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DESIGNING CONTROL LAWS IN TRACKING AND STABILIZATION LOOPS OF INERTIALLY STABILIZED PLATFORMS

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Abstract**—***The article deals with the approach to designing control laws of tracking and stabilization loops of inertially stabilized platforms operated on moving objects. The phases of designing controller are described. The process of choosing PID controller is represented. The ways of designing discrete controllers are shown and analysed. The possibility of using PID tuner by means of MatLab is represented. The necessity to use additional techniques of controller synthesis is grounded. The procedure of the structural robust synthesis based on the mixed sensitivity method and loop-shaping is represented. The technique of determining stiffness of the platform is proposed. The simulation results including step and impulse responses and sensitivity functions are shown. The possibility of industrial realization of controllers is considered. The proposed approach can be useful for designing stabilization systems of the wide class.*

Index Terms—Inertially stabilized platforms; tracking and stabilization loops; PID controller; robust structural synthesis; platform characteristics.

I. INTRODUCTION AND PROBLEM STATEMENT

Inertial stabilized platforms (ISP) are widely used to stabilize the position of various information and measuring systems on a moving vehicle [1] – [4]. As information and measuring systems we will consider optical systems, photo and video cameras [5], [6] television and telecommunication systems, radars of various applications [1], and various weapon systems [5]. As carriers of these systems, all kinds of moving vehicles are used, including aircraft, unmanned aerial vehicles (UAVs) and missiles, as well as other vehicles, including sea and land ones [7], [8]. The tasks solved by ISP are very different such as target search and target designation, tracking of moving targets, stabilization of photo and video equipment on moving vehicles in the process of tracking, stabilization of the position of navigation equipment in some inertial reference frames, stabilization of the position of radar antennas and telecommunication radio systems, etc.

The main goal of the article is representation of methodology of designing control laws for ISP in modes of tracking and stabilization.

II. DESIGN OF CONTROL LAWS FOR INERTIALLY STABILIZED PLATFORM

The sequence of steps necessary for designing control laws for ISP tracking and stabilization platforms can be represented in the following form.

At the beginning, the control laws of the internal and external control loops of ISP are synthesized. This synthesis could be both parametric and structural. In parametric synthesis, the structure of the controller (control law) is obtained, and the optimal values of the parameters of this structure are found based on the minimization of a certain quality index, which is chosen based on the requirements for static and dynamic accuracy. As a rule, one of the standard laws is chosen such as the control law PID, PD or PI [9].

Only if it is impossible to satisfy all the requirements for static and dynamic accuracy of ISP under the action of external (coordinate) and internal (parametric) disturbances using simple PID controllers, modern methods of structural synthesis based on the methods of the theory of robust systems, optimal stochastic systems, etc. can be used. Analytical assessments of the quality of the system functioning in various operating conditions must be especially carried out.

The next step is to simulate the dynamics of closed control loops in Simulink, taking into account all possible nonlinear functions and other features that could not be taken into account in the above synthesis procedure (elastic deformations of mechanical structure elements, the effect of misalignments and unbalances, etc). The behaviour of the system under the action of external and internal disturbances of various nature, arising during normal operation, is studied. According to [4], this stage is called model-in-loop-simulation (modelling with a plant in a closed loop). As a result, the dynamic and static indices of the system are estimated and their compliance with technical requirements is made. Based on the simulation results, an additional correction of the control laws is performed. At this stage, the discrete interval of digital controllers is chosen and the system with digital control is simulated with possible correction based on the simulation results.

The digital control laws verified at this step provide a basis for choosing control microprocessors, in which these laws will be implemented. In addition to the control laws, it is also possible to provide other additional algorithms that may be needed for the normal operation of the system, such as test algorithms, etc.

Systems of the considered type are systems with negative feedback on the angular rate signal. It should be noted that there are several approaches to the synthesis of control systems using MatLab software. In the first approach, the system is believed to be continuous. Therefore, continuous control laws are synthesized, and then the continuous controller is converted into a discrete one. In the second approach, the system is discretized, followed by the synthesis of a discrete controller. The third approach can be implemented using Simulink only. In the case of the second and third approaches, the synthesis of the control system should begin with the choice of sampling rate.

