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FAULT TOLERANT CONTROL FOR DAMAGED AIRCRAFT BASED ON SLIDING MODE CONTROL SCHEME

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Abstract. *In this paper, the problem of structural damage with partial loss vertical tail in aircraft dynamical system is investigated. A linearized aircraft model is introduced firstly, then a damage-tolerant controller based on an adaptive sliding mode control is proposed. Finally, simulations with an aircraft model are conducted to demonstrate the effectiveness and advantages of the proposed design techniques, which can be properly tuned according to structural fault of aircraft.*

Keywords: Structural damage, Damage-tolerant control, Adaptive sliding mode

1. **Introduction.** It may easily lead to different kinds of faults in flight control system due to its many requirements such as, rapid flight speed, big flight envelope, aerodynamic characteristics of rapid change and complex, changing environment of flight. Thus, it is great significant to improve safety and reliability of flight control system using fault diagnosis and fault-tolerant control (FTC) technology. Extensive studies on fault tolerant control have been conducted in the past years, and in particular, a number of FTC schemes have been developed in aerospace applications, see for example, [1-18] and the references therein. In general, there are mainly three types of faults: sensor faults, actuator faults, and structural damage. There have been so many researches on fault tolerant control for aircraft faults, for example, [1-3,18] and the references therein, in which many fault tolerant controllers for actuators or sensors are designed. However, so far there has been fairly small study on structural damage in aerospace field [4-6,8,10] compared with faults of actuator and sensor. As we all known, structural damage of flight system generally includes the partial loss of wing, vertical tail loss, horizontal tail loss, engine loss and so on. X. B. Li and H. T. H. Liu investigate a passive fault tolerant control of an aircraft that suffers from vertical tail damage [5]. J. D. Boškvić and R. K. Mehra propose an intelligent adaptive reconfigurable control scheme for a tailless advanced fighter aircraft in the presence of wing damage, and simulation results present the algorithm's excellent overall performance [6]. Thus, tolerant control scheme for structural damage of aircrafts is much more challenging and necessary due to fault-induced aerodynamics and flight dynamics change, which we can see from the following several examples. The first example is Japan Airlines flight 123 (B747SR-100), a domestic flight from Haneda to Itami, which

crashed into Mt. Takamagahara, 60 miles northwest of Tokyo on Aug 12, 1985 due to lost its vertical fin and its hydraulics [7]. The second example is American Airlines Flight AA191 where a McDonnell Douclas DC10 lost its left engine at the moment of takeoff rotation, and crashed minutest hereafter due to partial loss of hydraulics leading to asymmetric slat retraction and local wings tall. The last one is the well known DHL cargo flight above Bagdad involving an Airbus A300 cargo plane which suffered a surface-to-air missile impact and lost all hydraulics. The pilots managed to return to the airport, steering with the engines only [8]. As described in the illustrated examples, the faults involving physical damage on lifting or control surfaces pose much more complications on stability recovery and satisfying qualities because dynamics of damaged aircraft are highly uncertain and subject to un-predictive aerodynamic behaviors. The aerodynamics drastically change and the mass, inertia, and geometric properties of the aircraft may also change significantly depending on damaged parts; more literatures studied in the field of structural damage of flight system control please refer to [10,15-17]. Therefore, the investigation of damage tolerant control capability in presence of such structural damage on airframe, lifting or control surfaces is highly practical and meaningful. Sliding mode control is an important method to solve nonlinear systems issues due to its promising characteristics such as simple design, precise control and strong robustness with respect to system internal perturbations and external disturbances. Due to the traditional sliding mode control adopts linear switching function, which can guarantee the stability of the system, but need long time for the system and system error converge to the equilibrium point. Fortunately, dynamic sliding mode can make the designed system track desired signals within less time and greatly eliminate the chattering phenomenon. In addition, adaptive control strategies can well update both the information of faults and disturbances on line, for example, [9,11-14] and the references therein. In light of the advantages both of combination of dynamic sliding mode and adaptive control strategy, the FTC based on adaptive dynamic sliding mode approach is designed for aircrafts under actuator faults, external disturbances and model uncertainties [12], which can rapidly and accurately track desired signals within finite time.

Our main contribution in this paper is to design an adaptive dynamic sliding mode controller for the aircraft of damaged vertical tail, which can maintain flight control system's stability and reliability under different damage degree. Meanwhile, the proposed scheme can effectively overcome the chattering phenomenon, which can clearly provide from simulation results to show its effectiveness. The rest paper is organized as follows. The linearized model of aircraft with vertical tail loss is expressed into a linear parameter-dependent form in Section 2. An adaptive sliding mode damage-tolerant controller is designed for the case in presence of patrial loss vertical tail in Section 3. In Section 4, our control designs are applied to the Boeing 747 model and the performances are compared in several aspects. Finally, Section 5 draws a conclusion for this paper.

