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DESIGN OF ROBUST TRIAXIAL SYSTEMS FOR STABILIZATION OF AIRBORNE OBSERVATION EQUIPMENT

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Abstract. *The state space model of the stabilization plant, which represents a platform with observation equipment and measuring instruments installed in the triaxial gimbals, is developed. The approach to the robust structural synthesis based on the method of the mixed sensitivity is considered. The algorithm of the robust discrete controller design is shown. The synthesized controller structure in the form of the quadruple of state space matrices and the simulation results are represented.*

Keywords: method of mixed sensitivity; observation equipment; robust systems; structural synthesis; triaxial stabilization systems

1. Introduction

The modern aerial vehicles are used for solution of numerous and various problems.

One of these problems represents implementation of the photo and video surveys.

To solve this problem it is necessary to use the equipment of the different kind such as [1]:

1) photo and video cameras of the different destination;

2) systems for the remote control by the photo and video equipment;

3) systems for support and mounting of the photo and video equipment;

4) systems for stabilization and control by the lines of sights of the devices ensuring execution of the photo and video surveys.

This paper deals with the modern approaches to design of the equipment belonging to the fourth group.

Operation of the photo and video equipment installed on the aerial vehicles is implemented in conditions of the external disturbances first of all caused by wind action.

Stabilization of the observation equipment is one of the actual problems for aerial vehicles development.

The modern trend of the stabilization systems design lies in application of the robust control ensuring correspondence of a system to the given requirements in the complex conditions of operation, which are accompanied by action of both internal parametric and external coordinate disturbances.

Usage of the robust control ensures stabilization and control by the lines of sight of the observation equipment in conditions of the UAV angular motion caused by disturbances of the different kind.

Such approach allows to satisfy the requirements given to a system in the difficult operation conditions

2. Analysis of last researches

The modern approaches to design of the robust control systems are represented in many textbooks such as [2, 7].

It should be noted, that design problems of the robust systems for control by the motion of the aerial vehicles take significant place in the modern scientific-technical literature.

At the same time the problem of the robust systems for stabilization of operated on the aerial vehicles equipment just has been not got the appropriate development.

3. Mathematical description of the stabilization plant (platform with installed payload)

For the researched system the plant represents the platform with the observation equipment and measuring devices installed on it.

In the general case the equations of motion of the platform with payload installed on it may be described by the Euler equations [4]:

$$\begin{aligned}
&\dot{\omega}_x J_x + \omega_y \omega_z (J_z - J_y) - (\omega_y^2 - \omega_z^2) J_{yz} - \\
&-(\omega_x \omega_y + \dot{\omega}_z) J_{xz} + (\omega_x \omega_z - \dot{\omega}_y) J_{xy} = M_x; \\
&\dot{\omega}_y J_y + \omega_x \omega_z (J_x - J_z) - (\omega_z^2 - \omega_x^2) J_{xz} - \\
&-(\omega_z \omega_y + \dot{\omega}_x) J_{xy} + (\omega_x \omega_y - \dot{\omega}_z) J_{yz} = M_y; \\
&\dot{\omega}_z J_z + \omega_x \omega_y (J_y - J_x) - (\omega_x^2 - \omega_y^2) J_{xy} - \\
&-(\omega_x \omega_z + \dot{\omega}_y) J_{yz} + (\omega_x \omega_z - \dot{\omega}_x) J_{xz} = M_z,
\end{aligned} \qquad (1)$$

where $\omega_x, \omega_y, \omega_z$ – projections of the angular rates of the platform onto its eigenvalue axes;

J_x, J_y, J_z – inertia moments of the platform with installed on it payload relative to the gimbals axes;

J_{yz}, J_{xz}, J_{xy} – centrifugal inertia moments relative to the gimbals axes;

$\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$ – projections of the platform angular accelerations onto its eigenvalue axes;

M_x, M_y, M_z – the moments acting by the gimbals axes.

It should be noted, that J_x, J_y, J_z represent the equivalent inertia moments which take into consideration the inertia moment of the platform with payload installed on it J_{pi} and the inertia moments of the servomotors J_m.

These moments may be determined by the expressions

$$J_i = J_{pi} + n_r^2 J_m, \ i = x, y, z,$$

where J_{pi}, J_m are the inertia moments of the platform and the servomotor, n_r is the reducer gear-ratio [3].

In the similar way, the expressions for the centrifugal moments may be obtained.

