UDC 629.3.025.2(045)
DOI:10.18372/1990-5548.73.17011

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SIMULATION OF INERTIALLY STABILIZED PLATFORMS

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Abstract**—***The article describes the peculiarities of determining the characteristics of inertial stabilized platforms operating on land-based moving objects. A method for estimating the dynamic error and the influence of the unbalance moment is proposed. The possibilities of different ways of setting control signals during semi-natural tests were investigated. The results of experimental tests of inertial stabilized platforms intended for operation on ground moving objects are presented. The proposed approaches are important for evaluating the characteristics of the motion control system of the stabilized platform after performing its synthesis and organizing the process of semi-natural tests. The obtained results can be extended to inertial stabilized platforms of a wide class.*

Index Terms—Inertially stabilized platforms; dynamic error; unbalance moment; control signals; tested checks.

I. INTRODUCTION

Actual problems of ensuring high accuracy of stabilization and tracking processes for a wide class of information and measurement devices operated on moving objects can be solved based on the principles of inertial stabilization. Among the scientific and commercial applications that require the use of inertial stabilization principles, we can distinguish air and sea navigation, communication, and surveillance. Maintaining the constant orientation of information-measuring devices in the direction of the object of observation becomes a difficult task if the information-measuring devices are installed on a moving object. Controlling the orientation of information-measuring devices using the principles of inertial stabilization allows solving this complex problem. With the help of the mentioned approach, it is possible to stabilize conventional and infrared cameras and surveillance equipment of various types installed on land, water, air and space moving objects, which allows you to perform various tasks, for example, shooting the surrounding environment. The principles of inertial stabilization are used for stabilization and direction finding in communication antennas and laser devices. Stabilization of mobile satellite antennas belongs to the last in terms of time of application of inertial stabilization. Solving the problems of inertial stabilization of information-measuring devices intended for operation on land-based mobile objects is relevant for the instrument industry of Ukraine.

The need to improve inertial stabilized platforms is caused by some factors. It should be noted that the accuracy characteristics of the sensors of information-measuring devices have improved significantly in recent years. These achievements cannot be realized without corresponding progress in means of stabilization, which makes it necessary to improve the accuracy and dynamic characteristics of inertial stabilized platforms, including the improvement of algorithms for checking the characteristics of the designed system.

In the general case, the problem of inertial stabilization is a problem of managing the orientation of information-measuring devices of a wide class [1]. The main feature of inertial stabilization is the use of information obtained from inertial sensors in the control circuits. According to the inertial system terminology standards developed by the Institute of Electrical and Electronics Engineers (the Institute of Electrical and Electronics Engineers) in the USA and approved by many countries around the world (Europe, Japan, South Korea, Canada), an inertial sensor is a fully autonomous location sensor, spatial orientation or movement of the object excluding additional information necessary for its display [2].

Generalized structural control of a stabilized platform in inertial space, taking into account the contours of observation and tracking, is presented in Fig. 1.

The main goal of the control systems of stabilized platforms with a payload is to ensure the processes of their stabilization and tracking of a landmark in inertial space. Of course, specific tasks depend on the specifics of the application, but the main task is to control the line of some direction or the coordinate system of the stabilization object in inertial space or the relative position of two objects [1].

