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PRINCIPLES OF DESIGNING INERTIALLY STABILIZED PLATFORMS

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Abstract**—***The article deals with the description and analysis of the possible realization of inertial stabilized platforms intended for the operation of equipment installed on aircraft. The kinematic scheme of the two-axis gimballed inertially stabilized platform is represented. The generalized structure of the inertial stabilized platform is presented and researched. Basic components of the generalized structure and their connections are described. The different modes of functioning inertially stabilized platforms are listed and characterized. The basic stages of designing optimal inertially stabilized platforms are represented. The approaches to designing robust systems of the platform's motion control are represented. The appropriate software in MatLab system is characterized. Simulation of stabilization processes in an inertial platform was performed. The obtained results are useful for inertial stabilized platforms intended for operation on moving objects of a wide class.*

Index Terms—Inertially stabilized platforms; generalized structure; gimbals; operation modes; optimal system.

I. INTRODUCTION

An important direction in the development of modern instrumentation is the creation of inertially stabilized platforms capable of functioning as part of equipment assigned for various types of moving vehicles. Therefore, there is a problem of developing a platform motion control system to ensure high accuracy of stabilization of the equipment installed on it during operation in real conditions under the influence of external disturbances. Solving this problem requires determining the principles of constructing the structure of inertial stabilized platforms (ISP).

The main purpose of ISP is to stabilize and control the angular position of various information and measurement systems (IMS) on a moving base [1]. These systems include optical systems, surveillance cameras, photo and video cameras [2], [3], television and telecommunication systems, radar installations [1] and so on. Various moving vehicles are used as carriers of the above-mentioned systems, including aircraft, sea and land moving vehicles [1], [4], [5]. A large number of various tasks can be solved sing ISP such as searching for surveillance objects, tracking moving surveillance objects, stabilization of photo and video equipment, stabilization of the position of radar antennas and telecommunication radio systems, etc. It is also worth noting that the use of inertial-stabilized video cameras for precise landing of quadcopters on a moving platform (for example, on the deck of a ship) is a very relevant task [6], [7].

Control of the angular movement of the ISP is carried out both by tracking systems based on information from inertial measuring instruments, and in manual mode with the help of a human operator. Each of these methods has its own characteristics. This article deals with the analysis of features that are to some extent illustrated by the results of modeling the dynamics of ISP in manual mode.

II. GENERAL STRUCTURE OF ISP

We will assume that the ISP is mounted on a moving vehicle (for example, an aircraft) and is designed to track a moving observation object (MOO). Let the speed of motion of the aircraft (and, accordingly, the ISP) and the speed of the moving observation object are represented in the given inertial system by the vectors V_{ISP} and V_{MOO}. The main problem is to constantly track the line of sight of the observation camera for the position of the moving vehicle in such a way that the moving observation object image in the field of view of the observation camera remains stationary. Let us determine the angular rate of the azimuthal rotation of the observation camera, at which the image of the moving observation object will be stationary in the field of view of the surveillance camera for plane relative movements of the aircraft and the observation object. The angular speed of rotation of the image of moving observation object in the field of view of the surveillance camera is equal to ω_{MOO} [1]:

$$\omega_{\text{MOO}} = \frac{(V_{\text{MOO}} - V_{\text{ISP}})}{|R|} - \omega_{\text{OS}}, \qquad (1)$$

where $(V_{\text{MOO}} - V_{\text{ISP}})$ is the speed of parallax (relative) motion of the observation object and aircraft; $|R|$ is a distance between them, and ω_{OS} is the angular rate of the observation camera. To stabilize the platform, it is necessary to accept $\omega_{\text{MOO}} = 0$. As follows from the equation (1), the angular rate of the observation camera mounted on ISP, in this case, will be determined by linear speeds of moving observation object and aircraft, and also a distance $|R|$ between them

$$\omega_{\text{OS}} = \frac{(V_{\text{MOO}} - V_{\text{ISP}})}{|R|}, \qquad (2)$$

