Fuzzy Reliable Tracking Control for Flexible Air-breathing Hypersonic Vehicles

Xiaoxiang Hu, Huijun Gao, Hamid Reza Karimi, Ligang Wu, and Changhua Hu

Abstract

In this paper, we present a fuzzy reliable tracking control design method for flexible air-breathing hypersonic vehicles (FAHVs) subject to disturbances and possible sensor/actuator failures. This problem is challenging due to the strong coupling effects, variable operating conditions and possible failures in FAHVs. First, Takagi-Sugeno (T-S) fuzzy model is used to represent the longitudinal dynamics model of FAHVs. Then, by considering the disturbances and the faults, the fuzzy reliable tracking problem is proposed, and the tracking control problem is transformed into a stabilization problem. A fuzzy reliable state-feedback controller is designed to guarantee the asymptotic stability of the closed-system. By the Lyapunov approach, the existence conditions for such a controller are established in terms of linear matrix inequalities. With the designed controllers, the reference command can be tracked in spite of actuator/sensor faults. Simulation has demonstrated the proposed design scheme.

Keywords: Flexible air-breathing hypersonic flight vehicles (FAHVs), nonlinear dynamic system, Takagi-Sugeno (T-S) fuzzy modeling, fuzzy reliable control, actuator/sensor faults.

1. Introduction

The scramjet-powered air-breathing hypersonic vehicles (AHVs) presents a more cost efficient way to make access to space routine, or even make the space travel routine and intercontinental travel as easy as intercity travel [1, 2]. Compared to traditional flight vehicles, AHVs have irreplaceable advantage. Being different from rocket engine, scramjet is capable of obtaining oxygen directly from atmosphere, so the AHVs can carry more payloads. For the turbojet engine, the maximum speed is usually limited to a Mach number of about 3.5 by the allowable turbine blade temperature, while the AHVs can fly at a high Mach number (greater than 5) without carrying oxidizer. Just as every coin has two sides, there are disadvantage for the application of scramjet. AHVs use the technology of airframe integrated with scramjet engine configuration [3,4], which makes the interactions between the elastic airframe, the propulsion system, and the structural dynamics very strong [5]. Modeling and flight control of such vehicles has been an active subject of research in recent years.

For the modeling and flight control of AHVs, modeling is very important. The main modeling issue is how to clearly and accurately describe the propulsive forces and vehicle motions under the strong coupling among aerodynamics, propulsion system with scramjet, and flexibility of the aircraft. Due to the dynamics' enormous complexity, only the longitudinal dynamics models of AHVs were studied and the modeling and control problems of hypersonic aircrafts were discussed. Recently, in [6,7], a longitudinal nonlinear model suitable for control design was derived and could describe the complex dynamics with the flexible coupling effects in a scramjet-powered vehicle. Based on the nonlinear flexible air-breathing hypersonic vehicles (FAHVs) model, several studies on the flight control and navigation were conducted. In [8], a control-oriented model was derived for the FAHVs using curve fits calculated directly from the forces and moments included in the truth model, and then an approximate feedback liberalization example of control design was given to derive a nonlinear controller. In [9], the authors presented two output feedback control design methods for the FAHVs models, and adaptive control techniques were also considered in [10]. In [11], dynamic output feedback technique was used to provide robust reference velocity and altitude tracking control in the presence of model uncertainties and varying flight conditions, and in [12,13], linear controllers with input constraints using on-line optimization and anti-windup techniques were also proposed. More recently, a nonlinear robust adaptive control design method was presented in [14], and in [15], the authors considered the modeling of aerothermoelastic effects and gave a Lyapunov-based tracking controller. Though a lot of works have been done, the robust control for the high nonlinear dynamics of FAHVs is still a pendent problem, especially when possible sensor/actuator faults exist.

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In order to develop efficient control approaches to address the tracking control task of FAHVs subject to complex nonlinear and coupling, it is necessary to implement the Takagi-Sugeno (T-S) fuzzy control scheme. T-S modeling technique is an effective approach of nonlinear systems, which could approximate any smooth nonlinear function to any specified accuracy within any compact set [16]. The T-S fuzzy models is represented by a set of linear models by fuzzy IF-THEN rules, so it is possible for the existing traditional linear systems results to be applied to analysis and synthesis of nonlinear systems based on the parallel-distributed compensation (PDC) scheme [17]. There have been several results in literatures on the control of nonlinear systems based on T-S fuzzy technique [18-22].

Similar to all other airplanes and space vehicles, possible sensor/actuator failures are not avoidable in FAHVs. Due to the complexity of FAHVs, it is hard to completely avoid the faults existing in the sensors or actuators, which have much to do with the safety and accuracy of the rendezvous. Hence, reliable control against the possible faults is also a major challenge in the flight control of FAHVs. But to our knowledge, this problem has not been well discussed. Reliable control has attracted many researchers and a number of results have been reported. In [23-25], reliable controller design methods for linear systems are presented, which stability and the given performances are ensured in spite of some admissible control component outages. Fuzzy reliable control problem has also been studied in [26], but in most of the studies, the faults are assumed to be zero when faults occur. This modeling method can simplify the controller design method. However, it is significant to adopt a more general model to describe the faults with scaling factors with upper and lower bounds in practice.

Besides the possible faults, various disturbances always exist in the realistic environment, which can result and can have strong adverse effects on the performance of FAHVs control systems, so the disturbance attenuation problem must be considered in the control design. In recent years, the disturbance attenuation control problem has been wildly studied in [27-31], but there are few results on the reliable H_∞ control of FAHVs subject to possible sensor/actuator failures. The complex and challenging problem of robust disturbance attenuation control design for the longitudinal model of FAHVs has not been fully investigated and many important issues remain unsolved, which motivates the present study.