Components of moments acting by the platform axes may be represented in the following form [5]:

$$\begin{aligned} &M_{1i} = M_{fr}\text{sign}\omega_i; \\ &M_{2i} = c_m U_{a_i} / R_a; \\ &M_{3i} = M_{disti}; \\ &i = x_2, y_0, z_1, \end{aligned} \quad (2)$$

where M_{fr} – nominal moment of friction in the bearings installed in the gimbals;

c_m – the coefficient of loading at the servomotor shaft;

U_{a_i} – voltages of servomotor armature control windings;

R_a – the resistance of the servomotor armature winding;

M_{dist_i} – the disturbance moments.

Indexes 1, 2, 3 of the formula (2) correspond to the moments of the dry friction in the bearings of the gimbals, moments developed by the servomotors and disturbances moments.

Forming of the voltages in the servomotor armature control winding may be described by the expressions [3, 8]:

$$\begin{aligned} &T_a \dot{U}_{a_i} + U_{a_i} = k_{PWD} U_{PWD_i} - n_r c_e \omega_i, \\ &i = x_2, y_0, z_1, \end{aligned} \quad (3)$$

where T_a – the armature circuit time constant;

c_e – the coefficient of proportionality between the servomotor angular rate and the electromotive force;

k_{PWD} – the coefficient of the linearized pulse-width-modulator;

$U_{PWD\,i}$ – the voltages at the pulse-width-modulator input.

Control voltages at the outputs of the angular rate gyro sensors U_{ω_i} may be described in the following way [5]:

$$\begin{aligned} &T_g^2 \ddot{U}_{\omega_i} + 2\xi T_g \dot{U}_{\omega_i} + U_{\omega_i} = k_g \omega_i, \\ &i = x, y, z, \end{aligned} \quad (4)$$

where T_g – the time constant of the angular rate gyro sensor;

ξ – the attenuation coefficient;

k_g – the transfer constant of the angular rate gyro sensor.

The location of the body-axis reference frame $OX_pY_pZ_p$ in the inertial space relative to the aircraft reference frame $OX_{AV}Y_{AV}Z_{AV}$ is determined by sequence of three turns on the angles ψ, ϑ, γ as it is shown in Fig. 1:

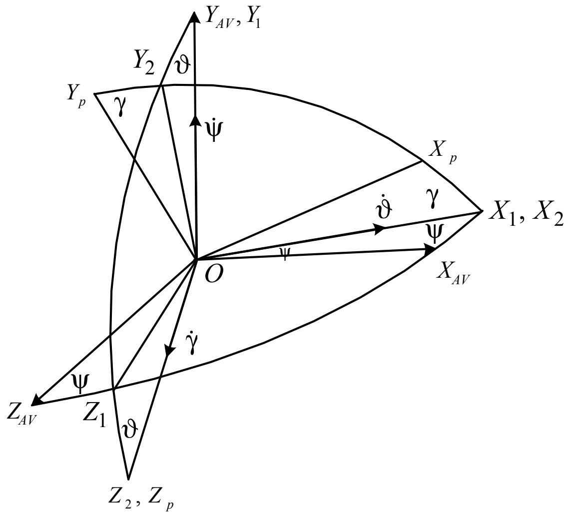


Fig. 1. Sequence of turns determining the location of the platform with installed on it payload

$$\mathbf{A}_1 = \begin{array}{c|ccc} & X_1 & Y_1 & Z_1 \\ X_{AV} & \cos\psi & 0 & \sin\psi \\ Y_{AV} & 0 & 1 & 0 \\ Z_{AV} & -\sin\psi & 0 & \cos\psi \end{array}; \qquad (5)$$

$$\mathbf{A}_2 = \begin{array}{c|ccc} & X_2 & Y_2 & Z_2 \\ X_1 & 1 & 0 & 0 \\ Y_1 & 0 & \cos\vartheta & -\sin\vartheta \\ Z_1 & 0 & \sin\vartheta & \cos\vartheta \end{array}; \qquad (6)$$

$$\mathbf{A}_3 = \begin{array}{c|ccc} & X_p & Y_p & Z_p \\ X_2 & \cos\gamma & -\sin\gamma & 0 \\ Y_2 & \sin\gamma & \cos\gamma & 0 \\ Z_2 & 0 & 0 & 1 \end{array}. \qquad (7)$$

If ω is an angular rate of the platform with observation equipment and measuring instruments installed in the gimbals and Ω is the angular rate of the platform caused by action of control moments determined in the control block, the condition of the precision stabilization becomes [6]

$$\Omega + \omega = 0. \qquad (8)$$

It should be noted, that the condition (8) is true for the case, when the gimbals axes are coincided with the aerial vehicle axes at the initial instant of time.

Taking this supposition into account the sequence of turns during the platform stabilization will correspond to Fig. 2.

