Compound control method for Anti-Unmanned Aerial Vehicle (UAV) vertical launch missile

Chang Jiapan¹, Liu Yongshan*¹
¹School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China

E-mail: liuysh@bit.edu.cn

Abstract. A compound control method with aerodynamic canard and reaction jet is proposed for anti-Unmanned Aerial Vehicle (UAV) vertical launch missile. The purpose of this method is to solve the problem of vertical launch with high angle of attack and low dynamic pressure. This paper first introduces the actuator layout and ignition strategy of reaction jet. Then the model of compound control system is established and compared with aerodynamic control in detail. Simulation studies demonstrate the effectiveness of the proposed method.

1. Introduction
The development of UAV has made the modern battlefield more complicated and changeable. The threat of UAV puts forward more stringent requirements for air defense missile. Compared with traditional tilted launch, the vertical launch is very suitable for the combat requirements of anti-UAV missiles due to the advantages of no dead angle, good concealment, fast response and high loading rate.

In the initial stage of vertical launch, the missile needs to start a turning maneuver after rising a few meters. In this case, the dynamic pressure of the missile is relatively low, and it is difficult to achieve steering control in a short time with the traditional aerodynamic control surface. Therefore, it is necessary to introduce thrust vector control (TVC) to achieve rapid turning. Common TVC includes gas rudder and reactive injection. The gas rudder is a movable blade or flap installed on the plane of the main engine exit, which uses the main exhaust flow to obtain the turning moment; while the turning moment of the reactive injection is generated by surrounding the missile. The external combustion, jet interaction and reaction jet generated by the body’s pulse engine can be collectively referred to as reactive injection control technology [1,2].

Although the use of TVC can effectively improve the rapid response capability during vertical launch, it also faces some problems. Firstly, TVC missiles require two types of actuators, which is a redundant control that requires consideration of control allocation. this increases the difficulty and cost in control system design. In addition, the change of attitude leads to high angle of attack, and serious channel interference and coupling will occur. This is also a problem that cannot be ignored for TVC missiles. Reference [1] carried out a nonlinear model of a vertical launch surface-to-air missile, and discussed the process of combining thrust vector control with conventional aerodynamic control to achieve a maneuver at high angle of attack. Reference [3] designed an autopilot with compound control of aerodynamic rudder and reaction jet based on sliding mode control, which improved the controllability of maneuvering at high angle of attack. Reference [4] gave a differential dynamic programming method to design the optimal thrust vector control of a vertical launch missile, and realized the missile turning control at a high angle of attack in a short time. Reference [5] studied the optimal lateral thrust control for vertical launch short-range tactical missiles, the missile can be
adjusted to a predetermined attitude angle in a minimum time. Reference [6] analysed the applicability of the vertical launch mode to ultra-short-range missiles, and applied thrust vectoring technology to satisfy the missile's rapid turn at the minimum altitude. To solve the problems above, this paper proposes a compound control method suitable for anti-UAV vertical launch missile based on previous studies. In this method, reaction jet adopts the corresponding ignition strategy to achieve all-directional launch, and then the exhaust flow of reaction jet is acted on the aerodynamic canard to solve the problems of low dynamic pressure and high angle of attack.

This paper is organized as follows. In section II we state the realization of the compound control method in detail, including the actuator layout and ignition strategy. The compound control missile dynamics and some preliminary analysis results are listed in Section III. In section IV simulation studies and analysis are carried out to illustrate the effectiveness of the proposed compound control method. Finally, in section V we draw the conclusions on our work.

2. Control Method in detail

2.1. Actuator layout and model

The actuator for the proposed method includes both aerodynamic canard and reaction jet. The reaction jet is installed in a proper position before the canard, so that the exhaust flow can fully acts on the canard. The illustration of the missile canard and reaction jet configuration is shown in Figure 1.

As shown in Figure 2, \( F \) is the thrust of reaction jet, \( L \) is the distance between the installation position and the center of mass, \( \varepsilon \) is the angle between the nozzle and the center axis of the missile, the eccentricity is \( d \). The control moment of reaction jet is given by

\[
M_{sp} = F(L + d \cot \varepsilon) \sin \varepsilon
\]  

The mathematical model of the reaction jet can be simplified as shown in Figure 3. \( \delta_p \) is the control flag, which is 1 at start and 0 at the end of reaction jet control; \( \tau \) is a delay period of ignition strategy, which is taken as 0.5 s; \( K_p \) is the jet flow amplification factor. According to the numerical analysis of flow field in reference [7], it is related to the missile flight Mach number, temperature, flight altitude and airflow torsion angle, which can be valued in the range of 0.4 to 1.6; The approximate time constant \( T \) is 0.02 s.

