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Unmanned cruciform winged glider dynamics and control

The paper focuses on the problems of unmanned cruciform winged glider dynamics and control in autonomous flight conditions, and studies the wing aspect ratio effect on its flight performance. The winged glider control structure in the longitudinal and lateral axes is proposed. We carried out a comparative analysis of the ballistic flight ranges of models of different configurations, as well as the flight ranges of models of different configurations in the operating conditions of the control system of the proposed structure. As a result, the structure of the unmanned winged glider targeting system is proposed. The targeting system in the longitudinal axis, unlike the samples used in currently operating models, consists of two subsystems responsible for the unmanned winged glider best range gliding at the first flight phase and the direct aimpoint guidance at the second, i.e. final flight stage.

Keywords: stabilization, unmanned winged glider, control, ballistics, wing aspect ratio, targeting.

Introduction

Nowadays, gliding unmanned aerial vehicles (GUAV) launched from airborne carriers (typically carrier aircraft) are widely used. Such aircraft can be used for civil or military purposes. There are multiple GUAV aerodynamic design configurations, but such aerodynamic design versions have not featured developed high-aspect-ratio wings so far. It should be noted that the GUAV of the type under study is not equipped with an on-board propulsion power plant, which significantly complicates the problems related to control of such aircraft.

The application of the high-aspect ratio wing solution in unmanned aerial vehicle (UAV) design regarding the aircraft type under study is based on more stringent requirements to the flight range. In fact, in most cases the GUAV autonomous flight range is of great importance, thus increasing the probability of the carrier integrity [1, 2]. For instance, the selected Point of Interest (POI) may be protected by the enemy air defence systems, or a hotspot of wildfire is located closer to the centre of fire outbreak. To reach such a point, the pilot has to deal with additional psychophysical stresses [3].

As previously stated, there are multiple GUAV aerodynamic design configurations of the type under study. Generally, such configurations feature the cruciform wing solution [3].

Aerodynamic design concept

In this study, we discuss several hypothetical GUAV aerodynamic configurations. The first aerodynamic configuration (hereinafter – option 1) is the GUAV based on the standard cruciform wing aerodynamic configuration with all-moving tail controls. For now, this configuration is the standard concept employed in the GUAV design in Russia (Fig. 1).

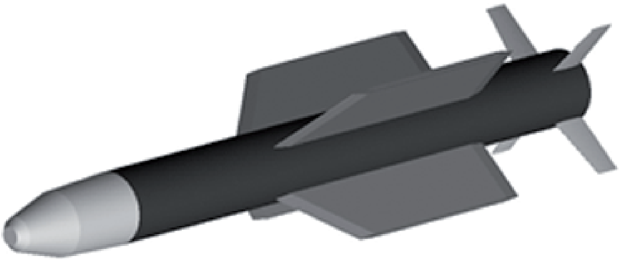

Fig. 1. GUAV with cruciform wing

The second variant of the aerodynamic configuration (hereinafter – option 2) is the GUAV based on the aerodynamic layout featuring a cruciform folding wing and a tail unit. By now, this design concept has never been implemented in Russia (Fig. 2). The paper describes three modifications of this option with various wing aspect ratios such as low, moderate, and high (here-

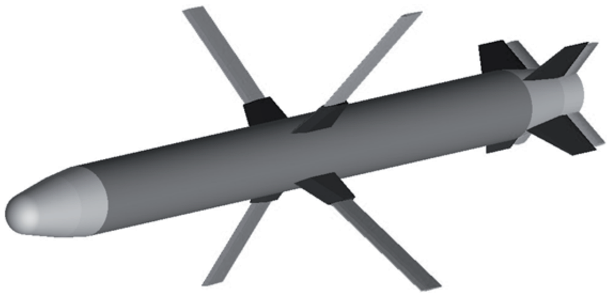

Fig. 2. GUAV with folding cruciform wing

inafter – options 2a, 2b, and 2c, respectively). We studied only the configuration with an unfolded wing; therefore, the problem related to the departure of the UAV from a carrier aircraft and its flight in the interference environment was not investigated.

