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PARAMETRICAL SYNTHESIS OF ROBUST SYSTEM FOR STABILIZATION OF AIRCRAFT EQUIPMENT

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Abstract*—The paper deals with parametrical synthesis of robust system assigned for stabilization of aircraft equipment. The mathematical model of the stabilization plant is represented. The algorithm of parametrical synthesis of robust system is given. Features of the optimization procedure including choice of programming tools are reprsented. The optimization criterion of parametrical synthesis of robust system is shown. Criteria of performance of the synthesied system including stabilization errors are analysed. Features of simulation tests are discussed. Results of synthesied system simulation are represented. The obtained results can be useful for moving vehicles of the wide class.*

Index Terms—Stabilization system; parametrical optimization; robust control; aiircraft equipment; stabilization errors.

I. INTRODUCTION

There are two known approaches to synthesis of optimal control systems. The first approach to synthesis of optimal multi-dimensional control systems uses optimization based on methods of calculus of variations [1]. It is known that using principles of optimality for design of multi-dimensional systems of the higher order is accompanied with computational constraints. The second approach is based on the previous definition of dynamic properties of the close-loop system and taking into consideration restrictions on the appropriate design parameters [2].

Complex multi-contour control systems are characterized by both global and local extremums. The cause of arising local extremums is presence of bounded restrictions in the space of design parameters. Such a situation requires repeated optimization procedure depending on analysis of obtained results. Obviously, analysis of results of optimization requires using a model that presents functioning of real system in the full measure.

Creation of high precision control systems operating under influence of parametric and coordinate disturbances is an important problem of design of modern control systems. Many classical approaches to synthesis of control systems in general and stabilization systems in particular use supposition that a system's parameters are known. Taking into consideration real conditions of control systems functioning it is necessary to consider the possibility of parameters changing in some range. A system is believed to be robust if it is characterized by sufficient level of stability and characteristics of for some range of a system's parameters changing and external disturbances.

II. ANALYSIS OF LAST PUBLICATIONS

Nowadays the great quantity of scientific papers deals with design of robust systems. The basic statement that determined arising of the theory of robustness is Kharitonov theorem, which firstly has been formulated in [3]. There are three basic directions of development of the theory of robustness [4]. The first approach is grounded in [5]. The concept of multi-dimensional stability threshold has been introduced in this paper. The second approach is presented in [6], where the concept of the structured singular number is represented. The third approach has been considered in [7] in details. It is based on the linear matrix nonequalities. Fundamentals of the third approach are grounded on the basic concepts of theory of stability developed by A. M. Lyapunov. The main goal of this method is an analytic search of linear controllers able to provide extremum of some given optimization functional. The optimization process is implemented on the set of permissible set of the linear controllers with the fixed or arbitrary structure. One of basic concepts, on which methods of analysis of the robust stability are based, uses a concept of the Nyquist criterion. It is known that the theorem of the small gain is based on this criterion.

It should be noted that most of above listed methods is oriented on linear systems. In many cases, results of synthesis based on application of the linearized model coincide with results obtained by means of more accurate and complex nonlinear model. Moreover, development of the model similar to a real system is sufficiently complex that can lead to errors comparable with linearization errors.

The first method of A. M. Lyapunov can be accepted as the theoretical basis of system synthesis. In accordance with such an approach stability of a nonlinear system can be researched by the first linear approximation under condition of smooth linear characteristic [1].

It should be noted that the well developed MatLab toolboxes (Control System, Robust System) are assigned for operation with linear time-invariant models. This requires to satisfy technical requirements to a system with some margin taking into consideration unsuspected errors.

III PROBLEM STATEMENT

The main goal of the paper is determination of basic approaches to developing an algorithm of parametrical synthesis of stabilization system.

The most important characteristic of a system of the researched class is stability to external disturbances, which can vary in a wide range. Synthesis of control systems, which are stable to disturbances, requires implementation of some stages.

1) Problem statement of the optimal synthesis.

2) Development of the full mathematical model taking into consideration all the non-linearities inherent to real systems.

3) Development of the linearized mathematical model in the state space.

4) Analysis of requirements given to a system and forming of the appropriate objective and penalty functions.

5) Development of a technique for reprersentation of the external disturbances taking into consideration features of motion of the moving vehicle, on which the researched stabilization system is mounted.

6) Choice of the optimization method.

7) Development of the algorithm of the synthesis of robust system directed on the modern automated means of the optimal synthesis of control systems.