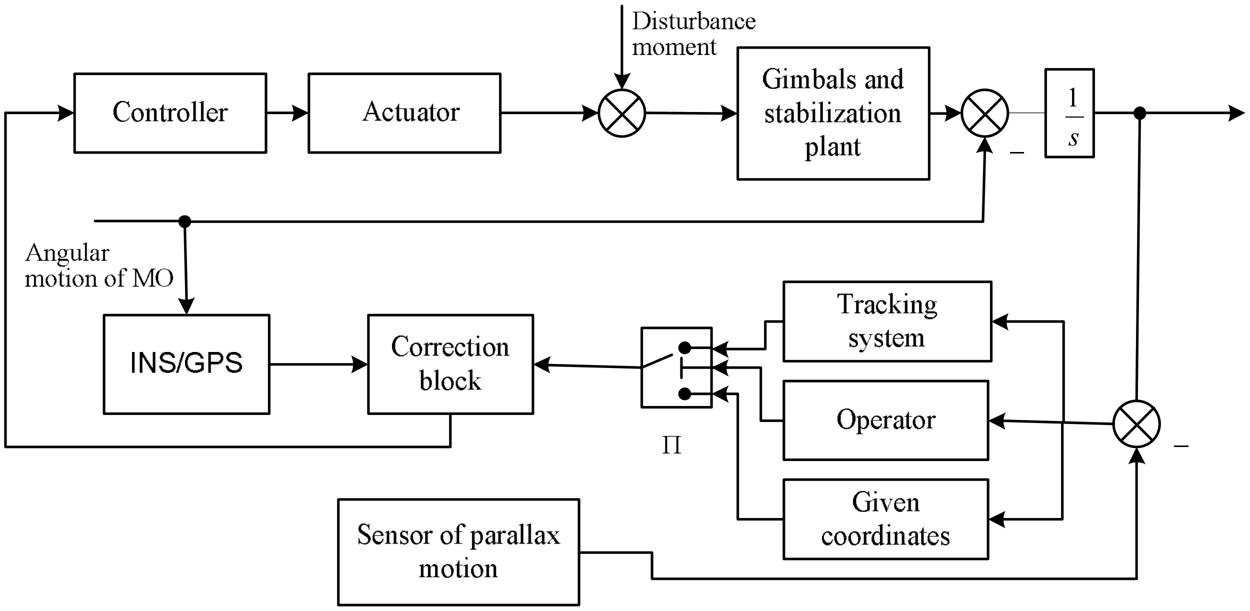


Fig. 1. Generalized block-chart of the inertially stabilized platform: *S* is the switch; INS is the inertially stabilized platform

II. STUDY OF LAST RESEARCHES AND PUBLICATIONS

The main trends in the design of inertial stabilized platforms are presented in works [1], [3]. The algorithm for designing a robust angular motion control system, provided in the work [4], provides the synthesis of a system capable of functioning in complex conditions of real operation, characterized by the influence of parametric and coordinate disturbances. The modern approach to the synthesis of robust control systems of a wide class consists of two stages [5]. At the first stage, the actual synthesis of the robust system is performed. At the second stage, the characteristics of the synthesized system are checked. Moreover, according to the results of these checks, it is possible to repeat the synthesis of the system after correcting the optimization criterion using weighting factors or new initial conditions. And if the features of the first stage are widely covered in modern scientific and technical literature, then the features of the second stage, that is, checking the characteristics of the synthesized system, require additional research.

III. PROBLEM STATEMENT

Carrying out the second stage of designing a robust system of stabilization of information and measuring devices requires an analysis of the features of the system, first of all, the type of moving object and the tasks to be solved. The article considers approaches to the design of inertial stabilized platforms, with the help of which stabilization processes and orientation tracking of surveillance equipment units operating on land-based mobile objects in difficult conditions of real operation are ensured. Such platforms are characterized by a significant change in such parameters as the moment of inertia and stiffness of the elastic connection between the executive mechanism and the platform on which the surveillance equipment unit is installed (50%). It is also necessary to take into account the effect of coordinate disturbances, first of all, caused by the moment of imbalance and the moment due to the action of the angular velocity, caused by the unevenness of the topography of the roads and the terrain on which the ground object moves.

The studied system includes a stabilization object (surveillance equipment block), a measuring system (HT gyrotachometer), an executive mechanism (a direct current motor with a gear drive) and a robust regulator, the need for which is due to significant parametric changes and the action of intense and various coordinate disturbances during real operating conditions.

IV. PROBLEM SOLUTION

For angular motion control systems of inertial stabilized platforms, the quality indicators of transient processes, especially speed, dynamic error, angular stiffness by moment, are of the greatest importance [6], [7].

Dynamic errors of control systems include all types of errors that occur during dynamic processes, for example, under changing external influences (disturbances or controls).

In general, an inertial stabilized platform designed for operation on land moving objects can operate in three modes: tracking, stabilization, and combined tracking and stabilization. The platform with the payload is controlled by the signal $U_{\text{con}}(t)$, which is set from the control panel, and the angular velocity of the ground moving object ω_{p} can be considered as a disturbance. At the same time, there are two features. First, the motion of the ground object is translational, while the motion of the stabilization object (equipment unit) is relative. Actually, stabilization is carried out on the basis of signals about the measured absolute angular speed of the platform. The second feature of this disturbance is the need to take it into account as a component of the moment acting on the drive of the inertial stabilized platform [8], [9].

Three of the most important components can be identified among the errors of the stabilization system of the ground moving object surveillance equipment.