Expression (2) allows us to determine the maximum and minimum rotation speeds of ISP drives (and, accordingly, the parameters of the drive) depending on the specific conditions of their use. It should be noted that even for a sufficiently small range and a sufficiently large speed of parallax movement, the angular speed of azimuthal rotation ω_r will be small (for example, if $V_{\text{MOO}} - V_{\text{ISP}} = 20$ m/s and $|R| = 100$ m, then $\omega_r = 0.1$ rad/s). During the disturbed motion of the aircraft, as well as the operation of the electric motor, vibrations acting on the stabilization object are arisen. The spectrum of these vibrations is much wider than the spectrum of the angular rate of the azimuthal rotation of the aircraft.

Usually, the movement of the ISP is characterized by two components such as low-frequency signals arising during tracking of the ISP by the position of the moving observation object, and high-frequency disturbances. The latter signals lead to high-frequency fluctuations of the moving observation object image in the field of sight of the observation camera. Suppression of the noise requires the use of special technical means.

As can be seen from equation (2), the control of the angular speed of the azimuthal rotation of the observation camera is based on information about the speed vectors of ISP and moving observation object (V_{ISP} and V_{MOO}), respectively. To obtain information about the speed of the aircraft, as well as to coordinate its position to some pre-selected coordinate system (geographical or topocentric), it is necessary to use the integrated inertial satellite navigation system (ISSN).

Thus, it can be concluded that the ISP is used to track the position of the moving observation object using slow signals and to simultaneously suppress broadband vibration effects.

It should also be noted that in ISP for moving objects of many types (airplanes, ground vehicles) mainly two-axis cardan gimbals are used [1], [3], [6], [7], [9]. A typical kinematic diagram of such gimbals is shown in Fig. 1.

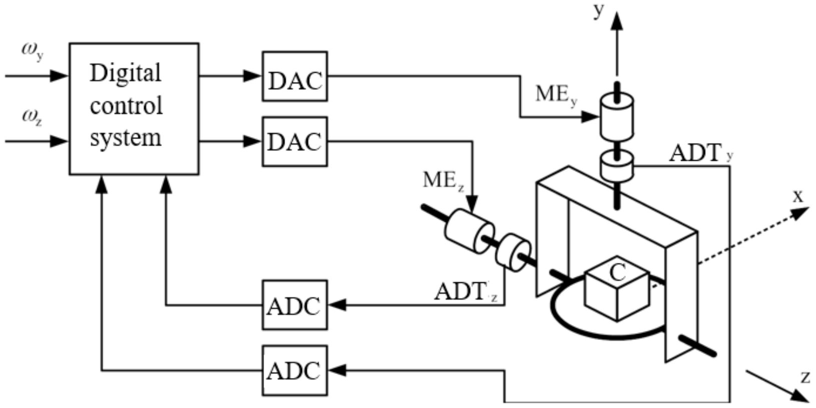


Fig. 1. Kinematic diagram of a two-axis gimbals: DAC is the digital-analog converter; ADC is the analog-digital converter; ME is the moment drive; ADT is the angle data transmitter; C is the camera

Therefore, the structure of the ISP, corresponding to the most widespread application, must satisfy the following requirements:

- automatic tracking of the ISP mounted on the aircraft according to the position of the moving observation object;
- the possibility of tracking the ISP mounted on the aircraft according to the position of the moving observation object by the operator;
- suppression of high-frequency oscillations of the moving observation object image in observation camerd, which occur during disturbed aircraft movement;

- the possibility of determination of the position of the aircraft in some pre-selected coordinate system.

Consider the structure of the ISP, which satisfies the above-mentioned requirements, for one of the control channels of the rotation of the gimbals around one of the axes (for example, azimuthal rotation) [1]. Structures of inertially stabilized platforms for other axes are completely similar and therefore will not be considered.

