AUTOMATIC CONTROL SYSTEMS

UDC 623.746-519(045)
DOI:10.18372/1990-5548.60.13806

[1]**N. F. Tupitsin,**
[2]**V. R. Mykolaichuk**

STABILIZATION OF THE UNMANNED AERIAL VEHICLE IN THE GAS-DYNAMIC COMPLEX

[1,2]Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine
E-mails: [1]tupitsyn2@gmail.com, [2]mukwira @ukr.net

Abstract—*The article is devoted to perfecting one of the perspective methods of take-off and landing without airfield, namely, gas-dynamic method. At first, this method accounts an application unmanned aerial vehicle with the aerodynamic controls. However, at the unmanned aerial vehicle take-off and landing with help of external gas-dynamic devices, exists a problem of its stabilization at small velocity of flight. Authors took out a patent on technical solution of the unmanned aerial vehicle stabilization at the unmanned aerial vehicle take-off and landing with help of external gas-dynamic devices, but there is not numerical proof of proposed solution efficiency. To this effect the mathematical model and calculation algorithm of automatic unmanned aerial vehicle stabilization system during take-off and landing in a gas-dynamic complex are developed. The calculations have proven that by using two gas-dynamic devices of matrix type the fundamental possibility appears of stabilizing unmanned aerial vehicle at its near-zero speeds, while the aerodynamic controls are not effective. The mathematical model of unmanned aerial vehicle motion in an artificial air flow is based on the equations of the longitudinal motion dynamics. The peculiarity of the proposed model is that during the stabilization of the angular motion of the unmanned aerial vehicle uses a partial flow around the unmanned aerial vehicle body additional artificial airflow.*

Index Terms—Gas-dynamic complex; automatic stabilization system; artificial air flow.

I. INTRODUCTION

For practice realization of the gas-dynamic method for take-off and landing it's necessary to solve a task of the unmanned aerial vehicle (UAV) stabilization at small velocity of flight [2], [4]. The peculiarity of this task is that the UAV control elements at small velocity of flight are not effective. At such regime the UAV stabilization is usually provided with the help of control jet [1]. However, mechanism of the jet deflector may complicate control system and decrease the payload weight.

The solution of the task is proposed in [2].

The functional scheme of the UAV automatic stabilization system (AUSS) with the gas-dynamic take-off and landing contains a gas-dynamic complex (GDC) 1 (Fig. 1), which houses the main 2 and auxiliary 3 matrix type gas-dynamic devices (GDD), control unit 4, connected on the one side with the ground equipment of the radiocommunication 5, and on the other with a sensor unit 6 for measuring the position of the UAV 7 relative to the GDC 1. In addition, the control unit 4 is connected to the main 2 and the auxiliary 3 matrix type GDDs.

The AUSS part on the UAV side is comprised by control system 8, which is connected to the roll, yaw and pitch angles setting device 9, with the block of angular position sensors and angular velocities 10 of the UAV 7, with the equipment of the radio communication 11, and the block 12 compares the signals from the roll, yaw and pitch angles setting device 9 and from the block 10. When the UAV deviates from the set angle position from the block 12, a signal is sent to the control system 8, otherwise a signal is sent to the data registration unit 13.

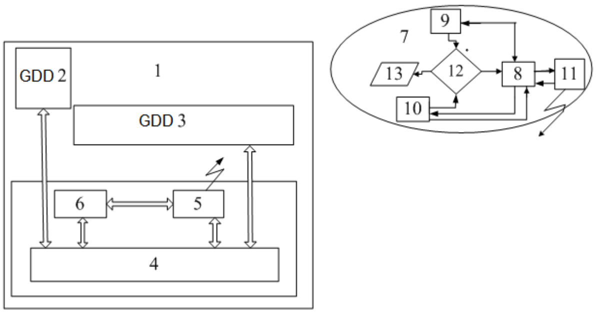


Fig. 1. Functional scheme of the system of automatic stabilization of the UAV with the gas-dynamic take-off and landing

Before take-off the given take-off angles of the roll, yaw and pitch are set in the AUSS. Upon the UAV take-off, the artificial air flow (AAF) is created in such a way that it is directed vertically upwards and has the required speed so that the UAV starts to rise upwards under the action of the ram-air flow. For example, when lifting UAV, signals, proportional to the flying angles of the roll, yaw and pitch are fed to the comparison unit from the block of UAV position

http://jrnl.nau.edu.ua/index.php/ESU, http://ecs.in.ua

sensors. In case of the UAV deviation from a given position, signals are transmitted to the control unit of the ground equipment 4 using the radio communication device, then redistribution of the velocity field of the AAF from the auxiliary GDD 3 is carried out.