The first component characterizes the tracking error, that is, the error of the determining influence, and is determined by the expression [10]

$$x_{\text{track}} = \frac{U_{\text{con}}}{[1+W(p)]}, \tag{1}$$

where $W(p)$ is the transfer function of the open loop control of platform motion.

The second component characterizes the error caused by the action of external moments. Usually, this error is determined relative to the position angle of the plant and can be described by the expression

$$x_{\text{dist}} = \frac{W_{\text{M}_1} M_{\text{nb}}}{[1+W(p)]p}, \tag{2}$$

де W_{M_1} is the transfer function by the unbalance moment, M_{nb} is the unbalance moment.

The third component is the stabilization error and takes into account the effect of the angular velocity of the ground object on which the inertial stabilized platform is installed. It is determined relative to the position angle of the plant. When determining it, the moment of rotation caused by the action of the angular velocity of the terrestrial moving object is also taken into account. The total stabilization error will be determined by the expression

$$x_{\text{stab}} = \frac{\left(1 - W_{\text{M}_2} W_{\text{r}} J p\right)\omega_{\text{g}}}{[1+W(p)]p}, \tag{3}$$

where W_{M_2} is the transfer function by the rotation moment caused by the angular rate of the ground moving vehicle; W_{r} is the transfer function of the reduced disturbance moment caused by the object's angular rate, J is the inertia moment of the stabilized platform.

The tracking error is determined by setting the control panel voltage and estimating the corresponding angular velocity. It is advisable to perform the simulation under the condition of immobility of the ground moving object. Then the error (1) will be determined by the equation of the transition function $x_{\text{track}} = x_{\text{st}} h(t)$.

It is expedient to estimate the moment error (2) by setting the jump-like moment of unbalance and determining the difference in the position angles of the control object of the stabilization system. The simulation is also performed under the condition of immobility of the ground moving object. This approach makes it possible to evaluate the angular stiffness of the system [11], [12].

It is expedient to estimate the stabilization error by modeling the movement of a ground moving object according to the harmonic law that corresponds to the control track. At the same time, the direction of movement of the ground object and, accordingly, the direction of action of the dry friction forces are continuously changing, which allows the most complete assessment of the dynamic properties of the motion control system of the inertial stabilized platform. The angular position error in the steady state will also vary according to the harmonic law with frequency $x(t) = x_{\max}\sin(\omega_k t + \psi)$.

The accuracy of the stabilization system can be estimated by the maximum error amplitude $x_{\max}$. The magnitude of the amplitude can be determined by the symbolic method using substitution $p = j\omega_k$ in expression (3)

$$x_{\max} = \frac{\omega_{\text{g}} - |W_{\text{M}_2}(j\omega) W_{\text{r}}(j\omega) J j\omega|\,\omega_{\text{g}}}{|1+W(j\omega)|\,j\omega}. \tag{4}$$

Since the amplitude of the error is much smaller than the amplitude of the input influence, expression (4) can be replaced by an approximate expression [7]

$$x_{\max} = \frac{\omega_{\text{g}} - |W_{\text{M}_2}(j\omega) W_{\text{r}}(j\omega) J j\omega|\,\omega_{\text{g}}}{|W(j\omega)|\,j\omega}, \tag{5}$$

where $|W(j\omega)|$ is the module of the frequency transfer function of the open control loop $\omega = \omega_{\mathrm{k}}$. The maximum value of the amplitude, calculated on the basis of formula (5), for the system of the studied type is 5 arcmins.

The disadvantage of this approach to modeling is determining a specific value of the test signal. This drawback can be avoided by using the relative amplitude error. For this, it is advisable to introduce two control measurements under the condition of angular velocities, $\omega_{\mathrm{k}_1}, \omega_{\mathrm{k}_2}$ which, for example, correspond to the maximum values of angles of 2 and 2.5 degrees, and consider the relative error

$$\Delta x_{\max} = \left(\frac{x_{\max_1}}{\varphi_{\max_1}} - \frac{x_{\max_2}}{\varphi_{\max_2}} \right) \cdot 100\% .$$

Expression (5) also makes it possible to formulate requirements for the logarithmic amplitude characteristic of the system, under the condition of fulfilment of which the amplitude of the stabilization error in the steady state will not exceed the specified value. These requirements can be determined by the condition [7]

$$L(\omega_{\mathrm{k}}) \geq 20\lg A(\omega_{\mathrm{k}})$$
$$\geq 20\lg \frac{\omega_{\mathrm{g}} - |W_{\mathrm{M}_2}(j\omega) W_{\mathrm{r}}(j\omega) J j\omega \,|\, \omega_g}{x_{\max}} .$$

