Fixed-Time Fuzzy Adaptive Fault-Tolerant Control for Hypersonic Flight Vehicles Using a New Prescribed Performance Function

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Abstract This article proposes a new fixed-time fuzzy adaptive fault-tolerant control methodology for the longitudinal dynamics of hypersonic flight vehicles (HFVs) in the presence of actuator faults, uncertain dynamics and external disturbances. In contrast with the conventional fixed-time control schemes that typically contain the fractional powers of errors in their designs, this work develops a low-complexity control structure in the sense of removing the dependence on the need of above-mentioned fractional power terms by means of prescribed performance control (PPC) method. Different from the most existing PPC approaches where the initial conditions of tracking errors are required to be known, the newly proposed prescribed performance function (PPF) can relax such restrictions through choosing properly small initial values of PPF. Fuzzy logic systems (FLSs) are employed to handle unknown dynamics and minimal learning parameter (MLP) technique is incorporated into the design for the purpose of alleviating computation burden. Closed-loop stability is rigorously proved via Lyapunov stability theory and simulation results are eventually given to validate the effectiveness of the proposed control strategy.

Keywords Fixed-Time Tracking Control · Hypersonic Flight Vehicles · Actuator Failure · Prescribed Performance Control

1 Introduction

Hypersonic flight vehicles have already attracted considerable attention due to their advantages of high flight speed, remarkable penetration ability and cost-effectiveness [1]-[3]. Nevertheless, the controller design for HFVs remains an intractable issue due to their peculiar features. For example, the engine-airframe structure results in strong couplings between propulsive and aerodynamic forces, and there exist intricate flexible deformation due to the slender geometry of vehicle structure, which influences the aerodynamic characteristics prominently [4]. In addition, the fast time-varying flight environment as well as the unknown external disturbances lead to frequent parameter variations and model uncertainties, dramatically increasing the difficulty of controller design for HFVs [5]. To address these problems, many effective methods have been presented, including robust control [4]-[6], neural/fuzzy control [7]-[9], prescribed performance control [10]-[12] and so on. Although these efforts solve the above-mentioned issues to some extent, these results rarely focus on the rate of convergence.

To be specific, only the exponential convergence of tracking error is guaranteed in the aforementioned work, which reveals the convergence time tends to be infinite. From a practical perspective, the rate of convergence is of great significance to the transient tracking performance [13]. Recently, the finite-time tracking control for HFVs is investigated in [13]-[16], which can make the tracking error converge into the predefined compact set within a finite time. Nevertheless, the convergence time, which is commonly achieved in [13]-[16], depends on the initial states of the system. It inevitably brings up a problem, that is, the convergence time can not be accurately settled when the initial states of the system are unknown. To solve such problem, the fixed-time control [17]-[20] is proposed skillfully, by which the tracking error can converge into a predefined impact set within a fixed time and the connection between the convergence time and initial states is eliminated.

However, there still exist some shortcomings with the conventional fixed-time tracking control scheme [17]-[20], where the inequation \( \dot{V}(x) \leq -\tau V^p(x)-\varsigma V^q(x)+k \) holds. On the one hand, the derivative of virtual and actual control laws will tend to infinite when the track-
ing error approaches to zero, giving rise to singularity issues in the control design [20]. On the other hand, when the system encounters the unknown external disturbances [21]-[24] or the system faults [25]-[29], it is complicated to both ensure the fixed-time stability of the system and predetermine the convergence accuracy by selecting the design parameters. Furthermore, it is well known that the transient and steady-state performances are important to the controller design for HFVs. It is crucial to select the design parameters. Furthermore, it is well known that the transient and steady-state performances are important to the controller design for HFVs [30]. Nonetheless, the existing PPC for HFVs commonly fails to explicitly contain a convergence time $T$ in the performance function. Thus, it is urgent to develop a new low-complexity fixed-time fault-tolerant control (FTFTC) strategy for HFVs with the prescribed performance. Motivated by these observations, we present a fixed-time adaptive fuzzy fault-tolerant control scheme for HFVs by utilizing a new prescribed performance function. The contributions mainly contain the follows:

1. This paper presents a structurally inexpensive FTFTC framework for HFVs in the sense that no fractional powers are involved in the design. Specifically, conventional fixed-time controllers in [18]-[20] need to satisfy the condition $\dot{V}(x) \leq -\tau V^p(x) - \varsigma V^q(x) + \kappa$. Nevertheless, merely the form $\dot{V}(x) \leq -\tau V(x) + \kappa$ is required in this work, which not only simplifies the control law but also removes the singularity problem caused by the derivative of fraction term.

2. As opposed to the state-of-the-art PPC methods [11]-[12] and [22], we propose a new PPC that not only enables us to obtain fixed-time convergence, but also removes the reliance on precise initial error values. This is done in combination with a newly proposed PPF.

3. By constructing the intermediate control laws and adaptive laws, the adverse impact of actuator faults of HFVs (e.g., loss of effectiveness, drift, etc.) is compensated effectively.

The remainder of the work is organized as follows. The HFV dynamics and preliminaries are introduced in Section 2. In Section 3, the FLSs-approximator-based FTFTC is designed and the closed-loop stability is verified in Section 4. Section 5 provides simulations to demonstrate the effectiveness of the proposed methods and the work is concluded in Section 6.

2 Problem formulation and preliminaries

2.1 Hypersonic flight vehicle dynamics

The longitudinal control-oriental model is originally developed by Parker [31], which can be formulated as

$$
\begin{align*}
\dot{V} & = T \cos(\theta - \gamma) - D - g \sin \gamma, \quad \dot{h} = V \sin \gamma, \\
\dot{\gamma} & = \frac{T \sin(\theta - \gamma) + L}{m V} - g \cos \gamma, \quad \dot{\theta} = Q, \\
\dot{Q} & = \frac{M + \dot{\psi}_1 \dot{\psi}_1 + \dot{\psi}_2 \dot{\psi}_2}{I_{yy}}, \\
k_1 \dot{\psi}_1 & = -2 \zeta_1 \omega_1 \psi_1 - \omega_2^2 \psi_1 + N_1 - \frac{\ddot{\psi}_1 M}{I_{yy}} - \frac{\ddot{\psi}_2 \ddot{\psi}_2}{I_{yy}}, \\
k_2 \dot{\psi}_2 & = -2 \zeta_2 \omega_2 \psi_2 - \omega_2^2 \psi_2 + N_2 - \frac{\ddot{\psi}_2 \ddot{\psi}_2}{I_{yy}} - \frac{\ddot{\psi}_2 \ddot{\psi}_2}{I_{yy}},
\end{align*}
$$

