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Thrust Control for Aircraft Landing on a Carrier

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Abstract—This paper considers aircraft landing on a carrier. We propose two schemes for calculating, first, the probability of a go-around due to disengaging the arresting gear and, second, the maximum descent of the aircraft's trajectory with respect to the deck level immediately after leaving the deck. The instant to increase the aircraft's thrust before touching the deck is a control parameter affecting these characteristics. The requirements imposed on the probability of a go-around and the maximum descent of the aircraft's trajectory allow determining an admissible range for the thrust increase instant. Numerical results are presented for a real aircraft landing on a real carrier.

Keywords: aircraft landing, carrier, probability, control, thrust, trajectory

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1. PROBLEM DESCRIPTION

As is well known, landing represents the most difficult and important stage of flight. The issues of accurate and safe aircraft landing, particularly on carriers, were considered by many domestic and foreign researchers; for example, see [1–13]. For a shipborne aircraft, additional complications arise because the landing surface is movable and limited in length. As a result, tougher requirements are applied for the accuracy of landing on carriers. This landing process has the following specifics: with the help of a hook, the aircraft should engage one of the arresting gear cables stretched across the landing section of the deck. If this engagement does not occur, the aircraft runs on the deck to take off and perform a go-around.[1] The number of such go-arounds is quite large, constituting 1–2% of the total number of landings according to available statistics.

In the case of disengaging the arresting gear, due to the small time of running on the deck (1.5–2 s), the pilot does not manage to reach the required velocity at the instant of turning off. As a result, immediately after leaving the deck, gravity prevails over the lifting force, and the initial section of the aircraft's trajectory has some descent with respect to the deck level. Under fixed angles of attack and pitch at the instant of leaving the deck and a given elevator control law, the maximum descent is uniquely determined by the aircraft's velocity at the instant of leaving the deck. To prevent water contact and ensure successful take-off, it is necessary to reduce the

[1] Of course, the go-around maneuver can be decided before the expected instant of touching the deck if it becomes clear that, for one reason or another, the probability of a successful landing is not high enough. This aspect of landing on carriers was discussed in detail in [10].

maximum descent as much as possible. The remedy is to increase the aircraft's velocity at the instant of leaving the deck.

The increase in velocity can be achieved through an additional aircraft's thrust. Due to lagging, it takes some time. Therefore, in the case of disengaging the arresting gear, the pilot must increase the aircraft's thrust before the expected instant of touching the deck to increase the velocity significantly while the aircraft is moving on the deck. In this case, the following circumstance should be taken into consideration. If the aircraft's thrust is increased early, the velocity of leaving the deck will be high and the maximum descent will be small. But an early increase in the aircraft's thrust will appreciably raise the landing velocity, causing a tendency to fly over the arresting gear zone (and reduce the probability of a successful landing). If the increase in the aircraft's thrust occurs late, the aircraft will have an insufficient velocity of leaving the deck and an unacceptably high value of the maximum descent in the case of disengaging the arresting gear.

Thus, we face the issue of finding an admissible range of instants to increase the aircraft's thrust. On the one hand, it is necessary to ensure a sufficiently high probability of a successful landing. On the other hand, in the case of disengaging the arresting gear, it is necessary to reduce the maximum descent to avoid a water touch. This paper aims to provide an answer.

