Dynamics Analysis of Carrier-based UAVs with Ski-jump Launch

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Abstract. Sinking has a direct influence on launch safety of carrier-based UAVs, occurred just while leaving carrier board caused of disappearance of ground effect. A dynamics model of an UAV was developed and some mechanical and dynamics analysis were given out to build its dynamics simulation model of ski-jump launch. Based on the simulation results, some important parameters were analyzed, such as trace, velocity and loadings of landing gears. By changing the values of engine thrust and mass of the UAV, it was validated that decreasing the mass properly or increasing thrust would reduce the sinking and improve launch trace to make it safer.

1. Introduction

Unmanned air vehicles (UAVs) can carry out different kinds of mission, such as reconnaissance, pre-warning, electromagnetic countermeasure and attack, and own attractive advantages of low cost and no casualties, to be more important in research of carrier-based equipment. For its specific environment, launch safety is one of key points in research of carrier-based UAVs, especially in the way of ski-jump, which is the first choice of our country to develop carrier-based UAVs for it requires less carrier equipments and works on deck, and owns higher stability.

Launch of UAVs is complex dynamics course of multi-system, disturbed by the motion of aircraft carrier, deck wind and ground effect. Dynamics analysis of launch is to seek its regularity and find solution of problems, especially to reject ground effect, which makes UAVs sink while leaving carrier board and influence launch safety directly.

Previous research work focused on dynamics analysis of catapult, for it is so popular and adopted on most of carriers in the world [1-5]. Fewer paper discussed ski-jump, and mostly studied on launching performance. Paper [6] presented a methodology for performance analysis and control system design for a naval combat aircraft. In paper [7], a simulation effort is underway to evaluate various ramp profiles, ramp optimization methodologies, and minimum launch airspeed criteria. An analytical study was shown to predict the reduction in takeoff distance that can be achieved with a jump nose gear in paper [8]. Paper [9] designed a new specific launch way which introduce ramp profile into catapult and only the nose landing gear went to the ramp profile after the catapult process, and its simulation results indicated that the flight path sinking was decreased obviously. However, few paper shown work on UAVs with ski-jump. UAVs own smaller mass and thrust, and can be influenced more easy by external disturbance while launching. So in this paper, some dynamics analysis work was done on ski-jump launch of UAVs, especially influence factors on sinking.
2. Dynamics Analysis of Launch

2.1. Dynamics Model of UAVs
For buffer system of landing gear is flexible, the UAV model is simplified as a multi-system dynamics model with 5 freedoms (figure 1), including vertical and horizontal motions of body, pitch motion of body, vertical motions of nose and main landing gears [10].

![Figure 1. A simplified dynamic model of UAV.](image)

2.2. Mechanical Analysis
Some assumed conditions are as follow: no wind; the mass of UAV and thrust of engine are invariable; no rolling and yaw motion. When launching, the forces on body include gravity, thrust of engine, aero dynamic, vertical forces and friction forces of tires (figure 1).

2.2.1. Gravity.
G = mg
(1)
In equation (1), m means mass of the UAV, g means the gravitational acceleration.

2.2.2. Thrust of Engine
Thrust of engine P is located in the symmetrical plane Ox, and makes up declination angle $\sigma$ with longitudinal axis $x$ and eccentricity is $e_p$ to center of mass O.

2.2.3. Aero-dynamics
For the UAV moves in the vertical plane, only consider three kinds of aero dynamic: lift $F_L$, drag $F_D$ and pitch moment $M_z$. Their calculating formulas are

$$F_L = \frac{1}{2} \rho v^2 S C_L$$
(2)

$$F_D = \frac{1}{2} \rho v^2 S C_D$$
(3)

$$M_z = \frac{1}{2} \rho v^2 S b_z m_z$$
(4)

where $\rho$ means the air density, $\rho = 1.225 \text{kg/m}^3$; $v$ means velocity of its mass center; $S$ means square of wings; $C_L$ means lift coefficient; $C_D$ means drag coefficient; $b_z$ means air-powered chord; $m_z$ means pitch moment coefficient.

2.2.4. Vertical Forces of Tires
$$F_i = K_\delta \delta + C_\delta \delta'$$
(5)
In the equation (5), $K_\delta$ means equivalent stiffness coefficient; $\delta$ means vertical decrement; $C_\delta$ means equivalent damp coefficient; $\delta'$ means vertical compress velocity.

### 2.2.5. Friction Forces of Tires

$$f = \mu F$$  \hspace{1cm} (6)$$

where $\mu$ means friction coefficient of tires.

### 2.3. Dynamic Equation of Launch

The launching course of UAVs can be divided as three phases: on horizontal deck, on curved deck and the instant of leaving out of carrier$^{(11)}$.

