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BASIC STAGES OF TECHNIQUE FOR DESIGNING SYSTEMS OF STABILIZATION FOR MOVING VEHICLES EQUIPMENT

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***Abstract*—*The basic stages of technique for designing systems for stabilization of apparatus operated on moving vehicles are described. The most important design stages are listed. The main features of forming specification of requirements are represented. The characteristic of choosing basic components for the stabilization system, first of all inertial rate sensors and electric motors, are described. Principles of simulation of basic components of the stabilization system are given. The approaches for designing control laws in stabilization and tracking loops are represented including designing PID regulators and robust controllers. The basic approaches for checks of synthesised stabilization system by means of simulation are represented. The simulation results on the example of the robust stabilization system are given. The advantages of application of the robust system in conditions of disturbances are shown. The obtained results can be useful for measuring and observation devices operated on moving vehicles of the wide class.*

Index Terms—Stabilization system; equipment of moving vehicles; design technique; specification of requirements; choice of rate sensors and motors; control laws in stabilization and tracking loops; simulation.

I. INTRODUCTION AND PROBLEM STATEMENT

Currently, in world practice, design technologies are intensively developing in various industries, transport, energy, etc. Despite the abundance of existing methods and standards for organizing design processes, the task of designing space stabilization systems for equipment of moving objects has so many specific features that it requires separate consideration [1] – [3].

Since space stabilization systems for equipment of moving objects are used in a wide variety of fields of technology, these features are primarily determined by the specific area and specific conditions of their application [4].

In this regard, the design process begins with an analysis of the specific conditions for using space stabilization systems for equipment of moving objects, as well as quantitative assessments of the dynamic factors that determine the functioning of space stabilization systems for equipment of moving objects in specific conditions [5], [6].

These estimates can be used as a basis for justifying the requirements for the accuracy and dynamic characteristics of the designed space stabilization systems for equipment of moving objects, which are determined during the justification and preparation of technical specifications for the design of a concrete system.

The goal of the paper is representation of the basic stages of the technique for designing systems assigned for space stabilization of moving vehicles instrumentation. This technique includes such basic stages as forming the specification of requirements; choice of components of stabilization system; simulation of the system's components; synthesis of control laws in stabilization and tracking loops; and simulation of the synthesised system.

II. FORMING SPECIFICATION OF REQUIREMENTS

This stage is key, because it determines the main direction of the design, including determining the structure of the space stabilization system and its individual elements (actuator drive, sensors, control processors, etc.), drawing up a mathematical description of the system and synthesis of control laws in closed loops. The stage consists of the following main steps:

1) The choice of the structure for the system to be designed, which is primarily determined by the intended purpose, type of moving object, requirements for accuracy, weight and size characteristics, and resistance to disturbances. It is also necessary to take into account the efficiency-cost criterion.

2) Justification of the numerical values of the main operating parameters taking into account the dynamic factors acting on the space stabilization system during its operation, namely:

- minimum and maximum speeds of rotation of the platform along all the axes;

- maximum value of angular acceleration of the external platform in the stabilization loop;
- static and dynamic accuracy of tracking and stabilization loops.

The above mentioned requirements do not exhaust all possible options that arise in specific situations, but form the basis of the content of the technical specifications for the development of the considered system [7].

III. Choice of Components of Stabilization System

The next important step is to choice the main components of the stabilization system such as:

- angular velocity sensors that meet the requirements for accuracy and application conditions (vibration, shock);
- angle sensors that meet the same requirements;
- torque motor of the outer frame of the platform gimbals with determination of such parameters as rated torque, starting torque, power, maximum and minimum rotation speeds;
- torque electric motor of the internal frame of gimbals with determination of the above mentioned parameters;
- amplification and conversion equipment, power supplies, etc.

Let us consider the choice of the main parameters of the individual components of the considered stabilization system.

The object of stabilization in this system is the platform, on which various types of equipment are installed. The main parameters of the stabilization object, which influence the choice of other elements of the system, are the moments of inertia of the platform along the corresponding axes. Important parameters of the stabilization object are the estimated values of the disturbance moments that can act in operating mode. In this case, it is necessary to take into account three main types of influences, namely: moments of friction in the gimbals bearings, moments of unbalance and moments arising as a result of the angular motion of the carrier object caused by external disturbances (aerodynamic, irregular waves, irregularities of roads and terrain relief for aircraft, sea and land moving objects, respectively). Important information for choosing these parameters is the characteristic of the payload.

