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THE PROBLEM OF MANNED AIRCRAFT CONVERSION INTO UNMANNED AERIAL VEHICLES

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Abstract

Purpose: *an attempt to systematize and outline the theoretical and practical methods for solving the problems that arise when creating a UAV based on mass-produced light and ultra-light aircraft.* ***Methods:*** *it is assumed that the aircraft as a multidimensional dynamic system can be described by a matrix of transfer functions, whose elements can be obtained from estimates of the spectral characteristics, which are calculated from the records of the input and output signals. A multi-stage process for achieving the goal is proposed. A multi-stage process for achieving the goal is proposed. At the first stage, a mathematical model of the aircraft is constructed using the methods of identification and estimation of the parameters of dynamic systems. At the first stage, a mathematical model of the aircraft is constructed using the methods of identification and estimation of the parameters of dynamic systems.* ***Results****: the algorithm for the conversion of light and ultra-light manned aircraft into unmanned aerial vehicles based on the statistical method of spectral analysis is formulated. Next, it is planned to adapt the developed control algorithm and carry out the necessary studies on a manned prototype aircraft. The implementation of the flight program on a manned prototype aircraft with readout of control parameters in the autopilot mode will make it possible to update the mathematical model and the control algorithm for an unmanned aerial vehicle.* ***Discussion:*** *questions of the evaluation of the effectiveness and practical value of the proposed control algorithm required a large amount of additional numerical experiments on the example of a specific unmanned aerial vehicle for agricultural purposes. Therefore, the conclusions on the methodological and practical value of the proposed approach to the design of agricultural unmanned aerial vehicles can be made only after performing the full volume of flight tests on the experimental sample.*

Keywords: conversion; frequency response; manned aircraft; spectral analysis; transfer function unmanned aerial aircraft; unmanned aerial vehicle.

1. Introduction

Obviously, any aircraft, including an unmanned aerial vehicle (UAV), originally developed to solve specific tasks, will be functionally more efficient than a modernized, converted manned airplane or helicopter.

But we should not forget that with a successful selection of a manned prototype, an unmanned conversion may be preferable to the originally designed version that meets all technical and economic requirements of the customer. This approach to creating a new UAV has several advantages, such as saving costs in the design, production and testing phases; availability and logistics of spare parts; the possibility of using the existing service base; shortening the terms of project development and launching the serial production of UAV.

The term "conversion" refers to the process of converting light and ultra-light manned aircraft into UAVs for their subsequent economically and technically efficient use in various sectors of the economy.

The effectiveness of such a UAV in many ways will be determined by how well the above-mentioned conversion will be performed. To solve the problem of conversion, an appropriate theoretical basis, some set of algorithmic and software tools, as well as technical means providing a full cycle of testing of UAV control systems in all modes of flight are needed.

2. Research tasks of conversion

Enlarged process of conversion can be represented as a sequence of tasks to be solved:

1. Development of the mathematical model of the aircraft in those modes of its flight, which are typical for a specific task (operation), for example, the use of aircraft in agriculture, monitoring agro-ecosystems, extra-cargo delivery, patrolling, etc.
2. Mathematical description of external and internal disturbances, impacts and interference that occur in the control circuits of aircraft, in its measuring systems and actuators;
3. Synthesis of aircraft control laws and their optimization for specific modes of its application;
4. Choice of hardware and software tools for implementing the obtained control laws.

The first two tasks are similar in their objectives, which consist in obtaining mathematical models of the aircraft as a control object, as well as mathematical models of external influences on this control object and signals circulating in the control loops. These mathematical models serve as initial information for solving subsequent problems of synthesis of optimal control laws and their hardware and software implementation. It is also important to note that when considering these control systems, one should take into account the presence of digital devices in the control loops that operate in discrete time. This circumstance suggests the expediency of using discrete mathematical models [1, 2] in the process of formalizing the problems listed above.

3. Presenting main material

Thus, for the construction of mathematical models of an aircraft, methods of identifying and estimating the parameters of dynamical systems [3, 4, 5, 6] can be used by means of full-scale ground and flight, as well as simulation experiments. At the output of the latter, we obtain the flight parameters of the aircraft and its systems. A wide variety of identification methods makes it difficult to choose a specific method for constructing the necessary models.

