UDC 629.3.025.2(045)
DOI:10.18372/1990-5548.80.18685

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SYNTHESIS OF ROBUST SYSTEM FOR SPATIAL STABILIZATION OF GROUND VEHICLE EQUIPMENT

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Abstract—*The article deals with the approach to designing robust system for stabilization of equipment assigned for operation on ground moving vehicles. The mathematical model of stabilization system including non-linear differential equations and state space representation is given. The features of basic external disturbances specific for ground moving vehicles are represented and analysed. The classification of external disturbances is suggested. Expressions for forming filters providing simulation of specific external disturbances are derived. The basic peculiarities of synthesis of spatial stabilization system for ground moving vehicle equipment are described. The simulation results are represented. During simulation, irregularities of different types are taken into consideration. The description of means for simulation of stabilization system of the studied type are considered. The obtained results can be useful for equipment operated on moving vehicles of the wide class.*

Index Terms—Spatial stabilization; equipment; robust system; mathematical model; state-space representation; external disturbances.

I. INTRODUCTION AND PROBLEM STATEMENT

Recently, the urgency of creating new promising systems for stabilizing ground moving objects has been increasing. The creation of such systems requires the use of methods of analysis and synthesis, which would allow the successful development of new samples of systems of the studied class, one of the features of which is the purpose for operation in off-road conditions and resistance to disturbances. In view of this, the synthesis of such systems should be carried out with simultaneous consideration of their quality and robustness. For this, it is necessary to create a model of the stabilization system of a moving ground equipment in the space of states, which allows the use of the Control Toolbox as a synthesis tool. Such an approach is characterized by a large set of design procedures of modern, including robust, control systems. The research also requires the possibility of taking into account random disturbances specific for such objects.

Considerable attention is now being paid to the creation of new promising systems of moving ground objects for various purposes. General problems of navigation of moving objects and a specific navigation system are described in [1], which emphasizes the use of autonomous navigation. Ways to improve the accuracy of navigation systems of ground moving objects are considered in paper [2], which deals with the improvement of navigation information processing algorithms. The general principles of creating models of drives of stabilization systems are considered in many publications, for example [3], [4]. A detailed model of a nonlinear system taking into account all inherent nonlinearities is presented in [5], [6]. It should be noted that the proposed method of synthesis foresees the use of a model in the space of states.

The aim of the article is description of the method of synthesising system for stabilization of ground vehicle equipment.

II. MATHEMATICAL MODEL OF SYSTEM FOR SPATIAL STABILIZATION OF GROUND VEHICLE EQUIPMENT

It is advisable to perform the synthesis of a robust stabilization system using the Control Toolbox, which provides for the presentation of the stabilization system model in the so-called LTI form. The main components of the stabilization system include the control unit, which performs the functions of signal processing and the formation of control laws, a pulse width modulator, a voltage amplifier, and such an actuator as a motor. Usually, the control unit includes high-pass and low-pass filters and a band-pass filter. Of the listed blocks, the pulse width modulator is a purely non-linear block, which must be replaced by a linear model. Other models also include non-linear elements that require replacement. A feature of the studied system is the presence of the so-called combined control, when along with error control, active disturbance control is used [7]. For this purpose, signals proportional to the motor armature current and voltage are used.

This approach allows you to avoid the use of additional devices, such as a gyroscopic tachogenerator, but leads to the complication of the control unit. A peculiarity of the studied system is also the presence of an elastic relationship between the actuator (motor) and the control object, in connection with which it is advisable to use a single model of the control object and the engine, represented in the space of states, since most methods of the Control Toolboox provides for the use of this type of LTI model as the main one. For models of electronic devices, the primary representation is in the form of transfer functions, which also belong to LTI models, since the transition from electrical schematic diagrams to transfer functions can be carried out according to certain rules. A gyro tachometer is used as a measuring tool in the studied stabilization system, which can also be represented in the form of a linear model. Then the model of the stabilization system as a whole can be created on the basis of individual models by the means provided by the Control Toolbox. It should be noted that the model of the studied system consists of models of vertical and horizontal channels, which are completely independent of each other. Further, we will consider the horizontal channel.

