Optimal Control and Output Feedback Considerations for Missile with Blended Aero-fin and Lateral Impulsive Thrust

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Abstract

For the missile with blended aero-fin and lateral impulsive thrust, a blended control autopilot is designed, which comprises an optimal controller and a control allocation module. The combined optimal/classical approach is applied to designing the optimal controller to determine the virtual controls, and the control allocation module is used to distribute the desired virtual controls onto the redundant control effectors. The autopilot holds some attractive characteristics, such as simple structure, good tracking performance and robustness; moreover the actual constraints of the control effectors can be taken into account. Based on this blended control autopilot, it is found that the conflict between stability and fast tracking performance is serious when using the total acceleration as feedback. In order to avoid this problem, the transient factors in total acceleration are eliminated, so the acceleration caused only by angle of attack is used as feedback, and obvious improvement is shown. Finally, how to get reasonable acceleration feedback is discussed, and conclusion is presented that after passing the low-pass filter, the total acceleration can also be used as feedback, and satisfied tracking performance can be obtained.

Keywords: missiles; optimal control systems; feedback control; blending control; lateral thrust

1. Introduction

After a long time research, it is found that the main factor to determine miss for high altitude interception is not the maneuver capability, but the agility, i.e. the speed of tracking response\cite{1}. In order to improve it, the blended control strategy using multiple control effectors is proposed\cite{2-4}. In this article, the lateral impulsive thrust used on a blended control missile helps the aero-fins establish the desired angle of attack more rapidly. During mathematical modeling, it is noticed that the input offered by impulsive thruster is discrete, while the aero-fins supply continuous inputs. As a result, the model of the blended control missile has hybrid inputs. The design of a blended control autopilot based on hybrid inputs model is a difficult problem and the focus of current research.

W. R. Chadwick\cite{1} proposed an intuitive blended control law with proportional structure, and its coefficients are determined by setting the expected frequency and damping. W. K. Schroeder, et al\cite{3} designed a nonlinear blended control autopilot using fuzzy logic. Other approaches such as coefficient diagram method\cite{6}, are also applied to designing blended control autopilot. All these researches have provided various ideas for blended control autopilot design, in which lateral thrust is assumed to be continuous. However, the hybrid inputs problem is not mentioned. For blended control missile, switching control is often used to design autopilot. In Ref\cite{7}, the switching blended control autopilot was designed for a spinning missile, and the lateral thrust was considered as discrete input. In Ref\cite{8} the mathematical models and controllers were switched according to angle of attack, and Ref\cite{9} used sliding mode method to design the switching controller. However, the characteristics of blended control strategy cannot be fully represented by using switching controllers.

For a dual aero/propulsive missile, D. Brett Ridgely, et al\cite{10} introduced the virtual controls and divided the autopilot into two parts. Inspired by it, here the virtual force and moment, which represent the total control effort, are brought in, and the autopilot is divided into two parts. One is the optimal controller, which is designed using combined optimal/classical control approach\cite{11}, the other is the control allocation, which is used to distribute the commands of the virtual controls.
onto individual control effectors. This design approach provides some potential benefits. The using of virtual controls makes the controller be designed directly based on a continuous model so the hybrid problem can be avoided. Because of the control allocation, it becomes more convenient to constrain the magnitude of the control effectors: if one control effector fails, reconfiguration can be done without redesigning the optimal control law. Furthermore, the utilization trade-off among the control effectors can be adjusted independently and changed according to different flight conditions.

It is found that, if the above-mentioned design approach is used and the total acceleration is taken as feedback, when the weights are regulated to get faster performance, the system becomes unstable. The weights which guarantee stability cannot supply satisfied response speed, which means the stability is in contradiction to the fast tracking performance. To solve this problem, an improved approach by deleting the transient factors from the total acceleration is proposed, i.e., to use the acceleration caused only by angle of attack as the acceleration feedback. The simulation results demonstrate that the tracking speed is obviously improved when adopting the proposed approach.

