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Adaptive Fault-Tolerant Tracking Control of Near-Space Vehicle Using Takagi–Sugeno Fuzzy Models

Bin Jiang, Zhifeng Gao, Peng Shi, and Yufei Xu

***Abstract*—Based on the adaptive-control technique, this paper deals with the problem of fault-tolerant tracking control for near-space-vehicle (NSV) attitude dynamics. First, Takagi–Sugeno (T–S) fuzzy models are used to describe the NSV attitude dynamics; then, an actuator-fault model is developed. Next, an adaptive fault-tolerant tracking-control scheme is proposed based on the online estimation of actuator faults, in which a compensation control term is introduced in order to reduce the effect of actuator faults. Compared with some existing results of fault-tolerant control (FTC) in nonlinear systems, the technique presented in this paper is not dependent on fault detection and isolation (FDI) mechanism and is easy to implement in aerospace-engineering applications. Finally, simulation results are given to illustrate the effectiveness and potential of the proposed FTC scheme.**

***Index Terms*—Actuator faults, adaptive control, fault-tolerant tracking control, Takagi–Sugeno (T–S) fuzzy models.**

I. Introduction

The near-space vehicle (NSV) is a kind of new aerospace vehicle that not only can make the supersonic speed cruising flight in the atmosphere but also can pass through the atmosphere and make the cruising flight [1]. Compared with the existing aerospace vehicles, NSV has many advantages in launch cost, reusability, rapidity, maintainability, etc. It can be seen that NSV has a very high value in military and civil applications; therefore, it has the broad prospects for development [2]. Different from the traditional flight vehicles, NSV possesses the following characteristics: multiduties, multiworking patterns, large-scale high-speed mobile, large flight envelope, etc., whose airborne condition and flying status change very rapidly; NSV dynamics show serious multivariate coupling and strong nonlinearity [3], [4].

In recent years, there has been a growing interest in the Takagi–Sugeno (T–S) fuzzy system since it is a powerful solution that bridges the gap between linear and nonlinear control systems. The important advantage of the T–S fuzzy system is its universal approximation of any smooth nonlinear function by a “blending” of some local linear-system models, which greatly facilitates the analysis and synthesis of the complex nonlinear system. Many important results on analysis and synthesis for the T–S fuzzy system have been reported (see [5]–[9] and the references therein). Considering the advantage of the T–S fuzzy system to approximating complex nonlinear systems, we will use it to describe the NSV attitude dynamics in this paper.

As a new aerospace vehicle, NSV attitude dynamics will inevitably be subjected to faults that can be caused by actuators, sensors, or system components. To improve NSV dynamics’s safety and reliability, fault-tolerant-control (FTC) scheme must be considered in designing stable NSV attitude dynamics [4]. The fault-tolerant-design approach can be mainly classified into two types: passive and active [10]. In the passive approach, the same controller is used throughout the normal case as well as the fault case such that this passive fault-tolerant controller can be easily implemented [11]–[14]. An active FTC system compensates for the effect of fault by synthesizing a new control strategy based on online accommodation [15]–[17]. Generally speaking, the active approach is less conservative than the passive one, which has increasingly been the main methodology in designing FTC systems [18].

On the other hand, tracking control plays an important role in the field of industry production, aeronautics, and astronautics, such as a flexible robotic, aerospace vehicle. Therefore, it has been a hot research topic for scientists and engineers over the past few years [19]. For a class of discrete stochastic fuzzy systems, a optimal tracking-control law has been proposed based on fuzzy-predictive control approach in [20]. Based on linear-matrix-inequality (LMI) optimization technique, a model reference fuzzy-tracking-control scheme is developed for nonlinear discrete-time systems in [21]. Based on adaptive-control technique, a sufficient condition is derived for fuzzy-output tracking control of a class of multi-input–multi-output (MIMO) nonlinear uncertain systems [22]. However, those results given in [20]–[22] are not suitable for the case of nonlinear faulty systems; namely, those designed control schemes do not have the fault-tolerant property. To the best of our knowledge, the problem of fuzzy-fault-tolerant tracking control for nonlinear systems has yet to be fully investigated, which motivates us for this study.

This paper addresses the fault-tolerant tracking-control problem for NSV attitude dynamics in the presence of actuator faults. The T–S fuzzy system is first employed to approximate the nonlinear NSV attitude dynamics, and then, the actuator-fault model is developed. The type of fault that is considered in this study is the loss of actuator effectiveness. Based on Lyapunov stability theory, a fault-tolerant tracking-control scheme is proposed, which can guarantees the stability of the closed-loop dynamics and maintains a satisfactory tracking performance in the event of actuator faults. Compared with some existing FTC schemes in nonlinear systems, our designed method is based on the online estimation of actuator faults and the addition of an adaptive compensation control term to the normal control law in order to reduce the actuator-fault effect without using the fault detection and isolation (FDI) mechanism. Finally, simulation results are presented to demonstrate the effectiveness of the proposed technique.

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II. Fuzzy Modeling for Near-Space Vehicle

The NSV attitude dynamics in entry phase is given by [19], [24]

$$\begin{cases} \dot{\omega} = J^{-1}\Omega_\omega J\omega + J^{-1}Gu + d(t) \\ \dot{\xi} = \Xi_\xi \omega \end{cases} \tag{1}$$

where $\omega = [p, q, r]^T$ is the angular rate, J is the inertia, $\xi = [\phi, \beta, \alpha]^T$ is the attitude angle, $u = [\delta_e, \delta_a, \delta_r]^T$ is the control surface deflection, p, q, r, ϕ, β, and α are the pitch rate, the roll rate, the yaw rate, the bank angle, the sideslip angle and the attack angle, respectively, δ_e, δ_a, and δ_r are the elevator deflection, the aileron deflection, and the rudder deflection, respectively, $d(t)$ is the bounded external disturbance vector, and

$$G = \begin{bmatrix} g_{p,\delta_e} & g_{p,\delta_a} & g_{p,\delta_r} \\ g_{q,\delta_e} & g_{q,\delta_a} & g_{q,\delta_r} \\ g_{r,\delta_e} & g_{r,\delta_a} & g_{r,\delta_r} \end{bmatrix}, \qquad \Omega(\omega) = \begin{bmatrix} 0 & r & -q \\ -r & 0 & p \\ q & -p & 0 \end{bmatrix}$$

$$\Xi(\xi) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ \sin\alpha & 0 & -\cos\alpha \\ 0 & 1 & 0 \end{bmatrix}$$

where G is the control allocation matrix from control torque to control surface.

