http://jecei.srttu.edu

SRTTU

Journal of Electrical and Computer Engineering Innovations

JECEI, Vol. 4, No. 2, 2016

Regular Paper

Robust Adaptive Attitude Stabilization of a Fighter Aircraft in the Presence of Input Constraints

Majid Bahmani[1] and Tahereh Binazadeh[1,*]

[1] Department of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran.

*Corresponding Author's Information: binazadeh@sutech.ac.ir

ARTICLE INFO

ARTICLE HISTORY:
Received 05 November 2016
Revised 03 January 2017
Accepted 17 January 2017

KEYWORDS:
Fighter Aircraft
Input Constraints
Composite Nonlinear Feedback (CNF)
Adaptive Integral Sliding Mode (AISM)

ABSTRACT

The problem of attitude stabilization of a fighter aircraft is investigated in this paper. The practical aspects of a real physical system like existence of external disturbance with unknown upper bound and actuator saturation are considered in the process of controller design for this aircraft. In order to design a robust autopilot in the presence of the actuator saturation, the Composite Nonlinear Feedback (CNF) controller along with the Adaptive Integral Sliding Mode (AISM) controller and the new robust controller that is called AISM-CNF control law is proposed. The CNF part of the controller is used for stabilization of the nominal system and also improvement of the transient performance by considering the actuator saturation. The AISM part guarantees robustness against the model uncertainties and/or external disturbances. Since in the proposed approach, the upper bound of the uncertain terms is estimated and therefore there is no need to the prior knowledge about the upper bound of the model uncertainties. Finally, simulation results show the performance of the proposed AISM-CNF controller in terms of attitude stabilization of fighter aircraft, robustness, and the good characteristics of the transient responses of the autopilot system in spite of actuator saturation and external disturbance.

1. Introduction

The attitude control and stabilization problem for the fighter aircraft systems with nonlinear characteristics have a great deal of interest for its vital application. Practical fighter aircraft attitude control systems should operate in the presence of uncertainties and actuator saturation. Therefore, design of a robust autopilot is an important task.

In the literature, there are many papers which consider the problem of robust nonlinear controller design for aerial vehicles. For example, methods like, control Lyapunov function [1, 2] and backstepping [3] partial sliding mode [4] have been used for this purpose.

On the other hand, actuator saturation is an important nonlinear feature in the physical systems that should be considered in the controller design and neglecting this feature may deteriorate the response of the closed-loop system. Aerial vehicles similar to the other physical systems encounter with this problem. In [5], a controller has been designed for a helicopter and in [6], controllers were given for attitude stabilization of a fighter aircraft. Stabilization of a spacecraft in the presence of actuator saturation was also studied in [7].

There are several techniques (such as anti-wind-up [8], Proximate Time Optimal Servo-mechanism (PTOS) [9] and Composite Nonlinear Feedback) (CNF) [10, 11]) which consider a limitation on the upper and lower bounds of the control input in the design procedure. However, these approaches are applicable only for linear systems and are not robust against disturbances. Among these methods, the CNF approach achieves more desirable response. The CNF controller has been implemented in many practical systems [12-15]; however, it is not robust against disturbances. In [16], a method has been proposed to create robustness against constant disturbances; however, it cannot reject the time-varying disturbances. Moreover, the authors of [17, 18] studied this problem by combining the Integral Sliding Mode (ISM) with CNF which called ISM-CNF controller.

The CNF controller can also be used for a class of nonlinear systems [6]. These nonlinear systems have a linear part which is connected to the nonlinear part and is called partially linear composite systems. Many of nonlinear systems can be transformed to partially linear composite systems [19].