However, in most practical cases, the investigated objects and control systems with some assumptions belong to the class of linear stationary systems that operate under random (stochastic) perturbations and interference. Since the description of such systems is conveniently represented, using the apparatus of transfer functions and frequency characteristics, classical statistical methods of spectral analysis [7, 8, 9] can be chosen as an identification method.

Such methods, although they require, as a rule, large volumes of experimental data, are characterized by relative simplicity and transparency of the physical meaning of the results obtained. The identification experiment itself is associated with the receipt in flight of deviation records of the steering surfaces as input signals (in the form of a certain vector r_0). And output signals of angular motion (roll, pitch, yaw), speed and altitude of flight in the form of some vector y_0. It is assumed that the aircraft as a multidimensional dynamic system can be described by a matrix of transfer functions, whose elements can be obtained by estimating the spectral characteristics, which are calculated from the input and output signals:

$$h_{ij} = s_{ij} / s_{ii} \qquad (1)$$

where s_{ij} is the estimate of the mutual spectral characteristics of the input i with the output j; s_{ii} – the estimation of the mutual spectral characteristics of the input i with the output j. Estimates (1) are accompanied by random and systematic errors, therefore simultaneously with them the so-called functions of ordinary, multiple and private coherence are estimated [7, 8], which allow to estimate such errors. The final step in the problem of obtaining models is their representation in an analytical form. For this purpose, according to the logarithmic frequency characteristics of each component of the transfer function matrix h_{ij}, the structure of the analytical model in the form of a fractional rational polynomial function is assigned whose coefficients can be calculated by least squares deviation of the experimental characteristic from its analytical model.

Having obtained the initial mathematical models, one can proceed to the problem of synthesis of the control system, which will make it possible to make the transition from manned flights to flights in automatic mode. The structure of such a control system is shown in Fig. 1.

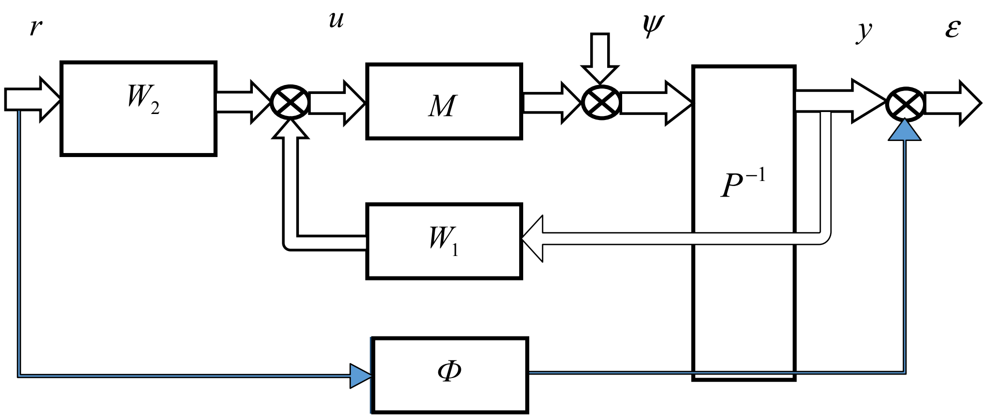

Fig. 1. Structure of the UAV control system

The motion of an aircraft as a linear multidimensional control object is described by the matrix equation of dynamics in the operator form

$$P(s)y(s) = M(s)u(s) + \psi(s), \qquad (2)$$

where $y(s)$ is the n-dimensional vector of the output signals, $u(s)$ is the m-dimensional vector of the control signals, $\psi(s)$ is the n-dimensional perturbation vector with the known spectral matrix $S_{\psi\psi}$; $P(s)$ and $M(s)$ – matrices with dimensions in the general case n × n and n × m, respectively, whose elements are polynomial functions of the argument of the Laplace operator s.