Motivated by the above discussions, in this paper, we study the fuzzy reliable tracking control problem for FAHVs with disturbance. Based on the T-S fuzzy modeling technology, a T-S fuzzy model, with possible actuator faults and sensor faults, is constructed to represented the complex nonlinear longitudinal model of FAHVs. By considering the two cases (actuator faults case and sensor faults case) respectively, the reference command tracking problem is transformed into a stabilization problem. Then, the fuzzy reliable state-feedback controller design method is developed by a Lyapunov approach. The existence conditions for the admissible reliable controllers, in spite of the sensor/actuator failures, are formulated in the form of liner matrix inequalities. After getting the fuzzy state-feedback controller, an illustrative example is provided to show the effectiveness and advantage of the proposed control design method.

The rest of this paper is organized as follows. In Section 2, the dynamic model of FAHVs is established, and then, a T-S model of FAHVs is constructed. Based on the established T-S model, the fuzzy reliable controller design problem is formulated. Section 3 presents the fuzzy controller design method. Then, an example is given to illustrate the applicability of the proposed approach in Section 4. Finally, we conclude the paper in Section 5.

Notation: The notations used throughout the paper are fairly standard. Throughout this paper, the superscript 'T' stands for matrix transposition; and $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ denotes the set of all n×m real matrices; diag{…} stands for a block-diagonal matrix, and sym{A} is defined as $A+A^T$; I and 0 denote the identity matrix and zero matrix with compatible dimensions. In symmetric block matrices or complex matrix expressions, we use an "*" to represent a term that is induced by symmetry. Matrices are assumed to be compatible for algebraic operations if their dimensions are not explicitly stated.

2. Problem Formulation

In this section, a Takagi-Sugeno fuzzy model of FAHVs is established with considering disturbances. The fuzzy model is described by fuzzy IF-THEN rules and is employed here to deal with the control design problem for the nonlinear longitudinal dynamics of FAHVs. Two kinds of possible faults, ~~that is,~~ actuator faults and sensor faults, are modeled. Then the fuzzy reliable tracking control problem is proposed.

A. *Model Description*

The hypersonic vehicle model considered in this paper was developed by Bolender and Doman [6, 7]. Flexibility effects are included in the model. A longitudinal sketch of the vehicle is given in Figure 1. The nonlinear equations are described as follows:

$$
\begin{cases}
\dot{h} = V\sin(\theta-\alpha) \\
\dot{V} = \dfrac{1}{m}(T\cos\alpha - D) - g\sin(\theta-\alpha) \\
\dot{\alpha} = \dfrac{1}{mV}(-T\sin\alpha - L) + Q + \dfrac{g}{V}\cos(\theta-\alpha) \\
\dot{\theta} = Q \\
\dot{Q} = \dfrac{M}{I_{yy}} \\
\ddot{\eta}_1 = -2\varsigma_1\omega_1\dot{\eta}_1 - \omega_1^2\eta_1 + N_1 \\
\ddot{\eta}_2 = -2\varsigma_2\omega_2\dot{\eta}_2 - \omega_2^2\eta_2 + N_2
\end{cases} \quad (1)
$$

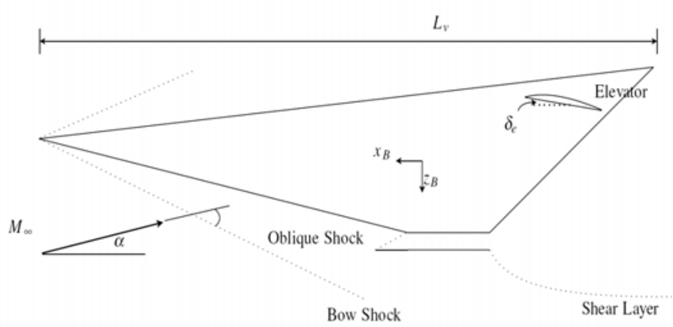

Figure 1. Geometry of the flexible hypersonic vehicle.

where h and V represent the flight altitude and velocity of FAHVs, respectively; α is the angle of attack of the vehicle and θ is the flight pitch angle with Q represents the pitch rate. η_i denotes the *ith* generalized elastic coordinate. T, L, D and N_i are the thrust, lift, drag, and generalized elastic forces, respectively; M is the pitching moment. This nonlinear model is composed of five rigid-body state variables $[h,V,\alpha,\theta,Q]^T$ and four flexible states $[\eta_1,\dot{\eta}_1,\eta_2,\dot{\eta}_2]^T$. The control inputs: fuel-to-air ratio Φ and elevator deflection δ_e, affect the forces and moment in these equations in a complex nonlinear way, the details can be found in [8].

Since the nonlinear dynamic of FAHVs is highly complex, designing a nonlinear controller directly is difficult. In this paper, we will utilize the well-known T-S fuzzy model technology to approach the nonlinear systems (1). In T-S fuzzy model constructing, V and α are chose as the premise variables and the modeling technique expressed in [32] is employed. Each premise variable is supposed to have three levels: a lower bound, a upper bound and a equilibrium point, which named as "small (S)," "big (B)," and "middle (M)," respectively. Consider the system with disturbances, the nonlinear model (1) can then be represented by a T-S fuzzy model composed of 9 (3^2) fuzzy rules, as listed in Table 1, where S, M, and B represent "small," "middle," and "big," respectively. An example of the fuzzy IF-THEN rules corresponding to Table 1 is explained as follow:

Table 1. List of fuzzy rules.

Rule NO.	Premise variables	
	V	α
1	S	S
2	S	M
3	S	B
4	M	S
5	M	M
6	M	B
7	B	S
8	B	M
9	B	B

