Adaptive Fuzzy Control for Input Restriction Airbreathing Hypersonic Vehicle

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Abstract. For the problem of actuator limitation in the control of aspirating hypersonic vehicle (AHV), this paper proposes a control strategy combined fuzzy approximation system with adaptive control. Firstly, the system is divided into velocity subsystem and altitude subsystem. Then, a new control law is designed. Finally, the uncertainty of the system is estimated based on the universal approximation theory of fuzzy system. This control strategy can both allow the control system with better robustness, and a good restraining effect for the uncertain disturbance. As shown from the simulation results, the method proposed in this paper has more stable than the traditional method in different situations and verifies the effectiveness of the control strategy.

1. Introduction

The Airbreathing Hypersonic Vehicles (AHV) is a new type of aircraft, which flies at ultra-high velocity and long distance in the near space, including hypersonic aircraft, missiles and circular use of various types of spacecraft between heaven and earth[1]. The AHV has its characteristics of high flying velocity, long maneuvering distance and strong penetration capability with approximately 20-100 km of flying altitude from the ground near the space, and more than 5 mach of flying velocity. With strong ability of movement and survivability, it can perform variety of tasks such as high-altitude reconnaissance, material delivery and strategic strike in the global military.

Recently, AHV developed into high precision, high velocity and high maneuverability. However, due to its inherent aerodynamic structure and elastic deformation, there are strong nonlinearity, fast time varying, strong coupling and uncertainty in the actual flight process, making it difficult for AHV to be controlled by conventional methods [2-4]. Meanwhile, various external uncertainties (such as external gust disturbance, turbulence, transition) will also affect the flight of the aircraft, which increase the uncertainty of the control model [5]. Therefore, it is the key for the development of AHV technology to establish a safe and stable AHV control model [6].

Throughout the research at home and abroad, many kinds of controller theories are emerged, such as feedback linearization control [7], sliding mode control [8] and inversion control [9-11]. AHV highly requires for flight attitude during flight and also needs to avoid a large amount of fuel consumption, therefore it is necessary to reduce or try to avoid lateral maneuvers during flying. Recently, most studies explore on longitudinal model, and the research on control method focuses on...
the aircraft affine model. [12] proposes the feedback linearization control; [13] proposes the second-order sliding film controller based on sliding mode control; [14] proposes the design of missile incremental dynamic inversion control law for tracking differentiator. It can be seen from the above researches that the design methods of adaptive fuzzy control is ability to deal with the uncertainty of aerodynamic model. On this basis, researchers continue to improve the existing methods and [15] introduces ESO adaptive fuzzy control; [16] adopts a AHV fuzzy tracking control design based on t-s model; recently, some other fuzzy control applications are proposed [17, 18]. However, using fuzzy control highly requires on various parameters, especially the uncertainty of aerodynamic parameters and the robustness, faced with the complex environment, so the structure design of the controller is very complex.

Beside the design and research of the controller, the problem of input restriction caused by actuator restriction is also widely concerned [19-23]. [21] handles the problem of input restriction by anti-windup control, and solves the problem of velocity tracking and altitude tracking when the actuator is input restriction; [22] adds auxiliary system to compensate the error signal and allow actuator making up for the loss and keeping stable in the restriction situation, but this method can not guarantee the convergence of tracking error; [23] introduces actuator into the adaptive control to eliminate the adverse effects of parameter uncertainty.

This paper designs a control method based on a fuzzy adaptive control for the bounded compensation of tracking error under the condition of input limited of AHV, combined fuzzy control with adaptive control which has the characteristics of low requirements but strong robustness for mathematical models, and a strong restraining force for uncertain factors.

The innovation of the methods are listed as follows:

1. The novel auxiliary error compensation design realizes elimination the influence of actuator saturation, ensures the stability of the closed-loop system, and still has the bound for the velocity and altitude tracking errors when the actuator is saturated.

2. Virtual controller doesn’t require for complex design. The method of fuzzy control proposed in this paper is simpler.

3. On the basis of fuzzy control technology, many uncertain constraints are eased. Compared with the traditional nonlinear or adaptive approximator, there is superior performance for unmodeled dynamic and uncertain disturbances.