In accordance with Fig. 2 projections of stabilization angular rates of platform onto its eigenvalue axes may be defined by the following relationships

$$\begin{aligned} \Omega_{xp} &= \dot\beta\cos\gamma + \dot\alpha\cos\vartheta\sin\gamma; \\ \Omega_{yp} &= -\dot\beta\sin\gamma + \dot\alpha\cos\vartheta\cos\gamma; \\ \Omega_{zp} &= \dot\varphi - \dot\alpha\sin\vartheta. \end{aligned} \qquad (9)$$

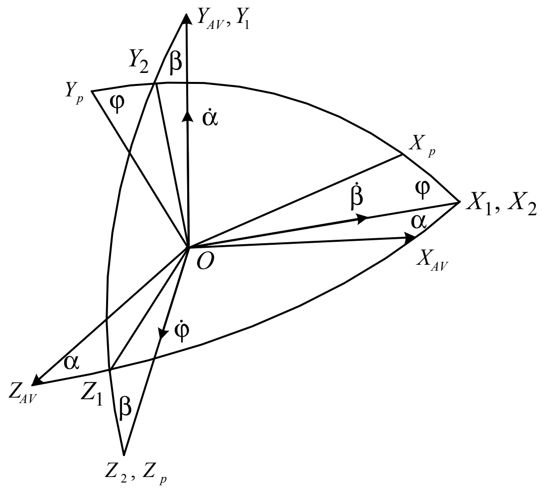


Fig. 2. Sequence of gimbals turns during platform stabilization

Based on stabilization condition it is possible to obtain the expressions for the platform angular rates

$$\begin{aligned} -\omega_{xp} &= \dot\beta\cos\gamma + \dot\alpha\cos\vartheta\sin\gamma; \\ -\omega_{yp} &= -\dot\beta\sin\gamma + \dot\alpha\cos\vartheta\cos\gamma; \\ -\omega_{zp} &= \dot\varphi - \dot\alpha\sin\vartheta. \end{aligned} \qquad (10)$$

Based on the expressions (10) after some transformations it is possible to obtain the differential equations of the stabilization angular rates of the gimbals frames

$$\begin{aligned} \dot\alpha &= -\frac{1}{\cos\vartheta}(\omega_{xp}\sin\gamma + \omega_{yp}\cos\gamma); \\ \dot\beta &= -\omega_{xp}\cos\gamma + \omega_{yp}\sin\gamma; \\ \dot\varphi &= \frac{\sin\vartheta}{\cos\vartheta}(\omega_{xp}\sin\gamma + \omega_{yp}\cos\gamma) - \omega_{zp}. \end{aligned} \qquad (11)$$

During creation of the stabilization system mathematical description it is necessary to take into consideration that moments forming in the system control block determine the angular rates of the gimbals frames motion.

At the same time the system dynamics model (1) is defined in projections onto the platform eigenvalue axes.

Expressions for determination of the control moments may be defined in the following way

$$\begin{aligned} M_{xp} &= \cos\gamma M_{x\vartheta} + \cos\vartheta\sin\gamma M_{y\psi}; \\ M_{yp} &= -\sin\gamma M_{x\vartheta} + \cos\vartheta\cos\gamma M_{y\psi}; \\ M_{zp} &= M_{z\gamma} - \sin\vartheta M_{y\psi}. \end{aligned} \qquad (12)$$

The relationships (1)–(7) and (11), (12) represent the mathematical description of the stabilization plant such as the observation equipment operated at the aircraft.

Implementation of the robust synthesis requires to use the stabilization plant lineriazed model in the state space.

Such model may be obtained based on the relationships (1)–(7) and (11), (12) using the following suppositions:

1) neglect of the centrifugal platform moments and differences of the axial moments for simplification of the expression (1);

2) taking into account the small platform turns only that allows to simplify the expression (5)–(7), (11), (12);

3) change of the non-linear dry friction moments by the linearized moments [3];

4) usage of the linear model of the pulse-width-modulator;

5) neglect of the disturbance moments applying to the platform in the expression (1).

The expressions (1)–(7), (11), (12) and above listed suppositions allow to describe the system by the set of the linearized equations