### 2. Mathematical Model

For the missile with blended aero-fin and lateral impulsive thrust, only the model of pitch channel is considered here. Assume the main thruster has been powered off, \( m \) and \( I_z \) are taken as constants, and the variations of height and magnitude of velocity as well as the gravity are ignored. After some simplification, the linear model is obtained. The inputs are the virtual fin-deflection and the lateral thrust \( U = [\delta z \ T_m] \), where the lateral thrust \( T_m \) represents the total effect of several impulsive thrusters and it is a discrete input. The state variables are the rate of pitch and the angle of attack \( X = [\alpha_2 \ \alpha_1] \), and the outputs are the total acceleration and the rate of pitch \( Y = [\alpha_1 \ \dot{\alpha}_2] \).

\[
\begin{align*}
\dot{X} &= AX + Bu \ U \\
Y &= CX + Du \ U
\end{align*}
\]  

where

\[
A = \begin{bmatrix}
M_{\alpha_2}/I_z & M_{\alpha_1}/I_z \\
1 & -Y_{\alpha_2}/(mV)
\end{bmatrix}
\]

\[
B_u = \begin{bmatrix}
M_{\delta z}/I_z & r_m/I_z \\
-Y_{\delta z}/(mV) & -1/(mV)
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
0 & Y_{\alpha_2}/m \\
1 & 0
\end{bmatrix}
\]

\[
D_u = \begin{bmatrix}
Y_{\delta z}/m & 1/m \\
0 & 0
\end{bmatrix}
\]

Herein the subscript \( U \) represents the actual inputs.

Then the virtual controls representing the total control effort are introduced, which are virtual moment and force \( V = [M \ F]^T \). The relationship between the virtual controls and the actual inputs is \( V = B_{vu} \ U \), where \( B_{vu} \) is the transfer matrix from actual inputs to virtual inputs and the expression in detail is

\[
\begin{align*}
M &= M_{\delta z} \delta z + r_m T_m \\
F &= Y_{\delta z} \delta z + T_m
\end{align*}
\]

where \( r_m \) is the distance from the location of the lateral thrust to the missile center of mass. As the virtual fin-deflection and the lateral thrust are independent, according to Eq.(2), the virtual moment and force are also uncoupled. When the virtual controls are used as the inputs of the model, the mathematical model is expressed as

\[
\begin{align*}
\dot{X} &= AX + Bu \ V \\
Y &= CX + Du \ V
\end{align*}
\]

where

\[
B_v = \begin{bmatrix}
1 & 0 \\
0 & -1/mV
\end{bmatrix}
\]

\[
D_v = \begin{bmatrix}
0 & 1/m \\
0 & 0
\end{bmatrix}
\]

Herein the subscript \( V \) represents the virtual inputs.

### 3. Blended Control Autopilot Design

#### 3.1. Scheme and method

By adopting the virtual controls, the autopilot is de-compounded into two parts. One is the optimal controller, whose inputs are the feedback terms of the acceleration and rate of pitch, the outputs are the desired virtual controls. The combined optimal/classical approach is applied to designing the optimal controller. The other is the control allocation, whose inputs are the desired virtual controls and outputs are the commands of actual control effectors. After model transformations, the control allocation problem can be solved by quadratic programming algorithm.

#### 3.2. Optimal controller design with combined optimal/classical approach

The main idea of combined optimal/classical approach is that, based on the simplified model, optimal control theory is applied to designing the controller. Meanwhile, the frequency domain analysis in classic
control theory is also used to verify the system’s frequency performance, including crossover frequency, phase margin and gain margin, which can bring restrictions to the weights in the performance index. In other words, the obtained controller is an optimal output feedback controller for the simplified model with certain robustness. The optimal control theory and frequency domain analysis are combined in this approach; the controller is optimized to obtain fast tracking performance, small steady-state error and certain robustness.

(1) Using optimal control to design controller

Based on the linear model Eq.(3), the optimal control theory is applied to designing the controller and the performance index is

$$\min J = \int_0^\infty \left[ Q(a_L - K w a_{1c})^2 + V R V^T \right] dt \quad (4)$$

where $Q$ is a scalar more than or equal to zero, and $R$ is a two-dimension positive definite diagonal matrix. Both of them are adjustable parameters for the controller.