When choosing an angular velocity sensor for a stabilization system, preference should be given to modern inertial technologies. Fiber-optic technologies can be excluded from consideration due to operating conditions accompanied by exposure to significant shocks. MEMS and Coriolis vibratory gyroscope technologies can be considered promising.

After choosing the type of technology, you should proceed to choosing the main characteristics of the angular velocity sensor for the stabilization and tracking loops.

The measurement range is selected based on the minimum and maximum speeds of the platform rotation. These speeds are determined as follows

$$\omega_p^{\max} = \frac{\Delta V_{par}^{\max}}{|R|_{\min}}, \qquad (1)$$

$$\omega_p^{\min} = \frac{\Delta V_{par}^{\min}}{|R|_{\max}}. \qquad (2)$$

The choice of sensitivity threshold in systems of the considered type is very important, since it is necessary to provide both high and low tracking speeds. In modern digital sensors, this characteristic is determined by the least of the least significant bit (sensitivity).

When choosing a sensor, it is necessary to take into account the conditions of shock resistance, taking into account the difficult conditions of real operation of systems.

Next, you should perform an analysis of drifts and errors, including temperature ones, which affect the achievement of the high accuracy of the angular velocity sensor during operation.

It is necessary to pay attention to the alignment error of the angular velocity sensor, since in some cases for MEMS gyroscopes they are quite large, which can nullify efforts to ensure high accuracy of the gyroscope itself.

Finally, the type of sensor is chosen from the point of view of its ability to meet the highest accuracy requirements.

When choosing the motor type, you should take into account the mass of the payload and, accordingly, dimensions of the platform. If dimensions of the platform with payload are significant, a motor and gearbox should be used. For systems of this type, it is advisable to use direct current motors. Their advantages include linear adjustment and mechanical characteristics that explains their choice for stabilization systems. If the weight and dimensions of the platform are sufficiently small, it is advisable to use gearless drives to design the high-precision stabilization systems. Then you should choose a contactless torque motor. In this case, the main goal is the choice of the permissible torque acting on the motor shaft, taking into account its load.

The choice of a torque contactless motor and the initial data for its design are determined in the following order.

First of all, the motor torque is determined based on the required angular acceleration and the moments of inertia of the internal and external gimbal frames, taking into account the moment of inertia of the motor

$$M_{in} = A^{in}_{req} J_{in}, \tag{3}$$

$$M_{ex} = A^{ex}_{req} J_{ex}, \tag{4}$$

where M_{in}, M_{ex} are the internal and external moments; A^{in}_{req}, A^{ex}_{req} are internal and external required accelerations; J_{in}, J_{ex} are internal and external moments.

In the general case, the value of the motor rotating torque must be determined taking into account the disturbance torque, which is, first of all, determined by two main components. The first component is caused by friction in the gimbals bearings and imbalance of the drive masses. The second component depends on the angular accelerations; caused by perturbed angular motion. The first component is determined based on an estimate of the maximum possible value of acceleration

$$M^{in}_{dist1} = A^{in}_{\max} J_{in}, \tag{5}$$

$$M^{ex}_{dist1} = A^{ex}_{\max} J_{ex}, \tag{6}$$

where $A^{in}_{\max}$, $A^{ex}_{\max}$ are internal and external maximum accelerations.

The second component is defined by the formula

$$M^{in}_{dist2} = A^{in}_{dist} J_{in}, \tag{7}$$

$$M^{ex}_{dist2} = A^{ex}_{dist} J_{ex}, \tag{8}$$

where A^{in}_{dist}, A^{ex}_{dist} are internal and external disturbing accelerations.

Finally, the rotating moment of the motor can be determined in the following way

$$M^{\max}_{in} = M_{in} + M^{in}_{dist\,1} + M^{in}_{dist\,2}, \tag{9}$$

$$M^{\max}_{ex} = M_{ex} + M^{ex}_{dist\,1} + M^{ex}_{dist\,2}. \tag{10}$$

Next, it is necessary to analyze the construction of the chosen or designed motor. For the classic brushed DC motors, the main factor is the choice of rated motor shaft power. The same approach is maintained for a commutator-type torque motor. For contactless torque motors, the main chosen parameter remains the value of the rated torque of the motor.

Based on the obtained values of torques (3) – (10) and maximum rotation speeds of the external and internal frames of the gimbal (1), (2) the nominal power is determined according to the expression

$$P_{in} = k_1 \frac{1}{\eta_1} M_{in} \omega^{in}_{p\max}, \tag{11}$$

$$P_{in} = k_2 \frac{1}{\eta_2} M_{in} \omega^{in}_{p\max}, \tag{12}$$

where k_1, k_2 are margin coefficients (1,2 – 2); η_1, η_2 are efficiencies of motors, which can be determined using the reference literature.

