World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:4, No:8, 2010

Adaptive Sliding Mode Observer for a Class of Systems

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Abstract**—**In this paper, the performance of two adaptive observers applied to interconnected systems is studied. The nonlinearity of systems can be written in a fractional form. The first adaptive observer is an adaptive sliding mode observer for a Lipchitz nonlinear system and the second one is an adaptive sliding mode observer having a filtered error as a sliding surface. After comparing their performances throughout the inverted pendulum mounted on a car system, it was shown that the second one is more robust to estimate the state.

Keywords**—**Adaptive observer, Lipchitz system, Interconnected fractional nonlinear system, sliding mode.

I. Introduction

DIFFERENT forms of nonlinear systems with varying parameters are presented in literature. For this reason many adaptation laws are developed for each system to estimate the unknown parameters. To have appropriate adaptation laws, some techniques are used such as an adaptive controller ([6], [7], [16]) and an adaptive observer ([2], [5], [8], [9], [17]), where an augmentation of the vectors of state including the state and the unknown parameters is used [10]. An observer is called adaptive observer if it uses an adaptation law to estimate the unknown parameters [10].

In literature ([1], [2], [3], [4]), most of the adaptive observers are developed for a class of lipchitz nonlinear systems throughout a classical observer. But the adaptation laws proposed for a class of systems are not usually robust for all systems of the same class.

In this work, we have shown the modest performance of an adaptation law proposed for a lipchitz nonlinear system which can be written in a fractional form. Then, an adaptive sliding mode observer designed to a fractional nonlinear system is applied. These adaptation laws have been compared through the inverted pendulum mounting on a cart system in the case of constant parameters.

II. Adaptive Sliding Mode Observer For A Class Of Lipchtiz System

In literature, the adaptive observers are more studied in the case of classical approaches. It is proved that the adaptation law depends on the class of nonlinear systems and on the technique applied to synthesize the observer.

A systematic approach to synthesize the adaptive observer is developed by [3] for Lipchitz nonlinear systems .Following that, an adaptive sliding mode observer for a system as in [3] will be studied. Consider the nonlinear systems.

$$\begin{cases} \dot{x} = Ax + \phi(x,u) + \theta^T f(x,u) \\ y = Cx \end{cases}$$

With: $x \in \Re^n$; $\phi \in \Re^n$; $f = diag(f_1, f_2 \cdots, f_n)$; A is a constant matrix; $\theta \in \Re^n$ parameter vector; $y \in \Re^p$

The nonlinear functions ϕ and f are two lipchitz matrices such as:

$$\| f(x,u) - f(\hat{x},u) \| \le \alpha_1 \| x - \hat{x} \|$$

$$\| \phi(x,u) - \phi(\hat{x},u) \| \le \alpha_2 \| x - \hat{x} \|$$

$\alpha_1, \alpha_2 \in \Re^n$.

Considering the following lyapunov function

$$V = \frac{1}{2} e^T e + \frac{1}{2} \rho \tilde{\theta}^T \tilde{\theta} \tag{1}$$

Where $\tilde{\theta} = \theta - \hat{\theta}$ and $e = x - \hat{x}$

This lyapunov function satisfies the condition of stability, the derivative of V is negative, if:

- The architecture of the adaptive sliding mode observer is:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + \phi(\hat{x},u) + \hat{\theta}^T f(\hat{x},u) + L(y - C\hat{x}) - \\ \quad \lambda sign(y - C\hat{x}) \\ \dot{\hat{\theta}} = \frac{1}{\rho} f^T(\hat{x},u)(y - C\hat{x}) \end{cases} \tag{2}$$

- This adaptive observer is stable and converges to the desired state if:

$$k > \lambda \tag{3}$$

In [14], it is shown that the adaptive sliding mode observer can give a good performance for a Lipchitz nonlinear system when the parameters are constant or varied.