8) Simulation and analysis of the obtained results.

Synthesis of robust systems can be based on minimization of the H_∞-norm of the matrix transfer function of the close-loop system. Another approach is based on minimization of the H_2-norm of the matrix transfer function of the close-loop system, which characterizes its accuracy. From the point of implementation of the calculating algorithms, the H_∞-optimization is the more complex in comparison with the H_2-optimization due to the necessity to use the search procedure. Methods of the synthesis based on minimization of the H_2-norm provide the high accuracy of the synthesized system. Unfortunately, the system keeps sensitivity both to the external disturbances and to the parametric disturbances of the plant under conditions of this method using. Application of the H_∞-norm allows achieving a system's stability to external disturbances in conditions of structured and unstructured parametric uncertainty. Optimization by means of each of considered approaches has its own advantages. And optimization by means of the mixed criterion provides combination of these advantages. In this case, the synthesized system will be characterized by the optimal quality in conditions of the possibility of its functioning under influence of disturbances. Features of design of robust stabilization systems, namely, H_2, H_∞ and mixed H_2/H_∞-optimization and their comparative analysis are presented in [8].

IV. MATHEMATICAL MODEL OF PLANT

Development of a procedure of the robust parametric synthesis requires using a set of models with different properties, which are defined by the goal of the design phase.

A feature of the researched system is application of the model of the plant and the motor united by the elastic connection. This model can be represented similar to results represented in [9]:

$$
\begin{aligned}
&J_p\ddot{\varphi}_p = -M_{fr}\operatorname{sign}\dot{\varphi}_p - M_{unb}\cos\varphi_p + \frac{c_r}{n_r}\varphi_p - c_r\varphi_p,\\
&J_m\ddot{\varphi}_m = -M_{frm}\operatorname{sign}\dot{\varphi}_m + \frac{c_m}{R_w}U + \frac{c_r}{n_r^2}\varphi_m - c_r\varphi_m,\\
&\dot{U}T_a + U = U_{pdm} - c_e\dot{\varphi}_m,
\end{aligned}
\tag{1}
$$

where J_p is the moment of inertia of the platform with payload; φ_p is the angle of the platform; M_{fr} is the nominal moment of friction in bearings of the platform gimbals; M_{unb} is the unbalance moment; $\tilde{n}_r$ is the reducer rigidity; n_r is the gear-ratio of the reducer; J_m is the moment of inertia of the rotor; φ_m is an angle of the motor rotation; M_{frm} is the nominal moment of friction of the motor; $\tilde{n}_m$ is the constant of moment of loading on the motor shaft; R_w is the resistance of motor armature windings; U is the voltage of the motor armature circuit; U_{pdm} is the voltage at the output of the pulse duration modulator (PDM); c_e is the constant of electromotive force.

Based on (1) the appropriate and results of [10], the linearized model becomes

$$
\begin{aligned}
&J_p\ddot{\varphi}_p = -f_p\dot{\varphi}_p - M_{unb} + \frac{c_r}{n_r}\varphi_p - c_r\varphi_p,\\
&J_m\ddot{\varphi}_m = -f_m\dot{\varphi}_m + \frac{c_m}{R_w}U + \frac{c_r}{n_r^2}\varphi_m - c_r\varphi_m, \qquad (2)\\
&\dot{U}T_a + U = U_{pdw} - c_e\dot{\varphi}_m,
\end{aligned}
$$

where f_p, f_m are coefficients of moments of friction of the platform and motor respectively. The most important feature of this model is change of nonlinear moments of friction with linear dependences.

The represented model (2) can be transformed to the general representation of models in the state space.

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

where $\mathbf{x}$ is the vector of state variables; $\mathbf{u}$ is the vector of controls; $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ are matrices, which characterize features of the system and controls; $\mathbf{y}$ is the vector of observations.

