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SHORT RUNWAY LANDING AUTOMATION

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Abstract—*The issues of automation of aircraft landing control on a short runway are considered. A scheme for constructing an approach tract along a steeper glide path and with a touchdown point located at the very beginning of the runway is proposed, which makes it possible to reduce the length of the air section and the required length of the runway. Formulas are proposed for recalculating the glide path holding parameters for the implementation of automatic control of the descent and landing of the aircraft. To reduce the size of the landing zone, it is proposed to construct a landing trajectory according to the method of controlling the final state during landing along a flexible trajectory. The principles of constructing systems for automatic control of aircraft landing based on algorithms with a predictive model with a gradual approach to the forecast horizon are considered.*

Index Terms—Runway length; short runways; landing point; short take-off and landing aircraft; steep glide path; forecasting; predictive model; optimal control.

I. INTRODUCTION

The analysis of airfields existing in Europe shows that today the largest group in terms of numbers is made up of airfields with "short" runways. In the future, the number of aerodromes with "short" runways will increase and the main reasons for this are:

- striving to bring airfields closer to cities,
- the need to develop densely populated regions and areas with complex terrain;
- low, in comparison with "elite" airfields, construction costs.

The increase in the number of aerodromes with "short" runways will be accompanied by the appearance of short take-off and landing (STL) passenger and transport aircraft suitable for operation from short runways.

To date, in the practice of world aircraft construction, various energy systems for increasing the lift of STL aircraft have been tested. For passenger and transport aircraft, it is of interest to use as an energy system the system of the blowing of the wing and multi-link flaps deflected at large angles by jet jets of engines, which makes it possible to increase the lift coefficient by 1.8 ... 2 times.

The family of STL aircraft is constantly growing. For example, these are Breguet-941, C-130 Hercules, C-17 by McDonnell Douglas, A-70, Airbus Military Co-A400M, as well as regional aircraft of the Antonov company. Optimization of the takeoff and landing modes of existing aircraft using the effect of blowing a highly mechanized wing with air jets from jet engines can significantly improve the takeoff and landing characteristics of these aircraft.

The runway length available for use may vary depending on the condition of the runway surface. On a wet runway, the landing distance increases by more than 10%, and if there is a water layer on the runway of more than 2–3 mm, the effect of hydrodynamic planing may occur, and then the landing distance increases by 50–70%.

There are many factors that affect the suitability of a runway for a particular aircraft model, and most of these factors are not addressed in the flight manual. These are the effects of wind, runway slope, air temperature and density, and many other factors. For example, a change in temperature by 10° leads to a change in the path length by an average of 3.5%, and a change in atmospheric pressure by 20 torr changes the length of the run by an average of 3%. An equally important factor is to reduce the size of the landing zone, i.e. improving landing accuracy so that after touchdown, leave as little part of the runway as possible behind the aircraft.

Analysis of materials published in recent years also shows that the interests of design bureaus involved in the development of STL aircraft have shifted from the issues of aerodynamics of aircraft with power systems to the use of modern piloting methods for landing on "short" runways, as well as the creation and construction of optimal multi-loop automatic control systems and information systems that ensure landing accuracy.

II. PROBLEM STATEMENT

The minimum runway length required for landing is the sum of the length of the airborne phase of landing, the length of landing run, and the size of the touchdown zone.

The size of the landing zone is determined by the piloting accuracy (the accuracy of the automatic control system at the landing stage), as well as the accuracy of the information and measurement systems.

The landing run depends primarily on the landing speed, as well as on the braking means used and the condition of the runway.

Increasing the angle of inclination of the glide path when landing along an exponential trajectory (without leveling and maintaining) allows to reduce not only the length of the air section of the landing distance, but also the required length of the runway. An approach with a steeper glide path is also preferable from the point of view of reducing the noise level of engines on the terrain in the airfield area. However, on the way of increasing the steepness of the landing glide path, there are limitations on the vertical landing speed associated with the strength of the landing gear, as well as issues of balancing and acceptable characteristics of stability and controllability of the aircraft when descending along a steep glide path.

The purpose of this work is to develop and research automatic control systems that implement high-precision landing with an increased glide path angle and with a touchdown point located at the very beginning of the runway.

III. PROBLEM SOLUTION

If several factors that affect the landing distance coincide, for example: adverse weather conditions, mountainous terrain and negative slope of the runway, etc. – then this can lead to a significant increase in landing distance and even disaster. When the landing point is transferred to the beginning (threshold) of the runway, the landing distance increases by 200 m, while the slope of the glide path plane increases, which in turn also decreases the landing distance. However, this raises the problem of generating control signals about the deviation of the aircraft from the newly formed glide path for the instrumental approach system.