From practical point of view, the design of a robust efficient control law is an important issue in the aerospace industry. Therefore, in this paper, instead of using the known upper bound (which is used in ISM-CNF in [18, 19]), the effects of the disturbances and model uncertainties of the system are estimated with adaptive gains. This goal is achieved by considering that the upper bound of the uncertain terms is unknown and in order to estimate it, an adaptive controller is taken into account. In this regard, an Adaptive-ISM (AISM) controller is suggested in this paper which is combined with the CNF controller. This new controller called AISM-CNF controller which has a robust effective performance in the presence of both model uncertainties and actuator saturation. The CNF part of controller is used to stabilize the nominal system and also improvement of the transient performance subject to actuator saturation. The AISM part guarantees robustness against the model uncertainties and/or external disturbances. In this regard, when the effects of uncertain terms are increased, the effect of AISM control law will be increase and for the uncertain terms with small effect, the AISM control signal will be reduced. Consequently, the AISM-CNF controller is less conservative than the ISM-CNF controller. Finally, the proposed controller is applied on the considered aircraft and simulation results illustrate the effective performance of the AISM-CNF controller in comparison with ISM-CNF control law.

In the remainder of this paper, first the dynamical model of the fighter aircraft is given. Actuator saturation and model uncertainties are considered in this dynamical model. After that, the procedure of the design of a robust controller by the AISM-CNF method (with considering the actuator saturation) is explained in detail. Also, the robust controller is designed for the fighter aircraft. Moreover, simulation results are given which verify the theoretical results and also show the effectiveness of the new AISM-CNF controller. At the end, conclusions are given in the last section.

2. PROBLEM FORMULATION

Consider the fighter aircraft which is shown in Figure 1. The dynamical equations for this aircraft are as follows [6]:

$$\begin{aligned}
\dot{\upsilon} &= 1.8254\cos(0.0175(\alpha+11.3404)) - 1.9821 \\
&\quad \times 10^{-3}(0.0886 + 1.75\times 10^{-2}\alpha)\upsilon^2 \\
\dot{\alpha} &= -0.5923\alpha + 50.729q - 0.1145\left(u+d\right) \\
\dot{q} &= -0.0178\alpha - 0.3636q - 0.0676\left(u+d\right)
\end{aligned} \tag{1}$$

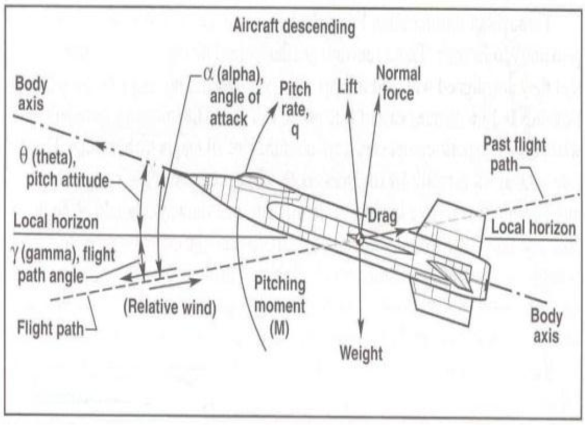

Figure 1: Fighter aircraft [20].

where the air speed: v (m/s), angle of attack: α (deg), and pitch angular rate: q (rad/s) are the state variables of this system. Deflection of the elevator: u (deg) is control input with a saturation level $u$max=4.5◦. d is the uncertain term. The model (1) is extracted from the nonlinear model of six degree of freedoms based on a steady flight condition with mach = 0.3, height = 1000m, and with a straight and horizontal flight. The control objective is to set the angle of attack to a reference attitude 4.8◦ quickly and without experiencing large overshoot.

In what follows, first the proposed procedure in the controller design is explained and then it is applied on the system (1).

3. DESIGN OF ADAPTIVE ISM-CNF CONTROL LAW

Many of nonlinear systems can be rewritten in the form of a linear part which is connected to a nonlinear part so-call partially linear composite system which is given as follows [6]:

$$\begin{aligned}
\dot{\xi} &= f(\xi, y) \\
\dot{x} &= Ax + Bu + Bd(x,t) \\
y &= Cx
\end{aligned} \tag{2}$$

where $x \in R^n, \xi \in \Omega \subseteq R^m$ and $\left[x^T, \xi^T\right]^T$ is the state vector. The $\dot{\xi}$ -equation are the nonlinear part and $\dot{x}$ -

equation are the linear part of system. $y \in R$ is the output and $u \in R$ is the control input, $d(x,t)$ is the matched bounded uncertain term that is due to model uncertainties and/or external disturbance, f is a nonlinear smooth vector function, *A, B* and *C* are constant matrices with appropriate dimension. The goal is to design a robust controller such that $y(t)$ tends to a desired time-invariant reference signal *r.*