2. AHV Kinematics Description

At present, the dynamic model of AHV mainly adopts the Paker elastomer model [24] proposed by the US Air Force laboratory, which it takes X-43A aircraft as the basic design and uses the elastomer integrated modeling. The geometric configuration of the model is shown in Figure 1, and the longitudinal dynamic equation is designed as follow:

\[
\dot{V} = \frac{T \cos \alpha - D}{m} - g \sin \gamma
\]

\[
\dot{h} = V \sin \gamma
\]

\[
\dot{\gamma} = \frac{L + T \sin \alpha}{mV} - \frac{g}{V} \cos \gamma
\]

\[
\dot{\phi} = Q
\]

\[
\dot{Q} = M + \ddot{\psi}_1 \ddot{h} + \ddot{\psi}_2 \ddot{I}_{yy}
\]

\[
k_1 \ddot{h} = -2 \gamma \omega_1 \ddot{h} - \omega_1^2 \ddot{h} + N_1 - \dot{\psi}_1 \frac{M}{I_{yy}} - \ddot{\psi}_1 \ddot{\psi}_2 \ddot{I}_{yy}
\]

\[
k_2 \ddot{I}_{yy} = -2 \gamma \omega_2 \ddot{I}_{yy} - \omega_2^2 \ddot{I}_{yy} + N_2 - \ddot{\psi}_2 \frac{M}{I_{yy}} - \ddot{\psi}_2 \ddot{\psi}_1 \ddot{h}
\]
Where, $V$ and $h$ respectively represent the flight velocity and altitude of AHV; $\gamma$ represents the flight path angle; $\theta$ and $\dot{\theta}$ respectively represent the flight pitch angle and pitch angle rate; $m$ are the mass of AHV; $I_{yy}$ represents the pitch moment of inertia; $\alpha = \theta - \gamma$ defines the flight angle of attack; the above parameters represent the rigid body state of AHV. $\eta_1$ and $\eta_2$ represent the elastic state of AHV, $\xi_1$ and $\xi_2$ represent the damping of elastic state, $\omega_1$ and $\omega_2$ represent the vibration frequency of elastic state, and $N_1$ and $N_2$ are the generalized elastic force;

\[
\begin{align*}
\dot{k}_1 &= 1 + \frac{\psi_1}{I_{yy}} \\
\dot{k}_2 &= 1 + \frac{\psi_2}{I_{yy}} \\
\psi_1 &= \int_{-L_y}^{0} \tilde{m}_y \tilde{\xi} \phi_1(\xi) \, d\xi \\
\psi_2 &= \int_{0}^{L_y} \tilde{m}_y \tilde{\xi} \phi_2(\xi) \, d\xi
\end{align*}
\]

(8)

Where, $\phi_1(\cdot)$ and $\phi_2(\cdot)$ represents the mode function, and the fitting equation for thrust $T$, resistance $D$, lift $L$, pitching moment $M$, and generalized elastic forces $N_1$ and $N_2$ of the aircraft are expressed in equation (9)

\[
\begin{align*}
T &= C_T \alpha^3 + C_T' \alpha^2 + C_T'' \alpha + C_T' \eta_1 \\
D &= qS(C_D \alpha^2 + C_D' \alpha + C_D'' \delta_e^2 + C_D' \delta_e + C_D' \eta_2) \\
L &= qS(C_L \alpha + C_L' \delta_e + C_L' \eta_2) \\
M &= z_T T + qSc[C_M \alpha^2 + C_M' \alpha + C_M' \delta_e + C_M' \delta_e + C_M' \eta_2] \\
N_1 &= N_1^0 \alpha^2 + N_1^0 \alpha + N_1^0 \\
N_2 &= N_2^0 \alpha^2 + N_2^0 \alpha + N_2^0 \delta_e + N_2^0
\end{align*}
\]

(9)

Where, $q = \frac{1}{2} \rho V^2$ and $\rho = \rho_0 \exp\left(\frac{h_0 - h}{h_s}\right)$; the fuel air ratio $\Phi$ and elevator deflection $\delta_e$ are the input of the control system, $q$ is the dynamic pressure of AHV, $\rho$ is the average air density, and $S$ and $c$ are reference aerodynamic area and the average aerodynamic chord length of the aircraft. Other parameters of the model are shown in [25].