Let us define the variables of NSV dynamics (1) as follows: $x_1 \triangleq p$, $x_2 \triangleq q$, $x_3 \triangleq r$, $x_4 \triangleq \phi$, $x_5 \triangleq \beta$, and $x_6 \triangleq \alpha$. For the purpose of this study, we choose roll rate q, attack angle α, and sideslip angle β as the output of NSV dynamics. NSV dynamics described by (1) can be rewritten as the following general MIMO nonlinear systems:

$$\begin{cases} \dot{x}(t) = f(x,t) + \sum_{k=1}^{m} g_k(x)u_k(t) + d(t) \\ y(t) = Cx(t). \end{cases} \tag{2}$$

A fuzzy-linear dynamic model has been proposed by Takagi and Sugeno to represent local linear input/output relations of the nonlinear systems [9]. The fuzzy-linear model is described by fuzzy If–Then rule and will be employed to deal with the fuzzy-control problem for NSV attitude dynamics in this paper. Systems (2) can be represented by blending the following linear models:

If $z_1(t)$ is M_1^i, $z_2(t)$ is M_2^i and ... $z_q(t)$ is M_q^i, Then

$$\begin{cases} \dot{x}(t) = A_i x(t) + B_i u(t) + B_d d(t) \\ y(t) = C_i x(t) \end{cases} \tag{3}$$

where $z(t) = [z_1(t)\ z_2(t) \ldots z_q(t)]$ are the premise variables, and $M_1^i \ldots M_q^i$ are the fuzzy sets. A_i, B_i, and C_i are known real constant matrices with appropriate dimensions, and $B_d = I$ is the disturbance-distribution matrix.

The overall fuzzy systems are inferred as follows:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{l} h_i(z)[A_i x(t) + B_i u(t) + B_d d(t)] \\ y(t) = \sum_{i=1}^{l} h_i(z) C_i x(t) \end{cases} \tag{4}$$

where l is the number of fuzzy rules, and

$$h_i(z) = \frac{\mu_i(z)}{\sum_{i=1}^{l}\mu_i(z)}, \qquad \mu_i(z) = \prod_{j=1}^{q} M_j^i(z).$$

Hence, $h_i(z)$ satisfies the following conditions:

$$h_i(z) > 0, \qquad \sum_{i=1}^{l} h_i(z) = 1.$$

To formulate the FTC problem, the fault model must be established. According to the fault type for flight-control system established in [23], the fault type considered in this study is the loss of actuator effectiveness. We use $u_s^F(t)$ to describe the control signal sent from the sth actuator [15] as follows:

$$\begin{aligned} &u_s^F(t) = f_s u_s(t), \qquad f_s \in [\underline{f_s}, \overline{f}_s] \\ &0 < \underline{f_s} \le 1, \qquad \overline{f}_s \ge 1, \qquad s = 1, 2, \ldots, m \end{aligned} \tag{5}$$

where f_s is an unknown constant, and $\underline{f_s}$ and $\overline{f}_s$ represent the known lower and upper bounds of f_s, respectively. When $\underline{f_s} = \overline{f}_s = 1$, it means that the sth actuator $u_s(t)$ is in the fault-free case.

The control input in the fault case can be described by

$$u^F(t) = [u_1^F(t),\ u_2^F(t), \ldots, u_m^F(t)]^T = Fu(t)$$

with $F = \text{diag}[f_1,\ f_2,\ \ldots, f_m]$, and

$$\mathbb{F} = \left\{F : F = \text{diag}[f_1,\ f_2,\ \ldots, f_m],\ \ f_s \in [\underline{f_s}, \overline{f}_s]\right\}.$$

Hence, the fuzzy systems (4) with actuator faults (5) can be transformed into

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{l} h_i(z)[A_i x(t) + B_i F u(t) + B_d d(t)] \\ y(t) = \sum_{i=1}^{l} h_i(z) C_i x(t). \end{cases} \tag{6}$$

Considering the lower and upper bounds $(\underline{f_s}, \overline{f}_s)$, the following set can be defined:

$$N_F = \left\{F : F = \text{diag}[f_1,\ f_2,\ \ldots, f_m],\ \ f_s = \underline{f_s},\ \text{or}\ f_s = \overline{f}_s\right\}.$$

It is well known that the tracking-error-integral action of a controller can effectively eliminate the steady-state tracking error [15]. In order to obtain an adaptive tracking controller with tracking-error integral $\eta(t) = \int_0^t e(s)\mathrm{d}s$, we combine (4) and $\eta(t)$ into the following augmented system:

$$\begin{aligned} \begin{bmatrix} \dot{\eta}(t) \\ \dot{x}(t) \end{bmatrix} = \sum_{i=1}^{l} h_i(z) \Bigg\{ &\begin{bmatrix} 0 & -C_i \\ 0 & A_i \end{bmatrix} \begin{bmatrix} \eta(t) \\ x(t) \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ B_i \end{bmatrix} u(t) + \begin{bmatrix} I & 0 \\ 0 & B_d \end{bmatrix} \begin{bmatrix} y_r(t) \\ d(t) \end{bmatrix} \Bigg\}. \end{aligned} \tag{7}$$

Letting $\varkappa(t) = [\eta^T(t)\ x^T(t)]^T$, then the augmented system (7) can be described by

$$\dot{\varkappa}(t) = \sum_{i=1}^{l} h_i(z)\left[\mathscr{A}_i \varkappa(t) + \mathscr{B}_i u(t) + \mathscr{B}_d \omega(t)\right] \tag{8}$$

where $\omega(t) = [y_r^T(t)\ \ d^T(t)]^T$

$$\mathscr{A}_i = \begin{bmatrix} 0 & -C_i \\ 0 & A_i \end{bmatrix}, \qquad \mathscr{B}_i = \begin{bmatrix} 0 \\ B_i \end{bmatrix}, \qquad \mathscr{B}_d = \begin{bmatrix} I & 0 \\ 0 & B_d \end{bmatrix}.$$

Moreover, the augmented system (8) with actuator faults (5) can be written as

$$\dot{\varkappa}(t) = \sum_{i=1}^{l} h_i(z)\left[\mathscr{A}_i \varkappa(t) + \mathscr{B}_i F u(t) + \mathscr{B}_d \omega(t)\right]. \tag{9}$$

Considering the fuzzy system (9) with actuator faults, the design problem under consideration is to find an adaptive FTC scheme such that the following cases are satisfied.

1) In the fault-free case, the closed-loop system is asymptotically stable, and the required output $y(t)$ can asymptotically track the given signal $y_r(t)$, i.e.,

$$e(t) = y_r(t) - y(t), \qquad \lim_{t\to\infty} e(t) = 0. \tag{10}$$

In addition, the following $\mathcal{H}_\infty$ tracking-performance index for all $\omega(t)$ is satisfied:

$$\int_0^t e^T(t)e(t)dt \le \gamma^2 \int_0^t \omega^T(t)\omega(t)dt. \tag{11}$$

2) In the event of actuator faults, the closed-loop system is asymptotically stable, and the required output $y(t)$ can still track the command signal $y_r(t)$ without steady-state error.