$$\lim_{t\to\infty} y(t) = r \tag{3}$$

Since in the practical systems, the actuator saturation should be considered in system modeling, thus; equation (2) is rewritten as follows:

$$\begin{aligned} \dot{\xi} &= f(\xi, y) \\ \dot{x} &= Ax + Bsat(u) + Bd(x,t) \\ y &= Cx \end{aligned} \tag{4}$$

where *sat*: $R \to R$ is defined as

$$sat(u) = sign(u)\min\{u_{\max}, |u|\} = \begin{cases} u_{\max} & u > u_{\max} \\ u & -u_{\max} < u < u_{\max} \\ u_{\max} & u < -u_{\max} \end{cases} \tag{5}$$

and $u_{\max} > 0$ is the maximum allowed amplitude of *u*. Consider the following assumptions which are standard in the tracking control literature [19]:

Assumption 1: (*A, B*) is controllable,
Assumption 2: (*A, B, C*) has no zeros at *s*=0.
Assumption 3: Considering $f(0,r) = 0$ $\dot{\xi}$-equation, is asymptotical stable (for $y = r$), according to the converse Lyapunov theorem, there exists a continuously differentiable function $V(\xi): \Omega \to R$ such that [21]:

$$\alpha_1(\|\xi\|) \le V(\xi) \le \alpha_2(\|\xi\|) \tag{6}$$

$$\frac{\partial V(\xi)}{\partial \xi} f(\xi, r) < 0 \tag{7}$$

where $\alpha_1(.)$ and $\alpha_2(.)$ are class K functions.

Remark 1: If $f(\xi^*, r) = 0$ for $\xi^* \neq 0$, then the transformation $\tilde{\xi} = \xi - \xi^*$ gives

$$\dot{\tilde{\xi}} = f(\tilde{\xi} + \xi^*, r) = \tilde{f}(\tilde{\xi}, r) \tag{8}$$

where $\tilde{f}(0,r) = 0$. The following theorem is used to prove the stability of the nonlinear sub-system (i.e., $\dot{\xi}$ -equation) before output y reaches to the constant reference input *r* [22].

Theorem 1: Consider the following nonlinear system:

$$\dot{\xi} = f(\xi, r + \eta(t)) \tag{9}$$

which satisfies conditions (6) and (7). For any given $\gamma > 0$ and $\hat{\beta} > 0$, there exists a scalar $a > 0$ such that for any

$$|\eta(t)| \le \hat{\beta} e^{-at}, \quad t \ge 0$$

The solution $\xi(t)$ for (9) exists and it is bounded for all $t \ge 0$ provided that $\|\xi(t)\| \le \gamma$.

Proof: see [22] ■

3.1. Design of the CNF controller

The CNF control law ($u_{CNF} = u_L + u_N$) includes a linear part u_L (for stabilization and quick response such that $|u_L| < u_{\max}$) and a nonlinear part u_N (for overshoot reduction). The structure of the linear part is as follows:

$$u_L = Fx + G_1 r \tag{10}$$

where F is the state feedback gain which will be designed such that (*A+BF*) is Hurwitz with a small damping ratio. Moreover, the matrix G_1 is as follows:

$$G_1 = -\left[C\left(A + BF\right)^{-1} B\right]^{-1} \tag{11}$$

Also, the nonlinear part of the CNF control law is as follows which is used to modify the damping ratio as the output *y* approaches the reference input *r*:

$$u_N = \psi(r, y) B^T P(x - x_e) \tag{12}$$

where $\psi(r, y)$ is locally Lipschitz function in y which is non-positive and *P* is obtained from the Lyapunov equation (13).

$$(A + BF)^T P + P(A + BF) = -Q \tag{13}$$

As the output y tends to the desired reference input r, the effectiveness of u_N increases. Therefore, damping ratio becomes larger and the overshoot of the transient response reduces [10].