Redistribution of the field of speed of the AAF occurs in such a way as to eliminate the deviation of the UAV from the set angle position without decreasing the total direct force action of the AAF on the UAV.

II. PROBLEM STATEMENT

The main task of work is to test efficiency of the UAV angular stabilization with help of two matrix type gas-dynamic devices.

For this purpose it is necessary:

- to develop a mathematical model and algorithm for calculation of UAV angular motion at GDC;
- to conduct calculation of the angular motion of the UAV with given aerodynamic characteristics with the included angular stabilization system.

Despite the fact that the AUSS is an automatic, the external pilot must carefully monitor the UAV modes of take-off and landing.

III. PROBLEM SOLUTION

The equations of the UAV short-period motion may be presented as [3]:

$$\begin{aligned} & mV_0\dot{\Theta} = P\ \alpha + Y_a - mg\cos\Theta, \\ & {}^{2}{}_{z}\dot{\omega}_z = M_z, \\ & \dot{\vartheta} = \omega_z, \\ & \alpha = \vartheta - \Theta. \end{aligned} \tag{1}$$

where g is the gravity acceleration; m is the UAV mass; V is the UAV velocity; Y_a is the lifting force, acting on the UAV; M_z is the pitching moment; I_z is the moment of inertia of the aircraft with respect to the associated axis "OZ"; ϑ is the pitch angle; θ is the angle of inclination of the velocity vector V to the horizon line; α is the angle of attack; ω_z is the angular velocity of the UAV with respect to the associated axis "OZ".

The controlling transverse force and the control torque acting on the UAV are created with the help of the GDDs of the matrix type on the command from the command control unit, as shown in Fig. 1, on which GDD 3 and GDD 2 – horizontally and vertically placed gas-dynamic devices. In this case, the command control unit performs general control of the take-off and landing processes of the UAV, and the gas-dynamic complex includes the measuring equipment unit and the GDC control system.

Measurement of the angles and angular velocities of the UAV is performed not only with the help of on-board measuring instruments, but also with the help of a block of measuring instruments located on the GDC.

When the UAV leaves a predetermined range of changes in the angles of roll, pitch and yaw, the command control unit performs switching on reinforced operation regime of the defined part of the fans, under or in front the UAV, thereby providing a parrying of the angular deviation. As example, Fig. 2 shows the UAV, which is out of permissible range of changes in the pitch angle ϑ_p and the creation of disturbing force Y_a^d and the appropriated torque M_z^d for parrying of the pitch angle using the GDD 3. Here the AAF velocity V_0 allows cancel out the UAV weight [4] and ΔV is the additional value of the AAF velocity, which namely creates the disturbing force and the torque M_z^d

Let us consider analytically the creation of control forces and torques by the example of a longitudinal channel. We factorize the additional transverse force ΔY_a, which is created on the part of the surface of the UAV S^* under the action of excessive ram air $(\rho\Delta V^2)/2$, into the following components:

$$\Delta Y_a = \frac{\partial \Delta Y_a}{\partial \alpha}\alpha + \frac{\partial \Delta Y_a}{\partial S^*}S^*, \tag{2}$$

where $\frac{\partial \Delta Y_a}{\partial \alpha}$ is the partial derivative of the ΔY_a by value α; $\frac{\partial \Delta Y_a}{\partial S^*}$ is the partial derivative of the ΔY_a by value S^*.

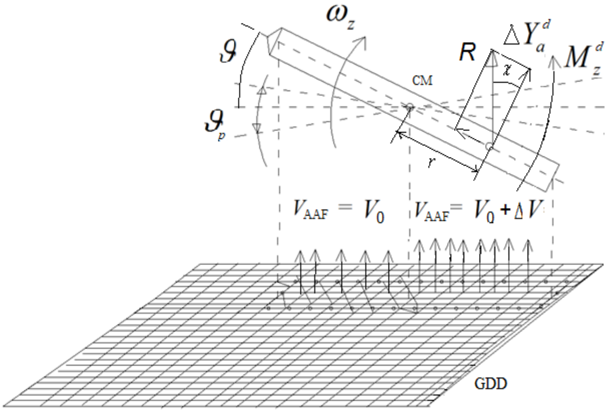


Fig. 2. The functioning of the GDC during parrying of the UAV angular deviation

The moment of forces created by the additional transverse force by AAF on the streamlined part of the UAV is equal to:

$$M_z = rR\cos\chi = rR\cos\vartheta = r\Delta Y_a,$$

where χ is the angle between the total aerodynamic force R, which is created by the AAF, and the force Y_a^d; r is the shoulder of force R relative to the centre of mass (CM) of the UAV.