So, the combined model of the engine and the control object can be presented in this way.

$$
\begin{aligned}
&J_e\ddot{\varphi}_e = -M_{fr} sign\dot{\varphi}_e - M_{imb}\cos\varphi_\mathrm{e} + \frac{c_r}{n_r}\varphi_e - c_r\varphi_e, \\
&J_m\ddot{\varphi}_m = -M_r sign\dot{\varphi}_m + \frac{c_m}{R_w}U + \frac{c_r}{n_r^2}\varphi_m - c_r\varphi_m, \qquad (1) \\
&\dot{U}T_a + U = U_{pwm} - c_e\dot{\varphi}_m,
\end{aligned}
$$

where J_e is the inertia moment of equipment; φ_m is an angle of rotation of equipment; M_{fr} is the nominal friction moment in bearings of platform gimbal; M_{imb} is the imbalance moment; c_r is the reducer rigidity; n_r is the transfer ratio of the reducer; J_m is the inertia moment of the electric motor; φ_m is an angle of electric motor shaft rotation; M_r is the nominal moment of the counteracting; c_m is the constant of loading at the electric motor shaft; R_w is the resistance of the electric motor armature windings; U is the voltage of the electric motor armature windings; U_{pwm} is the voltage of pulse-width-modulator; c_e is the electromotive force constant.

After linearization, model (1) becomes

$$
\begin{aligned}
&J_\mathrm{e}\ddot{\varphi}_\mathrm{e} = -f_\mathrm{e}\dot{\varphi}_\mathrm{e} - M_{imb} + \frac{c_r}{n_r}\varphi_\mathrm{e} - c_\mathrm{e}\varphi_\mathrm{e}, \\
&J_m\ddot{\varphi}_m = -f_m\dot{\varphi}_m + \frac{c_m}{R_w}U + \frac{c_r}{n_r^2}\varphi_m - c_r\varphi_m, \qquad (2) \\
&\dot{U}T_a + U = U_{pwm} - c_e\dot{\varphi}_m,
\end{aligned}
$$

where f_e, f_m are coefficients of friction moments of the equipment and electric motor, respectively. In this model, the most significant thing is the replacement of nonlinear moments of friction with linear dependencies.

Model (2) can be transformed to a model in the state space of the general form

$$
\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{Ax} + \mathbf{Bu}, \\
\mathbf{y} &= \mathbf{Cx} + \mathbf{Du},
\end{aligned} \qquad (3)
$$

where $\mathbf{x}$ is the vector variable states; $\mathbf{u}$ is the vector of controls; $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ are matrices of the system and controls, $\mathbf{y}$ is the vector of observations.

For model (3), the vector of state variables, controls and the corresponding matrices are

$$
\mathrm{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} \varphi_e \\ \dot{\varphi}_e \\ \varphi_m \\ \dot{\varphi}_m \\ U \end{bmatrix}, \quad \mathrm{u} = \begin{bmatrix} 0 & 0 \\ \frac{-M_{imb}}{J_e} & 0 \\ 0 & 0 \\ 0 & \frac{U_{pwm}}{T_a} \\ 0 & 0 \end{bmatrix},
$$

$$
\mathrm{A} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ \frac{-c_r}{J_e} & \frac{-f}{J_e} & \frac{c_r}{n_r J_e} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{-c_r}{n_r J_m} & 0 & \frac{-c_r}{n_r^2 J_m} & \frac{-f_m}{J_m} & \frac{c_m}{R_w J_m} \\ 0 & 0 & 0 & \frac{-c_e}{T_a} & \frac{-1}{T_a} \end{bmatrix},
$$

$$
\mathrm{B}^\mathrm{T} = \begin{bmatrix} 0 & \frac{-M_{imb}}{J_e} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{U_{pwm}}{T_a} \end{bmatrix},
$$

$$
\mathbf{C} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \qquad \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}. \qquad (4)
$$

As has been suggested, other models are clearly presented in the form of transfer functions. Models (1) – (4) are basics for the synthesis of the system for stabilization of ground moving vehicle equipment.

The mathematical model of the stabilizer as a whole is characterized by the following features:

1) Mathematical models of the equipment block and the rotary base are developed taking into account the action of moments of resistance, moments of unbalance and moments of inertia. The mathematical model also takes into account the presence of an elastic balancing system.