where $T, D, L, M, N_1$ and $N_2$ are defined as

$$
\begin{align*}
T & = \beta_1(h, \dot{q}) \delta_{\dot{\theta}} \alpha^3 + \beta_2(h, \dot{q}) \alpha^3 + \beta_3(h, \dot{q}) \delta_{\dot{\theta}} \alpha^2 + \beta_4(h, \dot{q}) \alpha^2 + \beta_5(h, \dot{q}) \alpha + \beta_6(h, \dot{q}) \delta_{\dot{\theta}} + \beta_7(h, \dot{q}), \\
D & = q \dot{S}_C^2 \alpha^2 + q \dot{S}_C^2 \beta^2 + q \dot{S}_C^2 \gamma^2 + q \dot{S}_C^2 \delta + q \dot{S}_C^2, \\
M & = \gamma T + q \dot{S}_C^2 \alpha^2 + q \dot{S}_C^2 \beta^2 + q \dot{S}_C^2 \gamma^2 + q \dot{S}_C^2, \\
N_1 & = N_2^2 \alpha^2 + N_2^2 \alpha + N_2^4 \delta_e + N_2^4, \\
N_2 & = N_2^2 \alpha^2 + N_2^2 \alpha + N_2^4 \delta_e + N_2^4, \\
\ddot{q} & = \frac{\ddot{V}^2}{2}, \quad \ddot{\rho} = \ddot{\rho}_0 \exp \left( \frac{h_0 - h}{h_s} \right),
\end{align*}
$$

and more detailed definitions can be found in [31].

2.2 The actuator-fault model

The actuator-fault model is developed by [26]

$$
v(u) = \omega u + \varepsilon, \quad (3)
$$

where $u$ and $v(u)$ denote the input and output signals of actuator, and $\omega$ and $\varepsilon$ represent the actual control effectiveness and drift distance, respectively.

**Assumption 1** There exists an unknown positive constant $\varepsilon$ such that $|\varepsilon| \leq \bar{\varepsilon}, 0 < \omega \leq 1$.

**Remark 1** Assumption 1 is commonly applied in FTC research to ensure the controllability of system when the actuator faults occur [26]. During flight, actuator fault inevitably occurs due to multiple factors such as aging and damage of components or screw shedding, which deteriorates the flight performance and even causes the serious flight accident in severe circumstance. Therefore, it is of great significance to consider the possible actuator faults when designing the control strategy. With different values of $\omega$ and $\varepsilon$, (3) can be divided into the following four cases

1. $\omega = 1$ and $\varepsilon = 0$, representing the fault-free case;  
2. $0 < \omega \leq 1$ and $\varepsilon = 0$, where $\omega$ and $\varepsilon$ are unknown positive constants, denoting partial loss of effectiveness;
where $f$ are unknown functions; standard ideas as [10]-[11], we assume there exist un-
known positive constants, signifying that partial loss of effectiveness and bias fault occur at the same
time.

2.3 Model transformation and decomposition

According to (1) and (2), $V$ and $h$ are mainly reg-
ulated by $\Phi$ and $\delta_e$, respectively. To facilitate the con-
troller design, the HFV’s dynamics are decomposed into
velocity subsystem and altitude subsystem.

Inspired by [32] and [33], the velocity subsystem is
considered as

$$V = f_V + g_V v(\Phi) + d_V,$$

where $f_V = \frac{8SC_D}{m} a^2 + qSC_D \sin \alpha + \frac{\cos \alpha}{\sin \theta} \left[ \beta_2(h, q) \alpha^3 + \beta_4(h, \eta) \alpha^2 + \beta_6(h, \dot{q}) \alpha + \beta_8(h, \ddot{q}) \right]$, $g_V = \frac{\cos \alpha}{\sin \theta} \left[ \beta_7(h, \dot{q}) + \beta_9(h, \ddot{q}) \alpha^2 + \beta_1(h, \dot{q}) \alpha \right]$, $f_V$ and $g_V$ stand for unknown functions due to the time-varying aerodynamic param-
eters, while $d_V$ represents the external disturbance on velocity.

Inspired by [34], we take the assumption $\sin(\gamma) \approx \gamma$
and $\cos(\gamma) \approx 1$, then the velocity subsystem can be considered as

\[
\begin{align*}
\dot{h} &= V_\gamma + d_h, \\
\dot{\gamma} &= f_\gamma + g_\gamma \theta + d_\gamma, \\
\dot{\theta} &= Q, \\
\dot{Q} &= f_Q + g_Q v(\delta_e) + d_Q,
\end{align*}
\]

where $f_\gamma = \frac{qS(C_D - C_D^*)}{m \nu V} T \sin \alpha - \frac{qS(C_D + C_D^*)}{m \nu V}$, $g_\gamma = \frac{qS(C_D + C_D^*)}{m \nu V}$, $f_Q = z_T T + \frac{qS(C_D + C_D^*)}{m \nu V}$ and $g_Q = \frac{qS(C_D + C_D^*)}{m \nu V}$. Similar to velocity subsystem, the functions $f_\gamma$, $g_\gamma$, $f_Q$ and $g_Q$ are unknown functions; $d_h$, $\gamma$, and $d_Q$ are the exter-
nal disturbances of altitude subsystem. Along the stan-
tard ideas as [10]-[11], we assume there exist un-
known positive functions $g_{V m}$, $g_{\gamma m}$ and $g_{Q m}$ such that

$$0 < g_{V m} \leq g_V, 0 < g_{\gamma m} \leq g_\gamma, 0 < g_{Q m} \leq g_Q.$$

Remark 2 In practice, it is rather difficult to know the values of functions $f_\gamma, g_\gamma \in \{V, \gamma, Q\}$ accurately. There are mainly the following reasons: on the one hand, the aerodynamic parameters are constantly changing with the flight environment (i.e. velocity, altitude, attack of angle, etc.), where there inevitably exist measuring er-
rors in the sensors of flight control system [1]. On the other hand, it is impossible to take all flight environ-
ment of HFVs into account in a wind tunnel, so that we have to rely on curve fitting technology to build the aerodynamic model [6]. Consequently, an exact model for HFVs is difficult to be obtained and in order to in-
crease the robustness of flight control system, we regard $f_\gamma, g_\gamma \in \{V, \gamma, Q\}$ as unknown functions.

Assumption 2 [35] The reference trajectory $y_{ref}(t)$, together with its i-order derivative $y_{ref}^{(i)}(t)$ are continuous and bounded ($i = 1, 2 \cdots n$).

2.4 A new fixed-time performance function

Definition 1 [35] A smooth function $\rho(t)$ is called fixed-
time performance function (FTPf), if the following conditions are satisfied

1. $\rho(t) > 0$, i.e., $\rho(t)$ is ensured to be a positive function;
2. $\dot{\rho} \leq 0$, that is, $\rho(t)$ is monotonically decreasing;
3. $\lim_{t \to T} \rho(t) = \rho(T)$ and $\rho(t) = \rho(T)$ for any $t > T$, where $\rho(T)$ and $T$ denote an arbitrarily small positive constant and settling time, respectively.

