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Determining the Optimal Conditions for Dropping a Load from an Aircraft

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Abstract: Optimum conditions for dropping a load from an aircraft are seen as conditions under which no collision with the aircraft is allowed, with stable flight of the load having a trajectory close to the calculated one. Depending on the aerodynamic characteristics, the weight of the load and the type of aircraft, it is necessary to determine the angle at which the load is attached to the aircraft, the initial angular velocity of the load at release, the forced vertical velocity of the load ejection, so that to prevent a collision with the aircraft. On the other hand, applying additional vertical speed to the load will reduce the detrimental effect of the disturbed air flow around the aircraft on its flight. All this is of great importance for ensuring the safe separation of the load from the aircraft and increases the accuracy of solving the targeting problem by a specific targeting system. Mathematical modelling of the flight of the load dropped by an aircraft with different initial vertical speeds of ejection was performed, for which the influence of the disturbed zone on the flight was investigated.

Keywords: Optimum conditions, Dropping, Aircraft, Load

Introduction

It is essential to ensure the safe release of loads from the aircraft during combat operations. For this purpose, it is necessary to know: the conditions for releasing the load (speed, altitude, orientation of the aircraft's axes in space), the aerodynamic characteristics of the aircraft, the dimensions of the disturbed zone around the aircraft in various flight modes, the coordinates of the load suspension point relative to the coordinate system associated with the aircraft, and the dimensions and aerodynamic characteristics of the load. Based on this information, it is necessary to preliminarily calculate the risk of collision between the load and the aircraft at the moment of release. If a collision condition exists, measures must be taken to prevent it. The measures that can be applied to prevent such a collision include:

- Providing additional vertical speed to the load using pyrotechnic devices;
- Releasing the load at an initial angle relative to the aircraft's axes;
- Applying initial rotary motion around the load's center of mass at the moment of separation;
- Limiting the conditions for releasing the load;
- Implementing measures to reduce the harmful effects of the disturbed zone at the moment of release (using additional fairings or mechanisms through which the load is released at the boundary of the disturbed zone).

Method

The conditions for preventing a collision during the release of load from an aircraft have been analytically determined, and it has been investigated what initial vertical speed needs to be applied to the load at the moment of release in order to avoid a collision. The relative distance between the load and the aircraft after release is determined using the following formulas:

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$$\begin{aligned} \Delta x &= x - x_0; \\ \Delta y &= y - y_0; \\ \Delta z &= z - z_0, \end{aligned} \qquad (1)$$

where x, y, z are the current coordinates of the load relative to the aircraft;

$-x_0$, y_0, z_0 are the coordinates of the load at the moment of separation.

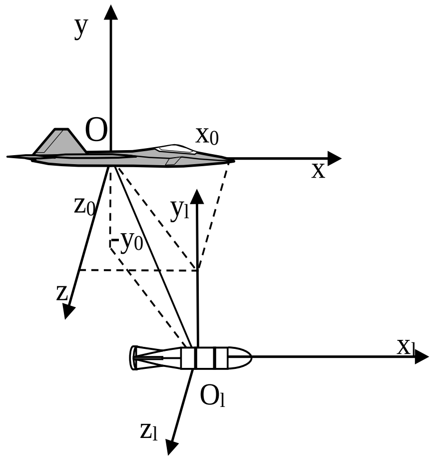

Figure 1. Determining the position of the load relative to the aircraft

The trajectory of the load is represented by a third-degree polynomial:
In general, the trajectory of the load at the moment of release is determined by solving the equations of motion for the center of mass (Bukhalev, 1966):

$$\dot{v} = \frac{1}{m}(P\cos\alpha\cos\beta - X - mg\sin\lambda);$$

$$\dot{\lambda} = \frac{1}{mv}[P(\cos\chi\sin\alpha + \sin\chi\sin\beta\cos\alpha) + \\ + Y\cos\chi - Z\sin\chi - mg\cos\lambda];$$

$$\dot{\varphi} = -\frac{1}{mv\cos\lambda}[P(\sin\chi\sin\alpha - \cos\chi\sin\beta\cos\alpha) + \\ + Y\sin\chi + Z\cos\chi]; \qquad 2)$$

$$\begin{aligned} \dot{x} &= v\cos\lambda\cos\varphi; \\ \dot{y} &= v\sin\lambda; \\ \dot{z} &= -v\cos\lambda\sin\varphi; \end{aligned}$$

where P is the thrust force of the engine expressed as a function P(t);

X, Y, Z are the aerodynamic forces corresponding to drag, lift, and lateral forces, expressed by the following known formulas:

$$\begin{aligned} X &= \left(C_{x0} + B(C_y^{\alpha})^2\alpha^2\right)\frac{S\rho v^2}{2}; \\ Y &= C_y^{\alpha}\alpha\frac{S\rho v^2}{2}; \\ Z &= C_z^{\beta}\beta_{\text{пл}}\frac{S\rho v^2}{2}, \end{aligned} \qquad (3)$$

C_{x0}, B, C_y^{α}, C_z^{β} are aerodynamic coefficients determined through calculating or experimental methods.

