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TWO-CIRCUIT SYSTEM OF AUTOMATED CONTROL OF LOW-ALTITUDE HELICOPTER FLIGHT

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Abstract*—The mode of automatic control of a low-altitude flight of a helicopter over heavily rugged terrain based on information about the inclined range is considered. It is shown that at high flight speeds it is impossible to overcome strictly vertical obstacles without changing the angle of inclination of the rangefinder antenna to the horizon depending on the flight speed, or without reducing the flight speed when approaching such an obstacle. Algorithms for controlling low-altitude flight using a two-channel scheme are proposed, namely, at high speeds through the longitudinal channel of the swashplate, and at low speeds – through the channel of the general pitch of the main rotor. The problem of optimal control of low-altitude helicopter flight is formulated, which can be presented as a variational problem with restrictions on phase coordinates and control influences. Ways to optimize the process of circumventing an obstacle with forecasting the trajectory of the helicopter on a certain section of the route with subsequent stabilization of the helicopter on this trajectory are shown.*

Index Terms—Total pitch of main rotor; swashplate; longitudinal channel; control law; low-altitude flight; rugged terrain; true height; inclined range.

I. INTRODUCTION

The methodology for designing special modes of operation of a helicopter automatic control systems (ACS), which includes the low-altitude flight mode (LAF), involves the selection of a mode implementation method and the development of control algorithms for this mode. The analysis of existing design solutions shows that the most common way of LAF in ACS of helicopters is the implementation of control through the channel of the general pitch of the main rotor based on information about the true flight height. For example [2], at the present time, the following control law is used in the helicopter-type self-propelled gun in the LAF mode:

$$\delta_{\text{mr}} = K_H \Delta H_{\text{f}} + K_{Vy} V_y, \tag{1}$$

where $\Delta H_{\text{f}} = \dfrac{\Delta H_{\text{RA}} + K^*_{Vy} V_y}{T_{\text{f}} p + 1}$, $\Delta H_{\text{RA}} = H_{\text{RA}} - H_{\text{RA}_\text{G}}$.

Here δ_{mr} deviation of the general pitch of the main rotor; H_{RA} is the true height measured by radio altimeter; H_{RA_set} is the given true altitude, the value of which is set by the pilot on the radio altitude indicator.

Since the radio altimeter signal contains high-frequency interference, as well as information about small folds of the relief, it is passed through a high-frequency filter $(T_{\text{f}} p + 1)^{-1}$, but any filter introduces a delay. To restore information about the true flight altitude, a component $K^*_{Vy} V_y$ is used. When $K^*_{Vy} = T_{\text{f}}$, information about the true flight altitude is completely restored.

The considered LAF algorithm, like other algorithms for automatic flight altitude control of existing ACS of helicopters, is based on the main rotor pitch channel, but, as evidenced by the practice of piloting helicopters, at high flight speeds, the height change must be made through the longitudinal channel of the swashplate, that is, like an aircraft. These is due, firstly, to the greater efficiency of such a maneuver at high speeds, and, secondly, to the emergence of critical modes of flow around the retreating rotor blades at high speeds when trying to increase the vertical speed due to an increase in the total pitch of the rotor blades.

Therefore, the development of flight control algorithms at low altitudes using a dual-circuit scheme (at high speeds – through the longitudinal channel of the swashplate, and at low speeds – through the channel of the general pitch of the main rotor) is very relevant

II. PROBLEM STATEMENT

At present, the most widespread LAF's control systems with obstacle flyby in the vertical plane, which implement stabilization modes of true (geometric) flight height.

Low-altitude flight over difficult, rugged terrain is only possible based on information about the terrain ahead. This information can be obtained with the help of a radar range finder, the visual beam of which is inclined to the earth's surface. With the help of such a rangefinder, a low-altitude flight with stabilization of an inclined range or an advanced height is realized.

The structure of the longitudinal movement control loop during inclined range stabilization does not differ from the control loop of the true flight height, therefore, the algorithm (1) developed for the stabilization of the true height can be taken as the basis of the LAF algorithm.

$$\delta_{\text{mr}} = K_D \Delta D + K_{Vy} V_y , \qquad (2)$$

where $\Delta D = (D - D_{\text{set}})/(T_{\text{f}} p + 1)$.

Here, D, D_{set} is the current and the set slant range, respectively.

