UDC 629.3.025.2(045)
DOI: 10.18372/2306-1472.74.12290

Olha Sushchenko

FEATURES OF TESTING OF INERTIALLY STABILIZED PLATFORMS

National Aviation University
1, Kosmonavta Komarova Avenue, Kyiv, 03058, Ukraine
E-mail: sushoa@ukr.net

Abstract

Purpose: *the paper focuses on problems of testing of inertially stabilized platforms operated on ground vehicles. The main goal is to consider possibilities to test such systems using simulation.* ***Methods:*** *to solve the given problem methods of inertilal stabilization, creation of mathematical models and simulation are used. MatLab possibilities are taken into consideration.* ***Results:*** *testing of basic accuracy characteristics by means of simulation is considered. The appropriate mathematical models are developed. Presence of different modes during functioning inertially stabilized platforms is taken into consideration. The approaches to estimation of static and dynamic errors are given. The ways to set tested signals taking into consideration features of testing bench are considered. The possibility to estimate angular rigidity by the moment is proposed.* ***Conclusions:*** *the results of simulation of different tested signals are represented. Proposed ways to estimation of operating characteristics of inertially stabilized platforms allow decrease time and cost losses of testing. Obtained results can be useful for design of inertially stabilized platforms for vehicles of the wide class.*

Keywords*:* dynamic error; inertially stabilized platforms; operating characteristics; simulation; tested signals.

1. Introduction

To provide the high accuracy of tracking and stabilization of inertially stabilized platforms operated on ground vehicles it is necessary to carry out testing of operating characteristics. Solving of this problem is important for Ukrainian instrument-making [1].

Creation of modern inertially stabilized platforms foresees using of discrete controllers. This gives the wide possibilities for testing by means of simulation [2]. So, creation of new approaches and techniques of operating characteristics testing will provide successful development of modern inertially stabilized platforms operated on ground vehicles in difficult conditions of real operation.

It should be noted that checking of accuracy characteristics is of great importance for platforms of the considered type [3]. Using of software for their testing will decrease time and cost of checking procedures.

2. Analysis of the latest researches and publications

General principles of checking methodical errors and their estimation are given in many books [4]. Analysis of gyroscopic stabilization systems similar to inertially stabilized platforms of the researched type is presented in [5]. The theoretical estimation of the dynamic error on the basis of the transfer functions is described in [6].

3. Research tasks

Development of inertially stabilized platforms operated on ground vehicles foresees estimation of accuracy characteristics in conditions of motion on the testing route. This process is sufficiently complex and requires using the vehicle and complex observation equipment. The goal of the paper is to consider features of inertially stabilized platforms testing by means of simulation. Using of discrete controllers provides setting of tested signals, which can be efficient in the semi-scale tests using testing bench.

4. Mathematical model of inertially stabilized platforms operated on ground vehicles

In the general case, inertially stabilized platforms functioned on ground vehicles can operate in three modes, such as tracking, stabilization and stabilized tracking. For such modes simulation it is convenient to accept following suppositions. The inertially stabilized platform in the tracking mode is controlled by the signal $U_c(t)$, which is given by means of the console. An angular rate ω_{gv} of the ground vehicle in the stabilization mode is considered as a disturbance. The basic disturbance of the tracking mode is the total moment acting on the drive of the inertially stabilized platform. The unbalanced moment is the main component of this disturbance. The vehicle angular rate as disturbance is characterized by two features. The first feature is that this angular rate influences on the stabilization plant as the translational angular rate. The motion of the platform (stabilization plant) is the relative motion. It should be noted that, as a rule, platforms operated on ground vehicles are stabilized in two planes such as the vertical and horizontal ones. Stabilization is implemented based on signals of the absolute angular rate, which are measured with the gyroscopic devices. The second feature is the necessity to take the translational angular rate into consideration as a cause of the moment acting on the drive of the inertially stabilized platform.

The structural schemes of the linearized models of the inertially stabilized platform in modes of tracking and stabilization are shown in Figures 1, 2.

