# Dynamic Analysis and Safety Study of Catapult Launch for UAV

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**Abstract:** Aiming at the selection of structural parameters and layout of the launch method, which are concerned by technicians at the initial stage of designing a new unmanned aerial vehicle (UAV), a dynamic model of catapult launch is established by taking a UAV as the research object. On this basis, the influence of the main parameters such as the length of the launch bar and the installation point of the launch bar on the fuselage on safety of the UAV catapult launch is analyzed, and the simulation results show that increasing the length of the launch bar, decreasing the horizontal distance and increasing the vertical distance between the installation point and the centroid of the UAV can increase the pitch angle of the UAV, reduce the axial load and slow down the oscillation of the nose landing gear during the process of catapult launch, which can effectively improve safety of catapult launch. When the length of the launch bar is increased to 800 mm, the horizontal distance is decreased to 289 mm or the vertical distance is increased to 365 mm, there is a risk that the nose landing gear will leave the track surface in advance. When the horizontal distance is increased to 589 mm or the vertical distance is decreased to 265 mm, the sudden-extension of the nose landing gear will appear.

**Key words:** unmanned aerial vehicle (UAV); catapult launch; launch bar; nose landing gear; dynamics

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## 0 Introduction

The take-off performance of unmanned aerial vehicle (UAV) is an important part that affects the combat effectiveness of UAV. At present, the ground take-off of medium and large UAVs mainly adopts two ways: Ground sliding and towed catapult launch. Among them, with the help of external propulsion, the towed catapult launch makes the UAV take off at a short distance and rapidly, which greatly improves the catapult efficiency.

Up to now, many scholars have done a lot of research on towed catapult launch. Ref.[1] conducted a full-scale experimental study on the front-wheel towed catapult launch of carrier-based aircraft. The U.S. Military Standard[2-4] gave the corresponding specifications and standards for the catapult system of the nose landing gear and the hold bar of carrier-based aircraft. Ref.[5] established safety criteria of the carrier-based aircraft catapult launch, and Ref.[6] conducted relevant research on the adaptability of aircraft and ships based on the safety criteria of catapult launch of carrier-based aircraft. Ref.[7] established the dynamic model of catapult launch of carrier-based aircraft. Refs.[8-9] conducted relevant studies on the adaptability of aircraft and ships. Ref.[10] designed the corresponding flight control system. Refs.[11-12] analyzed the dynamics of catapult sudden-extension. Ref.[13] analyzed the dynamic response of the structure, and Refs.[14-17] studied the influence factors of the catapult launch safety. In addition, a modified catapult type of a carrier-based UAV was taken as the research object to carry out the dynamic response analysis of towed

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catapult launch in Ref.[18]. It can be seen that at present, most scholars' researches on the dynamics of catapult launch mainly focus on the influence of overall parameters such as aircraft mass and drag force on the dynamic characteristics of catapulting process, while the impact of the structural changes of launch bar on the safety of aircraft has rarely been studied.

With the development of modern warfare situation and UAV technology, modern battlefield has put forward functional requirements such as stealth for some new UAVs, and the resulting limitations such as the structural size and the retraction space of the landing gear make some UAVs need to install launch bar on the fuselage abdomen, which is different from the traditional front-wheel towed catapult launch that installs the launch bar on the nose landing gear. The impact of the new launch method on the safety performance of aircraft catapulting is not clear yet, so it is necessary to study it in depth.

In this paper, aiming at the selection of structural parameters and layout of the launch method that the technicians concern at the initial stage of designing a new UAV, a dynamic model of catapult launch including the new structural layout of launch method is established. The influence of the main parameters such as the length and the installation position of the launch bar on the safety of the UAV catapult launch is analyzed. The research results can provide a certain theoretical references and technical reserves for the structural design, the overall adaptation layout and the formulation of the catapult launch safety criteria of the new UAV launch method.

## 1 Dynamic Model of UAV Catapult Launch

According to the motion characteristics during catapult launch process of the UAV, the fuselage is simplified to a rigid body, the whole aircraft mass is concentrated at the centroid of the UAV, and the UAV runs symmetrically in its own plumb plane. The dynamic modeling process of the catapulting and sliding process of the new UAV is as follows.