The generalized structure of the ISP based on the gimbals shown in Fig. 1 is presented in Fig. 2, which shows three types of connections between individual blocks: solid single lines indicate the transmission of electrical and code signals, solid double lines indicate mechanical movements (translational and rotational), dashed double lines indicate the transmission of optical signals (images).

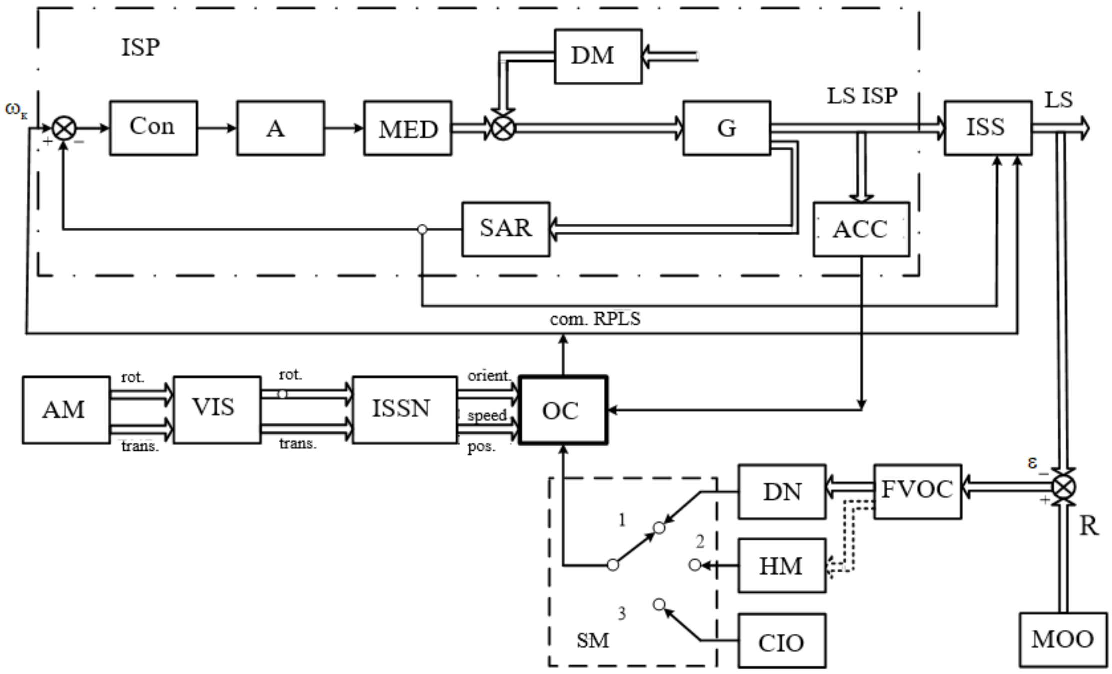


Fig. 2. Generalized structural scheme of ISP: Con is the controller; A is the amplifier; MED is the moment electric drive; G is the gimbals; DM is the disturbing moments; ISS is the image stabilization system; SAR is the sensor of angular rates; LS ISP is the line of sight of ISP; AM is the aircraft motion; VIS is the vibration isolation system; ISSN is the inertial satellite navigation system; AC is the airborne computer; ACC is the angle-code converter; FVOC is the field of view of the observation camera; MOO is the motion of the observation object; DN is the sensor of mismatching between field of view of the observation camera and position of moving observation object; rot. is the rotary motion; trans. is the translational movement; orient. is the orientation; SM is the switch of modes; com. RPLS is the reference position of the line of sight; ε is the mismatching; HM is the human operator, CIO is the coordinates of an immovable object, ω_r is the reference speed

The system presented in Fig. 2, contains three components: a subsystem of the external tracking circuit for moving observation object, a subsystem of the internal stabilization circuit or ISP, and a subsystem of image stabilization in field of view of the observation camera [1]. The ISP circuit represents a closed control system, shown in Fig. 2 inside the dash-dotted rectangle. The circuit of the ISP contains a controller – a microcontroller, in which the ISP motion control law is programmed, an amplifier, a moment electric drive – the actuator of the ISP, a two-axis gimbals (G) and a gyroscopic sensor of angular velocities. The diagram shows the disturbing moments (DM) that occur during the gimbals motion. The angular rate of the gimbal axis is measured by angular rate sensors. It is used for forming a negative feedback signal. The output signal of the ISP is taken as the rotation angle of the gimbal axis, which determines the direction of the ISP line of sight in the azimuthal plane.