For the researched model (2), vectors of state variables, controls and quadruple of the state space matrices (3) look like [10]

$$
\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} \varphi_p \\ \dot{\varphi}_p \\ \varphi_m \\ \dot{\varphi}_m \\ U \end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix} 0 & 0 \\ \frac{-M_{unb}}{J_p} & 0 \\ 0 & 0 \\ 0 & \frac{U_{pdw}}{T_a} \\ 0 & 0 \end{bmatrix}, \qquad (4)
$$

$$
\mathbf{B}^{\mathrm{T}} = \begin{bmatrix} 0 & \frac{-M_{unb}}{J_p} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{U_{pdw}}{T_a} \end{bmatrix}, \qquad (5)
$$

$$
\mathbf{C} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{D} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \qquad (6)
$$

$$
A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ \frac{-c_r}{J_p} & \frac{-f}{J_p} & \frac{c_r}{n_r J_p} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{-c_r}{n_r J_m} & 0 & \frac{-c_r}{n_r^2 J_m} & \frac{-f_m}{J_m} & \frac{c_m}{R_m J_m} \\ 0 & 0 & 0 & \frac{-c_e}{T_a} & \frac{-1}{T_a} \end{bmatrix}. \qquad (7)
$$

Basic components of stabilization system are control unit, which carries out functions of signal processing and forming of control signals, pulse-duration-modulator and amplifier of voltage. Usually the control unit includes filters of high and low frequencies. The full description of PDW is nonlinear. Therefore linearization is necessary in this case. Models of other units include nonlinear elements too and need linearization respectively. The feature of the researched system is application of two-degree-of freedom controller. In this case, both control by an error and control by the disturbance are used [11]. To implement such a control law it is necessary to use signals proportional to current and voltage of the motor armature.

V. ALGORITHM OF ROBUST SYSTEM SYNTHESIS

To calculate indices of quality of robust control system is possible based on H_2- norm of the transfer function of the close-loop system. A measure of robustness that is stability to both parametric and coordinate disturbances is the H_∞- norm. In other words, the H_∞- norm is an efficient index of reaction of a system on coordinate disturbances under conditions of uncertainty in the mathematical description of a system. The H_2- norm is a characteristic of the function of sensitivity of a system $S(s)$. The H_∞- norm is a characteristic of the function of complementary sensitivity $T(s)$. These functions are connected by relationship $S(s) + T(s) = 1$. This allows achieving a compromise between the quality and robustness of a system [12]. Therefore synthesis of the system it is convenient to carry out on the basis of the complex criterion including the H_2 and H_∞ -norms with weighting coefficients. Changing these coefficients it is possible to achieve a compromise between performance and robustness of the system. As robustness is a measure is a measure of parametric uncertainty of a system, it must H_∞ -norms of the nominal and parametrically disturbed systems. And H_2 -norms in the complex criterion can include appropriate norms of the deterministic and stochastic systems. Then the complex criterion can be described by the expression [13]

$$
\begin{aligned}
J = \lambda_2^{\text{nom}} H_2^{\text{nom}} + \lambda_\infty^{\text{nom}} H_\infty^{\text{nom}} + \lambda_2^{\text{dist}} H_2^{\text{dist}}\\
+ \sum_{i=1}^{n} \lambda_{2_i}^{\text{par}} H_{2_i}^{\text{par}} + \sum_{i=1}^{n} \lambda_{\infty_i}^{\text{par}} H_{\infty_i}^{\text{par}},
\end{aligned} \qquad (8)
$$

where $J = \lambda_2^{\text{nom}}, \lambda_\infty^{\text{nom}}, \lambda_2^{\text{dist}}, \lambda_{2_i}^{\text{par}}, \lambda_{\infty_i}^{\text{par}}$ are weighting coefficients for appropriate norms of nominal, disturbed and parametrically disturbed models of the system.

To implement the calculating procedure of the optimal synthesis it is necessary to choose an optimization method, define constraints by the design parameters and optimization criterion.

It is convenient to choose optimization methods based on MatLab, which nowadays is the most widespread tool of design of modern control systems including stabilization systems. Review of such optimization methods is represented in [14].

To solve optimization problems with nonstrict constraints, the method of penalty functions is widely used. Usually, this method is implemented in two stages.

At the first stage the objective function is formed. Such a function includes components, which are forfeited by great values during violation of the given constraints.

At the second stage a new objective function is minimized by means of a method, which is used for solving optimization problems without constraints. It should be noted that gradient methods can not be used in this situation. Therefore it is convenient to use genetic algorithms.

Procedures of parametric and structural-parametric optimal synthesis of robust systems for aircraft control based on the mixed H_2 / H_∞- approach are grounded in [13]. Development of appropriate procedures for systems of aircraft equipment stabilization requires further development.

Synthesis of stabilization system is convenient to create by means of toolboxes Control Toolbox and Robust Control Toolbox, which include a great number of functions providing analysis and optimal synthesis of control systems in general and stabilization systems in particular.