Let us decompose the moment of the forces M_z into three terms, the first two terms being given by the aerodynamic properties of the UAV, and the third term determines the perturbing effect of the GDD on the UAV:

$$M_z = \frac{\partial M_z}{\partial\alpha}\alpha + \frac{\partial M_z}{\partial\omega_z}\omega_z + \frac{\partial M_z}{\partial S^*}S^*. \tag{3}$$

Let centre of mass of the UAV is located in the middle of its fuselage, which has a form of cylinder.

The transverse force and the perturbing moment of this force acting on the UAV as a result of the action of the gas-dynamic device are equal:

$$\begin{aligned} \Delta Y_a &= \left[C_x^{90^\circ}\rho\frac{V_{\text{aaf}}^2}{2}S^*\right], \\ M_z &= \left[C_x^{90^\circ}\rho\frac{V_{\text{aaf}}^2}{2}S^* l^*\right], \end{aligned} \tag{4}$$

where $l^*=r$ is the distance between the centre of mass of the UAV and the point of application of the total disturbance force, and $l^* = S^*/d$ (d is the cylinder diameter).

Then the partial derivatives of the transverse force and the perturbing torque (4) will be the following:

$$\begin{aligned} (\Delta Y_a)^{S^*} &= C_x^{90^\circ}\rho\frac{V_{\text{aaf}}^2}{2}, \\ (M_z)^{S^*} &= C_x^{90^\circ}\rho\frac{V_{\text{aaf}}^2 S^*}{2d}. \end{aligned} \tag{5}$$

If substitute the values of the partial derivatives and coefficients into system (1), taking into account conditions $P = 0$ and $mg\cos\Theta \approx 0$ at $\Theta \approx \pi/2$, then obtain:

$$\begin{cases} \dot{\Theta} = C_x^{90^o}\rho\dfrac{V_{\text{aaf}}^2}{2mV}S^* + \dfrac{Y^\alpha}{mV}\alpha, \\ \dot{\vartheta} = \omega_z, \\ \dot{\omega}_z = \dfrac{C_x^{90^o}\rho\dfrac{V_{\text{aaf}}^2 S^*}{2d}}{I_z}S^* + \dfrac{M_z^{\omega_z}}{I_z}\dot{\vartheta} + \dfrac{M_z^{\alpha}}{I_z}\alpha, \\ \alpha = \vartheta - \Theta. \end{cases} \tag{6}$$

The resulting system of differential equations (6) with variable coefficients, which allows us to describe the motion of a UAV in an alternating flow, is not linear. Its analytic solution is complicated and, therefore, it is proposed its fourth-order Runge–Kutta numerical solution.

The simulation of UAV motion was carried out by solving the Cauchy problem for system (6) with initial data of the form:

$$\begin{aligned} \vartheta(t=0) &= \vartheta_0, \\ \omega_z(t=0) &= \omega_{z0}, \\ \Theta(t=0) &= \Theta_0. \end{aligned} \tag{7}$$

Two types of calculations were carried out: with and without the AUSS.

Calculation of the characteristics of the UAV during take-off was carried out according to the following scheme:

1) Set the initial data of the UAV, the mode of its flight, the characteristics of GDD 2 and GDD 3.

2) By formula (6), the right-hand sides of the differential equations with the chosen step of integration are calculated;

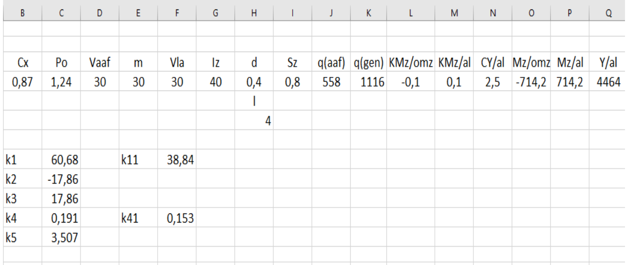
3) At each step of integration, the condition of finding for pitch angle in predetermined interval is checked. If the pitch angle enters a predetermined interval, then the condition for achieving by the angular velocity ω_z a predetermined interval is checked.