The bounded value of the sampling frequency can be determined based on the Kotelnikov theorem [9]

$$\Delta_d \le 1/(2f_b), \quad (1)$$

where Δ_d is sampling interval, f_b is the bounded frequency of the system.

For a system cut-off frequency of 100 Hz, the sampling interval in accordance with (1) must be at least 0.005 s.

To choose the range of sampling frequency variation, the formula, which relates the sampling rate and the bandwidth frequency of a closed system, can be applied

$$f_d = (2...8)\Delta f\ . \quad (2)$$

For the bandwidth 100 Hz, the frequency and interval in accordance with (2) will change in the range

$$800 < f_d \le 200\text{, Hz;}$$

$$0.00125 < \Delta_d \le 0.005\text{, s.}$$

Refinement of the sampling rate is carried out experimentally based on the analysis of the quality indices of transients at different sampling rates.

For systems of the considered type, it is necessary to take into account the fact that the real operating conditions are accompanied by the influence of shocks. Therefore, after analysing the characteristics of possible influences, it is necessary to carry out additional modelling with imitation of shocks. The final sampling rate is set based on the results of this simulation to ensure that the system is stable when subjected to shocks.

In the case of the first approach to system design, it is necessary to perform discretization. Various discretization methods can be implemented in MatLab using the Control System Toolbox, including zero-order (ZOH) and first-order (FOH) extrapolation, impulse-invariant sampling (IMP), Tustin bilinear fractional-rational approximation without correction (TUSTIN) and with frequency correction PREWARP, as well as the method of displaying poles and zeros (MATCHED) [10].

The choice of a method is made by comparing the transient and frequency characteristics of a continuous and sampled systems in the given bandwidth. Based on the experience of designing such systems, the Tustin method without correction (TUSTIN) can be recommended.

The choice of the type of a controller depends on the capabilities of the designer and the time of the system design. The simplest and most economical is the use of standard or serial P-, PI- and PID controllers. An important advantage of such controllers is the ability to use the embedded coder extension to automatically generate C code that can be implemented in a microcontroller.

To choose the type of a serial controller, it is necessary to take into account the static and dynamic characteristics of the stabilization plant, the requirements for the quality of the control process (transient processes) and the type of external disturbances.

In accordance with generally accepted recommendations [11], discrete PID controllers are used in payload platform stabilization systems, which provide high speed and maintain acceptable accuracy (unlike P-controllers).

PID controller coefficients, including discrete ones, can be tuned automatically using Simulink software. The most common choice of PID controller coefficients is based on the requirements for the quality of the transient process. This approach is consistent with the design of the considered system, since it allows satisfying the requirements for the accuracy and speed of the transient process. The Simulink model with a built-in block for automatic tuning of the PID controller based on the requirements for the quality of the transient process is shown in Fig. 1.