$$\dot{\alpha} = \omega_x ;$$

$$\dot{\beta} = \omega_y ;$$

$$\dot{\gamma} = \omega_z ;$$

$$\dot{U}_{\omega x} = U_{\omega dx} ;$$

$$\dot{U}_{\omega y} = U_{\omega dy} ;$$

$$\dot{U}_{\omega z} = U_{\omega dz} ;$$

$$\dot{U}_{ax2} = [-U_{ax2} + k_{PWD} U_{PWDx2} - n_r c_e \omega_{x2}] / T_a ;$$

$$\dot{U}_{ay0} = [-U_{ay0} + k_{PWD} U_{PWDy0} - n_r c_e \omega_{y0}] / T_a ;$$

$$\dot{U}_{az1} = [-U_{az1} + k_{PWD} U_{PWDz1} - n_r c_e \omega_{z1}] / T_a ;$$

$$\dot{\omega}_{x2} = [-f_x \omega_x + c_m U_{ax2} / R_a] / J_x ;$$

$$\dot{\omega}_y = [-f_y \omega_y + c_m U_{ay0} / R_a] / J_y ;$$

$$\dot{\omega}_z = [-f_z \omega_z + c_m U_{az1} / R_a] / J_z ;$$

$$\dot{U}_{\omega dx} = [-2\xi T_g U_{\omega dx} - U_{\omega x} + k_g \omega_x] / T_g^2 ;$$

$$\dot{U}_{\omega dx} = [-2\xi T_g U_{\omega dy} - U_{\omega y} + k_g \omega_y] / T_g^2 ;$$

$$\dot{U}_{\omega dx} = [-2\xi T_g U_{\omega dz} - U_{\omega z} + k_g \omega_z] / T_g^2 , \qquad (13)$$

where $U_{\omega dx,} U_{\omega dy}, U_{\omega dz}$ – derivatives by the voltages $U_{\omega x,} U_{\omega y}, U_{\omega z}$;

f_x, f_y, f_z – the coefficients of the linearized friction moments [5].

The stabilization plant linearized mathematical model (13) corresponds to the state space model with the vector of state variables

$$\mathbf{x}^T = [\alpha \;\; \beta \;\; \gamma \;\; U_{\omega x} \;\; U_{\omega y} \;\; U_{\omega z} \;\; U_{ax2} \;\; U_{ay0} \;\; U_{az1} \;\; \omega_x \;\; \omega_y \;\; \omega_z \;\; U_{\omega dx} \;\; U_{\omega dy} \;\; U_{\omega dz}], \qquad (14)$$

and quadruple of matrices **A**, **B**, **C**, **D**

$$\mathbf{A} = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & -1/T_a & 0 & 0 & -n_r c_e / T_a & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/T_a & 0 & 0 & -n_r c_e / T_a & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1/T_a & 0 & 0 & -n_r c_e / T_a & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & c_m/(R_a J_x) & 0 & 0 & -f_x / J_x & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & c_m/(R_a J_y) & 0 & 0 & -f_y / J_y & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & c_m/(R_a J_z) & 0 & 0 & -f_z / J_z & 0 & 0 & 0 \\
0 & 0 & 0 & -1/T_g^2 & 0 & 0 & 0 & 0 & 0 & k_g / T_g^2 & 0 & 0 & -2\xi / T_g & 0 & 0 \\
0 & 0 & 0 & 0 & -1/T_g^2 & 0 & 0 & 0 & 0 & 0 & k_g / T_g^2 & 0 & 0 & -2\xi / T_g & 0 \\
0 & 0 & 0 & 0 & 0 & -1/T_g^2 & 0 & 0 & 0 & 0 & 0 & k_g / T_g^2 & 0 & 0 & -2\xi / T_g
\end{bmatrix}$$

$$\mathbf{B}^T = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & k_{PWD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{PWD} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & k_{PWD} & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix};$$

$$\mathbf{C} = \begin{bmatrix}
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}; \qquad (15)$$

$$\mathbf{D} = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}.$$

The mathematical description (14), (15) may be used for implementation of the robust structural optimization procedure based on the H_∞-synthesis.

4. Algorithm of the robust stabilization system structural synthesis

One of the modern approaches to the structural synthesis of the robust stabilization system is the H_∞-synthesis. Its basic principles are represented in many textbooks [2, 7]. The standard configuration of the system designed by means of the H_∞-synthesis is represented in Fig. 3.

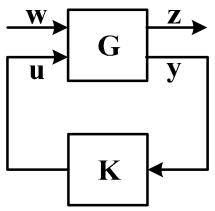


Fig. 3. The standard H_∞-configuration

Such system consists of a plant $\mathbf{G}$ and a controller $\mathbf{K}$ and may be represented by the output signals to be optimized $\mathbf{z}$, external input signals $\mathbf{w}$, control signals $\mathbf{u}$ and measured output signals $\mathbf{y}$, which enter to the controller [2, 7].

The statement of the H_∞-synthesis problem is based on introducing of the so-called generalized or interconnected system $\mathbf{P}$ [5].

Consider a system represented in Fig. 4, *a*.