In the algorithm, it is advisable to provide for a change in the nature of the helicopter's flyby of the front or back slope of the terrain, since the back slope must be flown carefully so that the helicopter is able to immediately go from the descent stage to the stage of gaining altitude. This can be done by changing the time constant of the filter, which increases by 2–3 times when flown around the rear slope of the terrain. Information about exiting the front or back slope of the terrain can be obtained using information about vertical speed.

After the helicopter realization the top of the obstacle (this moment is recorded as the loss of information from the range finder, namely by the instantaneous change of the inclined range), the barometric altitude stabilization mode is activated according to the control law:

$$\delta_{\text{mr}} = \Delta H_{\text{b}} + K_{Vy} V_y ,$$

where $\Delta H_{\text{b}} = H_{\text{b}} - H_{\text{enab}}$; H_{b} is the current barometric flight altitude; H_{enab} is the barometric height of enabling on the barometric height stabilization mode.

Switching back to the slant range stabilization mode requires the fulfillment of several conditions. First, the helicopter in the barometric altitude stabilization mode must fly the distance to the top. When the helicopter leaves above the top, the range to the top is fixed and the time of horizontal flight to it is calculated

$$t = \frac{D \cos \varphi}{V},$$

where φ is angle of inclination of the rangefinder antenna to the horizon; V is the helicopter flight speed.

In the mode of horizontal flight to the top, the sloped range to the relief is simultaneously measured, in the case of $D < D_{\text{set}}$ control from the barometric altitude stabilization mode switches back to the slant range stabilization mode. After flying over the top, when $D > D_{\text{set}}$, the helicopter begins to descend according to information about ΔD, with simultaneous control of the true flight height according to the information of the H_{RA} radio altimeter. Control of the true height is necessary in the case of the presence of small obstacles that did not hit the field of view of the rangefinder at the stage of passing over the top of the obstacle. When $H_{\text{RA}} < H^*_{\text{RA}}$ (H^*_{RA} is the some specified safe descent height of the helicopter), stabilization of the barometric flight height is turned on again.

The algorithm was researched in the middle of the visual modeling program Simulink. The oscillograms that illustrate the operation of the proposed algorithm are shown in Figs 1 and 2.

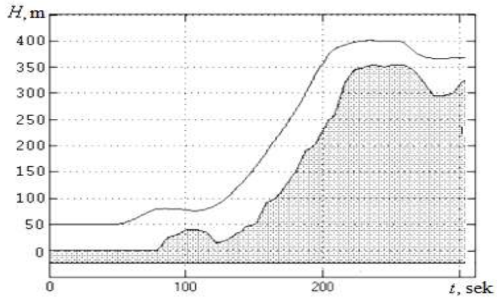

Fig. 1. Fly around the front slope of the obstacle at speed V = 50 km/h

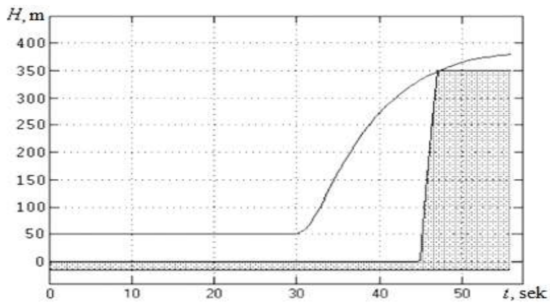

Fig. 2. An attempt to fly around a strictly vertical obstacle at a speed of V = 260 km/h

The oscillogram (Fig. 1) clearly shows areas of stabilization of barometric height and areas of working out the inclined range. The efficiency of the algorithm was also checked with changes of the flight speed and with different characteristics of the slopes of the obstacle (see Fig. 2). These studies show the impossibility of a helicopter overcoming high, strictly vertical obstacles at significant speeds without changing the angle of inclination of the rangefinder antenna to the horizon depending on the flight speed, or without reducing the flight speed when approaching such an obstacle.

All of the above algorithms were based on the channel of the general pitch of the main rotor, but, as the practice of piloting helicopters shows, at high flight speeds, the height change should be carried out through the longitudinal channel of the swashplate, that is, like an aircraft. This is connected, firstly, with the greater efficiency of such a maneuver at high speeds, and, secondly, with the appearance of critical modes of flow around the retreating blades of the main rotor at high speeds when trying to increase the vertical speed by increasing the total pitch of the main rotor.

