The Analysis of Compound Control in the Pre-launch Attitude of Internally Carried Air-launched Rocket Based on Simulink

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Abstract. With the development of modern war and the aggravation of space confrontation, modern battlefield has put forward a strong demand for the hidden, fast and flexible ability to enter space. All countries attach great importance to improving their space emergency launch capability in wartime. Air-launch rocket is based on aircraft, which can be rapidly deployed to any location in the world to achieve full launch. It is very suitable for rapid response to launch performance requirements. Internally Carried air-launched rocket is in the powerless flight state during the period when the main engine is ignited from the carrier, the position, motion and attitude of the carrier rocket are difficult to predict, and the initial position is located. The error of initial condition caused by orientation has a great influence on the precise guidance and navigation of rocket flight process. Prelaunch attitude control not only plays a significant role in the launching process of internally carried air-launched rocket, but also has an important influence on engine ignition and orbit injection accuracy. On the basis of full understanding of the attitude control methods of air launched rockets at home and abroad, also combined with the specific control requirements of pre-launch attitude control, a new control method using grid rudder and RCS and combined of aerodynamic force and direct force is proposed. The simulation of the compound control scheme is carried out by using Simulink. The control characteristics of the scheme are analyzed, and the feasibility of the scheme is verified.

1. Introduction
Internally carried air launched rocket has the characteristics of concealed launch, strong adaptability to payload and low requirements for airframe refitting. Therefore, it is the most potential for military applications in the air emergency launch mode. The study shows that the adjustment of the ignition attitude of the Internally carried air launched rocket directly determines the success or failure of launching the payload and the precision of orbit entry[1]. Therefore, it is necessary to adopt the auxiliary attitude stabilization control method to obtain the appropriate ignition time. After a detailed study of the single control method[2] and the control method of the "stable umbrella +" control method[3] for the forward attitude of the currently internally carried air launched rocket. Although these methods can achieve the purpose of attitude adjustment, there are some problems, such as poor stability, low control efficiency, insufficient anti-jamming ability and so on.

The compound control method of missile (rocket) body attitude has been mature and used in missile and reusable launch vehicle[4][5], but in the field of air launched rocket, there is no research precedent. In this paper, a combined control method of grid rudder and RCS is proposed, which can form a closed loop control by the combined action of continuous aerodynamic force and discrete direct
force, thus improving the control efficiency and control precision of the air launched rocket in the air. Improving the stability under the uncertain disturbance in the air.

2. Compound Control Scheme Design
In the design of composite control scheme, the control system is designed into redundant system by referring to the composite control idea of missile and adopting the combination of direct force and aerodynamic force. Through reasonable control allocation, the control efficiency of the control system is improved, and the control ability of the control system under complex external disturbance is improved. The layout design and control ability design of compound control are the key points in the design process.

2.1. Grid rudder design

According to the control characteristics of all kinds of pneumatic rudders and the existing application precedents of pneumatic rudder in carrier rocket, in the design of pneumatic device, a grid rudder of appropriate size is installed at the rear of the rocket to carry out aerodynamic control of the rocket body. In the design, refer to the mature application of the grid rudder on missiles, rockets and spaceships, and select the typical grid shape and layout (Figure 1). However, the effect of grid rudder in this scheme is different from that in other applications, so it is different from other applications in the design of rudder surface rotation. The rudder surface 1/3 is swinging back and forth in the vertical rocket plane of the grid rudder, the rudder surface 2/4 rotates around the symmetrical axis of the rudder plane, and in the process of control and adjustment, the four rudder faces are always in parallel plane.

According to the control characteristics of the grid rudder and the particularity of the attitude control before launching, the grid rudder control device is required to provide the maximum rotation moment for the rocket in the pitch channel, thus helping to realize the attitude adjustment. Therefore, in the selection and use of the grid rudder, it is required to produce as much aerodynamic control torque as possible. At the same time, in order to facilitate the separation of the rocket from the loader, the typical curved grid rudder is used in the design process, and the single rudder surface size is 0.6m×0.8m.