Modeling of the signal to which the control track corresponds should be carried out taking into account the characteristics of the control equipment. Therefore, it is necessary to carry out a study of the methods of setting signals corresponding to disturbances of the control track on the stand intended for semi-realistic tests of the angular movement control system of the platform. Firstly, the control signal can be set directly at the input of the integrator in the form of a voltage, secondly - in the integrator circuit after the demodulator; thirdly, at the input of the rate gyroscope by setting a signal proportional to the angular velocity. The simulation results, which show the transient processes in terms of angular velocity and the errors of determining the angular position for different ways of specifying angular signals, are presented in Fig. 2. When creating a system for controlling the angular movement of the platform, it is relevant to study the dependence of precision and dynamic parameters on the final moment of unbalance, which can be determined as follows:

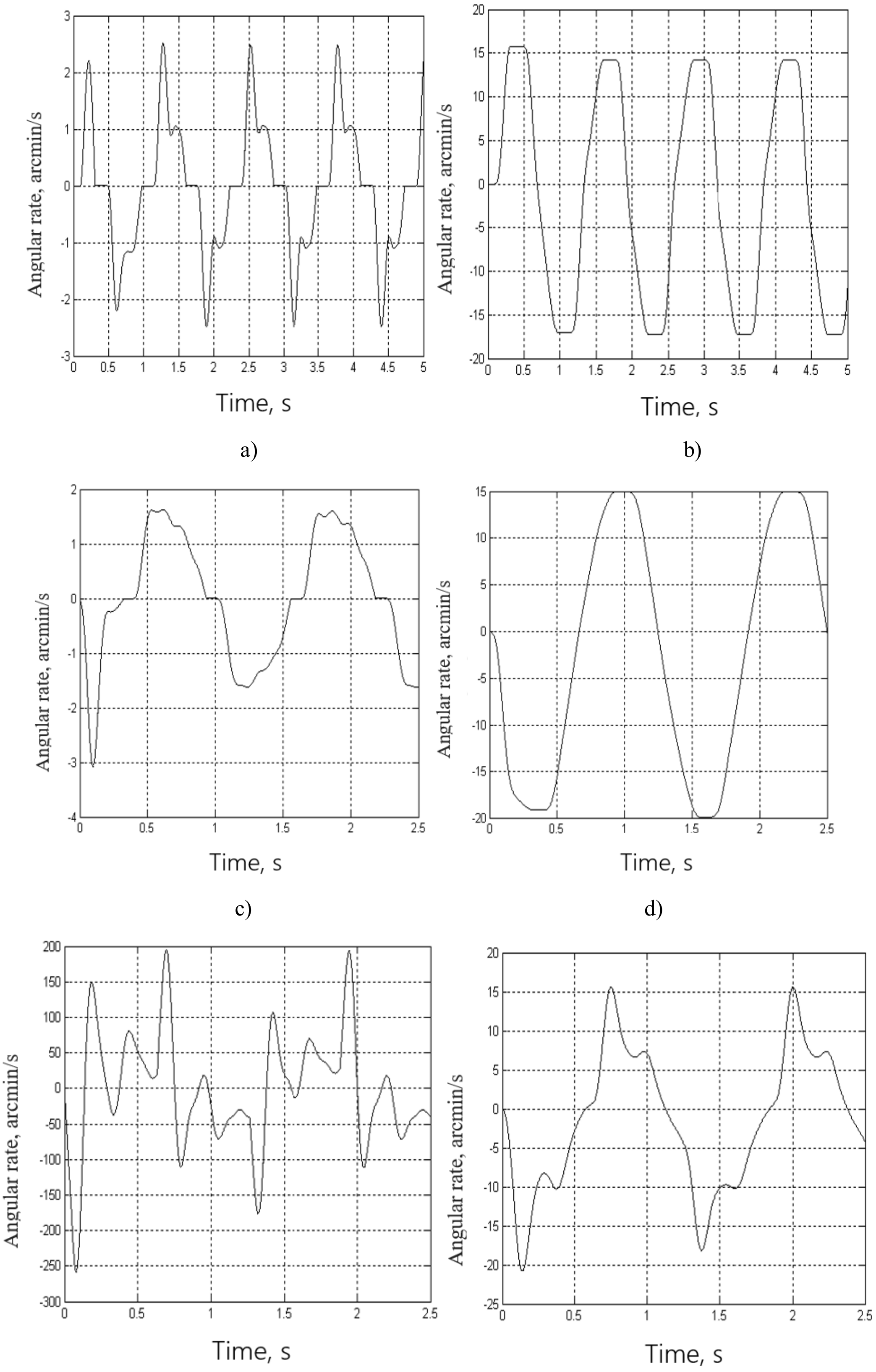
$$\Delta M_{\mathrm{n}} = -M_{\mathrm{nb}} \cos \varphi_{\mathrm{p}} + k_{\mathrm{spr}} A , \qquad (6)$$