Motor torques and powers (11), (12) are the initial information for selecting the type of torque motors for the outer and inner gimbal frames.

Next, the starting torque is determined, which should be 3–5 times the rated torque.

IV. Simulation of Basic Components

After choosing the main elements of the system and determining their mass and dimensional characteristics, you can begin to design the mechanical structure including the complex gimbals consisting of external and internal frames. The block structure of the designed system is drawn up and the issues of the spatial arrangement of the gimbals, the placement of torque motors and the main sensors of the system inside the gimbals, and the design of mechanical connections between individual components are resolved.

The space stabilization system represents a combination of a complex mechanical system and automatic stabilization and tracking loops. Therefore, at this stage it is advisable to assess the rigidity and elasticity of the mechanical structure, as well as assess the misalignment and unbalance of the gimbals and the errors that arise due its functioning.

Next, mathematical models of individual elements (external and internal torque motors along with gimbals), sensors, etc. are compiled [8]. After this, a mathematical model of the control object as a whole is compiled and this object is simulated to determine its dynamic characteristics. Based on the results of this simulation, it is possible to correct the mechanical structure of the system in terms of increasing or decreasing the rigidities and masses of individual elements.

It is advisable to create mathematical models of sensors and drives based on Simulink Toolbox as such models are the most visual for the researcher.

When creating the mathematical model of the angular velocity sensor, it is necessary to pay attention to the mathematical representation of the basic errors.

The example of the mathematical model of the angular velocity sensor based on MEMS rate gyroscope ADIS16488 is shown in Fig. 1.

Modeling an angular velocity sensor consists of studying the transient characteristics and frequency characteristics of the device. In this case, it is advisable to study the set of input signals belonging to the operating measurement range, including the minimum and maximum values. Separately, it is necessary to research the possibility of specifying and, accordingly, measuring low speeds. An important point is to study the influence of random errors on the functioning of the sensor. In this case, it is necessary to simulate the most difficult operating situations. Simulink model of the drive with the payload is represented in Fig. 2.