### 1.1 Aerodynamic model

Since the UAV moves symmetrically in the plumb plane, only the lift force, drag force and pitch moments of the aircraft are considered, and the specific expressions are as follows

$$L=\frac{1}{2}\rho_{\mathrm{air}}V^2SC_{\mathrm{L}} \tag{1}$$

$$D=\frac{1}{2}\rho_{\mathrm{air}}V^2SC_{\mathrm{D}} \tag{2}$$

$$M_z=\frac{1}{2}\rho_{\mathrm{air}}V^2SC_{mz}\bar{c} \tag{3}$$

where $L$ is the lift of aircraft; $D$ the air drag of aircraft; $M_z$ the pitch moment of aircraft; $\rho_{\mathrm{air}}$ the atmospheric density; $V$ the airspeed of aircraft; $S$ the reference area of aircraft wings; $C_{\mathrm{L}}$ the lift coefficient; $C_{\mathrm{D}}$ the drag coefficient; $C_{mz}$ the pitch moment coefficient; and $\bar{c}$ the mean aerodynamic chord.

### 1.2 Dynamic model of landing gear

Shock absorbers for aircraft landing gear are oil-gas shock absorbers, and the shock absorber strut force includes air spring force, oil damping force, internal friction and structural limiting force

$$F_{\mathrm{s}}=F_{\mathrm{a}}+F_{\mathrm{h}}+F_{\mathrm{f}}+F_{\mathrm{l}} \tag{4}$$

where $F_{\mathrm{s}}$ is the shock absorber strut force; $F_{\mathrm{a}}$ the air spring force; $F_{\mathrm{h}}$ the oil damping force; $F_{\mathrm{f}}$ the internal friction; and $F_{\mathrm{l}}$ the structural limiting force.

Assuming that the oil is not compressible and the volume of the shock absorber cavity is constant, the expression of the air spring force is

$$F_{\mathrm{a}}=A_{\mathrm{a}}\left[P_0\left(\frac{V_0}{V_0-A_{\mathrm{a}}s}\right)^{\gamma}-P_{\mathrm{atm}}\right] \tag{5}$$

where $A_{\mathrm{a}}$ is the pressure area of the shock absorber; $P_0$ the initial inflation pressure of the shock absorber; $V_0$ the initial inflatable volume of the shock absorber; $P_{\mathrm{atm}}$ the external atmospheric pressure; $\gamma$ the air variability coefficient; and $s$ the stroke of the shock absorber.

A constant oil hole shock absorber with side oil hole is used, and the expression of the oil damping force is

$$F_{\mathrm{h}}=\frac{\rho_{\mathrm{oil}}A_{\mathrm{h}}^3}{2C_{\mathrm{d}}^2A_{\mathrm{d}}^2}\dot{s}|\dot{s}|+\frac{\rho_{\mathrm{oil}}A_{\mathrm{hs}}^3}{2C_{\mathrm{ds}}^2A_{\mathrm{ds}}^2}\dot{s}|\dot{s}| \tag{6}$$

where $\rho_{\mathrm{oil}}$ is the oil density; $A_{\mathrm{h}}$ and $A_{\mathrm{hs}}$ are the oil pressure area in the main and return oil chamber of the shock absorber; $A_d$ and $A_{ds}$ the oil hole area of the main and return oil chamber; $C_d$ and $C_{ds}$ the shrinkage coefficient of the main and return oil chamber.

The internal friction of the shock absorber $F_f$ can be considered to be mainly composed of two parts: the friction $F_{f1}$ caused by the pressure on the inner wall of the shock absorber and the friction $F_{f2}$ caused by the bending of the shock absorber pillar, and its expression is

$$F_f = F_{f1} + F_{f2} \tag{7}$$

$$F_{f1} = k_m F_a \frac{\dot{s}}{|\dot{s}|} \tag{8}$$

$$F_{f2} = \mu_b \left( N_0 + |N_U| + |N_L| \right) \frac{\dot{s}}{|\dot{s}|} \tag{9}$$

where $k_m$ is the friction coefficient; $\mu_b$ the friction coefficient between the shock absorber strut and the outer cylinder; $N_0$ the preload force; $N_U$ the normal force at the upper bushing of the shock absorber strut; and $N_L$ the normal force at the lower bushing of the shock absorber strut.