ρ - is the density of the atmosphere, which depends on altitude. When performing calculations, the function ρ(H) is approximated with analytical relationships;

S - is the characteristic area (reference cross-section);

The motion of the load is considered in the vicinity of the aircraft, i.e., in the disturbed zone.

The system of equations (1) can be represented analytically as a third-degree polynomial (Bukhalev, 1966; Stoykov, 2021).

$$\begin{aligned} \Delta x &= a_{x1}t + a_{x2}t^2 + a_{x3}t^3; \\ \Delta y &= a_{y1}t + a_{y2}t^2 + a_{y3}t^3; \\ \Delta z &= a_{z1}t + a_{z2}t^2 + a_{z3}t^3, \end{aligned} \tag{4}$$

$a_{x1}=v_x$;
$a_{x2}=(1/2)\Delta J_x - (\omega_y v_z - \omega_z v_y)$;
$a_{x3}= - (1/6)\,[2(\omega_y \Delta J_z - \omega_z \Delta J_y)+\omega^2 v_x]$;

$$a_{y1}=v_y; \tag{5}$$

$a_{y2}=(1/2)\Delta J_y - (\omega_z v_x - \omega_x v_z)$;
$a_{y3}= - (1/6)\,[2(\omega_z \Delta J_x - \omega_x \Delta J_z)+\omega^2 v_y]$;
$a_{z1}=v_z$;
$a_{z2}=(1/2)\Delta J_z - (\omega_x v_y - \omega_y v_x)$;
$a_{z3}= - (1/6)\,[2(\omega_x \Delta J_y - \omega_y \Delta J_x)+\omega^2 v_z]$;

where ΔJ is the difference between the acceleration of the load and the aircraft - $\Delta J=J_l - J_a$;

ω - the acceleration of the aircraft;
v - the speed of the load.

It is assumed that for loads symmetric with respect to the longitudinal axis, the lateral velocity of the load v_z is very small, such that it can be neglected (vz=0v_z = 0vz=0). Accordingly, the coefficients $a_{z1}=a_{z2}=a_{z3}=0$.

The coefficients (5) take the form:

$a_{x1}=v_x$;
$a_{x2}=(1/2)\Delta J_x + \omega_z v_y$;
$a_{x3}= - (1/6)\,[2(\omega_y \Delta J_z - \omega_z \Delta J_y)+\omega^2 v_x]$;

$$a_{y1}=v_y \tag{6}$$

$a_{y2}=(1/2)\Delta J_y - \omega_z v_x$;
$a_{y3}= - (1/6)\,[2(\omega_z \Delta J_x - \omega_x \Delta J_z)+\omega^2 v_y]$.

When using overloads, the coefficients (6) take the form (Bukhalev, 1966):

$a_{x1}=v_x$;
$a_{x2}=(1/2)(n_{lx} - n_x)g + \omega_z v_y$;
$a_{x3}= - (1/6)[2g\omega_y (n_{lz} - n_z) - 2g\omega_z(n_{ly} - n_y)+\omega^2 v_x]$;

$$a_{y1}=v_y; \qquad 7)$$

$a_{y2}=(1/2)(n_{ly} - n_{y;})g - \omega_z v_x$;
$a_{y3}= - (1/6)\,[2g\omega_x (n_{lx} - n_x) - 2g\omega_x(n_{lz} - n_z)+\omega^2 v_{y,}$

where $n_x = \frac{P - X}{G}; n_y = \frac{Y}{G}; n_z = \frac{Z}{G}$ are the overloads of the aircraft along its respective axes; $n_{xl} = \frac{P_l - X_l}{G_l}; n_{yl} = \frac{Y_l}{G_l}; n_{zl} = \frac{Z_l}{G_l}$ - the overloads of the load along its respective axes.