Substituting $a_L$ which can be derived from output equation in model Eq.(3) into performance index Eq.(4), it is found that there is a cross term of the state variables and the input variables. Besides the quadratic terms of the state equation in model Eq.(3) into performance index is $V = kX = -R^{-1}_L (B'_L P + S^T)X \quad (5)$

where $P$ is the positive semi-definite stabilizing solution to the algebraic Riccati equation

$$(A - B'_L R^{-1}_L S^{-1}) P + P (A - B'_L R^{-1}_L S^{-1}) - P B'_L R^{-1}_L B'_L V + (Q_l - S R^{-1}_L S^T) = 0 \quad (6)$$

where

$$\begin{align*}
Q & = H^T Q H \\
S & = H^T Q L \\
R & = R + L^T Q L \\
H & = C(1,:) \\
L & = D_c(1,:)
\end{align*}$$

According to output equation $Y = CX + D_c V$, the state feedback control law can be transferred to the output feedback control law

$$V = K_c Y = [I + kC^{-1} D_c]^{-1} k C^{-1} Y \quad (7)$$

In the performance index, the coefficient $K_w$ is called the steady-state error coefficient, which is to guarantee the steady-state error is small enough. $K_w$ is calculated as a set point regulator problem, and the expression is

$$K_w = [C_c A'_c B'_c - D'_c]^{-1} \quad (8)$$

where $A_c, B'_c, C_c, D'_c$ are the coefficient matrices when the system model is shaped to equations with the command acceleration as input and the achieved acceleration as output. Until now, the optimal controller is completely determined, including approaches to obtain its structure and gains. This is a traditional two-loop controller, and the control law can be expressed in detail as

$$[M \quad F] = K_2 \begin{bmatrix} a_L - K_w a_{1c} \\ \omega_c \end{bmatrix} \quad (9)$$

(2) Restriction on weight selection through frequency domain analysis

When choosing the weights in the performance index, the focus should be on both the tracking performance and the robustness of the system. The frequency domain analysis is used to guarantee robustness of the system. The process is: first choose a set of initial weights, and use the above-mentioned method to calculate the gains for the controller. Then break the system at the acceleration feedback, and get the open-loop transfer function. After that, perform the frequency domain analysis, and verify the system’s stability margins, including crossover frequency, phase margin and gain margin. If the stability margins are not satisfied, regulate the weights and repeat the steps above. It is proved in Ref.[13] that standard LQR can provide $[-6 \, \text{dB}, +\infty]$ gain margin and $\pm 60^\circ$ phase margin. The crossover frequency $\omega_c$ is an important index for the verification. To restrict un-established high frequency dynamics, $\omega_c$ should be no more than one third of the bandwidth of the actuator. However, $\omega_c$ is also related to the tracking speed (bigger $\omega_c$ means faster tracking), therefore the tracking speed and robustness conflict with each other. It should be noticed that the stability margin is only one of the indexes representing system’s robustness, it is difficult to decide whether the system is robust to any uncertainty just based on it. Usually, small $\omega_c$ can guarantee the ability of high frequency attenuation.

3.3. Control allocation

For X type fin configuration, the relationship between the virtual fin-deflection and the actual four fin-deflections can be described as

$$\delta_2 = \frac{\sqrt{2}}{4} \delta_1 + \frac{\sqrt{2}}{4} \delta_3 + \frac{\sqrt{2}}{4} \delta_3 - \frac{\sqrt{2}}{4} \delta_4 \quad (10)$$

where $\delta_1$ is the fin-deflection at the left top corner seeing from missile tail; $\delta_2$, $\delta_3$ and $\delta_4$ are the ones located around the body by anticlockwise order. According to Eq.(2) and Eq.(10), the equality constraint $V = B U_d$ is obtained, where $B$ is a matrix of two rows and five columns. It can be seen that the equality is under-constrained. The effector magnitude constraints are taken into account in the control allocation, which can
be classified into two situations\cite{14}. One is control sufficiency, which means in the feasible region infinite solutions can satisfy the equality, and \(U_a\) is determined by minimizing the cost of control. The other is control deficiency, which indicates there is no solution which can satisfy the equality in the feasible region. Choose \(U_a\) so that \(B_a U_a\) approximates \(V\) as closely as possible.

