Methods of information systems synthesis

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Eu. Aleksandrov[1], T. Aleksandrova[2], I. Kostianyk[2]

[1] Kharkiv National Automobile and Highway University, Kharkiv, Ukraine
[2] National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

PARAMETRIC SYNTHESIS OF THE DIGITAL INVARIANT STABILIZER FOR A NON-STATIONARY OBJECT

Abstract. Two methods are considered for choosing the values of the variable parameters of the digital stabilizer for a non-stationary object, which ensures the invariance of the closed stabilization system to the action of external disturbances. The comparative analysis of the considered methods was carried out in order to identify their advantages and disadvantages. As an example, it is considered the problem of parametric synthesis of the digital stabilizer of the C5M cosmic stage of the Cyclone-3 carrier rocket as part of the program for the modernization of these objects created in the late 70s by the joint efforts of the Yuzhnoye Design Bureau and NPO Hartron, which contain an analog stabilization system and operating to date. It is concluded about advisability to replace the C5M analog stage stabilizer with the digital stabilizer in order to improve the quality of the stabilized process of the stage in the active part of the flight trajectory. It is shown that both methods considered in the article lead to the creation of the digital stabilizer that provides a significant reduction in the static error of the closed digital stabilization system of the cosmic stage of the carrier rocket and an increase in the quality of stabilization process.

Keywords: digital stabilizer; non-stationary object of stabilization; invariance of the stabilization system; quality of the stabilized process**;** the cosmic stage of the carrier rocket; parametric synthesis of the stabilizer.

Introduction

Problem statement. The perturbed motion of a non-stationary stabilization object is described by a vector-matrix differential equation

$$\dot{X}(t) = \Phi\left[X(t), t\right] + B(t)\cdot U(t) + C(t)\cdot F(t), \quad (1)$$

where $X(t)$ is the n-dimensional state vector of the stabilization object; $U(t)$ is the m-dimensional control vector; $F(t)$ is the k-dimensional vector of random external disturbances; $B(t)$ and $C(t)$ are rectangular matrices of sizes $n\times m$ and $n\times k$, respectively.

The digital stabilizer implements a linear stabilization algorithm

$$U[nT] = K[nT]\cdot \tilde{X}[nT], \quad (2)$$

where $\tilde{X}[nT]$ is the lattice vector-function at the output of the analog-to-code converter obtained by time quantization of the state vector $X(t)$) with a quantization period T, and subsequent filtering of the lattice function $X[nT]$ using a matrix filter Butterworth

$$Z\{\tilde{X}[nT]\} = W_B(z) Z\{X[nT]\}; \quad (3)$$

where z is the complex variable of the Z-transformation of the lattice function; $W_B(z)$ – diagonal matrix discrete transfer function of the Butterworth matrix filter; $K[nT]$ is a rectangular matrix of variable parameters of stabilizer of size $m\times n$, the elements of which vary in time nT. The code-to-analog converter converts the lattice vector-function $U[nT]$ into a piecewise constant vector-function $U(t)$, moreover

$$U(t) = U[nT] \ \ when \ \ nT \le t < (n+1)T. \quad (4)$$

The quality of the stabilizer (2) is usually estimated by the value of the integral quadratic functional

$$I(K[nT]) = \int_0^{\tau} \langle X(t), Q\cdot X(t)\rangle dt, \quad (5)$$

where τ is the analysis time of the stabilized process; Q is the diagonal Sylvester matrix.

The problem of parametric synthesis of stabilizer (2) is to find the elements of the matrix $K[nT]$ such that, on the solutions of the closed stabilization system (1)–(4), the integral quadratic functional (5) reaches a minimum. If for the object (1) the condition is satisfied

$$M\{F(t)\} = 0, \quad (6)$$

where M is the symbol of the vector mathematical expectation, then the formulated problem of the parametric synthesis of the stabilizer (2) is reduced to the problem of the analytical construction of the optimal controller (ACOC) [1–3].

If condition (6) is not fulfilled, which is typical for most non-stationary technical objects, then using the ACOC theory leads to a significant static error of a closed stabilization system [4]. The magnitude of this error depends on the nature of the change in the components of the vector of external disturbances $F(t)$, as well as on the structure and values of the elements of the matrix $K[nT]$ of the stabilization algorithm (2).

