Analysis of Parachute Recovery Process for UAV based on Launch Rocket

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Abstract. Taking a certain type of UAV as an object of study, this paper analyses the UAV emergency parachute recovery system based on parachute rocket. The dynamics and kinematics models of the parachute and UAV during recycling process are built respectively. The simulation results of recovery motion under windless conditions are given and the changes of attitude speed and other parameters of UAV in different stages of recovery process are analyzed. On this basis, the related factors affecting the safe landing of UAV are studied, which provides a reference for UAV to choose the time for opening the umbrella.

1. Introduction
With the development of science and technology and the change of military strategic thinking, the application of UAV in military and civil is expanding, and the demand is also increasing gradually [1]. During the development and flight test of UAV system, it is unavoidable to encounter various emergencies [2], so it is of great significance for the safe recovery of the failed UAV [3]. On the one hand, safe recycling can avoid the harm of UAV to ground researchers and reduce the economic losses. On the other hand, safe recovery can help to preserve the integrity of UAV equipment and data, so as to better study the causes of failure.

At present, the research on UAV recovery system at home and abroad mainly focuses on the normal recovery process of UAV after completing its mission [4-8], while the literature on UAV recovery at failure stage is less. Taking a certain UAV as an example, this paper analyses the UAV emergency parachute recovery system based on parachute rocket, establishes the dynamic model of each stage in the recovery process, and simulates the specific effect of the recovery system in failure stage, which provides a reference for engineering practice.

2. Design of Recovery System
Emergency recovery system has higher requirements than traditional recovery system. Because UAV is difficult to control in failure stage, it is easy to cause a lot of height loss before parachute opening is completed if the traditional parachute is used to straighten the main parachute, which can easily lead to aircraft crash. In order to avoid this situation, a new type of rocket forced parachute drawing is chosen. Under the action of fuel, the parachute rocket straightens the main parachute rapidly in a short time, which greatly reduces the time of straightening process and thus reduces the height loss.

Emergency recovery system is mainly composed of UAV fault judgment control system, parachute rocket system, parachute system, sling system and parachute cutting device. The UAV fault diagnosis system is composed of flight control system and external sensors. The flight control system monitors
the UAV’s status in real time according to the output of sensors. When the UAV's attitude, speed and other parameters change dramatically, the flight control system can detect and generate feedback in time, shut down the engine through internal control, and ignite the rocket by electric starting. The parachute rocket straightens the rocket connection belt and pulls the parachute out of the parachute cabin. The parachute inflates under the action of airflow, and gradually fills up under the action of the closing sliding cloth. When the parachute expands to the maximum volume, the UAV slowly drops at a steady speed. When the UAV landed, the parachute was separated from the UAV by the parachute cutting device to avoid the damage caused by the ground wind. The specific workflow is as follows:

3. Mathematical Model of Umbrella System Working Process

3.1. Establishment of coordinate system

To accurately analyze the motion state of the whole recovery process, it is necessary to select appropriate coordinate system. The coordinate system used is as follows:

1) Geographic coordinate system \(O_n - X_nY_nZ_n\)
   - \(X_n\) point north, \(Y_n\) point East and \(Z_n\) point ground, satisfy the right hand rule.
2) Body coordinate system \(O_b - X_bY_bZ_b\)
   - \(X_b\) point to the nose of the aircraft, \(Y_b\) point to the right side of the aircraft, \(Z_b\) point down, meet the right-hand rule. Rotate \(R_x(-\phi), R_y(-\theta)\) and \(R_z(-\psi)\) from body coordinate system to geographic coordinate system.
3) Local wind axis coordinate system \(O_w - X_wY_wZ_w\)
   - \(X_w\) coincides with the airspeed of the aircraft, \(Z_w\) is perpendicular to \(X_n\) in the plane of symmetry and points downward, \(Y_w\) is perpendicular to \(OX_nZ_w\) planes, which satisfies the right-hand rule.
4) Parachute coordinate system \(O_c - X_cY_cZ_c\)
   - Parachute coordinate system \(X_c\) is in the same direction as parachute axis and points to UAV. \(Y_c\) is perpendicular to the right side of the parachute at \(X_c\), \(Z_c\) is perpendicular to the top of the parachute at \(O_c - X_cY_c\) planes.

