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Research Article

DYNAMIC MODELING OF DRONE STABILITY UNDER AERODYNAMIC FORCES

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ABSTRACT

A new approach to the calculation of unmanned aerial vehicles in an environment with predetermined external disturbances is demonstrated. A geoscan is chosen as a control object because it is the most maneuverable among other unmanned aerial vehicles and is designed to operate in a limited space environment, designed to perform tasks in mountainous and urban environments. External disturbances, such as wind gusts, inevitably act on the geoscan during flight, so the article deals with the issues of analyzing the mathematical model of the geoscan taking into account external disturbing influences. Mathematically modeled dynamic actions to piecewise constant external disturbances, the worst disturbances occurring during the flight of the geoscan.

KEYWORDS

Geoscan; external perturbation; adaptive control; stability.

INTRODUCTION

UAVs (unmanned aerial vehicle) make it possible to solve a wide range of tasks in conditions where the use of manned aviation is impractical, costly or risky. Compared to manned aircraft, unmanned aircraft are characterized by relatively low cost, simplicity and availability of technologies. Lightweight unmanned aircraft consume significantly less fuel. Unlike manned aircraft, pilotless machines do not need concrete

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paved airfields, which is a significant advantage, since today most airfields need to be reconstructed, and the pace of reconstruction does not ensure that runways are suitable at the appropriate level.

Advantages of UAVs for a variety of civilian sector tasks:

- no danger to the pilot's life;
- compact geometric dimensions for transportation;
- short time of preparation for departure - 5-15 minutes;
- no restrictions on the size of takeoff sites;
- simple starting procedure, the ability to start practically from any site with dimensions of 2 × 2 meters, and, if necessary, from the hood of a car;
- ability to work at low altitudes from 0 to 100 m - detailed examination of the selected object from a close distance;
- possibility of on-board target load (optical video camera, digital camera, thermal imager, etc.) quick replacement in order to obtain photo and video material of specified quality;
- low weight in case of a fall reduces the size of probable damage to various objects and danger to life and health of personnel [1].

METHODS

The main quality of stable operation of a system is its stability, without which the concept of a system loses its meaning. There are two types of stability [2]:

1) material-energetic;

2) structural-functional.

The first type of stability is related to the constancy of the material composition and energy balance of the system. The second type of stability is related to the constancy of its reactions to the same external influences.

Depending on the type of complexity, a certain type of stability is realized. The first type of stability is characteristic of automatic systems: for example, a machine has a constant structure with a variable material composition. The second type of stability is possessed by solving subsystems, in particular, the simplest components of the system.

Since the middle of the last century, methods for investigating the stability of solutions of differential equations with consequence and more general functional-differential equations have been actively developed.

One of the main methods for investigating the stability of solutions of systems of differential equations with lags is the second Lyapunov method based on the

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application of Lyapunov-Krasovskii functionals in the case of nonlinear equations, and the method of functional series in the case of linear equations. Practical application of these criteria to rather general systems of differential equations with consequence can cause difficulties.

It should also be noted that recently there has been a tendency to abandon the previously used sequential design principles, when the definition of aerodynamic, weight, energy and other characteristics is performed iteratively one after another, being refined at each step. Such a method of determining the technical appearance at the initial stages of design is fraught with a significant increase in labor intensity and costs of time and money in case of assumption of any kind of inaccuracies in determining this or that characteristic at the next step. The sequential approach is replaced by methods of complex, simultaneous consideration of key performance indicators of the UAV on its technical appearance as a whole, using mathematical models from different subject disciplines and methods of multidisciplinary optimization with the possibility of formalization, algorithmization and automation of calculations [3-6]. The main ideas for the realization of such an approach are presented in [7], which can be substantially demonstrated by the example of the development of easy-to-manufacture training UAVs.

In this paper, the stability process of the drone is investigated using Hamilton's principle and Rouse's equation.

RESULTS

Day-to-day aviation operations are generally attributed to periodic and observed flights along a predetermined route (patrol route). They are usually accompanied by activities related to surveillance and communication procedures and are projected to represent a significant percentage of UAV flights between now and 2030. [1]. Accompanying such flights involves the observation of natural (natural) or geographical features such as coastlines, boundary lines, high-rise buildings and structures, forests, roads, pipelines, etc. Patrolling takes place using a wide range of unmanned vehicles in both lower (up to 1,000 m above terrain or water surface) and upper airspace (above 4,000 m). It can be performed using both instrument flight rules and visual flight rules, depending on the composition of the on-board equipment.

Axisymmetric UAVs (Fig. 1) are stabilized by imparting to them an angular velocity of rotation about the longitudinal axis. This imposes special requirements on the dynamics of the projectile motion. In deriving the equations of motion, we will assume, as above, that gravity forces can be neglected. Let us also assume that the angular velocities ω and ω_{yz} are small compared to ω_x.