The structural limiting force $F_l$ acts at the limit where the shock absorber operates, and its expression is

$$F_l = \begin{cases} k_l s & s < 0 \\ 0 & 0 \leqslant s \leqslant s_{max} \\ k_l(s - s_{max}) & s > s_{max} \end{cases} \tag{10}$$

where $k_l$ is the coefficient of structural limiting stiffness; and $s_{max}$ the maximum stroke of the shock absorber.

The dynamic model of the landing gear tire is established using the point contact theory, the calculation method of tire vertical force is shown in Fig.1, and the calculations for the action point $C_p$ and direction $g$ of the tire force $F_n$ are shown in Eqs.(11,12)[19].

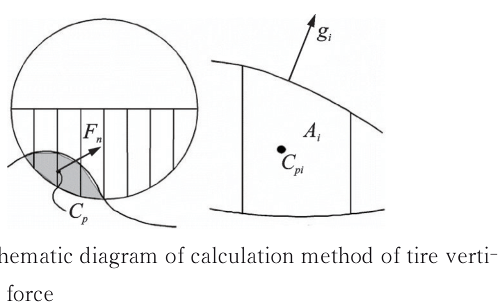



Fig.1 Schematic diagram of calculation method of tire vertical force

$$C_p = \frac{\sum A_i C_{pi}}{\sum A_i} \tag{11}$$

$$g = \frac{\sum A_i g_i}{\left| \sum A_i g_i \right|} \tag{12}$$

where $C_p$ is the tire force point; $C_{pi}$ the centroid coordinates of the compressive part of the $i$th element; $g_i$ the direction vector of the force on the $i$th element; and $A_i$ the compressed area of the $i$th element.

## 1.3 Dynamic model of UAV catapulting and sliding

In the process of UAV catapult launch, the forces during the catapulting and sliding process are complicated, and related to whether the UAV can take off safely. Therefore, according to the mechanical characteristics, the catapulting and sliding dynamic model is established and the dynamic analysis is carried out. The overall force diagram of the UAV during this process is shown in Fig.2.

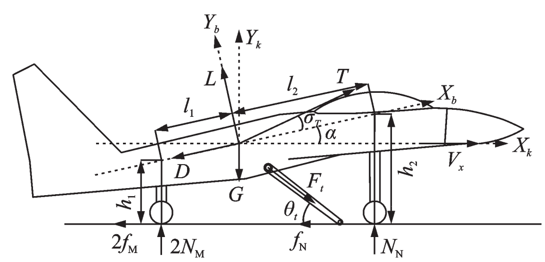



Fig.2 Force analysis of UAV in catapulting and sliding

$$\begin{cases} ma_x = T\cos(\sigma_T + \alpha) - L\sin\alpha - \\ \qquad D\cos\alpha + F_t\cos\theta_t - \left(2f_M + f_N\right) \\ ma_y = T\sin(\sigma_T + \alpha) + L\cos\alpha - D\sin\alpha - \\ \qquad F_t\sin\theta_t + 2N_M + N_N - G \\ I_z\dot{\omega}_z = M_z + M_T + N_N\cos\alpha l_2 - \\ \qquad f_N(h_2 - l_2\sin\alpha) - 2N_M l_1\cos\alpha - \\ \qquad 2f_M(h_1 - l_1\sin\alpha) + F_t\cos\theta_t l_t - F_t\sin\theta_t h_t \end{cases} \tag{13}$$