3.2. Working Stage of Parachute Launch Rocket

The flight control system controls the parachute launching rocket through internal decision-making. This part mainly includes two stages: the first stage is the initial stage of the parachute launching rocket, in which the parachute launching rocket accelerates and pulls the parachute package out of the UAV; the second stage is the parachute launching rocket pulls the parachute coat and the parachute rope out of the parachute bag in order to complete the straightening process.
In the first stage, after firing the parachute rocket, the fuel burns rapidly, which will produce an instantaneous impulse to the UAV. The impulse decreases rapidly to zero with the detachment of the parachute rocket. Due to the complexity of the process, the following models are used to simplify the force. In the geographic coordinate system, the following models are used:

\[
F = \frac{T}{T_{\text{max}}} F_{\text{max}}
\]  

(1)

After the parachute-launching rocket parachute-pulling bag is separated from the UAV, the weight of the UAV decreases. At this stage, the UAV is subjected to its own gravity, aerodynamic force and the impact of the parachute-pulling bag.

\[
\begin{bmatrix}
F_{wx} \\
F_{wy} \\
F_{wz}
\end{bmatrix} = \begin{bmatrix}
F_{sx} \\
F_{sy} \\
F_{sz}
\end{bmatrix} + \begin{bmatrix}
Q_{sx} \\
Q_{sy} \\
Q_{sz}
\end{bmatrix} + c_a \begin{bmatrix}
0 \\
0 \\
-(m_w - m_i) g
\end{bmatrix}
\]  

(2)

The parachute bag is affected by the pulling force of the parachute rocket, its own gravity and aerodynamic force.

\[
\begin{bmatrix}
F_{cx} \\
F_{cy} \\
F_{cz}
\end{bmatrix} = c_a \begin{bmatrix}
F_{cx} \\
F_{cy} \\
F_{cz}
\end{bmatrix} + \begin{bmatrix}
Q_{cx} \\
Q_{cy} \\
Q_{cz}
\end{bmatrix} + c_a \begin{bmatrix}
0 \\
0 \\
-(m_i g)
\end{bmatrix}
\]  

(3)

The second stage is the straightening process of parachute rocket. During parachute pulling, the mass of parachute bag decreases, which is restrained by the pulling force of parachute rocket and some parachutes pulled out. The parachute bag dynamics model can be expressed as follows:

\[
m_i \frac{dV_s}{dt} = F_s + m_i g
\]  

(4)

\[
\frac{dm_i}{dt} = -m_i u
\]  

(5)

Among them, \( V_s \) is the speed of the umbrella bag, \( F_s \) is the binding force acting on the umbrella bag, \( m_i \) is the mass of the umbrella bag, \( m_i \) is the linear density of the part being pulled out, and \( u \) is the straightening speed.

UAV is subject to its own aerodynamic force, parachute rope restraint and gravity.

\[
\begin{bmatrix}
F_{wx} \\
F_{wy} \\
F_{wz}
\end{bmatrix} = \begin{bmatrix}
F_{sx} \\
F_{sy} \\
F_{sz}
\end{bmatrix} + \begin{bmatrix}
Q_{sx} \\
Q_{sy} \\
Q_{sz}
\end{bmatrix} + c_a \begin{bmatrix}
0 \\
0 \\
-(m_w - m_i) g
\end{bmatrix}
\]  

(6)

3.3. Inflatable deceleration stage

The force model of the aeration UAV is the same as that of the straightening stage. The pulling force of the suspension belt is provided by the main umbrella, and the dynamic and kinematic models remain unchanged.

In the aeration stage, it can be considered that the direction of parachute velocity is the same as the direction of UAV wind axis velocity. The parachute is affected by its own gravity, aerodynamic drag and the pulling force of parachute rope. The aerodynamic drag is calculated by the method of aeration time [9]. In the parachute coordinate system, there are the following equations:
\[ T_s + G_s + (CA) = \frac{d(m_s + m_f)W_s}{dt} \]  

(7)

Among them, \( m_s \) and \( m_f \) are parachute mass and additional mass respectively.