In the tasks of developing digital control, a method of describing an airplane as a continuous dynamic system that is connected to a control computer via analog-digital and digital-to-analog converters is important. In a discrete time, systems of equations such as autoregressive moving average (ARCC) are used to describe such systems, which after z-conversion are written as

$$P(z)y(z) = M(z)u(z) + \psi(z) \qquad (3)$$

Equations (3) can be obtained by some structural transformations, for example, rules of the z-transformation [1, 2]:

$$F^u(z) = P^{-1}(z)M(z) = \frac{z-1}{z} Z\{\frac{1}{s} P^{-1}(s)M(s)\}, \qquad (4)$$

$$S^T_{\psi\psi}(z) = P(z) Z_2\{P^{-1}(s) S^T_{\psi\psi}(s) (P^{-1}(-s))^T\} P(z^{-1}) \qquad (5)$$

where Z, Z_2 are symbols of ordinary and two-sided z-transformations; $P(z)$ is a matrix whose elements are determined by the left-side reduction of the poles of the fractional-rational matrix $F^u(z)$; T is the transpose sign of the matrix or vector. After transformations (4), (5), equation (3) is a discrete equivalent of equation (2).

Let us turn again to the structural diagram in Fig. 1. Further, without loss of generality, we will not use the argument z to reduce the matrix entries, for example, instead of $W_1(z)$ we will write W_1.

The automatic control system consists of two controllers W_1 and W_2, which provide the specified flight program ($r-n$-dimensional vector is converted by the controller W_2) and stabilization of the aircraft on the specified program path (regulator in the feedback of the control object W_1).

It is assumed that the signals r, u, ψ, y are vectors of stationary centered random processes, and for the signals r and ψ, the matrices of the spectral densities $S_{rr}, S_{\psi\psi}, S_{r\psi}$ are known. The system is characterized by some ideal ("desired") transformation of Φ, and the control error is formed as the difference of signals of the real response of the investigated system and the output of this imaginary ideal transformation

$$\varepsilon = y - \Phi_r \ . \qquad (6)$$

The stability criterion of the discrete system under study is the location of the poles (roots) of its characteristic polynomial inside the unit circle [1, 2] of the plane of the complex variable z .

A more rigorous formulation of the synthesis problem is formulated as follows. The quality of the system under consideration can be characterized by the known functional [10, 11, 12, 13, 14]:

The task of synthesizing the optimal control system is to determine the transfer function matrices of the regulators W_1 and W_2 so as to guarantee the stability of the closed control system and to ensure the minimum of the functional (7).

To solve the synthesis problem, it is expedient to lead the system under investigation to a stabilization system with one generalized input using known transformations [10, 14], as shown in Fig. 2

$$J = E[\varepsilon^T R\varepsilon] + E[u^T Cu] = \frac{1}{2\pi i}\oint_L S_p\{S_{\varepsilon\varepsilon}^T R + S_{uu}^T C\}\frac{dz}{z} \qquad (7)$$

where R and C are weight matrices; E – symbol of mathematical expectation; S_p is the trace character of the matrix; $i=\sqrt{-1}$ is the imaginary unit; L – contour of integration (unit circle on the plane of a complex variable); $S_{\varepsilon\varepsilon}$, S_{uu} – matrix of the spectral densities of the signals, respectively, errors and controls. This functional characterizes the quality of the control system, taking into account both its accuracy and management costs.

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$$y_0 = \left\|y^T, r^T\right\|, \psi_0 = \left\|\psi^T, r^T\right\|, u_0 = u; \qquad (8)$$

$$P_0 = \begin{Vmatrix} P & 0 \\ 0 & E_n \end{Vmatrix}, M_0 = \begin{Vmatrix} M \\ 0_{n\times m} \end{Vmatrix}, W_0 = \left\|W_1 W_2\right\|$$

$$S_{\psi_0\psi_0} = \begin{Vmatrix} S_{\psi\psi} & S_{\psi_r} \\ S_{r\psi} & S_{rr} \end{Vmatrix}, \qquad (9)$$

where the matrices *Po* and *Mo* have the dimensions $2n\times 2n$ and $2n\times m$, respectively; *En* is an n-dimensional unit matrix; $0_{n\times m}$ is the zero matrix of size $n\times m$.