3. Stability analysis

**Theorem 1:** for the closed-loop velocity subsystem of AHV, if the control law and the adaptive law are adopted, the local of closed-loop velocity subsystem is asymptotically and uniformly stable.
\[ \dot{V} = \theta^T \xi'_i (X_i) + \mu_i + \Phi_c - \Delta \Phi - \dot{V}_{\text{ref}} \]
\[ = -k_{v1} V + k_{v1} \chi_i - k_{v2} \int_0^t \dot{V} \, d\tau \]
\[ + k_{v2} \int_0^t \chi_i d\tau + \theta_i^T \xi_i (X_i) \]
\[ - \frac{1}{2} \dot{V} \hat{\phi}_i^T (X_i) \xi_i (X_i) - \frac{V \partial_i (V)}{\tau_i^2 + V^2} + \Delta \Phi + \mu_i \]

The estimation error of definition \( \phi_i \) is:
\[ \dot{\phi}_i = \dot{\hat{\phi}}_i - \phi_i \]

Select the Lyapunov function as shown below:
\[ L_V = \frac{V^2}{2} + \frac{k_{v2}}{2} \left( \int_0^t \dot{V} \, d\tau \right)^2 + \frac{\hat{\phi}_i^2}{\lambda_i^2} + \frac{\chi_i^2}{2} + \frac{\tau_i^2}{2} \]

Solve first order derivative about time for equation (12)
\[ \dot{L}_V = \dot{V} \dot{V} + k_{v2} \int_0^t \dot{V} \, d\tau \dot{V} + \frac{\hat{\phi}_i \dot{\hat{\phi}}_i}{\lambda_i} + \chi_i \dot{\chi}_i + \tau_i \dot{\tau}_i \]
\[ = -k_{v1} V^2 + k_{v1} \chi_i - \chi_i \Delta \Phi - \frac{(\Delta \Phi)^2}{2} \]
\[ + k_{v2} \int_0^t \chi_i d\tau + \dot{V} \theta_i^T \xi_i (X_i) \]
\[ - \frac{1}{2} \dot{V} \hat{\phi}_i^T (X_i) \xi_i (X_i) - \frac{2k_{v1} \hat{\phi}_i \dot{\hat{\phi}}_i}{\lambda_i} \]
\[ - \frac{V \partial_i (V)}{\tau_i^2 + V^2} - \dot{\phi}_i (V) \frac{\tau_i^2}{\tau_i^2 + V^2} + \dot{V} \Delta \Phi \]
\[ - \left| \dot{V} \Delta \Phi \right| + \dot{V} \mu_i - \kappa_i \dot{\chi}_i^2 - l_i \dot{\tau}_i^2 \]

Because
\[ \dot{V} \theta_i^T \xi_i (X_i) \leq \frac{V^2}{2} \hat{\phi}_i^T (X_i) \xi_i (X_i) + \frac{1}{2} \]
\[ \frac{2k_{v1} \hat{\phi}_i \dot{\hat{\phi}}_i}{\lambda_i} \geq \frac{k_{v1} (\dot{\phi}_i - \phi_i)^2}{\lambda_i} \]
\[ \dot{V} \mu_i \leq \frac{V^2 \mu_{\text{max}}^2}{2} + \frac{1}{2} \]
\[ V \partial_i (V) = \frac{(V^2 + \tau_i^2 - \tau_i^2) \partial_i (V)}{\tau_i^2 + V^2} \]
\[ = -\partial_i (V) + \frac{\tau_i^2 \partial_i (V)}{\tau_i^2 + V^2} \]

Rewrite equation (13) is formulated as
\[ \dot{L}_V \leq -\left( k_{v1} - \frac{1}{2} \mu_{\text{max}}^2 \right) V^2 - (\kappa_i - 1) \chi_i^2 \]
\[ - l_i \tau_i^2 - \frac{k_{v1} \hat{\phi}_i^2}{\lambda_i} + 1 + \frac{k_{v1} \phi_i^2}{\lambda_i} \]

According to LaSalle Yoshizawa theory, the local of closed-loop system is uniformly asymptotically stable. The proof is complete.
Theorem 2: for the closed-loop altitude subsystem of AHV, if the control law and the adaptive law, the local fo closed-loop altitude subsystem is locally asymptotically uniformly stable.