#### 2.3.1. The Phase on Horizontal Deck

Forces on UAV in the phase on level deck is shown in figure 2. The dynamic equation of vertical movement of body is

$$m_y^* = P\sin(\sigma_p + \theta) + F_L \cos \theta - F_D \sin \theta - mg + 2F_{SM} + F_{SN}$$  \hspace{1cm} (7)$$

where $\sigma$ means the pitch angle; $\theta$ means the rake angle (In this phase, $\theta$ is equal to $\theta$); $F_{SN}$ and $F_{SM}$ mean the axial forces of buffer system of nose and main landing gears.

The dynamic equation of pitch movement is

$$I_z\theta^* = M_y(P) + 2M_y(F_{SM}) + M_y(F_{SN}) + M_z$$  \hspace{1cm} (8)$$

where $I_z$ means the rotary inertia around z axis; $M_y(P)$ means the force moment of thrust $P$ to mass center of UAV body; $M_y(F_{SM})$ and $M_y(F_{SN})$ mean the force moments of $F_{SM}$ and $F_{SN}$ to mass center of UAV body individually.

The vertical dynamic equations of inelastic stayed mass of nose and main landing gears are:

$$m_n y^* = F_{YN} - F_{SN} - m_n g$$  \hspace{1cm} (9)$$

$$m_M y^* = F_{YM} - F_{SM} - m_M g$$  \hspace{1cm} (10)$$

where $m_n$ and $m_M$ mean the inelastic stayed mass of nose and main landing gears; $F_{YN}$ and $F_{YM}$ mean the vertical opposite forces of tires.

The dynamic equation of horizontal movement is

$$(m + m_n + 2m_M) x^* = P\cos(\sigma_p + \theta) - F_D \sin \theta - F_D \cos \theta - F_f$$  \hspace{1cm} (11)$$

where $F_f$ means the friction force.
2.3.2. The Phase on Curved Deck
In this phase, the force of UAV is shown in figure 3. The dynamic equation of vertical movement is

\[ m\dddot{y} = P\sin(\sigma_p + \theta) + F_c \cos \theta - F_d \sin \theta - mg + (2F_{SM} + F_{SN}) \cos \delta \]  \hspace{1cm} (12)

where \( \delta \) means refluxed angle of curved deck. In this phase, \( \delta \) is equal to \( \theta \), and \( \theta = \alpha + \theta \), where \( \alpha \) means the angle of attack.

\[ \delta \]

Figure 3. Forces on UAV when moving on curved deck.

The dynamic equation of horizontal movement is

\[ mx = P\cos(\sigma_p + \theta) - F_c \sin \theta - F_d \cos \theta - (2F_{SM} + F_{SN}) \sin \delta \]  \hspace{1cm} (13)

while that of pitch movement is

\[ I_c \dddot{\theta} = M_c (P + 2M_c (F_{SM}) + M_c (F_{SN}) + M_z \]  \hspace{1cm} (14)

Similar with on horizontal deck, vertical dynamic equations of inelastic stayed mass of nose and main landing gears are written as:

\[ m_N y = F_{SN} \cos \delta - F_{SN} \cos \delta - f_N \sin \delta - m_N g \]  \hspace{1cm} (15)

\[ m_M y = F_{SM} \cos \delta - F_{SM} \cos \delta - f_M \sin \delta - m_M g \]  \hspace{1cm} (16)

and that of horizontal dynamic equations as

\[ m_N x = F_{SN} \sin \delta - F_{SN} \sin \delta - f_N \cos \delta \]  \hspace{1cm} (17)

\[ m_M x = F_{SM} \sin \delta - F_{SM} \sin \delta - f_M \cos \delta \]  \hspace{1cm} (18)

2.3.3. The Instant of Leaving out of Carrier
At the instant of leaving carrier, all of the vertical opposite forces of tires disappear, and also the axial force created by buffer system of landing gears. Figure 4 gives the forces on the UAV while leaving out of carrier.

\[ \delta \]

Figure 4. Forces on UAV while leaving out carrier.

The dynamic equation of horizontal movement is
\[(m + m_y + 2m_d)\psi = P \sin(\sigma + \vartheta) + F_L \cos \theta - F_D \sin \theta - (m + m_y + 2m_d)g\]  
(19)

and that of vertical movement is
\[(m + m_y + 2m_d)x = P \cos(\sigma + \vartheta) - F_L \sin \theta - F_D \cos \theta\]  
(20)

Also that of pitch movement cannot be ignored, written as
\[I_p \psi' = M_L(P) + M_T\]  
(21)

3. Building Dynamics Model in Adams

Dynamics analysis of launch has finished the pre-work of building dynamics simulation model of UAVs launch. Next, we will do it with popular dynamic simulation software named Adams.

3.1. Model of Carrier Deck

To describe the shape of runway more truly, cubic polynomial with adjustable curvature is used in model building. As shown in figure 5, the horizontal length of runway is defined as \(L_0\), while that of curved deck as \(L_1\) and the height of runway is defined as \(H\). Then, the shape of curved deck can be shown as
\[H = a(x - L_0 + L_1) + b(x - L_0 + L_1)^2 + c(x - L_0 + L_1) + d\]  
(22)

where \(a,b,c,d\) are all variable factors.