In order to combine the two situations, a vector of slack variables \(s\) is introduced to penalize the equality, and the control allocation problem can be described as

\[
\begin{align*}
\min_{U,a} & \quad \frac{1}{2} (s^T Q_s + U_a^T R_s U_a) \\
\text{s.t.} & \quad B_a U_a = V + s \\
& \quad u_{\min} \leq u \leq u_{\max}
\end{align*}
\]

where \(u\) represents the component in \(U_a\), \(u_{\min}\) and \(u_{\max}\) are the respective lower and upper boundaries. The problem expressed by Eq.(11) can be solved by quadratic programming algorithm. As the equality constraint is the most important one, the weight \(Q_s\) should be chosen much larger than \(R_s\). At each computation step, \(B_a\), \(Q_s\), \(R_s\) are re-determined, then it becomes very convenient to deal with the accidents, e.g., one control effector loses the effectiveness, or utilization tradeoff of the control effectors needs to be changed according to different flight conditions. If the fin-deflection rates are constrained, the inequality constraints in Eq.(11) need to be extended, and the principle is identical.

4. Autopilot with Total Acceleration as Feedback

Based on model Eq.(3), the autopilot obtained by applying the above-introduced method is a two-loop autopilot whose output feedback terms are the rate of pitch and the total acceleration (caused by angle of attack, fin-deflection and lateral thrust).

The detailed block diagram is shown in Fig.1. The actuators, rate gyro and accelerometer are all represented by two order transfer functions, and the parameters are \(\omega_{\text{act}}=120\ \text{rad/s}, \quad \zeta_{\text{act}}=0.65, \quad \omega_{\text{gyro}}=\omega_{\text{accel}}=440.528\ 6\ \text{rad/s}, \quad \zeta_{\text{gyro}}=\zeta_{\text{accel}}=0.4. \) The ignition period is assumed to be 0.02 s, and 2 100 N thrust can be supplied by one impulsive thruster. In control allocation, the magnitude boundary of the fin deflection is \(\pm 30^\circ\), and a maximum of 20 thrusters can be used at the same time. The flight condition in the simulation is \(h=17.5\ \text{km}, \quad Ma=3.5\).

Simulation result shows that discretizing the lateral thrust causes system unstable. Here Lyapunov’s direct method is used to analyze system’s stability. When the lateral thrust is continuous, the inputs are \(U=[\delta_1, T_m]^T\), after inserting ZOH the lateral thrust is changed to discrete \(H(U)=[\delta_1, H(T_m)]^T\). As the state feedback and output feedback control laws are convertible, the input is expressed as the state feedback form

\[
\dot{X} = AX + BH(U) =
\]
\[ AX + BH(\neg KX) = (A - BK)X + B(\neg(KX) - \neg(KX)) \] (12)

The terms in square bracket represent the error caused by discretizing the lateral thrust. Set \( e = H(-KX) - (-KX) \), then the system can be expressed as

\[ \dot{X} = (A - BK)X + Be \] (13)

As the continuous system is stable, according to Lyapunov stability theory, when a positive matrix \( Q_L \) is given, the positive \( P_L \) exists and satisfies the equation

\[ (A - BK)^T P_L + P_L (A - BK) = -Q_L \] (14)

Choose Lyapunov function as \( V = X^T P_L X \), then system’s stability is analyzed by judging whether the variation of \( V \) is negative or not.

\[ \dot{V} = X^T P_L X + X^T P_L \dot{X} = \]

\[ [(A - BK)X + Be]^T P_L X + X^T P_L [(A - BK)X + Be] = \]

\[ X^T [(A - BK)^T P_L + P_L (A - BK)]X + 2X^T P_L Be = \]

\[ -X^T Q_L X + 2X^T P_L Be \] (15)

where \(-X^T Q_L X < 0\). A sufficient condition to ensure \( \dot{V} < 0 \) is \( \|2X^T P_L Be\| < \|X^T Q_L X\| \). And the following inequalities are easy to be obtained:

\[ \left\| X^T QX \right\| \geq \| X \|^2 \sigma_{\min}(Q) \]

\[ \left\| 2P^T PB \right\| \leq 2\|X\| \sigma_{\max}(P) \sigma_{\max}(B) \|e\| \]

Unite the three inequalities to obtain

\[ \| e \| < \frac{\|X\|\sigma_{\min}(Q)}{2\sigma_{\max}(P)\sigma_{\max}(B)} \] (16)