2. **Damaged Aircraft Modeling.** This section will describe the modeling approach which presents different levels of damage severity. Some basic concepts and assumptions will be introduced in Section 2.1 for formulating the damaged aircraft model. Based on [8], the damaged dynamics of aircraft with partial and complete loss of the vertical tail are introduced in Section 2.2. Here an assumption need to be given for simplifying the vertical tail damage modeling as follows.

Assumption 1. It is supposed that the lateral center of gravity off-set due to the damage is negligible by the reason that the vertical tail damage/loss is thought to be symmetric in the $X-Z$ plane as shown in Figure 1. Meanwhile, it is also assumed that the mass loss due to the vertical tail damage is also negligible compared with the total vehicle mass [5].

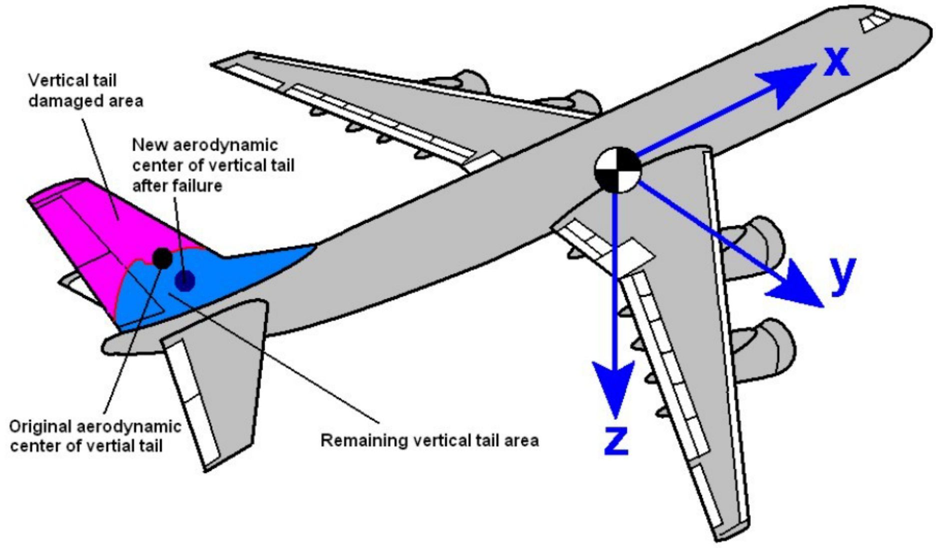


FIGURE 1. Image of aircraft with vertical tail loss [5]

2.1. **Aircraft model.** The aircraft dynamics model has been well developed. It is a standard practice to treat it as a linearized model around a certain steady flight operating point. Firstly, we consider the following linear aircraft model

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

where $x(t) = [u,\ \omega,\ q,\ \theta,\ v,\ p,\ r,\ \phi]^T$, and ϕ, θ respectively denote bank angle, pitch angle, u, v, w represent linear velocities along stability axis, and p, q, r are body axis roll rate, pitch rate, and yaw rate, respectively. $u(t) = [\delta_e,\ \delta_f,\ \delta_a,\ \delta_r]^T$, δ_e, δ_f, δ_a, δ_r express elevator, flap, aileron, and rudder effector deflections, respectively.

2.2. **Damaged aircraft modeling.** The following is a parameterized damaged aircraft model to be introduced. The above system (1) is subjected to a vertical tail damage. Meanwhile, uncertainties and/or disturbances are considered, then (1) can be rewritten in the form

$$\dot{x}(t) = (A - \mu\bar{A})x(t) + (B - \mu\bar{B})u(t) + Dd(t) \tag{2}$$

where $\mu = diag\{\mu_i\}$ $(i = 1, 2 \cdots 8)$ denotes damage degree. Specifically, $\mu_i = 0$ represents the conventional case. $\mu_i = 1$ represents the most critical damage on the tail loss, that is, the complete loss. $0 < \mu_i < 1$ represents partial vertical tail loss. $d(t) \in R^{8\times1}$ is the disturbance vector, and A, B, $\bar{A}$, $\bar{B}$, D are appropriate dimension matrices, and about $\bar{A}$, $\bar{B}$ please refer to [5] for more details.

