

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 stability analysis method for a nonlinear satellite attitude control system based on its mathematical model in linear form.

Relevance of the Research

Satellite attitude control systems are among the key onboard systems of a spacecraft, since they ensure the required spatial orientation of the spacecraft body, payload pointing, antenna and solar array orientation, as well as the implementation of mission-specific flight modes. This problem is of particular importance for small spacecraft and nanosatellites, where limited power, mass, dimensional, and computational resources require compact, reliable, and technically feasible control algorithms.

One of the widely used approaches to active three-axis stabilization is the satellite attitude control system (SACS) with reaction wheel actuators. In such systems, control torques are generated by changing the angular velocities of reaction wheels installed along the spacecraft axes. This technical solution does not require propellant consumption and enables precise attitude control over a long period of operation.

At the same time, the dynamics of the “satellite–reaction wheels” system is essentially nonlinear. It is associated with quaternion kinematics, redistribution of angular momentum, and dependence of motion on initial conditions. Existing studies on the analysis and synthesis of satellite attitude control systems use locally linearized models, Lyapunov methods, feedback linearization, backstepping, sliding mode control, SDRE/SDARE, H_2/H_∞ approaches, and other methods. However, a significant part of these approaches is either limited to the analysis of local stability in the neighborhood of a prescribed operating mode or requires the construction of special nonlinear, robust, or optimization-based control laws.

In this regard, the development of a method for stability analysis of the satellite attitude control system is relevant, as it preserves the connection with its original nonlinear model while enabling the use of the framework of linear automatic control theory. This approach makes it possible to analytically determine the conditions for asymptotic stability of the satellite attitude control system and the admissible parameters of the PD control law, taking into account the initial angular momentum of the satellite.

Aim of the Research

The aim of this dissertation is to develop and substantiate a method for stability analysis of a satellite attitude control system with reaction-wheel actuators based on representing its nonlinear dynamics in a linear form with time-varying coefficients, investigating the asymptotic properties of angular momentum, and

determining the stability conditions of the satellite attitude control system in the parameter space of the PD control law.

Research Objectives

To achieve the stated aim, the dissertation addresses the following tasks:

1. To develop a mathematical model of a satellite attitude control system with reaction-wheel actuators based on the equations of rotational dynamics, a quaternion representation of attitude, and a PD control law.
2. To substantiate the possibility of representing the original nonlinear system of differential equations describing the dynamics of the satellite attitude control system in a linear form with time-varying coefficients under a special choice of state variables.
3. To investigate the asymptotic properties of the angular momentum of the “satellite–reaction wheels” system and to establish the relationship between its limiting characteristics and the coefficients of the linear form.
4. To formulate a limiting linear system of equations with constant coefficients and to obtain the dependence of the coefficients of its characteristic polynomial on the parameters of the control law and the initial angular momentum of the satellite.
5. To determine the conditions for asymptotic stability of the satellite attitude control system in the parameter space of the PD control law based on coefficient stability criteria for control systems.
6. To perform an independent verification of the obtained stability conditions of the satellite attitude control system using classical criteria of linear automatic control theory.
7. To compare numerical solutions of the original nonlinear system of equations and its derived linear form under various initial conditions.
8. To experimentally verify the operability of the selected control structure on a prototype of a satellite attitude control system with reaction-wheel actuators.

Research Methods

The dissertation uses the mathematical apparatus of rigid body dynamics, methods of automatic control theory, quaternion attitude representation, methods for transforming nonlinear differential equations into a variable-coefficient linear form, coefficient-based stability criteria, the Sokolov–Lipatov criterion, the Hurwitz criterion, the Mikhailov criterion, computer simulation methods, numerical calculations, and hardware-in-the-loop experimental tests.

Scientific Novelty of the Research

The scientific novelty of the dissertation lies in the development of a method for stability analysis of a nonlinear satellite attitude control system with reaction wheel actuators based on representing its dynamics in a variable-coefficient linear form.

The new scientific results include the following:

1. A representation of the nonlinear system of differential equations describing the dynamics of a SACS with reaction wheels in a variable-coefficient linear

form has been developed, while preserving the connection with the original equations of motion.