2. THE PROPOSED SOLUTION SCHEME

We consider only the longitudinal motion of the aircraft. A landing trajectory without thrust until the instant of touching the deck under no perturbations will be called the nominal trajectory. The nominal trajectory is a straight line; see the sloping dashed line in Fig. 1. In the absence of pitching, it intersects the deck at a given point O (Fig. 1). Let s_{ag} denote the length of the deck section occupied by the arresting gear. To describe the landing trajectory, we introduce the auxiliary planes A–A, B–B, C–C, C_1–C_1, D–D, and E–E that are perpendicular to the vertical plane of the motions of the aircraft and ship. This plane coincides with that of Fig. 1. The lines A–A, B–B, C–C, C_1–C_1, D–D, and E–E are the projections of the corresponding planes on the plane of Fig. 1. The plane A–A is at a distance of a 2.5-second flight along the nominal trajectory until touching the deck. In the ship-fixed coordinate system, this plane is stationary. The plane B–B corresponds to the thrust increase instant: the pilot increases the engine thrust when the aircraft crosses the plane B–B. The planes C–C and C_1–C_1 are associated with the ship and limit the deck section occupied by the arresting gear. The plane D–D is also associated with the ship and corresponds to the instant of leaving the deck in the case of disengaging the arresting gear. In this paper, we assume that the arresting gear engagement does not occur only when flying over the zone s_{ag}. Otherwise, the arresting gear is supposed engaged with probability 1. Finally, the plane E–E corresponds to the instant of reaching the maximum descent by the aircraft after leaving the deck.

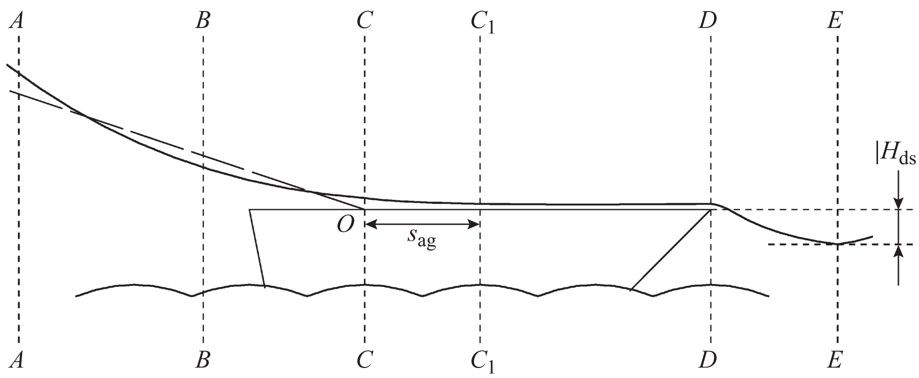

Fig. 1.

The proposed solution scheme is as follows. The probability P_{ag} of flying over the arresting gear zone s_{ag} (the probability of disengaging the arresting gear) is determined depending on the thrust increase instant t_{th} of the aircraft by the method[2] described in [5, 13]; also, see the books [2, 9]. Random perturbations are atmospheric turbulence and pitching. The analysis below deals with the trajectories corresponding to the factual overflight of the arresting gear zone. As it turns out, under the given thrust increase instant t_{th}, the magnitude $v = |\mathbf{v}|$ of the aircraft's velocity vector $\mathbf{v}$ at the instant of leaving the deck and the maximum descent $|H_{\text{ds}}|$ almost do not depend on the point of initial contact of the aircraft with the deck: they are uniquely determined by the instant t_{th} and the angle θ between the vector $\mathbf{v}$ and the horizontal plane at the instant of leaving the deck. Hence, the aircraft's motion on the deck and after leaving the deck can be simplified to a deterministic setting. In other words, the value H_{ds} as a function of the variables t_{th} and θ can be found by numerically integrating the motion equations.

As a result, we obtain two functions $P_{\text{ag}}(t_{th})$ and $H_{\text{ds}}(t_{th}, \theta)$. There are conventional constraints on P_{ag} and H_{ds} (for the latter function, in the absence of pitching, i.e., $\theta = 0$). Therefore, we make another simplification, neglecting pitching when the aircraft runs on the deck. The range of admissible instants t_{th} will be determined from satisfying these constraints on P_{ag} and H_{ds}.

3. THE PROBABILITY OF DISENGAGING THE ARRESTING GEAR

Assume that the aircraft's thrust $F(t)$ grows exponentially starting from the thrust increase instant t_{th}, i.e.,

$$F(t) = \begin{cases} F_0 \text{ for } t \leqslant t_{th} \\ F_0 + \Delta F \left(1 - \exp\left\{-\dfrac{t - t_{th}}{\tau}\right\}\right) \text{ for } t \geqslant t_{th}, \end{cases} \tag{1}$$

where the constant τ characterizes the engine acceleration time and F_0 and ΔF are some fixed values. The aircraft hits the ship's stern with a negligible probability.[3] Hence, the probability of disengaging the arresting gear, supposed equal to the probability of flying over the arresting gear zone s_{ag}, can be calculated as the difference $P_{\text{ag}} = 1 - P$, where P denotes the probability of landing on the deck section between the stern cut line and the line coinciding with the last arresting gear cable (the right end of the section s_{ag} in Fig. 1).