Rule i) *If V is V_i and α is α_i, then*

$$
\begin{cases}
\dot{x}(t) = A_i x(t) + B_i u(t) + D_i f(t) \\
y(t) = C_i x(t)
\end{cases}
$$

where $x(t) = [h,V,\alpha,\theta,Q,\eta_1,\dot{\eta}_1,\eta_2,\dot{\eta}_2]^T$, $f(t)$ is the uncertain extraneous disturbance or the nonlinearity, D_i is the gain matrix of $f(t)$, $C_1 = C_2 = \cdots = C_9 = C$, and

$$
C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.
$$

The fuzzy membership functions of V and α are defined as follows:

$$
if\ \ V > V_M, \quad
\begin{cases}
h_S(V) = 0 \\
h_M(V) = 1 - h_B(V) \\
h_B(V) = \exp\left(-3.5\times10^{-12}\left|V(t) - V_B\right|^4\right)
\end{cases}
$$

$$
if\ \ V < V_M, \quad
\begin{cases}
h_S(V) = \exp\left(-3.5\times10^{-12}\left|V(t) - V_S\right|^4\right) \\
h_M(V) = 1 - h_B(V) \\
h_B(V) = 0
\end{cases}
$$

$$
if\ \ \alpha > \alpha_M, \quad
\begin{cases}
h_S(\alpha) = 0 \\
h_M(\alpha) = 1 - h_B(\alpha) \\
h_B(\alpha) = \exp\left(-0.06\left|\alpha(t) - \alpha_B\right|^4\right)
\end{cases}
$$

$$
if\ \ \alpha < \alpha_M, \quad
\begin{cases}
h_S(\alpha) = \exp\left(-0.06\left|\alpha(t) - \alpha_S\right|^4\right) \\
h_M(\alpha) = 1 - h_B(\alpha) \\
h_B(\alpha) = 0.
\end{cases}
$$

Thus, the T-S fuzzy model which represents the nonlinear hypersonic vehicle model (1) can be described by

$$
\begin{cases}
\dot{x}(t) = \sum_{i=1}^{9} h_i(t)\left[A_i x(t) + B_i u(t) + D_i f(t)\right] \\
y(t) = Cx(t),
\end{cases} \quad (2)
$$

where $h_i(t)$ is corresponding to Table 1, with $h_i(t)\ge 0$, $i=1,2,\cdots,9$ and $\sum_{i=1}^{9} h_i(t)=1$.

The control objective is to track a command velocity and altitude vector $y_{\text{com}}(t)=[V_{\text{com}}(t),h_{\text{com}}(t)]^T$ without steady-state tracking error, that is,

$$\lim_{t\to\infty} e(t)=\lim_{t\to\infty}\left(y(t)-y_{\text{com}}(t)\right)=0.$$

In order to eliminate the steady-state tracking error, we introduce the error integral action in the controller. Define

$$d(t)=\int_0^t e(\tau)d\tau=\int_0^t (y(\tau)-y_{\text{com}}(t))d\tau,$$

then

$$\dot d(t)=e(t)=y(t)-y_{\text{com}}(t).$$

In order to obtain a robust tracking controller with state-feedback, the following augmented state-space description is introduced:

Rule i) If V is V_i and α is α_i, then

$$\begin{cases}\dot\zeta(t)=\bar A_i\zeta(t)+\bar B_i u(t)+G_i w(t)\\ y(t)=\bar C\zeta(t)\end{cases}$$

where

$$\bar A_i=\begin{bmatrix}A_i & 0\\ C & 0\end{bmatrix},\bar B_i=\begin{bmatrix}B_i\\ 0\end{bmatrix},G_i=\begin{bmatrix}D_i & 0\\ 0 & -I\end{bmatrix}$$

$$\zeta(t)=\begin{bmatrix}x(t)\\ d(t)\end{bmatrix},w(t)=\begin{bmatrix}f(t)\\ y_{\text{com}}(t)\end{bmatrix},\bar C=\begin{bmatrix}C & 0\end{bmatrix}.$$

For description brevity, the above equation is written as

$$\begin{cases}\dot\zeta(t)=\bar A_h\zeta(t)+\bar B_h u(t)+G_h w(t)\\ y(t)=\bar C\zeta(t)\end{cases}\tag{3}$$

where

$$\bar A_h=\sum_{i=1}^{9}h_i(t)\bar A_i,\quad \bar B_h=\sum_{i=1}^{9}h_i(t)\bar B_i, G_h=h_i(t)G_i.$$

Based on the parallel distributed compensation (PDC) concept, the fuzzy state-feedback controller for fuzzy model (2) is constructed as

$$u(t)=\sum_{i=1}^{9}h_i(t)K_i\zeta(t)=K_h\zeta(t)\tag{4}$$

where $K_h=\sum_{i=1}^{9}h_i(t)K_i$. The augmented close-loop system can be written as

$$\begin{aligned}\dot\varsigma(t)&=\left(\bar A_h+\bar B_h K_h\right)\zeta(t)+G_h w(t)\\ &=\sum_{i=1}^{9}\sum_{i=1}^{9}h_i(t)h_j(t)\left(\bar A_i+\bar B_i K_j\right)\zeta(t)+G_i w(t)\end{aligned}\tag{5}$$

Then the output tracking controller design problem can be transformed into a stabilization problem for (5).

B. *Fuzzy Reliable Controller Design Problem*

The fault model considered in this paper is supposed to depend on two different sources of possible faults, that is, actuator fault and sensor fault. In what follows, the two cases will be considered respectively.

- *Actuator fault case*

The type of actuator fault considered this paper is loss of actuator effectiveness, here we use $u^F(t)$ to describe the actuator signal and

$$u^F(t)=\sum_{i=1}^{9}h_i(t)F_a(t)K_{ai}\zeta(t)=F_a(t)K_{ah}\zeta(t)\tag{6}$$

where K_{ai} is the actuator faults-tolerant feedback controller which needs to be determined, $K_{ah}=\sum_{i=1}^{9}h_i(t)K_{ai}$, the fault matrix $F_a(t)=\text{diag}\{f_{a\Phi}(t),f_{a\delta_e}(t)\}$. $f_{ai}(t)$, $i=\{\Phi,\delta_e\}$ is an unknown function, which means the actuator reduction coefficient.

Assumption 1: $f_{ai}(t)$ is supposed to satisfy

$$f_{ali}\le f_{ai}(t)\le f_{aui},\tag{7}$$

where f_{ali} and f_{aui} are known constants which represent the lower and upper bounds of $f_{ai}(t)$, respectively, and $0\le f_{ali}\le f_{aui}<\infty$.

With Assumption 1, if $f_{ali}=f_{aui}$=0, the corresponding *ith* actuator $u_i(t)$ is complete broken down. If $f_{ali}=f_{aui}$=1, the ith actuator $u_i(t)$ is in the fault-free case. Otherwise, if 0< $f_{ali}<f_{aui}$, and $f_{ai}(t)\neq 1$, there exists the partial fault in the corresponding actuator.