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III. Adaptive Sliding Mode Observer Having A Filtered Error As A Sliding Surface

Some nonlinear systems are written in the general structure (4) like the robot manipulator ([11], [12]) and the inverted pendulum mounting on a cart [13].

$$\dot{x} = F(x, \dot{x}, u) \tag{4}$$

This form can be transformed into the fractional form .If the parameter vector of the system is unknown, the joint estimation of the parameter and that of the state becomes more complicated because the parameter vector is designed in the numerator and in the denominator. The form of system (4) is written as a set of interconnected fractional systems having the following form:

$$S_j \begin{cases} \dot{x}_{1j} = x_{2j} \\ \dot{x}_{2j} = \dfrac{f_j(x,u)}{\beta(x,u)} \\ y = x_{1j} \end{cases} \tag{5}$$

Where $j = 1 \cdots m$

For each subsystem the output is $y = x_{1j}$ and the output of all the system is $y = [x_{11}\ x_{12}\ x_{22} \cdots x_{1m}]$ and the state vector is $x = [x_{11}\ x_{21}\ x_{12}\ x_{22} \cdots x_{2m}]$.

The nonlinearity $f_j(x,u)$ and β_j are expressed such as $f_j(x,u) = f_{0j}(x) + \theta^T W_{fj}(x,u)$ and $\beta(x,u) = \beta_0(x) + \theta^T W_\beta(x,u)$

With $x \in \Re^n$, $\theta \in \Re^p$, $f_j(x,u)$ and $\beta(x,u) \in C^1$, $W_{fj}(x,u)$ and $W_\beta(x,u) \in \Re^p$.

The function $W_{fj}(x,u)$ and $W_\beta(x,u)$ must satisfy the following assumption.

A. Assumption:

- $W_{fj}(x,u) > W_\beta(x,u)$
- $W_{fj}(x,u) < \alpha$
- $W_{fj}(x,u)$ and $W_\beta(x,u)$ have the same sign

With $\alpha \in \Re^n$

B. Definition: Weighting Control Lyapunov Function (WCLF)

For a state vector bounded. We define the following function:

$$V = \int_0^{e_{sj}} \sigma \beta_\alpha (x, \sigma + l_j) d\sigma \tag{6}$$

Where $\beta_\alpha(x, \sigma + l_j) = \alpha(x)\beta(x, \sigma + l_j)$

The function V is a Weighting Control Lyapunov Function (WCLF) if:

- $\alpha(x)$ is a smooth function
- V is positive for an error e_{sj}
- V is radically unbounded with respect e_{sj} i.e $V \to \infty$ when $e_{sj} \to \infty$
- $\dot{V} \le 0 \quad \forall\ e_{sj} \ne 0$

The function $\alpha(x)$ is a weighting function.

Theorem:

If the system (5) satisfies the assumption and if the function WCLF (6) verifies the condition as [6], the adaptive sliding mode observer for the form of the system (5) is defined as follows:

$$S_j \begin{cases} \dot{\hat{x}}_{1j} = \hat{x}_{2j} - s_{1j} \\ \dot{\hat{x}}_{2j} = \dfrac{\hat{\theta}^T W_{fj}(\hat{x},u)}{\hat{\theta}^T W_\beta(\hat{x},u)} - s_{2j} \\ \dot{\hat{\theta}} = \Gamma^{-1} e_{sj} \begin{bmatrix} \sup(W_{fj}(x_{1j}, e_{sj} + l_j) W_\beta^T(\hat{x}) - \\ W_\beta(x_{1j}, l_j) \sup(W_{fj}^T(\hat{x}) + \alpha \end{bmatrix} \hat{\theta} \end{cases} \tag{7}$$

The stability of the adaptive observer is guaranteed for all gains verifying this relation:

$$\sum_{i=1}^{2} k_{ij} \ge \sum_{i=1}^{2} \lambda_{ij} \quad \text{and} \quad |\tau| > 1$$

With $\Gamma^{-1} \in \Re^{nxn}$

s_{ij} is the sliding surface which is written as

$s_{ij} = -k_{ij} e_{sj} + \lambda_{ij} sign(e_{sj})$, $i = 1,2$; $j = 1, \cdots\cdots, m$

$e_{sj} = \dot{e}_{1j} + \tau e_{1j}$: is the filtered error.