It means that the error caused by discretizing lateral thrust should be less than certain value related to the states and flight condition, then the stability can be retained. As the weight on acceleration error increases, the continuous lateral thrust varies more seriously at the initial phase, then the error caused by discretizing at the ignition period is bigger and the system becomes unstable. According to the structure of the controller, the total acceleration is in direct proportion to the lateral thrust input, and the total acceleration contains the transient factors (the accelerations generated by impulsive thrusters and the elevator). So in the establishment of angle of attack, both the total acceleration and the impulsive thrust input vary dramatically. If the transient factors are eliminated, i.e. smooth acceleration, such as the acceleration caused only by angle of attack \( a_{\alpha L} \), is used as output feedback, the conflict may be alleviated.

5. Autopilot with Acceleration Caused by Angle of Attack as Feedback

When the acceleration caused by angle of attack \( a_{\alpha L} \) is used as output feedback, model Eq.(3) should be changed by setting \( D_L = 0 \), and the output variables are \( a_{\alpha L} \) and the rate of pitch. \( K_a \) obtained by Eq.(8) makes the error of the command acceleration and \( a_{\alpha L} \) small enough, but the fact that steady-state values of fin-deflections and lateral thrust are not equal to zero also helps to generate acceleration, which leads to the steady-state error of the total acceleration and the command. To avoid this, \( K_a \) should be modified. Firstly, calculate the steady virtual force \( F_s \) which is equal to the magnitude of the steady error. According to the control law

\[
\begin{bmatrix}
M_s \\
F_s
\end{bmatrix} = K_a \begin{bmatrix}
a_{\alpha m} - K_a a_{\alpha L} \\
a_{\alpha L}
\end{bmatrix} = K_a \begin{bmatrix}
a_{\alpha s} - K_a a_{\alpha L} \\
0
\end{bmatrix}
\] (17)

Then the modification parameter is expressed as

\[ \frac{1}{K_a} = \frac{a_{\alpha s} + F_s / m}{a_{\alpha L}} \] (18)

\( K_a \) is changed to be \( K_{s1} = K_a / K_m \). After some calculation, \( K_{s1} \) can be represented by Eq.(19), in which the command acceleration is not involved.

\[ K_{s1} = K_a [(1 + K_a (2,1)(1 - K_a)) / m] \] (19)

The same flight condition is used here, and the true value of \( a_{\alpha s} \) is used as feedback. The simulation results are shown in Fig.4. With \( Q = 6000 \), when the total acceleration is used, the system is unstable in Fig.3. When the feedback is changed to \( a_{\alpha L} \), however, the system is stable, and satisfied tracking performance is gained with the rising time being \( \tau_{f0%=0.12} \). To improve tracking speed, increase \( Q \) to \( Q = 10000 \), then a faster response is obtained \( \tau_{f0%=0.10} \) s, and the overshoot at initial point also increases obviously. In Fig.5, comparison of the total acceleration responses using the two feedback types is given under the conditions of sine command acceleration. When \( a_{\alpha s} \) is taken as feedback, bigger \( Q \) can be chosen and better performance is obtained.

![Fig.4 Comparison of total acceleration responses.](image-url)
Large transient overshoot will lower the guidance precision. Therefore, when choosing the weights, the overshoot of the tracking response should be restricted to be less than 40%. Using the two feedback types respectively, the proper weights on the acceleration error versus some specified flight conditions are indicated in Fig.6. Choose the weight on the virtual controls in advance $R = \text{diag}(0.05, 1.00)$. The flight condition is described by the height and the Mach number. The heights $h = 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0$ km and Mach numbers $Ma = 2.75, 3.00, 3.25, 3.50, 3.75, 4.00$.

In Fig.6, the top surface represents the weights for $a_{L\alpha}$ as feedback, and the lower surface indicates the results for total acceleration $a_L$ as feedback. It is found that the weights of the former are much larger than those of the latter, especially under the conditions of high altitude and low speed. With low altitude and high speed, however, the same weight can be chosen for both feedback styles. Principles of weight selection can also be found in Fig.6. With the same altitude, $Q$ declines as Mach number increases. Keep the Mach number constant and $Q$ becomes larger as the altitude increases. The principles are more evident when $a_{L\alpha}$ is used as output feedback.