The effect of the linear part in the closed-loop system is as follows:

$$\dot{x} = (A + BF)x + BG_1 r \tag{14}$$

The Laplace transformation of $x(t)$ is:

$$X(s) = \left(sI - A - BF\right)^{-1} BG_1 R(s) \tag{15}$$

where $R(s) = \frac{r}{s}$. Now, if $\lim_{t\to\infty} y(t) = r$ then $\lim_{t\to\infty} x(t) = \lim_{s\to 0}(sX(s)) = x_e$ where

$$x_e = -\left(A + BF\right)^{-1} BG_1 r = G_e r \tag{16}$$

$$G_e = -(A + BF)^{-1} BG_1 \tag{17}$$

Consequently, the linear part (u_L) guarantees the convergence of the states of system (4) to x_e. Now, the region of state space that $\left|u_L(x,t)\right| \le u_{\max}$ should be determined. By coordinate transformation $\tilde{x} = x - x_e$, the linear part of the CNF control law may be rewritten as follows:

$$u_L = F\tilde{x} + Hr \tag{18}$$

where

$$H = \left[I - F(A + BF)^{-1} B\right] G_1 \tag{19}$$

and $Ax_e + Hr = 0$ therefore,

$$\dot{\tilde{x}} = (A + BF)\tilde{x} \tag{20}$$

For any $\delta \in (0,1)$, then $c_\delta > 0$ is the greatest possible value for which the following condition is satisfied:

$$\left|F\tilde{x}\right| \le u_{\max}(1-\delta) \quad \forall x \in X_\delta = \left\{\tilde{x} \mid \tilde{x}^T P \tilde{x} \le c_\delta\right\} \tag{21}$$

and

$$\left|Hr\right| \le \delta u_{\max} \tag{22}$$

Hence

$$\left|F\tilde{x} + Hr\right| \le \left|F\tilde{x}\right| + \left|Hr\right| \le (1-\delta)u_{\max} + \delta u_{\max} \le u_{\max} \tag{23}$$

Therefore, in the region X_δ, the condition $\left|u_L\right| = \left|F\tilde{x} + Hr\right| < u_{\max}$ is satisfied and since (A+BF) is Hurwitz, thus $\tilde{x} \to 0$ and therefore X_δ is an invariant set for the closed-loop system (20).

For nonlinear part of the CNF controller (i.e., u_N), several suggestions exist for $\psi(r, y)$. One of them is given as follows [18]:

$$\psi(r, y) = -\beta(e^{-|y-r|} - e^{-|y_0 - r|}) \tag{24}$$

where $y_0 = y(0)$, and the positive constant β is the tuning parameter. By combining the linear and nonlinear parts, the CNF control law is obtained as follows:

$$\begin{aligned} u_{CNF} &= u_L + u_N \\ &= F\tilde{x} + Hr + \psi(r, y)B^T P(x - x_e) \end{aligned} \tag{25}$$

In what follows, the CNF controller is combined with AISM method to compensate the uncertainties and results in a robust manner in the face of $d \ne 0$ and also in the presence of actuator saturation.

3.2. Design of the Robust AISM-CNF Controller

This section contains the main contribution of this paper. In order to achieve robustness with reduction of conservatism, the AISM-CNF controller is designed which is a robust adaptive control law. For this purpose, the following sliding surface is considered:

$$S(x,t) = \hat{G}\left\{x(t) - x(0) - \int_0^t (Ax(\tau) + Bu_0(\tau))d\tau\right\} \tag{26}$$

where $x(t)$ is the state of the uncertain system (4) and $x_{nom}(t) - x_{nom}(0) = \int_0^t (Ax(\tau) + Bu_L(\tau))d\tau$ is related to the closed-loop nominal system and the differences between $x(t)$ and $x_{nom}(t)$ should be nullified through the design of an appropriate robustifying control term ($x(0) = x_{nom}(0)$). Also, $\hat{G}$ is a raw vector and may be chosen arbitrarily.