For such system the interconnection between signals using the generalized system concept may be written in the form [2]:

$$\mathbf{w}=\mathbf{r};\ \mathbf{z}=\begin{bmatrix}\mathbf{e}\\ \mathbf{u}\\ \mathbf{y}\end{bmatrix};\ \mathbf{P}=\begin{bmatrix}\mathbf{P}_{11} & \mathbf{P}_{12}\\ \mathbf{P}_{21} & \mathbf{P}_{22}\end{bmatrix}=\begin{bmatrix}\mathbf{I} & -\mathbf{G}\\ \mathbf{0} & \mathbf{I}\\ \mathbf{0} & \mathbf{G}\\ \mathbf{I} & -\mathbf{G}\end{bmatrix}, \quad (16)$$

and the transfer function from the input $\mathbf{w}$ to the output $\mathbf{z}$ becomes

$$\mathbf{T}_w^z=\mathbf{P}_{11}+\mathbf{P}_{12}\mathbf{K}(\mathbf{I}-\mathbf{P}_{22}\mathbf{K})^{-1}\mathbf{P}_{21}.$$

The statement of the optimization problem may be represented in the following form [2, 7]:

$$\mathbf{K}_{opt}=\arg\inf_{K_{opt}\in K_{per}} J(\mathbf{G},\mathbf{K}), \quad (17)$$

where $\mathbf{K}_{opt}$ – optimal controller chosen from the set of the stabilizing controllers $\mathbf{K}_{per}$

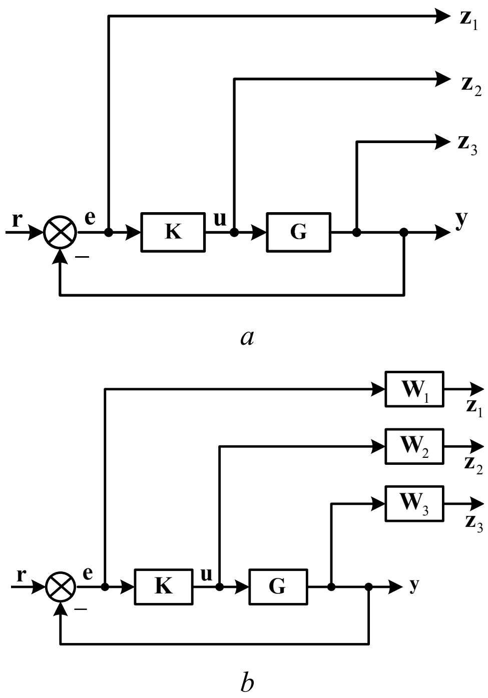


Fig. 4. The structural scheme of the designed (*a*) and the augmented (*b*) systems

$$J(\mathbf{G},\mathbf{K})=\left\|\begin{bmatrix}(\mathbf{I}+\mathbf{GK})^{-1}\\ \mathbf{K}(\mathbf{I}+\mathbf{GK})^{-1}\\ \mathbf{GK}(\mathbf{I}+\mathbf{GK})^{-1}\end{bmatrix}\right\|_\infty. \quad (18)$$

The optimization problem (17) may be solved by means of the method of mixed sensitivity [2, 7].

The modern approach to solution of the robust structural optimization problem is based on forming of the system desired frequency characteristics (loop shaping) [3].

This approach may be implemented by means of the augmented object forming due to introducing of the weighting transfer functions, as it is shown in Fig. 4, *b*.

For method of the mixed sensitivity the expression, which represents H_∞-norm of the augmented system function of sensitivity as the optimization criterion instead of the formula (18) may be used [2, 7]:

$$J(\mathbf{G},\mathbf{K})=\left\|\begin{bmatrix}\mathbf{W}_1(\mathbf{I}+\mathbf{GK})^{-1}\\ \mathbf{W}_2\mathbf{K}(\mathbf{I}+\mathbf{GK})^{-1}\\ \mathbf{W}_3\mathbf{GK}(\mathbf{I}+\mathbf{GK})^{-1}\end{bmatrix}\right\|_\infty=\left\|\begin{bmatrix}\mathbf{W}_1\mathbf{S}\\ \mathbf{W}_2\mathbf{R}\\ \mathbf{W}_3\mathbf{T}\end{bmatrix}\right\|_\infty, \quad (19)$$

where $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$ – the weighting transfer functions;

$\mathbf{S}$, $\mathbf{R}$, $\mathbf{T}$ – the sensitivity functions by the given signal and control and the complementary sensitivity function.

Implementation of the H_∞-synthesis by the method of the mixed sensitivity is based on solution of two Riccati equations, check of some conditions and minimization of the system mixed sensitivity function H_∞-norm (19) [2, 7].

It is should be noted, that there are automated means of this problem solution, which require mathematical description of the interconnected system (16).