To find the probability P, we use the method described in [5, 13]. This method consists in linearizing the aircraft's motion equations (equations (9) from the paper [5]) in a neighborhood of the nominal landing trajectory along which the aircraft moves in the absence of perturbations. The distinction from the papers [5, 13] has a purely technical nature: the nominal landing trajectory below is a straight line only up to the thrust increase instant t_{th}, deviating from the straight line after this instant due to the new thrust law (1); in [5, 13], the aircraft's thrust was considered constant until touching the deck.

The calculations were performed for $\Delta F = F_0$, i.e., the aircraft's thrust after the instant t_{th} asymptotically increased twice. We considered three values of the constant τ characterizing the engine acceleration time: $\tau = 1$ s, $\tau = 1.5$ s, and $\tau = 2$ s. The same automatic feedback control law was applied to the same aircraft as in the papers [5, 13]. This aircraft is identical to the shipborne MiG-29K by performance characteristics. The resulting values of the probability P_{ag} are presented in Table 2. The value $\Delta t = t_{land} - t_{th}$ on the horizontal axis of Fig. 2, determining the thrust increase instant t_{th}, is the time between the instant t_{th} and the expected instant t_{land} of touching the deck in the case of no thrust increase. The values of the probability P_{ag} to plot the graphs in Fig. 2 are given in the Appendix; see Table 1.

[2] This method is based on the results originally obtained in [14] and subsequently refined in [15, 16].

[3] It is less than 10^{-5} under moderate sea state; see [1].

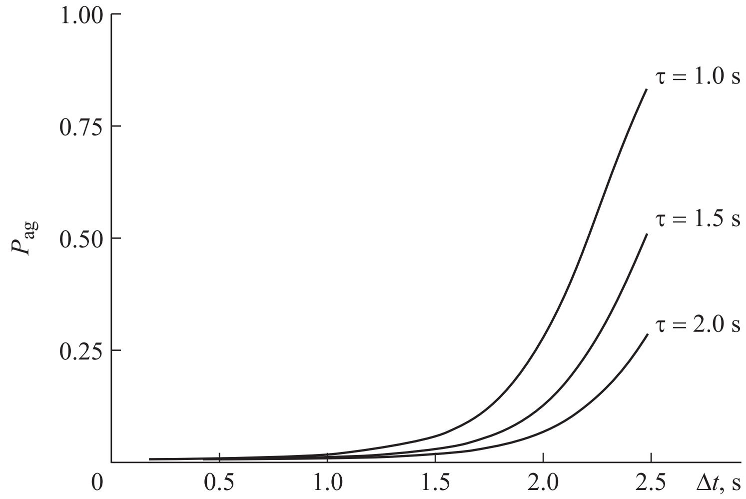

Fig. 2.

4. AIRCRAFT'S VELOCITY AT THE INSTANT OF TOUCHING THE DECK

This velocity is necessary to find the descent H_{ds}. Let the longitudinal motion of the aircraft in a turbulent atmosphere be described by system (9) from [5]. We find the velocity in a deterministic problem statement (no atmospheric turbulence and pitching). In the ship-fixed coordinate system Oxy (Fig. 3), the system (9) mentioned above yields

$$\begin{cases} m\dfrac{dv}{dt} = F(t)\cos\alpha - mg\sin(\vartheta-\alpha) - qSC_x \\ mv\dfrac{d(\vartheta-\alpha)}{dt} = qSC_y + F(t)\sin\alpha - mg\cos(\vartheta-\alpha) \\ \dfrac{d\vartheta}{dt} = \omega_z \\ I_z\dfrac{d\omega_z}{dt} = qSb_Am_z \\ \dfrac{dy}{dt} = v\sin(\vartheta-\alpha) \\ \dfrac{dx}{dt} = v\cos(\vartheta-\alpha) - V. \end{cases} \tag{2}$$