In order to deal with the information of uncertainties and damage, system (2) can be rewritten as the following form

$$\begin{aligned} \dot{x}(t) &= Ax + Bu - \mu\bar{A}x(t) - \mu\bar{B}u(t) + Dd(t) \\ &= Ax + Bu + f(t) \end{aligned} \tag{3}$$

where let $f(t) = -\mu\bar{A}x(t) - \mu\bar{B}u(t) + Dd(t)$, here one assumption need to be given for $f(t)$.

Assumption 2. It is assumed that $\|f(t)\| < F$, $\|d(t)\| \le \bar{D}$, where F, $\bar{D}$ are constants denoted the boundlessness of uncertainties and disturbances, respectively.

Remark 2.1. *Due to vertical tail damage likely effects lateral states, such as, the three factors p, q, r rapidly variation, thus in this paper $y = [q, p, r]^T$ is just regarded as the tracking objectiveness, that is,*

$$\begin{cases} \dot{x} = Ax + Bu - \mu\bar{A} - \mu\bar{B}u + Dd \\ y = Cx \end{cases} \tag{4}$$

where $C \in R^{3\times8}$ is the controlled output distribution matrix.

3. Damage-Tolerant Controller Design.

3.1. Control objectives.

One of the objectives of fault tolerant control in this paper is to ensure stability and to maintain certain performance requirements in the case of damage occurrence. Meanwhile, the other one is for given any initial attitude angular velocity to design a FTC for structural damaged flight system such that attitude angular velocity can accurately and promptly track the desired signals.

3.2. Damage tolerant controller design.

Let $y_d = [q_d, p_d, r_d]^T$ be the tracked objective, tracking error can be expressed as $e = y - y_d$, and its derivative $\dot{e} = \dot{y} - \dot{y}_d = C\dot{x}$, then a dynamic sliding mode surface is adopted as the switch function s

$$s = Ke + Pu \tag{5}$$

where $s = [s_1, s_2, s_3, s_4]^T$; $K \in R^{4\times3}$; $P = diag\{p_1, p_2, p_3, p_4\}$, $p_i > 0$ will be designed.

Then the derivative of s can be obtained

$$\dot{s} = K\dot{e} + P\dot{u} \tag{6}$$

In order to ensure that the system reaches the sliding mode surface within finite time, so the asymptotical reaching law is adopted

$$\dot{s} = -\rho_1 s - \rho_2 sgn(s) \tag{7}$$

Based on (6) and (7), the proposed fault-tolerant control law is designed in the following form

$$\dot{u} = P^{-1}\{-\rho_1 s - \rho_2 sgn(s) - KC(Ax + Bu + \hat{\mu}(\bar{A}x + \bar{B}u) + \bar{D}\hat{d})\} \tag{8}$$

where $\rho_i > 0$ $(i = 1, 2, 3)$ are the sliding mode gains, and P^{-1} always exists due to P is non-singular.

The following adaptive laws to estimate μ and $d(t)$ respectively are as follows:

$$\dot{\hat{\mu}} = -\Gamma(s^T KC)^T \|\bar{A}x + \bar{B}u\| sgn(\Lambda) \tag{9}$$

$$\dot{\hat{d}} = \eta\bar{D}(s^T KC)^T sgn(\Psi) \tag{10}$$

where $\Gamma \in R^{8\times8}$ is a diagonal matrix and $\Gamma > 0$, here Λ, Ψ can be expressed in the forms as follows:

$$sgn(\lambda_i) = \begin{cases} 1, & s_i^T k_{ii} c_{ij} \tilde{\mu}_i < 0 \\ -1, & s_i^T k_{ii} c_{ij} \tilde{\mu}_i \geq 0 \end{cases} \tag{11}$$

$$sgn(\psi_i) = \begin{cases} 1, & s_i^T k_{ii} c_{ij} d \geq 0 \\ -1, & s_i^T k_{ii} c_{ij} d < 0 \end{cases} \tag{12}$$

where $i = 1, 2, 3$ and $j = 1, 2, \cdots, 8$. From the above analysis, we can obtain the following results.