where $m$ is the mass of the aircraft; $I_z$ the movement of inertia of the aircraft rotating around the $z$-axis that goes through the aircraft's centroid; $\dot{\omega}_z$ the pitch angle acceleration; $T$ the thrust of the engine; $F_{tx}$ the traction that acts directly on the end of the launch bar; $F_{ty}$ the vertical binding force; $F_t$ the axial force of the launch bar; $\theta_t$ the angle between the launch bar and the road surface; $G$ the gravity of the aircraft; $M_T$ the thrust torque of the engine; $\sigma_T$ the installation angle of the engine; and $\alpha$ the angle of attack of the aircraft. $a_x$ and $a_y$ are the accelerations of the aircraft's centroid in the horizonal and vertical directions along the track surface respectively; $f_{\mathrm{M}}$ and $f_{\mathrm{N}}$ the frictional force of the main and nose landing gear tires respectively; $N_{\mathrm{M}}$ and $N_{\mathrm{N}}$ the supporting force of the main and nose landing gear tires, respectively; $l_1$ and $l_2$ the distances form the aircraft centroid which is projected onto the $X_b$-axis of the body coordinate system; $h_1$ and $h_2$ the distances from the action points on the main and nose landing gear tires to the $X_b$-axis along the $Y_k$-axis of the aircraft; $l_t$ and $h_t$ the distances from the installation point of launch bar to the aircraft centroid along the horizontal and vertical directions of the track surface, respectively.

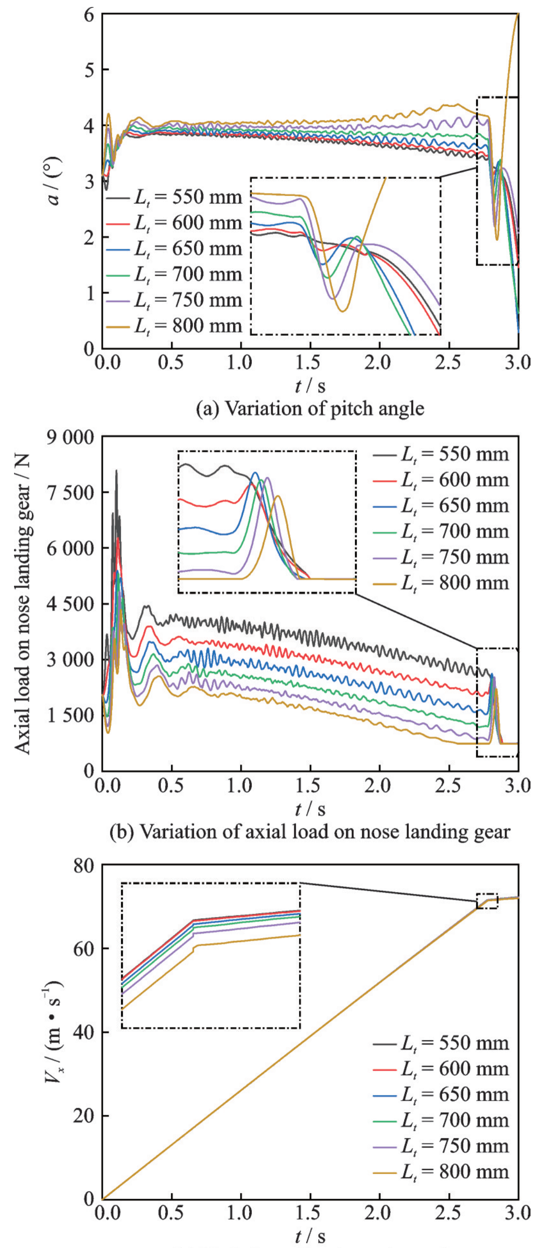
## 2 Analysis of Influence of Launch Bar Parameters on Catapulting Take-Off Performance of UAV

Taking a new UAV as an example to study the influence of launch bar parameters on the catapulting take-off performance. The catapulting stroke was set to 100 m, the thrust-to-weight ratio was 0.4, and the constant traction force at the end of the launch bar was 30 kN. The initial installation point of the launch bar on the UAV was ($x_0$, $y_0$), where $x_0$=389 mm, $y_0$=315 mm. The simulation time was 3 s. This paper mainly discussed the influence of the structural parameters and installation position of the launch bar on the safety performance of catapult launch from the pitch angle at the end of the catapulting and sliding stage, the axial load of nose landing gear and the speed of the UAV.