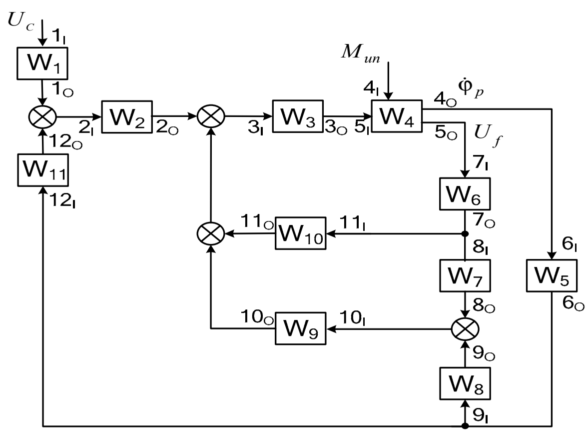

Fig. 1. Structural scheme of the model of the inertially stabilized platform in the tracking mode

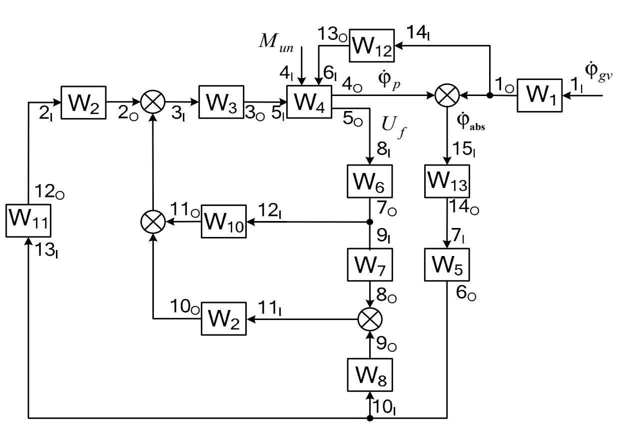

Fig. 2. Structural scheme of the model of the inertially stabilized platform in the stabilization mode

Figures 1, 2 use the following notations. W_1 is the console transfer function in the tracking mode and the unit for setting of the translational angular rate (vehicle angular motion) in the stabilization mode. W_2 is the transfer function of the serial connection of the integrator and amplifier. W_3 is the transfer function of the serial connection of the amplifier and pulse width modulator. W_4 is the united model of the drive and stabilization plant in the space state. W_5 is the transfer function of the rate gyroscope. W_6 is the transfer function of the serial connection of the amplifier and the low-pass and high-pass filters. The voltage of the motor armature circuit is the input signal of this combination of units. W_7 is the transfer function of the low-pass filter for the total signal of the motor armature current and the plant angular acceleration. W_8 is the transfer function of the serial connection of the amplifier and the low-pass filter (differentiator) of the rate angular signal. W_9 is the transfer function of the parallel function of the low-pass filter for disturbance and the band-pass filter, which provides operation of the rate gyroscope on the safe frequencies. W_{10} is the transfer function of the amplifier. W_{11} is the transfer function of the low-pass filter for the basic feedback signal, which enters from the rate gyroscope. $W_{12} = I_p \frac{1}{p}$ is the transfer function of the unit, which forms the moment caused by the translational angular rate of the stabilization plant that is the vehicle angular rate. W_{13} is the transfer function of the amplifier, which increases the total signal of the translational and relative rate of the stabilization plant. It should be noted that models W_{12} and W_{13} are used in the stabilization mode only. Numbers with indices I and O mark inputs and outputs of the separate models. Using structural schemes represented in Figures 1, 2 and the mathematical description represented in [7] it is possible to obtain full transfer functions of the open-loop and closed-loop systems. Transformations can be automated using MatLab software [8].

The united model of the motor and stabilization plant can be represented in the following form [6]

$$J_p\ddot{\varphi}_p = -M_{fp}\mathrm{sign}\varphi_p - M_{un}\cos\varphi_p + k_s(A-\varphi_p) + \frac{c_r}{n_r}\varphi_e - c_r\varphi_p;$$

$$J_e\ddot{\varphi}_e = -M_{fe}\mathrm{sign}\varphi_e + \frac{c_m}{R_{arm}}U + \frac{c_r}{n_r^2}\varphi_e - \frac{c_r}{n_r}\varphi_p;$$