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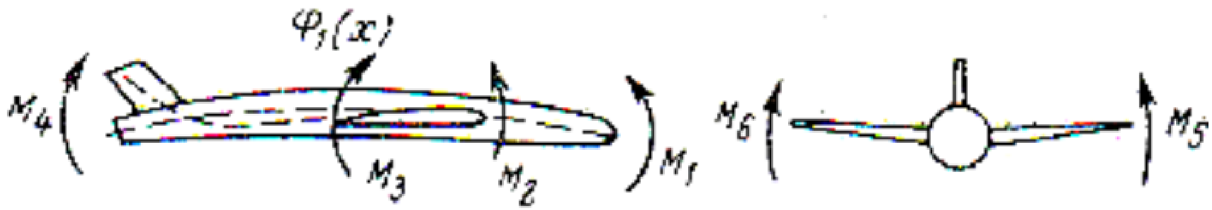

Fig.1. Schematic of forces and moments acting on an elastic aircraft

c_{yM}, c_{zM} и m_{yM}, m_{zM} – Magnus force and moment coefficients; *q* - velocity head;

c_{y1}, c_{z1} и m_{y1}, m_{z1} – coefficients of forces and moments resulting from asymmetry of bearing surfaces;

Y_p, Z_p и M_{yp}, M_{zp} – forces and moments due to misalignment of the thrust vector with the axis ox and due to misalignment of the thrust line with the center of mass.

Obviously, the forces *Yp Zp* and moments, *Myp Mzp* can be specifically designed for the purpose of controlling a drone. At the same time to control the motion of the center of mass the forces must be created *Yp u Zp* and for angle control ψ and ϑ – moments *Myp Mzp.*

The torque *Mx* can be represented as

$$M_x = c_x^{\bar{\omega}_z} q d^2 \frac{\omega_x d}{V} + M_{xp},$$

here *Mxp* – a component of the torque produced by special vernier motors or aerodynamic rudders, which is used to give the projectile a rotational velocity of ω_x.

Find the general system of the equation

$$m\left(\frac{dV_x}{dt} + \omega_y V - \omega_z V_y\right) = -c_\varphi .. - .. + X_p + X_{demr} + X_{vnezap\ turb-ti} + X_{vnesh\ sili}$$
$$= \cdots + M_{demr} + M_{vnezap\ turb-ti} + M_{vnesh\ sili}$$

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$$\left.\begin{aligned}
&m\left(\frac{\mathrm{d}V_y}{\mathrm{d}t}+\omega_z V-\omega_x V_z\right)=-c_\varphi q d^2\frac{V_y}{V}-\\
&-c_\omega q d^3\frac{\omega_z}{V}-c_M q d^3\frac{\omega_x}{V}\frac{V_z}{V}++c_{y1}qd^2+Y_p;\\
&m\left(\frac{\mathrm{d}V_z}{\mathrm{d}t}+\omega_x V_y-\omega_y V\right)=-c_\varphi q d^2\frac{V_z}{V}+c_\omega q d^3\frac{\omega_y}{V}+\\
&+c_M q d^3\frac{\omega_x}{V}\frac{V_y}{V}++c_{z1}qd^2+Z_p;\\
&J_y\frac{\mathrm{d}\omega_x}{\mathrm{d}t}+(J_x-J)\omega_x\omega_y=m_\varphi q d^3\frac{V_z}{V}+m_\omega q d^4\frac{\omega_y}{V}+\\
&+m_M q d^4\frac{\omega_x}{V}\frac{V_y}{V}++m_{y1}qd^3+M_{y\,p};\\
&J_z\frac{\mathrm{d}\omega_z}{\mathrm{d}t}+(J-J_x)\omega_x\omega_y=-m_\varphi q d^3\frac{V_y}{V}+m_\varphi q d^4\frac{\omega_z}{V}+\\
&+m_M q d^4\frac{\omega_x}{V}\frac{V_z}{V}++m_{z1}qd^3+M_{z\,p}.
\end{aligned}\right\}$$

Multiply the first and third equations of the system by *j* and add them to the second and fourth equations, respectively. By introducing the notation

$$V_1=V_z+jV_y,\quad \omega_1=\omega_z+j\omega_y$$

We'll get

$$\left.\begin{aligned}
&(p+A)V_1-B\omega_1=c_1V^2+N_p;\\
&CV_1+(p+D)\omega_1=m_1V^2+M_p,
\end{aligned}\right\}\quad(1)$$

here $A=j\omega_x\left(1-\frac{c_M}{\overline{m}}\right)+\frac{c_\varphi}{md}V;\quad B=jV\left(1+\frac{c_M}{\overline{m}}\right);\quad c_1=\frac{c_{z1}+jc_{y1}}{md};$