4) If ω_z enters a predetermined interval, then the stabilization system is switched off, the next integration step is calculated.

Let's rewrite the system of equations (6) in the form:

$$\begin{cases} \dot{\vartheta} = \omega_z, \\ \dot{\omega}_z = k_1 S^{*2} + k_2\dot{\vartheta} + k_3\alpha, \\ \dot{\Theta} = k_4 S^* + k_5\alpha, \\ \alpha = \vartheta - \Theta. \end{cases} \tag{8}$$

Preliminary calculation of the coefficients of the system of equations (8) $k_1,\ldots,k_5$ was conducted using Microsoft Office Excel. In Figure 3 is a screenshot of the calculation of the coefficients of the system of equations (8).



B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Cx	Po	Vaaf	m	Vla	Iz	d	Sz	q(aaf)	q(gen)	KMz/omz	KMz/al	CY/al	Mz/omz	Mz/al	Y/al
0,87	1,24	30	30	30	40	0,4	0,8	558	1116	-0,1	0,1	2,5	-714,2	714,2	4464
						l									
						4									
k1	60,68		k11	38,84											
k2	-17,86														
k3	17,86														
k4	0,191		k41	0,153											
k5	3,507														

Fig. 3. Screenshot of the calculation table of the coefficients (8)

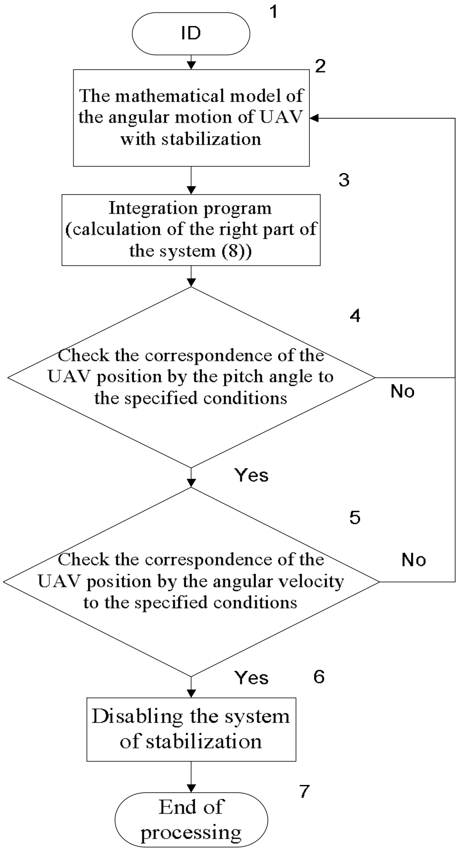


Fig. 4. Simplified block diagram of the algorithm for calculating of the UAV angular motion

A simplified block diagram of the algorithm for calculating the angular motion of the longitudinal channel of a UAV with an included stabilization system is shown in Fig. 4.

A description of the block diagram of the algorithm for solving the problem is given below:

1) In Block 1 is the input of initial data and calculation of the coefficients of the system (8).

2) Block 2 describes the mathematical model of the angular motion of the UAV with stabilization by means of the GDD from the gas-dynamic take-off and landing complex.

3) Block 3 calls the standard (Runge–Kutta) integration program, that is, the calculation of the right part of the system (8).

4) The correspondence of the UAV pitch angle to the specified conditions is checked.

5) The correspondence of the UAV angular velocity to the specified conditions is checked.

6) Disabling the system of stabilization.

7) End of processing.

A. Selection and justification of the initial data

Flight characteristics of the hypothetical UAV, which were used in the calculations, are given in Table I.

TABLE I FLIGHT CHARACTERISTICS OF THE HYPOTHETICAL UAV

Name	Designation, dimention	Value
UAV mass	m, kg	30
Hull length	l, m	4
Moment of inertia of UAV	I_z, kg·m^2	40
Hull diameter	d, m	0.4
Area of the axial section of the UAV hull	S^*, m^2	1.6
The derivative of pitch moment coefficient by angle of attack	m_z^{α}	0.1
The derivative of pitch moment coefficient by angular velocity ω_z	$m_z^{\omega_z}$	–0.1
The derivative of transverse force by angle of attack	c_y^{α}	2.5
Drag coefficient of the hull of a UAV (cylinder) at its transverse flow	$c_x^{90°}$	0.87

The delay in the transmission of data from the sensors determining the angular position of the UAV was not taken into account. The loss of the speed of the GDD at a distance from the edge of the fan to the hull of the UAV was also not taken into account.