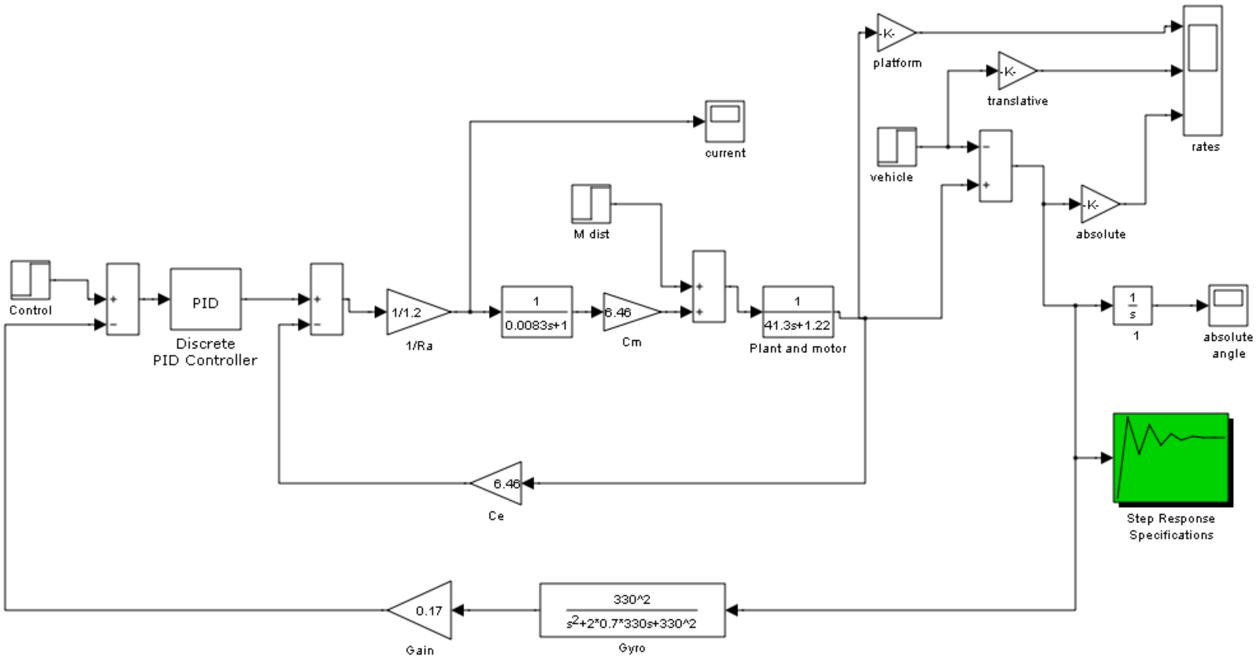

Fig. 1. Simulink model with PID-tuner

The disadvantages of the above-mentioned approach include the fixed structure of the controller and the impossibility of introducing correction units. Therefore, a model with a discrete PID controller is proposed. It is tuned experimentally by changing the controller settings and analysing their effect on the system dynamics [12]. This approach is more flexible. When analysing quality indices, transient processes should be considered under the driving and perturbing influences. Both transients in terms of the angular rate of the platform and transients in terms of current in the armature circuit of the motor winding should be analysed. In the end, getting good settings for a particular stabilization system is guaranteed. The corresponding model of the stabilization system is shown in Fig. 2.