- *Sensor fault case*

Similarly to actuator fault, the sensor fault considered in this paper can be defined in the following form:

$$u^F(t)=\sum_{i=1}^{9}h_i(t)K_{si}F_s(t)\zeta(t)=K_{sh}F_s(t)\zeta(t),\tag{8}$$

where K_{si} is the sensor faults-tolerant feedback controller to be determined, $K_{sh}=\sum_{i=1}^{9}h_i(t)K_{si}$, the sensor failure matrix $F_s(t)=\{f_{sh}(t),f_{sV}(t),f_{s\alpha}(t),f_{s\theta}(t), f_{sQ}(t),f_{s\eta_1}(t),f_{s\dot\eta_1}(t),f_{s\eta_2}(t),f_{s\dot\eta_2}(t),f_{sd_h}(t),f_{sd_V}(t)\}$. $f_{si}(t), i=\{h,V,\alpha,\theta,Q,\eta_1,\dot\eta_1,\eta_2,\dot\eta_2,d_h,d_V\}$ is an unknown function, which stands for the sensor reduction coefficient.

Assumption 2: $f_{si}(t)$ is supposed to satisfy

$$f_{sli} \le f_{si}(t) \le f_{sui} \tag{9}$$

where f_{sli} and f_{sui} are known constants which represent the lower and upper bounds of $f_{si}(t)$, respectively, and $0 \le f_{sli} \le f_{sui} < \infty$.

Here, $f_{sli} = f_{sui}$ =0, and $f_{sli} = f_{sui}$ =1, denote the cases of complete signal loss and no fault in the corresponding sensor, respectively, and other values of $f_{si}(t)$ represent partial fault of the sensor.

Then the close-loop system with state-feedback controller can be written as

$$\dot{\varsigma}(t) = \left(\bar{A}_h + \bar{B}_h \bar{K}_h\right)\zeta(t) + G_h w(t) \tag{10}$$

where $\bar{K}_h = F_a(t)K_{ah}$ for the actuator faults case, or $\bar{K}_h = K_{sh}F_s(t)$ for the sensor faults case.

Because of the existence of $w(t)$, the disturbance attenuation must be considered when designing the state-feedback controller. To this end, disturbance attenuation performance is set as follow:

$$\int_0^\infty y^T(t)\Omega y(t)dt \le \rho^2 \int_0^\infty w^T(t)w(t)dt \tag{11}$$

where $w(t) \in L_2[0,\infty)$, Ω is a positive definite weighting matrix, ρ is a prescribed attenuation level. Consider FAHVs with possible sensor/actuator faults, the fuzzy reliable controller design problem is to find a state-feedback controller, such that:

- The closed-loop system is robustly stable;
- The output of the system can track a command vector $y_{com} = [V_{com}, h_{com}]^T$ without steady-error;
- In the event of possible sensor/actuator faults, the stability and the tracking performance of the system can be guaranteed.

3. Main Results

In this section, based on the parallel distributed compensation (PDC) scheme, the fuzzy state-feedback reliable controller design problem will be investigated. Before proceeding, the following lemmas are given.

Lemma 1 [33]: Let E, F and Σ are matrices of appropriate dimensions with $\|\Sigma\| \le 1$. Then, for any scalar ε>0,

$$E\Sigma F + F^T\Sigma^T E^T \le \varepsilon^{-1}EE^T + \varepsilon F^T F.$$

Lemma 2 [34]: For a time-varying diagonal matrix $\Phi(t) = diag\left\{\sigma_1(t), \sigma_2(t), \cdots, \sigma_p(t)\right\}$ and matrices R and S with appropriate dimensions, if $|\Phi(t)| \le V$, where $|\Phi(t)| = diag\left\{|\sigma_1(t)|, |\sigma_2(t)|, \cdots, |\sigma_p(t)|\right\}$ and V>0 is a known diagonal matrix, then for any scalar ε>0,

$$R\Phi S + S^T\Phi^T R^T \le \varepsilon RVR^T + \varepsilon^{-1}S^T VS.$$

Lemma 3 [35]: The parameterized linear matrix inequalities,

$$\sum_{i=1}^{n}\sum_{i=1}^{n}\mu_i\mu_j M_{ij} < 0,$$

is fulfilled, if the following condition holds:

$$M_{ii} < 0;$$

$$\frac{1}{k-1}M_{ii} + \frac{1}{2}\left(M_{ij} + M_{ji}\right) < 0, \quad 1 \le i \ne j \le k.$$

A. *Actuator Faults-Reliable controller*

We introduce

$$F_{a0} = \text{diag}\{f_{a\Phi 0}, f_{a\delta_e 0}\}$$
$$L_a = \text{diag}\{l_{a\Phi}, l_{a\delta_e}\}$$
$$J_a = \text{diag}\{j_{a\Phi}, j_{a\delta_e}\}$$

where $f_{ai0} = (f_{ali} + f_{aui})/2$, $l_{ai} = [f_{ai}(t) - f_{ai0}]/f_{ai0}$ and $j_{ai} = (f_{aui} - f_{ali})/(f_{aui} + f_{ali})$ with $i = \{\Phi, \delta_e\}$. Then, we have $F_a = F_{a0}(I + L_a)$ and $L_a^T L_a \le J_a^T J_a \le I$.

A sufficient condition for the stability of the fuzzy system (10) to solve the problem of actuator faults-reliable controller design for FAHVs is given as follows.

