ABSTRACT

of the dissertation submitted for the degree of Doctor of Philosophy (PhD) in the specialty 8D07105 – "Space Engineering and Technologies"

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Development of a parameter synthesis method for a nonlinear satellite attitude control system based on its mathematical model in linear form.

Relevance of the Research

The satellite attitude control system is one of the main onboard systems determining the possibility of performing mission flight modes. For small spacecraft and nanosatellites, the attitude control problem is of particular importance, since limited mass-dimensional, power, and computational resources require the use of control algorithms that are technically feasible and require minimal tuning complexity.

One of the widely used means of active three-axis stabilization is reaction wheel actuators. In such a system, control torques are generated by changing the angular velocities of reaction wheels installed along the axes of the body-fixed coordinate system. This technical solution does not require propellant consumption and enables long-term satellite attitude control.

At the same time, the "satellite–reaction wheels" system is a nonlinear mechanical system whose motion is described by rotational dynamics equations, quaternion kinematic equations, and actuator equations. The nonlinearity of the model, cross-channel coupling, the influence of the initial angular momentum, as well as constraints on control torques and angular velocities of reaction wheels complicate the problem of synthesizing the control law parameters.

Known approaches to SACS synthesis use locally linearized models, Lyapunov methods, feedback linearization, SDRE/SDARE approaches, robust and optimal controllers, as well as numerical optimization methods. These methods make it possible to solve a wide range of satellite stabilization and reorientation problems. However, when they are applied, the relationship between the control law parameters, the roots of the characteristic equation, the shape of the transient response, the response speed, and the physical constraints of reaction wheel actuators is often not defined in an explicit analytical form. As a result, the choice of controller parameters requires additional numerical tuning and verification for each specific object.

Thus, the development of a method for synthesizing the parameters of a satellite attitude control system with reaction wheel actuators is relevant, as it enables simultaneous consideration of its stability requirements, transient response shape, response speed, and physical constraints of the actuator system.

Aim of the Research

The aim of the research is to develop a method for synthesizing the parameters of the satellite attitude control law with reaction wheel actuators based on the linear form of a nonlinear mathematical model, ensuring a prescribed aperiodic shape of

the transient response, selection of the required response speed, and consideration of constraints on the control torque and angular velocity of the reaction wheels.

Research Objectives

To achieve the stated aim, the following tasks are addressed in the dissertation:

1. To review and analyze existing methods for the synthesis of satellite attitude control systems with reaction-wheel actuators.
2. To formulate the mathematical basis for synthesizing the parameters of the control law based on the linear form of the nonlinear satellite attitude control system.
3. To develop a method for decomposing the synthesis problem of the satellite attitude control system into the problem of forming the required shape of its transient response and the problem of ensuring its speed of response.
4. To obtain analytical relations for selecting the parameters of the PD control law that ensure an aperiodic transient response.
5. To develop a procedure for taking into account the physical constraints of the actuators.
6. To calculate the parameters of the control law and perform numerical simulation of the nonlinear satellite attitude control system for two research objects.
7. To verify the operability of the satellite attitude control system with the calculated control law parameters in a satellite simulation model.

Research Methods

To solve the tasks required to achieve the stated aim, methods of automatic control theory, rigid body dynamics, stability theory of linear and nonlinear systems, methods for analyzing characteristic equations, quaternion representation of attitude motion, numerical integration of systems of differential equations, as well as simulation modeling in MATLAB/Simulink and Simscape Multibody environments were used.

Scientific Novelty of the Research

The scientific novelty of the work consists in the development of a method for synthesizing the parameters of a satellite attitude control system with reaction-wheel actuators, in which the parameters of the PD control law are determined based on the linear form of the original nonlinear system and the normalized characteristic equation.

The new results of the dissertation include the following:

1. A method has been developed for synthesizing the parameters of the PD control law for satellite attitude control with reaction-wheel actuators based on the linear form of the original nonlinear system.
2. A decomposition of the synthesis problem is proposed into the formation of an aperiodic transient response in relative time and the selection of the scaling factor for the transition to real time.
3. Analytical relations have been obtained for the optimal parameters of the control law corresponding to the maximum degree of stability of the satellite attitude control system, which is associated with multiple real negative roots of the normalized characteristic equation.

4. An algorithm has been developed for selecting the scaling factor for the transition from relative time to absolute time, ensuring compliance with the requirements imposed by the constraints on control torques and angular velocities of the reaction wheels.

5. It has been shown that the proposed computational procedure is applicable to objects with different mass-inertial characteristics and preserves a unified structure for synthesizing the parameters of the control law.

6. Simulation verification of the synthesized control law has been performed using a model of the experimental prototype of the satellite attitude control system in the Simscape Multibody environment.