### 2.1 Influence of launch bar length

Assuming that the launch bar was located at the initial installation point ($x_0$, $y_0$), the effects on the dynamic characteristics of the UAV catapult launch were studied when the length of the launch bar $L_t$ was 550, 600, 650, 700, 750, 800 mm, respectively.

The simulation results were shown in Fig.3. It can be seen that when the position of the installation point of the launch bar remains unchanged, with the increase of $L_t$, the maximum pitch angle of the UAV during catapulting and sliding process increases. At the same time, the maximum axial load of the nose landing gear decreases, the oscillation slows down, and the UAV heading speed $V_x$ at the moment of traction sudden unloading decreases slightly. When $L_t$ is increased to 800 mm, the axial load of the nose landing gear decreases to the load value when it is full elongation, that is, leaving the




(a) Variation of pitch angle

(b) Variation of axial load on nose landing gear

(c) Variation of horizontal speed

Fig.3 Parameter curves of the UAV catapult launch with different length of launch bar ($L_t$)

track surface, before the traction suddenly unload, due to the excessive head-up torque of the UAV during this process, which does not meet the safety performance requirements of the UAV catapult launch.

Therefore, on the premise of ensuring catapulting the UAV safely, increasing the length of the launch bar appropriately can increase the pitch angle of the UAV during the catapulting and sliding process, improve the lift of the UAV, reduce the axial vibration load of the nose landing gear, and then improve the catapult launch safety.

### 2.2 Influence of horizontal distance between installation point of launch bar and centroid of UAV

Assuming that $L_t$=650 mm, the installation point of the launch bar on the fuselage was $(x_t, y_0)$, where $x_t$ is the horizontal distance forward from the centroid of the UAV. When $x_t$ was 289, 389, 489, 589, 689, and 789 mm, the influence of the catapult launch performance of the UAV was studied.

According to the simulation results shown in Fig.4, it can be known that with the increase of $x_t$, the pitch angle of the UAV during the catapulting and sliding process decreases. The peak value of the axial load of the nose landing gear increases, and the oscillation intensifies. The $x_t$ has little influence on the speed of the UAV, and the take-off speed can be researched in all conditions. When $x_t$ is increased to 589 mm, sudden-extension of the nose landing gear appears after the sudden unloading of the traction, and the sudden-extension become more obvious with the increase of $x_t$. When $x_t$ is decreased to 289 mm, the nose landing gear of the UAV leaves the track surface before the traction suddenly unload, making the UAV unable to catapult and take off safely.

Therefore, under the premise of meeting the structural strength requirements of the UAV, taking the axial load and the oscillation situation of the nose landing gear into account, appropriately increasing the horizontal distance between the installation point of the launch bar and the centroid of the UAV can increase the pitch angle of the UAV at the end moment of the nose landing gear sudden-extension, which is conductive to the safe catapulting take-off of the UAV.