$$\dot{U}T_{arm} + U = -c_e\dot{\varphi}_e + U_{PWM};$$

$$\ddot{U}_g T_g^2 + \dot{U}_g 2\zeta T_g + U_g = k_g\dot{\varphi}_p, \quad (1)$$

where J_p is the moment of inertia of the platform; φ_p is the rotation angle of the platform; M_{fp} is the nominal friction moment of the platform; M_{un} is the unbalanced moment; k_s is the rigidity of the spring of the balancing system; A is an angle of spring resetting; c_r is the reducer rigidity; n_r is the reducer ratio; J_e is the moment of inertia of the motor; φ_e is the angle of motor rotation; M_{fe} is the nominal friction moment of the motor; c_m is the constant of the loading moment; T_{arm} is the time constant of the motor armature; R_{arm}, U are the resistance and the voltage of the motor armature winding; U_{PDM} is the voltage of the pulse duration modulator; c_e is the electromotive force constant; U_g is the voltage at the gyroscope output; T_g, k_g are time and transfer constants; ζ is the damping coefficient.

Respectively, the first two equations of the model (1) after linearization become

$$J_p\ddot{\varphi}_p = -f_p\varphi_p - M_{un} + k_s(A-\varphi_p) + \frac{c_r}{n_r}\varphi_e - c_r\varphi_p; \quad (2)$$

$$J_e\ddot{\varphi}_e = -f_e\varphi_e + \frac{c_m}{R_{arm}}U + \frac{c_r}{n_r^2}\varphi_e - \frac{c_r}{n_r}\varphi_p,$$

where f_p, f_e are coefficients of linearized friction moments for the stabilization plant and the motor respectively.

The mathematical models (1), (2) are components of the structural schemes represented in Figures 1, 2.

5. Testing of accuracy characteristics of inertially stabilized platforms by simulation

The most important characteristics of inertially stabilized platforms are static and dynamic errors. Based on the theorem of the boundary transition the expression for the static error determination can be represented in the following form [4]:

$$x(t) = \left[\frac{g(t)}{1+W(p)}\right]_{p\to 0} + \left[\frac{\sum_{k-1}^{n} W_k(p) f_k}{1+W(p)}\right]_{p\to k}, \quad (3)$$

where $x(t)$ is the static error; $g(t)$ is the reference signal; $W(p)$ is the transfer function of the open-loop system by the reference signal; $W_k(p)$ is the transfer function of the closed-loop system by the disturbance; f_k is the disturbance; k is quantity of disturbances.

Based on the expression (3) errors of the inertially stabilized platforms for ground vehicles can be divided in three components [5].

The first component is the tracking error, which can be determined by the expression [5]

$$x_{tr} = \frac{U_c}{[1+W(p)]}, \quad (4)$$

where U_c is the console reference signal; $W(p)$ is the transfer function of the open-loop system for control by the platform motion.

The second component is the error caused by influence of external moments. Usually, this error is defined relative an angle, which determines the platform position. This error can be described by the expression [5]

$$x_{dist} = \frac{W_1(p)M_{un}}{[1+W(p)]p}, \quad (5)$$

where $W_1(p)$ is the transfer function by the unbalanced moment; M_{un} is the unbalanced moment.

The third component is the stabilization error. It is determined relative angular position of the plant. Obtaining this error it is necessary to take into consideration the angular rate of the vehicle. The total stabilization error can be determined by the expression [5]

$$x_{stab} = \frac{[1-W_2(p)W_r(p)J_p p]\omega_{gv}}{[1+W(p)]p}, \quad (6)$$

where $W_2(p)$ is the transfer function by the rotation moment caused by the angular rate of the vehicle; $W_r(p)$ is the transfer function of the reduced moment of disturbance caused by the angular rate of the vehicle, J_p is the moment of inertia of the stabilized platform.

Consider features of tracking error (4) determination by means of simulation.

Tracking error can be determined by setting of the console reference signal and estimation of the appropriate angular rate. Simulation is convenient to carry out in conditions of the immovable ground vehicle. Then the error (4) will be determined by the equation of the transient process $x_{tr} = x_0 h(t)$.

The error caused by the disturbance moment (5) can be estimated by setting of the step-wise unbalanced moment. Further the difference between angular platform positions is determined. Simulation is carried out in conditions of immovable vehicle too. Such approach allows estimating the rigidity by the moment.