At that it is possible to design digital optimal controllers of a continuous system that is one of the most important problems of the modern instrument making industry taking into consideration the fast development of computer engineering.

To analyze results of the synthesized system it is convenient to use models, which take into consideration all the typical non-linearities inherent to real systems. MatLab has wide possibilities for creation such models based on toolbox Simulink.

An algorithm of synthesis of the robust system for stabilization of aircraft equipment includes following stages.

1) Creation of the mathematical model of the two-mass system “plant – motor” as a whole unit with parts united by the elastic connection taking into consideration reducer rigidity.

2) Choice of a controller based on experimental researches and theoretical approaches to design of controllers of the considered kind.

3) Development of the stabilization system including the two-mass model of the plant, and models of measuring instrument, controller and additional devices namely voltage amplifier and PDW.

4) Development of the full model of the researched system taking into consideration all the non-linearities inherent to real systems such as restriction of signals, hysteresis, dead zone.

5) Development of the mathematical model in the state space.

6) Determination of the minimal realization of a model.

7) Scaling of the model based on the balanced realization.

8) Determination of initial values and execution of the genetic algorithm including following steps:

a. calculation of the H_2 and H_∞-norms of the synthesised system;

b. calculation of poles, analysis of their location on the plane of the complex variable and determination of the appropriate penalty function;

c. calculation of the complex index of performance taking into consideration the penalty function.

9) Analysis of the synthesized system including steps:

a. calculation of the H_2, H_∞ -norms and plotting of the logarithmic amplitude-frequency characteristics with determination of the margin;

b. analysis of the indices of transient processes using the model of the system taking into consideration nonlinearities inherent to real systems.

10) Termination of the procedure of the parametrical optimization or its repetition with new initial conditions or new weighting coefficients of the complex optimization criterion.

The mathematical models (4) – (7) and the optimization criterion (8) provide parametrical synthesis of the robust system for stabilization of aircraft equipment.

To estimate performance of the stabilization system it is convenient to determine errors in different typical modes. The stabilization error can be determined in conditions of aircraft motion with the constant angular rate. The tracking mode error can be determined in conditions of immovable aircraft. It is convenient also to estimate the dynamic error in the stabilization mode using harmonic motion. Checking in such conditions provides estimating of dynamical properties of the researched system. During motion by the harmonic law, direction of the motion of the aircraft and respectively stabilized platform with equipment are changed. Direction of the friction forces is changed too. These factors provide assessment of dynamical properties of the stabilization system in the full measure. During simulation of such a motion, an error in the stable mode will change by the harmonic law $x(t) = x_{\max} \sin(\omega_k t + \psi)$. In this case, accuracy of the stabilization system can be estimated by the maximum amplitude $x_{\max}$.

Simulation for checking a dynamical error of the stabilization system must include following stages.

1) Simulation of influence of the harmonic angular rate.

2) Determination of an amplitude of the angular position of the stabilization plant and estimation of a difference between the obtained amplitude and simulated value. This estimate represents a dynamic error.

Results of dynamical error assessment are represented in Figs 1, 2.