All the notations used here were described in detail in [5, 13]. They are conventional for aircraft flight dynamics problems. In particular,

$$C_y = C_{y0} + C_y^{\alpha}\alpha + C_y^{\delta}\delta,\ C_x = C_{x0} + AC_y^2,$$
$$m_z = m_{z0} + m_z^{\alpha}\alpha + m_z^{\delta}\delta + \frac{b_A}{v_0}m_z^{\bar{w}_z}w_z,\ q = \frac{\rho v^2}{2},$$

where: δ is the deviation of the longitudinal control lever; v is the magnitude of the aircraft's velocity vector in the stationary Earth-based coordinate system; C_{y0}, C_y^{α}, C_y^{δ}, A, C_{x0}, m_z^{α}, m_z^{δ}, m_{z0}, and $m_z^{\bar{w}_z}$ are the aerodynamic coefficients of the aircraft; $\bar{w}_z = \frac{w_z b_A}{v_0}$; C_x is the dimensionless coefficient of the aerodynamic drag component $\mathbf{X}$ (Fig. 4): $C_x = |\mathbf{X}|/qS$; C_y is the dimensionless coefficient of the aerodynamic lift component $\mathbf{Y}$: $C_y = |\mathbf{Y}|/qS$; b_A is the mean aerodynamic wing chord; m_z is the dimensionless coefficient of the longitudinal moment M_z: $M_z = m_zqSb_A$; I_z is the corresponding moment of inertia of the aircraft; ϑ is the pitch angle, i.e., the angle between the

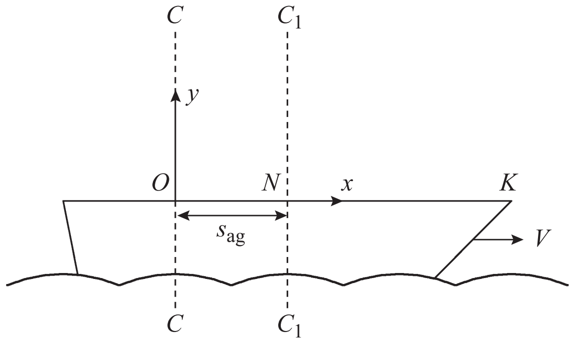

Fig. 3.

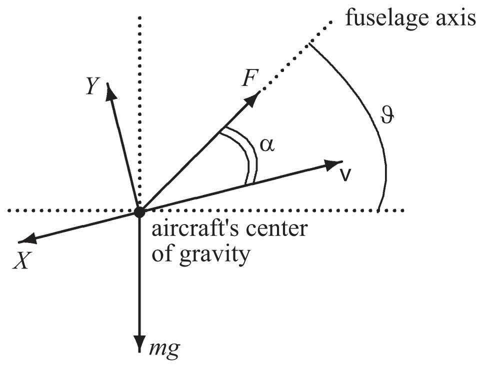

Fig. 4.

fuselage axis and the horizontal plane; S is the wing planform area; finally, $g = |\mathbf{g}|$, where $\mathbf{g}$ is the gravity vector.

Let the control law for δ be the same as in the papers [5, 13]. With this control law, the system of equations (2) becomes closed and can be integrated numerically.

According to real observations, in the case of disengaging the arresting gear, the aircraft's velocity at the instant of leaving the deck is almost independent of the point of initial contact with the deck and is uniquely determined by the instant t_{th}. Therefore, as the point of initial contact with the deck, we can choose the point N (i.e., the aircraft touches the deck immediately after the last arresting gear cable, see Fig. 3). Furthermore, we can find the aircraft's velocity v_{tc} at the instant of touching as $v_{\text{tc}} = v(t_{\text{tc}})$, where the function $v(t)$ is obtained by integrating system (2) numerically and the instant t_{tc} is determined in advance from the condition $x(t_{\text{tc}}) = s_{\text{ag}}$ (Fig. 3).