\[
\text{Missile body model}
\]
2.2. Ignition strategy of reaction jet

For the purposes of this paper, the turning process of vertical launch is divided into two stages. In the first stage, the aerodynamic force just ensures the stability of roll channel and the reaction jet is used to achieve all-directional launch. According to the relative azimuth of the missile and UAV target, four launch surfaces are divided as shown in Figure 4. The launch surfaces of 1# and 3# adopt I ignition strategy while 2# and 4# launch surfaces adopt II ignition strategy. The launching coordinate system $OXYZ$ is established based on the launch surface. To capture the target quickly and stably, three attitude channels need to satisfy field of view (FOV) limit for homing head as shown in Figure 5. Thus, we can get the final control command of three attitude channels $\Delta \psi, \gamma, \vartheta$.

The ignition strategy of 1# launch surface and 2# launch surface are shown in Figure 6. The ignition strategies of the other launch surfaces are determined by the same rules.

In the second stage, the exhaust flow of reaction jet acts on the aerodynamic canard (similar to the jet vane), which can improve the problem of low dynamic pressure and high angle of attack. It should be noted that the exhaust flow of reaction jet also brings uncertain interference to the aerodynamic parameters of the missile. When the angle of attack is too high, the flow direction of exhaust flow and airspeed are inconsistent, resulting in turbulence. This interference will increase with the angle of attack, which undoubtedly worsened the problem of high angles of attack.
3. Dynamic modeling and analysis

The difference between the proposed compound control and traditional aerodynamic control is the effect of reaction jet. The actual aerodynamic conditions behind the reaction jet are very complicated, which requires CFD simulation and wind tunnel experiments. To facilitate theoretical modeling and analysis, ideal conditions are proposed as follows:

- The exhaust flow behind the nozzle of reaction jet is a uniform and steady flow.
- The influence of exhaust flow temperature on canard is ignored.
- The fluid nature of the exhaust stream is seen as air.

Under the above ideal conditions, the force and moment coefficients of canard can be equivalent to aerodynamic parameters at high Mach numbers. The lift coefficient and moment coefficient are generally expressed as

\[ c_\delta = c_\delta w + c_\delta\alpha + c_\delta\dot{\delta} \]
\[ M_{\dot{\delta}} = M_{\dot{\delta}} w + M_{\dot{\delta}}\alpha + M_{\dot{\delta}}\dot{\delta} + M_{\dot{\delta}}\omega \]  

(2)

the force and moment coefficients of canard is given by

\[ c_\delta = f(M\dot{\alpha}, \dot{\varepsilon}) \]
\[ M_{\dot{\delta}} = f(M\dot{\alpha}, \dot{\varepsilon}) \]  

(3)

where \( M\dot{\alpha} \) is the equivalent Mach number, which is determined by the exhaust flow velocity. \( \dot{\varepsilon} \) is the angle between the nozzle and central axis of the missile, which can be equivalent to the angle of attack.

The linearized equations of missile dynamics for I ignition strategy are shown in equation (4). \( d_x, d_y, d_z \) are the external disturbances of pitch, yaw, and roll channels. The parameters of reaction jet are shown in section II, and the definitions of other parameters are referred to Pages 83-102 in reference [8].

The state space equation of the pitch channel is given by

\[
\begin{align*}
\dot{\alpha} &= \omega_\alpha - \beta_\alpha - \frac{P + Y^\alpha + 4F}{mV} \alpha - \frac{Y^\delta}{mV} (\delta_z + d_z) + \frac{2F\delta_p}{mV} \alpha \\
\dot{\beta} &= \omega_\beta + \alpha_\beta - \frac{P - Z^\beta + 4F}{mV} \beta - \frac{Y^\delta}{mV} (\delta_z + d_z) + \frac{2F\delta_p}{mV} \beta \\
\dot{\omega}_\alpha &= \frac{M^\alpha}{J_\alpha} \omega_z + \frac{M^\alpha}{J_\alpha} \alpha + \frac{M^\delta}{J_\alpha} (\delta_z + d_z) + \frac{(J_z - J_x)}{J_x} \omega_x + \frac{\sqrt{2M_{\dot{\psi}}}}{J_x} \delta_p \\
\dot{\omega}_\beta &= \frac{M^\beta}{J_y} \omega_z + \frac{M^\beta}{J_y} \beta + \frac{M^\delta}{J_y} (\delta_z + d_z) + \frac{(J_z - J_y)}{J_y} \omega_x + \frac{M^\alpha}{J_x} \omega_z + \frac{M^\delta}{J_z} \delta_z \\
\dot{\omega}_x &= \frac{M^\alpha}{J_x} \omega_z + \frac{M^\beta}{J_x} \beta + \frac{M^\delta}{J_x} (\delta_z + d_z) + \frac{(J_z - J_x)}{J_x} \omega_x + \frac{M^\alpha}{J_x} \omega_z + \frac{M^\delta}{J_z} \delta_z
\end{align*}
\]