The error vector of each subsystem is

$e_j = [x_{1j} - \hat{x}_{1j} \quad x_{2j} - \hat{x}_{2j}]^T$

To design the observer, the expression (6) becomes:

$$V = \int_0^{e_{sj}} \sigma \beta_\alpha (x_{1j}, \sigma + l_j, \hat{x}_{2j}) d\sigma \tag{8}$$

Where $\alpha(x)$ will be $\beta(\hat{x}_{2j})$,

$\beta_\alpha(x_{1j}, \sigma + l_j, \hat{x}_{2j}) = \beta(x_{1j}, \sigma + l_j)\beta(\hat{x}_{2j})$ and $l_j = \hat{x}_{2j} - [\tau \ \ 0] e_j$

The state vector of each subsystem becomes:

$x_j = (x_{1j}, e_{sj} + l_j)$

The lyapunov function (8) satisfies the same condition as (6).

These two architectures of adaptive observer are applied to an inverted pendulum mounted on a cart to test their performance.

IV. Example

The studied adaptive observers are applied to the inverted pendulum mounting on a cart [15] having a Lipchitz nonlinearity which can be transformed into a fractional form. The equations of motion of the systems are:

$$\begin{cases}(M+m)\ddot{x}+F_x\dot{x}+ml(\ddot{\theta}\cos(\theta)-\dot{\theta}^2\sin(\theta))=u\\ j\ddot{\theta}+F_\theta\dot{\theta}-m\lg\sin(\theta)+ml\ddot{x}\cos(\theta)=0\end{cases}$$

With x is the linear displacement and θ is the angular displacement; m the pendulum mass; M the car mass; l the link length and F_x and F_θ are the forces.

In the state space, the system is written as:

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=\left[\theta_1F_xx_2+\theta_2(\dot{x}_4\cos(x_3)-x_4^2\sin(x_3))\right]\\ \dot{x}_3=x_4\\ \dot{x}_4=j^{-1}\left[\theta_3(g\sin(x_3)-\dot{x}_2\cos(x_3))+F_\theta x_4\right]\\ y=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\end{bmatrix}\end{cases} \tag{9}$$

Where $\theta=\begin{bmatrix}\theta_1=-\dfrac{1}{M+m}\\ \theta_2=-\dfrac{ml}{m+M}\\ \theta_3=ml\end{bmatrix}$, $A=\begin{bmatrix}0&1&0&0\\0&0&0&0\\0&0&0&1\\0&0&0&\dfrac{F_\theta}{j}\end{bmatrix}$,

$\phi(\hat{x},u)=0$,

$$f(x,u)=\begin{bmatrix}0&0&0\\ F_xx_2&\begin{bmatrix}\dot{x}_4\cos(x_3)-\\ x_4^2\sin(x_3)\end{bmatrix}&0\\ 0&0&0\\ 0&0&\begin{bmatrix}g\sin(x_3)-\\ \dot{x}_2\cos(x_3)\end{bmatrix}\end{bmatrix}$$

Applying the adaptive observer (2) to this system, the following expressions are obtained:

- The sliding mode observer:

$$\begin{cases}\dot{\hat{x}}_1=\hat{x}_2+L_1(x_1-\hat{x}_1)-\lambda_1 sign(x_1-\hat{x}_1)\\ \dot{\hat{x}}_2=\left[\hat{\theta}_1F_x\hat{x}_2+\hat{\theta}_2(\dot{\hat{x}}_4\cos(\hat{x}_3)-\hat{x}_4^2\sin(\hat{x}_3))\right]+\\ L_2(x_2-\hat{x}_2)-\lambda_2 sign(x_2-\hat{x}_2)\\ \dot{\hat{x}}_3=\hat{x}_4+L_3(x_3-\hat{x}_3)-\lambda_3 sign(x_3-\hat{x}_3)\\ \dot{\hat{x}}_4=j^{-1}\left[\hat{\theta}_3(g\sin(\hat{x}_3)-\dot{\hat{x}}_2\cos(\hat{x}_3))+F_\theta\hat{x}_4\right]+\\ L_4(x_i-\hat{x}_i)-\lambda_4 sign(x_i-\hat{x}_i);\quad i=1,2\, or\, 3\end{cases} \tag{10}$$