The stabilization error (6) can be determined in conditions of the zero console reference signals. The relative angular rate is set as the step-wise signal. To analyse the stabilization error it is necessary to analyze the transient process by the absolute angular rate of the stabilization plant.

One of the most important accuracy characteristics for any stabilization system including inertially stabilized platforms is the dynamic error. Dynamic errors of the control systems of the wide class are all the errors, which arise during dynamic processes in conditions of changing influences (disturbances and controls).

The dynamic error can be estimated by simulation of the vehicle motion in accordance with the harmonic law, which corresponds to the testing road. In this case, the direction of the ground vehicle angular motion is continuously changed. Respectively, direction of the friction forces is changed too. This allows carrying out the fullest estimation of the dynamic properties of the system for control by the motion of the inertially stabilized platform. The error of the platform angular position in the stable mode will be changed by the harmonic law $x(t) = x_{\max} \sin(\omega_к t + \psi)$.

Dynamic accuracy of stabilization can be estimated by the maximum amplitude of the error $x_{\max}$. Value of the amplitude can be obtained by the symbol method by means of substitution $p = j\omega_{gv}$ into the expression (3) [4]

$$x_{\max} = \frac{\omega_{gv} - |W_2(j\omega)W_r(j\omega)J_p j\omega|\,\omega_{gv}}{|1+W(j\omega)|\,j\omega}. \qquad (7)$$

As amplitude of the error is sufficiently less than amplitude of the input influence, the expression (7) can be changed by the approximate expression

$$x_{\max} = \frac{\omega_{gv} - |W_2(j\omega)W_r(j\omega)J_p j\omega|\,\omega_{gv}}{|W(j\omega)|\,j\omega}, \qquad (8)$$

where $|W(j\omega)|$ is the module of the frequency characteristic of the open-loop system for $\omega = \omega_{gv}$. The maximal amplitude calculated by the formula (8) for the system of the researched type is 5 arcmin.

Estimation of the maximum amplitude error can be obtained by means of the linearized model of the inertially stabilized platform. Such a stabilization error is represented in Fig. 3.

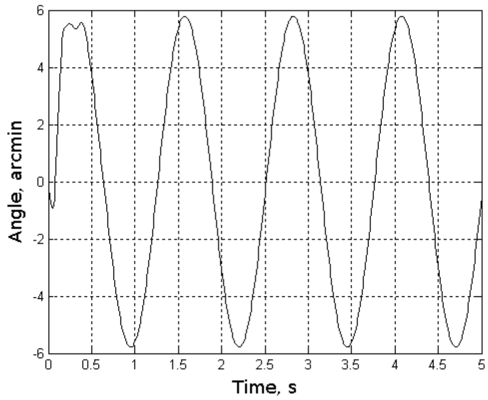

Fig. 3. Stabilization error

Disadvantage of such approach is using the concrete value of the tested signal. To avoid this disadvantage it is possible using a relative amplitude error. For this it is necessary to carry out two checked measurements in conditions of influence of angular rates ω_{gv1}, ω_{gv2}, which, for example, correspond to maximum values of amplitudes 2 and 2.5 deg.

$$\Delta x_{\max} = \left(\frac{x_{\max_1}}{\varphi_{\max_1}} - \frac{x_{\max_2}}{\varphi_{\max_2}} \right) \cdot 100\%, \qquad (9)$$

where $x_{\max_1}$, $x_{\max_2}$ are maximum amplitudes for two measurements; $\varphi_{\max_1}$, $\varphi_{\max_2}$ are angular positions of the platform, which correspond to these measurements.

The expression (9) allows formulating requirements to the logarithmic amplitude characteristics of the system. Execution of these requirements means that the stabilization error in the stable mode will not exceed a given value. The requirements can be defined by the condition [4]

$$L(\omega) \ge 20\lg A(\omega) \ge$$
$$\ge 20\lg \frac{\omega_{gv} - |W_2(j\omega)W_r(j\omega)J_p \cdot j\omega|\,\omega_{gv}}{x_{\max}}.$$

Simulation results, which represent transient processes by angular rate and angular position of the platform, are shown in Fig. 4.