Since the angular rate feedback in the ISP is very broad-band, the internal circuit provides a sufficiently effective suppression of broad-band external disturbances arising during the disturbed motion of the object. This is sufficient for a platform with equipment, taking into account its sufficiently large mass and inertia, and not enough for an observation camera. Hence, the high-frequency fluctuations of the moving observation object image are arisen in field of view of the observation camera.

To remove these fluctuations, the image stabilization subsystem is used in the observation camera. The output signal of the image stabilization system is the stabilized angular orientation of the line of sight, which is one of the input signals of the external tracking circuit, which is called a compensation system for the parallax movement of the observation object relative to the moving object carrier.

The input of the external circuit receives information about the motion of the object (aircraft) and information about the parallax movement of the observation object relative to the object carrier. The motion of the aircraft consists of rotational motion and translational motion, which are determined by the vector of the speed V_{ISP}. These motions are taken by the passive vibration isolation system, on which the base for mounting of the system is installed. The rotational movement of the base is a source of external disturbance for the gimbaled platform.

Both motions are taken by inertial sensors of the integrated inertial satellite navigation system. At the output of this system, we receive information about the object's speed vector, its position in the given coordinate system, and the angular orientation vector, which consists of Euler angles. This information comes to the input of the computer. The third input of the computer takes information about the current angular orientation of the ISP sighting line from the angle-code converter mounted on the azimuth axis of the gimbals. The fourth input of the computer receives information from the moving observation object channel, which is formed in the following way. The stabilized angular orientation of the line of sight at the output of the image stabilization system and the parallax movement of the stabilization object, determined by the vector V_{MO}, forms a mismatch in the field of view of the observation camera between the vectors of the line of sight and R (distance) in the form of a deviation of the moving observation object image from the coordinate system on the display of the observation camera. The conversion of this mismatching from an optical signal into a code signal and the formation of the mismatching signal depends on the method of technical implementation of the image stabilization system and is generally carried out by a separate mismatching sensor [2], [5]. The division into blocks of the image stabilization system, the field of view of the observer, and the sensor of mismatching is conditional and depends on the method of technical implementation of the image stabilization system. Quite often, these three blocks are combined into the single unit [1].

The signal of mismatching is sent to the computer of the automatic tracking system of the outer contour, which combines the image of the moving moving observation object with the coordinate system on the display of the observation camera. This combination can be performed in three ways, which correspond to the three modes of operation of the external circuit, which are chosen by the mode switch (see Fig. 2).

1) Automatic mode, in which the code signal from the mismatching sensor is sent to the computer and the observation camera is pointed at the observation object automatically (1st position of the mode switch).

2) Manual mode, when the alignment of the image of the moving target with the coordinate system on the screen of the observation camera is carried out by a human operator manually (2nd position of the mode switch).

3) The mode of pointing the observation camera at a stationary object with known coordinates (3rd position of the mode switch). In this case, the computer receives both the coordinates of the stationary object of observation and the coordinates of the aircraft from inertial satellite navigation system. The computer calculates the coordinates of the vector R and generates a control signal based on the condition $\varepsilon = 0$.

Thus, the external tracking system compensates for the parallax motion of the aircraft and moving observation object, and the internal stabilization circuit compensates for high-frequency fluctuations that occur during the turbulent motion of the aircraft.