For the three values of the engine acceleration time τ ($\tau = 1$ s, $\tau = 1.5$ s, and $\tau = 2$ s), the velocities v_{tc} calculated depending on the instant t_{th} are presented in the Appendix, see Table 3.

5. AIRCRAFT'S VELOCITY AT THE INSTANT OF LEAVING THE DECK

The aircraft's motion on the deck is described by the equation

$$m\frac{dv}{dt} = F(t) - \frac{\rho v^2}{2} S C_x - fG, \tag{3}$$

where $G = mg$, f denotes the friction coefficient, and ρ is sea level atmospheric density. Let $\alpha \equiv 0$ and $\delta \equiv 0$ when the aircraft is on the deck. We represent $v(t)$ as the sum

$$v(t) = v_{\text{tc}} + \Delta v(t), \quad t_{\text{tc}} \leqslant t \leqslant t_{\text{lv}},$$

where $t_{\rm lv}$ is the instant of leaving the deck. Note that $\Delta v(t) \ll v_{\rm tc}$ due to the small time $t_{\rm lv} - t_{\rm tc}$ of running on the deck. Therefore, we linearize equation (3) with respect to the function $\Delta v(t)$ to obtain

$$\frac{d\Delta v}{dt} + \rho\frac{C_x}{m/S}v_{\rm tc}\Delta v = g\left(\frac{F_0}{G} - f - \frac{C_x}{m/S}\frac{\rho v_{\rm tc}^2}{2}\right) + g\frac{F(t) - F_0}{G},$$

where $C_x = C_{x0} + AC_{y0}^2$ because $\alpha = \delta = 0$, and $\Delta v(t_{\rm tc}) = 0$. Solving this equation, we arrive at the explicit formula

$$\Delta v(t) = \frac{b_1 + g\Delta F_0/G}{a_1}\Big(1 - \exp\{-a_1(t - t_{\rm tc})\}\Big)$$
$$+ \frac{g\Delta F_0}{G}\frac{\tau}{1 - a_1\tau}\exp\left\{-\frac{t_{\rm tc} - t_p}{\tau}\right\}\left(\exp\left\{-\frac{t - t_{\rm tc}}{\tau}\right\} - \exp\{-a_1(t - t_{\rm tc})\}\right), \quad t_{\rm tc} \leqslant t \leqslant t_{\rm lv},$$

where

$$a_1 = \rho\frac{C_x v_{\rm tc}}{m/S}, \quad b_1 = g\left(\frac{F_0}{G} - f - \frac{C_x}{m/S}\frac{\rho v_{\rm tc}^2}{2}\right).$$

Let T denote the aircraft's running time on the deck from the instant $t_{\rm tc}$ to the instant $t_{\rm lv}$, i.e., $T = t_{\rm lv} - t_{\rm tc}$, and let L denote the length of the deck section between the points of touching and leaving by the aircraft (the instants $t_{\rm tc}$ and $t_{\rm lv}$). As has been emphasized in Section 4, the aircraft's velocity at the instant of leaving the deck is almost independent of the point of initial contact with the deck. Therefore, we assume that $L = NK$ (Fig. 3) and, consequently,

$$NK = \int\limits_{t_{\rm tc}}^{t_{\rm tc}+T}(v_{\rm tc} + \Delta v(t) - V)dt = \left(v_{\rm tc} - V + \frac{b_1 + g\Delta F_0/G}{a_1}\right)T$$
$$+ \frac{g\Delta F_0}{G}\frac{\tau^2}{1 - a_1\tau}\exp\left\{-\frac{t_{\rm tc} - t_p}{\tau}\right\}\left(1 - \exp\left\{-\frac{T}{\tau}\right\}\right)$$
$$- \left(\frac{b_1 + g\Delta F_0/G}{a_1} + \frac{g\Delta F_0}{G}\frac{\tau}{1 - a_1\tau}\exp\left\{-\frac{t_{\rm tc} - t_p}{\tau}\right\}\right)\frac{1 - \exp\{-a_1 T\}}{a_1}.$$