2) The transfer of rotational motion from the engine to the equipment unit and the rotary base is provided through gearboxes, the mathematical models of which are built taking into account the presence of backlashes and the elasticity of the drive structure.

3) Control of the drive motors of the vertical and horizontal channels of the stabilizer is provided by a sequence of pulses, the formation of the duration of which in real equipment is carried out by a pulse width modulator.

4) The formation of stabilizer control laws is carried out on the basis of information about the absolute angular velocity of the equipment block and the rotary base, respectively, as well as using feedback from the voltage and current signals in the motor armature winding of the drives of the vertical and horizontal channels, respectively.

5) The elastic connection of the engine and the equipment block is modeled taking into account the turning angles of the block, respectively, of the rotating base and the turning of the engine rotor.

6) The formation of the control laws in the horizontal channel of the stabilizer is carried out based on information about the absolute angular velocity of the rotary base and feedback on the current in the motor armature winding.

7) The absolute angular speed of the equipment unit is determined by the speed of the portable angular movement of the object body and the relative angular movement of the equipment unit.

8) The absolute angular velocity of the rotary base is determined by the angular velocity of the transferable angular motion of the object body and the relative angular motion of the rotary base.

V. RANDOM DISTURBANCES TYPICAL FOR GROUND MOVING OBJECTS

For the system of the studied class, it is of great importance to carry out its synthesis taking into account the current disturbances. For ground objects on which the designed system is intended to be used, the effect of disturbances is determined by the influence of road irregularities. In turn, the impact of road irregularities is determined by their topography. One of the methods of its modeling is the use of the so-called road profile, that is, the intersection of the terrain in the direction of movement of the vehicle.

Usually, the road bump profile is described by a random function of the road bump heights. This function can depend on length, i.e. traversed distance, or time. Functions of the latter type can be used for the perturbation task.

It should be noted that in many sources of information, distance functions are given, but this does not pose a problem, since these functions are related to each other by certain ratios [8].

In many cases, a so-called micro-profile is used instead of a profile during the determination of disturbances. Its difference from the profile is the absence of the lowest frequency components. The main advantages of such a replacement include the fact that the micro-profile can be considered a stationary random function, which ensures the possibility of its use in the tasks of synthesis and analysis of stabilization systems of a moving ground object. The transition from a profile to a micro-profile is carried out using a fractional-rational transfer function.

Since profile and micro-profile characteristics are random values, it is most expedient to use such characteristics as spectral density. At the same time, the spectral densities of processes specified as functions of distance and time, i.e. processes and , are related by the relations [8]

$$K_l(\lambda) = vK_t(\lambda v), \quad K_t(\omega) = \frac{1}{v}K_l\left(\frac{\omega}{v}\right). \qquad (5)$$

Based on (5) the spectral density of the micro-profile can be represented as follows

$$K_q(\omega) = |H_q(\omega)|^2 K_h(\omega). \qquad (6)$$

In (6), $H_q(\omega)$ is the transfer function of the micro-profile conversion

$$H_q(\omega) = \frac{(j\omega)^2}{(j\omega)^2 + \sqrt{2}\omega_n j\omega + \omega_n^2}. \qquad (7)$$

Expression (5) in a simplified form looks like

$$H_q(\omega) \approx \frac{j\omega}{j\omega + \omega_n}. \qquad (8)$$

Based on expressions (5) – (8), the classification of spectral densities of the profile of roads and terrain is performed according to the level of short irregularities of the micro-profile. At the same time, depending on the wavelength, three spectral groups are distinguished, which are described by the following formulas:

$$K(\lambda)=\frac{D_m}{\lambda^2},\quad K(\lambda)\approx\frac{D_c}{\lambda^n},\quad (0\le n\le 4),\quad K(\lambda)\approx\frac{D_n}{\lambda^2}. \tag{9}$$

Formulas (9) contain coefficients D_m, D_c, D_n that characterize the type and features of the road. Each group of irregularities is divided into several sections. At the same time, it is advisable to choose:

1) D_m = 10^{-1}m, which corresponds to group 4, i.e. hilly and very rugged terrain;

2) $D_c\approx 10^{-2}$, n = 2 for a field or meadow with a high degree of unevenness and with approximately equal action of short and long waves;

3) D_n = $3\cdot 10^{-3}$, which corresponds to an area with non-homogeneous soil, arable land, the presence of stony inclusions.