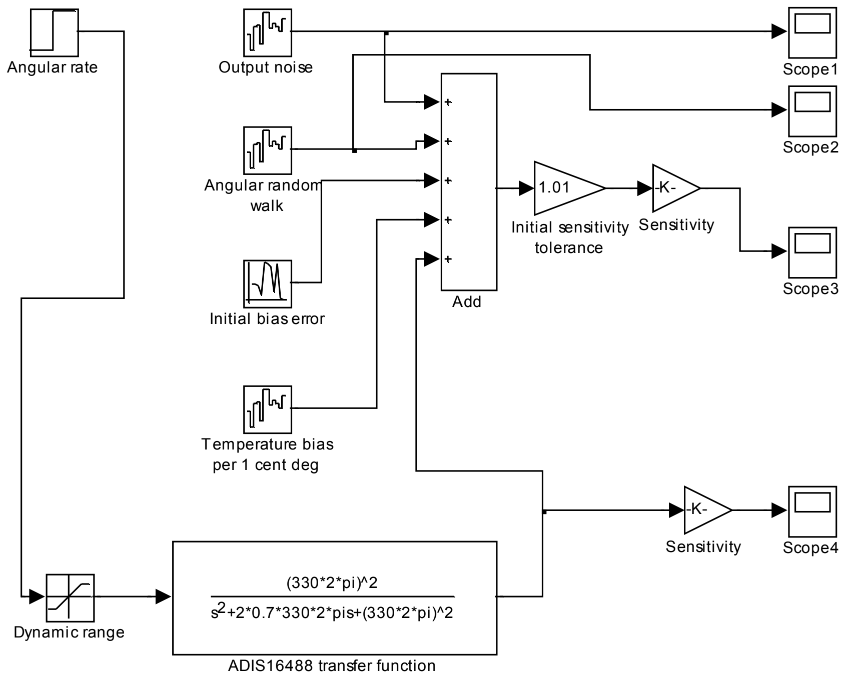

Fig. 1. Simulink model of the rate gyroscope

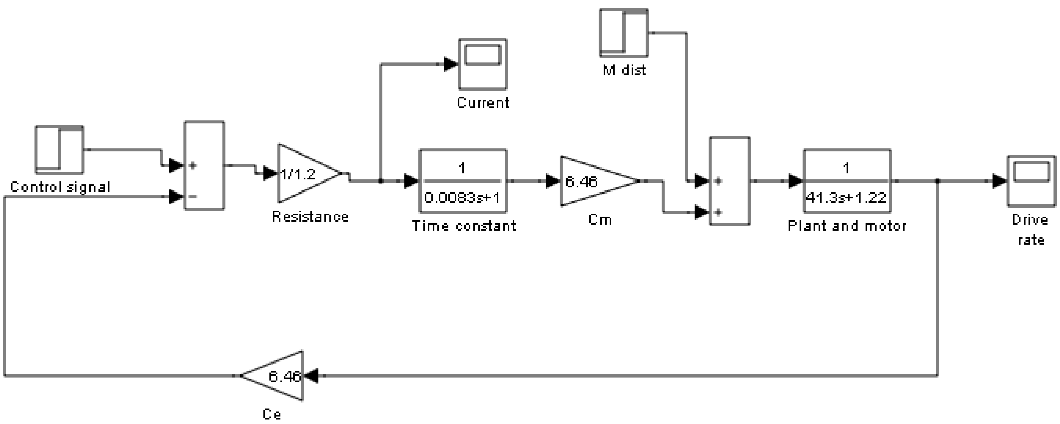

Fig. 2. Simulink model of the drive with payload

This model makes it possible to study the response and frequency characteristics of the drive according to both driving and disturbing influences. In some cases, it is convenient to use the transient response from input to output, specified as a transfer function

$$W_{drive} = \frac{\omega(s)}{U(s)}$$

$$= \frac{c_m}{L(J_{fr} + J_m)p^2 + [R(J_{fr} + J_m) + Lf_m]p + Rf_m + c_m c_e}, \quad (13)$$

where J_{fr} is the moment of inertia of gimbals; J_m is the moment of inertia of the motor; f_m is the coefficient of harmonic realization of the dry friction forces.

When modeling the drive with the transfer function (13), it is necessary to specify both constant disturbing influences (in the form of a step signal) and random influences due to them (for example, due to uneven roads and terrain for equipment of a ground moving object).

The latter disturbances are modeled by applying white noise to shaping filters that correspond to the spectral densities of road surface irregularities and different types of terrain. It is also advisable to simulate a sinusoidal motion corresponding to the profile of the test track.

V. Designing of Stabilization and Tracking Loops

The choice of a type of the regulator depends on the experience of the researcher and the requirements for time of the system design. The simplest and most economical is to use standard or serial P-, PI- and PID regulators. An important advantage of such regulators is the ability to extend the Embedded Coder to automatically generate code in the C language, which can be implemented in a microcontroller.

To choose the type of regulator, it is necessary to take into account the static and dynamic characteristics of the stabilization object, the requirements for the quality of the control process (transient processes) and the type of external disturbances [9].

In accordance with generally accepted recommendations, discrete PID controllers are used in stabilization systems for platforms with payloads, which provide high performance and maintain acceptable accuracy indicators (unlike P-controllers).

Adjustment of PID regulator coefficients, including discrete ones, can be performed in an automated mode using Simulink Toolbox. The most common choice of PID regulator coefficients is based on the requirements for the quality of the transient process. This approach is consistent with the design of a system of the type under consideration, since it allows satisfying the requirements for accuracy and speed of the transient process.

At the beginning of the tuning process, it is necessary to set the initial values of the PID regulator parameters. “Goals option” allows you to set design aims, “Optimization option” allows you to start the process of the regulator configuration.

The disadvantages of this approach include the fixed structure of the regulator and the impossibility of introducing correction units.

One of the approaches to the design of stabilization systems is the method of analytical design of controllers, which is carried out on the basis of the theory of optimal control and a mathematical description of the object in the space of states. In this case, it is necessary to create optimization programs (quite complex and labor-intensive) using automated design aids, for example, Control System Toolbox and Robust Control Toolbox. The results of the synthesis of stabilization systems are checked using mathematical models compiled using Simulink, since such models are quite complete and include nonlinearities inherent in real systems.

In the case of a significant change in system parameters during operation, it makes sense to synthesize a robust controller. There are many methods for synthesizing robust controllers, for example, the method of the mixed sensitivity represented in [10], [11].

VI. Simulation Results

The results of the robust synthesis by the method of the mixed sensitivity of the system for stabilization of measuring and observation devices operated on moving vehicles are represented in Figs 3, 4. The represented results of the synthesis of the one-axis stabilization system have been obtained for the equipment assigned for operation at the land moving vehicle.