According to Definition 1, we construct an FTPf in the form of

$$\rho(t) = \begin{cases} 
\coth(\frac{\theta}{\pi} + r) - 1 + \rho(T), & 0 < t < T \\
\rho(T), & t \geq T.
\end{cases}$$

Proof In view of (6), it can be derived that
\[ \rho(T^-) = \lim_{t \to T^-} \left[ \coth \left( \frac{t}{T-t} + r \right) - 1 + \rho(T) \right] \]
\[ = \lim_{t \to T^-} \left[ e^{\frac{2}{T-t} + r} + e^{-\frac{2}{T-t} + r} - 1 + \rho(T) \right] \]
\[ = \rho(T) = \rho(T^+) , \]

that is, \( \rho(t) \) is a continuous function. Furthermore, we can deduce that
\[ \hat{\rho}(t) = -\frac{\vartheta}{T} \left( \frac{T}{T-t} \right)^2 \text{csch}^2 \left( \frac{t}{T-t} + r \right) \]
\[ = -\frac{\vartheta}{T} \left( \frac{T}{T-t} \right)^2 \left( e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r} \right)^2 \]

when \( t < T \), and \( \hat{\rho}(t) = 0 \) when \( t \geq T \). For the sake of simplification, we denote \( x = \frac{t}{T-t} \) and the fact \( \lim_{t \to T^-} x = +\infty \) holds. Then, we can obtain
\[ \lim_{t \to T^-} \hat{\rho}(t) = \lim_{x \to +\infty} \frac{4\vartheta}{T} \left( 1 + x \frac{1}{e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r}} \right)^2 . \]

With the help of L’Hospital’s rule, we get that
\[ \lim_{t \to T^-} \hat{\rho}(t) = \lim_{x \to +\infty} \frac{4\vartheta}{T} \left( e^{-\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r} \right)^2 = \hat{\rho}(T^+) . \]

Next, \( \frac{d^2\hat{\rho}(t)}{dx^2} \) can be derived as
\[ \frac{d^2\hat{\rho}(t)}{dx^2} = \frac{8\vartheta (1+x)}{T(e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r})^2} - \frac{8\vartheta^2(1+x)^2(e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r})}{T(e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r})^3} \]
\[ = \frac{4\sqrt{\vartheta/T}}{e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r}} + \frac{T}{4} \hat{\rho}(t) \left( 1 + \frac{2e^{-\frac{2}{T-t} + r}}{e^{\frac{2}{T-t} + r} - e^{-\frac{2}{T-t} + r}} \right) . \]

Then, we have \( \lim_{t \to T^-} \frac{d^2\hat{\rho}(t)}{dx^2} = \frac{d^2\hat{\rho}(T^+)}{dx^2} \) and \( \frac{d^2\hat{\rho}(T^+)}{dx^2} = 0 \), i.e., \( i = 3, \ldots, n \).

That is to say, \( \rho(t) \) is a smooth function. Furthermore, we can also see that \( \hat{\rho}(t) \leq 0 \) and the function \( \rho(t) \) is continuous at \( T \). Thus, we can conclude that the function \( \rho(t) \) is a FTPF. This completes the proof. ■

Remark 3 We can easily obtain sufficiently large \( \rho(0) \) by selecting a sufficiently small \( r \), that is to say, the initial error need not to be known accurately. Consequently, the FTPF without initial error constraint is achieved. Furthermore, we can also conclude that, the convergence rate of the error depends on \( \dot{\vartheta} \), which can be seen in Fig. 1 (a). By setting the steady-state error boundary as \( \rho(T) = 1 \) and choosing different values of \( \vartheta \), we can obtain that a larger \( \vartheta \) means a faster convergence rate of the error.

Consider the following transformation
\[ q(t) = \frac{e(t)}{\rho(t)} , \quad (7) \]
where the error transformation function is chosen as
\[ z(q) = \frac{q}{1-q^2} , \quad (8) \]
and we abbreviate \( q = q(t) \) there-in-after.

Remark 4 From (8), it can be observed that the inequality \( -1 < q < 1 \) holds if \( z(q) \) is bounded. In view of (7), we conclude that \( |e(t)| < |\rho(t)| \) holds as long as \( |e(0)| < |\rho(0)| \). Choosing \( \vartheta = 0.5 \), \( r = 0.1 \), \( T = 6 \) and \( \rho(T) = 1 \), the convergence performance of the proposed FTPF is shown in Fig. 1 (b). In contrast to traditional PPC [10], where the prescribed performance function is in the form of \( \rho(t) = \coth(\vartheta t + r) - 1 + \rho_\infty \), the proposed control scheme explicitly contains a convergence time \( T \) in the FTPF. By this means, we can easily preset the convergence time as needed.

Fig. 1: The convergence performance of the proposed FTPF

2.5 Fuzzy logic system

Define a set of fuzzy IF-THEN rules, where the \( l \)th IF-THEN rule is written as [21]-[22]

\[ \mathcal{R}^l: \text{IF } x_1 \text{ is } F_{l_1}^1, \ldots \text{ and } x_n \text{ is } F_{l_n}^1, \text{ then } y \text{ is } B^l , \]

where \( x = [x_1, \ldots, x_n]^T \in \mathbb{R}^n \), and \( y \in \mathbb{R} \) are the input and output of the FLSs respectively, and \( F_1^1, \ldots, F_n^1 \) and \( B^l \) are fuzzy sets in \( \mathbb{R} \). Let \( F(x) \) be a continuous function defined on a compact set \( \Omega_x \). Then, for a given desired level of accuracy \( \varepsilon > 0 \), there exists a FLS \( W^T S(x) \) such that \( \sup_{x \in \Omega_x} |F(x) - W^T S(x)| \leq \phi \), where \( \begin{bmatrix} x \in \Omega_x \end{bmatrix} \)

\[ W = [w_1, \ldots, w_p]^T \] is the adaptive fuzzy parameter vector in a compact set \( \Omega_W \). \( p \) is the number of the fuzzy rules, and \( S(x) = [S_1(x), \ldots, S_n(x)]^T \) is the fuzzy basis function vector with \( S_i(x) = \prod_{j=1}^n \mu_{F_j^1}(x_j) / \prod_{j=1}^n \mu_{F_j^1}(x_j) \) where \( \mu_{F_j^1}(x_j) \) is a fuzzy membership function of the variable \( x_j \) in IF-THEN rule. Let \( W^\star \) be the optimal parameter vector, which is defined as
\[ W^\star = \arg \min_{W \in \Omega_W} \left\{ \sup_{x \in \Omega_x} |F(x) - W^T S(x)| \right\}. \quad (9) \]
Then, we can further obtain
\[ F(x) = W^TS(x) + \phi, \]  
where \( \phi \) is the minimum fuzzy approximation error. 

**Lemma 1** [36] The hyperbolic tangent function \( \tanh(\bullet) \) is continuous and differentiable, for \( \forall \varsigma \in R \) and \( \forall \mu > 0 \), it has
\[ 0 \leq |\varsigma| - \varsigma \tanh \left( \frac{\varsigma}{\mu} \right) \leq 0.2785\mu. \]  

**Lemma 2** [37] For any positive constants \( \omega \) and \( \delta \), the following inequation holds
\[ 0 \leq |\omega| - \frac{\omega^2}{\sqrt{\omega^2 + \delta^2}} \leq \delta. \]  

The control objective of this article is to design an adaptive tracking controller such that
1. The velocity and altitude control design and an altitude control design.