Theorem 1: For the T-S fuzzy system (10) associated with actuator faults described in (6), if there exist matrix P>0, $Y_j\left(j = 1,2,\ldots,9\right)$, and a scalar $\varepsilon_{a1}>0$, satisfying

$$\Theta_{ii} < 0, i = 1,2,\ldots,9.$$
$$\frac{1}{k-1}\Theta_{ii} + \frac{1}{2}\left(\Theta_{ij} + \Theta_{ji}\right) < 0, 1 \le i \ne j \le 9, \tag{12}$$

where

$$\Theta_{ij} = \begin{bmatrix} sym\left\{\bar{A}_i X + \bar{B}_i Y_j\right\} + \varepsilon_{a1}\bar{B}_i J_a \bar{B}_i^T & Y_j^T & G_h & XC^T \\ * & -\varepsilon_{a1}J_a^{-1} & 0 & 0 \\ * & * & -\rho^2 I & 0 \\ * & * & * & -\Omega^{-1} \end{bmatrix} \tag{13}$$

then there exists a proper actuator faults-tolerant controller such that the close-loop system in (10) is asymptotically stable in spite of the actuator faults, and the disturbance attenuation performance in (11) is guaranteed for a prescribed performance index ρ. The desired state-feedback control gain is given by

$$K_{ai} = F_{a0}^{-1}Y_i X^{-1}. \tag{14}$$

Proof: For system (1), define the following Lyapunov function

$$V(t) = \zeta(t)^T P\zeta(t),$$

then take time derivative of $V(t)$, we have

$$\dot{V}(t)=\zeta(t)^T\left[P\left(\bar{A}_h+\bar{B}_h\bar{K}_h\right)+\left(\bar{A}_h+\bar{B}_h\bar{K}_h\right)^T P\right]\zeta(t) \\ +\zeta(t)^T PG_h w(t)+w^T(t)G_h^T P\zeta(t). \quad (15)$$

The close-loop fuzzy system (10) is stable with disturbance attenuation performance ρ if the following inequality holds:

$$\dot{V}(t)+y^T(t)\Omega y(t)-\rho^2 w^T(t)w(t)dt<0 \quad (16)$$

By Lemma 1

$$\zeta(t)^T PG_h w(t)+w^T(t)G_h^T P\zeta(t) \\ \le \rho^{-2}\zeta(t)^T PG_hG_h^T P\zeta(t)+\rho^2 w^T(t)w(t) \quad (17)$$

from (15) and (6), we can get that (16) lead to

$$sym\left[P\bar{A}_h+P\bar{B}_hF_{a0}K_{ah}+P\bar{B}_hF_{a0}L_aK_{ah}\right] \\ +\rho^{-2}PG_hG_h^TP+C^T\Omega C<0. \quad (18)$$

For the structure of F_{a0} and L_a, it can be easily obtained that $F_{a0}L_a=L_aF_{a0}$, by defining $X=P^{-1}$, $Y_h=F_{a0}K_{ah}X$ and performing a congruence transformation to above inequality by P^{-1}, we have

$$sym\left[\bar{A}_hX+\bar{B}_hY_h+\bar{B}_hL_aY_h\right]+\rho^{-2}G_hG_h^T+XC^T\Omega CX<0$$

By Lemma 2, for a scalar $\varepsilon_{a1}>0$, we have

$$\bar{B}_hL_aY_h+Y_h^TL_a^T\bar{B}_h^T\le\varepsilon_{a1}\bar{B}_hJ_a\bar{B}_h^T+\varepsilon_{a1}^{-1}Y_h^TJ_aY_h$$

then (18) can be rewritten as:

$$sym\left\{\bar{A}_hX+\bar{B}_hY_h\right\}+\varepsilon_{a1}\bar{B}_hJ_a\bar{B}_h^T \\ +\varepsilon_{a1}^{-1}Y_h^TJ_aY_h+\rho^{-2}G_hG_h^T+XC^T\Omega CX<0$$

By Schur complement, the above inequality equals to

$$\sum_{i=1}^{9}\sum_{i=1}^{9}h_i(t)h_j(t)\begin{bmatrix}\Psi_{aij} & Y_j^T & G_h & XC^T\\ * & -\varepsilon_{a1}J_a^{-1} & 0 & 0\\ * & * & -\rho^2 I & 0\\ * & * & * & -\Omega^{-1}\end{bmatrix}<0$$

where $\Psi_{aij}=sym\left\{\bar{A}_iX+\bar{B}_iY_j\right\}+\varepsilon_{a1}\bar{B}_iJ_a\bar{B}_i^T$, that is,

$$\sum_{i=1}^{9}\sum_{i=1}^{9}h_i(t)h_j(t)\Theta_{ii}<0,\quad i=1,2,\ldots,9.$$

Then by Lemma 3, inequalities (12) and (13) can easily be obtained. The proof is completed. □

B. *Sensor Faults-Reliable controller*

Similarly to the actuator fault case, we introduce the following matrices:

$$F_{s0}=diag\{f_{sh0},f_{sV0},f_{s\alpha0},f_{s\theta0},f_{sQ0}, \\ f_{s\eta_1 0},f_{s\dot{\eta}_1 0},f_{s\eta_2 0},f_{s\dot{\eta}_2 0},f_{sd_h 0},f_{sd_V 0}\},$$

$$L_s=diag\{l_{sh},l_{sV},l_{s\alpha},l_{s\theta},l_{sQ}, \\ l_{s\eta_1},l_{s\dot{\eta}_1},l_{s\eta_2},l_{s\dot{\eta}_2},l_{sd_h},l_{sd_V}\},$$

$$J_s=diag\{j_{sh},j_{sV},j_{s\alpha},j_{s\theta},j_{sQ}, \\ j_{s\eta_1},j_{s\dot{\eta}_1},j_{s\eta_2},j_{s\dot{\eta}_2},j_{sd_h},j_{sd_V}\},$$

where $f_{si0}=(f_{sli}+f_{sui})/2$, $l_{si}=[f_{si}(t)-f_{si0}]/f_{si0}$, and $j_{si}=(f_{sui}-f_{sli})/(f_{sui}+f_{sli})$ with $i=\{h,V,\alpha,\theta,Q,\eta_1,\dot{\eta}_1,\eta_2,\dot{\eta}_2,d_h,d_V\}$. Thus, we have $F_s=F_{s0}(I+L_s)$ and $L_s^TL_s\le J_s^TJ_s\le I$.