The UAV take-off and landing simulation was carried out under the following modes of the GDC (Table II).

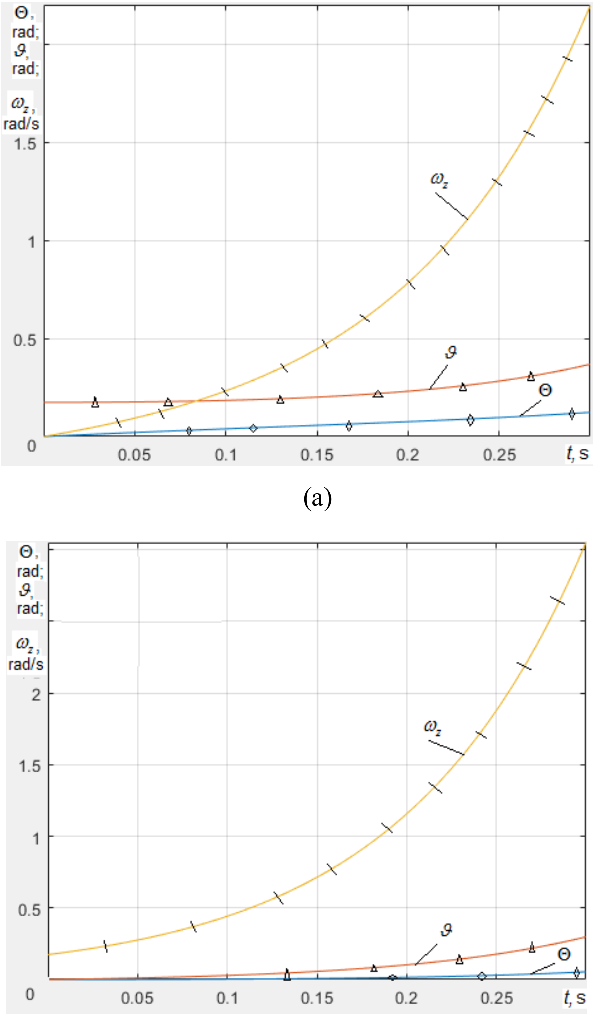
TABLE II CALCULATING MODES OF UAV FLIGHT

Name	Designation, dimention	Value
Speed of GDD 2	V, m/s	15, 30, 45
Speed of GDD 3	V, m/s	15, 30, 45
Air density at the ground	ρ, kg/m^3	1.25

Algorithm was realized in programming environment Matlab 2018a using Symbolic Math Toolbox, which provides an opportunity to work with systems of ordinary differential equations and greatly simplifies the implementation of calculations.

B. Calculation of the UAV's angular motion without and with inclusion of stabilization system

Under given initial conditions (see Table I and II), the dynamics of the angular motion of the longitudinal channel without the inclusion of the stabilization system is characterized by a significant increase of the UAV angular velocity, as shown in Figs 5 – 7.



(a)

(b)

Fig. 5. Calculation of the UAV's angular motion at initial conditions: (a) $\vartheta_0 = 10^\circ$; $\omega_{z0} = 0$; $\Theta_0 = 0$; (b) $\vartheta_0 = 0$; $\omega_{z0} = 10^0$; $\Theta_0 = 0$

Calculations indicated in Fig. 5 are carried out at the same speeds of horizontal and vertical GDDs:

$$V_{\text{hor. aaf}} = V_{\text{vert. aaf}},$$

$$V = \sqrt{V^2_{\text{hor. aaf}} + V^2_{\text{vert. aaf}}}.$$

In Figure 5 the time range of take-off is up to 0.3 s and $V_{\text{hor. aaf}} = V_{\text{vert. aaf}} = 30$ (m/s). At further the interval of time calculations of the UAVs angular motion is decreased to 0.1s. With help of the AUSS, at given initial data, the pitch angle is decreased from 10 degrees to zero during 0.09 s (Fig. 6). On this interval time the UAV angular velocity reaches of level minus 4 rad/s, and the angle of inclination of the velocity vector V to the horizon line isn't changed practically. Parry of the UAV angular velocity from 10 deg/s to zero is reached during 0.01 s (Fig. 7).