3 The FTFTC design

Corresponding to the decomposition in Sect. II.C, the control design is also decomposed into a velocity control design and an altitude control design.

3.1 Velocity controller design

We first define the velocity tracking error as
\[ e_V = V - V_{\text{ref}}, \]  
where \( V_{\text{ref}} \) is the velocity reference trajectory. In view of (4), (7) and (8), the time derivative of \( e_V \) is
\[ \dot{e}_V = f_V + g_V \varphi + \dot{V}_{\text{ref}} - \dot{V}_{\text{ref}} = \dot{\varphi}(t) q + \dot{\varphi}(t) \frac{\partial q}{\partial z}. \]  

Then \( \dot{\varphi} \) can be rewritten as
\[ \dot{\varphi} = \frac{f_V + g_V \varphi + \dot{V}_{\text{ref}} - \dot{V}_{\text{ref}}}{\rho(t) \frac{\partial q}{\partial z}} = \dot{\varphi}(t) (f_V + g_V \varphi + \dot{V}_{\text{ref}} - \dot{V}_{\text{ref}}), \]  

with
\[ \rho(t) E_V = \frac{1}{\rho(t) \frac{\partial q}{\partial z}}. \]  

It can be deduced from (8) that \( \frac{\partial q}{\partial z} = (1-q^2)^2 \leq 1 \) when \( -1 < q < 1 \), and noticing the fact \( g_V \geq g_V m > 0 \) leads to
\[ E_V g_V = \frac{g_V}{\rho(t) \frac{\partial q}{\partial z}} \geq \frac{g_V m}{\rho(0)} = \tilde{g}_V m > 0. \]  

Choose the following quadratic function
\[ L_V = \frac{1}{2} \dot{\varphi}^2 + \frac{1}{2\mu V} \tilde{g}_V m \dot{\varphi}^2, \]  
with \( \tilde{g}_V \dot{\varphi} = \ell V - \dot{\varphi} \dot{V}, \) in which \( \dot{\varphi} \dot{V} \) denotes the estimation of adaptive parameter \( \ell V, \) and \( \mu \dot{V} \) is the positive user-defined parameter.

Utilizing (3) and (14), the time derivative of \( L_V \) is
\[ \dot{L}_V = z_V (T_V + E_V f_V + E_V g_V \varphi + E_V g_V \varphi) + E_V d_V - E_V \dot{V}_{\text{ref}}) - \frac{1}{\mu V} \tilde{g}_V m \dot{\varphi} \dot{V}. \]  

Define the nonlinear function
\[ F_V = T_V + E_V f_V + E_V d_V - E_V \dot{V}_{\text{ref}} + \frac{1}{2} \dot{\varphi}^2, \]  
where \( f_V \) and \( d_V \) are unknown due to the existence of unknown external disturbances and fast time-varying flight environment. A FLSS-approximator is constructed to estimate \( F_V \) as
\[ F_V = W^TS_V \varphi_V + \phi_V, \]  
where \( \varphi_V = [V, V_{\text{ref}}, \dot{V}_{\text{ref}}]^T. \) Substituting (19) and (20) into (18), we have
\[ \dot{L}_V = z_V (W^TS_V + \phi_V + E_V g_V \varphi + E_V g_V \varphi) + E_V d_V - E_V \dot{V}_{\text{ref}}) - \frac{1}{\mu V} \tilde{g}_V m \dot{\varphi} \dot{V} - \frac{1}{2} \dot{\varphi}^2. \]  

According to Young’s inequality, we can further have
\[ z_V W^TS_V \leq \frac{z_V^2}{4} \|W_V\|^2 S_V T S_V + \tau_V, \]  
\[ z_V \dot{\varphi}^2 \leq \frac{1}{2} \dot{\varphi}^2 + \frac{1}{2} \dot{\varphi}^2, \]  
where \( \tau_V \) is a positive constant, then we can rewrite (21) as
\[ \dot{L}_V \leq z_V (E_V g_V \varphi + E_V g_V \varphi) + \frac{z_V^2}{4} \|W_V\|^2 S_V T S_V \]  
\[ + \tau_V + \frac{1}{2} \dot{\varphi}^2 - \frac{1}{\mu V} \tilde{g}_V m \dot{\varphi} \dot{V}. \]  

According to Assumption 1, \( \omega \dot{V} \) and \( \varepsilon \dot{V} \) are unknown. Therefore, we define the upper and lower bounds of fault parameters to achieve robustness, which are expressed as
\[ \omega_V = \inf (E_V g_V \omega_v), \quad \vartheta \dot{V} = \frac{1}{\omega_V}, \]  
\[ \xi_\dot{V} = \sup (E_V g_V \varepsilon \dot{V}). \]
Consider the Lyapunov function candidate
\[
L_V = L_V + \frac{1}{2\nu}\varpi_V \tilde{\nu}_V^2 + \frac{1}{2\nu}\tilde{\varepsilon}_V^2,
\]
where \( l_V > 0 \) and \( r_V > 0 \) are the parameters to be designed, \( \tilde{\varpi}_V = \varpi_V - \hat{\varpi}_V \) and \( \tilde{\varepsilon}_V = \varepsilon_V - \hat{\varepsilon}_V \) represent estimation errors with \( \varpi_V \) and \( \varepsilon_V \) being the estimations of \( \varpi \) and \( \varepsilon \), respectively.

The time derivative of \( L_V \) gives
\[
\dot{L}_V = \dot{L}_V - \frac{1}{r_V}\varpi_V \dot{\varpi}_V \frac{2}{r_V} \tilde{\varepsilon}_V \frac{\tilde{\varpi}_V}{r_V} - \frac{1}{r_V} \tilde{\varepsilon}_V \tilde{\varepsilon}_V.
\]

Define \( \ell_V = \frac{\|W_m\|_2}{\sigma_m} \) and choose the intermediate control law as
\[
\dot{\Phi} = k_V z_V + \frac{z_V \tilde{V}_V S_V S_V^T}{4r_V} + \tau_V \tanh\left(\frac{z_V}{a_V}\right).
\]

It can be induced that
\[
\dot{L}_V \leq z_V E_V \varpi_V \gamma V + \frac{z_V \ell_V \bar{g} V m S_V S_V^T}{4r_V} + \tau_V + \frac{1}{2} \varpi_V^2
\]
\[
- \frac{\varpi_V}{l_V} \tilde{\varpi}_V \dot{V}_V + z_V \dot{\Phi} - k_V z_V^2 \frac{\varpi_V^2 \bar{g} V m S_V S_V^T}{4r_V}
\]
\[
+ \frac{\varepsilon_V}{l_V} \left[ |z_V| - z_V \tanh\left(\frac{z_V}{a_V}\right) \right] \frac{\bar{g} V m}{\mu_V} \varepsilon_V \dot{V}_V
\]
\[
+ \frac{1}{r_V} \dot{\varepsilon}_V \left[ r_V z_V \tanh\left(\frac{z_V}{a_V}\right) - \tilde{\varpi}_V \right].
\]

Choose the adaptive laws as follows
\[
\dot{\tilde{\varpi}}_V = \frac{\nu \varepsilon_V S_V S_V^T}{2r_V} - \bar{g} V m \dot{V}_V,
\]
\[
\dot{\tilde{\varepsilon}}_V = r_V z_V \tanh\left(\frac{z_V}{a_V}\right) - b_V \varpi_V,
\]
\[
\dot{\varpi}_V = l_V z_V \Phi - c_V \dot{\varpi}_V,
\]
where \( a_V > 0 \), \( b_V > 0 \) and \( c_V > 0 \) are the parameters to be designed.