Main material

Solving the problem of optimizing parametric synthesis using the method of "frozen" coefficients. In accordance with the method of “frozen" coefficients [5], the time interval for the analysis of the stabilized process τ is divided into N identical sections of duration Δt, moreover $\Delta t = \tau / N$.

At time $t_i = i \cdot \Delta$, $\left(i = \overline{1, N}\right)$, the values of the parameters of the stabilization object (1) and stabilizer (2) are fixed and assumed to be unchanged in the region $\left(t_i, t_{i+1}\right)$. Then equation (1) and relation (2) take the following form

$$\dot{X}(t) = \Phi\left[X(t), t_i\right] + B(t_i) \cdot U(t) + C(t_i) \cdot F(t_i); \quad (7)$$

$$U[nT] = K(t_i) \cdot \tilde{X}[nT]. \quad (8)$$

We add another differential equation to differential equation (7)

$$\dot{x}_{n+1}(t) = \left\langle X(t), Q \cdot X(t) \right\rangle, \quad (9)$$

from which, as well as from relation (5),

$$I\left[K(t_i)\right] = x_{n+1}(\tau); \quad \left(i = \overline{1, N}\right). \quad (10)$$

Using the algorithmic method of parametric synthesis of stabilization systems described in [6,7], we find the matrix $K(t_i)$ that delivers the minimum of function (10) on the solutions of closed system (7)–(9), (3), (4). Note that the mentioned method of parametric synthesis in parallel includes determining the diagonal elements of the matrix Q of functional (5). As a result, the dependences of the matrix elements $K^*[nT]$ are constructed in the form of a piecewise constant function with a step Δt including an integer q of quantization periods T: $\Delta t = qT$.

To minimize the objective function (10), the algorithmic method of parametric synthesis used uses the Optimization Toolbox software package MATLAB or Minimize software MATHCAD, which implements the Nelder-Mead method for solving nonlinear programming problems [8]. To use the above products in order to solve the optimization problem, it is necessary to choose the region of admissible values G_k of matrix elements матрицы $K(t_i) \in G_k$. In [6, 7], it is proposed to choose the stability region of a closed stabilization system in the space of variable stabilizer parameters as a region G_k (2). To estimate the region G_k we neglect the own dynamics of the Butterworth matrix filter and take

$$W_B(z) = E. \quad (11)$$

Then, taking into account relations (3) and (11), we write down the formulas

$$\tilde{X}[nT] = X[nT]; \quad (12)$$

$$U[nT] = K(t_i) X[nT], \quad (13)$$

as well as the equation of the first approximation of the perturbed motion of the stabilization object

$$\dot{X}(t) = A(t_i) \cdot X(t) + B(t_i) \cdot U(t) + C(t_i) \cdot F(t). \quad (14)$$

Using the results of [9], we write the characteristic equation of a closed discrete system of first approximation (14), (13), (4):

$$\det\left[R(t_i) + H(t_i) \cdot K(t_i) - Ez\right] = 0, \quad (15)$$

where the matrices $R(t_i)$ and $H(t_i)$ are written in the form

$$R(t_i) = \sum_{j=0}^{\infty} \frac{1}{j!} A^j(t_i) T^j; \quad (16)$$

$$H(t_i) = \sum_{j=0}^{\infty} \left[\frac{1}{(j+1)!} A^j(t_i) T^{j+1}\right] B(t_i). \quad (17)$$

The number of taken into account the terms of the matrix series (16) and (17) depends on the magnitude of the quantization period T. Usually, when using modern digital computers with a short quantization period, it is assumed with sufficient accuracy

$$R(t_i) = E + A(t_i) T;$$

$$H(t_i) = B(t_i) T.$$

In the characteristic equation of the closed discrete system (15), we make the change

$$z = (1 + w) / (1 - w).$$

As a result, equation (15) takes the form

$$\det\left[R(t_i) + H(t_i) \cdot K(t_i) - E\frac{1+w}{1-w}\right] = 0. \quad (18)$$

Assuming $w = j\omega$ in (18), we write the expression for the characteristic vector of a closed discrete system

$$P(j\omega, t_i) = \det\left[R(t_i) + H(t_i) \cdot K(t_i) - E\frac{1+j\omega}{1-j\omega}\right]. \quad (19)$$

Using the relation for characteristic vector (19), we construct the stability regions of a closed discrete system in the planes of variable stabilizer parameters, the union of which represents the region $G_k(t_i)$ for each of the fixed time instants $t_i \left(i = \overline{1, N}\right)$.