Now the gyro sensors of the angular rate (fiber-optic gyros, MEMS-gyros) are the most widespread gyro instruments.

The stabilization system of this type may be considered as the servo system (Fig. 5).

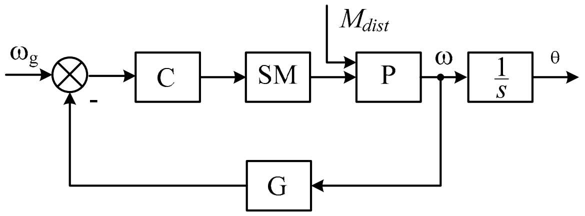


Fig. 5. Structural scheme of the rate servo system:
C – controller;
SM – servomotor;
P – plant;
M_{dist} – disturbance moment;
ω – angular rate of the line of sight;
θ – angular location of the line of sight

The basic approaches to the robust structural synthesis of the information-measuring devices of the wide class are represented in the paper [9]. Features of the H_∞-synthesis procedure for the information-measuring devices operated at the ground vehicles are represented in the paper [10]. The developed model (14), (15) allows to carry out the H_∞-synthesis of the system for stabilization of the observation devices operated at the aerial vehicles.

The stabilization system is configured as the rate servo one, since many types of the modern gyros sense angular rates [2].

The procedure of the H_∞-synthesis includes such stages as creation of the system mathematical description (both linearized and taking into consideration non-linearities inherent to the real systems), choice of the weighting transfer functions, augmentation of the plant and properly structural synthesis.

All these stages may be implemented by means of the Robust System Toolbox representing components of the calculating system MatLab.

Now usage of the discrete controllers is the most actual for the practical applications.

There are two known approaches to creation of the discrete controllers [2].

The first approach is based on discretization of the model of the plant augmented by means of the weighting transfer functions.

Further the w-transformation, structural synthesis and z-representation of the controller by means of the inverse w-transformation [2].

All above listed actions may be automated by means of the imbedded function *dhinfopt* incoming in the Robust Control Toolbox of the computing system MatLab.

The second approach lies in the automated design of the continuous robust controller, for example, by means of the H_∞-synthesis.

Further discretization of the controller by means of the embedded function *c2d* is carried out.

Such discretization must satisfy some requirements.

In the first the Tustin bilinear transformation as the discretization method must be used.

Such choice ensures the discretiaztion accuracy.

In the second, the discretization sampling must exceed in some times the bandwidth frequency of the system.

Design of the discrete controller of the researched system was implemented based on the second approach.

The flow chart of this process is represented in Fig. 6.

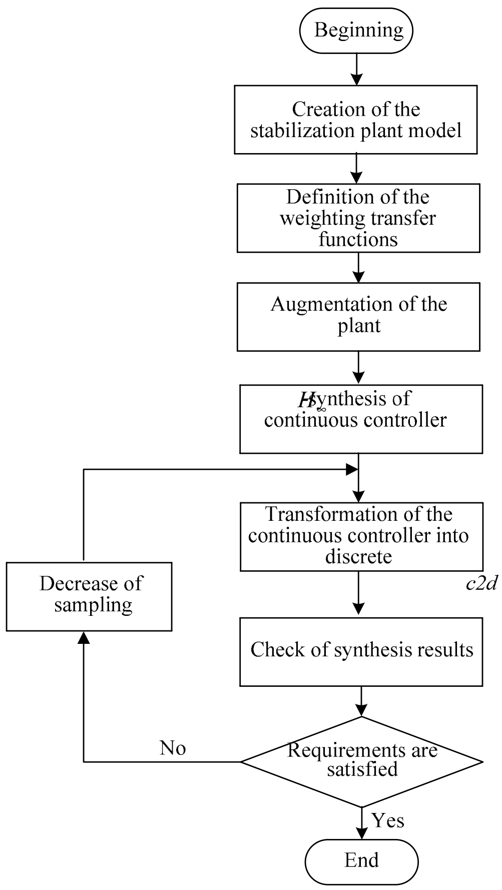


Fig. 6. Flow chart f the discrete controller design

One of the most important stages of the robust structural optimization is the choice of the weighting transfer functions, which is implemented based on the heuristic approaches.