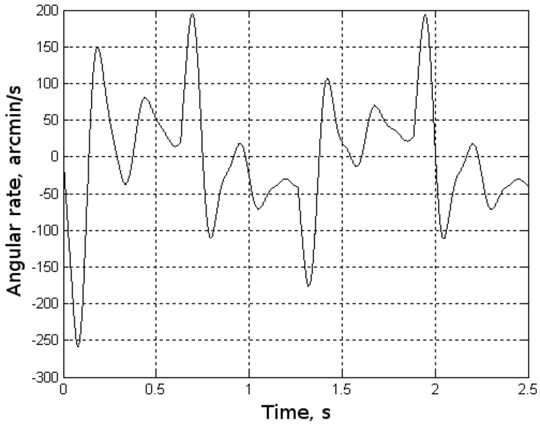

Fig. 1. Random angular rate of the stabilization system

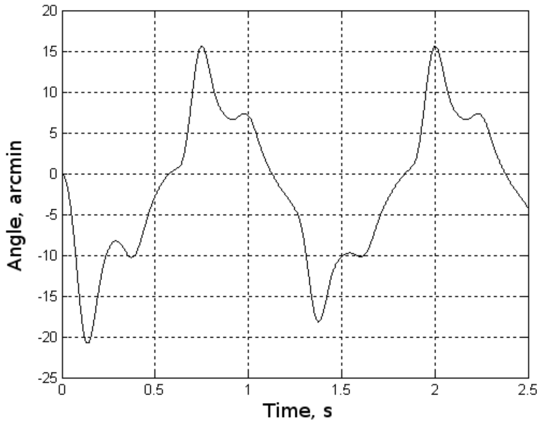

Fig. 2. Error of the angular position of the stabilization system

For stabilization systems of the researched class it is important to check influence of the residual unbalance moment. This check is carried out similar to check of the dynamic error but is implemented for different given values of the unbalance moments. Feature of this simulation is that the harmonic signal is given with some delay after beginning of simulated system function. This is done with the goal to except influence of the transient process. Result of such a checking is given in Fig. 3.

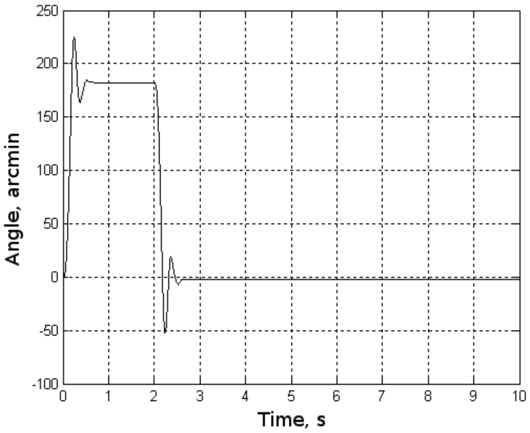

Fig. 3. Process of changing of the stabilization plant angular position

An assessment of margin of stability is carried out in the following way. The angular rate is entered on the input of the stabilization system and then is cancelled after some time delay. Margin of the stability is determined based on parameters of the transient process by the expression

$$\sigma = \frac{A_{\max}100}{A_{\text{giv}}}.$$

Margin of the stability is believed to be sufficient if the value σ is in the range (10…30)%.

All the indices of the transient process must be checked after termination of the synthesis procedure. Analysis of the obtained results allows making decision about termination of the parametrical optimization or repetition of the optimization procedure. The repeated optimization procedure is carried out after change of initial conditions or weighting coefficients in the optimization criterion.

The procedure of the parametrical optimization has following features. It is necessary to carry out the minimal and balanced realization of the stabilization plant model to provide the possibility of the calculating process. These actions optimize the calculating process and are necessary for provision of calculations accuracy, which depends on large quantity of matrix transformations.

VI. CONCLUSIONS

The features of the procedure of the parametrical optimization for system of aircraft equipment stabilization are analyzed. The criterion of optimization is determined. Procedures of simulation experiments for determination of quality indices are represented. Efficiency of the represented approaches is proved by results of simulation. The algorithm of synthesis of robust system for stabilization of aircraft equipment is given. The basic characteristic of the optimization procedure stages are represented.

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О. А. Сущенко, С. Д. Єгоров. Параметричний синтез робастної системи стабілізації обладнання літальних апаратів

В статті розглянуто параметричний синтез робастної системи, призначеної для стабілізації обладнання літальних апаратів. Представлено математичну модель об’єкта стабілізації. Приведено алгоритм параметричного синтезу робастної системи. Представлено особливості оптимізаційної процедури, включаючи вибір програмних засобів.

Показано критерій параметричного синтезу робастної системи. Проаналізовано критерій якості синтезованої системи, включаючи похибки стабілізації. Представлено результати моделювання синтезованої системи. Отримані результати можуть бути корисними для рухомих об'єктів широкого класу.

Ключові слова: система стабілізації; параметрична оптимізація; робастне управління; обладнання літальних апаратів; похибки стабілізації.

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О. А. Сущенко, С.Д. Егоров. Параметрический синтез робастной системы стабилизации оборудования летательных аппаратов

В статье рассмотрен параметрический синтез робастной системы, предназначенной для стабилизации на летательных аппаратах. Представлена математическая модель объекта стабилизации. Приведен алгоритм параметрического синтеза робастной системы. Представлены особенности оптимизационной процедуры, включая выбор программных средств. Показан критерий параметрического синтеза робастной системы. Проанализированы критерии качества синтезированной системы, включая погрешности стабилизации. Представлены результаты моделирования синтезированной системы. Полученные результаты могут быть полезными для подвижных объектов широкого класса.

Ключевые слова: система стабилизации; параметрическая оптимизация; робастное управление; оборудование летательных аппаратов; погрешности стабилизации.

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