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$$N_p = \frac{Z_p + jY_p}{m}; \quad C = \frac{m_\varphi}{\bar{J}d} V - \frac{m_M}{\bar{J}} \omega_x; \quad D = j\omega_x \left(1 - \frac{\bar{J}_x}{\bar{J}}\right) - \frac{m_\omega}{\bar{J}} V;$$

$$m_1 = \frac{m_{z1} + jm_{y1}}{Jd}; \quad M_p = \frac{M_{zp} + jM_{yp}}{J};$$

$$\bar{m} = \frac{2m}{\rho d^3}; \quad \bar{J} = \frac{2J}{\rho d^4}.$$

Expressions (1) are linear differential equations of the second order. The complex variables W and ω introduced here allowed us to lower the order of the differential equations from the fourth to the second order, which simplifies the study of dynamics

Let us investigate the stability of motion of rotating projectiles. For this purpose, consider the characteristic equation of the system (1):

$$\Delta(p) = p^2 + (A + D)p + AD + BC = 0.$$

The coefficients of this equation are complex. The roots of the equation will be

$$p_1 = -\delta_1 - j\omega_1 + \delta_2 + j\omega_2; \quad p_2 = -\delta_1 - j\omega_1 - \delta_2 - j\omega_2 \quad (2)$$

$$\delta_1 = \frac{V}{2}\left(\frac{c_\varphi}{md} - \frac{m_\omega}{j}\right); \quad \omega_1 = \frac{\omega_x}{2}\left(2 - \frac{c_M}{\bar{m}} - \frac{\bar{J}_x}{\bar{J}}\right);$$

here

$$\delta_2 = \frac{1}{\sqrt{2}}\sqrt{\sqrt{A^2 + B^2} + A_2}; \quad \omega = \frac{1}{\sqrt{2}}\sqrt{\sqrt{A_1^2 + B_1^2} - B_1};$$

$$A_1 = V^2\left(\frac{c_\varphi}{md} + \frac{m_\omega}{\bar{J}}\right)^2 - \omega_x^2\left(\frac{\bar{J}_x}{\bar{J}} - \frac{c_M}{\bar{m}}\right)^2;$$

$$B_1 = 2V\left(\omega_x\left(\left(\frac{\bar{J}_x}{\bar{J}} - \frac{c_M}{\bar{m}}\right)\left(\frac{c_\varphi}{md} + \frac{m_\omega}{\bar{J}}\right) + 2\left(1 + \frac{c_\omega}{m}\right)\frac{m_M}{J}\right) - \right.$$
$$\left. - 2V\frac{m_\varphi}{\bar{J}d}\left(1 + \frac{c_\omega}{\bar{m}}\right)\right).$$

For the stability of the system it is necessary that the real parts of the roots of (2) are negative. This requirement is reduced to the fulfillment of two inequalities: $-\delta_1 + \delta_2 - \delta_d < 0$; $-\delta_1 - \delta_2 + \delta_d < 0$; δ_d - additional parameters.

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From these inequalities for given projectile parameters we can determine the stability boundaries.

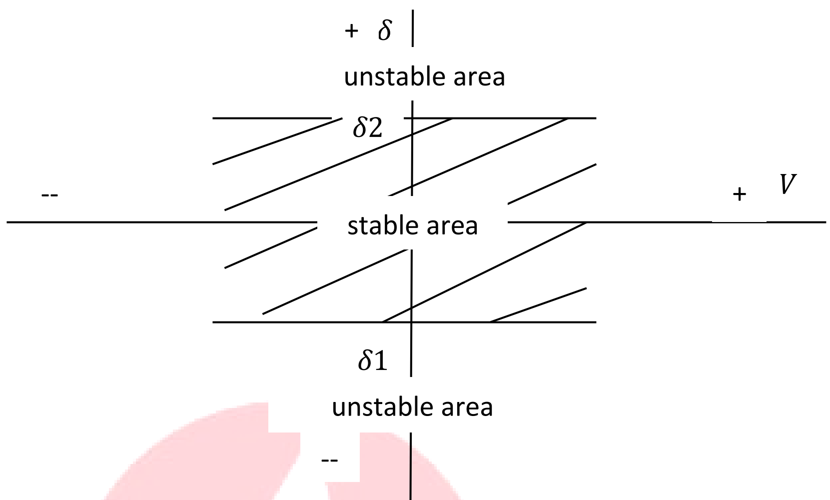

Fig.2 - Analytical records of stable drone operating areas

CONCLUSIONS

Thus, the paper presents an important scientific result - a model of analytical synthesis of vector control strategy of geoscan - unmanned aerial vehicle in an environment with external disturbances using full nonlinear models of motion. The specified control strategy provides asymptotic stability of the closed-loop system, and clear fulfillment of the given invariants. The presented synergetic control law takes into account random external perturbations (piecewise constant perturbations as the worst kind of perturbations), by using the method of synergetic synthesis of adaptive control systems, in particular integral adaptation takes into account sudden turbulent air media, mountain gravity forces, excessive vibration of own engine and power transmissions.

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