Solving the problem of parametric synthesis of a digital invariant stabilizer using time series. The method of “frozen" coefficients used above to solve the problem of parametric synthesis of the stabilizer of a non-stationary object allows one to obtain time-varying values of the variable parameters of the digital stabilizer, which increases the degree of astatism of the stabilization system, gives the system the invariance property to the external disturbance $F(t)$ and reduces the static errors of the stabilized process [4]. However, despite the widespread use of the method of "frozen" coefficients in engineering practice, this method does not have a rigorous theoretical justification and does not always lead to the desired results.

It was indicated above that the magnitude of the static error of the stabilized process substantially depends on the nature of the change in time of the external disturbance $F(t)$. The above algorithmic method of parametric synthesis of the stabilizer, based on the "freezing" of the coefficients of the mathematical model of the stabilization object, takes into account the change in the disturbance $F(t)$ indirectly when integrating matrix equation (14), which does not exclude a significant static error when the stabilizer processes the disturbance $F(t)$.

A much more effective method for the parametric synthesis of an invariant stabilizer of a non-stationary object is the method described below, based on the representation of an external disturbance in the form of a time series

$$F(t) = F_0 + F_1 t + F_2 t^2 + ... + F_l t^l, \qquad (20)$$

where F_0, F_1, F_2, ..., F_l are vectors of dimension k with constant values component.

The higher the degree of polynomial (20), the more complicated the vector function $F(t)$. The matrix of variable parameters of the digital stabilizer (2) will be found in the form of a time series

$$K[nT] = K_0 + K_1 nT + K_2 (nT)^2 + ... + K_l (nT)^l, \qquad (21)$$

where K_0, K_1, K_2, ..., K_l are rectangular matrices with constant values of elements of size $m \times n$ each.

Any of the elements $k_{ij}[nT]$ of the matrix (21) is also written in the form of a time series

$$k_{ij}[nT] = k_{0ij} + k_{1ij} nT + k_{2ij} (nT)^2 + ... + k_{lij} (nT). \qquad (22)$$

From relation (22) it is clear that each of the elements of matrix (21) contains $(l+1)$ variable parameters; therefore, matrix (21) contains such parameters $m \cdot n \cdot (l+1)$.

The problem of parametric synthesis of an invariant digital stabilizer (2) for a non-stationary object (1) is to find $m \cdot n \cdot (l+1)$ variable parameters of matrix (21) such that the integral quadratic functional (5) reaches its minimum on solutions of a closed system (1)–(4). If the parametric synthesis procedure for the stabilizer based on the use of the "frozen" coefficients method is a solution to a sequence of optimization problems of N functionals (10) with respect to $m \cdot n$ variable parameters of the matrices $K(t_i), (i = \overline{1, N})$, then a procedure based on the use of time series is a solution to the problem of optimizing one functional (5), calculated along the trajectory of a non-stationary object during the time τ of a motion relative to $m \cdot n \cdot (l+1)$ of the variable matrix parameters (21).

The second approach to solving the problem of parametric synthesis of the stabilizer is much more complicated than the first, but it allows to obtain a significantly higher quality of the stabilized process.

Example. As an example, we consider the problem of parametric synthesis of the stabilizer of the C5M cosmic stage (CS) of the Cyclone-3 carrier rocket, the mathematical model of the disturbed motion of which is given in [11] and in the channel of angular stabilization for the yaw angle has the following form:

$$\begin{aligned} &\ddot{\psi}(t) = a'_{\psi\psi}\,\psi(t) + a''_{\psi\beta_1}\,\ddot{\beta}_1(t) + \\ &\qquad + a''_{\psi\beta_2}\,\ddot{\beta}_2(t) + a_{\psi\delta}\delta(t) + m_\psi(t); \\ &\ddot{\beta}_1(t) + 2\xi_1\omega_1\dot{\beta}_1(t) + \omega_1^2\beta_1(t) = a''_{\beta_1\psi}\,\ddot{\psi}; \\ &\ddot{\beta}_2(t) + 2\xi_2\omega_2\dot{\beta}_2(t) + \omega_2^2\beta_2(t) = a''_{\beta_2\psi}\,\ddot{\psi}, \end{aligned} \qquad (23)$$