Study of GUAV ballistic characteristics

For the GUAV aerodynamic configurations under study, we developed a flight simulation model in order to simulate the GUAV launch with fixed zero deviations of control surfaces. We used the standard spatial motion simulation model described in [2, 4]. We simulated several variants of the GUAV design configurations for two initial altitude-velocity modes – at low and high altitudes.

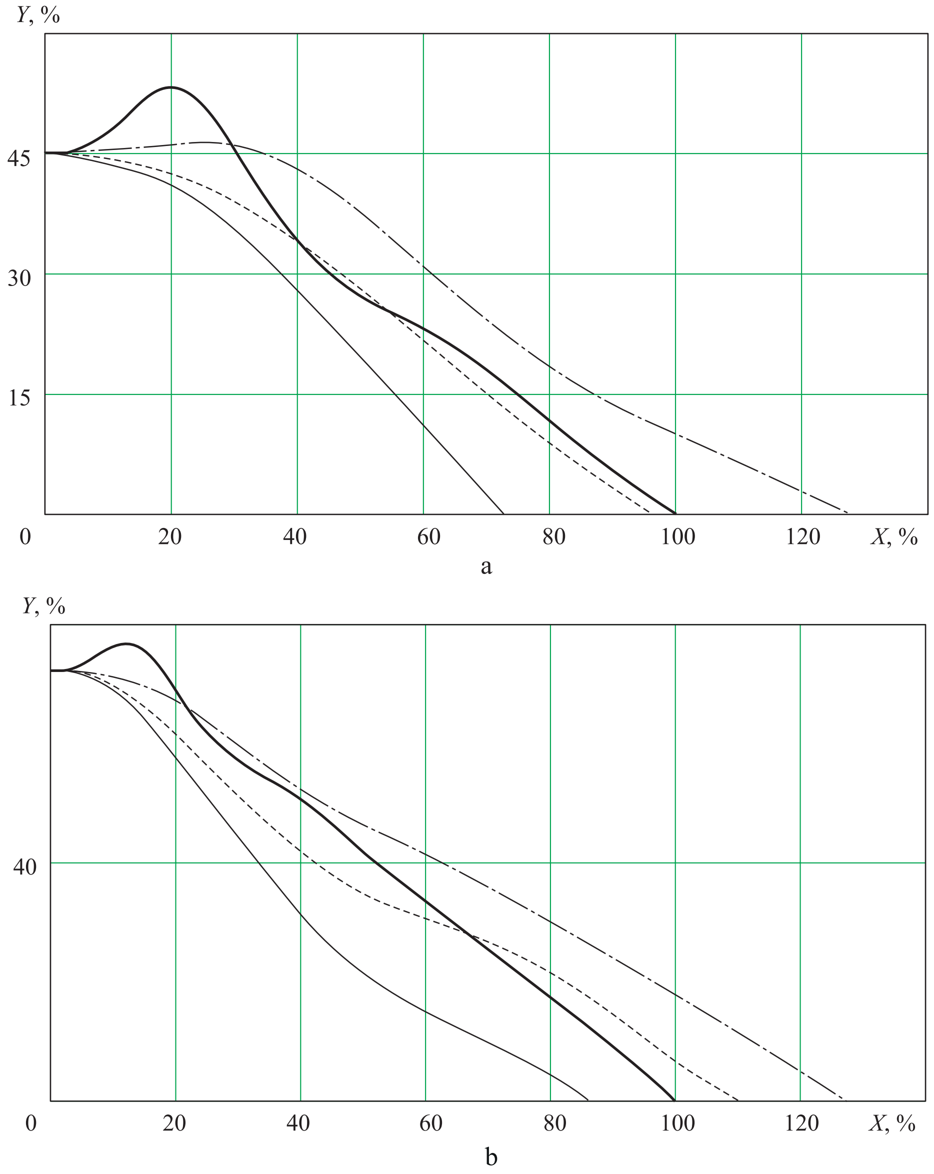

Fig. 3. Comparison of various GUAV design versions by ballistic flight range:
a – low-altitude launch, b – high-altitude launch; ━━ – option 1; ---- – option 2a; –·– – option 2b; —— – option 2c

Fig. 3 shows the results of ballistic flight simulation for various GUAV design version in the vertical plane. Maximum relative ranges of the ballistic flight for the analysed variants of the GUAV (the flight range of the first variant of the GUAV is assumed to be equal to 100 %) are as follows:

- low-altitude launch: option 1 – 100 %, option 2a – 97 %, option 2b – 128 %, option 2c – 73 %;
- high-altitude launch: option 1 – 100 %, option 2a – 111 %, option 2b – 128 %, option 2c – 86 %.