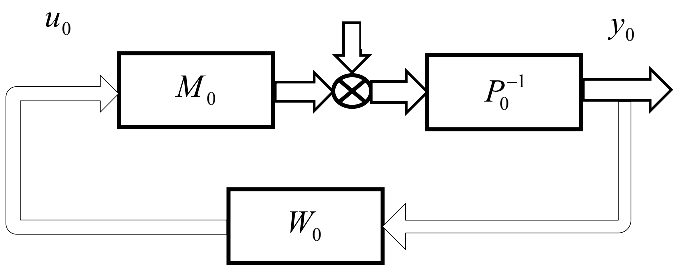

Fig. 2. The system with the generalized control input of the UAV

After such transformations, the equations of the generalized object will have the form

$$P_0(z)y_0(z) = M_0(z)u_0(z) + \psi_0(z), \qquad (10)$$

and the desired control law can be written as

$$u_0 = W_0 y_0 \ . \qquad (11)$$

To solve the problem, we introduce the transfer function matrix of a closed system [12],

which connect the vectors y_0, u_0 with the generalized perturbations ψ_0 :

$$y_0 = F_0^y \psi_0, u_0 = F_0^u \psi_0, \qquad (12)$$

where the matrices F_0^y, F_0^u. F_0^y and F_0^u have dimensions of $2n \times 2n$ and $2n \times m$, respectively. From the expressions (10) and (11) for these matrices, we can write

$$F_0^y = (P_0 - M_0 W_0)^{-1}, F_0^u = W_0 (P_0 - M_0 W_0)^{-1} \qquad (13)$$

from which it follows that the desired matrix of the generalized regulator W_o can be expressed in terms

$$W_0 = F_0^u (F_0^y)^{-1} \qquad (14)$$

Now, we express the matrices of the spectral densities of the error signals $S_{\varepsilon\varepsilon}$ and the control S_{uu} entering into the functional (7) through the matrices of the transfer functions F_0^y and F_0^u. You can write for a matrix

$$S_{uu} = F_0^u S_{\psi_0\psi_0}^T F_{0^*}^u, \qquad (15)$$

where the sign "*" means the Hermitian conjugation of the matrix. An error vector can be written as $\varepsilon = \| E_n - \Phi \|$, $y_0 = \| E_n - \Phi \| F_0^y \psi_0$.

Then for the matrix of spectral densities, we obtain the error signals

$$S_{\varepsilon\varepsilon} = \| E_n - \Phi \| F_0^y S_{\psi_0\psi_0}^T F_{0^*}^y \begin{Vmatrix} E_n \\ -\Phi_* \end{Vmatrix} . \qquad (16)$$

Taking into account (15), (16), the quality functional (7) after simple transformations can be rewritten as:

$$J = \frac{1}{2\pi i} \int_L S_p \{ (F_{0^*}^y R_0 F_0^y + F_{0^*}^u C F_0^u) S_{\psi_0\psi_0}^T \} \frac{dz}{z}, \qquad (17)$$

where

$$R_0 = \begin{Vmatrix} E_n \\ -\Phi_* \end{Vmatrix} R \| E_n - \Phi \| .$$

Thus, the problem of synthesizing an optimal discrete multidimensional control system reduces to determining the matrix of a generalized discrete regulator W_0 such that the transfer function matrix of the closed system F_0^y and F_0^u do not have poles outside the unit circle, and the quality functional (17) would have reached a minimum.

The minimization of such a functional with the stability condition of a closed system is carried out by the Wiener-Hopf method [10-14], when from the condition that the first variation of the functional (17), that is $\partial J = 0$, identifies zero, we choose variations ∂W_0 such that the corresponding variations ∂F_0^y, ∂F_0^u would have poles only inside the unit circle on the z-plane. We give the main steps in obtaining a solution [12].