But there is another classification of unevenness, in which four types are distinguished, namely, with the majority of long unevennesses, roads of the "valley", "piles" type, and with uniform unevennesses. Accordingly, the spectral density for each type is determined by the following formulas

1) $K(\lambda)=\dfrac{D_2(3{,}1^2+\lambda^2)}{\lambda^2(\lambda_2^2+\lambda^2)}$ (there are 5 groups, for the fifth group, i.e. very crossed locality D_2 =10^{-2}, $\lambda_2=1$);

2) $K(\lambda)=\dfrac{D_2}{\lambda^2}\dfrac{(10+\lambda^2)(\lambda_1^2+\lambda^2)}{(1+\lambda^2)(1+\lambda^2)}$ (there are 5 groups, for the fourth group, that is, the group with large ramparts $D_2=3.16\cdot 10^{-3}$, $\lambda_1=0.178$);

3) $K(\lambda)=\dfrac{D_2}{\lambda^2}\dfrac{\lambda_1^2+\lambda^2}{10^2+\lambda^2}$ (there are 6 groups, for the fifth group, that is, the group with large clusters $D_2=10^{-1}$, $\lambda_1=1$);

4) $K(\lambda)=\dfrac{D_2}{\lambda^2}$ (there are 5 groups, for the fourth group, that is, the group with a high level of spectral density $D_2=10^{-2}$).

Therefore, for modeling disturbances caused by road irregularities, one can start from either the first or the second classification. At first glance, the use of the second classification appears to be the most appropriate for a ground object under study.

Since the disturbance from the micro-profile of the relief is a normal random process, its simulation can be carried out by passing normal white noise $\boldsymbol{\delta}(t)$ through the matrix of transfer functions H_m.

Spectral density of the vector process looks like

$$\mathbf{K}_q(\omega)=\mathbf{H}_м(j\omega)\mathbf{K}_\delta(\omega)\mathbf{H}_м^*(j\omega), \tag{9}$$

where $\mathbf{K}_\delta(\omega)$ is the spectral noise density $\boldsymbol{\delta}(t)$, * is the symbol of the operation of finding the complex-conjugate matrix.

Since the white noise generator is characterized by a constant spectral density $\mathbf{K}_\delta$, we can write $\mathbf{K}_\delta(\omega)=\mathbf{K}_\delta\mathbf{I}$, where is the unit matrix.

The synthesis of the forming filter is performed by the methods given in [8], based on the need to satisfy the condition

$$\mathbf{H}_м(j\omega)\,\mathbf{H}_м^*(j\omega)=\mathbf{K}_\delta^{-1}\mathbf{K}_q(\omega). \tag{10}$$

Using expressions (9), (10) we can define the forming filters for models of disturbances from road bumps according to the first classification:

$$K_h(j\omega)=\frac{\sqrt{D_м v}}{j\omega},\qquad K_h(j\omega)\approx\frac{\sqrt{D_с v}}{j\omega},$$

$$(0\le n\le 4, n=2),\qquad K_h(j\omega)=\frac{\sqrt{D_к v}}{j\omega}.$$

As for the second classification, the forming filters for it will look like this:

1) $K_h(j\omega)=\dfrac{\sqrt{D_2 v}}{j\omega}\dfrac{(3{,}1v+j\omega)}{(v\lambda_2+j\omega)}$,

2) $K_h(j\omega)=\dfrac{\sqrt{D_2 v}}{j\omega}\dfrac{(10v+j\omega)(v\lambda_1+j\omega)}{(v+j\omega)(v+j\omega)}$,

3) $K_h(j\omega)=\dfrac{\sqrt{D_2 v}}{j\omega}\dfrac{v\lambda_1+j\omega}{10v+j\omega}$,

4) $K_h(j\omega)=\dfrac{\sqrt{D_2 v}}{j\omega}$.

The final forming filters will be determined by the formula

$$\mathbf{K}_q(\omega)=\mathbf{K}_h(j\omega)\mathbf{H}_q(j\omega), \tag{11}$$

where $\mathbf{H}_q(j\omega)$ is transfer function of the micro profile transformation.