Simulation results prove that during the ballistic flight (there are no pitch, roll or yaw deviations of control surfaces, $\delta_\text{в} = \delta_\text{н} = \delta_\text{кр} = 0°$) at low and high altitudes the maximum flight range is reached for the GUAV with the moderate relative wing aspect ratio (option 2b) while the flight range excess is 28 % in comparison with option 1 of the GUAV configuration.

The GUAV control system may be divided into two subsystems: stabilization and guidance.

GUAV acceleration and attitude stabilization system

The stabilization system implemented by means of PID controllers is developed as a uniform system suitable for any flight configuration (folded and unfolded wing).

Longitudinal axis:

$$\Delta\delta_\text{в} = K_\theta \Delta\theta + K_{p\theta}\Delta\omega_z + K_{\int\theta}\int \Delta\theta dt;$$

$$\Delta\theta = \theta_\text{упр} - \theta_\text{тек}.$$

Lateral axis:

$$\Delta\delta_\text{н} = K_{n_z}\Delta n_z + K_{n_z p}\int \Delta n_z dt + K_{\omega_y}\Delta\omega_y;$$

$$\Delta\delta_\text{кр} = K_\gamma \Delta\gamma + K_{\int\gamma}\int \Delta\gamma dt + K_{p\gamma}\Delta\omega_x;$$

$$\Delta\gamma = \gamma_\text{упр} - \gamma_\text{тек};\ \gamma_\text{упр} = 0.$$

Here, $\Delta\delta_\text{в}$, $\Delta\delta_\text{н}$, $\Delta\delta_\text{кр}$ – pitch, yaw, and roll deviations of control surfaces, respectively, deg;

K_θ, $K_{p\theta}$, $K_{\int\theta}$, K_{n_z}, $K_{n_z p}$, K_{ω_y}, K_γ, $K_{\int\gamma}$, $K_{p\gamma}$ – gain factors;

$\Delta\theta$, $\Delta\gamma$ – pitch and roll angle interments, deg;

$\Delta\omega_z$, $\Delta\omega_y$, $\Delta\omega_x$ – angular velocity increments in pitch, yaw, and roll channels, respectively, deg/s;

$\Delta\theta_\text{упр}$, $\gamma_\text{упр}$ – preset values of pitch and roll angles (calculated within the control system), deg;

$\Delta\theta_\text{тек}$, $\gamma_\text{тек}$ – current values of pitch and roll angles, deg;

Δn_z – lateral acceleration increment.

For the problem under study, it is assumed that control is enabled through the control surfaces of the tail unit.

The GUAV has an adaptive stabilization system developed with account for the principle of gain factor adaptation to current GUAV altitude-velocity flight parameters. Gain factors are selected for various altitude-velocity flight modes according to the procedure described in [1, 2]. Current values of gain factors are calculated using the linear interpolation methods.

Guidance system

The purpose of the guidance system is to generate control signals to be transmitted to the stabilization system in order to fulfil a particular task. To improve the effectiveness of the GUAV, its autonomous flight range shall be maximized. Moreover, an aircraft shall deliver the payload to the destination point. To solve both problems, it is proposed to divide the GUAV guidance system into two subsystems: one of them is responsible for the autonomous gliding flight to cover a maximum possible distance and another – for delivery of the GUAV to the destination point.

Fig. 4 shows the operational guidance system diagram depending on the GUAV flight profile.

The proposed flight control diagram is a fundamentally new solution for the GUAV of the type under study. We should emphasize that, for example, unlike missiles the GUAV is not equipped with its own power plant. This leads to substantial difficulties in the control configuration, especially when forming a control system for maximum range gliding.