\[
\dot{E} = F_h + \delta_c + 3\mu^2 \dot{e} + 3\mu^2 \dot{e} + \mu^3 e - \dot{\gamma}_d
\]

\[
= \theta_2^T \xi_2(X_2) + \mu_2 + \delta_{\alpha_c} + \Delta \delta_e
\]

\[
+ 3\mu^2 \dot{e} + 3\mu^2 \dot{e} + \mu^3 e - \dot{\gamma}_d
\]

\[
= -k_h E + k_h \chi_2 + \theta_2^T \xi_2(X_2)
\]

\[
- \frac{1}{2} E \phi_2^{T} \xi_2(X_2) \xi_2(X_2) - \frac{E \partial_1(E)}{\chi_2^2 + E^2}
\]

\[
+ \Delta \delta_e + \mu_2
\]

The estimation error of definition $\phi_2$ is:

\[
\phi_2 = \phi_2 - \varphi_2
\]

(16)

Select the Lyapunov function shown below

\[
L_h = \frac{E^2}{2} + \frac{\phi_2^2}{2\lambda_2} + \frac{\chi_2^2}{2} + \frac{\tau_2^2}{2}
\]

(17)

Solve first order derivative about time for equation (17), equation (11), respectively and obtain:

\[
i_h = E \dot{E} + \frac{\phi_2 \dot{\phi}_2}{\lambda_2} + \chi_2 \ddot{\chi}_2 + \tau_2 \ddot{\tau}_2
\]

\[
= -k_h E^2 + k_h E \chi_2 - \chi_2 \Delta \delta_e - \frac{(\Delta \delta_e)^2}{2} + E \theta_2^T \xi_2(X_2)
\]

\[
- \frac{1}{2} E^2 \phi_2^{T} \xi_2(X_2) \xi_2(X_2) - \frac{2k_h \phi_2 \dot{\phi}_2}{\lambda_2} - \frac{E \partial_2(E)}{\tau_2^2 + E^2}
\]

\[
- \frac{\partial_2(E) \tau_2^2}{\tau_2^2 + E^2} + E \Delta \delta_e - |E \Delta \delta_e| + E \mu_2 - \kappa_2 \chi_2^2 - l_2 \tau_2^2
\]

(18)

Because

\[
E \theta_2^T \xi_2(X_2) \leq \frac{1}{2} E^2 \phi_2^{T} \xi_2(X_2) \xi_2(X_2) + \frac{1}{2}
\]

\[
\frac{2k_h \phi_2 \dot{\phi}_2}{\lambda_2} \geq \frac{2k_h (\phi_2 - \dot{\phi}_2)^2}{\lambda_2}
\]

\[
E \mu_2 \leq \frac{E^2 \mu_{\text{Max}}}{2} + \frac{1}{2}
\]

\[
\frac{E^2 \partial_2(E)}{\tau_2^2 + E^2} = - \frac{(E^2 + \tau_2^2 - \tau_2^2) \partial_2(E)}{\tau_2^2 + E^2}
\]

\[
= - \partial_2(E) + \frac{\tau_2^2 \partial_2(E)}{\tau_2^2 + E^2}
\]

\[
\partial_2(E) = \frac{1}{2} k_h E^2
\]

\[
k_h E \chi_2 - \chi_2 \Delta \delta_e \leq \frac{1}{2} k_h E^2 + \chi_2^2 + \frac{1}{2} (\Delta \delta_e)^2
\]

\[
E \Delta \delta_e - |E \Delta \delta_e| \leq 0
\]

Then, equation (18) can be rewritten into equation (19) as.
\[ \dot{z}_k \leq - \left( k_h - \frac{1}{2} k_{\mu_{\text{Max}}} \right) E^2 - (\kappa_2 - 1) \chi_2^2 \\
- l_2 \chi_2^2 - \frac{k_h \phi_2}{\lambda_2} + 1 + \frac{k_h \phi_2}{\lambda_2} \tag{19} \]

Therefore, according to LaSalle Yoshizawa theory, the local of closed-loop system is uniformly asymptotically stable. Furthermore, since \((s + \mu)^3\) is a Hurwitz polynomial, the error \(e\) of \(E\) is also bounded. The proof is complete.