As a rule, one of the main assumptions of such movement is the assumption of point contact of the tires with the road. But it is more appropriate to use a smoothed profile or a profile averaged over the area of the contact surface as a disturbance model. The transmission characteristic of averaging over the contact area, which corresponds to the smoothing property of the wheels, can be approximately given in the following form:

$$H_{\text{к}}(\omega)=\frac{\omega_{\text{в}}^{2}}{(j\omega)^{2}+\sqrt{2}\omega_{\text{в}}j\omega+\omega_{\text{в}}^{2}} \qquad (12)$$

or simplified

$$H_{\text{к}}(\omega)\approx\frac{\omega_{\text{в}}}{j\omega+\omega_{\text{в}}}, \qquad (13)$$

where $\omega_{\text{в}}$ = (0.9 – 1.3) v/a, here v is the speed of the ground moving object, a is the width of the contact area. Realization of forming filters (11) – (13) of various types is illustrated in Figs 1 and 2. Logarithmic amplitude-frequency characteristics of the disturbed and undisturbed systems are shown in Fig. 3.

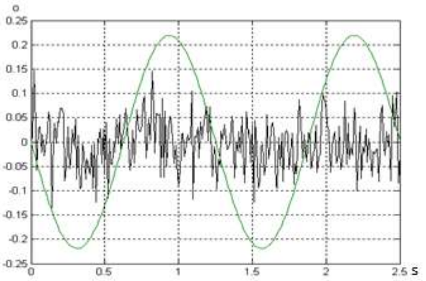


Fig. 1. The signal at the output of the forming filter for disturbances of road irregularities of the first type

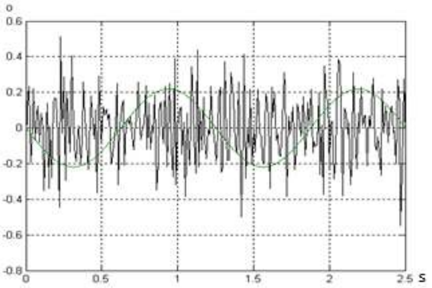


Fig. 2. The signal at the output of the forming filter type for disturbances of road irregularities of the third type

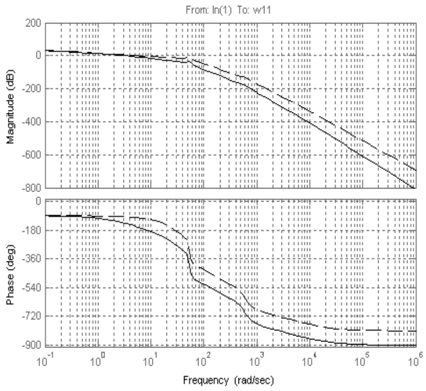


Fig. 3. Logarithmic amplitude-frequency characteristics of undisturbed and disturbed systems

III. METHOD OF SYNTHESIS OF ROBUST SYSTEM FOR SPATIAL STABILIZATION

To perform the synthesis, it is necessary to choose an optimization criterion that would take into account various aspects of the created system. The most expedient is the use of the complex quality - robustness criterion, which allows taking into account both the necessary quality indicators of the system and the resistance to current disturbances [9], which is very important for the studied systems. Such an indicator can be determined on the basis of H_2 , H_∞ norms. The H_2 norm H_∞ is the square root of the average value of the square of the impulse transition function of the system. It can also be understood as the steady-state power of the output signal when exposed to a white noise system of unit intensity. The norm is equal to the maximum value of the frequency characteristic of the system. The impact of each component in the complex quality indicator is regulated using weighting factors that depend on the features of the system.

One of the direct assessments of stabilization processes is the quality of the transient characteristic of the system relative to the determining influence. For systems of the studied class, such characteristics as overregulation σ and regulation time t_r are especially important. The overshoot characterizes the difference between the maximum value of the transient characteristic and its steady value. The adjustment time allows you to estimate the duration of the transition process. The transient characteristic depends on the distribution of zeros and poles. The quality of stabilization also depends on the mutual location of the zeros and poles of the image of the external disturbance. The location of the poles is determined by the parameters η , ξ , an $\mu=\text{tg}\psi$ [10]. In some sources, the parameter is called the degree of stability. It represents the distance from the imaginary axis to the nearest root, that is, the value of its real part. The parameter is the distance from the imaginary axis to the farthest root, that is, the value of its real part. The parameter is called oscillation. It is the ratio of the minimum part of the nearest complex root to its real part.