Therefore, the problem statement is formulated as the development of algorithms for controlling LAF behind a dual-channel circuit – through the longitudinal channel of the swashplate and through the channel of total pitch of the main rotor.

III. Problem Solution

Changing the flight height through the longitudinal channel of the swashplate in the automatic control mode can occur in the flight speed control mode by reducing the set speed *V*set to 100 km/h while simultaneously limiting the pitch angle to the maximum operational values. In this case, the helicopter will be transferred to a climb with a simultaneous decrease in speed. When approaching the speed *V*set, the stabilization of pitch angle must be turned on, and the further control of the vertical speed should be switched to the channel of the general pitch of the main rotor. Algorithm of two-loop control of LAF is shown in Fig. 3.

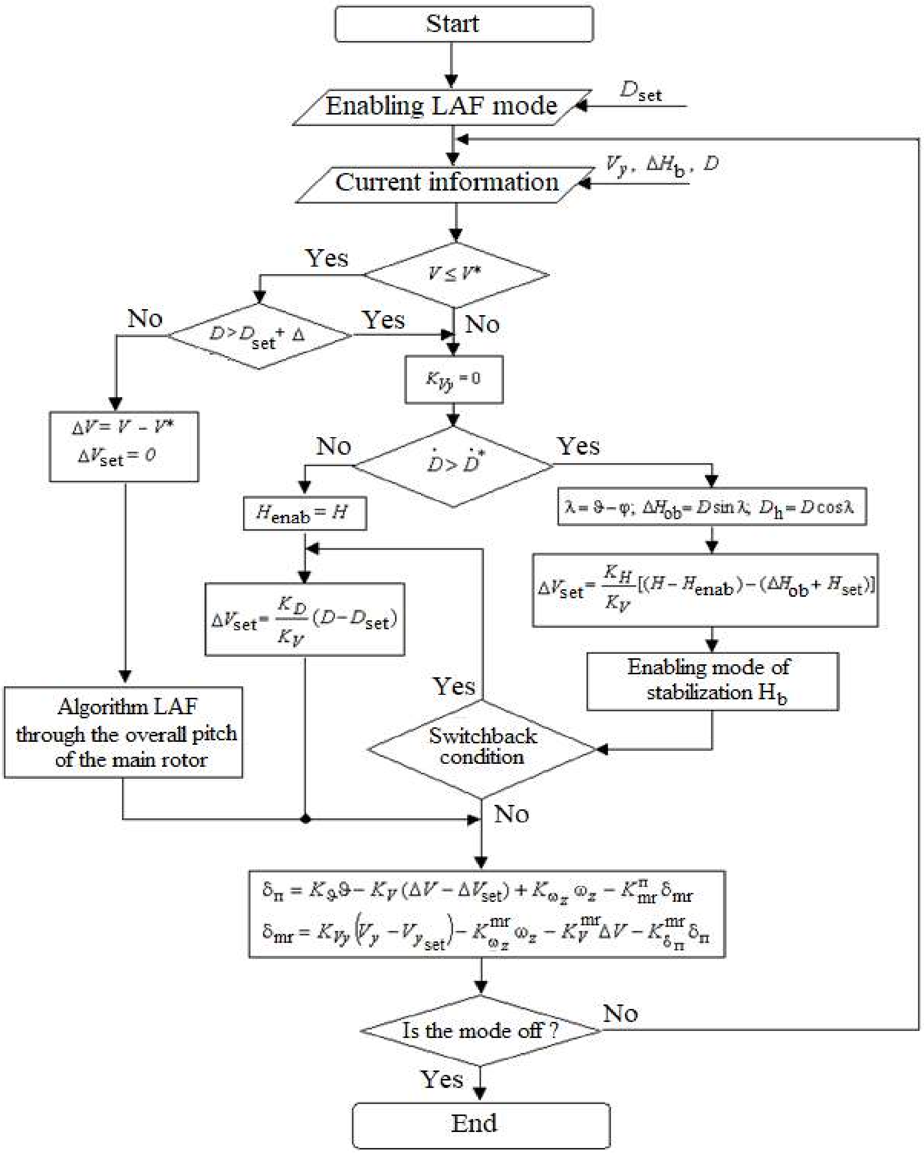

Fig. 3. Algorithm of two-loop control of LAF

In the channel of the general pitch of the main rotor δ_{mr} and in the longitudinal channel of the swashplate δ_{lc}, taking into account the algorithms of cross-connections between the control channels [1], [3], the control laws are implemented