Hence, T satisfies the equation

$$T = \psi(T), \tag{4}$$

where

$$\psi(T) = \tilde{\psi}(T)\Big/\left(v_{\rm tc} - V + \frac{b_1 + g\Delta F_0/G}{a_1}\right),$$
$$\tilde{\psi}(T) = NK + \left(\frac{b_1 + g\Delta F_0/G}{a_1} + \frac{g\Delta F_0}{G}\frac{\tau}{1 - a_1\tau}\exp\left\{-\frac{t_{\rm tc} - t_p}{\tau}\right\}\right)$$
$$\times\frac{1 - \exp\{-a_1 T\}}{a_1} - \frac{g\Delta F_0}{G}\frac{\tau^2}{1 - a_1\tau}\exp\left\{-\frac{t_{\rm tc} - t_p}{\tau}\right\}\left(1 - \exp\left\{-\frac{T}{\tau}\right\}\right).$$

The solution of (4) is found by the method of successive approximations:

$$T = \lim_{n\to\infty} T_n, \quad T_n = \psi(T_{n-1}),\ n = 1, 2, \ldots,$$

where T_0 is an initial approximation. The aircraft's velocity v_{lv} at the instant of leaving the deck is given by

$$v_{\text{lv}} = v_{\text{tc}} + \Delta v(t_{\text{tc}} + T),$$

where $\Delta v(t_{\text{tc}} + T)$ is the value of the function $\Delta v(t)$ for $t = t_{\text{tc}} + T$. The numerical calculations were performed for the ship characteristics corresponding to the aircraft carrier Admiral Kuznetsov. The calculation results for the velocity v_{lv} as a function of the thrust increase instant t_{th} in the three cases (the engine acceleration times $\tau = 1$ s, $\tau = 1.5$ s, and $\tau = 2$ s) are presented in the Appendix; see Table 4.

6. THE MAXIMUM DESCENT OF THE AIRCRAFT'S TRAJECTORY AFTER LEAVING THE DECK

After leaving the deck, the aircraft's motion is considered in the deterministic statement. In other words, it is described by system (2) with the following initial conditions:

$$v = v_{\text{lv}}, \quad \alpha = 0, \quad \vartheta = 0, \quad \omega_z = 0, \quad y = 0, \quad x = s_{ag} + NK, \tag{5}$$

where NK is the length of the deck section between the points N and K (Fig. 3). By assumption, the deviation δ of the longitudinal control lever is constant and can be determined from the balancing condition

$$m_{z0} + m_z^{\alpha}\alpha + m_z^{\delta}\delta = 0$$

with $\alpha = \alpha_{\text{bal}} = 15°$.

The maximum descent $|H_{\text{ds}}|$ (Fig. 1), representing the minimum value of the coordinate y, is obtained by integrating numerically system (2) with the initial conditions (5). The resulting graphs of H_{ds} are shown in Fig. 5. As in Fig. 2, the value $\Delta t = t_{land} - t_{th}$ on the horizontal axis of Fig. 5, determining the thrust increase instant t_{th}, is the time between the instant t_{th} and the expected instant t_{land} of touching the deck in the case of no thrust increase. The values of the descent H_{ds} to plot the graphs in Fig. 5 are given in the Appendix; see Table 2.

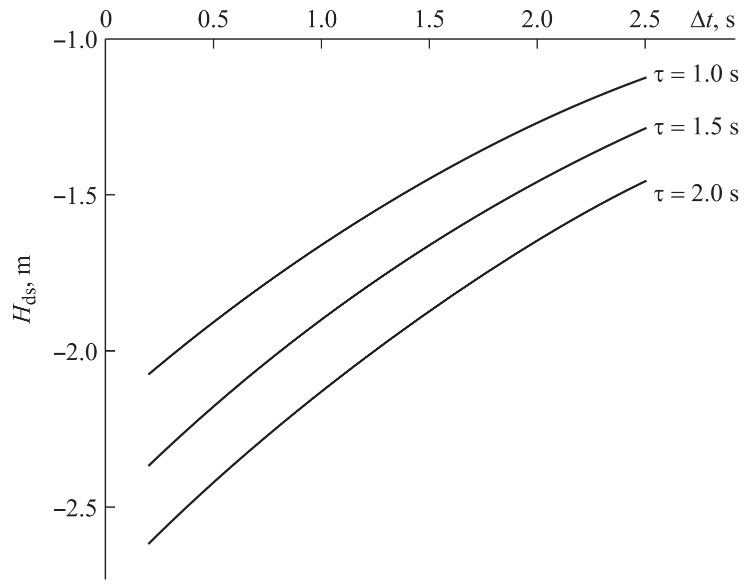

Fig. 5.