where $\psi(t)$ is the angle of rotation of the longitudinal axis of the stage relative to the plane of the orbit; $\beta_1(t)$, $\beta_2(t)$ are the angles of deviation of the free surface of the fuel and oxidizer, respectively, from the unperturbed position; $m_\psi(t)$ is the reduced disturbing moment; $\delta(t)$ is the angle of deviation of the axis of the marching engine from the longitudinal axis of the stage in the channel of yaw; $a'_{\psi\psi}$, $a_{\psi\delta}$ – time-varying coefficients characterizing the movement of the stage; $a''_{\psi\beta_1}$, $a''_{\psi\beta_2}$ are the coefficients of the influence of fluid oscillations in the fuel and oxidizer tanks on the angular movement of the stage; $a''_{\beta_1\psi}$, $a''_{\beta_2\psi}$ are the coefficients of the influence of the angular movement of the stage on the oscillations of the liquid in the fuel and oxidizer tanks; ξ_1, ξ_2 – damping coefficients of the vibrations of the fuel and oxidizer in the tanks of the stage; ω_1, ω_2 are the natural frequencies of free vibrations of the fuel and oxidizer in the tanks of the stage.

The continuous part of the closed stabilization system, in addition to the stabilization object (23), also contains an electro-hydraulic amplifier (EHA), which rotates the combustion chamber of the marching engine by an angle $\delta(t)$, the disturbed motion of which is described by a system of differential equations [4]

$$\begin{aligned} &L_y \frac{di(t)}{dt} + r_y i(t) = U(t) - \frac{k_\delta}{k_s}\delta(t); \\ &I_k \frac{d^2\beta(t)}{dt^2} + f_k \frac{d\beta(t)}{dt} + c_k\beta(t) = k_\beta i(t); \\ &\frac{d\delta(t)}{dt} = k_h k_s \beta(t), \end{aligned} \qquad (24)$$

where $i(t)$ is the current in the control winding of the EHA; $\beta(t)$ is the angle of rotation of the rocker arm of the EHA electromagnet; $U(t)$ is the control signal at the output of the code-to-analog converter of the digital stage stabilizer; L_y – inductance of the control winding of the EHA; r_y is the resistance of the control winding of the EHA; I_k - moment of inertia of the rocker arm of the EHA; f_k is the coefficient of liquid friction in the axis of the rocker arm; c_k is the stiffness coefficient of the fixing spring of the EHA rocker arm; k_δ, k_s, k_β, k_h are the proportionality coefficients.

The continuous part of the closed stabilization system should also include a set of command devices, namely a gyrostabilized platform (GSP) with a gyroscopic angular velocity sensor (GAVS) installed on it. It was shown in [12] that the intrinsic dynamics of GSP and GAVS in the process of parametric synthesis of a digital stabilizer can be neglected and it can be assumed that GSP and GAVS absolutely accurately measure $\psi(t)$ and $\omega_z(t)=\dot{\psi}(t)$. On the one hand, this assumption is associated with the high accuracy of modern gyroscopic instruments and devices, and, on the other hand, with the use of low-frequency Butterworth filters in the digital stabilizer, which efficiently filter high-frequency noise associated with the intrinsic dynamics of gyroscopic instruments and vibration of the stage casing caused by the operation of the marching engine.

Continuous time functions $\psi(t)$ and $\omega_z(t)$ are supplied to the inputs of the analog-to-code converter from command devices GSP and GAVS, where they are transformed into lattice functions $\psi[nT]$ and $\omega_z[nT]$, noisy by the natural vibrations of the gyroscope frames and vibrations of the stage casing . These functions go to the inputs of Butterworth digital recursive filters [13, 14]. From the outputs of the filters, the lattice functions $\tilde{\psi}[nT]$ and $\tilde{\omega}_z[nT]$ filtered from high-frequency noise arrive at the processor, which forms the stabilization algorithm in the form

$$G_\psi[nT]=k_\psi\tilde{\psi}[nT]+k_{\dot{\psi}}\tilde{\omega}_z[nT], \quad (25)$$

where k_ψ and $k_{\dot{\psi}}$ are the variable constants of stabilizer.