III. Main Results

In this section, a new FTC control law is proposed based on the adaptive-control technique, which can reduce the effect of actuator faults without using the FDI mechanism, and the desired control objective can be achieved by the developed control scheme.

When system (8) is in fault-free case, we consider the following $\mathcal{H}_\infty$ state-feedback controller:

$$u_N(t) = \sum_{j=1}^{l} h_j(z)\mathscr{K}_j \mathscr{x}(t). \tag{12}$$

By substituting (12) into (8), the closed-loop fuzzy system can be represented as

$$\dot{\mathscr{x}}(t) = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)\left[(\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j)\mathscr{x}(t) + \mathscr{B}_d\omega(t)\right]. \tag{13}$$

Now, the objective is to design $\mathscr{K}_j$ $(j = 1, 2, \ldots, l)$, such that the closed-loop fuzzy systems (13) is asymptotically stable with γ-disturbance attenuation. To solve the controller gains $\mathscr{K}_j$ $(j = 1, 2, \ldots, l)$, the following lemma is introduced.

Lemma 1: For a given positive constant $\gamma > 0$, if there exist symmetric matrices $\mathcal{R}$ and a set of real matrices $\mathcal{Z}_j$ with appropriate dimensions, such that the following LMIs hold:

$$\mathscr{M}_{ii} < 0, \qquad i = 1, 2, \ldots, l \tag{14}$$

$$\frac{1}{l-1}\mathscr{M}_{ii} + \frac{1}{2}(\mathscr{M}_{ij} + \mathscr{M}_{ji}) < 0, \qquad 1 \le i \ne j \le l \tag{15}$$

where

$$\mathscr{M}_{ij} = \begin{bmatrix} (\mathscr{A}_i\mathcal{R} + \mathscr{B}_i\mathcal{Z}_j) + (\mathscr{A}_i\mathcal{R} + \mathscr{B}_i\mathcal{Z}_j)^T & \mathscr{B}_d & \mathcal{R} \\ \mathscr{B}_d^T & -\gamma^2 I & 0 \\ \mathcal{R} & 0 & -I \end{bmatrix}$$

then the closed-loop fuzzy system (13) is asymptotically stable with γ-disturbance attenuation under the following $\mathcal{H}_\infty$ state-feedback controller:

$$u_N(t) = \sum_{j=1}^{l} h_i(z)\mathscr{K}_j\mathscr{x}(t), \qquad \mathscr{K}_j = \mathscr{Z}_j\mathcal{R}^{-1}, \qquad j = 1, 2, \ldots, l.$$

Proof: Let us consider the following Lyapunov function candidate:

$$V(\mathscr{x}, t) = \mathscr{x}^T(t)\mathscr{P}\mathscr{x}(t), \qquad \text{with } \mathscr{P} = \mathscr{P}^T > 0. \tag{16}$$

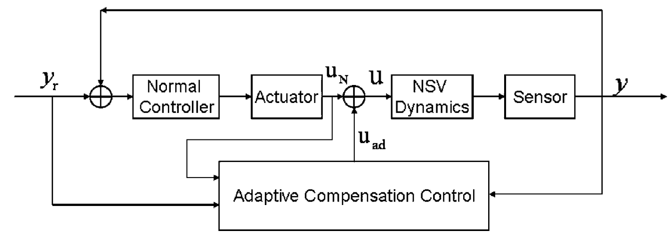

Fig. 1. Adaptive FTC scheme.

The stability of the closed-loop fuzzy system (13) with attenuation level γ can be guaranteed if the following inequality holds:

$$\dot{V}(\mathscr{x}, t) + \mathscr{x}^T(t)\mathscr{x}(t) - \gamma^2\omega^T(t)\omega(t) < 0 \tag{17}$$

which leads to

$$\mathscr{x}^T\left[\sum_{i,j=1}^{l} h_ih_j[\mathscr{P}(\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j) + (\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j)^T\mathscr{P} + I]\right]\mathscr{x}$$
$$+\mathscr{x}^T(t)\mathscr{P}\mathscr{B}_d\omega(t) + \omega^T(t)\mathscr{B}_d^T\mathscr{P}\mathscr{x}(t) - \gamma^2\omega^T(t)\omega(t) < 0$$

or is equivalent to the following:

$$\begin{bmatrix}\mathscr{x}\\ \omega\end{bmatrix}^T \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)$$
$$\begin{bmatrix}\mathscr{P}(\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j) + (\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j)^T\mathscr{P} + I & \mathscr{P}\mathscr{B}_d \\ \mathscr{B}_d^T\mathscr{P} & -\gamma^2 I\end{bmatrix}$$
$$\begin{bmatrix}\mathscr{x}\\ \omega\end{bmatrix} < 0$$

which, considering Schur complement and the work of Tuan *et al.* [25], is satisfied if the conditions (14) and (15) hold. The proof is completed. □

It should be remarked that the results in Lemma 1 only applies to the case when the system (13) is free of actuator faults. When some actuator faults occur, namely some actuators loss partial control effectiveness, the $\mathcal{H}_\infty$ state-feedback control proposed in (12) will not be working effectively to achieve the desired tracking objective, which motivates us to design a new FTC control strategy. Here, an FTC scheme based on adaptive compensation control is presented, i.e.,

$$u(t) = u_N(t) + u_{\mathrm{ad}}(t) \tag{18}$$

where $u_N(t)$ is the normal control proposed in (12), and $u_{\mathrm{ad}}(t)$ is the adaptive compensation control term, which is zero in the fault-free case and different from zero in the fault case. The basic configuration of the adaptive FTC scheme proposed in this study is shown in Fig. 1.

Next, the following target model is presented to acquire the necessary online estimated information of actuator faults:

$$\begin{cases}\dot{\hat{x}}(t) = \displaystyle\sum_{i=1}^{l} h_i(z)[A_i\hat{x}(t) + B_i\hat{F}r(t)] \\ \hat{y}(t) = \displaystyle\sum_{i=1}^{l} h_i(z)C_i\hat{x}(t)\end{cases} \tag{19}$$

where $\hat{F} = \mathrm{diag}[\hat{f}_1 \ldots \hat{f}_m]$ denotes the estimation of actuator efficiency factor. The input $r(t)$ will be determined later to achieve the control objective.