Theorem 3.1. *For the system (4) with disturbances and structure damage, under the designed dynamic sliding mode surface (5), the sliding mode FTC law (8) and adaptive algorithms (9) and (10), the system tracked error e can converge to zero, and the closed-loop system is globally asymptotically stable within a finite reaching time.*

Proof: Taking the Lyapnuov function as follows:

$$V = \frac{1}{2}s^T s + \frac{1}{2}\tilde{\mu}\Gamma^{-1}\tilde{\mu}^T + \frac{1}{2\eta}\tilde{d}^T\tilde{d} \tag{13}$$

where $\tilde{\mu} = \mu - \hat{\mu}$, $\tilde{d} = d - \hat{d}$, and $\hat{\mu}$, $\hat{d}$ are respectively the estimations of μ, d. The derivative of V is identified as follows:

$$\dot{V} = s^T\dot{s} - \dot{\hat{\mu}}\Gamma^{-1}\hat{\mu}^T - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \tag{14}$$

Further step simplification to yield

$$\begin{aligned}\dot{V} &= s^T(K\dot{e} + P\dot{u}) - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &= s^T(KC\dot{x} + P\dot{u}) - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &= s^T[KC(Ax + Bu - \mu\bar{A}(x)x - \mu\bar{B}u + Dd(t) + P\dot{u})] - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}}\end{aligned}$$

Substituted with the fault-tolerant-control law (8), one obtains

$$\begin{aligned}\dot{V} &= s^T\{KC(Ax + Bu - \mu\bar{A}x - \mu\bar{B}u + Dd(t)) + P\dot{u}]\} - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &\leq -\rho_1 s^T s - \rho_2\|s\| + s^T KC\{\hat{\mu}(\bar{A}x + \bar{B}u) - \mu(\bar{A}x + \bar{B}u) \\ &\quad + Dd - \|D\|\hat{d}\} - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &\leq -\rho_1 s^T s - \rho_2\|s\| + s^T KC[\hat{\mu}(\bar{A}x + \bar{B}u) - \mu(\bar{A}x + \bar{B}u)] \\ &\quad + s^T KC[Dd - \|D\|\hat{d}] - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &\leq -\rho_1 s^T s - \rho_2\|s\| + s^T KC(\hat{\mu} - \mu)(\bar{A}x + \bar{B}u) \\ &\quad + s^T KC\|D\|(d - \hat{d}) - \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} \\ &= -\rho_1 s^T s - \rho_2\|s\| + s^T KC\bar{D}\tilde{d} - \frac{1}{\eta}\tilde{d}^T\dot{\hat{d}} - [s^T KC\tilde{\mu}\|\bar{A}x + \bar{B}u\| + \tilde{\mu}^T\Gamma^{-1}\dot{\hat{\mu}}] \\ &\leq -\rho_1 s^T s - \rho_2\|s\| + \left(s^T KC\bar{D}\tilde{d} - \frac{1}{\eta}\dot{\hat{d}}^T\tilde{d}\right) - [\|\bar{A}x + \bar{B}u\|s^T KC\tilde{\mu} + \dot{\hat{\mu}}^T\Gamma^{-1}\tilde{\mu}] \\ &\leq -\rho_1 s^T s - \rho_2\|s\| + \left(s^T KC\bar{D} - \frac{1}{\eta}\dot{\hat{d}}^T\right)\tilde{d} - [\|\bar{A}x + \bar{B}u\|s^T KC + \dot{\hat{\mu}}^T\Gamma^{-1}]\tilde{\mu}\end{aligned}$$

Substituted with the adaptive laws (9) and (10), one obtains

$$\dot{V} \leq -\rho_1 s^T s - \rho_2\|s\| < 0 \tag{15}$$

Thus, the stability of the overall system is proved and $\dot{V} = 0$ only if $s = 0$, which ends the proof of Theorem 3.1.

Remark 3.1. *$sgn(\Lambda)$ and $sgn(\Psi)$ designed in (11) and (12) respectively, can ensure the stability of system in the proof of Theorem 3.1.*

Remark 3.2. *$sgn(s)$ function will be taken place of saturation function $sat(s)$ in the above controller (8) which can eliminate chattering generated by sliding mode switchings.*

$$sat(s_i) = \begin{cases} 1, & s_i > \delta_i \\ \dfrac{s_i}{\delta_i}, & |s_i| \le \delta_i \\ -1, & s_i < -\delta_i \end{cases} \tag{16}$$

where $\delta_i > 0$ $(i = 1, 2, 3)$ are constants.

Remark 3.3. *The control law is presented by $\dot{u}$ in (8), which may generate new noises and increase calculation amount, so here its integral form is adopted. Thus, the proposed control law is given in this paper by (17).*

$$u = P^{-1} \int_0^t \{-\rho_1 s - \rho_2 sat(s) - KC[Ax + Bu + \hat{\mu}(\bar{A}x + \bar{B}u) + \bar{D}\hat{d})]\} d\tau \tag{17}$$

Remark 3.4. *Consider the structural damage of system (4), the proposed adaptive dynamic sliding mode damage-tolerant controller (8)-(10) and (17) can compensate the uncertainties or disturbances completely and also has the tolerant ability under the flight control system of damage case.*

4. **An Aircraft Example.**

To verify the effectiveness of the proposed method in this paper, we applied it on the *Boeing*747100/200 model. Taking tracked objective as $y_d = [q_d, p_d, r_d]^T = [0, 0, 0]^T$ rad/s and some parameters are referred to [5].