7. ADMISSIBLE THRUST INCREASE INSTANTS

When choosing admissible thrust increase instants, a common technique is to consider constraints on the probability $P_{\rm eb}$ of landing on the emergency barrier instead of the probability $P_{\rm ag}$ of disengaging the arresting gear. The probability $P_{\rm eb}$ is set equal to the probability of disengaging the arresting gear after n landing approaches, i.e., $P_{\rm eb} = P_{\rm ag}^n$. Due to limited fuel reserves, the value $n = 3$ is often chosen, and consequently, $P_{\rm eb} = P_{\rm ag}^3$.

The aircraft can be seriously damaged during landing on the emergency barrier. According the existing standards [1], $P_{\rm eb} < 10^{-4}$, which is equivalent to $P_{\rm ag} < 0.0464$. Considering the above results for $P_{\rm ag}$, we arrive at the following constraints on the time Δt :

$$\Delta t < \Delta t_{\max}, \quad \text{where} \quad \Delta t_{\max} = \begin{cases} 1.40\,\text{s} \;\; \text{for } \tau = 1\,\text{s} \\ 1.65\,\text{s} \;\; \text{for } \tau = 1.5\,\text{s} \\ 1.85\,\text{s} \;\; \text{for } \tau = 2\,\text{s}. \end{cases}$$

In other words, we have the following picture for different engine acceleration times τ : for $\tau = 1$ s, the thrust should be increased not earlier than 1.40 s before the expected instant of touching the deck; for $\tau = 1.5$ s, not earlier than 1.65 s before the expected instant of touching the deck; for $\tau = 2$ s, not earlier than 1.85 s before the expected instant of touching the deck.

Now we study the constraints imposed on Δt due to the limited maximum descent of the aircraft's trajectory after leaving the deck. In the previous section, we have determined the descent without pitching. Clearly, in the presence of pitching, the maximum descent increases noticeably due to leaving the deck with negative angles θ. Nevertheless, the descent is normalized in the absence of pitching under the assumption that it will increase with pitching. For example, according to the norms for US shipborne aircraft and carriers [1], the maximum descent in the absence of pitching must satisfy the condition $H_{\rm ds} > -3$ m. Let us follow this criterion for the example above, where the numerical values of the parameters characterize the aircraft and carrier under consideration. As it turns out, thrust may remain the same up to the instant of touching the deck, and the only constraint on the thrust increase instant is the condition $\Delta t < \Delta t_{\max}$. However, this condition, among other factors, is determined by the carrier's height above the water surface. When a stricter condition is imposed on $H_{\rm ds}$, e.g., $H_{\rm ds} > -2$ m, we arrive at a bilateral constraint on Δt :

$$\Delta t_{\min} < \Delta t < \Delta t_{\max}, \quad \text{where} \quad \Delta t_{\min} = \begin{cases} 0.30\,\text{s} \;\; \text{for } \tau = 1\,\text{s} \\ 0.75\,\text{s} \;\; \text{for } \tau = 1.5\,\text{s} \\ 1.20\,\text{s} \;\; \text{for } \tau = 2\,\text{s}. \end{cases}$$

In other words, we have the following picture for different engine acceleration times τ: for $\tau = 1$ s, the thrust should be increased not earlier than 1.40 s but not later than 0.3 s before the expected instant of touching the deck; for $\tau = 1.5$ s, not earlier than 1.65 s but not later than 0.75 s before the expected instant of touching the deck; for $\tau = 2$ s, not earlier than 1.85 s but not later than 1.20 s before the expected instant of touching the deck.

