработан метод повышения точности и снижения чувствительности к неопределенности параметров объекта управления на основе многокритериального синтеза нелинейного робастного управления с двумя степенями свободы дискретно-континуальным объектом управления. Синтез нелинейных робастных регуляторов и нелинейных робастных наблюдателей сводится к решению уравнений Гамильтона-Якоби-Айзекса. Вектор цели робастного управления определяется на основе решения многокритериальной задачи нелинейного программирования, в которой векторная целевая функция является вектором показателей качества, предъявляемых к системе в разных режимах ее работы. Эта векторная целевая функция вычисляется при моделировании синтезированной нелинейной робастной системы для разных режимов работы с различными входными сигналами и для различных значений параметров объекта управления. Приведены результаты моделирования и экспериментальных исследований динамических характеристик указанной системы. Библ. 8, рис. 1.

Ключевые слова: дискретно-континуальный объект управления, нелинейное робастное управление, моделирование динамических характеристик, экспериментальные исследования динамических характеристик.

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