$\Gamma = diag\{0.45, 0.75, 0.35, 0.35, 0.50, 0.25, 0.65\}$, $\eta = 5$, $\delta = 0.01$, $\bar{D} = 8$, $\rho_2 = 10$, $\rho_1 = 5$, $d(t) = [\sin t, \sin t, \sin t, \sin t, \sin t, \sin t, \sin t, \sin t]^T$.

$$A = \begin{bmatrix} -0.0119 & 0.0237 & -11.7461 & -32.1804 & 0 & 0 & 0 & 0 \\ -0.1086 & 0.5165 & 654.8360 & -1.1238 & 0 & 0 & 0 & 0 \\ 0.0000 & -0.0020 & -0.6444 & 0.0002 & 0 & 0 & 0 & 0 \\ 0 & 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.1068 & 0 & -673.0000 & 32.1804 \\ 0 & 0 & 0 & 0 & -3.5276 & -0.8442 & 0.3088 & 0 \\ 0 & 0 & 0 & 3.6534 & -0.0401 & -0.2479 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 0.0349 & 0 \end{bmatrix}$$

$$\bar{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -11.166 & -1.342 & 7.0467 & 0 \\ 0 & 0 & 0 & 0 & -0.150 & -0.044 & 0.201 & 0 \\ 0 & 0 & 0 & 0 & 7.051 & 0.065 & -0.343 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -25.138 & -98.758 & 0 & 0 \\ -1.689 & 0.0155 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 9.585 \\ 0 & 0 & 0.221 & 0.103 \\ 0 & 0 & 0.015 & -0.62 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The disturbed distribution matrix

$$D=\begin{bmatrix} 0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&\\ 0&0&0&0&0&1&0&0\\ 1&0&0&0&1&0&0&0\\ 0&0&0&0&1&0&0&0\\ 0&0&0&0&1&0&0&0\\ 0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&1&0 \end{bmatrix},\ \bar{B}=\begin{bmatrix} 0&0&0&0\\ 0&0&0&0\\ 0&0&0&0\\ 0&0&0&0\\ 0&0&0&9.5858\\ 0&0&0&0.1030\\ 0&0&0&0.6208\\ 0&0&0&0 \end{bmatrix}$$

Choosing the dynamic sliding mode surface matrices

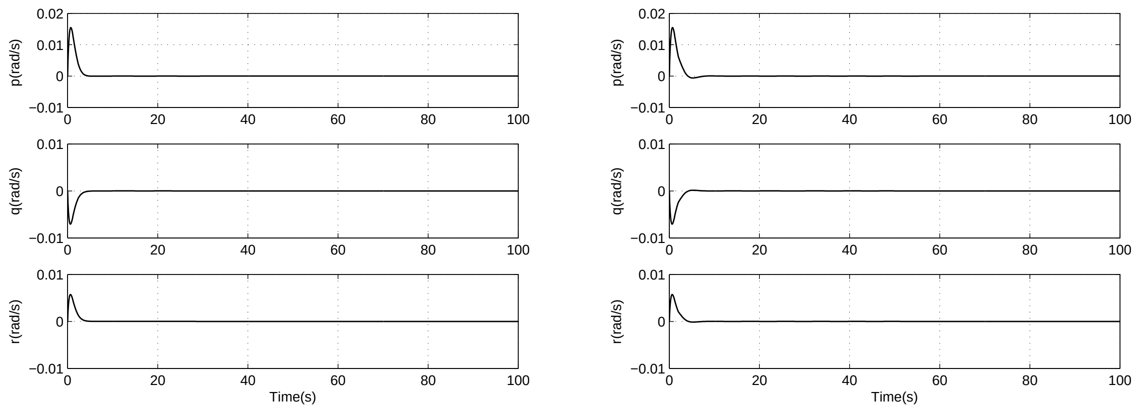
$$K=\begin{bmatrix} -10&0&0\\ 0&-8&0\\ 0&0&-15 \end{bmatrix},\ P=\begin{bmatrix} 20&0&0\\ 0&20&0\\ 0&0&20 \end{bmatrix}$$

The controlled outputs are $C=\begin{bmatrix} 0&0&1&0&0&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&1&0 \end{bmatrix}$.