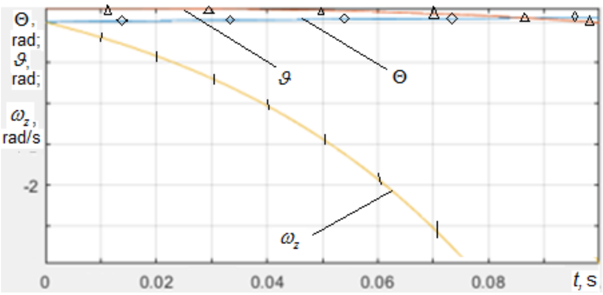


Fig. 6. Simulation of CC work at counteracting of the initial pitch angle 10 deg

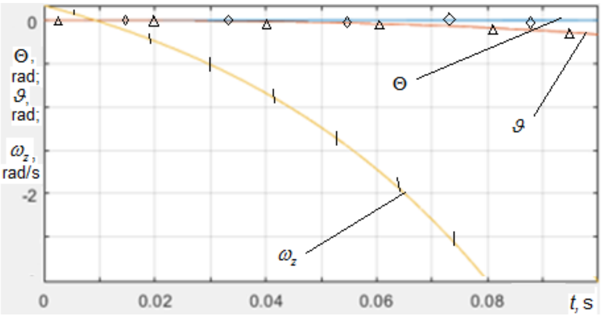


Fig. 7. Simulation of CC work at counteracting of the initial angular velocity 10 deg/s

IV. CONCLUSION

In work the mathematical model and the algorithm for calculation of UAV motion at GDC with and without the angular stabilization system are developed.

Conducted calculations showed principal possibility to use the proposed stabilization system, which allows parry of the UAV perturbed angular motion at its take-off and landing.

These calculations allow define the requirements to the angular position and angular velocity sensors also.

However, the mathematical model and the algorithm of the UAV perturbed motion calculation need modified, namely: 1) in mathematical model add models of sensors, which measure the UAV angular position and its angular velocities should be added; 2) include to the algorithm of the AUSS work and mathematical model the switching element, which will be turning on and off the AUSS.

Besides, it follows to specify more accurate of the UAV aerodynamic characteristics.

REFERENCES

[1] N. F. Tupitsyn, "Influence of natural gas-dynamic streams of flying vehicle jet engine on its flight conditions," *Artillery and Rifle Armaments*. no.1(38), pp. 41–46, 2011.

[2] N. F. Tupitsyn, “Automatic stabilization system of the UAV at gas-dynamic method takeoff and landing// Abstracts the report,” *Eighth World Congress "Aviation in the XXI Century"* Kyiv, Ukraine, October 10-12, 2018.

[3] V. M. Sineglazov, M. K. Filyashkin, M. F. Typitsyn, and O. O. Gurska, *Aircraft Active Control Systems*, Kyiv: Publisher NAU, 2010,160 p.

[4] N. F. Tupitsyn and A. V. Bondarchuk, “Calculation of the characteristics of gas-dynamic landing gear,” *Electronic and control systems*, no. 2(28), pp. 161–164, 2011.

Received March 23, 2019.

Tupitsin Nikolay. Candidate of Engineering Sciences. Associate Professor.
Aviation Computer-Integrated Complexes Department, National Aviation University, Kyiv, Ukraine.
Education: Moscow Institute of Physics and Technology, Moscow, Russia, (1975).
Research area: dynamic of flight, experimental methods of aerodynamic, aviation simulators.
Publications: 92.
E-mail: tupitsyn2@gmail.com

Mykolaichuk Vira. Teaching Fellow.
Department of Information Systems and Technologies, State University of Telecommunications, Kyiv, Ukraine.
Research area: intelligent data analysis.
Publications: 4.
E-mail: mukwira@ukr.net

М. Ф. Тупіцин, В. Р. Миколайчук. Стабілізація безпілотного літального апарата в газодинамічному комплексі