It follows from (10) that the matrices F_0^y and F_0^u are connected by the relation

$$P_0 F_0^y - M_0 F_0^u = E_{2n} \ , \qquad (18)$$

using which the functional (17) can be expressed in terms of a single variable function, for example, F_0^u, and then for the first variation of the functional J we can write the following expression:

$$\partial J = \frac{1}{2\pi i} \oint_L S_p \{ (\partial F_{0^*}^u (\Gamma_{0^*} \Gamma_0 F_0^u + M_{0^*} P_{0^*}^{-1} R_0 P_0^{-1}) +$$

$$(P_{0^*}^{-1} R_0 P_0^{-1} M_0 + F_{0^*}^u \Gamma_{0^*} \Gamma_0) \partial F_0^u) S_{\psi_0\psi_0}^T \} \frac{dz}{z},$$

(19)

where

$$\Gamma_{0^*} \Gamma_0 = M_{0^*} P_{0^*}^{-1} R_0 P_0^{-1} M_0 + C \ . \qquad (20)$$

We introduce the notation:

$$D_0 D_{0*} = S^T_{\psi_0\psi_0} \quad (21)$$

$$N^0_0 + N^0_+ + N^0_- = \Gamma^{-1}_{0*} M_{0*} P^{-1}_{0*} R_0 P^{-1}_0 D_0 . \quad (22)$$

Then, the integrand for the variation of the functional (19) takes the following form

$$\partial F^u_{0*}\Gamma_{0*}(\Gamma_0 F^u_0 D_0 + N^0_0 + N^0_+ + N^0_-)D_{0*} +$$
$$D_0(N^0_{0*} + N^0_{+*} + N^0_{-*} + D_{0*}F^u_{0*}\Gamma_{0*})\Gamma_0 \partial F^u_0 .$$

Hence we obtain a solution for the unknown matrix F^u_0 on the class of stable discrete functions for which the first variation of the functional (19) is identically equal to zero, and therefore the functional (17) itself reaches a minimum:

$$F^u_0 = -\Gamma^{-1}_0 (N^0_0 + N^0_+) D^{-1}_0 \quad (23)$$

where Γ_0 is the result of the Wiener factorization of the matrix (20), D_O is the result of the Wiener factorization of the matrix of spectral densities (21), $(N^0_0 + N^0_+)$ is the Wiener separation result of expression (22). The Wiener factorization implies splitting by a special algorithm (see, for example, [15]) matrices with fractional rational elements into two Hermitian conjugate matrices Γ_0 and Γ_{0*} whose poles of characteristic polynomials are located inside the unit circle for Γ_0 and outside the unit circle for Γ_{0*}. For matrices D_0 and D_{0*} is similar.

Wiener separation implies the decomposition of a rational-fractional matrix into terms $N^0_0 + N^0_+ + N^0_-$, where N^0_0 is a polynomial matrix that contains in its elements entire parts of discrete functions if there are irregular fractions, N^0_+ is composed of fractional-rational discrete functions whose poles are concentrated inside the unit circle, and for N^0_- – respectively outside the unit circle.

In other words, $N^0_0 + N^0_+$ is a stable part of the original matrix (22), and N^0_- are the unstable part of the matrix (22), respectively.

4. Conclusions

Thus, we can formulate the following algorithm for the conversion of light and ultra-light manned aircraft into UAVs.

1. Based on the results of identification procedures, obtain the initial models of the control object, control signals, disturbances and interference.
2. From the data obtained, form the matrices $P_0, M_0, S_{\psi_0\psi_0}$.
3. Having defined the weight matrices R and C (their values are established from the experiment), find the matrix
4. $R_0 = \begin{Vmatrix} E_n \\ -\Phi \end{Vmatrix} R \begin{Vmatrix} E_n & -\Phi \end{Vmatrix}$ and form the matrix (20) $\Gamma_{O*}\Gamma_O$.
5. Performing the factorization of the matrix (21) and the matrix (20), we find the result of the matrix D_0 and Γ_0.
6. Using D_0 and Γ_0 as well as a priori data, form expression (22) and after its separation find the matrix $(N^0_0 + N^0_+)$.
7. Using formula (23), define the matrix F^u_0 and then, using expression (18), determine F^y_0.
8. Using expression (14), find the desired transfer function matrix of the optimal generalized discrete controller $W_0 = \|W_1 W_2\|$ which, in fact, is the solution of the optimal control synthesis problem.