Now, the AISM control law (u_{AISM}) is added to u_L and the new robust control law is given as follows (According to Lemma 1, u_N has no effect on the stability of the system and is only effective on the characteristics of the transient responses):

$$\bar{u} = u_L + u_{AISM} \tag{27}$$

Assume that the upper bound of $d(x,t)$ is not exactly known and satisfy the following condition:

$$\left|d(x,\xi,t)\right| \le k_1(t) + k_2(t)\left\|x\right\| \tag{28}$$

where $k_1(t)$ and $k_2(t)$ are unknown non-negative parameters which should be estimated through the appropriate adaptation rules. This approach leads to reduction of conservatism in comparison with the ISM-CNF method which was given in [6, 18]. In order to design the u_{AISM}, the following Lyapunov function is considered:

$$V(t)=\frac{1}{2}\left[S^2+\frac{1}{p_1}\tilde{k}_1^2+\frac{1}{p_2}\tilde{k}_2^2\right] \tag{29}$$

where p_is (for $i=1,2$) are positive constants, $\tilde{k}_i(t)=k_i-\hat{k}_i(t)$ and also $\hat{k}_i(t)$ is the estimated value of $k_i(t)$ (i=1, 2).

The time derivative of $V(t)$ is as follows:

$$\dot{V}=S\dot{S}-\frac{1}{p_1}\tilde{k}_1\dot{\hat{k}}_1-\frac{1}{p_2}\tilde{k}_2\dot{\hat{k}}_2 \tag{30}$$

According to equation (26), $\dot{S}$ is achieved and thus,

$$\begin{aligned}\dot{V}&=S\left[\hat{G}\left(Ax(t)+B(u_L(t)+u_{AISM}(t))+Bd(t)-Ax(t)-Bu_L(t)\right)\right]\\&\quad-\frac{1}{p_1}\tilde{k}_1\dot{\hat{k}}_1-\frac{1}{p_2}\tilde{k}_2\dot{\hat{k}}_2\\&=S\left[\hat{G}\left(Bu_{AISM}(t)+Bd(t)\right)\right]-\frac{1}{p_1}\tilde{k}_1\dot{\hat{k}}_1-\frac{1}{p_2}\tilde{k}_2\dot{\hat{k}}_2\\&\le S\hat{G}Bu_{AISM}(t)+|S|\left|\hat{G}B\right||d(t)|-\frac{1}{p_1}\tilde{k}_1\dot{\hat{k}}_1-\frac{1}{p_2}\tilde{k}_2\dot{\hat{k}}_2\\&\le S\hat{G}Bu_{AISM}(t)+|S|\left|\hat{G}B\right|\left(k_1+k_2\|x\|\right)\\&\qquad-\frac{1}{p_1}\tilde{k}_1\dot{\hat{k}}_1-\frac{1}{p_2}\tilde{k}_2\dot{\hat{k}}_2\end{aligned} \tag{31}$$

By choosing the adaptation rules as follows:

$$\dot{\hat{k}}_1(t)=p_1|S(t)|\left|\hat{G}B\right|sign(|S(t)|) \tag{32}$$

$$\dot{\hat{k}}_2(t)=p_2|S(t)|\left|\hat{G}B\right||x_1(t)|sign(|S(t)|) \tag{33}$$

then,

$$\dot{V}\le S\hat{G}Bu_{AISM}(t)+|S|\left|\hat{G}B\right|\left(\hat{k}_1+\hat{k}_2\|x\|\right) \tag{34}$$

Considering $u_{AISM}(t)$ as follows:

$$u_{AISM}(t)=-L(x,t)\,sign\left((\hat{G}B)S\right) \tag{35}$$

where

$$L(x,t)=\hat{k}_1+\hat{k}_2\|x\|+\bar{\eta} \tag{36}$$

$\bar{\eta}>0$ is a small value and also:

$$L(x,t)<u_{\max}\ ,\ \forall\, x\in R^n\ ,\ t\in[0,\infty) \tag{37}$$

Inserting (36) into (35) results in:

$$\dot{V}\le-\bar{\eta}|S|\left|\hat{G}B\right|<0 \tag{38}$$

Therefore, according to Barbatal's Lemma [29], the system's states can be driven to the sliding surface which guarantees that the state variables of the closed-loop uncertain system via the AISM-CNF controller follows the state response of the closed-loop nominal system. ■

Remark 2: There are limitations on the maximum amplitude of the uncertain terms and also the maximum amplitude of reference input which can be tracked [19]. Since, according to Lemma 1, u_N has no effect on the stability of the closed loop system. The following Lemma shows that if the condition $|\bar{u}|\le u_{\max}$ is satisfied, then, the AISM-CNF controller guarantees the robust output regulation.