Theorem 2: For the T-S fuzzy system (10) associated with sensor faults described in (8), if there exist matrix X>0, Y_j, V_j, $(j=1,2,\ldots,9)$, and a scalar $\varepsilon_{s1}>0$, satisfying

$$\Theta_{ii}<0, i=1,2,\ldots,9. \\ \frac{1}{k-1}\Theta_{ii}+\frac{1}{2}\left(\Theta_{ij}+\Theta_{ji}\right)<0, 1\le i\ne j\le 9, \quad (20)$$

where

$$\Theta_{ij}=\begin{bmatrix}sym\left\{\bar{A}_iX+\bar{B}_iY_j\right\}+\varepsilon_{s1}\bar{B}_iV_j\bar{B}_i^T & X & G_h & XC^T\\ * & -\varepsilon_{s1}J_s^{-1} & 0 & 0\\ * & * & -\rho^2 I & 0\\ * & * & * & -\Omega^{-1}\end{bmatrix} \quad (21)$$

$$J_s-X\le 0 \quad (22)$$

$$\sum_{j=1}^{9}h_j(t)\begin{bmatrix}-V_j & Y_j\\ Y_j^T & -X\end{bmatrix}<0 \quad (23)$$

then there exists a proper sensor faults-tolerant controller such that the close-loop system in (10) is asymptotically stable in spite of the sensor faults, and the disturbance attenuation performance in (11) is guaranteed for a prescribed performance index ρ. The desired state-feedback control gain can be given by

$$K_i=Y_iX^{-1}F_{s0}^{-1}. \quad (24)$$

Proof: Similarly to the proof of Theorem 1, for sensor faults case, the close-loop system in (10) is asymptotically stability if (15) holds. Defining $X=P^{-1}$ and performing a congruence transformation to (15) by P^{-1}, we have

$$sym\left\{\left[\bar{A}_h+\bar{B}_hK_{sh}F_{s0}(I+L_s)\right]X\right\}+XC^T\Omega CX+\rho^{-2}G_hG_h^T<0$$

By defining $Y_h=K_{sh}F_{s0}X$, we have

$$sym\left(\bar{A}_hX+\bar{B}_hY_h\right)+\bar{B}_hK_{sh}F_{s0}L_sX \\ +XL_s^TF_{s0}^TK_{sh}^T\bar{B}_h^T+XC^T\Omega CX+\rho^{-2}G_hG_h^T<0 \quad (25)$$

By Lemma 2, for any scalar $\varepsilon_{s1}>0$,

$$\bar{B}_hK_{sh}M_{s0}L_sX+XL_s^TM_{s0}^TK_{sh}^T\bar{B}_h^T \\ \le\varepsilon_{s1}\bar{B}_hK_{sh}F_{s0}J_sF_{s0}^TK_{sh}^T\bar{B}_h^T+\varepsilon_{s1}^{-1}XJ_sX.$$

From (22) and (23), we have

$$\begin{aligned}&\varepsilon_{s1}\bar{B}_h K_{sh} F_{s0} J_s F_{s0}^T K_{sh}^T \bar{B}_h^T\\ &= \varepsilon_{s1}\bar{B}_h Y_h X^{-1} J_s X^{-1} Y_h^T \bar{B}_h^T\\ &\le \varepsilon_{s1}\bar{B}_h Y_h X^{-1} Y_h^T \bar{B}_h^T \le \varepsilon_{s1}\bar{B}_h V_h \bar{B}_h^T\end{aligned}$$

and thus,

$$\begin{aligned}&\bar{B}_h K_{sh} M_{s0} L_s X + X L_s^T M_{s0}^T K_{sh}^T \bar{B}_h^T\\ &\le \varepsilon_{s1}\bar{B}_h V_h \bar{B}_h^T, +\varepsilon_{s1}^{-1} X J_s X\end{aligned} \tag{26}$$

By Schur complement, the above inequality equals to

$$\sum_{i=1}^{9}\sum_{i=1}^{9} h_i(t) h_j(t) \begin{bmatrix} \Psi_{sij} & X & G_h & XC^T \\ * & -\varepsilon_{s1} J_s^{-1} & 0 & 0 \\ * & * & -\rho^2 I & 0 \\ * & * & * & -\Omega^{-1} \end{bmatrix} < 0$$

where $\Psi_{sij} = sym\left\{\bar{A}_i X + \bar{B}_i Y_j\right\} + \varepsilon_{s1}\bar{B}_i V_j \bar{B}_i^T$, that is,

$$\sum_{i=1}^{9}\sum_{i=1}^{9} h_i(t) h_j(t) \Theta_{ii} < 0, \quad i = 1, 2, \ldots, 9.$$

Then by Lemma 3, inequalities (20)-(23) hold. The proof is completed. □

4. Simulation Results

In this section, a numerical example is provide to illustrate the effectiveness and advantages of the fuzzy reliable controller design methods proposed in this paper. For the construct of T-S fuzzy model, the lower and the upper bounds of V and α are chosen as: $V_B = 9000\,ft/s$, $V_S = 6400\,ft/s$, and $\alpha_B = 5\deg$, $\alpha_S = -2\deg$, other states are chosen according to the flight envelop. The membership functions of the fuzzy model re shown in Figures 2-3, where Figure 2 is the membership function of V and Figure 3 is that of α. The hypersonic vehicle model parameter values are borrowed from [8]. By using the fuzzy modeling method described in Section 2, the T-S fuzzy tracking model of hypersonic vehicle can be established.

The control objective is to track a set step with respect to a trim condition, which are reasonable requirements for FAHVs. The input reference commands are chosen as step inputs, so each command will pass through a prefilter as

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{27}$$

where ζ denotes damping ratio, ω_n stands for natural frequency. The signal out of the prefilter is defined as reference command which is aimed to be tracked. In simulation, to illustrate the effectiveness of the proposed controller, we will use the original nonlinear model (not the constructed fuzzy model) to test the performance of the control system. According to [36], the disturbance are assumed to be bounded, which can be regarded as a gust of wind in aerospace. In order to compare the tracking performances of FAHVs with fuzzy reliable controller and the nominal controller, a nominal fuzzy state-feedback controller $u(t) = K_{nom}\varsigma(t)$ is introduced which is designed without considering the possible faults.