The augmented target model can be described by

$$\begin{bmatrix} \dot{\hat{\eta}}(t) \\ \dot{\hat{x}}(t) \end{bmatrix} = \sum_{i=1}^{l} h_i(z)\Bigg\{ \begin{bmatrix} 0 & -C_i \\ 0 & A_i \end{bmatrix} \begin{bmatrix} \hat{\eta}(t) \\ \hat{x}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ B_i\hat{F} \end{bmatrix} r(t) + \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} y_r(t) \\ d(t) \end{bmatrix} \Bigg\}$$

which can be rewritten as follows:

$$\dot{\hat{\mathbb{x}}}(t) = \sum_{i=1}^{l} h_i(z)\left[\mathscr{A}_i\hat{\mathbb{x}}(t) + \mathscr{B}_i\hat{F}r(t) + \mathscr{G}_d\omega(t)\right] \tag{20}$$

where $\mathscr{A}_i$ and $\mathscr{B}_i$ are the same as those in normal operation (8), and $\hat{\mathbb{x}}(t) = [\hat{\eta}^T(t)\ \ \hat{x}^T(t)]^T$

$$\hat{\eta}(t) = \int_0^t \hat{e}(s)ds, \qquad \hat{e}(t) = y_r(t) - \hat{y}(t), \qquad \mathscr{G}_d = \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix}.$$

Defining the state-error vector of the augmented systems as $\mathbb{e}(t) = \hat{\mathbb{x}}(t) - \mathbb{x}(t)$ and letting the control input $u(t) = r(t) - \sum_{j=1}^{l} h_j(z)\mathcal{K}_j\mathbb{e}(t)$, then the augmented state-error dynamics between (9) and (20) can be written as

$$\dot{\mathbb{e}}(t) = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)[(\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j)\mathbb{e}(t) + \mathscr{B}_i\tilde{F}r(t) + \widetilde{\mathscr{B}}_d\omega(t)] \tag{21}$$

where $\tilde{F} = \hat{F} - F = \mathrm{diag}[\tilde{f}_1 \ldots \tilde{f}_m]$, $\tilde{f}_s = \hat{f}_s - f_s (s = 1, 2, \ldots, m)$, $\widetilde{\mathscr{B}}_d = \mathscr{G}_d - \mathscr{B}_d$. Here, $\mathcal{K}_j (j = 1, 2, \ldots, m)$ is the error-feedback gain to be determined later, which make the augmented state-error dynamics asymptotically stable.

Letting $\mathscr{B}_i = [b_{i1} \ldots b_{im}]$ and $r(t) = [r_1(t) \ldots r_m(t)]^T$, the augmented state-error dynamics (21) can then be transformed into

$$\dot{\mathbb{e}}(t) = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)[(\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j)\mathbb{e}(t) + \sum_{s=1}^{m} b_{is}\tilde{f}_s r_s(t) + \widetilde{\mathscr{B}}_d\omega(t)]. \tag{22}$$

Theorem 1: The augmented state-error dynamics (22) are asymptotically stable with γ-disturbance attenuation, if there exist a symmetric matrix $\mathcal{Q} > 0$ and a set of real matrices $\mathscr{W}_j > 0$ with appropriate dimensions, such that the following LMIs hold for all $F \in \mathbb{F}$:

$$\mathscr{N}_{ii} < 0, \qquad i = 1, 2, \ldots, l \tag{23}$$

$$\frac{1}{l-1}\mathscr{N}_{ii} + \frac{1}{2}(\mathscr{N}_{ij} + \mathscr{N}_{ji}) < 0, \qquad 1 \le i \ne j \le l \tag{24}$$

where

$$\mathscr{N}_{ij} = \begin{bmatrix} (\mathscr{A}_i\mathcal{Q} + \mathscr{B}_iF\mathscr{W}_j) + (\mathscr{A}_i\mathcal{Q} + \mathscr{B}_iF\mathscr{W}_j)^T & \widetilde{\mathscr{B}}_d & \mathcal{Q} \\ \widetilde{\mathscr{B}}_d^T & -\gamma^2 I & 0 \\ \mathcal{Q} & 0 & -I \end{bmatrix}$$

and $\hat{f}_s$ is determined according to the following adaptive estimation algorithm:

$$\dot{\hat{f}}_s = \mathrm{Proj}_{[\underline{f_s}, \overline{f_s}]}\{-l_s\mathbb{e}^T\mathscr{P}\bar{b}_{is}r_s\} = \begin{cases} 0, & \text{if } \hat{f}_s = \underline{f_s}, -l_s\mathbb{e}^T\mathscr{P}\bar{b}_{is}r_s \le 0 \\ & \text{or } \hat{f}_s = \overline{f_s}, -l_s\mathbb{e}^T\mathscr{P}\bar{b}_{is}r_s > 0 \\ -\sum_{i=1}^{l} h_i(z)l_s\mathbb{e}^T\mathscr{P}\bar{b}_{is}r_s, & \text{otherwise} \end{cases} \tag{25}$$

where $l_s > 0$ is the adaptive learning gain to be determined according to the lower and upper bounds of actuator faults $(\underline{f_s}, \overline{f}_s)$, $s = 1, 2, \ldots, m$, $\mathrm{Proj}\{\cdot\}$ denotes the projection operator, whose role is to project the estimates $\hat{f}_i(t)$ in the interval $[\underline{f_i}, \overline{f_i}]$, and the error feedback gain $\mathcal{K}_j$ is determined by $\mathcal{K}_j = \mathscr{W}_j\mathcal{Q}^{-1}$.

Proof: The following Lyapunov candidate is chosen:

$$V(t) = \mathbb{e}^T(t)\mathscr{P}\mathbb{e}(t) + \sum_{s=1}^{m}\frac{\tilde{f}_s^2(t)}{l_s} \tag{26}$$

where $\mathscr{P} = \mathcal{Q}^{-1}$. The derivative of $V(t)$ along the trajectory of the augmented state-error dynamics (22) can be written as

$$\begin{aligned}\dot{V}(t) = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z) & \\ & [\mathbb{e}^T(t)\mathscr{P}(\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j) + (\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j)^T\mathscr{P}\mathbb{e}(t)] \\ & + \mathbb{e}^T(t)\mathscr{P}\mathscr{B}_d\omega(t) + \omega^T(t)\mathscr{B}_d^T\mathscr{P}\mathbb{e}(t) \\ & + 2\sum_{i=1}^{l}\sum_{s=1}^{m} h_i(z)\tilde{f}_s\mathbb{e}^T\mathscr{P}b_{is}r_s + 2\sum_{s=1}^{m}\frac{\tilde{f}_s\dot{\tilde{f}}_s}{l_s}.\end{aligned} \tag{27}$$