2.2. Side injection device design
On the basis of the research on the RCS control scheme proposed by Northwestern Polytechnic University[6], combined with the difference of control gain between upwind and leeward surfaces of RCS and the characteristics of pre-launch attitude control of internally carried air-launched rocket[7], the RCS is selected to be arranged on the head of rocket body. According to the literature[8], to reduce rocket costs without affecting rocket payloads, direct force control is provided by satellite attitude
control engines. The layout scheme (Figure 2) uses a simple cross distribution, 1/3 side jet device to control the pitch channel and the 2/4 side jet device to control the yaw passage.

At the same time, according to the control ability of attitude control engine mentioned in the literature[9], the engine can produce a maximum control force of 3000 N, and at this time it can produce a control torque of about 50000 N·m to the rocket body in the head. According to the moment of inertia of the rocket, under the action of the torque, the attitude control engine can produce enough control effect to the rocket body, so the control force of the side injection device can be set to 3000 N.

![Figure 2. RCS layout and distribution](image)

3. Establishment of Motion Model for Attitude Control

Pre-launch attitude control is a control process to control the internal air-launched rocket in its proper posture, when leaving from the aircraft, so as to help the ignition of the main engine. It is a high angle of attack and low mach control in the atmosphere, which needs to consider various factors such as the influence of gravity comprehensively, loss of altitude and velocity, gusty winds and crosswind effects in atmospheric environment[10].

The aim of this paper is to design a new compound control scheme to improve the rapidity and stability of attitude control before launching. At the same time, the control method is simulated and analyzed. According to the US launch experiment of its internally carried air-launched rocket QuickReach[11], the key point for the attitude control of the internally carried air-launched rocket before launch is the change control of the pitch channel at high angle of attack at low mach number. In the control time of 3 to 4 seconds, the change of yaw and roll passage is not obvious. At the same time, adding the spoiler to the QuickReach later basically eliminated the adverse effects caused by asymmetric vortices[12]. Therefore, in the process of establishing the model, only the pitching channel is discussed. In the process of modeling, in order to facilitate simulation analysis, the following reasonable assumptions are put forward.

1. the change of the height of the control process is less than 100, and the change of atmospheric density is ignored;
2. the mass of the rocket is constant, and the position of the center of mass is unchanged;
3. the rocket has axisymmetric aerodynamic shape and stable yawing and rolling channel.
4. free falling body motion with initial velocity in vertical direction;
5. the RCS control force is a switch and acts vertically on the longitudinal axis of the rocket.

In the attitude control process, only the change of pitch channel is considered, so the modeling process only needs to consider the dynamic equations of rotation around the center of mass and the kinematics equation of rotation around the center of mass in the rocket coordinate system.

The kinetic equation of rotating around the center of mass:

\[ J \cdot \frac{d\omega}{dt} = M \]  \hspace{1cm} (1)

To rotate the kinematic equation about the center of mass:

\[ \frac{d\varphi}{dt} = \omega \]  \hspace{1cm} (2)

\[ J \]: moment of inertia;
At the same time, the process of establishing the attitude control model of compound control is as follows:

The combined external force of the rocket consists of four forces:

\[ F = Z_a + T + G + \Delta Z_a \]  

\[ F : \text{combined external force;} \]

\[ Z_a : \text{aerodynamic force;} \]

\[ T : \text{direct force;} \]

\[ G : \text{gravity;} \]

\[ \Delta Z_a : \text{interference caused by tail flow and gusts} \]

Because gravity acts directly on the center of mass, it has no effect on the pitching channel. It only affects the angle of attack of the rocket by influencing the angle of the velocity of the rocket, thus exerting an effect on the variation of the angle of attack of the rocket.

The angle of attack \( \alpha \) and the total moment \( M \) can be expressed by analyzing the characteristics of attitude control before launching:

\[ \alpha = \varphi + \arctan \left( \frac{v_y}{v_z} \right) \]  

\[ M = M_a + M_t + \Delta M \]  

\[ v_y : \text{vertical velocity;} \]

\[ v_z : \text{horizontal velocity;} \]

\[ M_a : \text{aerodynamic moment;} \]

\[ M_t : \text{direct moment;} \]

\[ \Delta M : \text{disturbance torque (mainly caused by wake and gusts).} \]

The expressions of \( M_a \) and \( M_t \) are as follows:

\[ \begin{cases} 
M_a = q(S_1L,m_\alpha \alpha + S_2L,m_\alpha \delta_yr) \\
M_t = TL_r 
\end{cases} \]  

\[ q,S,L : \text{dynamic pressure, characteristic area, characteristic length;} \]

\[ m_\alpha, m_\delta : \text{aerodynamic moment coefficient;} \]

\[ \delta_yr : \text{rudder angle.} \]

The value of disturbance torque \( \Delta M \) is about 10% of the total torque.