Using formula (7), the polynomial (4) describing the motion of the load in the vicinity of the aircraft takes the form:

$$\begin{aligned}
\Delta x &= v_x t + \left[\frac{1}{2}(n_{lx} - n_x)g + \omega_z v_y\right]t^2 - \frac{1}{6}\left[2g\omega_y(n_{lz} - n_z) - 2g\omega_z(n_{ly} - n_y) + \omega^2 v_x\right]t^3; \\
\Delta y &= v_y t + \left[\frac{1}{2}(n_{ly} - n_y)g - \omega_z v_x\right]t^2 - \frac{1}{6}\left[2g\omega_z(n_{lx} - n_x) - 2g\omega_x(n_{lz} - n_z) + \omega^2 v_y\right]t^3.
\end{aligned} \tag{8)}$$

To avoid a collision in the vertical plane between the aircraft and the released load, it is necessary to meet the condition:

$$\Delta y = y - y_0 = v_y t + \left[\frac{1}{2}(n_{ly} - n_y)g - \omega_z v_x\right]t^2 - \frac{1}{6}\left[2g\omega_z(n_{lx} - n_x) - 2g\omega_x(n_{lz} - n_z) + \omega^2 v_y\right]t^3 < 0 \tag{9}$$

Assuming that the load is released freely without applying vertical speed and the engine thrust P=0, (v_{ly}=v_{ly}=0), then $n_{lz} - n_z \cong 0$ and n_{lx} is significantly less than zero (Bukhalev, 1966; Stoykov, 2020). Accepting these assumptions, formula (8) takes the form:

$$\begin{aligned}
\Delta x &= \frac{1}{2}(n_{lx} - n_x)gt^2 + \frac{1}{3}\omega_z(n_{ly} - n_y)gt^3; \\
\Delta y &= \frac{1}{2}(n_{ly} - n_y)gt^2 - \frac{1}{3}\omega_z(n_{lx} - n_x)gt^3.
\end{aligned} \tag{10}$$

In the case of free release of the load (formula 8), the condition for safe release (9) takes the form:

$$3(n_{ly} - n_y) < 2\omega_z(n_{lx} - n_x)t \tag{11}$$

In the case of horizontal flight, the angular velocity of the aircraft is $\omega_z \cong 0$, therefore:

$$n_y > n_{ly}, \text{ or} \tag{12}$$

$$\frac{C_y^\alpha \alpha S V^2}{m} > \frac{C_{yl} S_l v^2}{m_l} \tag{13}$$

For horizontal flight, it is necessary to meet the condition n_y=1, therefore it is necessary $\frac{C_{yl} S_l v^2}{m_l} < 1$. For high speeds of the aircraft and for loads that have a large mass (unguided bombs) and a small lift force approaching zero, the condition for safe release of the load is satisfied. For low speeds of the aircraft and for loads that have a small mass (containers) relative to their lift force, it is necessary to apply a forced vertical speed. Assuming we have a forced vertical speed v_y, the second equation of formula (10) takes the form:

$$\Delta y = y - y_0 = v_y t + \left[\frac{1}{2}(n_{ly} - n_y)g\right]t^2 - \frac{1}{6}\left[2g\omega_z(n_{lx} - n_x) + \omega^2 v_y\right]t^3 < 0 \tag{14}$$

From formula (14), the necessary vertical speed that must be applied to the load for it to safely separate from the aircraft is calculated:

$$v_y < \frac{2g\omega_z(n_{lx} - n_x)t^2 - 3(n_{ly} - n_y)gt}{6 - \omega^2 t^2} \quad (15)$$

he forced vertical speed v_y has a negative value, from which it follows that in absolute terms:

$$v_y > \frac{2g\omega_z(n_{lx} - n_x)t^2 - 3(n_{ly} - n_y)gt}{6 - \omega^2 t^2}. \quad (16)$$

For horizontal flight, condition (16) takes the form:

$$v_y > \frac{-(n_{ly} - 1)gt}{2}. \quad (17)$$

Results and Discussion

The relative distance Δy between the load and the aircraft after release has been calculated. The study is conducted for releases at speeds V ranging from 180 m/s to 300 m/s, from an altitude H=500 m, during horizontal flight and dive at an angle $\lambda = -30^0$. The release of two loads has been simulated:

1. The first load has a characteristic time Θ_1= 20.44 s, a diameter d_1=0.4 m, mass m_{l1}=520 kg
2. The second load has a characteristic time Θ_2= 21.39 s, a diameter d_2=0.203 m, mass m_{l2}=64 kg.

For this purpose, a simplified model of the aircraft's motion has been developed (Biliderov et al., 2024; Kambushev et al., 2020) using equations (1). From the aircraft model, the overloads on the aircraft and the loads under specific conditions are determined. Then, the relative distance Δy between the load and the aircraft is calculated, as well as the necessary vertical speed for the load's safe separation. When releasing the two loads from horizontal flight, the overload n_y on the aircraft is approximately 1 (from the condition for horizontal flight - n_y=1). The overload n_x is approximately 0.