Substituting (31)-(33) into (30) yields
\[
\dot{L}_V \leq z_V E_V \varpi_V \gamma V + \tau_V + \frac{1}{2} \varpi_V^2 + \frac{\bar{g} V m \varepsilon_V}{\mu_V} \tilde{\varpi}_V
\]
\[
- \frac{\varpi_V}{l_V} \tilde{\varpi}_V \dot{V}_V + \frac{\varpi_V \varepsilon_V}{l_V} \bar{g} V m \tilde{\varpi}_V \dot{V}_V + z_V \dot{\Phi} - k_V z_V^2 \frac{\varpi_V^2 \bar{g} V m S_V S_V^T}{4r_V}
\]
\[
+ \frac{\varepsilon_V}{l_V} \left[ |z_V| - z_V \tanh\left(\frac{z_V}{a_V}\right) \right] \frac{\bar{g} V m}{\mu_V} \varepsilon_V \dot{V}_V
\]
\[
+ \frac{1}{r_V} \dot{\varepsilon}_V \left[ r_V z_V \tanh\left(\frac{z_V}{a_V}\right) - \tilde{\varpi}_V \right].
\]

Now we design the actual control law as
\[
\Phi = \frac{z_V \tilde{V}_V \dot{V}_V^2}{\sqrt{z_V^2 \tilde{V}_V \dot{V}_V^2 + \sigma_V^2}},
\]
where \( \sigma_V > 0 \) is a predefined constant. According to Young’s inequation, one has
\[
\tilde{\varpi}_V \tilde{\nu}_V = \left( \ell_V - \hat{\ell}_V \right) \tilde{\nu}_V \leq -\frac{\sigma_V}{2} \tilde{\nu}_V + \frac{1}{2} \varpi_V^2,
\]
\[
\varepsilon_V \tilde{V}_V = \left( \varepsilon_V - \hat{\varepsilon}_V \right) \tilde{V}_V \leq -\frac{\sigma_V}{2} \tilde{V}_V + \frac{1}{2} \varpi_V^2,
\]
\[
\tilde{\varpi}_V \tilde{\varepsilon}_V = \left( \tilde{\varpi}_V - \hat{\tilde{\varpi}}_V \right) \tilde{\varepsilon}_V \leq -\frac{\sigma_V}{2} \tilde{\varepsilon}_V + \frac{1}{2} \tilde{\varpi}_V^2.
\]

Substituting (35)-(38) into (34) and applying Lemma 1 and Lemma 2, we can rewrite (34) as
\[
\dot{L}_V \leq -k_V z_V^2 \frac{\varpi_V}{2l_V} + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V - \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V \tilde{V}_V
\]
\[
+ \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V + \frac{1}{2} \frac{\varpi_V \nu \varepsilon_V}{l_V} \tilde{\varpi}_V \tilde{V}_V + \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]
\[
+ \frac{1}{2} \varpi_V \varpi_V \tilde{V}_V + \frac{1}{2} \bar{g} V m \bar{g} V m \tilde{\varpi}_V \tilde{\varpi}_V
\]

### 3.2 Altitude controller design

In the process of altitude controller design, the backstepping methodology is adopted to deal with complex dynamics. The virtual controllers will be designed at first, and then the intermediate control law the actual control law will be constructed to counteract the impact of actuator fault. To initiate the design process, we first define the following tracking errors
\[
\begin{align*}
\dot{e}_h &= \dot{h} - \dot{h}_{ref}, \\
\dot{e}_q &= \dot{q} - \dot{q}_{ref},
\end{align*}
\]
with \( \dot{h}_{ref} \) and \( \dot{q}_{ref} \) representing the virtual control laws.

#### Step 1: Similarly to velocity controller design, one reaches

\[
\dot{e}_h = V \gamma + d_h - \dot{h}_{ref} = \dot{\rho}(t) q + \ddot{\rho}(t) \frac{\partial q}{\partial z}.
\]

Then we have

\[
\dot{z}_h = V \gamma + d_h - \dot{h}_{ref} - \rho(t) \frac{\partial q}{\partial z} = \tilde{f}_h E_h = \tilde{f}_h \frac{\rho(t) \frac{\partial q}{\partial z}}{\rho(t) \frac{\partial q}{\partial z}} = \tilde{f}_h,
\]

with

\[
\tilde{f}_h = \frac{\rho(t) \frac{\partial q}{\partial z}}{\rho(t) \frac{\partial q}{\partial z}}.
\]

Noting that \( \frac{\partial q}{\partial z} = \frac{1}{1 + \rho(t) \frac{\partial q}{\partial z}} \leq 1 \) when \( -1 < \rho(t) < 1 \) and the fact that \( V \geq V_m > 0 \) where \( V_m \) is minimum permissible flight velocity, yields

\[
E_h V = \frac{V}{\rho(t) \frac{\partial q}{\partial z}} \geq \frac{V_m}{\rho(0) \frac{\partial q}{\partial z}} = \tilde{V}_m > 0.
\]
Consider the following Lyapunov function candidate
\[ L_h = \frac{1}{2} \tilde{z}_h^2 + \frac{1}{2\mu_h} \tilde{V}_m \tilde{\gamma}_h, \]  
(45)
with \( \tilde{\ell}_h = \ell_h - \tilde{\ell}_h \), in which \( \tilde{\ell}_h \) denotes the estimation of adaptive parameter \( \ell_h \), \( \mu_h \) is the positive design parameter.

The time derivative of \( L_h \) gives
\[ \dot{L}_h = z_h \left( W_h^T S_h + \phi_h + E_h V \gamma \right) - \frac{1}{\mu_h} \tilde{V}_m \tilde{\ell}_h - \frac{1}{2} \dot{z}_h^2, \]  
(46)
with \( F_h = Y_h + E_h d_h - E_h \hat{h}_{ref} + \frac{1}{2} z_h \) being approximated by FLS \( W_h^T S_h (x_h) + \phi_h \), where \( x_h = \begin{bmatrix} h, h_{ref}, \hat{h}_{ref} \end{bmatrix}^T \).