4. Simulink simulation

According to the established system model, the control process is simulated by Simulink (Figure.3) , and the control characteristics and feasibility of the compound control method are analyzed.

The control model module is written according to the formulas (1) and (2), the angle calculation module is written according to the formula (4), and the velocity variation module is based on the aerodynamic characteristics of the initial velocity of the rocket and the different angles of attack. Combined with the effect of external forces to calculate the results. At the same time, the angle of
velocity inclination is combined. The core module is the interactive realization of two control torque. The following main pneumatic torque and direct force torque control module to explain.

Because the main task of the attitude control engine is to adjust the attitude and orbit of the satellite, its fuel stock is an important factor affecting the satellite's life, so in the process of attitude adjustment before launching, it should be controlled mainly by aerodynamic force. Reduce fuel use of side injection device as far as possible and use direct force as auxiliary control force. In this paper, a control instruction allocation algorithm based on grid rudder saturation is proposed. In the process of attitude adjustment, when the control ability of the rudder is limited, the side spray device will intervene when the control torque can not be provided. Provide direct force to ensure the initiative and rapidity of pre-launch attitude control.

When using the grid rudder to control the rudder, according to the feedback of the rocket angle of attack, the rudder deflection angle is adjusted in real time, so that the grid rudder can be kept at the angle of attack which can produce the maximum pitching moment on the rocket body. The variation of the moment produced by the grid rudder to the rocket body is calculated.

In the use of side spray device for auxiliary control, according to the target state (expected pitch angle 80 ± 4 °, expected angular velocity 0 ± 4 °/s) and the control ability of the grid rudder, the side jet device can be used to determine whether the side jet device is involved in the control and produces direct force torque. There are two specific cases:

\[
\begin{align*}
(1) \text{ when } \left( \frac{2 \varphi}{\omega} \right)^2 < \frac{J \omega - \omega^2}{M}, & \quad \text{open side spray device.} \\
(2) \text{ when } \left( \frac{2 \varphi}{\omega} \right)^2 \geq \frac{J \omega - \omega^2}{M}, & \quad \text{close side spray device.}
\end{align*}
\]

In the case of the current aerodynamic torque, the time required to reach the desired angular velocity is longer than the desired angle at the current angular velocity, then the side spray device is opened. On the other hand, the side spray device does not work.

*Figure 3. Simulink model simulation diagram*
5. Numerical Example and Analysis
Because of the particularity of attitude control before launching, the control process should reduce the loss of altitude and velocity and at the same time take into account the safety distance of the carrier. Therefore, according to the existing experiments, the control time is required, that is, the desired attitude is achieved at 3.5 seconds. At the same time, the loss of altitude and velocity of the rocket can be minimized under the premise of ensuring the safety of the carrier. In addition, at an altitude of 9000 meters, there are aerodynamic disturbances such as tail current and gusts, so the following disturbance torque is introduced (Figure 4), because the tail current of the body after it is out of the cabin accelerates the rotation of the rocket’s pitching channel, contrary to the control direction. At the same time, in order to verify whether the control ability of the scheme can meet the control requirements, taking the gust disturbance torque is also opposite to the control direction, that is, negative values.

![Figure 4. Wake and gust interference](image)

The feasibility of the proposed control scheme is analyzed by using Simulink. According to the experimental data, the initial state and expected state of the rocket are set as follows (Table 1):

| Parameter          | Initial state 1 | Initial state 2 | Initial state 3 | Initial state 4 | Expectation  |
|--------------------|-----------------|-----------------|-----------------|-----------------|--------------|
| Angle of pitch (°) | 20              | 25              | 20              | 25              | 80±4         |
| Rate of pitch (°/s)| 30              | 30              | 35              | 35              | 0±4          |

Control of aerodynamic moment and direct force moment of rocket under wake and gust disturbance, and variation of pitch angle and pitch angle velocity in different initial states (Figure 5-Figure 8).