If the digital stabilizer implements second-order Butterworth filters with the transfer function

$$W_{B2}(z)=\frac{a_{12}\left(1+2z^{-1}+z^{-2}\right)}{1+d_{12}z^{-1}+d_{22}z^{-2}}, \quad (26)$$

where z is the complex variable of the z-transformation of the lattice function, then, taking into account relations (3) and (26), the difference equations that describe the process of filtering of noisy lattice functions $\psi[nT]$ and $\omega_z[nT]$ are written as

$$\begin{aligned}&\tilde{\psi}[nT]=a_{12}\{\psi[nT]+2\psi[(n-1)T]+\\&+\psi[(n-2)T]\}-d_{12}\tilde{\psi}[(n-1)T]-d_{22}\tilde{\psi}[(n-2)T];\\&\tilde{\omega}_z[nT]=a_{12}\{\omega_z[nT]+2\omega_z[(n-1)T]+\\&+\omega_z[(n-2)T]\})-d_{12}\tilde{\omega}_z[(n-1)T]-d_{22}\tilde{\omega}_z[(n-2)T].\end{aligned} \quad (27)$$

In this case, the control lattice function $U[nT]$ is formed in accordance with the algorithm

$$U[nT]=\begin{cases}\delta_\psi[nT] & when\ \left|\delta_\psi[nT]\right|\le u^*;\\ u^*\operatorname{sign}\delta_\psi[nT] & when\ \left|\delta_\psi[nT]\right|>u^*,\end{cases} \quad (28)$$

where u^* is the value of the saturation zone of the EHA.

The lattice function (28) is supplied to the input of the code-analog converter, which converts the function (28) into a piecewise constant function (4).

Thus, relations (25), (27), (28) and (4) are a mathematical model of a digital stabilizer, and in combination with differential equations (23) and (24), they are a mathematical model of a digital system of angular stabilization of C5M cosmic stage in the channel of yaw. The values of the variable coefficients of the mathematical model of the stabilization object were obtained in [11]. The time dependence of the perturbed moment $m_\psi(t)$ is shown in Fig. 1 [11].

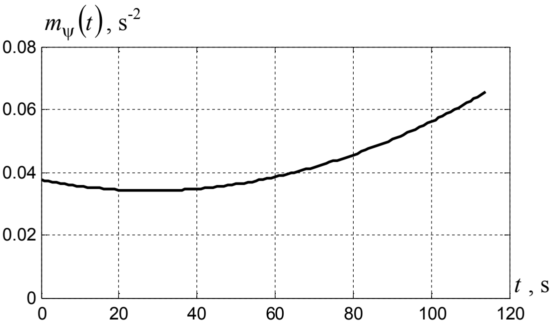

Fig. 1. The time dependence of the perturbed moment $m_\psi(t)$

The type of curve shown in Fig. 1, we can conclude that the curve $m_\psi(t)$ is well approximated by a parabola

$$m_\psi(t)=m_{\psi 0}+m_{\psi 1}t+m_{\psi 2}t^2, \quad (29)$$

whose coefficients are $m_{\psi 0}=3{,}75\cdot 10^{-2}\ c^{-2}$; $m_{\psi 1}=\text{-}2{,}4\cdot 10^{-4}\ c^{-3}$; $m_{\psi 2}=4{,}26\cdot 10^{-6}\ c^{-4}$.

Then the variable parameters of the digital stabilizer of the space stage C5M should be presented in the form

$$\begin{aligned}&k_\psi=k_{\psi 0}+k_{\psi 1}nT+k_{\psi 2}(nT)^2;\\&k_{\dot{\psi}}=k_{\dot{\psi}0}+k_{\dot{\psi}1}nT+k_{\dot{\psi}2}(nT)^2.\end{aligned} \quad (30)$$

Using the method of parametric synthesis of a digital stabilizer described above, based on finding the minimum of the integral quadratic functional

$$I(K)=\int_0^\tau\left[\alpha_1^2\psi^2(t)+\alpha_2^2\dot{\psi}^2(t)\right]dt, \quad (31)$$

where K is the vector of variable parameters $K=\left[k_{\psi 0}\ k_{\psi 1}\ k_{\psi 2}\ k_{\dot{\psi}0}\ k_{\dot{\psi}1}\ k_{\dot{\psi}2}\right]$, calculated on the solutions of a closed stabilization system, we obtain the following values of the variable parameters of the stabilizer:

$$k_{\psi 0}^*=69{,}23;\ k_{\psi 1}^*=\text{-}0{,}4427\ c^{-1};$$
$$k_{\psi 2}^*=0{,}7864\cdot 10^{-2}\ c^{-2};\ k_{\dot{\psi}0}^*=0{,}01\ c;$$
$$k_{\dot{\psi}1}^*=-0{,}64\cdot 10^{-4};\ k_{\dot{\psi}2}^*=1{,}136\cdot 10^{-6}\ c^{-1}.$$