Applying Young’s inequality, it gives
\[ z_h W_h^T S_h \leq \frac{\| W_h \|^2}{4\tau_h} S_h + \tau_h, \]  
(47)
where \( \tau_h \) is a positive constant, noting that \( \gamma = \gamma + \gamma \gamma \) we can further rewrite (46) as
\[ \dot{L}_h \leq E_h V z_h \gamma + z_h E_h V \gamma + \frac{1}{2} \tilde{\gamma}_h V_m \tilde{\ell}_h - \frac{1}{2} \tilde{\gamma}_h, \]  
(48)
\[ + \frac{1}{\mu_h} \tilde{V}_m \tilde{\ell}_h \]  
with the definition of \( \ell_h = \frac{\| W_h \|^2}{V_m} \). Choose the virtual control law and updating law as follows
\[ \chi_h = -k_h z_h - \frac{1}{\mu_h} \tilde{V}_m \tilde{\ell}_h, \]  
(50)
\[ \tilde{\gamma}_h = \frac{\mu_h z_h^2}{4\tau_h} S_h + \Gamma_h \tilde{\gamma}_h. \]  
(51)

Substituting (50)-(51) into (48) yields
\[ \dot{L}_h \leq -k_h z_h^2 + \frac{1}{\mu_h} \Gamma_h \tilde{V}_m \tilde{\ell}_h + E_h V z_h \gamma + \frac{1}{2} \tilde{\gamma}_h + \tau_h. \]  
(52)

**Step 2** Take the Lyapunov function candidate as
\[ L_\gamma = L_\gamma \gamma + \frac{1}{2} \tilde{\gamma}_h^2 + \frac{1}{2\mu_h} g_{ym} \tilde{\gamma}_h^2. \]  
(53)

Similar to step 1, by defining \( \tilde{\ell}_\gamma = \frac{\| W_\gamma \|^2}{g_{ym}} \), the time derivative of \( L_\gamma \) can be formulated as
\[ \dot{L}_\gamma = \dot{L}_\gamma + \gamma (W_\gamma^T S_\gamma + \phi_\gamma + g_\gamma \theta) - \frac{1}{\mu_h} g_{ym} \tilde{\gamma}_h \]  
\[ - E_h V z_h \gamma - \frac{1}{2} \dot{z}_h^2, \]  
(54)
with \( F_\gamma = F_\gamma + E_h V z_h + d_\gamma - \dot{\gamma}_h + \frac{1}{2} z_h \) being approximated by FLS \( W_\gamma^T S_\gamma (x_\gamma) + \phi_\gamma \), where \( \chi_\gamma = \frac{\partial \gamma}{\partial \gamma} \hat{h} + \frac{\partial \gamma}{\partial \gamma} \) and \( \gamma = \begin{bmatrix} h, \gamma, h_{ref}, \hat{h}_{ref}, h_{ref}^2, \hat{h}_{ref}^2, \end{bmatrix}^T \).

Design the virtual control law and adaptive law as
\[ \chi_\theta = -k_\gamma \gamma - \frac{z_h \ell_h^2}{4\tau_h}, \]  
(55)
\[ \hat{\gamma}_h = \frac{\mu_h z_h^2}{4\tau_h} S_h - \Gamma_h \tilde{\gamma}_h. \]  
(56)

Based on (52)-(56), we obtain
\[ \dot{L}_\gamma \leq -k_\gamma z_h \gamma - \gamma z_h + \frac{1}{\mu_h} \Gamma_h \tilde{V}_m \tilde{\ell}_h + \frac{1}{\mu_h} \Gamma_h g_{ym} \tilde{\gamma}_h \]  
\[ + g_\gamma z_h \gamma + \frac{1}{2} \tilde{\gamma}_h + \gamma \theta + \gamma \tau_h. \]  
(57)

**Step 3** Consider the following Lyapunov function candidate
\[ L_\theta = L_\theta + \frac{1}{2} \tilde{\tau}_\theta^2 + \frac{1}{2\mu_\theta} \tilde{\gamma}_\theta^2. \]  
(58)

Defining \( \ell_\theta = \| W_\theta \|^2 \), the time derivative of \( L_\theta \) gives
\[ \dot{L}_\theta = \dot{L}_\theta + \gamma \theta (W_\theta^T S_\theta + \phi_\theta + Q) - \frac{1}{\mu_\theta} \tilde{\tau}_\theta \]  
\[ - g_\theta z_h \gamma + \frac{1}{2} \tilde{\gamma}_\theta, \]  
(59)
with \( F_\theta = g_\gamma z_h - \dot{\chi}_\theta + \frac{1}{2} z_h \) being approximated by FLS \( W_\theta^T S_\theta (x_\theta) + \phi_\theta \), where \( \chi_\theta = \sum_{x=h, \gamma} \frac{\partial \gamma}{\partial \gamma} x + \sum_{x=h, \gamma} \frac{\partial \gamma}{\partial \gamma} \hat{\gamma}_h + \sum_{i=1}^{2} \frac{\partial \gamma}{\partial \gamma} h_{ref}^{(i+1)} \) and \( x_\theta = \begin{bmatrix} h, \gamma, \theta, h_{ref}, \hat{h}_{ref}, h_{ref}^2, \hat{h}_{ref}^2, \end{bmatrix} ^T \).

Construct the virtual control law and adaptive law
\[ \chi_Q = -k_\theta z_h - \frac{z_h \ell_\theta^2}{4\tau_\theta}, \]  
(60)
\[ \hat{\tau}_\theta = \frac{\mu_\theta z_h^2}{4\tau_\theta} S_\theta - \Gamma_\theta \tilde{\gamma}_\theta. \]  
(61)

From (58)-(61), one has
\[ \dot{L}_\theta \leq -k_\gamma z_h ^2 - k_\gamma z_h ^2 - k_\theta z_h ^2 + \frac{1}{\mu_h} \Gamma_h \tilde{V}_m \tilde{\ell}_h + \frac{1}{\mu_h} \Gamma_h g_{ym} \tilde{\gamma}_h + \frac{1}{\mu_\theta} \tilde{\tau}_\theta \tilde{\tau}_\theta \]  
\[ + g_\gamma z_h \gamma + \frac{1}{2} \tilde{\gamma}_\theta + \gamma \theta + \gamma \tau_h. \]  
(62)

**Step 4** Choose the following Lyapunov function candidate
\[ L_Q = L_\theta + \frac{1}{2} \tilde{z}_Q^2 + \frac{1}{2\mu_Q} g_{QM} \tilde{z}_Q^2. \]  
(63)
Constructing \( \ell_Q = \frac{||W_Q||^2}{\gamma_Q} \) and taking the derivative of \( L_Q \) yield

\[
L_Q = \dot{L}_\theta + z_Q (W_Q^T S_Q + \phi_Q + g_Q \omega_Q \delta_Q + g_Q \xi_Q) - \frac{1}{\mu_Q} g_Q \dot{z}_Q \dot{\ell}_Q - z_\theta z_Q - \frac{1}{2} \dot{z}_Q^2,
\]

(64)

with \( F_Q = f_Q + z_\theta + d_Q - \dot{z}_\theta + \frac{1}{2} z_Q \) being approximated by FLS \( W_Q^2 S_Q (x_Q) + \phi_Q \), where \( \chi_Q = \sum_{x=\theta,\gamma,\theta} \frac{\partial \chi}{\partial x} \dot{x} + \sum_{x=\theta,\gamma,\theta} \frac{\partial \chi}{\partial x} \dot{x} + \sum_{i=0}^{3} \frac{\partial \chi}{\partial x} \dot{x} \), and \( x_Q = [h, \gamma, \theta, h_{\text{ref}}, h_{\text{ref}}, h_{\text{ref}}, h_{\text{ref}}, \dot{h}, \dot{\gamma}, \dot{\theta}]^T \).