- The adaptation law:

$$\begin{cases}\dot{\hat{\theta}}_1=-\dfrac{1}{\rho_1}F_x\hat{x}_2e_2\\ \dot{\hat{\theta}}_2=-\dfrac{1}{\rho_2}(\dot{\hat{x}}_4\cos(\hat{x}_3)-\hat{x}_4^2\sin(\hat{x}_3))e_2\\ \dot{\hat{\theta}}_3=-\dfrac{1}{\rho_3}j^{-1}(g\sin(\hat{x}_3)-\dot{\hat{x}}_2\cos(\hat{x}_3))e_4\end{cases} \tag{11}$$

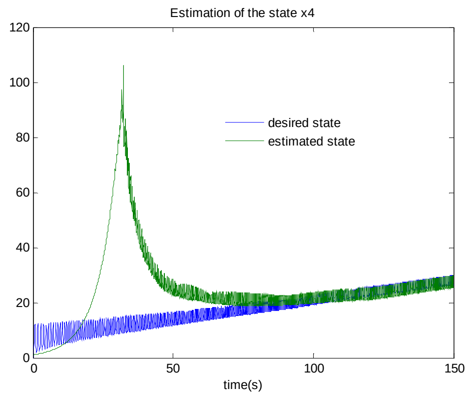
The nominal parameters used in simulations are:

$M=3.2Kg$; $m=0.535Kg$; $j=0.062Kgm^2$;
$l=0.365m$; $F_x=6.2Kg/s$; $F_\theta=0.009Kg/m^2$ *and* $g=9.807m/s^2$

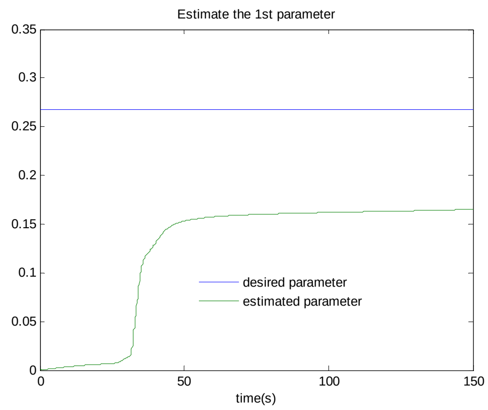
And the simulation conditions are:

$L_1=40$; $L_2=25$; $L_3=20$; $L_4=35$; $\lambda_1=\lambda_2=\lambda_3=10^{-3}$, $\lambda_4=-8$; $\hat{\theta}_1(0)=\hat{\theta}_2(0)=\hat{\theta}_3(0)=\hat{\theta}_4(0)=0$; $\hat{x}_1(0)=1$; $\hat{x}_2(0)=3$; $\hat{x}_3(0)=10^{-3}$; $\hat{x}_4(0)=1$; $x_1(0)=1$; $x_2(0)=3$; $x_3(0)=10^{-3}$; $x_4(0)=1$; $\dfrac{1}{\rho_1}=7*10^{-6}$; $\dfrac{1}{\rho_2}=2*10^{-6}$; $\dfrac{1}{\rho_3}=2*10^{-6}$;

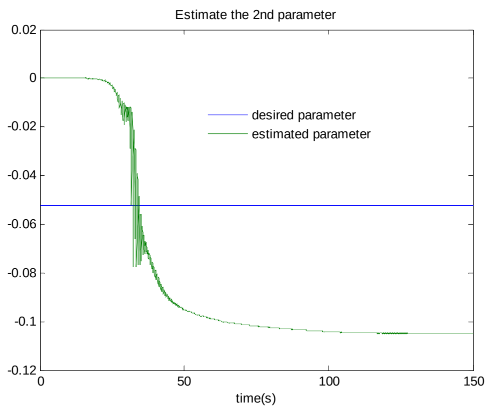
In figure (1), it is shown that the adaptive sliding mode observer designed for a Lipchtiz nonlinear system has a modest performance to estimate the angular speed and the parameters.