We consider different damage cases occur at 2s respectively as $\mu=0$, $\mu=0.25$, $\mu=0.35$, $\mu=0.45$, $\mu=0.55$, $\mu=0.60$, and the corresponding simulation results are depicted in Figures 2-5, which show time responses of attitude rates p, q, r between the cases of the free damage and different damage degrees.

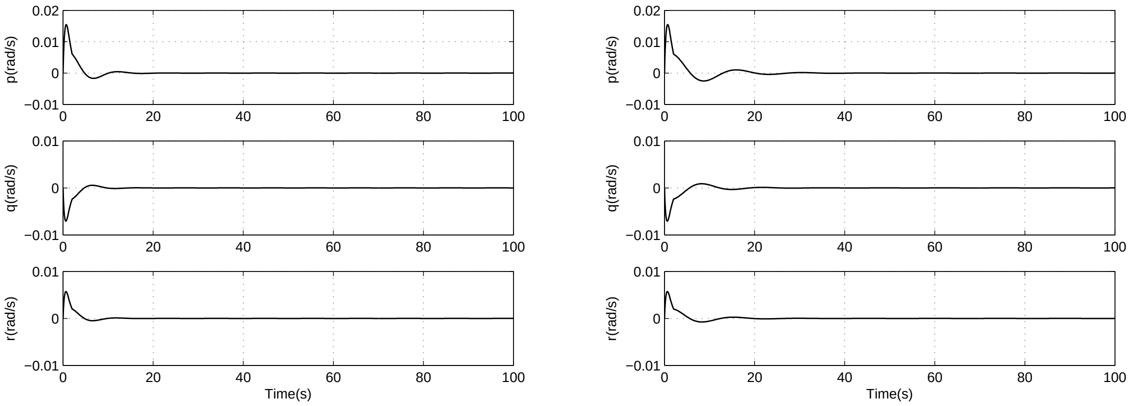
It easily can be seen from Figure 2 that both the responses of attitude angle rates can track quickly the desired signals in the cases of $\mu=0$, and $\mu=0.15$. In addition, from Table 1 we can also see that the regulation time of p, q, r is respectively 2.5, 1, 0.5, which still meet the requirements of the flight control system under structural damage case $u=0.15$.

As we can see from Figure 3, attitude angle rates p, q, r can be tracked promptly, as the damage degree respectively increases to $\mu=0.25$ and $\mu=0.35$, the accommodated time need 10s and 20s more. what is more, from Table 1, the proposed algorithm can make p track the desired signal at 15s and 26s. From Figure 4, attitude angle rates p, q, r tracking can be stable as the damage degree increases to $\mu=0.45$ and $\mu=0.50$, although the accommodated time needed more 35s and 38s. Respectively from Table 1, p can track the desired signal at 40s and 43s respectively, which can be compensated successfully via our proposed FTC algorithm.