![Figure 5. Initial state 1 simulation results](image)
Figure 6. Initial state 2 simulation results

Figure 7. Initial state 3 simulation results

Figure 8. Initial state 4 simulation results

It can be seen from the figure 5 to figure 8 that the pitch angle and the velocity of the pitch angle are shown in Table 2 at 3.5 s.

Table 2. Pitch angle and pitch velocity at different initial states at 3.5 s

| Parameter      | Initial state 1 | Initial state 2 | Initial state 3 | Initial state 4 |
|----------------|-----------------|-----------------|-----------------|-----------------|
| Angle of pitch (°) | 72.85           | 76.08           | 83.88           | 89.58           |
| Rate of pitch (°/s) | 3.44            | 2.21            | 2.01            | 2.58            |
| Requirements   | ×               | √               | √               | ×               |
It can be seen from the above simulation results that the control accuracy of the composite control scheme can not reach the expected requirement of the forward attitude of the rocket body in different initial states. The initial state 3 and 4, the control scheme has been saturated control, and the side spray device has always maintained the open state from the beginning to the 3.5 s. Therefore, the simulation study of the next step is carried out, that is, when the initial state is in the range of the control scheme, the control method can complete the forward attitude control task. The simulation results are shown in Table 3.

| Initial state parameter | Rate of pitch (°/s) |
|-------------------------|---------------------|
|                         | 30 | 31 | 32 | 33 | 34 | 35 |
| Angle of pitch (°)      |    |    |    |    |    |    |
| 20                      | ×  | ×  | ×  | √  | ☆  | √  |
| 21                      | ×  | ×  | √  | √  | ☆  | ×  |
| 22                      | ×  | ×  | √  | √  | √  | ×  |
| 23                      | ×  | √  | √  | ☆  | √  | ×  |
| 24                      | ×  | √  | ☆  | ☆  | ×  | ×  |
| 25                      | √  | √  | ☆  | √  | ×  | ×  |

×:Unable to meet the requirements
√:To meet the requirements normally;
☆:Meet the requirements, and the accuracy is (80±2)° and (0±2)°/s

The simulation results show that the designed composite control scheme can not meet the expected requirements of the attitude of the rocket body in different initial states. In the initial state 3/4, the control scheme has been saturated and the side injection device has been involved to 3.5s from the beginning. Table 3 shows that the control scheme presents different control effects and control precision in the process of initial state change. In order to ensure better control effect, the pitch angle should be controlled at 23°-25° and the pitch angle velocity should be controlled at 31°/s-33°/s at the time of complete separation of the rocket. In this region, the average control precision of the rocket is the highest.

The simulation results also show that when there is redundancy between direct force and aerodynamic force, this method can achieve the reasonable distribution of control force requirements of two control mechanisms without too complicated control allocation strategy, but there is still room for improvement of control accuracy. In addition, in the subsequent optimization design, the control ability of each control mechanism should be increased appropriately within a reasonable range, so as to ensure that there are redundant control quantities for different initial states, which provides the possibility for increasing the control range of the scheme. At the same time, the adaptive gain value can be set according to different initial states, so that the control range of the system can be improved and the fault-tolerant rate of the system to the initial state can be improved.

6. Tag
In this paper, a method of combining aerodynamic force and direct force is proposed for the pre-launch attitude control of an internally carried air-launched rocket. By means of the grid rudder designed on the rocket body and the satellite attitude control engine, the attitude of the rocket body is fully adjusted to meet the ignition condition in the uncontrolled section between the rocket body and the carrier before ignition. Compared with the stable umbrella and the "stable umbrella" control method carried out in foreign countries, the compound control scheme has obvious advantages: ①. closed loop active control, strong anti-jamming ability. ②. no umbrella surface, so the horizontal velocity loss is small. ③. at the same time of controlling the pitch angle.④. there is no complex rope
connection to control the pitch angle velocity. The model is relatively simple and easy to establish in
the simulation research, and it is also helpful to improve the actual control efficiency. The simulation
results show that the designed scheme fully meets the control requirements and has a strong feasibility
in theory and has a certain reference value for the design and research of the air-launched rocket.

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