For the studied system the expressions for the matrix weighting transfer functions may be represented in the following form

$$\mathbf{W}_1 = \begin{bmatrix} \frac{1}{s}\frac{0,1s+20}{s+0,005} & 0 & 0 \\ 0 & \frac{1}{s}\frac{0,02s+10}{s+0,002} & 0 \\ 0 & 0 & \frac{1}{s}\frac{0,01s+10}{s+0,001} \end{bmatrix};$$

$$\mathbf{W}_2 = \begin{bmatrix} 0,04 & 0 & 0 \\ 0 & 0,04 & 0 \\ 0 & 0 & 0,04 \end{bmatrix};$$

$$\mathbf{W}_3 = \begin{bmatrix} \frac{s}{0,005s+50} & 0 & 0 \\ 0 & \frac{s}{0,002s+20} & 0 \\ 0 & 0 & \frac{s}{0,001s+10} \end{bmatrix}.$$

Structure of the synthesized robust controller may be described by the following quadruple of matrices

$$\mathbf{A}_c = \begin{bmatrix} 186,3 & 352,6 & 45,83 & 11,33 & 43,7 \\ 711,8 & -966,3 & -179,7 & -12,17 & -11,6 \\ -117,75 & 126,7 & -18,41 & -15,84 & -15,62 \\ -343,7 & 517,3 & 136,8 & 19,39 & -23,43 \\ -218,3 & 268,8 & 20,53 & 18,75 & -25,89 \end{bmatrix}$$

$$\mathbf{B}_c^T = \begin{bmatrix} 20,98 & -37,1 & -8,3 & -5,36 & -7,25 \\ 17,6 & -32,1 & -7,3 & -4,2 & 6,23 \\ 15,6 & -30,5 & 5,4 & -3,1 & -5,21 \end{bmatrix};$$

$$\mathbf{C}_c = \begin{bmatrix} 8,31 & -9,8 & -4,78 & -1,43 & 2,35 \\ 9,6 & -6,4 & 12,2 & -1,2 & 16,3 \\ 11,2 & -7,5 & 9,2 & -11,1 & -15,21 \end{bmatrix};$$

$$\mathbf{D}_c = \begin{bmatrix} -0,9 & -0,543 & -0,217 \\ -0,6 & -0,312 & -0,123 \\ -0,4 & -0,213 & -0,223 \end{bmatrix}.$$

The simulation results of the synthesized system are represented in Figs 7-9.

The represented results include simulation for both previous and precise stabilization modes.

At the represented graphs the angular motion of the aerial vehicle was considered as the disturbance.

The represented results prove the possibility to achieve the stabilization accuracy and speed of operation sufficient for the observation equipment operated at the aerial vehicle.

These results prove efficiency of the researched robust discrete controller design procedure based on the method of the mixed sensitivity.

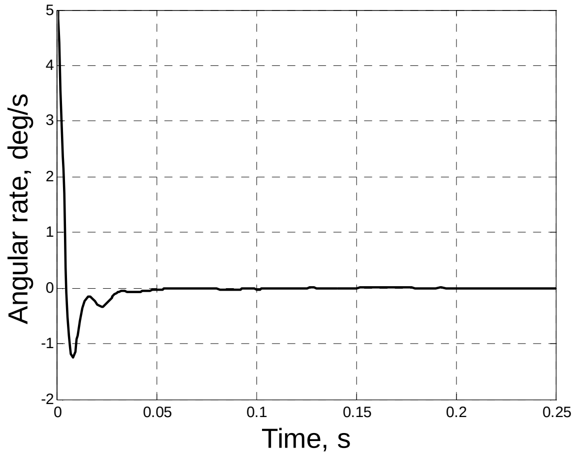
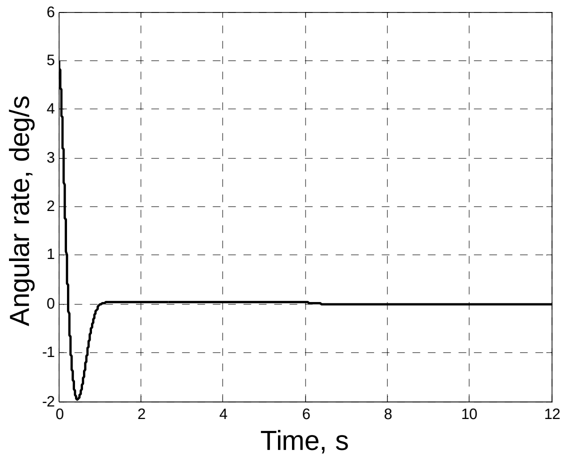
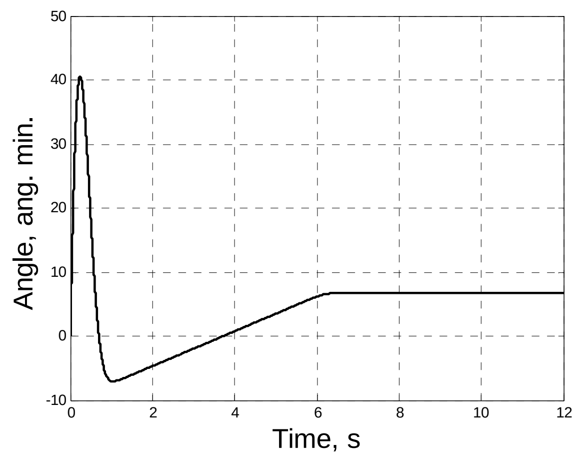