$$\delta_{\text{lc}} = K_{\vartheta}(\vartheta - \vartheta_{\text{set}}) + K_{\omega_z}\omega_z - K_{\text{mr}}^{\text{lc}}\delta_{\text{mr}},$$

$$\delta_{\text{mr}} = K_{Vy}\left(V_y - V_{y\text{set}}\right) - K_{\omega_z}^{\text{mr}}\omega_z - K_V^{\text{mr}}\Delta V - K_{\delta_{\text{lc}}}^{\text{mr}}\delta_{\text{lc}},$$

where $\vartheta_{\text{set}} = \begin{cases} K_V \cdot K_{\vartheta}^{-1}(V - V_{\text{set}}) & \text{at} \quad V < V_{\text{set}} + \sigma, \\ \vartheta^* & \text{at} \quad V = V_{\text{set}} + \sigma, \end{cases}$

$$K_{V_y} = \begin{cases} 0 & \text{at} \quad V < V_{\text{set}} + \sigma, \\ K_{V_y} & \text{at} \quad V = V_{\text{set}} + \sigma, \end{cases}$$

where σ is the tolerance zone, at which the flight speed reduction mode is turned off; ϑ^* is the pitch angle at which the speed reduction is stopped; $V_{y\text{set}}$ is the vertical rate of climb, which was at the time of switching the control channels.

If the LAF mode is turned on at a speed of more than 150 km/h, then the control begins to be implemented through the channel of the swashplate, therefore, when the rangefinder beam meets an obstacle, the helicopter goes into pitch-up, stabilizing the inclined range $D = D_{\text{set}}$, with a simultaneous decrease in flight speed. In this case, the control law in the longitudinal channel of the swashplate has the form:

$$\delta_{\text{lc}} = K_{\vartheta}\vartheta - K_V(\Delta V - \Delta V_{\text{set}}) + K_{\omega_z}\omega_z - K_{\text{mr}}^{\text{lc}}\delta_{\text{mr}},$$

where $\Delta V = V - V_{\text{enab}}$, $\Delta V_{\text{set}} = K_D \cdot K_V^{-1}(D - D_{\text{set}})$,

V_{enab} is the switching speed in LAF mode.

The channel of the general pitch of the main rotor works in the mode of isolation the control loops. The control law in this channel looks like this:

$$\delta_{\text{mr}} = K_{Vy}\left(V_y - V_{y\text{set}}\right) - K_{\omega_z}^{\text{mr}}\omega_z - K_V^{\text{mr}}\Delta V - K_{\delta_{\text{lc}}}^{\text{mr}}\delta_{\text{lcп}},$$

where $K_{Vy} = 0$.

At the moment of finding the top of the obstacle (this moment is defined as a sudden change in the inclined range $\dot{D} > \dot{D}^*$), the barometric height of the flight H_{enab} is fixed and the height of the obstacle ΔH_{ob} and the distance to the top D_{h} (Fig. 4) are calculated by the formula:

$$\Delta H_{\text{obs}} = D\sin\lambda, \quad D_{\text{h}} = D\cos\lambda,$$

where $\lambda = \vartheta - \varphi$; ϑ is the pitch angle; φ is the installation angle of the rangefinder antenna relative to the longitudinal axis of the helicopter.

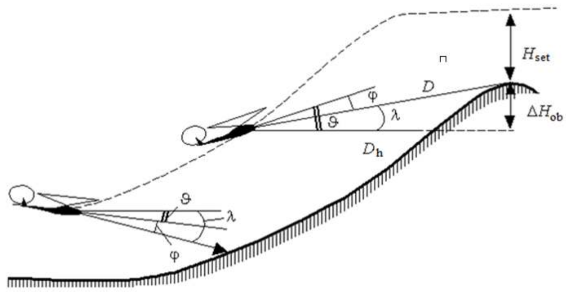

Fig. 4. How a helicopter flies around the top of an obstacle

The helicopter continues to gain altitude up to $H = H_{\text{set}} + \Delta H_{\text{ob}}$ (V_{set} is formed in the form of $\Delta V_{\text{set}} = K_H \cdot K_V^{-1}[(H - H_{\text{enab}}) - (\Delta H_{\text{ob}} + H_{\text{set}})]$) and then transfers to horizontal flight. Further work of the algorithm, namely the transition to the mode of stabilization of inclined range, implemented according to an earlier developed scheme.