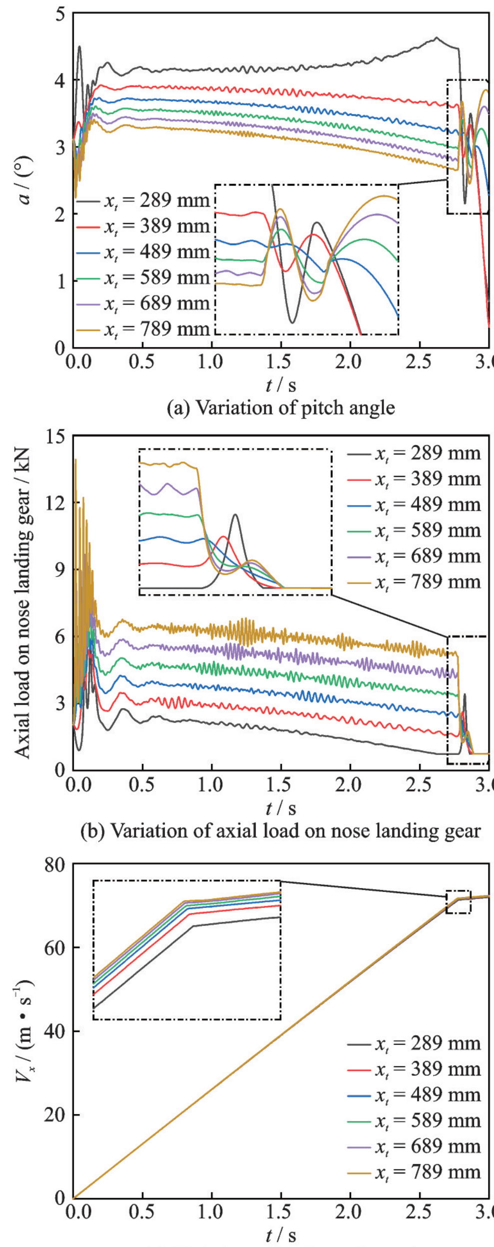


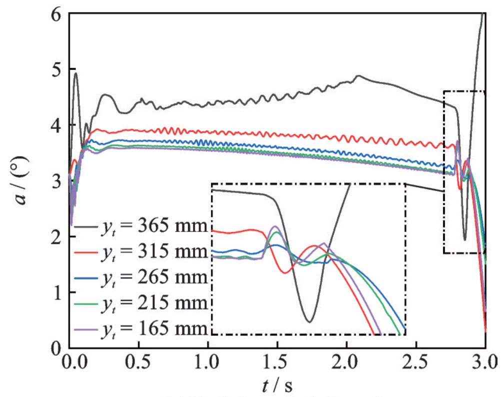

Fig.4 Parameter curves of the UAV catapult launch with different horizontal distance forward from the centroid of the UAV ($x_t$)

### 2.3 Influence of vertical distance between installation point of launch bar and centroid of UAV

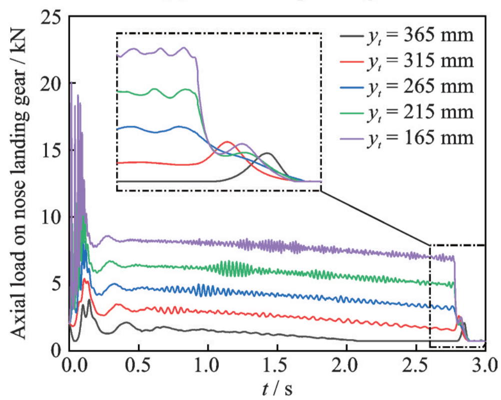
Assuming that $L_t$=650 mm, the installation point of the launch bar on the fuselage was $(x_0, y_t)$, where $y_t$ is the vertical distance downward from the centroid of the UAV. When $y_t$ was 365, 315, 265, 215, and 165 mm, the influence of the catapulting take-off performance of the UAV was studied.

According to the simulation results shown in

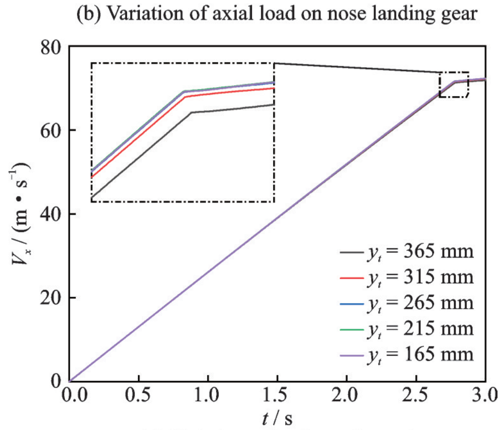
Fig.5, it can be known that with the decrease of $y_t$, the pitch angle of the UAV during the catapulting and sliding process decreases. The peak value of the axial load of the nose landing gear increases, and the oscillation intensifies. The $y_t$ has little influence on the speed of the UAV. When $y_t$ is decreased to 265 mm, sudden-extension of the nose landing gear appears after the sudden unloading of the traction, and the pitch angle of the UAV increases with the decrease of $y_t$ at the end moment of the sudden-extension. When $y_t$ is increased to 365 mm, the nose



(a) Variation of pitch angle



(b) Variation of axial load on nose landing gear



(c) Variation of horizontal speed

Fig.5 Parameter curves of UAV catapult launch with different vertical distance downward from the centroid of the UAV ($y_t$)

landing gear of the UAV leaves the track surface before the traction suddenly unload, making the UAV unable to catapult and take off safely.