(4)

The state space equation of the pitch channel is given by

\[
\dot{x} = Ax + Bu + g(\omega_x, \omega_y, \beta) + d
\]

(5)

where the state \( x = [\alpha, \dot{\alpha}]^T \), the control \( u = [\delta_z, \dot{\delta}_p]^T \), the channel coupling \( g(\omega_x, \omega_y, \beta) \), the disturbances \( d = [d_x, 0]^T \), matrix A and B are

\[
A = \begin{bmatrix} -b_{\alpha} & b_p \\ -a_{\alpha} & -a_p \end{bmatrix}; B = \begin{bmatrix} -b_{\delta} \\ -a_{\delta} \end{bmatrix}
\]

\[
b_{\alpha} = \frac{P + Y^\alpha + 4F}{mV}; b_{\delta} = \frac{Y^\delta}{mV}; b_p = \frac{2F\delta_p}{mV}; a_{\alpha} = -\frac{M^\alpha}{J_\alpha}; a_{\delta} = -\frac{M^\delta}{J_z}; a_p = \frac{\sqrt{2M_{\dot{\psi}}}}{J_x}
\]
The input of the control system includes two channels: the reaction jet control flag \( \delta_p \) and canard control deflection \( \delta_c \). In the first stage \( \delta_p = 1, \delta_c = 0 \) and \( M_x \) is the main control moment. In second stage, the control system degenerates to the Single Input and Single Output (SISO) model. When the channel coupling and external disturbance are ignored, the pitch rate transfer function can be obtained from equation (5) as follows.

\[
G_{\alpha}(s) = \frac{\dot{\alpha}(s)}{\delta_{\alpha}(s)} = \frac{k_{\alpha}(T_{\alpha}s + 1)}{T_{\alpha}^2s^2 + 2\xi\omega_{\alpha} T_{\alpha}s + 1}
\]

where \( \xi \) and \( \omega_{\alpha} \) is referred to reference [8], \( k_{\alpha} \) and \( T_{\alpha} \) are related to reaction jet.

\[
k_{\alpha} = \frac{a_{\alpha}b_{\alpha} - a_{\beta}b_{\alpha}}{a_{\alpha} + a_{\beta}b_{\alpha}} T_{\alpha} = \frac{a_{\alpha}b_{\alpha} - a_{\beta}b_{\alpha}}{a_{\alpha}}
\]

\[
k_{\alpha} = \lim_{s \to 0} \frac{\dot{\alpha}(s)}{\delta_{\alpha}(s)} \approx \frac{a_{\alpha}b_{\alpha} - a_{\beta}b_{\alpha}}{a_{\alpha}}
\]

\[
\text{Table 1. Dynamic coefficients of the feature point.}
\]

| System model    | \( a_{\alpha}(s^{-2}) \) | \( a_{\alpha}(s^{-1}) \) | \( b_{\alpha}(s^{-2}) \) | \( a_{\beta}(s^{-2}) \) | \( b_{\beta}(s^{-1}) \) |
|-----------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Compound control| 32.7                      | 1.3                       | 1.27                      | -1401.2                   | 0.32                      |
| Aerodynamic control| 32.7                      | 1.3                       | 1.27                      | -43.6                     | 0.01                      |

It can be seen from equation (2)-(8) that compound control increases \( k_{\alpha} \) compared with aerodynamic control, which means the maneuverability of the missile is improved. However, the increase of transfer coefficient is not without cost. Table 1 shows the feature point dynamic coefficients of the vertical launch missile with proposed compound control and aerodynamic control.