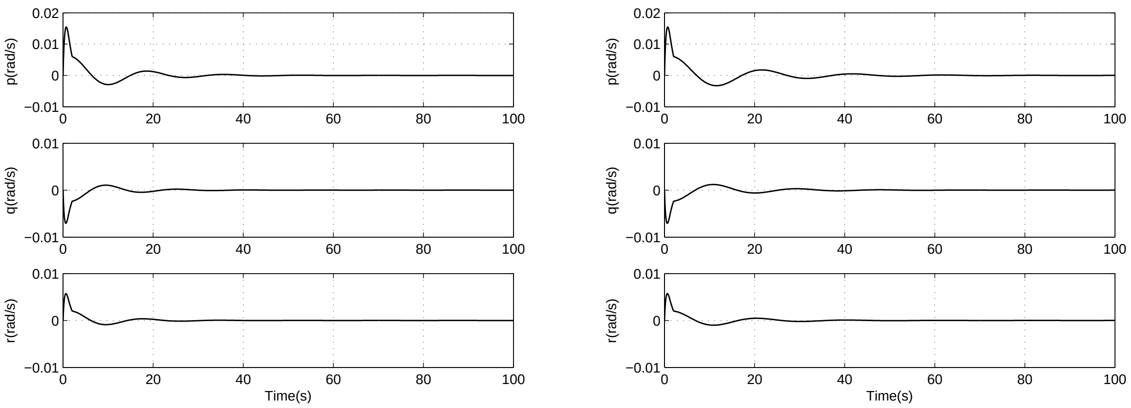
(a) $\mu=0$ (b) $\mu=0.15$

FIGURE 2. Responses of roll, pitch, and yaw rates



(a) $\mu = 0.25$ (b) $\mu = 0.35$

FIGURE 3. Responses of roll, pitch, and yaw rates

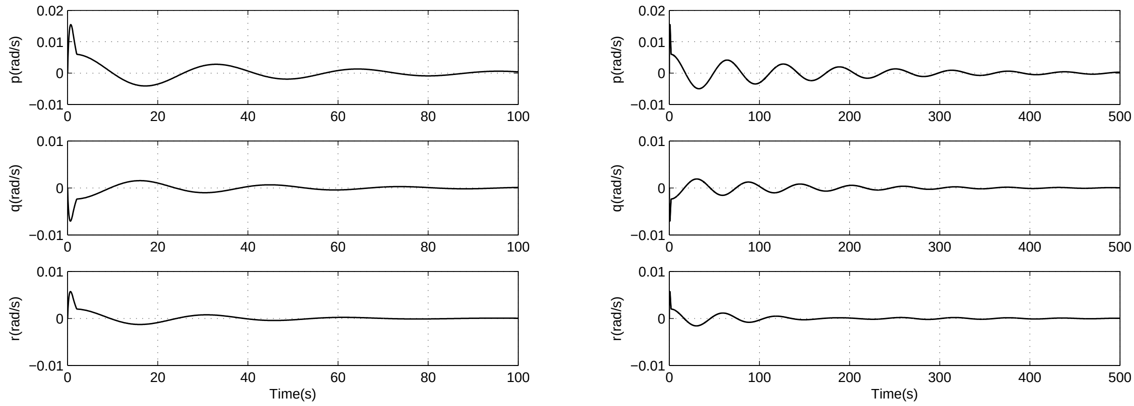


(a) $\mu = 0.45$ (b) $\mu = 0.50$

FIGURE 4. Responses of roll, pitch, and yaw rates

Although the proposed algorithm can still track the system finally in the cases of $u = 0.55$ and $u = 0.65$, the accommodated time of the two cases needed is respectively 68 seconds and 395 seconds. Thus, we can make a conclusion from Figure 5 as the damage degree is bigger than $\mu = 0.50$ and increases to $\mu = 0.60$, the targets cannot be fully tracked timely, even at 300s. Meanwhile, we can make a conclusion from Table 1 that the proposed method can make the target tracked within 50s in the case of structural damage as damage degree $\mu \in [0, 0.5]$ while damage is greater than 0.5, that is, $\mu \in (0.5, 0.6]$, although the target can be tracked finally, the accommodated time is rather long beyond the required time range of the flight control system.

Remark 4.1. *Due to the advantages of the combination of adaptive control and dynamic sliding mode control, the proposed scheme is successful in reconfiguring aircraft suffering from the challenging structural faults. However, from Table 1, it can be seen that there is a certain limitation of the proposed algorithm in this paper as damage degree μ is greater than 0.50 according to the requirements of flight control system. While, compared with [5], the ability of fault tolerance of our approach is improved, which is practical and effective within the damaged degree of 0.5, while it is effective within the damaged degree of 0.205 by using the method in [5].*



(a) $\mu = 0.55$ (b) $\mu = 0.60$

FIGURE 5. Responses of roll, pitch, and yaw rates

TABLE 1. Tracking performance analysis

Damage degree μ	Track State	Accommodated time (s) p, q, r	Tracking time (s) p, q, r
0	Yes	0, 0, 0	5, 5, 5
0.15	Yes	2.5, 1, 0.5	7.5, 6, 5.5
0.25	Yes	10, 5, 5	15, 10, 10
0.35	Yes	21, 13, 13	26, 18, 18
0.45	Yes	35, 22, 17	40, 27, 22
0.50	Yes	38, 28, 20	43, 33, 25
0.55	Yes	68, 60, 50	73, 65, 55
0.60	Yes	395, 295, 155	400, 300, 160

5. **Conclusion.** In this paper, a novel adaptive dynamic sliding mode fault-tolerant control methodology is developed for aircraft system subjected to structural damage, specifically the vertical tail damage or loss. Meanwhile the impact of outer disturbance is taken into account. A novel notion of damage degree is introduced to parameterize the damaged flight dynamics as a linear parameter-dependent model. In order to verify effectiveness of the proposed algorithm to damaged system, the design algorithm is presented and illustrated through numerical simulations on a Boeing-747 100/200 model. Simulation results are provided to show that the proposed damage-tolerant control scheme can completely adjust to flight body damaged case in some extent as the damaged degree at the most 0.55. Thus, it is undoubtable that the tolerant capability of our proposed in this paper has some limitations. In our future work, we will study the design improvement aiming at its tolerant limitation for the higher damage degree.