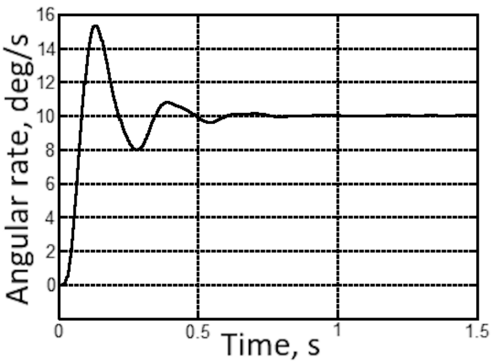

Fig. 3. Stabilization of the angular rate

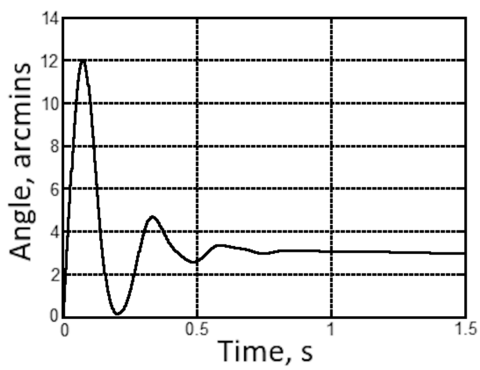

Fig. 4. The location of the stabilized platform

Figures 3, 4 show transient process on the stabilization angular rate and stabilized position of the platform with the payload (measuring and observation devices). The graphical dependences prove the high accuracy of stabilization processes.

VII. TESTED SIMULATION OF SYNTHESIZED SYSTEM

The most important characteristics of the design stabilization system can be tested using checks based on simulation [12].

The assessment of the static accuracy of the stabilization system is carried out in steady state modes at constant values of the reference action. This study is performed in tracking modes (setting the angular velocity) and stabilization modes (the given angular velocity is zero, and the angular velocity of the object on which the platform is installed is considered as a disturbing influence).

An assessment of the dynamic properties of the system can be performed based on an analysis of the quality of transient processes. In this case, it is necessary to evaluate the speed of the transient process, overshoot and oscillation.

For systems of the type under study, an important and necessary characteristic is angular rigidity, which is determined as follows.

At zero reference influence, an increased constant value of the disturbance moment is supplied to the disturbance input of the system. After some time (10–20 s) the moment of disturbance decreases to the nominal value. Thus, the law of change in the moment of disturbance applied to the stabilization object changes in the form of a step

$$M\ (t) = M_1[1(t)] - M_2[1(t)]. \qquad (14)$$

Next, the values of stabilization angles are recorded at different moments of disturbance and their difference is determined

$$M\ (t) = M_1[1(t)] - M_2[1(t)]. \qquad (15)$$

Angular rigidity is defined as the ratio of the difference in disturbing moments (14) to the difference in values that determine the angular position (15) of the object

$$c = (M_1 - M_2) / \Delta\varphi. \qquad (16)$$

VIII. CONCLUSIONS

A technique for designing space stabilization systems for equipment of moving objects is presented. The design stages are listed and their main features are characterized.

The features of the stage of drawing up technical specifications are given.

The main features of the stage of choosing components of the space stabilization system, including angular velocity sensors, drive and motors are presented.

The stage of modelling the main components of the system is described. Models of the angular velocity sensor and the system drive are given.

The stage of synthesis of control laws for the space stabilization system is characterized. Key capabilities in this area are listed, including PID controller choice and robust controller design.

A characteristic is given of such an important stage in the design of space stabilization systems as simulation to verify the characteristics of the synthesized system.

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О. О. Салюк, О. А. Сущенко. Основні етапи методики проектування систем стабілізації обладнання рухомих об'єктів

Описані основні етапи методики проектування систем стабілізації обладнання, що експлуатується на рухомих об'єктах. Перераховані найважливіші етапи проектування. Наведено основні особливості формування технічного завдання. Описано особливості вибору основних компонентів системи стабілізації, насамперед інерціальних датчиків швидкості та електродвигунів. Наведено принципи моделювання основних компонентів системи стабілізації. Представлено підходи до розробки законів керування в контурах стабілізації та стеження, включаючи проектування ПІД-регуляторів та робастних регуляторів. Представлено основні підходи до перевірки синтезованої системи стабілізації за допомогою моделювання. Наведено результати моделювання на прикладі робастної системи стабілізації. Показано переваги застосування робастної системи для стабілізації в умовах збурень. Отримані результати можуть бути корисними для вимірювально-спостережувальних приладів, що експлуатуються на рухомих об'єктах широкого класу.

Ключові слова: система стабілізації; обладнання рухомих об'єктів; методика проектування; технічне завдання; вибір датчиків швидкості та двигунів; закони керування в контурах стабілізації та стеження; моделювання.

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