$$\bar{u}=u_L+u_{AISM} \tag{39}$$

Lemma 2: Consider the Lyapunov equation which is given as follows:

$$(A+BF)^T P+P(A+BF)=-Q$$

where Q and P, are positive definite matrices. If $\left|u_{ISM}\right|=L<(1-\varepsilon)u_{\max}$ where $\varepsilon\in(0,1)$, then the feedback control $\bar{u}$ forces the output to track the reference input r, when $\tilde{x}\in X_\delta$ and r satisfy $\left|Hr\right|\le\delta_1 u_{\max}$, where $\delta_1=\varepsilon+\delta-1$.

According to the given analysis, the complete procedure for design of the AISM-CNF controller is as follows:

1) Determining the region X_δ, and the maximum admissible value of r, by choosing δ.
2) Designing the linear part of the CNF control law, such that $A+BF$ is Hurwitz.
3) Solving the Lyapunov equation to obtain P.
4) Tuning β for the nonlinear part of the CNF control law.
5) Designing the AISM control law to compensate the disturbances. Then tuning the parameters p_is.
6) Obtaining the robust controller $u=u_{CNF}+u_{AISM}$

4. Computer Simulation

In this section, the robust controller is designed based on the proposed AISM-CNF controller for the attitude stabilization of the fighter aircraft. Since the discontinuous controller (36) suffers from chattering, thus the sign function is approximated by a saturation function with a high slope ($\frac{1}{\varepsilon}$).

Consider equations (1), in the structure of (4), then $x = [\alpha \quad q]^T$, $\xi = \upsilon$, $y = \alpha$, and A, B and C are as follows:

$$A = \begin{bmatrix} -0.5923 & 50.7290 \\ -0.0178 & -0.3636 \end{bmatrix} \quad B = \begin{bmatrix} -0.1145 \\ -0.0676 \end{bmatrix}$$

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

Assume u_{max}=4.8 and the time-varying external disturbance as $d = 3\sin(10t)$. The design parameters are selected as follows: $F = [0.9253 \quad 35.5945]$ (the eigenvalues of $(A+BF)$ are $-1.7677 \pm j1.7677$), $G_1 = -1.5966$, $G_e = [1 \;\; 0.0097]^T$, r=5, $\psi(r, y) = -(e^{-|y-r|} - e^{-|y_0-r|})$, $\hat{G} = B^T$ and $Q = \begin{bmatrix} 0.4 & 9.4 \\ 9.4 & 2568.7 \end{bmatrix} > 0$, $p_1 = 1000$, $p_2 = 2000$, $x(0) = 0$, $\xi(0) = 100$.

Figures 2 and 3 show the time responses of the angle of attack α (deg) and pitch angular rate q (rad/s) of closed-loop system, respectively. In these figures, the proposed controller (AISM-CNF) is compared with the ISM-CNF controller. As seen, the state variables of the closed-loop system have better responses via the proposed AISM-CNF controller in terms of steady state error. Moreover, the time response of the AISM-CNF controller and ISM-CNF controller are shown in Figure 4.

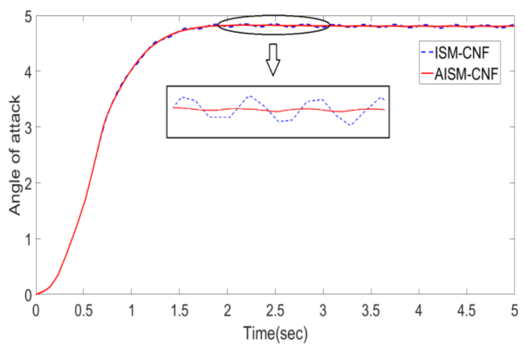

Figure 2: Time response of the output.

5. Conclusion

This paper proposed the AISM-CNF control law for robust stabilizing of a class of nonlinear systems with actuator saturation and in the presence of external disturbances and/or model uncertainties.