Therefore, under the premise of meeting the structural strength requirements of the UAV, taking the axial load and the oscillation situation of the nose landing gear into account, appropriately decreasing the vertical distance between the installation point of the launch bar and the centroid of the UAV can increase the pitch angle of the UAV at the end moment of the nose landing gear sudden-extension, which is conductive to the safe catapulting take-off of the UAV.

## 3 Conclusions

A catapult launch dynamic model including the structural layout of a new launch method was established for a UAV, and the influence of the structural parameters and layout of the launch bar on the catapult launch performance of the UAV was analyzed in detail, and the following conclusions are obtained:

(1) During the catapulting and sliding process, the structural parameters and installation position of the launch bar have a great influence on the pitch angle of the UAV and the dynamic response of the nose landing gear, but have little influence on the heading speed of the UAV.

(2) With the increase of the length of the launch bar, the decrease of the horizontal distance between the installation point of the launch bar and the centroid of the UAV, or the increase of the vertical distance, the pitch angle during the catapulting and sliding process can be increased, which is beneficial to the UAV to obtain greater lift; and at the same time, the axial load of the nose landing gear can be reduced, the oscillation can be slowed down, and the fatigue can be alleviated. When the length of the launch bar is increased to 800 mm, the horizontal distance between the installation point of the launch bar and the centroid of the UAV is decreased to 289 mm, or the vertical distance is increased to 365 mm, the head-up torque of the UAV is too large so that the nose landing gear leaves the

track surface before the sudden unloading of the traction, which is not conductive to safe catapult launch.

(3) When the horizontal distance between the installation point of the launch bar and the centroid of the UAV is increased to 589 mm, the vertical distance is decreased to 265 mm, the nose landing gear can extend suddenly after the sudden unloading of the traction, assisting the UAV to obtain a larger pitch angle to take off, which is conductive to improving the safety of the catapult take-off of the UAV.

(4) The influence of the structural layout of the new launch method on the dynamic characteristics of the UAV catapult launch was investigated by the dynamic research on the structural parameters and layout form of the new launch method. The research results can provide a certain theoretical references and technical reserves for the structural design, the overall adaptation layout and the formulation of the catapult launch safety criteria of the new UAV launch method.

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**Author contributions** Prof. **NIE Hong** designed the study and raised the idea. Ms. **LUO Jiangxue** built the simulation model, analyzed the results and wrote the manuscript. Dr. **PENG Yiming** and Prof. **WEI Xiaohui** contributed to data for the analysis, and the discussion and background of the study. Mr. **HAO Jiayu** helped build the simulation model. All authors commend on the manuscript draft and approved the submission.

**Competing interests** The authors declare no competing interests.

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# 某无人机弹射起飞动力学分析与安全性研究

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**摘要：**针对新型无人机设计初期技术人员关心的弹射方式的结构参数与布局形式的选型问题，以某无人机为研究对象，建立了无人机弹射起飞动力学模型。在此基础上分析了弹射杆长度、弹射杆机身安装点等主要参数对无人机弹射起飞安全性的影响，仿真结果表明：弹射杆长度增加、安装点距无人机质心水平距离减小、垂直距离增加均可增加弹射过程无人机俯仰角，减小前起落架轴向载荷及振荡，能够有效提高弹射起飞安全性；当弹射杆长度增加至800 mm，安装点距无人机质心水平距离减小至289 mm，垂直距离增加至365 mm，会有前起落架提前离地的风险；当安装点距无人机质心水平距离增加至589 mm，垂直距离减小至265 mm，前起落架会出现突伸现象。

**关键词：**无人机；弹射起飞；弹射杆；前起落架；动力学