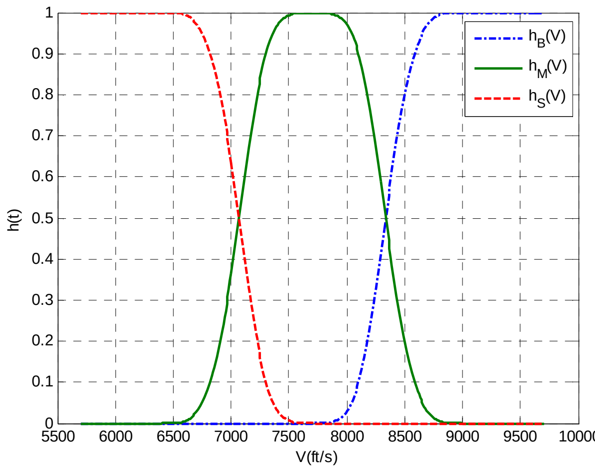

Figure 2. Membership Functions of V.

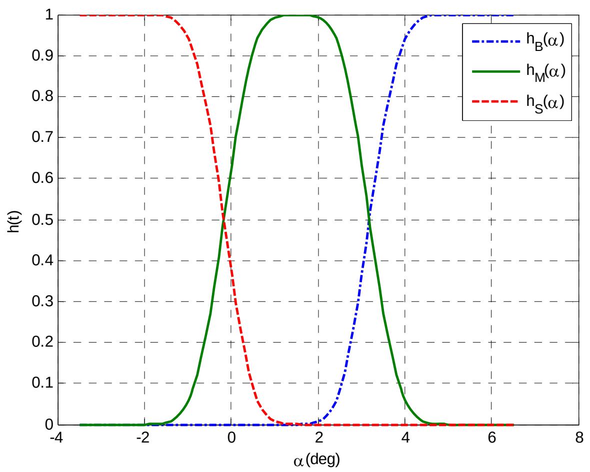

Figure 3. Membership Functions of α.

Here, we consider a climbing maneuver with longitudinal acceleration using separate reference commands for altitude and velocity. In this simulation, the reference commands for altitude and velocity are chosen as follow: *100ft/s* for velocity and *1000ft* for altitude, respectively. The parameters of (27), ζ and ω_n are chosen as *0.9* and *0.1rad/s*, respectively, which can make the climbing of velocity and altitude finish in about 50s. In the following, we will discuss the actuator faults and sensor faults, respectively.

A. *Actuator Faults Case*

In realistic environment, both of the two actuators may lose its effectiveness. So for actuator faults case, suppose that $f_{ali} = 0.6$, $f_{aui} = 1$, $i = \{\Phi, \delta_e\}$, then $F_{a0} = diag\{0.8, 0.8\}$. Then, our purpose is to design a fuzzy reliable state-feedback controller $K_{ah} = \sum_{i=1}^{9} h_i(t) K_{ai}$, such that FAHVs can track the reference command in spite of the actuator faults and external disturbances. Letting $\gamma = 2, \Omega = 1\times 10^{-4} I$, and by Theorem 1, we can obtain the controller gains K_{ai}, *(i=1,2,...,9)*, then the fuzzy reliable state-feedback controller can be constructed.

To illustrate the advantage of the fuzzy faults-tolerant controller design method, we compare the effectiveness of the controller K_{ah} which is designed by Theorem 1 and the nominal controller K_{nom}. The effectiveness and tracking performance for FAHVs with K_{nom} and K_{ah} are depicted in Figure 4, where the solid line is the reference command, dashed line is for fuzzy reliable controller K_{ah} and dash-dotted line is for nominal controller K_{nom}. It is observed from Figure 4 that, the proposed fuzzy reliable controller and the nominal controller all achieves good performance for the tracking problem. Compared to the nominal controller, under the same faults, the fuzzy reliable control strategy ensures better tracking performance. This confirms that the proposed fuzzy reliable control strategy can realize excellent performance with highly nonlinear system in (1).

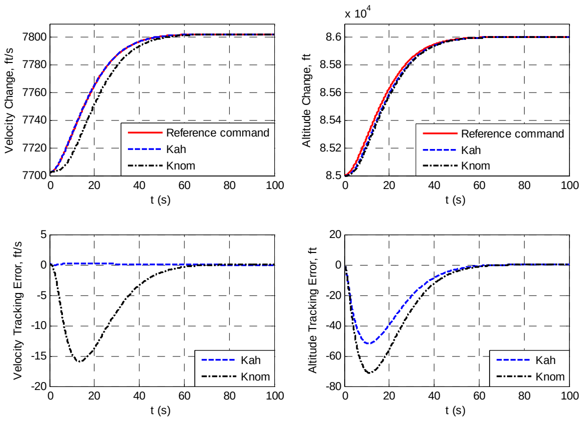

Figure 4. Tracking performance of actuator faults.

Figures 5 and 6 show the other important states and the inputs of FAHVs, respectively. More specifically, the angle of attack, flight path angle and the inputs of the plant: fuel-to-air ratio *Φ* and elevator deflection δ_e are shown. The angle of attack is of great importance since it represents the vehicle's attitude. If the amplitude of α becomes too large, the vehicle may not function. From Figure 5, α remains within about *0.8deg* from the trim condition and the pitch angle θ is kept reasonably small in the above two cases. Figure 6 gives the inputs of the plant. The inputs are all smooth and bounded. In summary, the simulations results demonstrate that the proposed fuzzy reliable controller is effective in presence of actuator faults and external disturbances.

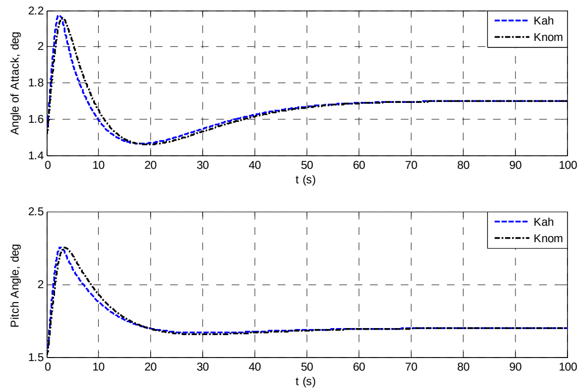

Figure 5. Angle of attack, flight path angle of actuator faults.