Роботу присвячено вдосконаленню перспективного методу безаеродромного зльоту і посадки безпілотного літального апарата, а саме, газодинамічного методу. Даний метод, в першу чергу, розрахований на безпілотний літальний апарат з аеродинамічними органами управління. При зльоті і посадці безпілотного літального апарата, за допомогою зовнішніх газодинамічних пристроїв, існує проблема його стабілізації на малих швидкостях польоту. Запатентовано технічне рішення стабілізації безпілотного літального апарата під час його зльоту та посадки за допомогою зовнішніх газодинамічних пристроїв, але немає чисельного підтвердження ефективності запропонованого рішення. Для цього розроблено математичну модель і алгоритм розрахунку автоматичної системи стабілізації безпілотного літального апарата під час його зльоту та посадки в газодинамічному комплексі. Наведені розрахунки показали принципову можливість стабілізації безпілотного літального апарата для його близьконульових швидкостей, коли аеродинамічні органи керування не ефективні, за рахунок двох газодинамічних пристроїв матричного типу. Математичну модель руху безпілотного літального апарата в штучному повітряному потоці засновано на рівняннях динаміки поздовжнього руху. Особливість запропонованої моделі полягає в тому, що для стабілізації кутового руху безпілотного літального апарата застосовується часткове обтікання корпусу безпілотного літального апарата додатковим штучним повітряним потоком.

Ключові слова: газодинамічний комплекс; система автоматичної стабілізації; штучний повітряний потік.

Тупіцин Микола Федорович. Кандидат технічних наук. Доцент.
Кафедра авіаційних комп’ютерно-інтегрованих комплексів, Національний авіаційний університет, Київ, Україна.
Освіта: Московський фізико-технічний інститут, Москва, Росія (1975).
Напрям наукових досліджень: динаміка польоту, експериментальні методи аеродинаміки.
Кількість публікацій: 100.
E-mail: tupitsyn2@gmail.com

Миколайчук Віра Романівна. Асистент.
Кафедра інформаційних систем та технологій, Державний університет телекомунікацій, Київ, Україна.
Освіта: Національний авіаційний університет, Київ, Україна, (2018).
Напрям наукових досліджень: інтелектуальний аналіз даних.
Кількість публікацій: 4.
E-mail: mukwira@ukr.net

Н. Ф. Тупицин, В. Р. Миколайчук. Стабилизация беспилотного летательного аппарата в газодинамическом комплексе

Работа посвящена совершенствованию одного из перспективных методов безаэродромного взлета и посадки беспилотного летательного аппарата, а именно, газодинамического метода. Данный метод, в первую очередь, рассчитан на беспилотный летательный аппарат с аэродинамическими органами управления. При взлете и посадке беспилотного летательного аппарата, с помощью внешних газодинамических устройств, существует проблема его стабилизации на малых скоростях полета. Запатентовано техническое решение стабилизации беспилотного летательного аппарата при его взлете и посадке с помощью внешних газодинамических устройств, но нет численного подтверждения эффективности предложенного решения. Для этого разработана математическая модель и алгоритм расчета автоматической системы стабилизации беспилотного летательного аппарата при его взлете и посадке в газодинамическом комплексе. Приведенные расчеты показали принципиальную возможность стабилизации беспилотного летательного аппарата при его околонулевых скоростях, когда аэродинамические органы управления не эффективны, за счет двух газодинамических устройств матричного типа. Математическая модель движения беспилотного летательного аппарата в искусственном воздушном потоке основана на уравнениях динамики продольного движения. Особенность предложенной модели заключается в том, что для стабилизации углового движения беспилотного летательного аппарата применяется частичное обтекание корпуса беспилотного летательного аппарата дополнительным искусственным воздушным потоком.

Ключевые слова: газодинамический комплекс; автоматическая система стабилизации; искусственный поток воздуха.

Тупицин Николай Федорович. Кандидат технических наук. Доцент.
Кафедра авиационных компьютерно-интегрированных комплексов, Национальный авиационный университет, Киев, Украина.
Образование: Московский физико-технический институт, Москва, Россия, (1975).
Направление научной деятельности: динамика полета, экспериментальные методы аэродинамики.
Количество публикаций: 100.
E-mail: tupitsyn2@gmail.com

Миколайчук Вера Романовна. Ассистент.
Кафедра информационных систем и технологий, Государственный университет телекоммуникаций, Киев, Украина.
Образование: Национальный авиационный университет, Киев, Украина, (2018).
Направление научной деятельности: интеллектуальный анализ данных.
Количество публикаций: 4.
E-mail: mukwira@ukr.net