3.4. Stable decline stage
In the stable landing stage, the UAV is reduced uniformly by the parachute. In this stage, the relative motion between the parachute and the UAV is not considered, and the drag characteristics and additional mass of the parachute are not changed. The whole system is only subject to gravity and aerodynamic forces, and they are equal, so there are:

\[ (CA)_s + F_q - (m_u + m_s + m_f)g = 0 \]  

(8)

4. Simulation results and analysis

4.1. Recovery results
Based on the actual requirements of a certain type of UAV, when the parachute opening height is 100 meters, the landing speed is less than 6 m/s and the attitude angle is less than 20 degrees as the safety recovery standard.

Using the dynamics and kinematics equations of the recovery system, the simulation is carried out by MATALB to simulate the parameter changes of the system after the failure of the UAV. Taking the flat flight stage as an example, the results are as follows.

![Figure 2](image1.png)  
**Figure 2. Diagram of position**

The altitude decreases rapidly. After the parachute is fully opened and decelerated, the steady speed decreases. The forward channel increases rapidly at the initial higher forward speed, and stabilizes with the decrease of forward speed.

![Figure 3](image2.png)  
**Figure 3. Diagram of speed**

The forward velocity of UAV drops rapidly from the initial 30m/s to zero under the action of aerodynamic drag and parachute. The vertical speed increases gradually under the action of body gravity at first, and decreases with the process of parachute inflation. After the parachute is fully opened, the vertical speed decreases rapidly and oscillates. Gradually reaching equilibrium, the steady falling speed is near 6m/s.

![Figure 4](image3.png)  
**Figure 4. Diagram of attitude**

As the inflation process goes on, the parachute resistance increases, the forward torque received by the UAV increases continuously, and the pitching Angle increases again, and then gradually oscillates to zero. The roll Angle channel has less fluctuation.

It can be concluded that when the UAV opens its parachute at a height of 100 meters, all three channels can enter a stable state before landing, and the flight parameters meet the requirements of safe landing, so the emergency recovery system is feasible.
4.2. The influence of elevation angle on parachute opening process

The simulation results show that the yaw angle and roll angle have little influence on the recovery process, but the pitch angle has a great influence on the whole recovery process. When the pitch angle is lower than a certain angle, the following conditions will happen:

As can be seen from the figure, due to the small pitch angle at the time of parachute opening, the vertical speed increases rapidly and the maximum critical value of vertical speed increases, which leads to the rapid loss of the height of the recovery system. When the parachute is not fully decelerated, the UAV has landed, which is easy to cause the crash of the UAV.

In the actual flight process, when the UAV breaks down, the corresponding parachute opening height and speed change little in a short time, but the attitude changes rapidly. At the same altitude, the different pitch angles of the UAV when it opens the parachute affect whether it can land safely or not. Through simulation, the critical safe parachute opening elevation diagrams corresponding to different heights are obtained as follows:

As shown in the figure, when the parachute opening height is 200 meters, the critical elevation angle of the unmanned aerial vehicle when it can safely land is -23 degrees, and with the decrease of the parachute opening height, the critical elevation angle is getting larger and larger. When the parachute opening height is below 70 meters, the positive elevation angle is needed to ensure the safe parachute opening.

But in the actual flight process, after the failure of UAV, the pitch angle will be lower than zero due to its own gravity and aerodynamic force in the unpowered flight phase. Therefore, UAV must open its parachute at a height of more than 70 meters, otherwise it is easy to cause crash.

5. Conclusion

In this paper, we analyzed the emergency recovery system using parachute rockets, and analyze the effect of the system through mathematical modeling and simulation, and analyze the influence of pitch angle on the recovery process. The results show that the system can meet the urgent recovery needs. In
order to increase the success rate of safe parachute opening, the flight control system should try to decide the time of parachute opening before the height is less than 70 meters.

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