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REFERENCES

[1] H. Li, L. Wu, Y. Si, H. Gao and X. Hu, Multi-objective fault-tolerant output tracking control of a flexible air-breathing hypersonic vehicle, *Proc. of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol.224, pp.647-666, 2010.

[2] J. Zhao, B. Jiang, P. Shi et al., Fault tolerant control design for near space vehicles based on dynamic terminal sliding mode technique, *Proc. of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol.226, no.6, pp.787-794, 2012.

[3] Q. K. Shen, B. Jiang and V. Cocquempot, Fault diagnosis and estimation for near-space hypersonic vehicle with sensor faults, *Proc. of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol.225, pp.302-312, 2011.

[4] C. Edwards, T. Lombaerts and H. Smaili, *Fault Tolerant Flight Control, A Benchmark Challenge*, Spring-Verlag Berlin Heidelberg, 2010.

[5] X. B. Li and H. T. H. Liu, A passive fault tolerant flight control for maximum allowable vertical tail damaged aircraft, *Journal of Dynamic Systems, Measurement and Control Journal*, vol.134, no.3, 2012.

[6] J. D. Boškvić and R. K. Mehra, Intelligent adaptive control of a tailless advanced fighter aircraft under wing damage, *Journal of Guidance, Control, and Dynamics*, vol.23, no.5, pp.876-884, 2000.

[7] R. Isermann, *Fault-Diagnosis Systems: An Introduction from Detection to Fault Tolerance*, Springer-Verlag, Berlin, 2006.

[8] Y. Hitachi, *Damage-Tolerant Control System Design for Propulsion-Controlled Aircraft*, Master Thesis, Institute for Aerospace Studies, University of Toronto, 2009.

[9] H. J. Xu, M. D. Mirmirani and P. A. Ioannou, Adaptive sliding mode control design for a hypersonic flight vehicle, *AIAA Journal of Guidance, Control, and Dynamics*, vol.27, no.5, pp.829-838, 2004.

[10] T. Lombaerts, P. Chu, J. A. Mulder and D. Joosten, Flight control reconfiguration based on a modular approach, *The 7th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes Barcelona*, Spain, pp.259-264, 2009.

[11] J. Zhao, B. Jiang, F. N. Chowdhury and P. Shi, Active fault-tolerant control for near space vehicles based on reference model adaptive sliding mode scheme, *Int. J. of Adaptive Control and Signal Processing*, DOI: 10.1002/acs.2354, 2013.

[12] Z. Gao, B. Jiang, P. Shi, M. Qian and J. Lin, Active fault tolerant control design for reusable launch vehicle using adaptive sliding mode approach, *J. of Franklin Institute*, vol.349, no.4, pp.1543-1560, 2012.

[13] J. Zhang, P. Shi and Y. Xia, Robust adaptive sliding mode control for fuzzy systems with mismatched uncertainties, *IEEE Trans. on Fuzzy Systems*, vol.18, no.4, pp.700-711, 2010.

[14] H. Yang, Y. Xia, M. Fu and P. Shi, Robust adaptive sliding mode control for uncertain delta operator systems, *Int. J. of Adaptive Control and Signal Processing*, vol.24, no.8, pp.623-632, 2010.

[15] T. J. J. Lombaerts, H. O. Huisman, Q. P. Chu, J. A. Mulder and D. A. Joosten, Nonlinear reconfiguring flight control based on online physical model identification, *AIAA Journal of Guidance, Control and Dynamics*, vol.32, no.3, pp.727-748, 2009.

[16] T. J. J. Lombaerts, M. H. Smaili, O. Stroosma, Q. P. Chu, J. A. Mulder and D. A. Joosten, Piloted simulator evaluation results of new fault-tolerant flight control algorithm, *AIAA Journal of Guidance, Control and Dynamics*, vol.32, no.6, pp.1747-1765, 2009.

[17] T. J. J. Lombaerts, E. R. Van Oort, Q. P. Chu, J. A. Mulder and D. A. Joosten, On-line aerodynamic model structure selection and parameter estimation for fault tolerant control, *AIAA Journal of Guidance, Control and Dynamics*, vol.33, no.3, pp.707-723, 2010.

[18] Y. Xu, B. Jiang, G. Tao and Z. Gao, Fault accommodation for near space hypersonic vehicle with actuator fault, *International Journal of Innovative Computing, Information and Control*, vol.7, no.5(A), pp.2187-2200, 2011.