If, after maneuvering, the speed of the flight decreases to the speed $V \le V^*$ set in the algorithm, for example, up to 50 km/h, the swashplate channel is switched to the mode of stabilization of the speed, and the channel of the main rotor is switched to control of LAF behind algorithm (2). The reversal switch to the swashplate channel occurs when the inclined range increases by a significant amount Δ, namely when $D > D_{\text{set}} + \Delta$.

The developed algorithm was studied in the environment of the Simulink visual modeling program. Oscillograms illustrating the operation of the proposed algorithm when bypassing a vertical obstacle are shown in Figs 5 and 6.

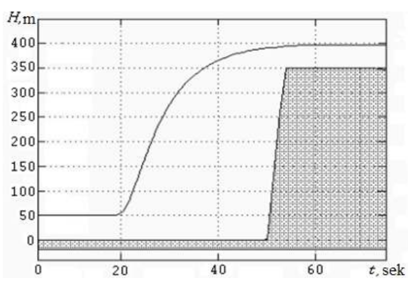

Fig. 5. Obstacle flying using a two-channel control algorithm

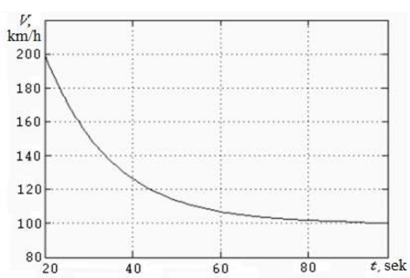

Fig. 6. Change in flight speed when performing a vertical maneuver

Flying around a similar obstacle with an almost vertical front slope was impossible when implementing the LAF algorithm in the mode of stabilizing a given flight speed (see Fig. 2). In this case, overcoming the obstacle is carried out with a decrease in flight speed (see Fig. 6) and the quality of the flight satisfies the main requirements for flying around the top of the obstacle – horizontal flight over the top at a given height.

If there is information about the pre-emptive flight altitude, in order to optimize obstacle avoidance, it is advisable to predict the movement of the helicopter on a certain section of the route with subsequent stabilization of the helicopter on the programmed trajectory.

In a mathematical formulation, the problem of optimal control of a helicopter at low altitude can be presented as a variational problem and formulated as follows.

Let the topography of the area in the form of a function $h(x)$ be known on the section of the route $\{x_0, x_k\}$. The dynamic system – a helicopter is characterized by an n-dimensional vector of phase coordinates $P = \{x, y_1 \ldots y_{n-1}\}$, an r–dimensional vector of controlling influences $U = \{u_1, u_2 \ldots u_r\}$ and a differential equation of motion:

$$\frac{dP}{dt} = f(P, U).$$

The space of vectors of phase coordinates P and control influences U is limited by admissible regions Ω_1 and Ω_2, i.e. $P \in \Omega_1(P)$ and $U \in \Omega_2(U)$. It is necessary to find such a control U that minimizes the selected quality functional Q on the route section $\{x_0, x_k\}$ while fulfilling the existing restrictions on the phase coordinates and control. The formulated problem can be solved as follows.

Trajectory movement of the center of mass of the helicopter in the longitudinal plane, without taking into account high-frequency angular movements, can be described by a system of differential equations:

$$\begin{aligned} \frac{d\theta}{dt} &= \frac{g}{V_{\text{gr}}}\Delta n_y, \\ \frac{dy}{dt} &= V_{\text{gr}} \sin\theta, \\ \frac{dx}{dt} &= V_{\text{gr}} \cos\theta, \end{aligned} \qquad (1)$$

where y is the absolute altitude of the helicopter; V_{gr} is the ground speed; θ is the the angle of inclination of the trajectory; Δn_y is the excessive normal overload.

There are certain limitations when performing a low-altitude flight:

- the true height should not be less than the specified height;
- the angle of inclination of the trajectory does not exceed the specified limits;
- excessive normal overload, which in this case acts as a control signal, is limited to a maximum and minimum value.

Restrictions imposed on the vector of phase coordinates and the control vector can be formulated in the form:

$$\begin{aligned} & y \ge h(x) + H_{\text{set}}; \\ & \theta_{\min} \le \theta \le \theta_{\max}; \\ & \Delta n_{y\min} \le \Delta n_y \le \Delta n_{y\max}, \end{aligned} \qquad (2)$$

where H_{set} is set flight altitude.