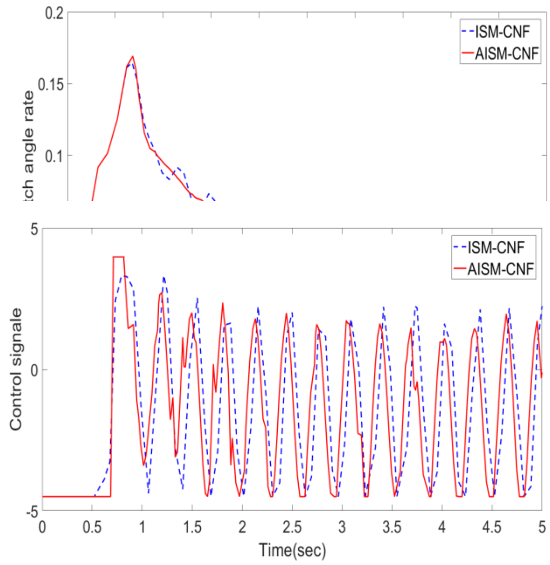

Figure 4: Time response of the ISM-CNF and AISM-CNF Controllers.

The procedure of controller design was explained in detail. Then, the proposed method was used to design a robust controller for a fighter aircraft in the presence of actuator saturation and external disturbances. Computer simulation showed the effectiveness of the proposed controller in robust output tracking.

References

[1] T. Yamasaki, S.N. Balakrishnan, and H. Takano, "Integrated guidance and autopilot design for a chasing UAV via high-order sliding modes," *Journal of the Franklin Institute,* vol. 349, no. 2, pp. 531–558, 2012.

[2] B. Chen, Z. Jiao, and Sh.S. Ge, "Aircraft-on-ground path following control by dynamical adaptive backstepping," Chinese Journal of Aeronautics, vol. 26, no. 3, pp. 668–675, 2013.

[3] J.W. Wang, H.N. Wu, L. Guo, and Y.S. Luo, "Robust H∞ fuzzy control for uncertain nonlinear Markovian jump systems with time-varying delay," *Fuzzy Sets and Systems*, vol. 212, no. 1, pp. 41–61, 2013.

[4] K. Peng, G. Cai , B.M. Chen, M. Dong, K.Y. Lum, and T.H. Lee, "Design and implementation of an autonomous flight control law for a UAV helicopter," *Automatica*, vol. 45, no. 10, pp. 2333–2338, 2009.

[5] W. Lan, B.M. Chen, and Y. He, "On improvement of transient performance in tracking control for a class of nonlinear systems with input saturation," *Systems & Control Letters*, vol. 55, no. 2, pp. 132–138, 2006.

[6] Z. Zhu, Y. Xia, and M. Fu, "Adaptive sliding mode control for attitude stabilization with actuator saturation," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4898-4907, 2011.

[7] K. Lu, Y. Xia, and M. Fu, "Controller design for rigid spacecraft attitude tracking with actuator saturation," *Information Sciences*, vol. 220, no. 2, pp. 343–366, 2013.

[8] A.R. Teel, "Anti-windup for exponentially unstable linear systems," *International Journal of Robust Nonlinear Control*, vol. 9, no. 10, pp. 701–716, 1999.

[9] M.L. Workman, "Adaptive proximate time optimal servomechanisms," Ph.D. dissertation, Stanford University, Stanford, CA, 1987.

[10] B.M. Chen, T.H. Lee, K. Peng, and V. Venkataramanan, "Composite nonlinear feedback control for linear systems with input saturation: theory and an application," *IEEE Transactions on Automatic Control*, vol. 48, no. 3, pp. 427–439, 2003.

[11] Y. He, B.M. Chen, and C. Wu, "Composite nonlinear control with state and measurement feedback for general multivariable systems with input saturation," *Systems Control Letters*, vol. 54, no. 5, pp. 455–469, 2005.

[12] T. Binazadeh and M. Bahmani, "Robust time-varying output tracking control in the presence of actuator saturation," *Transactions of the Institute of Measurement and Control* (2016), DOI: https://doi.org/10.1177/0142331216650022

[13] J. Wang and J. Zhao, "On improving transient performance in tracking control for switched systems with input saturation via composite nonlinear feedback," *International Journal of Robust and Nonlinear Control*, vol. 26, no. 9, pp. 509-518, 2015.