Considering that f_i is an unknown constant, we can easily know that $\dot{\hat{f}}_s(t) = \dot{\tilde{f}}_s(t)$. If the adaptive estimation algorithm is chosen as (25), then we have

$$\frac{\tilde{f}_s(t)\dot{\tilde{f}}_s(t)}{l_s} \le -\sum_{i=1}^{l} h_i(z)\tilde{f}_s(t)\mathbb{e}^T(t)\mathscr{P}b_{is}r_s. \tag{28}$$

From (27) and (28), we can get the following inequality:

$$\begin{aligned}\dot{V}(t) \le \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z) & \\ & \mathbb{e}^T(t)\mathscr{P}(\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j) + (\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j)^T\mathscr{P}\mathbb{e}(t) \\ & + \mathbb{e}^T(t)\mathscr{P}\widetilde{\mathscr{B}}_d\omega(t) + \omega^T(t)\widetilde{\mathscr{B}}_d^T\mathscr{P}\mathbb{e}(t).\end{aligned}$$

Under zero initial condition, considering the $\mathcal{H}_\infty$ performance index, we have the following:

$$\dot{V}(\mathbb{x}, t) + \mathbb{e}^T\mathbb{e} - \gamma^2\omega^T\omega = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)\begin{bmatrix} \mathbb{e} \\ \omega \end{bmatrix}^T \begin{bmatrix} \mathscr{P}(\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j) + (\mathscr{A}_i + \mathscr{B}_iF\mathcal{K}_j)^T\mathscr{P} + I & \mathscr{P}\widetilde{\mathscr{B}}_d \\ \widetilde{\mathscr{B}}_d^T\mathscr{P} & -\gamma^2 I \end{bmatrix} \begin{bmatrix} \mathbb{e} \\ \omega \end{bmatrix}. \tag{29}$$

From (23) and (24), and $\mathcal{K}_j = \mathscr{W}_j \mathcal{Q}^{-1}$, with $\mathcal{Q} = \mathscr{P}^{-1}$, it follows that for $\forall\, F \in N_F$, we have

$$\begin{bmatrix} \mathscr{P}(\mathscr{A}_i + \mathscr{B}_i F\mathcal{K}_j) + (\mathscr{A}_i + \mathscr{B}_i F\mathcal{K}_j)^T \mathscr{P} + I & \mathscr{P}\widetilde{\mathscr{B}}_d \\ \widetilde{\mathscr{B}}_d^T \mathscr{P} & -\gamma^2 I \end{bmatrix} < 0.$$

Furthermore, the following inequalities can be obtained for $\forall\, F \in \mathbb{F}$:

$$\begin{bmatrix} \mathscr{P}(\mathscr{A}_i + \mathscr{B}_i F\mathcal{K}_j) + (\mathscr{A}_i + \mathscr{B}_i F\mathcal{K}_j)^T \mathscr{P} + I & \mathscr{P}\widetilde{\mathscr{B}}_d \\ \widetilde{\mathscr{B}}_d^T \mathscr{P} & -\gamma^2 I \end{bmatrix} < 0. \tag{30}$$

According to Lyapunov stability theory, when actuator faults in the form of (5) occur, it can be seen from (29) and (30) that the augmented state-error dynamics (22) are asymptotically stable with disturbance attenuation γ under the adaptive estimation algorithm (25). □

Here, $r(t)$ is to be determined such that the augmented target model (19) matches that of the normal model (9). Letting $r(t) = \sum_{j=1}^{l} h_j(z)\hat{F}^{-1}\mathscr{K}_j\hat{\varkappa}(t)$, then (19) can be rewritten as

$$\dot{\hat{\varkappa}}(t) = \sum_{i=1}^{l}\sum_{j=1}^{l} h_i(z)h_j(z)\left[(\mathscr{A}_i + \mathscr{B}_i\mathscr{K}_j)\hat{\varkappa}(t) + \mathscr{G}_d\omega(t)\right] \tag{31}$$

which matches the closed-loop augmented system (13) in the fault-free case.

Based on the above analysis, we can easily know that $\mathbb{e}(t)$ is bounded. It follows that $\dot{\mathbb{e}}(t)$ is also bounded according to the state-error dynamics (21). Take into account the fact that $\mathbb{e}(t) \in L_\infty \cap L_2$, which implies that $\lim_{t\to\infty} e(t) = 0$, i.e., $\varkappa(0) = \hat{\varkappa}(0) = \varkappa_N(0)$, where $\varkappa_N(0)$ represents the state vector of the augmented dynamics (9) in the fault-free case. According to the above description, it can be seen that the state vector in the fault cases can asymptotically tracks that of the fault-free case. In other words, fault-tolerant operation is realized.

Now, a novel adaptive FTC law can be chosen as

$$\begin{aligned} u(t) = r(t) - \sum_{j=1}^{l} h_j(z)\mathcal{K}_j\mathbb{e}(t) &= \sum_{j=1}^{l} h_j(z)\hat{F}^{-1}\mathscr{K}_j\hat{\varkappa}(t) \\ &- \sum_{j=1}^{l} h_j(z)\mathcal{K}_j\mathbb{e}(t) = u_N(t) + u_{\mathrm{ad}}(t) \end{aligned} \tag{32}$$

where $u_N(t) = \sum_{j=1}^{l} h_j(z)\mathscr{K}_j\varkappa(t)$, and $u_{\mathrm{ad}}(t) = \sum_{j=1}^{l} h_j(z)[\hat{F}^{-1}(I - \hat{F})\mathscr{K}_j\hat{\varkappa}(t) + (\mathscr{K}_j - \mathcal{K}_j)\mathbb{e}(t)]$.

When no actuator faults occur, the error dynamics is at its equilibrium, i.e., $\mathbb{e}(t) = 0$, and $\hat{f}_i(t) = 1$, if choosing $\mathbb{e}(0) = 0$, and $\hat{f}_i(t) = 1$. In this stage, $u(t) = u_N(t)$, and $u_{\mathrm{ad}} = 0$, which implies that the closed-loop system with FTC law (32) in the fault-free case can achieve a satisfactory tracking performance. When actuator faults occur, the corresponding efficiency factor f_i deviates from 1, thus producing a mismatch between $\varkappa(t)$ and $\hat{\varkappa}(t)$. Hence, nonzero state-error dynamic occurs, and the adaptive estimation of the actuator efficiency factor become active. A new adaptive compensation control term $u_{\mathrm{ad}}(t)$ is added to the normal law $u_N(t)$, which can reduce the effect of actuator faults, and a satisfactory tracking performance can still be maintained.