In [4], transients were constructed in a closed digital stabilization system with constant values of the variable parameters of the digital stabilizer equal to $k_{\psi}[nT]=k^{*}_{\psi 0}$; $k_{\dot{\psi}}[nT]=k^{*}_{\dot{\psi} 0}$. These processes are shown in Fig. 2.

Analysis of the processes shown in Fig. 2, shows, firstly, the presence of a significant static error and, secondly, the noticeable effect of fluid oscillations in the fuel and oxidizer tanks from the 20th to 40th seconds of flight in an active part with a duration of 114 s.

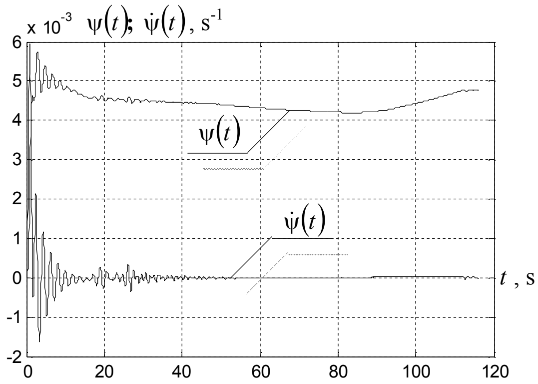

Fig. 2. Transients in a closed stabilization system with constant values of the variable parameters of the stabilizer

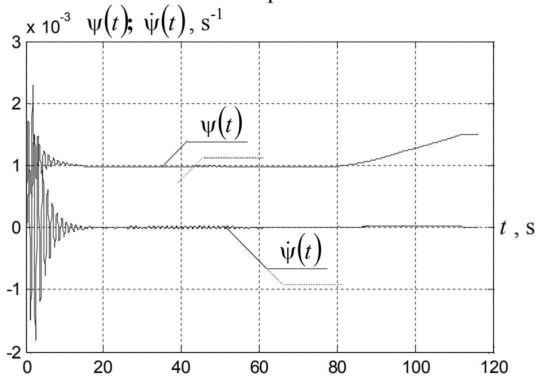

Fig. 3. Transients in a closed stabilization system with variable values of the variable parameters of the stabilizer

Comparison of the processes shown in Fig. 2 and Fig. 3, leads to the conclusion that the use of the proposed method for the parametric synthesis of the stabilizer CS can improve the performance of a closed stabilization system, significantly reduce the static error in lateral displacement and significantly reduce the effect of fluid oscillations in the fuel and oxidizer tanks on the stabilized motion of the CS. So, the processes of calming the CS after its separation from the carrier rocket decreased by an average of 25% and their duration does not exceed 10 s. The static error in the angular deviation of the cosmic stage does not exceed 0,0015 rad compared to 0,005 rad, which occurs in the case of constant values of the variable parameters of the stabilizer.

Conclusions

A comparative analysis of the two methods used in the article for the parametric synthesis of a digital stabilizer for a non-stationary object allows us to identify the advantages and disadvantages of each of them.

The first method, which uses the "freezing" of the coefficients of the mathematical model of a stabilized object at separate time intervals, followed by finding the variable parameters of the stabilizer at each of the intervals, is notable for its simplicity of implementation, but not a rigorous mathematical justification and, as a result, it not provides an effective reduction in the static errors of the stabilization process.

The second method for the parametric synthesis of a digital stabilizer, based on the presentation of external perturbations and variable parameters of the stabilizer in the form of time power series, is much more effective in the sense of imparting a closed stabilization system the property of invariance to the action of external perturbations. The practical implementation of the second method is associated with significant computational difficulties, but this drawback is compensated by the fact that the constructed digital stabilizer is highly accurate in processing external perturbations acting on a stabilized object.