Maximum range gliding. Intuitively, it is evident that the maximum flight range can be

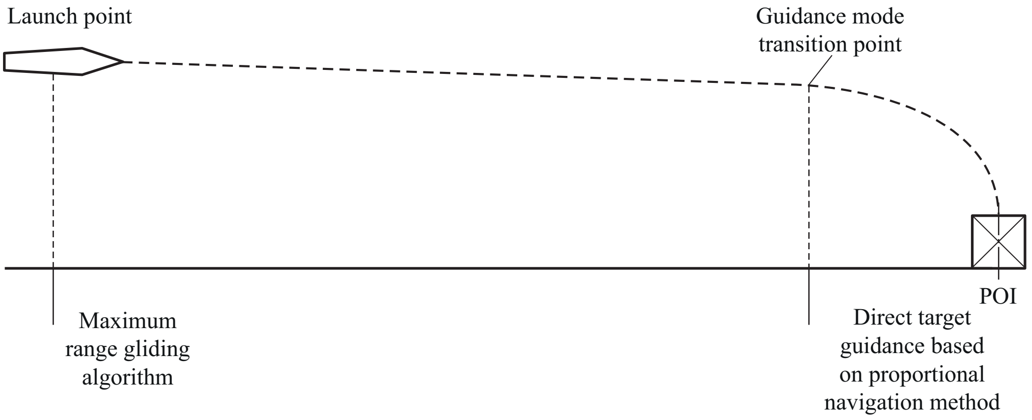

Fig. 4. Operation of GUAV guidance system

reached by a GUAV with the maximum lift-drag ratio.

The dependence of the pitch angle on the lift-drag ratio $K_{\max}$ is calculated using the equations of motion for the descending aircraft, according to [4]. Let us introduce gain factor K_{tet} to generate the control signal. In this case, its value will be calculated as follows:

$$\theta_{\text{упр}} = -K_{tet}\,\text{arctg}\frac{1}{K_{\max}}.$$

Value $K_{\max}$ is known for various altitude-velocity flight modes according to results of wind-tunnel tests or an aerodynamic performance analysis. For the current flight mode, this value is determined by interpolation.

Aiming point guidance. Let us calculate target range $D_{\text{м}}$, absolute value of horizontal target range $D_{\text{гор м}}$, ground speed $V_{\text{м}}$, and speed of horizontal approach to target $V_{\text{гор м}}$ by means of the following parameters: GUAV coordinates – $X_{g\text{м}}, Y_{g\text{м}}, Z_{g\text{м}}$, target coordinates – $X^{\text{ц}}_{gi}$, $Y^{\text{ц}}_{gi}, Z^{\text{ц}}_{gi}$, GUAV speed components – $V_{x\text{м}}, V_{y\text{м}}, V_{z\text{м}}$:

$$D_{\text{м}} = \sqrt{\left(X_{g\text{м}} - X^{\text{ц}}_{g\text{м}}\right)^2 + \left(Y_{g\text{м}} - Y^{\text{ц}}_{g\text{м}}\right)^2 + \left(Z_{g\text{м}} - Z^{\text{ц}}_{g\text{м}}\right)^2};$$

$$V_{\text{м}} = \sqrt{\left(V_{x\text{м}}\right)^2 + \left(V_{y\text{м}}\right)^2 + \left(V_{z\text{м}}\right)^2};$$

$$D_{\text{гор м}} = \sqrt{\left(X_{g\text{м}} - X^{\text{ц}}_{g\text{м}}\right)^2 + \left(Z_{g\text{м}} - Z^{\text{ц}}_{g\text{м}}\right)^2};$$

$$V_{\text{гор м}} = \sqrt{\left(V_{x\text{м}}\right)^2 + \left(V_{z\text{м}}\right)^2}.$$

We will apply the proportional approach method for GUAV homing guidance [1–3, 5].