4. Simulation experiment

The model is simulated in a closed-loop system, in which the longitudinal motion model of the aircraft is the controlled object of the system, and the reference velocity and reference altitude are tracked and simulated. The fourth-order Runge-Kutta method is used to solve the problem, and the simulation step is set to 0.001 s. The initial velocity of the aircraft is 2500 m/s and the altitude of motion is \(h = 27000\) m. The controller parameters are designed as: \(k_{\gamma_1} = 0.2, k_{\gamma_2} = 0.8, \tau_{v_1} = 2, \tau_{v_2} = 0.8, \tau_{h_1} = 2, k_{h_2} = 0.8, k_h = 50, \lambda_1 = 0.05, \lambda_2 = 0.005, k_{\gamma} = 0.5, k_{\theta} = 0.5, \sigma_1 = 0.0001, \sigma_2 = 0.0001, \sigma_h = 0.0001, \chi_1 = 0.0001, \chi_2 = 0.0001, l_1 = 0.0001, l_2 = 0.0001.\) The damping ratio of the reference input for velocity and altitude is 0.9, and the natural frequency is 0.1 rad/s. In the fuzzy system, the Gauss function is selected as the membership function, and the fuzzy set of each variable is set to 100. In the velocity subsystem, the input variable is \(V\), and the fuzzy center \(i_v\) of each fuzzy set of velocity \(V\) is uniformly distributed within [2500, 2800]. In the altitude subsystem, the fuzzy centers \(i_h, i_\gamma, i_\theta\) and \(i_Q\) of each fuzzy set of input variables, \(\gamma, \theta\) and \(Q\) are evenly distributed in the regions of [-5.7°/s, 5.7°/s], respectively.

The following uses the method of this paper to simulate in two scenarios.

The velocity phase step is set as \(\Delta V = 100\) m/s and the altitude phase step is set as \(\Delta H = 700\) m. When the control input of the system is not restricted, the method of this paper is compared and simulated with the method of [31]. In order to verify the robustness of the control law, it is assumed that the aerodynamic parameters of the AHV model have ±40% perturbation: \(C = C_0 [1 + 0.4 \sin(0.1 \pi t)]\), where, \(C_0\) represents the nominal value of the aerodynamic coefficient of the AHV, and \(C\) is the value of \(C_0\) in the simulation;

(a) Velocity tracking curve

(b) Velocity tracking error curve
(c) High tracking error curve

(d) Altitude tracking curve

(e) Change curve of elastic state $\eta_1$

(f) Change curve of elastic state $\eta_2$

(g) Track angle curve

(h) Fuel-air ratio curve

(i) Rudder angle curve

(j) Pitch angular velocity curve
The constraints cause to executable range to be smaller than the theoretical value: 
\[ \Phi \in [0.05, 1.2] \], and 
\[ \delta_e \in [-18^\circ, 18^\circ] \]. Meanwhile, in order to verify the robustness of the control law, it is assumed that the 
\[ \pm40\% \] perturbation is existed in AHV model aerodynamic parameters: 
\[ C = C_0\left[1 + 0.4\sin(0.1\pi t)\right] \]. 

\( \hat{C} \) represents the nominal value of AHV aerodynamic coefficient, and \( C \) is the value \( C_0 \) in the simulation. When the aerodynamic parameters of AHV model are perturbed, the method in this paper has better stability and accuracy in velocity and altitude tracking, which shows the superiority of the method.

As seen from above simulation results in Figure 2, the case 1 shows that if the velocity of phase step is 100, the tracking error curve (a, b, d, e) of velocity and altitude is more obvious, but traditional methods could not be stable track. At the same time, Figure (c, f) shows elastic state cannot be effectively suppressed, and this method can suppress it well. In case 2, when restriction factors are added and the aerodynamic parameters of the AHV model are perturbed, the method can still maintain high stability at the velocity and altitude. And, in the Figure (g, l, j), attitude angle and control input can also be controlled within a reasonable value range. As can be seen from figure (h) and figure (i), the elastic state (c, f) also don't show high buffeting under normal state. In conclusion, this method proposed in this paper can achieve robust tracking of velocity and altitude reference input, and has some advantages with the method in [26].

5. Conclusion

(1) Based on the adaptive fuzzy control method, the method proposed in this paper can guarantee that when the actuator reaches saturation, the closed-loop control system can still maintain good stability and keep the boundedness of tracking error.

(2) When the model exists the perturbation of aerodynamic parameters and external interference, the velocity and altitude tracking obtained in this paper is good stability, and the algorithm has strong anti-interference ability.

(3) Under the condition of actuator restriction, the algorithm designed in this paper can still effectively suppress the elastic state, which proves the stability of the control system.

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