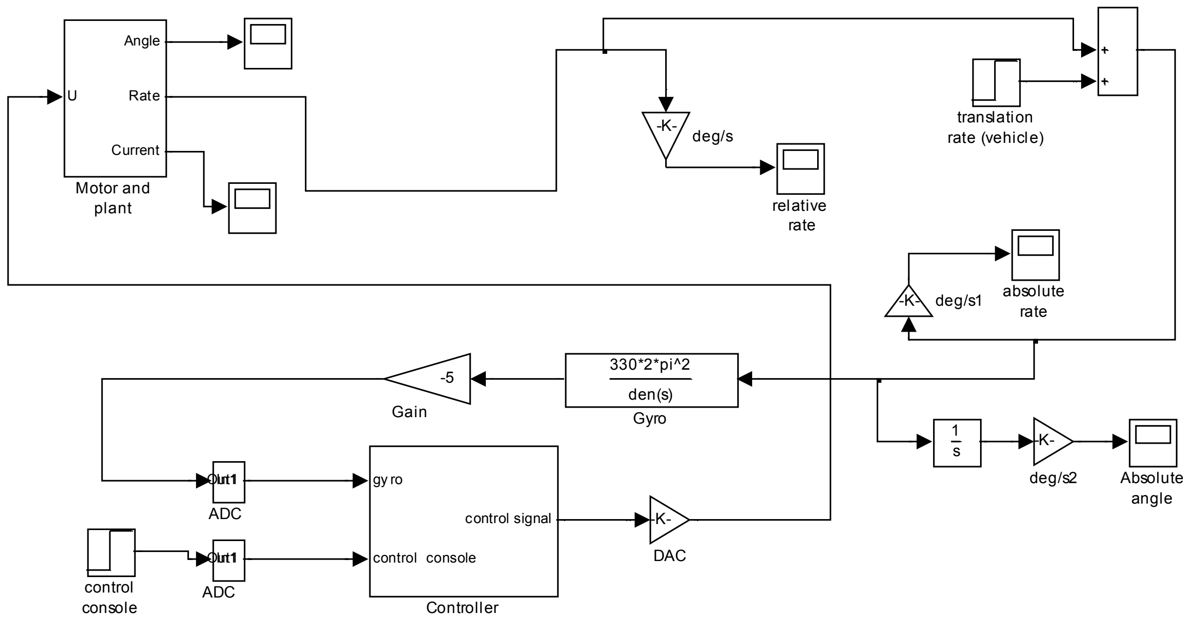

Fig. 2. The model of the closed loop of the tracking and stabilization system

It is necessary to create optimization programs (rather complex and time-consuming) in MatLab software using automated optimal means, for example, Control System Toolbox and Robust

Control Toolbox. The results of the synthesis of stabilization systems are verified using mathematical models developed by Simulink, since such models are quite complete and include nonlinearities inherent in real systems.

In the case of a significant change in the system parameters during operation, it makes sense to synthesize a robust controller. There are many methods for the synthesis of robust controllers, one of which is H_∞-synthesis, which includes the following main steps.

The first step is creation of a mathematical description of the stabilization plant in the space of states. An example of such a model for a system of the considered type is given in [13], [14]. In the process of applying this method, an approach based on the formation of the desired frequency characteristics (loop shaping) is used.

In this case, the block diagram of the stabilization system is presented in Fig. 3.

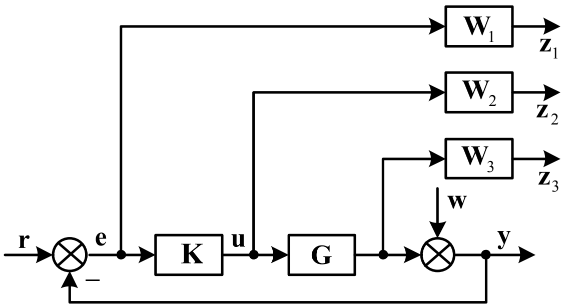

Fig. 3. The structural scheme of the augmented system: K is the controller; G is the stabilization plant with the measuring system and actuator; W_1, W_2, W_3 are weighting transfer functions

The next step in the synthesis of the controller is the choice of weighting transfer functions. Next, the augmented model of the plant can be obtained. Then the search for the optimal controller is performed, which includes [9]:

1) search of state Riccati algebraic solution X_∞

$$A^T X_\infty + X_\infty A + C_1^T C_1 + X_\infty(\gamma^{-2} B_1 B_1^T - B_2 B_2^T) X_\infty = 0, \quad (3)$$

2) search of observation Riccati algebraic solution Y_∞

$$A Y_\infty + Y_\infty A^T + B_1 B_1^T + Y_\infty(\gamma^{-2} C_1^T C_1 - C_2^T C_2) Y_\infty = 0 \quad (4)$$

3) checking conditions

$$\mathrm{Re}\lambda_i[A + (\gamma^{-2} B_1 B_1^T - B_2 B_2^T) X_\infty] < 0, \forall i, \quad (5)$$

$$\mathrm{Re}\lambda_i[A + Y_\infty(\gamma^{-2} C_1^T C_1 - C_2^T C_2)] < 0, \forall i, \quad (6)$$

$$\rho(X_\infty Y_\infty) < \gamma^2, \quad (7)$$

where γ is a small number.

It should be noted that expressions (3) – (7) are automated in Robust Control System Toolbox. They can be implemented using the hinfopt function.

Using the most common mixed sensitivity method, the quality functional can be minimized. This functional consists of H_∞-norms of the mixed sensitivity function [9]

$$J = \left\| \begin{bmatrix} W_1(I+GK)^{-1} \\ W_2 K(I+GK)^{-1} \\ W_3 GK(I+GK)^{-1} \end{bmatrix} \right\|_\infty \text{ or } J = \left\| \begin{bmatrix} W_1 S \\ W_2 R \\ W_3 T \end{bmatrix} \right\|_\infty, \quad (8)$$

where W_1, W_2, W_3 are weighting transfer functions, S, R, T are sensitivity functions on the given signal, control, and complementary sensitivity function.