[14] L. Wei, F. Fang, and Y. Shi, "Adaptive backstepping-based composite nonlinear feedback water level control for the nuclear utube steam generator," *IEEE Transactions on Control Systems Technology*, vol. 22, pp. 369-377, 2014.

[15] W. Lan, C. K. Thum, and B. M. Chen, "A hard-disk-drive servo system design using composite nonlinear-feedback control with optimal nonlinear gain tuning methods," *IEEE Transactions on Industrial Electronics*, vol. 57, pp. 1735-1745, 2010.

[16] G. Cheng and K. Peng, "Robust composite nonlinear feedback control with application to a servo positioning system," *IEEE Transactions on Industrial Electronics*, vol. 54, pp. 1132-1140, 2007.

[17] B. Bandyopadhyay, F. Deepak, and K.-S. Kim, "Integral sliding mode based composite nonlinear feedback control," in Sliding Mode Control Using Novel Sliding Surfaces, ed: Springer, pp. 83-95, 2009.

[18] Z. Zheng, W. Sun, H. Chen, and J. T. Yeow, "Integral sliding mode based optimal composite nonlinear feedback control for a class of systems," *Control Theory and Technology*, vol. 12, pp. 139-146, 2014.

[19] A. Isidori, Nonlinear Control Systems, Springer, London, 1995

[20] http://www.klabs.org/DEI/References/contents_detailed/aircraft_nomenclature/index.htm.

[21] H.K. Khalil, Nonlinear systems, 3rd edition, Prentice hall, 2002.

[22] H.J. Sussmann, P.V. Kokotovic, "The peaking phenomenon and the global stabilization of nonlinear systems," *IEEE Transactions on Automatic Control*, vol. 36, no. 4, pp. 424–440, 1991.

[23] W. Lan and B.M. Chen, "On selection of nonlinear gain in composite nonlinear feedback control for a class of linear systems," in *Proc. 46th IEEE Conference on Decision and Control Conf.*, New Orleans, LA, USA, pp. 12-14.

[24] F. Castanos and L. Fridman, "Analysis and design of integral sliding manifolds for systemswith unmatched perturbations," *IEEE Transactions on Automatic Control*, vol. 51, no. 5, pp. 853–858, 2006.

[25] V.I., Utkin and J. Shi, "Integral sliding mode in systems operating under uncertainty conditions," in *Proc. 35th conference on decision and and control*, *Conf.*, Kobe, Japan, pp. 4591–4596, 1996.

[26] F.J. Bejarano, L. Fridman, and A. Poznyak, "Output integral sliding mode control based on algebraic hierarchical observer," *International Journal of Control*, vol. 80, no. 3, pp. 443–453, 2006.

[27] V.I. Utkin, "Variable structure system with sliding mode," *IEEE Transactions on Automatic Control*, vol. 22, no. 2, pp. 212–221, 1977.

[28] V.I. Utkin, J. Guldner, and J. Shi, Sliding Mode Control in Electromechanical Systems, Taylor & Francis, Abington, 1999.

[29] J. E. Slotine and W. Li, Applied Nonlinear Control, Englewood Cliffs, NJ: Prentice-Hall, 1991.

Biographies

Majid Bahmani received the B.Sc. degree in Communication Engineering from the Jundishapoor University in 2013. He received M.Sc. degree in Control Engineering from Shiraz University of Technology in 2015. His research interests include Robust nonlinear control, Autopilot design, UAV control. Currently he is working on robust autopilot design.

Tahereh Binazadeh received her B.Sc. degree in 2003 and M.Sc. degree in 2005 from Shiraz University in Control Engineering. Also, she received Ph.D. degree from University of Tehran in 2011 in Control Engineering. She is now Associate Professor in Shiraz University of Technology. Her research interests include Robust and optimal nonlinear control. Currently, she is working on robust control of time-delay systems, Fractional order systems and Singular systems.

How to cite this paper:

M. Bahmani and T. Binazadeh, "Robust adaptive attitude stabilization of a fighter aircraft in the presence of input constraints," Journal of Electrical and Computer Engineering Innovations, vbol. 4. no. 2, pp. 149-155, 2016.

DOI: 10.22061/jecei.2017.575

URL: http:// jecei.srttu.edu/article_575.html