Guidance by flight path angle

As previously stated, to plan the flight within the maximum range, in this work we used the method based on flight path angle stabilization. The target's line of sight angle $\varphi_{\text{лв}}$ can be calculated at any time during the GUAV flight:

$$\varphi_{\text{лв}} = \arccos\frac{D_{\text{гор}}}{D},$$

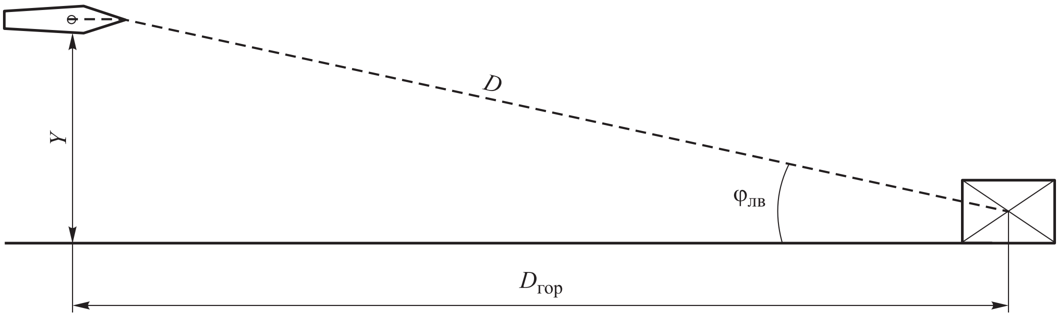

Fig. 5. Relative position of GUAV and target

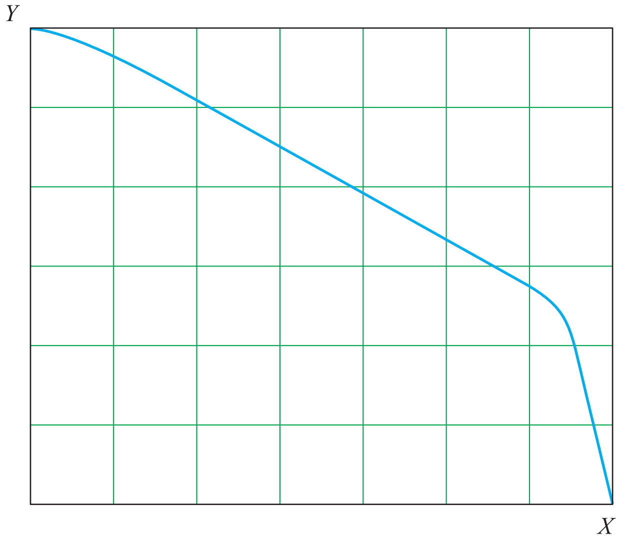

Fig. 6. GUAV flight path in vertical plane (option 2a)

where $D_{гор}$ – horizontal range to target;

D – line-of-sight range to target (Fig. 5).

To improve the effectiveness of the GUAV, sometimes it is necessary to maximize the angle of approach to the flight path final point. In order to implement guidance functions and to maximize the final angle of approach in the longitudinal axis, it is proposed to use the GUAV attitude stabilization system described above.

At a certain time, the relative position of the GUAV and the target will be at the target’s line of sight angle corresponding to $\varphi_{гр}$ – the threshold selected depending on an actual mission to be accomplished by the GUAV. Therefore, after this time point is passed, the control signal by the flight path angle is expressed as follows

$$\theta_{упр} = -\varphi_{лв}.$$

The use of the algorithm allows to guide the GUAV to the final point of the flight path with a sufficient accuracy and to let the aircraft approach to the point at the desired flight path angle.

Simulation results

With the help of the simulation model described above we have managed to simulate the flight of the GUAV of the certain design configurations and to conduct a comparative analysis of aircraft performance. For clarity, simulation was conducted in similar initial conditions.

Typical results of simulation and the aircraft flight path curve are shown in Fig. 6 and 7.

The simulation results for GUAV of all design configurations under study are similar to the represented result.

Conclusion

The paper describes the study of the effect produced by various factors on the dynamics and control of the unmanned cruciform winged glider. For this purpose, the following steps were taken:

- the GUAV spatial motion simulation model was built;
- the concept of the GUAV acceleration and attitude stabilization system was designed;