As stated above, checking of operating characteristics of inertially stabilized platforms operated on ground vehicles is carried out by means of testing road.

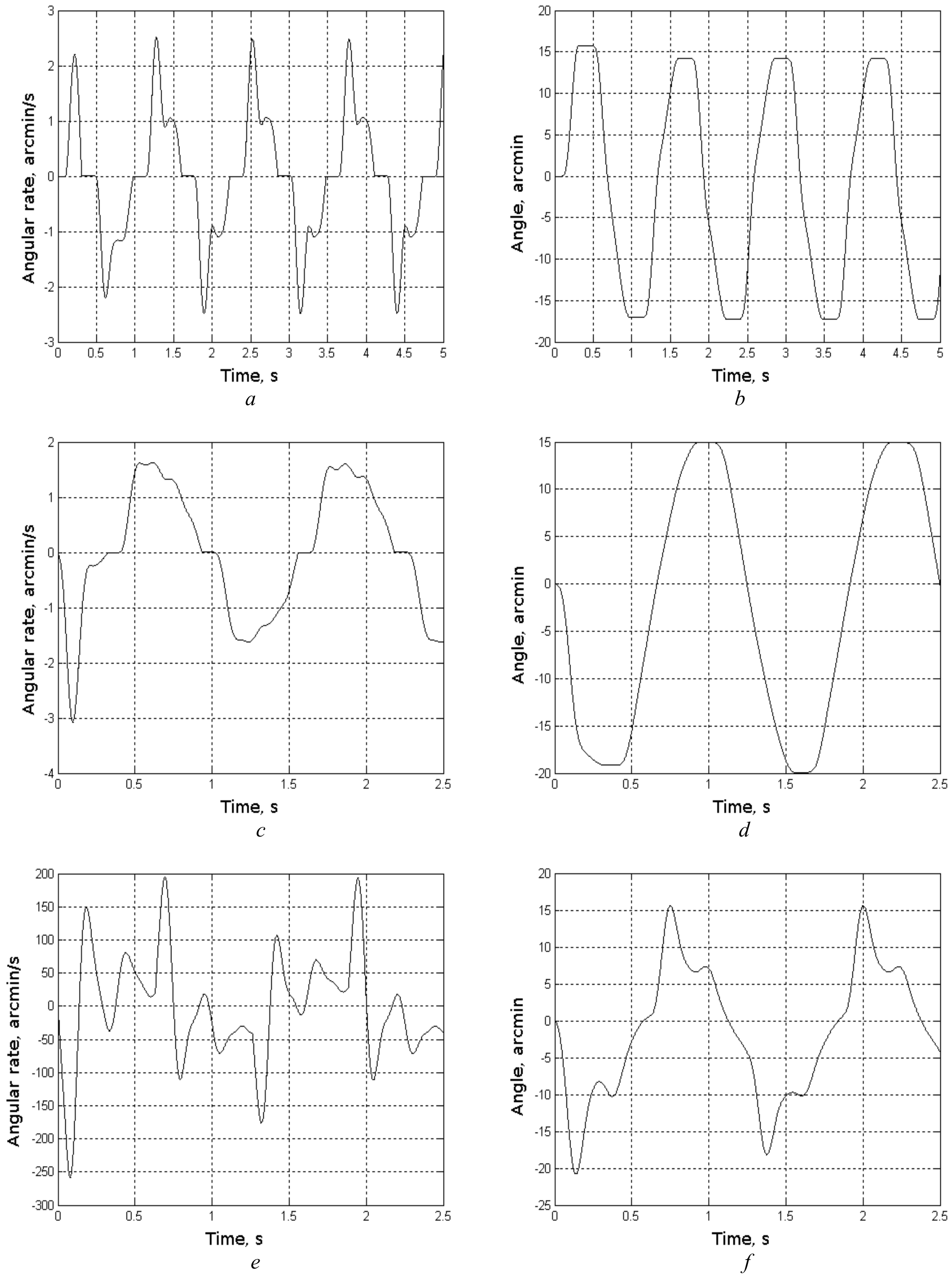

Fig. 4. Angular rates and angular positions of the inertially stabilized platforms in conditions of different types of tested signals: *a*, *b* – at the integrator input; *c*, *d* – at the demodulator input in the integrator circuit; *e*, *f* – at the input of the rate gyroscope

In conditions of simulation and testing bench using these checks are similar to angular rate changing by the harmonic law, which corresponds to the profile of the testing road. This harmonic law is determined by the expression $\varphi(t) = \varphi_{\max} \sin \omega_к t$ for changing angular position. The angular rate will be determined by the expression $\omega_н = \dot{\varphi}(t) = \varphi_{\max} \omega_к \cos \omega_к t$.