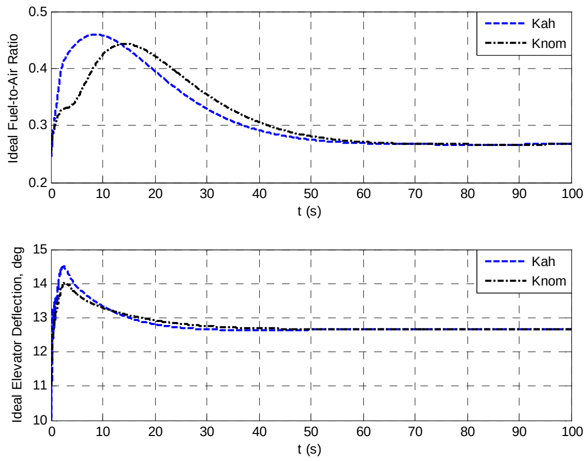

Figure 6. Input of actuator faults.

B. *Sensor Faults Case*

For sensor faults case, suppose that $m_{sli} = 0.4$, $m_{sui} = 1$, $i = \{h, V, \alpha, \theta, Q, \eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, d_h, d_V\}$, then we have $M_{s0} = diag\{0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7, 0.7\}$. Assume that the faults of the sensors occur simultaneously, then, our purpose is to design a fuzzy reliable state-feedback controller K_{sh}, such that the FAHVs can track the reference command in spite of the sensor faults and external disturbances. Letting $\gamma = 2.5$, $\Omega = 1\times 10^{-6} I$, and by Theorem 2, we can obtain the controller gains K_{si}, *(i=1,2,...,9)*. In the simulation, we compare the control performance of the fuzzy faults-tolerant controller K_{sh} and the nominal controller K_{nom}. The tracking performance for FAHVs with K_{sh} and K_{nom} is given in Figures 7-9.

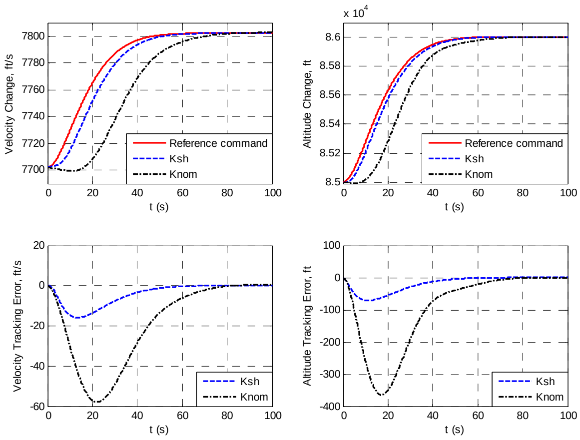

Figure 7. Tracking performance of sensor faults.

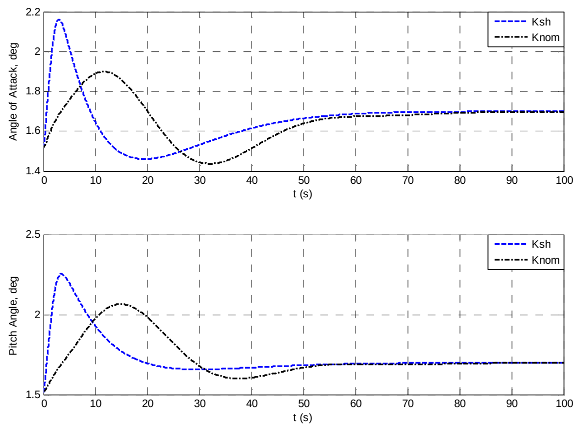

Figure 8. Angle of attack, flight path angle of sensor faults.

From Figure 7, we can see that, the proposed fuzzy reliable controller can still get a good tracking performance in presence of sensor faults, but under the same faults, the tracking error of the nominal controller is more bigger than the fuzzy reliable controller. This confirms that the proposed fuzzy reliable control strategy ensures better tracking performance for FAHVs in spite of the sensor faults.

The other important states and the inputs are shown in Figures 8 and 9, respectively. From the simulations results we can see that, the proposed fuzzy reliable controller can get a good performance in presence of sensor faults and external disturbances.

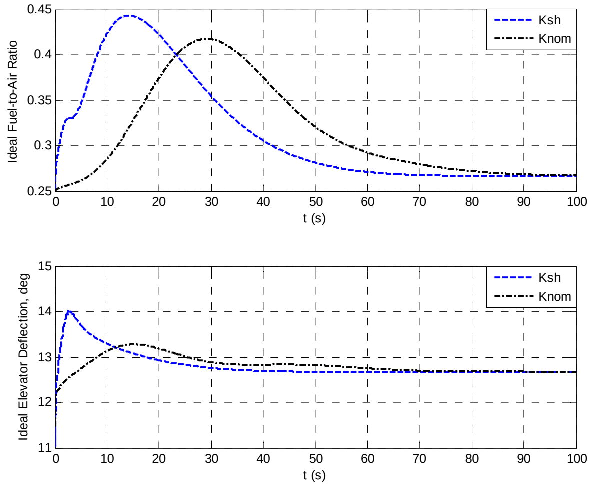

Figure 9. Input of sensor faults.

5. Conclusion

In this paper, a fuzzy reliable control strategy has been presented for the tracking problem of the longitudinal dynamics of FAHVs model with actuator or sensor faults and external disturbance. Based on the T-S fuzzy modeling technology, a T-S fuzzy model has been constructed to represent the nonlinear dynamics of the FAHVs. By defining an augmented system and considering the two cases (actuator faults and sensor faults) respectively, the tracking problem has been transformed into a disturbance attenuation problem of the close-loop problem. Then, based on PDC scheme, fuzzy reliable controller design problems have been studied for the mentioned two fault cases by using Lyapunov method, respectively. Sufficient conditions for designing such a controller have been proposed in terms of LMIs. Illustrative examples have shown the effectiveness of the proposed controller design method.

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