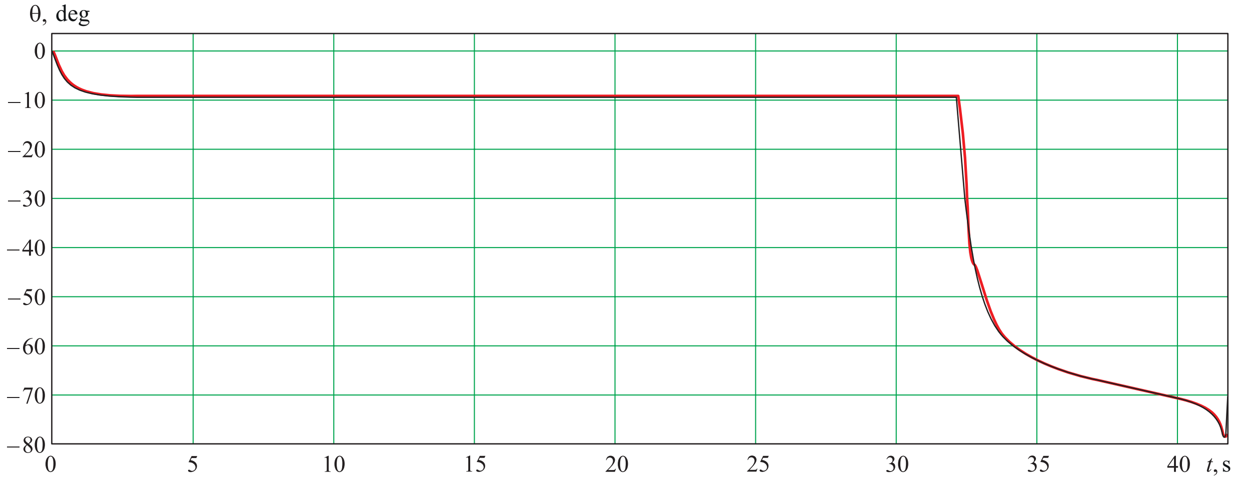

Fig. 7. Results of operation of the flight path angle stabilization system (option 2a):
— – current pitch angle θ; — – pitch angle defined by control system $\theta_{упр}$

- the concept of the target guidance system was designed.

Unlike other applicable guidance systems, the represented system comprises two subsystems responsible for GUAV gliding within the maximum range at the first flight phase and direct target guidance at the second or final flight phase. Application of such a control system is a new design solution for the GUAV, which allows to drastically increase the flight performance of such aircraft.

Bibliography

1. *Grumondz V. T., Polishchuk M. A., Chertoryzhskaya S. S.* Synthesizing the control system of a small gliding unmanned aerial vehicle with high-aspect ratio wing // Izvestiya vuzov. Aviatsionnaya tekhnika. 2012. T. 55. No. 3. S. 251–258. (Russian)

2. *Grumondz V. T., Polishchuk M. A., Chertoryzhskaya S. S.* The choice of the pilotless plane vehicle dynamic image // MAI Journal. 2012. V. 19. No. 4. P. 5–12. (Russian)

3. *Solovei E. Ya., Khrapov A. V.* Dinamika sistem navedeniya upravlyaemykh aviabomb. M.: Mashinostroenie, 2006. 328 s. (Russian)

4. Dinamika poleta // *Efremov A. V, Zakharchenko V. F, Ovcharenko V. N.* i dr. M.: Mashinostroenie, 2011, 776 s. (Russian)

5. *Grumondz V. T., Polishchuk M. A.* The problem of guidance of a gliding unmanned aerial vehicle onto a moving target // MAI Journal. 2014. V. 21. No. 4. P. 7–12. (Russian)

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Динамика и управление беспилотного планирующего крылатого летательного аппарата крестообразной схемы

Рассмотрены вопросы динамики и управления беспилотного планирующего крылатого летательного аппарата крестообразной схемы в условиях автономного полета, исследовано влияние относительного удлинения крыла на его летно-технические характеристики. Предложена структура системы управления беспилотным планирующим крылатым летательным аппаратом в продольном и боковом каналах. Проведен сравнительный анализ баллистических дальностей полета изделий разных конфигураций, а также дальностей полета изделий разных конфигураций в условиях работы системы управления рассмотренной структуры. Предложена структура системы наведения беспилотного планирующего крылатого летательного аппарата на цель. Система наведения в продольном канале, в отличие от используемых в действующих в настоящее время образцах, состоит из двух подсистем, отвечающих за планирование беспилотного планирующего крылатого летательного аппарата на максимальную дальность на первом этапе полета и наведение непосредственно на точку цели на втором, заключительном этапе полета.

Ключевые слова: стабилизация, беспилотный летательный аппарат, управление, баллистика, удлинение крыла, наведение.

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