Fig. 7. Transient by the roll angular rate

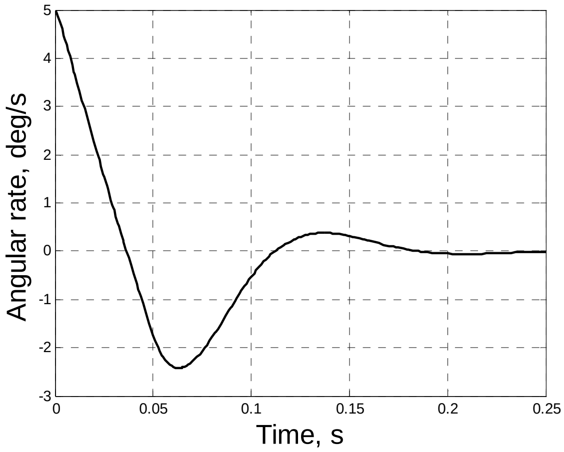


a

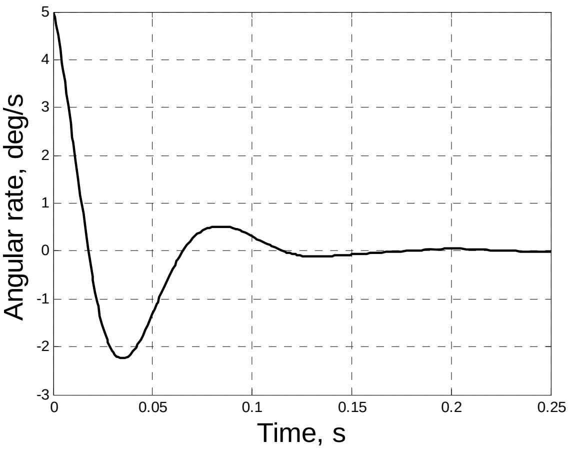


b

Fig. 8. Results of the gyrostabilized platform simulation in the mode of the pre-leveling:
a – transient by the angular rate;
b – the angular position error



a



b

Fig. 9. Results of the gyrostabilized platform simulation in the mode of the precision stabilization:
a – transient by the yaw angular rate;
b – transient by the pitch angular rate

5. Conclusions

The basic approach to the robust structural synthesis of the stabilization system of the observation equipment operated at the aerial vehicles is represented. The mathematical description of the system providing stabilization and control by orientation of the observation devices lines of sight is obtained. The matrix weighting transfer functions for the robust structural synthesis are chosen. The simulation results are represented.

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О.А. Сущенко. Проектування робастних тривісних систем стабілізації бортової апаратури спостереження
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Присвячено дослідженню особливостей проектування робастних тривісних систем стабілізації бортової апаратури спостереження. Подано математичну модель у просторі станів об’єкта стабілізації, який являє собою платформу з апаратурою спостереження та вимірювальними пристроями, встановлену у тривісному кардановому підвісі. Розглянуто підхід до робастного структурного синтезу на підставі методу змішаної чутливості. Показано алгоритм проектування робастного дискретного регулятора. Описано структуру синтезованого регулятора у вигляді четвірки матриць у просторі станів. Наведено результати моделювання. Зазначено, що результати дослідження становлять інтерес для галузі систем стабілізації інформаційно-вимірювальних пристроїв, призначених для експлуатації на рухомих об’єктах широкого класу.

Ключові слова: апаратура спостереження; метод змішаної чутливості; структурний синтез; робастні системи; тривісні системи стабілізації;

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Исследованы особенности проектирования робастных трехосных систем стабилизации бортовой аппаратуры наблюдения. Приведена математическая модель в пространстве состояний объекта стабилизации, представляющего собой платформу с аппаратурой наблюдения и измерительными устройствами, установленную в трехосном кардановом подвесе. Рассмотрен подход к робастному структурному синтезу на основании метода смешанной чувствительности. Показан алгоритм проектирования робастного дискретного регулятора. Описана структура синтезированного регулятора в виде четверки матриц в пространстве состояний. Представлены результаты моделирования. Отмечено, что результаты исследования представляют интерес для отрасли систем стабилизации информационно-измерительных устройств, предназначенных для эксплуатации на подвижных объектах широкого класса.

Ключевые слова: аппаратура наблюдения; метод смешанной чувствительности; робастные системы; структурный синтез; трехосные системы стабилизации.

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