![Figure 5. Shape of Ski-jump Runway.](image)

As shown before, build a realistic model of runway in Solidworks, which is a professional three-dimensional model-building software and compatible with Adams. In the runway model (figure 6), the curvature of curved deck was defined as \(14^\circ\) [12].

![Figure 6. Built Runway Model in Adams.](image)

3.2. Models of Tires and Landing Gears

We chose UA tire model belongs to Adams, and built landing gears shown in figure 7.

![Figure 7. Model of Tires and Landing Gears in Adams.](image)
3.3. Building Model of UAV Body
We chose an existed plane model in Adams block, only inputting necessary relation parameters. (figure 8)

![Figure 8. Existed Plane Model.](image)

3.4. Create Restraint
Created restrained relationship of all the components in the simulation model.

3.5. Create Sensors
When the tensile force of drag lever arrive releasing value, it will depart with the UAV body. Therefore, created a sensor to percept the tensile force, and set the releasing value as 80KN. Also, created another sensor to percept the running distance of UAV to get the time to inactivate the force relationship between tires and runway, set as 105m.

4. Dynamic Simulation

4.1. Values of Variable Parameters
Some parameters were designed as variable to try different values for seeking its regularity. Their values in first simulation are shown in table 1.

| Variable Parameters                  | Values       |
|--------------------------------------|--------------|
| Radius of front wheel                | 200mm        |
| Radius of main wheel                 | 300mm        |
| Mass of UAV                          | 4370kg       |
| Stiffness of nose landing gear bumper| 6900KN/m     |
| Stiffness of main landing gear bumper| 12750 KN/m   |
| Initial attack angle                 | 2°           |

4.2. Simulation and Analysis
The simulation curves of mass center show that its vertical velocity oscillated around zero because of dilation movement of landing gears’ bumper and vertical deformation of tires (figure 9 and figure 10). At time 2.5s, climbing rate arrived 9m/s.

![Figure 9. Vertical Location of Mass Center.](image) ![Figure 10. Vertical Velocity of Mass Center.](image)

Figure 11 and 12 show the curves of mass center’s horizontal location and velocity. We can see that they all increased quickly, almost as the shape of line. At the time 4.7s, the horizontal velocity of leaving carrier arrived 39m/s.
From the curves of vertical loading of tires (figure 13 and figure 14), we can see that when UAV moved, that of nose landing gear increased quickly and arrived the maximum value at time 0.3s. At the time 3s, its value changed to zero, that means the nose landing gear had been raised and separated from runway. Corresponding, at the same time, vertical loading of main landing gears reaches its maximum value. Then, it kept oscillating until the time 4s, decreased to zero, which mean main landing gears had been raised.

4.3. Limitation of Thrust and Mass to Sinking

Because of disappearing of ground effect when leaving carrier, sinking of UAV brings unsafe element in launch. Thrust of engine and mass of body are two important influence factors on sinking. Therefore, seek the regularity of influence by simulation.

4.3.1. Limitation of Thrust to Sinking

Set mass 4370kg, and thrust three values 60KN, 50 KN, 40 KN. The simulation results are shown in figure 15-17.

Figure 11. Vertical Location of Mass Center.
Figure 12. Vertical Velocity of Mass Center.

Figure 13. Vertical Loading of Nose Landing Gear.
Figure 14. Vertical Loading of Main Landing Gear.

Figure 15. Trace of UAV when Thrust Was 60KN.
Figure 16. Trace of UAV when Thrust Was 50KN.
When thrust is set as 60KN, sinking is 3.01m. When 50 KN, sinking is 5.05m and 40 KN corresponded to 6.83m. From the figures and data, find that if mass fixed, thrust stronger, running faster, leaving velocity bigger, and sinking smaller. Acceptably, the safe sinking is no higher than 3.05m. Therefore, in our simulation, if the mass is 4370 kg , the thrust cannot be less than 60KN.

4.3.2. Limitation of Mass to Sinking
Set thrust 50KN, and mass of UAV three choices 3000 kg , 4000 kg , 5000 kg . The simulation results are shown in figure 18-20.

When mass is set as 3000kg, sinking is 3.05m. When 4000kg, sinking is 5.14m and 5000kg corresponds to 7.43m. From the figures and data, we find that if thrust fixed, mass smaller, running faster, leaving velocity bigger, and sinking smaller. If the thrust is 50KN, mass of UAV cannot be heavier than 3000KN for safety.

5. Conclusion
(1) Loading of nose landing gear increases quickly, and then keeps oscillating until nose landing gear raises and be separated with the runway, which causes loadings of main landing gears arrive the maximum value instantly;
(2) The mass of UAV and thrust of engine have great influence on launch safety. Decreasing the mass properly and increasing thrust would improve the launch trace and reduce sinking caused by disappearing of ground effect, making launch more safely.

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