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ВІДОМОСТІ ПРО АВТОРІВ / ABOUT THE AUTHORS

Александров Євген Євгенович – доктор технічних наук, професор кафедри автомобілів, Харківський національний автомобільно-дорожній університет, Харків, Україна;
Eugene Aleksandrov – Doctor of Technical Sciences, Professor, Department of automobiles, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine;
e-mail: aleksandrov.ye.ye@gmail.com; ORCID ID: https://orcid.org/0000-0001-9596-0669.

Александрова Тетяна Євгеніївна – доктор технічних наук, професор кафедри «Системний аналіз та інформаційно-аналітичні технології», Національний технічний університет «Харківський політехнічний інститут», Харків, Україна;
Tetiana Aleksandrova – Doctor of Technical Sciences, Professor, Department of Systems Analysis and Information-Analytical Technologies, National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine;
e-mail: aleksandrova.t.ye@gmail.com; ORCID ID: https://orcid.org/0000-0001-9596-0669.

Костяник Ірина Віталіївна – кандидат технічних наук, доцент кафедри інформаційних технологій і систем колісних та гусеничних машин імені О. О. Морозова, Національний технічний університет «Харківський політехнічний інститут», Харків, Україна;
Iryna Kostianyk – PhD, Associate Professor, Department of Information Technologies and Systems of Wheel and Track Machines named after Morozov, National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine;
e-mail: kostyanik-irina@ukr.net; ORCID ID: http://orcid.org/0000-0003-0289-2869.

Параметричний синтез цифрового інваріантного стабілізатора для нестаціонарного об’єкта

Є. Є. Александров, Т. Є. Александрова, І. В. Костяник

Анотація. Розглядаються два методи вибору значень варійованих параметрів цифрового стабілізатора для нестаціонарного об'єкта, що забезпечує інваріантність замкненої системи стабілізації до дії зовнішніх збурень. Проведено порівняльний аналіз розглянутих методів з метою виявлення їх переваг та недоліків. Як приклад розглянуто задачу параметричного синтезу цифрового стабілізатора космічного ступеня С5М ракети-носія «Циклон-3» в рамках програми модернізації зазначених об'єктів, створених наприкінці 70-х років об'єднаними зусиллями фахівців КБ «Південне» і НВО «Хартрон», що містять аналогову систему стабілізації і експлуатуються до теперішнього часу. Зроблено висновок про доцільність заміни аналогового стабілізатора ступеня С5М цифровим стабілізатором з метою підвищення якості процесу стабілізації ступеня на активній ділянці траєкторії польоту. Показано, що обидва розглянутих в статті методи призводять до створення цифрового стабілізатора, що забезпечує значне зменшення статичної помилки замкнутої цифрової системи стабілізації космічного ступеня ракети-носія та підвищення якості процесу стабілізації.

Ключові слова: цифровий стабілізатор; нестаціонарний об'єкт стабілізації; інваріантність системи стабілізації; якість процесу стабілізації; космічний ступінь ракети-носія; параметричний синтез стабілізатора.

Параметрический синтез цифрового инвариантного стабилизатора для нестационарного объекта

Е. Е. Александров, Т. Е. Александрова, И. В. Костяник

Аннотация. Рассматриваются два метода выбора значений варьируемых параметров цифрового стабилизатора для нестационарного объекта, обеспечивающего инвариантность замкнутой системы стабилизации к действию внешних возмущений. Проведен сравнительный анализ рассмотренных методов с целью выявления их достоинств и недостатков. В качестве примера рассмотрена задача параметрического синтеза цифрового стабилизатора космической ступени С5М ракеты-носителя «Циклон-3» в рамках программы модернизации указанных объектов, созданных в конце 70-х годов объединенными усилиями специалистов КБ «Южное» и НПО «Хартрон», содержащих аналоговую систему стабилизации и эксплуатирующихся до настоящего времени. Сделан вывод о целесообразности замены аналогового стабилизатора ступени С5М цифровым стабилизатором с целью повышения качества стабилизируемого процесса ступени на активном участке траектории полета. Показано, что оба рассмотренных в статье метода приводят к созданию цифрового стабилизатора, обеспечивающего значительное уменьшение статической ошибки замкнутой цифровой системы стабилизации космической ступени ракеты-носителя и повышение качества процесса стабилизации.

Ключевые слова: цифровой стабилизатор; нестационарный объект стабилизации; инвариантность системы стабилизации; качество стабилизируемого процесса; космическая ступень ракеты-носителя; параметрический синтез стабилизатора.