In the simulations, the true value of $a_{L\alpha}$ is used as feedback, and satisfied tracking performance is obtained. But in practical application, the precise value of $a_{L\alpha}$ is difficult to get, and incorrect $a_{L\alpha}$ will affect the tracking performance.

6. Output Feedback Consideration

Generally, the total acceleration of the missile can be measured by sensor, but it is found that, for the missile with blended aero-fin and lateral impulsive thrust, eliminating the transient factors in the total acceleration is helpful to improve the system’s tracking performance. This article presents several methods to get this acceleration and conduct discussion respectively.

(1) Method 1

Use $a_{L\alpha}$ as feedback, the value of angle of attack is obtained by estimator, and multiply it by the related aerodynamic parameter to obtain the value of $a_{L\alpha}$. The inputs of the estimator of angle of attack are usually the measured values of total acceleration and rate of pitch. More simply, only the rate of pitch can be used to estimate the angle of attack, and the relationship is

$$\frac{a(s)}{a_{\alpha}(s)} = \frac{1}{s + k}$$

where $k$ is determined by aerodynamic parameter and the flight conditions.

The same flight condition $h = 17.5$ km, $Ma = 3.5$ is used here. In Fig.7 the estimated and true values of $a_{L\alpha}$ are used respectively. Set $Q = 10,000$ for both of them, the comparison shows that the acceleration responses are almost identical, and the rising time is still 0.1 s. For the missile with blended aero-fin and lateral impulsive thrust, the precise value of the aerodynamic parameter is hard to be obtained because of jet interaction. To analyze the robustness, assume that parameter $Y^\alpha$ used in the airframe model has some uncertainty, but in $a_{L\alpha}$ estimation, the nominal value of $Y^\alpha$ is still used. The responses are given in Fig.8 when the uncertainty is set to be $\pm 10\%$ and $\pm 20\%$ respectively. It is found that the system can keep stable, but the steady state error increases as uncertainty grows.
Fig.8 Acceleration responses with parameter uncertainties (Method 1).

(2) Method 2
Make the total acceleration pass the low-pass filter with appropriate bandwidth, and the high frequency signal can be removed, then the output is used as feedback. Firstly, the proper time constant should be chosen for the low-pass filter. The simulation results with different time constants are shown in Fig.9. Considering both high frequency filtering and time delay effect, the time constant is set to 0.04 s, then the rising time of the response is 0.12 s, a little bigger than using that of $a_{Lr}$ as feedback. Based on it, the robustness is verified, and the same uncertainty in aerodynamic parameter is used. The results are shown in Fig.10. Compared with Fig.8, better robustness is obtained. The system is still stable and has satisfied tracking performance. Only the rising process is influenced by the uncertainty.

Other methods can also be used to get the acceleration feedback, such as the idea of waiting “clean” flow field[15]. The impulsive thrusters work for an ignition period, stop for a while, then work for next ignition period. During the interval, the measured total acceleration does not include lateral thrust, so it can be used as feedback of the optimal controller.

7. Conclusions
For missiles with blended aero-fin and lateral impulsive thrust, a blended control autopilot is designed. The autopilot is decomposed into two parts, the optimal controller and the control allocation module. Based on the linear model, the controller is designed by applying the combined optimal/classical approach and is used to determine the virtual controls which can represent total control effect. The control allocation is used to calculate the commands of the control effectors, which can generate equivalent effect with the virtual control commands. Based on this autopilot, two feedback types are adopted. One takes the total acceleration as output feedback, the other is the acceleration caused by angle of attack. It is demonstrated that the conflict exists between stability and fast tracking performance when using the total acceleration. When the transient factors in total acceleration are eliminated, this conflict is alleviated and better tracking performance is obtained. At last, a practical method to obtain the acceleration feedback is discussed. It is found that, when the total acceleration which passes the low-pass filter with appropriate bandwidth is used as feedback, satisfied tracking performance can be obtained.

Until now, the hybrid-input problem has not been completely solved, because in control allocation module the lateral thrust is still continuous. Future research will be focused on the improvement of control allocation to establish a mathematical model of discrete lateral thrust and propose the corresponding control allocation algorithm.

References


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