Further, optimization problem (8) is solved and transition to the discrete controller is carried out.

Finally, simulation of the synthesized system is implemented. This process is carried out by full nonlinear model implemented in Simulink.

III. SIMULATION RESULTS

The results of simulation taking into account parametric perturbations of a system [14] are shown in Fig. 4.

To test the proposed approaches to designing a robust system, changes in the moment of inertia of the plant, were considered as parametric disturbances, since for the example under consideration, changes in this parameter during operation can reach 50%.

The most important characteristics of the system are evaluated through the following steps.

Evaluation of the static accuracy of the stabilization system is carried out in steady state modes at constant values of the given influence.

This study is performed in tracking modes (setting the angular velocity) and in stabilization modes (the specified angular velocity is equal to zero, and the angular velocity of the object with the mounted platform is considered as a disturbing influence).

Assessment of the dynamic properties of the system can be performed based on the analysis of the quality of transients. In this case, it is necessary to estimate the speed of the transient process, overshoot and oscillation.

For systems of the type under study, an important and necessary characteristic is the angular stiffness, which is determined as follows [10].

With a zero reference signal, an increased constant value of a moment on the system's input by perturbation is applied.

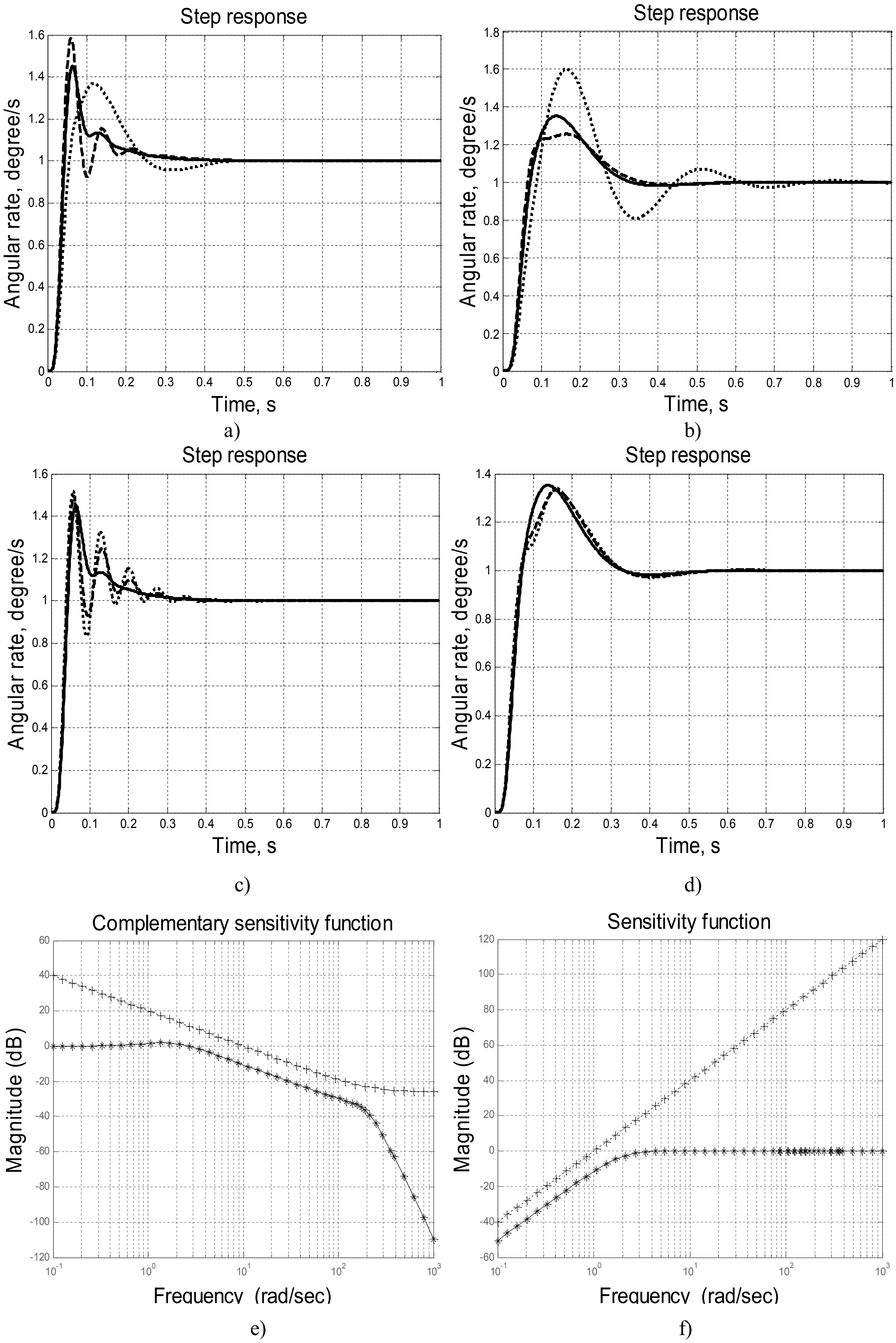

Fig. 4. Results of simulation of tracking and stabilization system: (a), (b) are step responses for horizontal and vertical channels, respectively; (c), (d) are impulse responses for horizontal and vertical channels; (e), (f) are complementary sensitivity and sensitivity functions

After some time (10–20) s, the moment of perturbation decreases to the nominal value. Thus, the law of change of the moment of perturbation applied to the object of stabilization becomes

$$M\ (t) = M_1[1(t)] - M_2[1(t)]. \qquad (9)$$

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

$$\Delta\varphi = \varphi_1 - \varphi_2. \qquad (10)$$

Angular stiffness is defined as the ratio of the difference of disturbing moments to the difference in quantities that determine the platform's position

$$c = (M_1 - M_2) / \Delta\varphi. \qquad (11)$$

Carrying out (9) – (11) provides the check of one of the most important property of ISP.