Scientific and Practical Significance of the Dissertation

The scientific significance of the work lies in the development of a method for synthesizing the parameters of a nonlinear SACS according to the performance indicators of linear systems. The proposed approach does not replace the original nonlinear model with a local linear approximation, but uses its linear form and establishes a direct relationship between the control law parameters and the structure of the characteristic equation.

The practical significance of the dissertation lies in the possibility of applying the developed method in the design of attitude control systems for small spacecraft with reaction wheel actuators.

The proposed method can be used for preliminary selection of PD control law parameters, determination of the admissible response speed of a SACS, assessment of the influence of actuator constraints, selection of reaction wheel parameters, and construction of simulation models for testing attitude control algorithms.

The practical value of the method is that the calculation of the control law parameters is performed analytically and does not require iterative tuning based on the transient response. At the same time, the controller parameters are directly related to the inertia characteristics of the object, the time scale, and the constraints on the control torque and angular velocity of the reaction wheels.

Main Provisions Submitted for Defense:

1. A method for synthesizing the parameters of the PD control law for satellite attitude control with reaction-wheel actuators based on the linear form of the original nonlinear system.

2. A method for decomposing the synthesis problem of the satellite attitude control system into two subproblems: obtaining an aperiodic transient response in relative time and selecting the scaling factor for the transition to real time.

3. Analytical relations for the parameters of the PD control law that ensure the maximum speed of response of the satellite attitude control system, corresponding to multiple real negative roots of the normalized characteristic equation.

4. An algorithm for selecting the scaling factor for the transition from relative time to absolute time, ensuring compliance with the requirements imposed by the constraints on control torques and angular velocities of the reaction wheels.

5. Results of numerical and simulation modeling confirming the applicability of the developed method to a model microsatellite and an experimental prototype of the satellite attitude control system.

Personal Contribution of the Applicant

The author analyzed modern methods for synthesizing satellite attitude control systems with reaction-wheel actuators, considered the mathematical model of the dynamics of the "satellite–reaction wheels" system, investigated the linear form of the original nonlinear system of differential equations describing the dynamics of the satellite attitude control system, developed a method for synthesizing the parameters of the PD control law according to the prescribed shape of the transient response and the required speed of response of the satellite attitude control system, calculated the scaling factor for the transition to real time taking into account actuator constraints, performed numerical simulations of a model microsatellite and an experimental prototype of the satellite attitude control system, and developed a simulation model of the experimental prototype in the Simscape Multibody environment.

Approbation of the Dissertation Results

The main provisions and results of the dissertation were presented and discussed at scientific seminars, department meetings, and scientific and practical events devoted to space engineering, dynamics and motion control of spacecraft, automatic control theory, and the development of attitude control systems for small satellites.

Scientific Publications

Based on the research results, 13 printed works were published, including:

- articles in international journals indexed in the Scopus and Web of Science databases – 3;
- articles recommended by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan – 4;
- publications in Springer proceedings – 2;
- articles published in proceedings of international scientific and practical conferences – 4.

Scope and Structure of the Dissertation

The dissertation consists of an introduction, four chapters, a conclusion, a list of references, and an appendix.

The Introduction substantiates the relevance of the research topic, defines the object and subject of the study, presents the scientific novelty and practical significance, the main provisions submitted for defense, the reliability of the obtained results, and provides information on the approbation of the work and publications.

In Chapter 1, a review of methods for synthesizing the parameters of satellite attitude control systems is carried out, and the research problem is formulated. The satellite attitude control system is considered as an object of synthesis; the specific features of systems with reaction-wheel actuators, the main directions of synthesis methods, and the methodological foundations for synthesizing dynamic parameters are analyzed; the aim and objectives of the work are formulated.

In Chapter 2, a method for synthesizing a nonlinear satellite attitude control system based on the performance indices of linear systems is developed. The chapter considers the linear form of the mathematical model of the satellite attitude control system, the analysis of stability and quality of control processes, the decomposition of the problems of obtaining the required shape of the transient response and the required speed of response, optimal synthesis of the transient response shape, an analytical method for determining the parameters of the control law, and the consideration of constraints on control torques and angular velocities of the reaction wheels.

Chapter 3 presents the calculation of parameters and simulation of a nonlinear satellite attitude control system based on its linear form. The characteristics of a model microsatellite and an experimental SACS prototype are considered, their parameters and transient responses are calculated, and a comparative analysis of the simulation results is performed.

Chapter 4 presents a simulation model of an experimental satellite prototype with reaction wheel actuators. The synthesized control law is verified for single-channel, two-channel, and three-channel commands; the influence of the time scale and the processes of damping the initial angular velocity are analyzed.

The conclusion reflects the main results and conclusions of the dissertation.

The appendix presents the simulation model of the experimental satellite prototype with reaction wheel actuators.