8. CONCLUSIONS

This paper has proposed an algorithm for finding an admissible range of the thrust increase instant for aircraft landing on a carrier. Based on the previously published results, we have proposed two schemes for calculating, first, the probability $P_{\rm ag}$ of disengaging the arresting gear and, second, the maximum descent $H_{\rm ds}$ of the aircraft's trajectory with respect to the deck level immediately after leaving the deck (if the arresting gear is not engaged). The probability $P_{\rm ag}$ and the descent $H_{\rm ds}$ have been calculated numerically as functions of the thrust increase instant. As a result, the conventional constraints on $P_{\rm ag}$ and $H_{\rm ds}$ have been adopted to determine an admissible range for the thrust increase instant. The proposed scheme has been numerically implemented for the landing process of the real shipborne aircraft MiG-29K on the real carrier Admiral Kuznetsov.

APPENDIX

Table 1

Δt, s	P_{ag}		
	$\tau = 1$ s	$\tau = 1.5$ s	$\tau = 2$ s
0.2	0.0081	0.0079	0.0078
0.3	0.0086	0.0082	0.0079
0.4	0.0090	0.0085	0.0081
0.5	0.0096	0.0088	0.0083
1.0	0.0172	0.0129	0.0108
1.5	0.0545	0.0302	0.0206
1.7	0.1003	0.0498	0.0307
1.8	0.1385	0.0658	0.0389
1.9	0.1917	0.0885	0.0501
2.0	0.2635	0.1202	0.0658
2.1	0.3562	0.1642	0.0876
2.2	0.4689	0.2237	0.1178
2.3	0.5945	0.3015	0.1592
2.4	0.7205	0.3987	0.2148
2.5	0.8312	0.5123	0.2873

Table 2

Δt, s	H_{ds}, m		
	$\tau = 1$ s	$\tau = 1.5$ s	$\tau = 2$ s
0.2	−2.052	−2.334	−2.590
0.3	−1.993	−2.270	−2.523
0.4	−1.937	−2.208	−2.458
0.5	−1.881	−2.147	−2.394
1.0	−1.633	−1.871	−2.099
1.5	−1.425	−1.635	−2.844
1.7	−1.352	−1.552	−1.752
1.8	−1.317	−1.512	−1.708
1.9	−1.284	−1.473	−1.666
2.0	−1.251	−1.436	−1.625
2.1	−1.220	−1.400	−1.585
2.2	−1.190	−1.365	−1.546
2.3	−1.161	−1.332	−1.509
2.4	−1.133	−1.299	−1.472
2.5	−1.106	−1.268	−1.437

Table 3

Δt, s	v_{tc}, m/s		
	$\tau = 1$ s	$\tau = 1.5$ s	$\tau = 2$ s
0.2	67.210	67.039	66.944
0.3	67.389	67.174	67.053
0.4	67.591	67.322	67.173
0.5	67.786	67.482	67.304
1.0	68.930	68.407	68.079
1.5	70.166	69.464	68.991
1.7	70.664	69.904	69.380
1.8	70.912	70.125	69.577
1.9	71.157	70.348	69.776
2.0	71.402	70.570	69.976
2.1	71.644	70.793	70.177
2.2	71.883	71.014	70.379
2.3	72.120	71.235	70.581
2.4	72.354	71.455	70.783
2.5	72.585	71.674	70.985

Table 4

Δt, s	v_{lv}, m/s		
	$\tau = 1$ s	$\tau = 1.5$ s	$\tau = 2$ s
0.2	76.941	75.952	75.208
0.3	77.198	76.192	75.430
0.4	77.453	76.433	75.652
0.5	77.705	76.674	75.876
1.0	78.929	77.859	76.991
1.5	80.077	78.997	78.084
1.7	80.153	79.436	78.511
1.8	80.727	79.651	78.722
1.9	80.935	79.865	78.931
2.0	81.142	80.075	79.137
2.1	81.345	80.283	79.342
2.2	81.543	80.487	79.545
2.3	81.739	80.689	79.746
2.4	81.931	80.888	79.944
2.5	82.120	81.084	80.140

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