where φ_{p} is an angle of turn od a plant, k_{spr} is the transfer coefficient of the spring compensator, A is an angle of spring setting.

In order to determine the requirements for the permissible value of this moment, simulations were carried out for two values of the final unbalance moment: 70 Nm and 30 Nm. Considering the angles of inclination of the equipment block to be small, we can take =1 in expression (6). For the values =470 Nm, 200.8 Nm/rad, the spring cocking angles of the balancing device for the final unbalance moments of 70 Nm and 30 Nm are 114.2°, 125.6°.

The dynamic error of the control object is most accurately estimated during its movement according to the harmonic (sinusoidal) law. The impact of the final unbalance moment can be assessed by simulation. The place of the test signal is the output of the integrator of the control unit of the platform motion control system. This check is carried out in two stages. At the first stage, the calibration of the reference effect is carried out in static mode, that is, the maximum voltage at the output of the integrator, which corresponds to the initial angular position, is selected. At the second stage, a harmonic signal with this amplitude is set, which corresponds to the divergence angle. In order to eliminate the influence of the transient process, the sinusoidal signal is applied during some time after the start of the system operation, for example, 10 s. To estimate the stability margin, the maximum voltage at the output of the integrator is selected. Then this signal is applied to the output of the integrator and is removed after some time. The stability reserve is determined by the formula. The margin of stability is considered satisfactory if the value is within 10÷30%.

To determine the angular stiffness, some unbalance moment is first given, and then an additional moment is added. Next, the difference between the angular position values is determined. Angular stiffness is determined by the formula [kgm/min] To achieve the necessary accuracy of stiffness estimation, the main and additional moments are set after a certain time interval, for example, 10 s.



a) b)

c) d)

e) f)

Fig. 2. Angular velocities and errors of the angular position of the inertial stabilized platform under the condition of different methods of setting control signals: (a), (b) – at the input of the integrator; (c), (d) – at the input of the demodulator in the integrator circuit; (d), (f) – at the input of the rate gyroscope

V. CONCLUSIONS

The concept of an inertial stabilized platform is analyzed. An approach to the stage of testing the characteristics of the synthesized system is proposed, taking into account the specifics of inertial stabilized platforms intended for operation on land-based mobile objects. A method for estimating the dynamic error and angular stiffness of the motion control system of a stabilized platform operated on a ground moving object is proposed. The impact of the final unbalance moment on the system characteristics was evaluated. Simulation results for different ways of specifying control signals are given. Prospects for the further development of the conducted research are the spread of the above approaches to other types of moving objects.

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Received September 27, 2022

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О. А. Сущенко, О. О. Салюк, С. Г. Єгоров. Імітаційне моделювання інерціальних стабілізованих платформ

У статті описано особливості визначення характеристик інерційних стабілізованих платформ, що працюють на рухомих наземних об'єктах. Запропоновано метод оцінки динамічної помилки та впливу моменту неврівноваженості. Досліджено можливості різних способів завдання керуючих сигналів при напівнатурних випробуваннях. Наведено результати експериментальних випробувань інерційно-стабілізованих платформ, призначених для експлуатації на наземних рухомих об'єктах. Запропоновані підходи є важливими для оцінки характеристик системи управління рухом стабілізованої платформи після виконання її синтезу та організації процесу напівнатурних випробувань. Отримані результати можуть бути поширені на стабілізовані інерційні платформи широкого класу.

Ключові слова: інерціальні стабілізовані платформи; динамічна похибка; момент неврівноваженості; контрольні сигнали; тестові перевірки.

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