The upper and lower bounds of fault parameters are defined as

\[
\omega_Q = \inf (g_Q \omega_Q), \quad \bar{Q}_Q = \frac{1}{\omega_Q},
\]

(65)

\[
\xi_Q = \sup (g_Q \xi_Q).
\]

(66)

Construct the Lyapunov function

\[
L_Q = L_\theta + \frac{1}{2L_Q} \omega_Q \bar{Q}_Q + \frac{1}{2r_Q} \bar{Q}_Q,
\]

(67)

where \( L_\theta > 0 \) and \( r_Q > 0 \) are designed parameters, \( \bar{Q}_Q = \bar{Q}_Q - \dot{\bar{Q}}_Q \) and \( \xi_Q = \xi_Q - \dot{\xi}_Q \) represent estimation errors with \( \dot{\bar{Q}}_Q \) and \( \xi_Q \) being the estimations of \( \bar{Q}_Q \) and \( \xi_Q \), respectively. Choose the intermediate control law and adaptive laws as follows

\[
\ddot{z}_Q = k_Q z_Q + \frac{z_Q \dot{S}_Q}{4\eta_Q} + \xi_Q \tanh\left( \frac{z_Q}{a_Q} \right),
\]

(68)

\[
\dot{\ell}_Q = \frac{\mu_Q g_Q \dot{S}_Q}{4\eta_Q} - \Gamma_Q \dot{\ell}_Q,
\]

(69)

\[
\hat{\ell}_Q = r_Q z_Q \tanh\left( \frac{z_Q}{a_Q} \right) - b_Q \xi_Q.
\]

(70)

\[
\hat{\theta}_Q = l_Q z_Q \dot{\theta}_Q - c_Q \dot{\theta}_Q.
\]

(71)

where \( k_Q, r_Q, a_Q, b_Q \) and \( c_Q \) are designed positive parameters.

Finally, we choose the actual control law as

\[
\delta_Q = -\frac{z_Q \dot{\theta}_Q \dot{S}_Q}{\sqrt{z_Q^2 \dot{\theta}_Q^2 \dot{S}_Q^2 + \sigma^2_Q}},
\]

(72)

where \( \sigma_Q > 0 \) is a predefined constant. Following similar analysis to velocity subsystem, we can further deduce that

\[
L_Q \leq -k_h \dot{z}_h^2 - k_{\gamma} \dot{z}_\gamma^2 - k_{\theta} \dot{z}_\theta^2 - k_Q \dot{z}_Q^2 - \frac{\Gamma_Q \tilde{V}_m \tilde{\gamma}_h}{2\eta_V}
\]

\[
- \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}}
\]

\[
- \frac{\omega_V \dot{\gamma}_V}{2\eta_V} - \frac{\omega_V \gamma_m \dot{\gamma}_V}{2\eta_V} - \frac{b \dot{\gamma}_V}{2\eta_V} - \frac{b \gamma_m \dot{\gamma}_V}{2\eta_V}
\]

\[
+ \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}}
\]

(73)

The whole FTFTC design for HFVs is shown in Fig.2.

4 Closed-loop stability analysis

**Theorem 1** Despite the occurrence of unknown actuator fault (3), consider the closed-loop system composed by (4) and (5), the virtual control laws (50), (55) and (60), the intermediate control laws (29) and (68), the actual control laws (35) and (72), and the parameter adaptation laws (31)-(33), (51), (56), (61) and (69)-(71). Let Assumptions 1-2 hold. By designing the parameters properly, it therefore holds that

1. The tracking errors \( e_V \) and \( e_h \) can converge into a predefined residual set within an user-defined time \( T \).
2. The overshoot and convergence rate are guaranteed by FTPF and all signals of the closed-loop system are SGPFS.

**Proof** Take the Lyapunov function candidate as

\[
L = L_V + L_Q.
\]

(74)

Applying (39) and (73), the derivative of \( L \) gives

\[
\dot{L} \leq -k_v \dot{z}_V^2 - k_h \dot{z}_h^2 - k_{\gamma} \dot{z}_\gamma^2 - k_{\theta} \dot{z}_\theta^2 - k_Q \dot{z}_Q^2 - \frac{\Gamma_Q \tilde{V}_m \tilde{\gamma}_h}{2\eta_V}
\]

\[
- \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} - \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}}
\]

\[
- \frac{\omega_V \dot{\gamma}_V}{2\eta_V} - \frac{\omega_V \gamma_m \dot{\gamma}_V}{2\eta_V} - \frac{b \dot{\gamma}_V}{2\eta_V} - \frac{b \gamma_m \dot{\gamma}_V}{2\eta_V}
\]

\[
+ \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \tilde{V}_m \tilde{\gamma}_h}{\mu_{\gamma}} + \frac{\Gamma_h \gamma_m \tilde{\gamma}_h}{\mu_{\gamma}}
\]
that the velocity and altitude tracking errors converge to a residual set within a fixed time $T$ and the prescribed performances are guaranteed. Besides, all signals of closed-loop system are SGPFS. This completes the proof.

**Remark 5** The existing fixed-time control strategies for HFVs [17]-[19] fail to take system transient and steadystate performances into account and it is fairly complicated to make tracking error convergence into a pre-specified compact set within the fixed-time by selecting design parameters. It is worth noting that the fixed-time tracking control is achieved as long as the bounded condition is satisfied in the proposed design. Consequently, the complexity of the control structure is reduced and the initial states need not to be known accurately via the proposed control approach.

**Remark 6** It is worth mentioning that the control performance is depended closely on the designed parameters of prescribed function. In (6), large initial errors are allowed by choosing a small enough $r$, larger $\theta$ and smaller $T$ will increase the convergence rate. However, too large $\theta$ or too small $T$ will give rise to actuator input saturations. In (29), (50), (54), (66) and (68), designed parameters $k_V, \gamma_V, a_V, k_h, k_\theta, k_\gamma, k_\beta, k_Q, a_V$ and $a_Q$ determine the convergence rate and convergence accuracy. In (31)-(33), (51), (66), (61) and (69)-(71), designed parameters $\mu_V, \gamma_V, r_V, b_v, l_V, c_V, a_\mu, a_\gamma, a_\theta, a_\beta, a_\phi, a_Q$ and $c_Q$ effect convergence rate of the adaptive parameters. In the controller design, we need to design the parameters properly to improve the tracking performance and avoid the saturation phenomenon.