Remark 1: Using MATLAB LMI toolbox, (23) and (24) can be directly solved for all $F \in N_F$, and a feasible solution of $\mathcal{Q}$ and $\mathscr{W}_j$ $(j = 1, 2, \ldots, l)$ can be obtained. Then, the corresponding error-feedback gain $\mathcal{K}_j$ can be easily obtained by $\mathcal{K}_j = \mathscr{W}_j\mathcal{Q}^{-1}$ $(j = 1, 2, \ldots, l)$.

Remark 2: It should be mentioned that our study in this paper is motivated by the work of Ye and Yang [15]. There are three major differences between the work given in [15] and ours. First, the system studied in [15] is a linear time-invariant system, and in our study, a nonlinear flight-control system is investigated. Second, the effect of external disturbance input is not considered in [15] but is taken into account in our study. Third, the technique presented in [15] is single adaptive control, while the proposed method in our study is a combination of $\mathcal{H}_\infty$ control with adaptive control. To be more precise, based on $\mathcal{H}_\infty$ control and LMI techniques, we extend the results in [15] to a class of nonlinear NSV attitude dynamics with external disturbance input. The fuzzy-FTC approach proposed in this study can reduce the effect of actuator faults on NSV dynamics without the FDI mechanism, such that the tracking work can still be accomplished, although the steady-state process is extended.

Remark 3: Compared with the passive FTC results obtained in [11]–[14], the FTC approach proposed in this paper is based on the online adaptive accommodation technique, which is less conservative in accommodating the dynamics performance of faulty systems. Meanwhile, compared with the active FTC results obtained in [16]–[18], our approach is not dependent on the FDI mechanism, which can reduce the complexity of FTC system design and is easy to implement in engineering applications.

Remark 4: In this paper, we only consider the state-feedback-control problem, and it is assumed that the real-time state signals can be transmitted accurately. It is worth mentioning that the output-feedback-control problem is more important in practical applications, and the possible data-missing phenomena should also be taken into consideration [8]. As NSV attitude dynamics, the output-feedback-control problem with possible missing measurements deserves to be further studied in our future work.

IV. Illustrative Example

In this section, simulation results are presented to demonstrate the effectiveness of the proposed adaptive FTC scheme. For the purpose of this study, the aerodynamic coefficients are taken as the nominal cruising flight. The nominal flight of NSV is at a trimmed cruise condition (i.e., $V = 2500$ m/s, and $h = 40$ km).

Let us consider the nonlinearity of NSV dynamics that mainly come from attack angle α and angular rate ω. Assuming that α has two related fuzzy sets $\{\alpha = 0 \text{ rad}\}$ and $\{\alpha = \pi/4 \text{ rad}\}$, then the corresponding membership functions are given by

$$\begin{aligned} M_{\alpha=0} &= \left(1 - \frac{1}{1+\exp(6-16\alpha)}\right)\frac{1}{1+\exp(-6-16\alpha)} \\ M_{\alpha=\pi/4} &= 1 - M_{\alpha=0} \end{aligned}$$

and $\omega \in [-0.5 \text{ rad/s}, 0.5 \text{ rad/s}]$. Assuming that angular rate ω has three related fuzzy sets $\{\omega = -0.5\,\text{rad/s}\}$, $\{\omega = 0\,\text{rad/s}\}$, and $\{\omega = 0.5\,\text{rad/s}\}$, then the corresponding membership functions are given as follows:

$$\begin{aligned} M_{\omega=-0.5} &= \left(\frac{1}{1+\exp(6+28\omega)}\right) \\ M_{\omega=0} &= \left(1 - \frac{1}{1+\exp(-6+28\omega)}\right) \\ M_{\omega=0.5} &= \frac{\exp(6-28\omega)}{1+\exp(6-28\omega)}\left(\frac{1}{1+\exp(-6-28\omega)}\right). \end{aligned}$$

We choose the following six operating points: $[\alpha, \omega] = [0\ -0.5]$, $[0\ 0]$, $[0\ 0.5]$, $[\pi/4\ -0.5]$, $[\pi/4\ 0]$, and $[\pi/4\ 0.5]$. Under the membership functions and the six operating points, six plant rules and six control

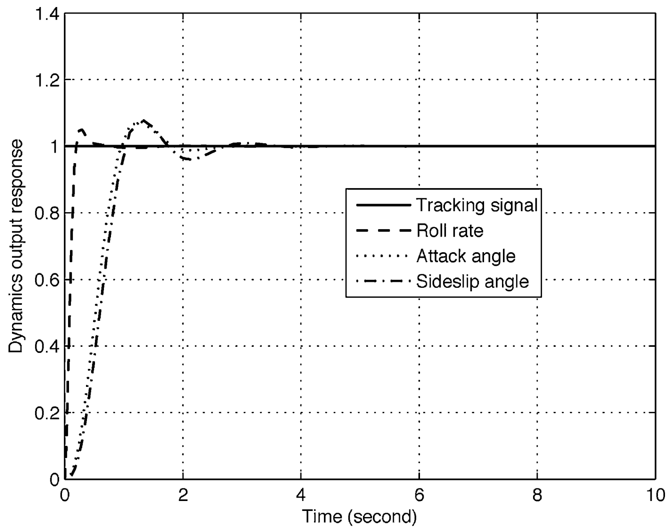

Fig. 2. NSV dynamic output responses with adaptive FTC in fault-free case.

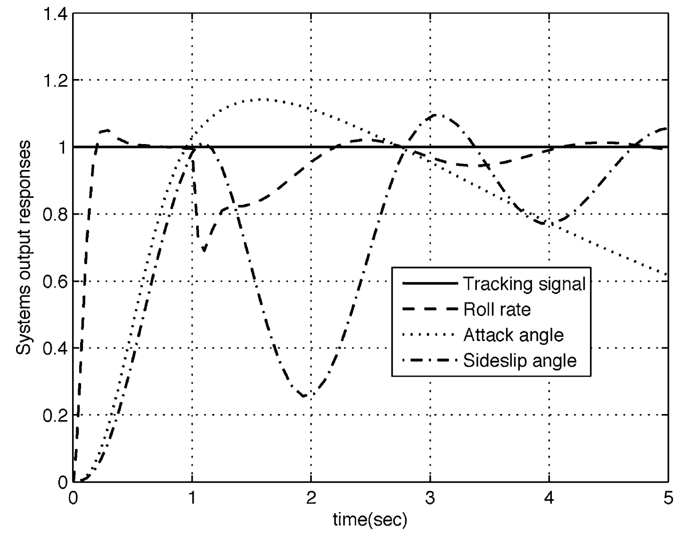

Fig. 3. NSV dynamic output responses with passive FTC in fault case 1.

rules can be defined. All A_i, B_i, and C_i can be obtained by substituting the six operating points to $f(x,t)$ and $g_k(x)$. For the detailed presentation, see [19].