The recalculation of the control parameters implies the need to obtain certain parameters that characterize the kinematics of the longitudinal motion of the aircraft relative to the equisignal zone of glide-path beacon (GPB) (Fig. 1).

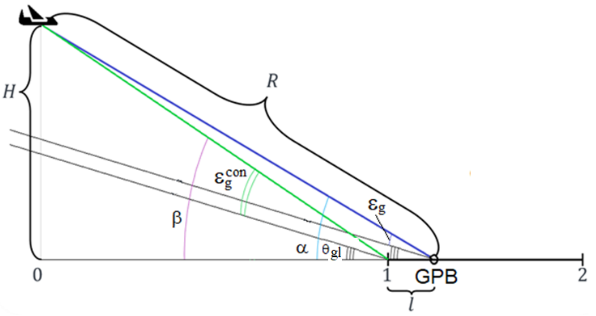

Fig. 1. Parameters characterizing the kinematics of the aircraft longitudinal motion relative to the glide path plane: *R* is the distance to GPB; *H* is the flight altitude; ε_g is the angular deviation from the plane of the glide path; ε_g^{con} is the angular deviation from the plane of the recalculated glide path; *l* is the distance from the beginning of the runway to GPB

Based on the graph, we have:

$$\alpha = \theta_{gl} + \varepsilon_g, \qquad \beta = \theta_{gl} + \varepsilon_g^{con}. \tag{1}$$

The angle of inclination of the glide path plane is expressed by the formula:

$$\theta_{gl} = \alpha - \varepsilon_g.$$

Taking into account the trigonometric ratio of angles, we obtain:

$$\begin{aligned} \alpha &= \arcsin\frac{H}{R}, \\ \beta &= \mathrm{arctg}\frac{H}{\left(\sqrt{R^2 - H^2}\right) - l}. \end{aligned} \tag{2}$$

From the equations of angles (1) we express the required signal:

$$\varepsilon_g^{con} = \beta - \alpha + \varepsilon_g.$$

Then, taking into account (2), the recalculation formula takes the form:

$$\varepsilon_g^{con} = \mathrm{arctg}\frac{H}{\left(\sqrt{R^2 - H^2}\right) - l} - \arcsin\frac{H}{R} + \varepsilon_g.$$

The landing approach according to information about ε_g^{con} ends at a height of 15 m. This is followed by the stage of descent according to the information about the vertical descent speed memorized during flight along the glide path (the stage of descent along the continuation of the glide path).

Starting from a height of $H \approx 8$ m, landing is realized along an exponential trajectory, which is not rigidly specified relative to the runway. In the case of deviation of the aircraft under the influence of perturbations from the specified trajectory, the new trajectory is shifted along the axis of the runway, that is, the same trajectory is built from a new point, the location of the aircraft. This method of trajectory formation leads to a significant scatter of landing points, so its use for landing on a short runway raises some doubts.

The article proposes to form the landing trajectory using the method of controlling the final state of the object. If an object is affected by an external disturbance that displaces it from the primary trajectory, then, realizing this method of control from a new location point, a new trajectory is constructed, which leads the plane to the specified end point. A necessary element of such a control method is the forecasting of the aircraft motion parameters.

The theory of dynamic object control using predictive models, known as Model Predictive Control (MPC), is one of the modern formalized approaches to the synthesis of control systems based on mathematical optimization methods.

The essence of the MPC approach is the following control scheme for dynamic objects based on the feedback principle.

1) Some (relatively simple) mathematical model of an object is considered, the initial conditions of which are its current states. For a given program control on an accelerated time scale, the equations of this model are integrated, which makes it possible to predict the movement of an object at a certain finite time interval (forecast horizon).

2) By enumerating options for program control, its optimal value is sought, which maximally brings the adjustable variables of the forecast model to the corresponding values set on the forecast horizon. Optimization is carried out taking into account the whole set of restrictions imposed on control and regulated variables.

3) On the calculation step, which is a small fixed part of the forecast horizon, the found's optimal control is realise and the actual state of the object is measured at the end of this step.

4) The forecast horizon is shifted one step forward, and steps 1 ... 3 of the given sequence of actions are repeated.

At the stage of landing at a given point on the runway using prediction, it is important to choose an independent variable for prediction. Obviously, as an independent variable you need to take one of the coordinates, the value of which determines the end of the landing process. This coordinate when controlling longitudinal motion, it is advisable to choose the distance to the calculated landing point.