Simulation of the signal, which corresponds to the testing road, it is necessary to implement taking into consideration features of testing equipment [9]. Therefore it is necessary to research ways to set signals, which correspond to disturbances of testing road on the bench assigned for testing of the system for control by the platform motion [10].

Tested signals represented in Fig. 4 can be characterized in the following way. Firstly, the tested signal can be set directly at the integrator input. Secondly, the tested signal can be set on the integrator circuit after demodulator. Thirdly, it can be set at the input of the rate gyroscope. The last signal is similar to the angular rate.

To determine the angle rigidity it is necessary to set some unbalanced moment and then add the complementary unbalanced moment. Further the difference between angular positions of the platform is determined. The angle rigidity is calculated by the formula

$$k_g = \Delta_M / \Delta\varphi ,$$

where Δ_M is difference of the given unbalanced moments; $\Delta\varphi$ is difference of angular positions.

To achieve the necessary accuracy of the angular rigidity estimation the basic and additional unbalanced moments are set through some instant of time, for example, 10 s.

6. Conclusions

The approaches to testing of basic accuracy characteristics of inertially stabilized platforms by means of simulation are considered. The appropriate mathematical models are developed. Different modes of inertially stabilized platforms functioning are taken into consideration. The approaches to estimation of static and dynamic errors are given. The ways to set tested signals taking into consideration features of testing bench are represented. The possibility to estimate angular rigidity by the moment is proposed. The results of simulation of the different tested signals are represented. Proposed ways to estimation of operating characteristics of inertially stabilized platforms allow decrease time and cost losses of testing. Obtained results can be useful for design of stabilized platforms for vehicles of the wide class.

References

[1] Kuznetsov B.I., Nikitina T.B., Kolomyets V.V., Hhomenko V.V. (2015) Eksperymental'nie yssledovanyya dynamycheskykh kharakterystyk maketa dvukhmassovoy elektromekhanycheskoy systemy s anyzotropyynimy rehulyatoramy pry mnohokryteryal'nom synteze [Experimental researches of dynamic characteristics of prototype of two-mass electromechanical system with anisotropic controllers for multi-criteria synthesis]. *System Technologies*, issue 3, pp. 40–47. (in Russian)

[2] Hilkert J.M. (2008) Inertially stabilized platform technology. *IEEE Control Systems Magazine*, vol. 28, no. 1, pp. 26–46. doi:0.1109/ MCS.2007.910256.

[3] Masten M.K. (2008) Inertially Stabilized Platforms for Optical Systems. *IEEE Control Systems Magazine*, vol. 28. no. 1. pp. 47–64. doi:10.1109/MCS.2007.910201.

[4] Besekerskyy V.A., Popov E.P. (2003). *Teoryya system avtomatycheskoho rehulyrovanyya* [Theory of systems of automatic regulation]. St. Petersburg, Professiya, 752 p. (in Russian)

[5] Kocherhyn V.V. (1988) *Sledyashchye systemi s dvyhatelem postoyannoho toka* [Servo-systems with direct current motors]. Leningrad, Energoatomizdat, 168 p. (in Russian)

[6] Sushchenko O. A. (2013) Features of computer-aided design of robust discrete controllers for information-measuring devices stabilization systems. *Electronics and Control Systems*, no. 4(38), pp. 79–85. doi: 10.18372/1990-5548.38.7285

[7] Sushchenko O.A., Sayfetdynov R.A. (2007) Matematychna model' systemy stabilizatsiyi rukhomoho nazemnoho ob"yekta [Mathematical model of stabilization system of ground vehicle]. *Electronics and Control Systems*, no. 3(13), pp. 146-151. (in Ukrainian)

[8] Gu D.W., Petkov P., Konstantinov M. (2013) *Robust control design with MATLAB*. Berlin, Springer, 465 p.