Rule 1: IF ω is about –0.5 rad/s and α is about 0 rad, THEN

$$\dot{x}(t) = A_1x(t) + B_1u(t) + B_d d(t), \qquad y(t) = C_1x(t).$$

Rule 2: IF ω is about –0.5 rad/s and α is about $\pi/4$ rad, THEN

$$\dot{x}(t) = A_2x(t) + B_2u(t) + B_d d(t), \qquad y(t) = C_2x(t).$$

Rule 3: IF ω is about 0 rad/s and α is about 0 rad, THEN

$$\dot{x}(t) = A_3x(t) + B_3u(t) + B_d d(t), \qquad y(t) = C_3x(t).$$

Rule 4: IF ω is about 0 rad/s and α is about $\pi/4$ rad, THEN

$$\dot{x}(t) = A_4x(t) + B_4u(t) + B_d d(t), \qquad y(t) = C_4x(t).$$

Rule 5: IF ω is about 0.5 rad/s and α is about 0 rad, THEN

$$\dot{x}(t) = A_5x(t) + B_5u(t) + B_d d(t), \qquad y(t) = C_5x(t).$$

Rule 6: IF ω is about 0.5 rad/s and α is about $\pi/4$ rad, THEN

$$\dot{x}(t) = A_6x(t) + B_6u(t) + B_d d(t), \qquad y(t) = C_6x(t).$$

In this study, we consider the external disturbance described by $d(t) = [0.1\sin t,\ 0.01\sin t,\ 0.01\sin t,\ 0,\ 0,\ 0,]^T$, which is borrowed from [19]. Here, each of the three actuators may lose its effectiveness. The lower and upper bounds of each effectiveness factor are 0.1 and 1, respectively. Letting $\gamma = 1.5$, then by using the MATLAB LMI toolbox, we can obtain the controller gains $\mathscr{K}_j$ and $\mathcal{K}_j$ $(j = 1, 2, \ldots l)$; furthermore, considering the adaptive fault-estimation law (25), the adaptive FTC law (32) developed in this paper can be constructed.

The tracking commands of q, α, and β are unit steps. We assume that the following possible actuator faults are considered: 1) At $t = 1$ s, the elevator control input shows a loss of effectiveness of 40%, and the aileron control input exhibits a loss of effectiveness of 70%; 2) at $t = 2$ s, the aileron control input shows a loss of effectiveness of 60%, and the rudder control input exhibits a loss of effectiveness of 50%. From Fig. 2, we can see that the adaptive-based FTC approach that is proposed in this paper guarantees that NSV dynamics have a satisfactory tracking performance in the fault-free case.

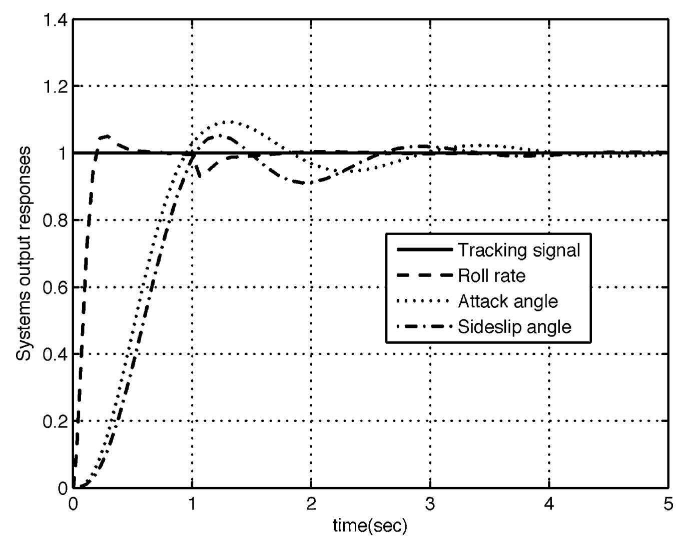

Fig. 4. NSV dynamic output responses with adaptive FTC in fault case 1.

For the purpose that of comparison, the adaptive FTC in this study and a passive FTC in [12] are carried out in simulations. When NSV dynamics create actuator faults, it can be seen from Figs. 3–10 that the required output signals of NSV dynamics cannot track the command ones using the passive FTC proposed in [12], and the output error responses cannot asymptotically converge to zero. However, utilizing the adaptive FTC developed in this paper, it can be found that the required NSV dynamics output signals can also track the command ones, and the output error responses can asymptotically converge to zero; namely, fault-tolerant operation has been realized. From the simulation comparison, we can see that the passive-FTC approach proposed in [12] has relatively worse dynamics-control performance for the case of multiple actuator faults, while our designed adaptive FTC approach has satisfactory dynamics-control performance. Meanwhile, to show the superiority of our approach, we give the lowest level of $\mathcal{H}_\infty$ disturbance attenuation in Table I by using different FTC design approaches. It can be seen that our designed FTC systems have better disturbance-attenuation ability than that developed in [12], [26], and [27].

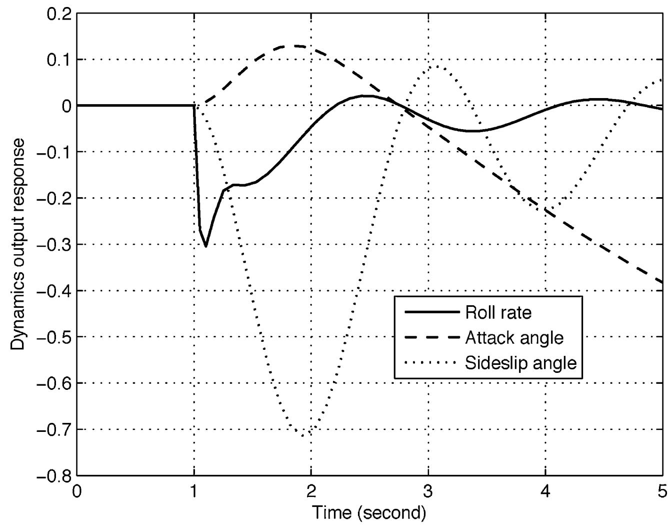

Fig. 5. NSV dynamic output error responses with passive FTC in fault case 1.