### 5 Simulations

In this section, simulation results are used to demonstrate the effectiveness and superiority of the proposed methodology. The model parameters of HFVs can be consulted from [31]. HFVs are expected to climb a maneuver from the initial trim conditions, depicted in Ta-
The uncertain aerodynamic coefficients are modelled as $C_i = C_i^* (1 + \Delta_i)$, where $C_i^*$ represents the nominal coefficient and $\Delta_i$ represents the uncertain factor ranging from $-20\%$ to $20\%$. The external disturbances in velocity subsystem and altitude subsystem are set as $d_V = 10 \sin (t) \text{ ft/s}$, $d_h = 5 \sin (0.1 t) \text{ ft}$, $d_\gamma = 0.05 \sin (t) \text{ deg}$, $d_\phi = 0.5 \sin (0.1 t) \text{ deg/s}$. The reference trajectories of velocity and altitude are generated via the following filters [10]

$$V_{\text{ref}} (s) = \frac{0.03^2}{s^2 + 2 \times 0.95 \times 0.03 \times s + 0.03^2}, \quad (79)$$

$$h_{\text{ref}} (s) = \frac{0.03^2}{s^2 + 2 \times 0.95 \times 0.03 \times s + 0.03^2}, \quad (80)$$

where $V_{\text{ref}} (s)$ and $h_{\text{ref}} (s)$ represent the inputs of filters, $V_c (s)$ and $h_c (s)$ represent the outputs of filters, respectively. It is assumed that HFVs actuators failed at 100s, and the details of failure are formulated in the form of

$$v (\Phi) = 0.8 \Phi - 0.1, \quad (81)$$

$$v (\delta_e) = 0.8 \delta_e + 0.0349. \quad (82)$$
The FTPFs are selected as
\[ \rho_{V}(t) = \begin{cases} \coth \left( \frac{t}{50} + 0.4 \right) - 0.9 , & 0 \leq t < 50 \\ 0.1 , & t \geq 50 \end{cases} \] (83)
\[ \rho_{h}(t) = \begin{cases} \coth \left( \frac{t}{50} + 0.4 \right) - 0.5 , & 0 \leq t < 50 \\ 0.5 , & t \geq 50 \end{cases} \] (84)

The fuzzy rules in \( W_{V}^{T}S_{V} \) are listed as
\( R_{i}^{l} \): If \( V \) is \( F_{i}^{l} \), then \( y \) is \( B^{l} \), where \( i = 1, 2, 3; l = 1, 2, 3 \).

The fuzzy rules in \( W_{h}^{T}S_{h} \) are listed as
\( R_{i}^{l} \): If \( h \) is \( F_{i}^{l} \), and \( \gamma \) is \( F_{j}^{l} \), then \( y \) is \( B^{l} \), where \( i = 1, 2, 3; j = 1, 2, 3; l = 1, 2, \ldots, 9 \).

Then, the fuzzy rules in \( W_{\theta}^{T}S_{\theta} \) are listed as
\( R_{i}^{l} \): If \( h \) is \( F_{i}^{l} \), and \( \gamma \) is \( F_{j}^{l} \), and \( \theta \) is \( F_{k}^{l} \), then \( y \) is \( B^{l} \), where \( i = 1, 2, 3; j = 1, 2, 3; k = 1, 2, 3; l = 1, 2, \ldots, 27 \).
of the proposed FTFTC over the conventional fixed-time control (CFTC) in [38] is explained in the second example.

**Example 1** In this example, two different initial states cases, i.e., case 1 (\(e_V(0) = e_h(0) = 0\)) and case 2 (\(e_V(0) = e_h(0) = 1\)) are considered respectively.

The obtained simulation results, depicted in Figs. 3-4, reveal that the proposed FTFTC has full capabilities to deal with the condition that aerodynamic parameters are perturbed and initial states are uncertain. It can be observed from Figs. 3 (a)-(b) that the velocity and altitude tracking errors are guaranteed not to exceed the prescribed bounds. Furthermore, the velocity and altitude can rapidly track their reference trajectories even if the actuator fails. Fig. 3 (c) and Fig. 4 (a) depict there is no high-frequency chattering in the attitude angles as well as the flexible states, and they can converge to their steady values rapidly. Fig. 4 (b) shows that the control inputs are smooth and within realistic limits. The estimated values of adaptive parameters are bounded, which is presented in Fig. 4 (c).

**Example 2** In this example, simulations via the CFTC [38] and the proposed FTFTC are demonstrated, where the initial states are set as \(e_V(0) = e_h(0) = 1\). In order to expound the advantages of tracking performances of the proposed FTFTC, the performance index \(E = \int_0^t e^2 dt\) is introduced where \(e\) denotes the tracking error.

Simulation results are depicted in Figs. 5-6. Figs. 5 (a)-(b) shows the velocity and altitude tracking performance, in which the velocity and altitude tracking errors are limited in the preset bounds by the proposed FTFTC and the proposed FTFTC can provide higher rate of convergence compared with the CFTC. Besides, the attitude angles and flexible states are shown in Fig. 5 (c) and Fig. 6 (a), indicating that smaller oscillation amplitudes of attitude angles and flexible states are achieved in the presence of actuator failures by means of the proposed FTFTC. In addition, Fig. 6 (c) gives that less error energy is produced via the proposed FTFTC in contrast with the CFTC. That is to say, the proposed FTFTC can achieve more accurate tracking.

### 6 Conclusions

A novel fixed-time fuzzy adaptive fault-tolerant control methodology based on performance function is developed for hypersonic flight vehicles in this work. In contrast with the conventional fixed-time control, the proposed approach not only guarantees that the velocity and altitude tracking errors converge into a pre-assigned compact set, but also satisfies both the prescribed transient and steady performance. In addition, the proposed scheme can avoid the singularity problem caused by the differential of fractional order tracking error and remain valid in spite of actuator faults. Comparative simulation results confirm the validity and superiority of the proposed control strategy.

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**Conflict of interest**

The authors declare that they have no conflict of interest.

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Figures

Figure 1
The convergence performance of the proposed FTPF

Figure 2
Overall fixed-time tolerant-control scheme for HFVs
Figure 3

The velocity, altitude tracking performance and attitude angles under different initial states

(a) Velocity tracking performance  
(b) Altitude tracking performance  
(c) Attitude angles

Figure 4

The flexible states, control inputs and adaptive parameters under different initial states

(a) Flexible states  
(b) Control inputs  
(c) Adaptive parameters
Figure 5

The velocity, altitude tracking performance and attitude angles via different methodologies

Figure 6

The flexible states, control inputs and performance indexes via different methodologies