[9] Sol'nytsev R.I., Charishev S.F. (1990) *Avtomatyzatsyya proektyrovanyya, yzhotovlenyya y yspitanyya avyatsyonnikh pryborov y system* [Automation of design, production and test of aviation devices and systems]. Moscow, Nauka, 150 p. (in Russian)

[10] Sushchenko O.A.. (2010) Osoblyvosti proektuvannya system inertsial'noyi stabilizatsiyi informatsiyno-vymiryuval'nykh prystroyiv [Features of design of systems for inertial stabilization of information and measuring devices]. *Electronics and Control Systems*, no. 4(26), pp. 80–85. doi: 10.18372/1990-5548.26.856 (in Ukrainian)

О.А. Сущенко
Особливості тестування інерціальних стабілізованих платформ
Національний авіаційний університет, пр. Космонавта Комарова, 1, Київ, 03058, Україна
E-mail: sushoa@ukr.net

Мета: у статті розглянуто проблеми перевірок інерціальних стабілізованих платформ, які експлуатуються на наземних рухомих об'єктах. Головною ціллю є розгляд можливостей перевірок систем за допомогою використання імітаційного моделювання. **Методи:** для розв'язання цієї проблеми використовуються методи інерціальної стабілізації, методи створення математичних моделей, а також імітаційного моделювання. При цьому враховуються можливості обчислювальної системи MatLab. **Результати:** Розглянуто можливості перевірок точнісних характеристик засобами моделювання. Розроблено відповідні математичні моделі. Враховано наявність різних режимів функціонування інерціальних стабілізованих платформ. Представлено підходи до оцінювання статичних і динамічних похибок. Розглянуто можливість оцінки кутової жорсткості за моментом. Розглянуто способи завдання різних тестових сигналів з урахуванням особливостей випробувального стенда. **Висновки:** представлено результати моделювання різних тестових сигналів. Запропоновані способи оцінки експлуатаційних характеристик інерціальних стабілізованих платформ дозволяють зменшити часові та вартісні витрати на тестування. Отримані результати можуть бути корисними під час проектування інерціальних стабілізованих платформ для рухомих об'єктів широкого класу.

Ключові слова: динамічна похибка; експлуатаційні характеристики; інерціальні стабілізовані платформи; імітаційне моделювання; тестові сигнали.

О.А. Сущенко
Особенности тестирования инерциальных стабилизированных платформ
Национальный авиационный университет, пр. Космонавта Комарова, 1, Киев, 03058, Украина
E-mail: sushoa@ukr.net

Цель: в статье рассматриваются проблемы проверок инерциальных стабилизированных платформ, эксплуатируемых на наземных подвижных объектах. Главной целью является рассмотрение возможностей проверок систем посредством использования имитационного моделирования. **Методы:** для решения данной проблемы используются методы инерциальной стабилизации, методы создания математических моделей, а также имитационного моделирования. При этом учитываются возможности вычислительной системы MatLab. **Результаты:** рассмотрены возможности проверок точностных характеристик посредством моделирования. Разработаны соответствующие математические модели. Учтено наличие разных режимов функционирования инерциальных стабилизированных платформ. Представлены подходы к оценке статических и динамических погрешностей. Рассмотрена возможность оценки угловой жесткости по моменту. Рассмотрены способы задания разных тестовых сигналов с учетом особенностей испытательного стенда. **Выводы:** представлены результаты моделирования разных тестовых сигналов. Предложенные способы оценки эксплуатационных характеристик инерциальных стабилизированных платформ позволяют уменьшить временные и стоимостные затраты на тестирование. Полученные результаты могут быть полезны при проектировании инерциальных стабилизированных платформ для подвижных объектов широкого класса.

Ключевые слова: динамическая погрешность; инерциальные стабилизованные платформы; эксплуатационные характеристики; имитационное моделирование; тестовые сигналы.

Olha Sushchenko (1956). D. Sci., Associate Professor.
Aircraft Control Systems Department, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1980).
Research area: systems for stabilization of information and measuring devices.
Publications: 200.
E-mail: sushoa@ukr.net