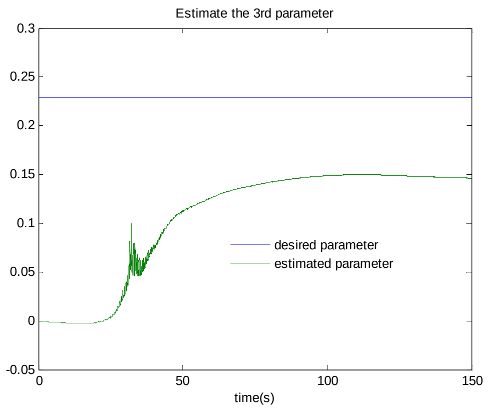
(a) Estimation of the state x_4



(b) Estimation of the parameter θ_1



(c) Estimation the parameter θ_2



(d) Estimation the parameter θ_3

Fig.1: Estimation of the state and the parameters by an adaptive sliding mode observer

To apply the second adaptive observer the system should be put on fractional form.

After development and simplification, the equation of the system (9) becomes:

$$s_1\begin{cases}\dot{x}_{11} = x_{21} \\ \dot{x}_{21} = \dfrac{[-F_x x_{21} + j^{-1}(ml)^2 g\sin(x_{12})\cos(x_{12}) - (ml)(j^{-1}F_\theta x_{22}\cos(x_{12}) - x_{22}^2\sin(x_{12})]}{(m+M) - j^{-1}(ml)^2((\cos(x_{12}))^2)}\end{cases} \quad (12)$$

$$s_2\begin{cases}\dot{x}_{12} = x_{22} \\ \dot{x}_{21} = \dfrac{j^{-1}\begin{bmatrix}(M+m)F_\theta x_{22} - \\ (ml)^2 x_{22}^2\sin(x_{12})\cos(x_{12}) + \\ (ml)F_x x_{21}\cos(x_{12}) + (m+ \\ M)(ml)g\sin(x_{12}))\end{bmatrix}}{(m+M) - j^{-1}(ml)^2((\cos(x_{12}))^2)}\end{cases} \quad (13)$$

The output vector is $y = \begin{bmatrix} x_{11} & x_{12}\end{bmatrix}$ and the parameter vector is

$$\theta = \begin{bmatrix} -(ml)^2 & -(ml) & (m+M) & (m+M)(ml)\end{bmatrix}^T$$

With: $\theta_1 = -(ml)^2$; $\theta_2 = -(ml)$; $\theta_3 = (m+M)$ and $\theta_4 = (m+M)(ml)$

Applying the architecture (9), it yields to the following systems:

The sliding mode observer having a filtered error is:

$$s_1\begin{cases}\dot{\hat{x}}_{11} = \hat{x}_{21} - s_{11} \\ \dot{\hat{x}}_{21} = \dfrac{[-F_x\hat{x}_{21} + j^{-1}(ml)^2 g\sin(\hat{x}_{12})\cos(\hat{x}_{12}) - (ml)(j^{-1}F_\theta\hat{x}_{22}\cos(\hat{x}_{12}) - \hat{x}_{22}^2\sin(\hat{x}_{12}))]}{(m+M) - j^{-1}(ml)^2((\cos(\hat{x}_{12}))^2)} - s_{21}\end{cases}$$

$$s_2\begin{cases}\dot{\hat{x}}_{12}=\hat{x}_{22}-s_{12}\\ \dot{\hat{x}}_{21}=\dfrac{j^{-1}\begin{bmatrix}(M+m)F_\theta\hat{x}_{22}-(ml)^2\hat{x}_{22}^2\sin(\hat{x}_{12})\cos(\hat{x}_{12})\\ +(ml)F_x\hat{x}_{21}\cos(\hat{x}_{12})+\\ (m+M)(ml)g\sin(\hat{x}_{12}))\end{bmatrix}}{(m+M)-j^{-1}(ml)^2((\cos(\hat{x}_{12}))^2)}-s_{22}\end{cases}\tag{20}$$