A simplified model of the motion of the center of mass of an aircraft in the form can be chosen as a predictive mathematical model:

$$\begin{aligned} \dot{\Theta} &= \left(n_{y_g} - \Theta/T_{\Theta}\right), \\ \dot{H} &= V_y = V\sin\Theta, \\ \dot{D} &= V\cos\Theta, \end{aligned} \qquad (3)$$

where n_{y_g} is the control action; Θ is the trajectory slope; V_y is the vertical speed; D is the traversed path; T_{Θ} is the time constant characterizing aircraft type.

At the stage of decrease along the "glide path continuation", the control action $n_{y_g} = K_{\dot{H}}\left(V_y - V_{y_g}\right)$ is formed according to the information about the memorized vertical speed of decrease $V_{y_g} = V\sin\Theta_{gl}$, and starting from the height H ≈ 8 m, the value V_{y_g} is formed by the exponential law of alignment:

$$V_{y_g} = -\frac{H + H_{as}}{T_{\exp}}.$$

Here H_{as} is the asymptote depth; $T_{\exp}$ is the time constant of the exponent, which at the forecasting stage is the main wanted control parameter.

According to a similar algorithm, the elevator control of the controlled object is formed. Any optimal control problem consists of the search for such a control action that ensures the achievement of the goal

$$\lim_{x\to\infty}\left\|\mathbf{x}(t) - \mathbf{r}_x(t)\right\| = 0, \quad \lim_{x\to\infty}\left\|\mathbf{u}(t) - \mathbf{r}_u(t)\right\| = 0,$$

and delivers a minimum to the specified quality functional. Here $\mathbf{r}_x(t)$ and $\mathbf{r}_u(t)$ is the given vector functions that determine the desired motion of the object subject to the constraints $x(t)\in X\ \forall\ t \in [0,\infty)$.

Defining the controls $u = u(\tau)$ as a function of time on the interval $\tau \in \lfloor t, t + T_p \rfloor$ and integrating the system (3) on the specified segment with the initial conditions $\bar{x}\big|_{\tau=t} = x(t)$, we obtain a separate solution $x(t) = x\left(\tau, x(t), u(\tau)\right)$, which is interpreted as a forecast of the behavior of the control object with the forecast horizon T_p.

To build a landing trajectory, the main thing is the landing accuracy (final state) - how this state is achieved (in what time) is not important. Therefore, when forming control algorithms, it is advisable to switch to the concept of controlling the final state of the object, and as an independent variable for forecasting, choose not the time, but the distance D. For this concept, the control goal is formed as

$$\lim_{D\to D_c}\left\|\mathbf{x}(D)-\mathbf{r}_x(D)\right\|=0,\quad \lim_{D\to D_c}\left\|\mathbf{u}(D)-\mathbf{r}_u(D)\right\|=0,$$

where D_c is the distance to the calculated touchdown point (TP).In this case, the optimal control $\mathbf{u}(\cdot)$ for the predictive model is sought by minimizing the functional

$$J(\mathbf{x}(D),\mathbf{u}(\cdot),D,D_c)\to\min_{\bar{\mathbf{u}}(\cdot)\in\Omega_u},$$

where Ω_u is a valid set of controls

As the sought control parameter, the time constant of the alignment exponent $T_{\exp}$ is selected, at which the deviation of the coordinate of the point of contact of the aircraft to the runway from the specified coordinate of the touchdown point is minimized. In this case, multiple predictions are performed with an interval $(D_c - D)$ that gradually decreases. Wherein the optimal control $\mathbf{u}(D_c - D)$ (in the case considered $T_{\exp}$) is that found for the predictive model on the interval $(D_c - D)$ is fed to the real object

$$\mathbf{u}(D_c - D)\equiv\mathbf{u}^*(D_c - D),$$

or after concretizing control parameters

$$T_{\exp}(D_c - D)\equiv T_{\exp}{}^*(D_c - D),$$

Then the search is performed on an already reduced forecast interval $(D_c - (D + \Delta D))$. As the forecast interval decreases, the control accuracy gradually increases.

The above method for optimizing predictive control uses a forecast with a gradual approach to the horizon. Within the framework of this approach, control is carried out according to the principle of feedback with a discrete receipt of information about the current state of the object at times $(D+\Delta D)$.

Thus, the distance to the calculated touchdown point is chosen as the independent variable for prediction. The position of the landing point must be calculated taking into account many factors. Therefore, the choice of the landing point is a separate task of constructing the landing trajectory and is not considered in this work.