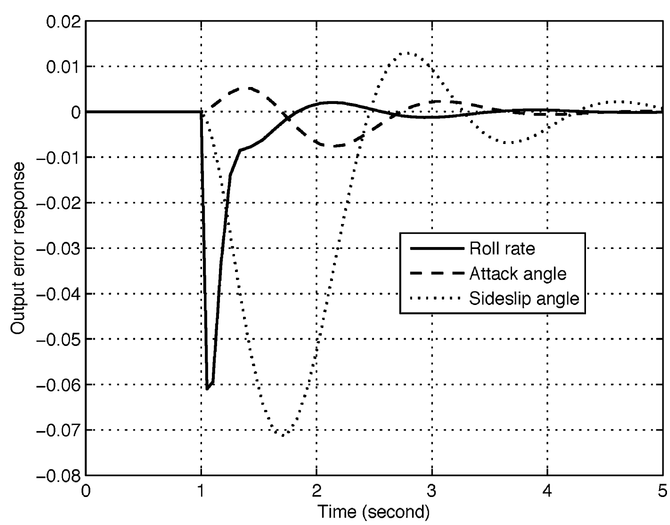

Fig. 6. NSV dynamic output error responses with adaptive FTC in fault case 1.

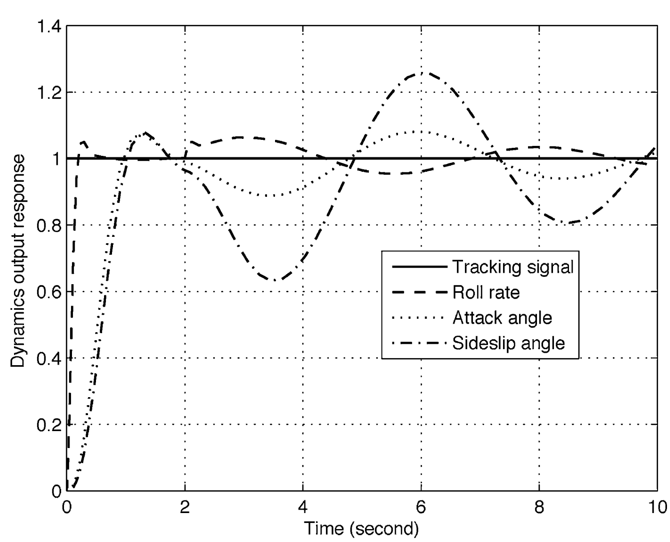

Fig. 7. NSV dynamic output responses with passive FTC in fault case 2.

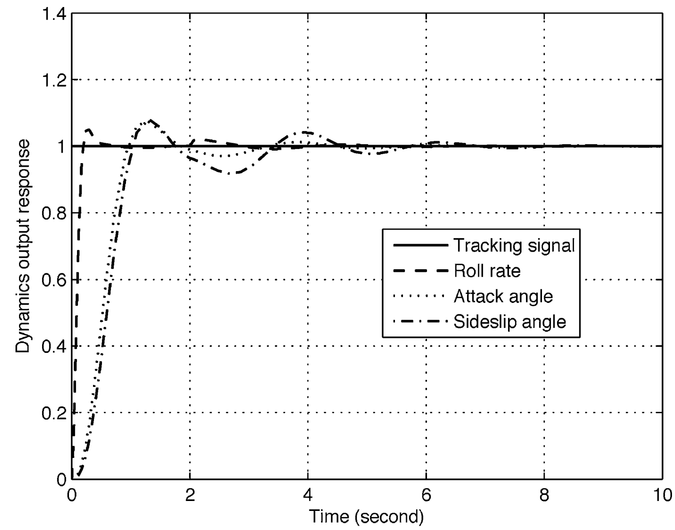

Fig. 8. NSV dynamic output responses with adaptive FTC in fault case 2.

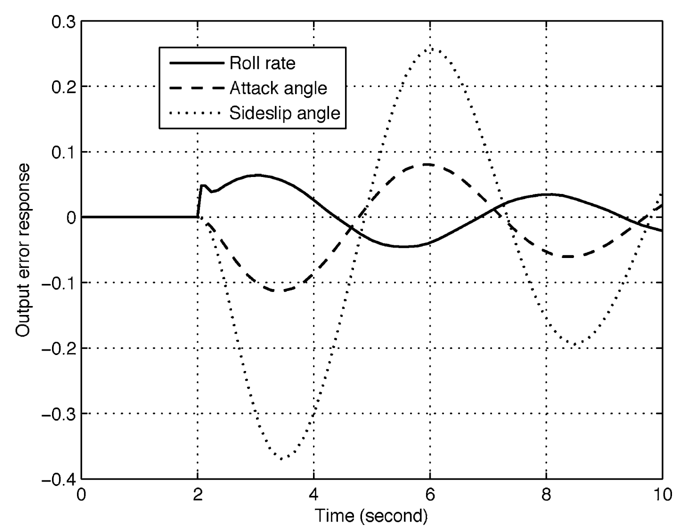

Fig. 9. NSV dynamic output error responses with passive FTC in fault case 2.

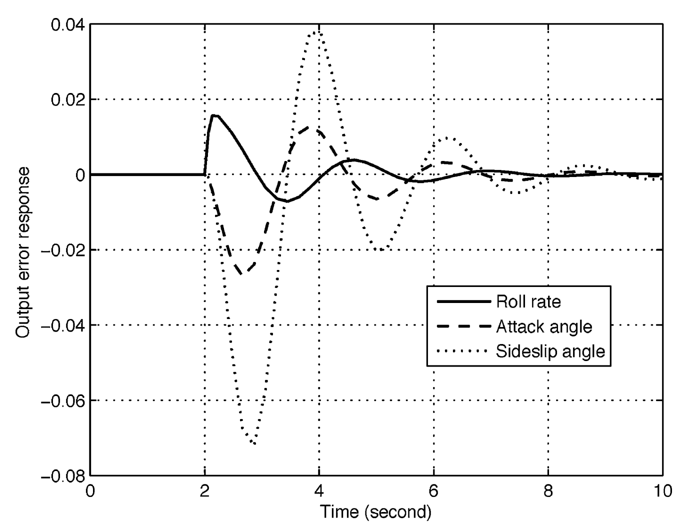

Fig. 10. NSV dynamic output error responses with adaptive FTC in fault case 2.

TABLE I
$\mathcal{H}_\infty$ DISTURBANCE-ATTENUATION-LEVEL COMPARISON

	Ref.[12]	Ref.[26]	Ref.[27]	Adaptive FTC
Min.γ	1.8536	2.1974	2.0482	1.7630

V. CONCLUSION

Based on the fuzzy adaptive-control technique, the fault-tolerant tracking-control problem for NSV attitude dynamics via T–S fuzzy models is investigated in this study. A novel FTC law, which consists of both a normal control law and an adaptive compensation control term, is proposed based on the online estimation of actuator faults. The adaptive compensation control law is introduced in order to reduce the effect of actuator faults on NSV dynamics. Compared with some existing results, our approach does not rely on the FDI mechanism, which can reduce the complexity of FTC system design and is easy to implement in aerospace-engineering applications. Finally, simulation results of NSV dynamics show the effectiveness of the FTC approach developed in this study.

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