III. WAYS OF DESIGNING ISP

Usually, the ISP represents an automatic control system, the operation of which must satisfy requirements for accuracy and resistance to disturbances [10], [11]. Therefore, methods of analysis and synthesis of modern control theory should be used to solve stabilization problems. At the same time, it is necessary to take into account the dynamic characteristics of both the stabilization object and the disturbances acting on the object in real operating conditions. Modern ISP are characterized by a number of features that significantly complicate their analysis and synthesis. Such difficulties include their multi-channel nature, a significant number of modes, a high order of the system of differential equations describing the system, a complex structure of the controller and, accordingly, control laws, certain requirements for the quality of transient processes, and some specific requirements, for example, definite angular rigidity by moment for the ISPs assigned for ground vehicles and the given speed of setting to the meridian for the system of stabilization and determination of the course of the marine vehicle.

The classical approach to the synthesis of optimal multidimensional control systems uses optimization methods based on classical methods of variational calculus. It is known that the application of optimality principles for the design of high-order multidimensional systems is characterized by significant computational difficulties. The modern approach is based on the preliminary task of the dynamic properties of the closed-loop control system and taking into account the constraints on the permissible design parameter.

Complex multi-loop control systems are characterized by the presence of not only global, but also a significant number of local extrema, one of the reasons for their appearance is the limitation of the space of design parameters. Therefore, there is a problem of analyzing the obtained results and, if necessary, repeating the parametric optimization procedure. At the same time, it is convinient to use simulation methods. The use of simulation methods in parametric optimization problems leads to the need to use not analytical methods, but numerical optimization algorithms.

As already mentioned, for ISPs, the most important is to ensure the resistance to external random disturbances, which can change within unpredictable limits. The synthesis of disturbance-resistant ISPs for moving vehicles requires solving a number of problems, which include.

1) Formulation of the problem of optimal synthesis.

2) Creation of a complete mathematical description of the system with maximum possible consideration of all nonlinearities inherent in real systems.

3) Creation of a linearized mathematical model of the system in the space of states.

4) Analysis of the requirements that are given to the system in general and the formation of the corresponding objective function and penalty functions.

5) Creation of a methodology for the task of external disturbances with the condition of the specificity of the movement of the carrier on which the ISP is mounted.

6) The choice of the optimization method.

7) Creation of an algorithm for the synthesis of a robust system with a focus on modern automated means of optimal synthesis of control systems.

8) Simulation and analysis of the obtained results.

The creation of a robust parametric and structural-parametric synthesis procedure requires the use of a set of system models with different properties, which are determined by the purpose of the phase of the research.

The creation of complete mathematical models of the ISP is impossible without taking into account typical nonlinearities (dead zones, saturation, and hysteresis, etc.). This approach ensures similarity of the created model and the real equipment [12] – [14]. One of the best tools for creating models that take into account all the nonlinearities inherent in real hardware is Simulink Toolbox, which is a component of MATLAB software. But the synthesis of the system in the early phases of its designing is expedient to be carried out by means of Control System Toolbox and Robust Control Toolbox, which include a large set of procedures that provide the analysis and optimal synthesis of control and stabilization systems. At the same time, it is possible to design optimal digital controllers for a continuous system, which is one of the most important tasks of modern instrument engineering in view of the rapid development of modern computer technology. Among the advantages of the mentioned Toolboxes should also be attributed the possibility of implementing robust control, which is relevant for the synthesis of ISPs.