But setting the alignment distance D_{alig}, we choose the distance to the calculated landing point $D_{\text{alig}} = D_c$. Therefore, when optimizing the control, it is necessary to take into account the whole set of restrictions, in particular the restrictions on the vertical landing speed V_y, which should not exceed 1.2 m/s.

Research has shown that approach speed has the most significant effect on the landing distance.

To study the effect of wind perturbations on the landing accuracy during modeling, models of these perturbations were formed. The graphs (Fig. 2) provide the results of modeling the landing phase of the aircraft when hit by ascending and descending wind currents. In the case of using only preliminary prediction, the runway contact error relative to the landing point LP is about 50 m, and in the case of control according to the forecast model, the runway contact error relative to the LP does not exceed 5 m.

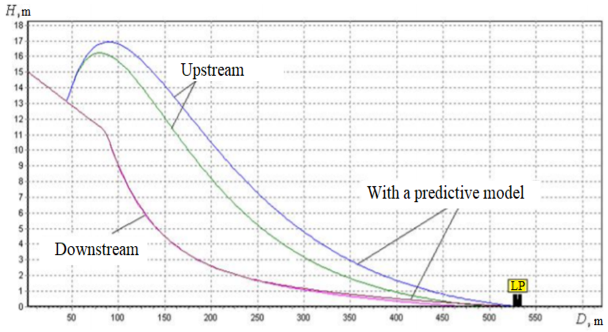

Fig. 2. Landing trajectories under the influence of wind disturbances

IV. CONCLUSIONS

The proposed approach to constructing the landing trajectory, based on the method of controlling the final state during landing along a flexible trajectory, makes it possible to significantly to increase the accuracy of landing and prevent the aircraft from rolling out of the final safety strip when landing on a short runway, and the implementation of landing control based on algorithms with a predictive model with a gradual approach to the forecast horizon retains the specified landing accuracy even under the influence of certain disturbances on the aircraft.

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М. К. Філяшкін, М. В. Сідоренко. Автоматизація посадки на короткі злітно-посадкові смуги

Розглянуто питання автоматизації керування посадкою літаків на коротку злітно-посадкову смугу. Запропоновано схему заходу на посадку за крутою глисадою з точкою дотику, розташованою на самому початку злітно-посадкової смуги, що дозволяє зменшити довжину повітряної ділянки заходу на посадку та необхідну довжину злітно-посадкової смуги. Представлено формули перерахунку параметрів глісади для реалізації автоматичного управління зниженням і посадкою літака. Для зменшення розміру зони посадки пропонується будувати траєкторію посадки за методом контролю кінцевого стану під час посадки за гнучкою траєкторією. Розглянуто принципи побудови систем автоматичного управління посадкою літаків на основі алгоритмів з прогнозуйочою моделлю з поступовим наближенням до горизонту прогнозування.

Ключові слова: довжина злітно-посадкової смуги; короткі злітно-посадкові смуги; точка приземлення; літак скороченого зльоту і посадки; крута глисада; прогнозування; прогнозна модель; оптимальне керування.

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Напрям наукової діяльності: комплексна обробка інформації в пілотажно-навігаційних комплексах, автоматизація та оптимізація керування повітряними суднами на різних етапах польоту.
Кількість публікацій: більше 150 наукових робіт.
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Н. К. Филяшкин. М. В. Сидоренко. Автоматизация посадки на короткие взлетно-посадочные полосы

Рассмотрены вопросы автоматизации управления посадкой самолетов на короткую взлетно-посадочную полосу. Предложена схема захода на посадку по крутой глиссаде с точкой касания, расположенной в самом начале взлетно-посадочной полосы, что позволяет уменьшить длину воздушного участка захода на посадку и необходимую длину взлетно-посадочной полосы. Получены формулы пересчета параметров глиссады для реализации автоматического управления заходом на посадку на короткую взлетно-посадочную полосу. Для уменьшения размера зоны посадки предлагается формировать траекторию посадки по методу управления конечным состоянием при посадке по гибкой траектории. Рассмотрены принципы построения систем автоматического управления посадкой самолетов на основе алгоритмов с прогнозирующей моделью с постепенным приближением к горизонту прогнозирования.

Ключевые слова: длина взлетно-посадочной полосы; короткие взлетно-посадочные полосы; точка приземления; самолет укороченного взлета и посадки; крутая глиссада; прогнозирование; прогнозирующая модель; оптимальное управление.

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