The minimum value of the quality criterion is determined by substituting the matrices F^u_0 and F^y_0 obtained in the given weight matrices R and C into the functional (17). If the achieved quality level does not satisfy the developer, then the synthesis procedure should be repeated with new values of the weight matrices.

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Проблема конверсії пілотованого літака в безпілотний літальний апарат

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Мета: спроба систематизувати і намітити теоретичні та практичні методи вирішення завдань, що виникають при створенні безпілотних літальних апаратів на базі серійно вироблюваних легких і ультра-легких літаків. **Методи:** передбачається, що літак як багатовимірна динамічна система може бути описаний матрицею передавальних функцій, елементи якої можна отримати за оцінками спектральних характеристик, які обчислюються за записами вхідних і вихідних сигналів. Пропонується багатоетапний процес досягнення поставленої мети. На першому етапі будується математична модель літака з використанім методів ідентифікації та оцінювання параметрів динамічних систем. **Результати:** сформульовано алгоритм процесу конверсії легких і ультра-легких пілотованих літаків в безпілотні літальні апарати, заснований на статистичному методі спектрального аналізу. Далі планується адаптація розробленого алгоритму управління і проведення необхідних досліджень на пілотованому літаку - прототипі. Реалізація польотної програми на пілотованому літаку- прототипі зі зчитуванням параметрів управління в режимі автопілотування дозволить ввести уточнення в математичну модель і алгоритм управління безпілотних літальним апаратом. **Дискусія:** в опитування оцінки ефективності та практичної цінності пропонованого алгоритму управління зажадали великого обсягу додаткових численних експериментів на прикладі конкретного безпілотного літального апарату сільськогосподарського призначення. Підсумкові результати цих експериментів - в процесі обробки. Тому остаточні висновки про методологічної та практичної цінності пропонованого підходу до проектування сільськогосподарських безпілотних літальних апаратів можна буде зробити тільки після виконання повного обсягу льотних випробувань на експериментальному зразку.

Ключові слова: безпілотний літальний апарат; конверсія; передавальна функція; пілотований літак; спектральний аналіз; частотна характеристика

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Проблема конверсии пилотируемого самолёта в беспилотный летательный аппарат

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Цель: попытка систематизировать и наметить теоретические и практические методы решения задач, возникающих при создании беспилотных летательных аппаратов на базе серийно производимых лёгких и ультра-лёгких самолётов. **Методы:** предполагается, что самолет как многомерная динамическая система может быть описан матрицей передаточных функций, элементы которой можно получить по оценкам спектральных характеристик, которые вычисляются по записям входных и выходных сигналов. Предлагается многоэтапный процесс достижения поставленной цели. На первом этапе строится математическая модель самолёта с использованием методов идентификации и оценивания параметров динамических систем. **Результаты:** сформулирован алгоритм процесса конверсии лёгких и ультра-лёгких пилотируемых самолётов в беспилотные летательные аппараты, основанный на статистическом методе спектрального анализа. Далее планируется адаптация разработанного алгоритма управления и проведение необходимых исследований на пилотируемом самолете-прототипе. Реализация полётной программы на пилотируемом самолёте-прототипе со считыванием параметров управления в режиме автопилотирования позволит внести уточнения в математическую модель и алгоритм управления беспилотным летательным аппаратом. **Дискуссия:** вопросы оценки эффективности и практической ценности предлагаемого алгоритма управления потребовали большого объёма дополнительных численных экспериментов на примере конкретного беспилотного летательного аппарата сельскохозяйственного назначения. Итоговые результаты этих экспериментов – в процессе обработки. Поэтому окончательные выводы о методологической и практической ценности предлагаемого подхода к проектированию сельскохозяйственных беспилотных летательных аппаратов можно будет сделать только после выполнения полного объёма лётных испытаний на экспериментальном образце.

Ключевые слова: беспилотный летательный аппарат; конверсия; передаточная функция; пилотируемый самолёт; спектральный анализ; частотная характеристика

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