The results obtained for the relative distance Δy for the two loads during horizontal flight are presented in Table 1. From Table 1, it can be seen that for the entire range of conditions for releasing the load from horizontal flight, the safety condition is met, i.e., Δy<0. As the release speed of both loads increases, Δy decreases in absolute value. This can be explained by the fact that with increasing release speed, the lift force of the load increases. It is observed that the load with a greater mass has a larger Δy in absolute terms during its passage through the disturbed zone of the aircraft (Table 1). This is due to the greater mass of the second load. Under the specified conditions for releasing from horizontal flight for both loads, it is evident that condition (12) is satisfied. The overload $n_{lx1,2}$ for both loads increase in absolute value due to the increase in release speed.

Table 1. The relative distance Δy between the load released from horizontal flight and the aircraft

Relative distance Δy			
	V=180 m/s	**240 m/s**	**300 m/s**
Δy_1, m	-2.0287	-1.7641	-1.4319
n_{lx1}	-0.5705	-1.0494	-2.3703
n_{ly1}	0.1463	0.2601	0.4063
Δy_2, m	-2.2048	-2.0770	-1.9147
n_{lx2}	-0.1383	-0.2544	-0.5746
n_{ly2}	0.0699	0.1243	0.1942

In Table 2, the relative distances Δy for the two loads released from a dive with negative overload - n_y= - 1 and very small values of overload n_x are presented. From the table, it can be seen that for the entire range of release speeds of both loads, the condition for safe separation from the aircraft is not met. Therefore, under these conditions, it is necessary to apply additional vertical speed to the load at the moment of separation. It is evident that forces are acting on both loads that prevent them from separating from the aircraft. For both loads, as the speed increases, $\Delta y_{1,2}$ also increase due to the increase in $n_{ly1,2}$ for both loads. Similarly, as with the release from horizontal flight, during the release from a dive, as the mass of the load increases, Δy_1 decreases.

Table 2. The relative distance Δy between the load and the aircraft released from a dive with $\lambda = -30^0$

Relative distance Δy			
	V=180 m/s	**240 m/s**	**300 m/s**
Δy_1, m	2.6835	2.9263	3.2014
Δy_2, m	2.5242	2.6483	2.7974

In Table 3, the minimum values of the vertical speed that must be applied to the loads to ensure safe separation are presented. The nature of the variation in $v_{y1,2}$ is the same as that of $\Delta y_{1,2}$.

Table 3. The calculated necessary vertical speed for the safe separation of the load released from a dive with $\lambda = -30^0$

Nessessary vertical speed v_y			
	V=180 m/s	**240 m/s**	**300 m/s**
v_{y1}, m/s	-3.8612	-4.2104	-4.6063
v_{y2} m/s	-3.6320	-3.8105	-4.0250

The release of two loads with approximately the same external dimensions but different characteristics has been simulated from horizontal flight at an altitude of H=500H = 500H=500 m and a speed of V=300V = 300V=300 m/s:

1. The first load has a characteristic time Θ_1= 21 s, C_{y1} = 0.23, d_1=0.4 m, mass m_{l1}=120 kg.
2. The second load has a characteristic time Θ= 20 s, C_y = 0.17, d_2=0.4 m, маса m_{l2}=520 kg.

Table 4. The relative distance Δy for loads with identical dimensions released from an aircraft in horizontal flight

Relative distance Δy	
	V=300 m/s
Δy_1 m	0.6699
n_{lx1}	-1.5922
n_{ly1}	1.2902
Δy_2, m	-2.0314
n_{lx2}	0.4030
n_{ly2}	0.1406
v_{y2} m/s	2.9228

From the table, it is evident that the first load, which has a smaller mass but a larger lift coefficient, does not meet the condition for safe release. For the first load, condition (12) is also not satisfied, $n_y > n_{ly}$. It is necessary to apply an initial vertical speed v_{y2} >2.9228 m/s to this load.

Conclusion

From the conducted study, the following conclusions can be drawn:

1. The derived analytical formulas for determining the safe conditions for the separation of loads from the aircraft and the minimum vertical speed to be applied to the load can be used for preliminary calculations for the release of specific load samples.
2. To ensure the safe separation of the load, the aircraft must be piloted in such a way that the overload on the aircraft n_y is greater than the overload n_{yl} on the load.
3. For the safe release of bulky loads with a small mass from an aircraft, mechanisms for applying an initial vertical speed upon separation must be used.

Recommendations

For each specific aircraft, it is essential to strictly adhere to the requirements for the safe separation of loads, ensuring that for loads with a large mass and a low lift coefficient, a solid piston should not be used to apply initial vertical speed to the load. This could lead to the breaking of the supporting levers of the locking mechanism. When releasing bulky loads with a small mass, mechanisms must be employed to apply initial vertical speed to ensure safe separation from the aircraft.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the author.

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