Compared with aerodynamic control, the transfer function of compound control from equation (6) increases the gain while reducing the stability margin, which means relax the static stability of the missile. However, by introducing a damping loop, angular rate compensation can eliminate such negative effects. This is also the purpose of designing the attitude autopilot. Two-loop attitude autopilot are designed for compound control and aerodynamic control respectively according to the same requirements. The results are shown in Figure 7 and Table 2.

\[
\text{Table 2. Autopilot performance.}
\]

| System model    | Phase margin (deg) | Settling time (s) | Overshoot (%) |
|-----------------|--------------------|-------------------|---------------|
| Compound control| 88.7               | 0.21              | 0             |
| Aerodynamic control| 61.7               | 1.16              | 4             |
It can be seen from the results that lower dynamic pressure reduces the response speed of aerodynamic control. The compound control proposed in this paper ensures the maneuverability of the vertical launch missile under low dynamic pressure. Through reasonable design, the closed-loop attitude autopilot is significant for improving the phase margin, settling time and overshoot, which effectively enhance the robustness and rapid response of the system.

4. Simulation research

A simulation of vertical launch missile is carried out to demonstrate the effectiveness of the proposed compound control method. Simulation framework is shown in Figure 8. The control command $\Delta \psi_n$, $\gamma_n$, $\theta$ are selected as $10^\circ$, $0^\circ$, $10^\circ$ respectively. Normal distribution disturbance and $\pm 20\%$ aerodynamic deflection are introduced when the angle of attack is greater than $15^\circ$.

Response curves of three channel attitude are shown in Figure 9(a), (b), (c). There is a deviation of about $0.4^\circ$ in yaw channel because of coupling effects. The control deviation of the pitch and roll channels is close to 0, which are within the allowable regions. It can be observed that the pitch channel oscillates within $0.5\ s ~ 1\ s$, which is the transition between first and second stages. The curve of pitch rate change in Figure 9 (d) is large in this transition. Based on the simulation conditions, it can be seen from Figure 10(a) that the state of angle of attack greater than $15^\circ$ occurs between $0.5\ s$ and $1\ s$. Thus, Figure 10(b) shows that the pitching moment coefficient has a strong nonlinear problem in this
transition. Such atmospheric disturbance problem may be dealt with robust control according to reference [9].

Figure 9. Response curves of three attitude channels.

Figure 10. Variation curve of angle of attack and aerodynamic parameter.

The oscillates in transition put forward high requirements on actuator. But the rudder actuator has limited position in actual situation. Comparing the control deflection of different control methods in figure 11, the rudder deflection of aerodynamic control reached the limit after 0.5 s and compound control can be very effective in the transition. The reason has been analysed in Section III. Compound control has greater rudder effect than aerodynamic control under the low dynamic pressure.
5. Conclusion and prospect
This paper proposed a compound control method for anti-UAV vertical launch missile to solve the problem of high angle of attack and low dynamic pressure. Compared with aerodynamic control, the proposed compound control system is much more effective because the canard efficiency is improved under the negative conditions. Finally, the effectiveness of the proposed method is demonstrated in simulation. In the following study, the effect of exhaust flow on canard will be researched exactly by CFD and experiment.

6. References
[1] Tekin, Raziye, Özgür Atesoglu, and K. Leblebicioglu. "Modeling and Vertical Launch Analysis of an Aero- and Thrust Vector Controlled Surface to Air Missile." Aiwa Atmospheric Flight Mechanics Conference 2010.
[2] Facciano, Andrew B., K. G. Seybold, and T. L. Westberry-Kutz. "Evolved SeaSparrow Missile jet vane control system prototype hardware development." Journal of Spacecraft & Rockets 39.4 (2002): 522-531.
[3] Thukral, et al. "A sliding mode missile pitch autopilot synthesis for high angle of attack maneuvering." Control Systems Technology, IEEE Transactions on 6.3 (1998): 359-371.
[4] H-0., Jonsson, G., & Malmberg. "Optimal Thrust Vector Control for Vertical Launch of Tactical Missiles." Journal of Guidance Control & Dynamics (1982).
[5] Taur, Der-Ren & Chern, Jeng-Shing. "Optimal side jet control for vertically cold launched tactical missiles." (2000):10.2514/6.2000-4164.
[6] Solis R. An analysis of the vertical launch phase of a missile concept[C]//21st Aerospace Sciences Meeting, 2013: 569-578.
[7] Jia Xiaohong, fan Yonghua, and Yang Jun. "Design of an aerodynamic/direct force compound control missile autopilot." Journal of missile, rocket and guidance 03 (2005): 3-5 (in Chinese)
[8] Garnell, P. D. J. East, and G. M. Siouris. "Guided Weapon Control Systems." IEEE Transactions on Systems Man and Cybernetics 9.11 (1977): 740-741.
[9] Trifonov Maksim, Prochazka Karl and Krüger Saleh. "Robust Control of an Input-redundant Aircraft against Atmospheric Disturbances and Actuator Faults." International Journal of Mechanical Engineering and Robotics Research 8.6 (2019): 905-910.