At the last design stage, using the Simulink / Embedded Coder, C/C++ code is automatically generated, which is essentially the program code for the microprocessor [11]. The resulting code is implemented in a closed loop along with the plant model. In article [11], this stage is called software-in-loop-simulation (simulation of software operation in a closed loop with a plant model). When using this approach, it becomes possible at the stage of simulation to identify a large number of syntactic, semantic and logical errors that occur when programming algorithms for functioning the system. The implementation of this stage significantly reduces the time of design implementation and simplifies its further maintenance. Further stages of verification are carried out during the manufacturing and testing of the system. Based on the analysis of the results of the above-mentioned stages, a decision is made to start the development and manufacture of ISP.

V. CONCLUSIONS

The procedure of designing control laws for tracking and stabilization loops of inertially stabilized platforms is represented. The approach to the choice of the controller is proposed. The technique of designing robust inertially stabilized platform is described. The simulation results of the robust system synthesis are shown.

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О. А. Сущенко, О. О. Салюк. Синтез законів керування в контурах стеження та стабілізації інерціальних стабілізованих платформ

У статті розглянуто підхід до побудови законів керування контурами стеження та стабілізації інерціальних стабілізованих платформ, що експлуатуються на рухомих об'єктах. Описано етапи проектування регулятора. Представлено процес вибору ПІД-регулятора. Показано та проаналізовано шляхи проектування дискретних регуляторів. Представлена можливість використання ПІД-тюнера засобами MatLab. Обґрунтовано необхідність використання додаткових методів синтезу регулятора. Представлено процедуру структурного робастного синтезу на основі методів змішаної чутливості та формування частотних характеристик. Запропоновано методику визначення жорсткості платформи. Показано результати моделювання, включаючи перехідні та імпульсні характеристики та функції чутливості. Розглядається можливість промислової реалізації контролерів. Запропонований підхід може бути корисним для проектування систем стабілізації широкого класу.

Ключові слова: інерціальні стабілізовані платформи; контури стеження та стабілізації; ПІД-регулятор; робастний структурний синтез; характеристики платформи.

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