The quality function Q on the route section $\{x_0, x_k\}$ should ensure the minimization of the deviation from the given true height, taking into account the existing restrictions. Let's write the quality functional in this form:

$$Q = \int_{x_0}^{x_k} \left[y(x) - h(x) \right] \cdot F(x) \cdot dx,$$

where $F(x)$ is penalty function that reflects condition (2).

$$F(x) = \begin{cases} 1 & \text{when condition (2) is met,} \\ \infty & \text{if condition (2) is not met.} \end{cases}$$

The level system (1) can be presented in algebraic form:

at $\Delta n_y \neq 0$

$$\begin{cases} \theta(t+\Delta t) = \dfrac{g\Delta n_y}{V_{\text{gr}}}\Delta t + \theta(t), \\ y(t+\Delta t) = -\left[\cos\theta(t+\Delta t) - \cos\theta(t)\right]\dfrac{V_{\text{gr}}^2}{g\Delta n_y} + y(t), \\ x(t+\Delta t) = \left[\sin\theta(t+\Delta t) - \sin\theta(t)\right]\dfrac{V_{\text{п}}^2}{g\Delta n_y} + x(t), \end{cases} \qquad (3)$$

at $\Delta n_y = 0$

$$\begin{cases} \theta(t+\Delta t) = \theta(t), \\ y(t+\Delta t) = V_{\text{gr}} \sin\theta(t)\Delta t, \\ x(t+\Delta t) = V_{\text{gr}} \cos\theta(t)\Delta t, \end{cases} \qquad (4)$$

where Δt is time discretization step.

The algorithm for building the program trajectory on the interval $(t + \Delta t)$ assumes:

- knowing the final location of the control object and solving the system of equations (3), (4) in reverse time under various control influences, we will obtain a set of possible trajectories on a given interval;

- comparing the quality functionals corresponding to each trajectory, we choose the best trajectory one based on the minimum of the functional;
- the best trajectory uniquely determines the next starting point for solving systems (3), (4) at the next step of constructing the trajectory.

The process of building the software trajectory will be carried out until the *x*-coordinate of the end of the trajectory becomes less than the *x*-coordinate of the helicopter.

Mathematical modeling of a helicopter overflight of the scoring track showed that the developed algorithm provides good quality overflight of an obstacle with moderate and excessive overloading.

IV. CONCLUSIONS

At high flight speeds, the helicopter cannot overcome strictly vertical obstacles without reducing the flight speed when approaching such an obstacle. The proposed low-altitude flight control algorithms using a two-channel scheme will help to solve this problem, namely, at high speeds through the longitudinal channel of the swashplate, and at low speeds – through the channel of the general pitch of the main rotor.

The construction of the optimal obstacle bypassing trajectory can be formulated a variational problem of predicting the trajectory of the helicopter movement on a certain section of the route with subsequent stabilization of the helicopter on this trajectory under restrictions on phase coordinates and control influences.

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М. К. Філяшкін. Двоконтурна система автоматизованого керування маловисотним польотом гелікоптера

Розглянуто режим автоматичного управління маловисотним польотом гелікоптера над сильно пересеченою місцевістю за інформацією про похилу дальність. Показано, що на великих швидкостях польоту не можна подолати суворо вертикальні перешкоди без зміни залежно від швидкості польоту кута нахилу антени далекоміра до горизонту, або без зменшення при підході до такої перешкоди швидкості польоту. Запропоновані алгоритми управління маловисотним польотом за двоканальною схемою, а саме на великих швидкостях через поздовжній канал автомата перекосу, а на малих швидкостях – через канал загального кроку несного гвинта. Сформульована задача оптимального управління маловисотним польотом гелікоптера, яка може бути подана як варіаційна задача з обмеженням на фазові координати і керуючі впливи. Показані шляхи оптимізації процесу огинання перешкоди з прогнозуванням траєкторії руху гелікоптера на певній ділянці маршруту з подальшою стабілізацією гелікоптера на цієї траєкторії.

Ключові слова: загальний крок несного гвинта; автомат перекосу; поздовжній канал; закон керування; політ на малій висоті; пересічена місцевість; справжня висота; похила дальність.

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