2. A relationship has been established between the asymptotic properties of the angular momentum of the “satellite–reaction wheels” system and the coefficients of the characteristic polynomial of the limiting linear system.
3. Conditions for asymptotic stability of the SACS have been obtained, expressed through the stability of the limiting linear system and the behavior of the variable coefficients of the original linear form.
4. The influence of the initial angular momentum of the satellite on the coefficients of the characteristic polynomial of the limiting system and on the admissible parameter region of the PD control law has been shown.
5. The stability of the limiting system has been verified through the combined application of coefficient-based, algebraic, and frequency-domain methods for the stability analysis of the satellite attitude control system.
6. Experimental verification of the selected control structure has been performed on a laboratory prototype of the SACS with reaction wheel actuators.

Scientific and Practical Significance of the Dissertation

The scientific significance of the work consists in the development of a method for stability analysis of nonlinear satellite attitude control systems that enables the transition from the original nonlinear model to a variable-coefficient linear form without replacing the full dynamics by a local approximation. This approach expands the possibilities of applying classical stability criteria to the analysis of SACS with reaction wheel actuators.

The practical significance of the dissertation lies in the possibility of using the obtained method in the design of attitude control systems for small spacecraft with reaction wheel actuators. The developed approach can be applied in mathematical modeling of SACS, preliminary selection of PD control law parameters, construction of stability regions, analysis of the influence of initial angular momentum, and development of laboratory test benches and prototypes for testing attitude control algorithms for small satellites.

Main Provisions Submitted for Defense

1. A method for representing the original nonlinear system of differential equations describing the dynamics of a SACS with reaction wheel actuators in a variable-coefficient linear form.
2. A method for investigating the asymptotic stability of the satellite attitude control system, which reduces the analysis of the original nonlinear model to the stability analysis of the model represented in a linear form.
3. A coefficient-based method for constructing the stability region of the satellite attitude control system in the parameter space of the PD control law, considering the initial angular momentum of the satellite.
4. Results of numerical and experimental confirmation of the operability of the proposed approach.

Personal Contribution of the Applicant

The author analyzed modern methods of satellite attitude control and stability analysis methods for control systems, developed a mathematical model of the

dynamics of the “satellite–reaction wheels” system, transformed the original nonlinear system of differential equations describing the dynamics of the satellite attitude control system into a linear form with time-varying coefficients, investigated the asymptotic properties of the satellite angular momentum, derived stability conditions for the limiting linear system, performed numerical calculations, and constructed stability regions in the parameter space of the control law. The author also experimentally verified the selected control structure on a prototype of the satellite attitude control system.

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 results of the dissertation research, 13 scientific papers were published, reflecting the main provisions and results of the work, including:

- 3 Q1 articles in the journals indexed in the Scopus and Web of Science databases;
- 4 articles in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan;
- 2 publications in Springer proceedings;
- 4 papers in proceedings of international scientific and practical conferences.

Scope and Structure of the Dissertation

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

The introduction substantiates the relevance of the research topic, formulates the aim and objectives of the work, defines the object and subject of the research, presents the scientific novelty and practical significance, states the main provisions submitted for defense, and provides information on approbation and publications.

In Chapter 1, a review of stability analysis methods for satellite attitude control systems is carried out. The specific features of a satellite with reaction-wheel actuators as a control object are considered, the limitations of locally linearized models are shown, and the need to develop a method that preserves the connection with the original nonlinear dynamics is substantiated. The research objectives are also formulated.

In Chapter 2, a mathematical model of the dynamics of a satellite attitude control system with reaction-wheel actuators is developed. A linear form of the original nonlinear system is obtained, and necessary and sufficient stability conditions are derived based on the asymptotic properties of angular momentum. The influence of the initial angular momentum on the stability of the nonlinear satellite attitude control system is considered, and sufficient conditions for global asymptotic stability are formulated.

In Chapter 3, stability regions of the satellite attitude control system with reaction wheels are constructed in the parameter space of the PD control law.

Numerical solutions of the nonlinear and linear systems of equations describing the dynamics of the satellite attitude control system are compared. Stability analysis is performed using the Sokolov–Lipatov method, the Hurwitz criterion, and the Mikhailov criterion, followed by a comparative analysis of the obtained results.

Chapter 4 presents the results of testing the satellite attitude control system. The chapter describes the laboratory prototype and the measurement and control system, the methodology for grouping experimental data, tests along the yaw, roll, and pitch channels, tests under external disturbance, and integrated tests.

The conclusion summarizes the main results of the dissertation and presents the final conclusions.