The parameter ξ is the distance from the imaginary axis to the farthest root, that is, the value of its real part. The parameter is called oscillation. It is the ratio of the minimum part of the nearest complex root to its real part

$$\mu=\frac{\beta}{\alpha}=\text{tg}\psi .$$

It is advisable to use the parameters η, ξ, μ for the synthesis of the stabilization system based on their given values.

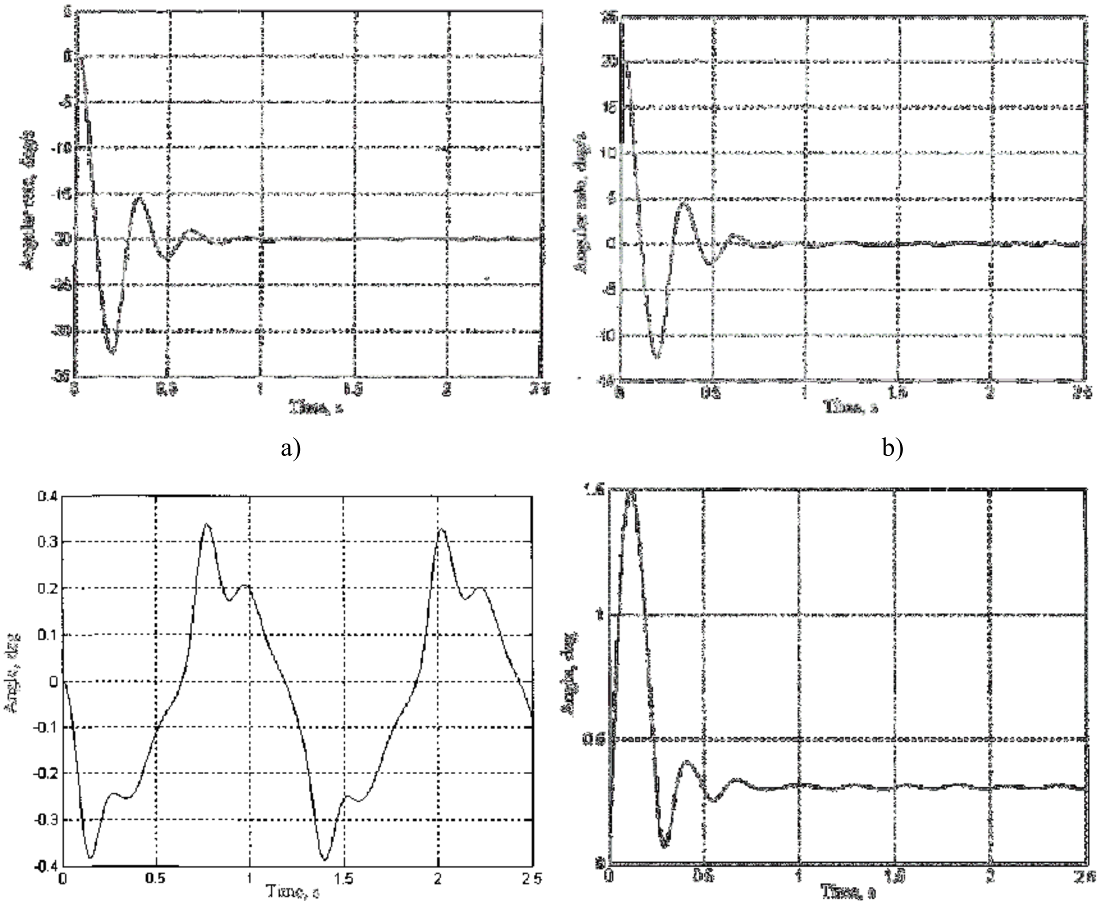
For the system of the studied class, it seems appropriate to use indicators of transient processes as restrictions that are subject to unconditional fulfillment.

The actual optimization can be carried out using the Nelder–Mead method [11], [12].

Taking into account the independence of the stabilizer control channels, its mathematical description can be presented in the form of two separate models:

- a mathematical model of the dynamics of the equipment block, which contains mathematical models of the gearbox and the drive of the stabilization channel in the vertical plane;
- a mathematical model of the dynamics of the rotary base, which contains mathematical models of the gearbox and the drive of the stabilization channel in the horizontal plane.