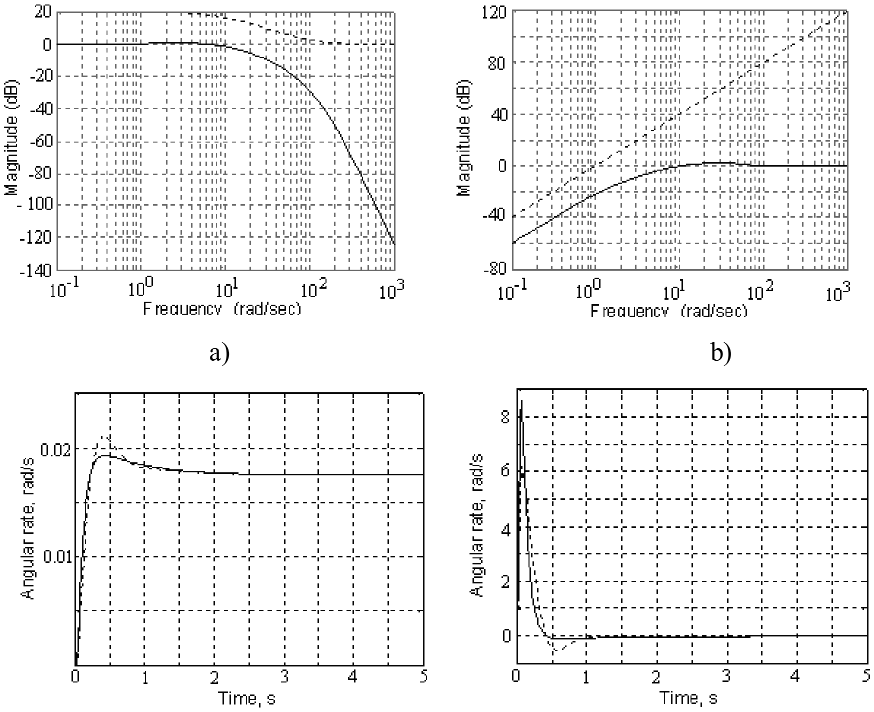
IV. SIMULATION RESULTS

The results of the robust synthesis by the method of the mixed sensitivity of the ISP assigned for application at the ground vehicle are represented in Fig. 3. The simulation was carried out for the ISP with the following parameters: moment of inertia of the platform is 270 $\text{kg}\cdot\text{m}^2$; moment of inertia of the actuator is 0.0003 Nms^2; armature time constant is 0.0015 s; nominal resistance of the armature winding is 0.1 Ohm; the coefficient of electromotive force is 0.053 V/rad; the starting moment is 1.27 Nm; nominal power is 400 W. The ADIS16488 MEMS gyroscope is used as an angular rate sensor.

V. CONCLUSIONS

The general structure of ISP including the tracking system based on high-speed gyroscopes, electric motors and controllers is represented and analysed.

Simulation results of inertial stabilization processes based on procedure of the robust synthesis is given. The combination of robust control and the use of MEMS gyroscopes provides sufficient stabilization accuracy, resistance to external random disturbances, and reduction of the cost of the system.



a) b)

c) d)

Fig. 3. Results of robust controller synthesis by the method of mixed sensitivity: (a) is the sensitivity function (solid line) and weighting transfer function W_1^{-1} (dotted line); (b) is the complementary sensitivity function (solid line) and weighting coefficient W_3^{-1} (dotted line); (c) is the step response of the nominal (solid line) and disturbed (dotted line) systems; (d) is the impulse response of the nominal (solid line) and disturbed (dotted line) systems

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О. А. Сущенко, О. О. Салюк, С. Г. Єгоров. Принципи проектування інерціальних стабілізованих платформ

У статті описано та проаналізовано можливу реалізацію інерціальних стабілізованих платформ, призначених для експлуатації обладнання, встановленого на літальних апаратах. Представлено кінематичну схему інерціальної стабілізованої платформи у двовісному кардановому підвісі. Представлено та досліджено узагальнену структуру інерціальної стабілізованої платформи. Описано основні компоненти узагальненої структури та їх зв'язки. Перераховано та охарактеризовано різні режими функціонування інерціальних стабілізованих платформ. Представлено основні етапи проектування оптимальних інерціальних стабілізованих платформ. Представлено підходи до проектування робастних систем керування рухом платформи. Охарактеризовано відповідне програмне забезпечення в системі MatLab. Проведено моделювання процесів стабілізації в інерціальній платформі. Отримані результати є корисними для інерціальних стабілізованих платформ, призначених для експлуатації на рухомих об'єктах широкого класу.

Ключові слова: інерціальні стабілізовані платформи; узагальнена структура; кардановий підвіс; режими функціонування; оптимальна система.

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