The results of the stabilizer simulation, namely the development of the set transmission speed, small and set harmonic speed, are presented in Fig. 4.



a) b)

c) d)

Fig. 4. Simulation results: (a) is the transient by angular rate 20 deg/s in the tracking mode; (b) is the transient by angular rate 20 deg/s in the stabilization mode; (c) is the transient by the absolute angle for the given harmonic angular rate; (d) is the transient by the absolute angle for the given constant angular rate

V. SIMULATION AIDS

Modeling tools should provide early stages of creation of new and modernization of existing stabilizers of mobile ground objects. This article analyzes the software tools for creating a stabilizer block of equipment installed on some rotating base, which, in turn, is located on a moving ground object. In order to solve the given problem, it is necessary to perform a study of two modes: stabilization of the absolute angular velocity of the apparatus block and working out of the given angular velocity in both the vertical and horizontal planes [13].

It is most expedient to synthesize the stabilizer of the specified class using automated procedures for optimal design of systems resistant to external disturbances. At the same time, it is also necessary to provide the possibility of creating both systems with a digital regulator, which is relevant for modern developments, and systems with a continuous regulator, which allows performing a comparative analysis of both systems. The tasks can be solved using two types of software tools. The first type of programs represents stabilization system synthesis procedures based on optimal control methods and the use of the Control System Toolbox package. A significant place in the proposed programs is occupied by the modeling of external disturbances and shaping filters. The second type of programs can be created by means of the Simulink system using the transfer functions of system devices. This approach makes it possible to bring the model closer to the real system, taking into account all nonlinearities, and, accordingly, to obtain an effective tool for studying the stabilizer of a moving ground object. This makes it easier to compare the results of the model and the results of tests of real system components, for example, mock-up samples, or the results of modeling electronic devices in the Workbench, MultiSIM systems. The results of the first type of programs must be checked and refined with the help of programs of the second type. The programs of the second type take into account all moments acting on the system (resistance, imbalance, inertia, elastic balancing system), as well as nonlinearities inherent in real systems.

This approach ensures the correspondence of the created model to real equipment. For the first time, for the stabilizers of the studied class, it is proposed to use a statistical approach, not a deterministic one, to take into account disturbances. In general, modeling tools are automated parametric optimization procedures that provide compensation for external disturbances with the help of robust control. The effectiveness of using the proposed programs is confirmed by the results of experimental developments [14].

It is expedient to identify the mathematical model of the stabilizer taking into account the experimental data on the frequency characteristics of individual parts of the regulators by comparing the simulation results with the similar results of the regulators on the test bench. In the same way, the identification of the combined model of the control object and the engine should be carried out.

V. CONCLUSIONS

A model n the space of states of the stabilization system of a moving ground object has been created. I will consider approaches to modeling disturbances caused by road irregularities using shaping filters. A block diagram of the algorithm for the synthesis of a robust system for stabilizing a moving ground object is presented.

The analysis of the means of modeling the stabilizer of a moving ground object was performed and the ways of implementing the software development of the stabilizer at the early stages of its creation were proposed.

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Received March 17, 2024

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О. О. Салюк, О. А. Сущенко. Синтез робастної системи просторової стабілізації обладнання рухомих об'єктів

У статті розглянуто підхід до проектування робастної системи стабілізації обладнання, призначеного для роботи на наземних рухомих об'єктах. Наведено математичну модель системи стабілізації, що включає нелінійні диференціальні рівняння та представлення у просторі станів. Представлено та проаналізовано особливості основних зовнішніх завад, характерних для наземних рухомих об'єктів. Наведено класифікація зовнішніх завад. Отримано вирази для формування фільтрів, що забезпечують імітацію специфічних зовнішніх збурень. Описано основні особливості синтезу системи просторової стабілізації обладнання наземного руху. Представлені результати моделювання. Під час моделювання враховуються нерівності доріг різного типу. Розглянуто опис засобів моделювання системи стабілізації досліджуваного типу. Отримані результати можуть бути корисними для обладнання, що експлуатується на рухомих об'єктах широкого класу.

Ключові слова: просторова стабілізація; обладнання; робастна система; математична модель; представлення у просторі станів; зовнішні збурення.

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