(21)

With:

$s_{11}=-k_{11}\,\mathrm{e}_{s1}+\lambda_{11}\mathrm{sat}(\mathrm{e}_{s1})$; $s_{21}=-k_{21}\,\mathrm{e}_{s1}+\lambda_{21}\mathrm{sat}(\mathrm{e}_{s1})$

; $s_{12}=-k_{12}\,\mathrm{e}_{s2}+\lambda_{12}\mathrm{sat}(\mathrm{e}_{s2})$; $s_{22}=-k_{22}\,\mathrm{e}_{s2}+\lambda_{22}\mathrm{sat}(\mathrm{e}_{s2})$;

$e_{s1}=\dot{e}_{11}+\tau e_{11}$; $e_{s2}=\dot{e}_{12}+\tau e_{12}$;

$e_{11}=x_{11}-\hat{x}_{11}$; $e_{12}=x_{12}-\hat{x}_{12}$; *and* $x_{22}=e_{s2}+l_2$

The adaptation law is expressed to the subsystems s_2 because it contains all the parameters. Since we have

$$\sup\left(W_{f22}(x_{12,}e_{s2}+l_2)\right)=\begin{bmatrix}j^{-1}x_{22}^2\\ -j^{-1}F_x x_{21}\\ j^{-1}F_\theta\hat{x}_{22}\\ j^{-1}g\end{bmatrix};$$

$$W_\beta(x)=\begin{bmatrix}j^{-1}(\cos(\hat{x}_{12}))^2\\ 0\\ 1\\ 0\end{bmatrix}$$

$$;\sup\left(W_{f22}(\hat{x}_{22})\right)=\begin{bmatrix}j^{-1}\hat{x}_{22}^2\\ -j^{-1}F_x\hat{x}_{21}\\ j^{-1}F_\theta\hat{x}_{22}\\ j^{-1}g\end{bmatrix}$$

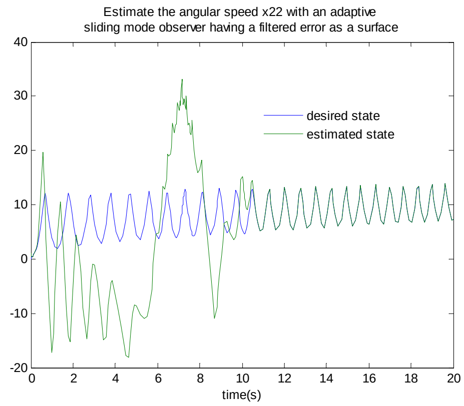
The adaptation law is the following:

$$\begin{cases}\dot{\hat{\theta}}_1=\Gamma_1^{-1}e_{s2}\begin{bmatrix}j^{-2}(\cos(\hat{x}_{12}))^2((e_{s2}+l_2)^2-\hat{x}_{22}^2)\hat{\theta}_1-\\ j^{-2}F_x\hat{x}_{21}\hat{\theta}_2+(-j^{-2}F_\theta\hat{x}_{22}(\cos(\hat{x}_{12}))^2\\ +j^{-1}(e_{s2}+l_2)^2)\hat{\theta}_3-\\ \hat{\theta}_4 j^{-2}g(\cos(\hat{x}_{12}))^2+21000\end{bmatrix}\\ \dot{\hat{\theta}}_2=\Gamma_2^{-1}e_{s2}\begin{bmatrix}-j^{-2}F_x\hat{x}_{21}(\cos(\hat{x}_{12}))^2\hat{\theta}_1+j^{-1}F_x\hat{x}_{21}\hat{\theta}_3\\ -80\end{bmatrix}\\ \dot{\hat{\theta}}_3=\Gamma_3^{-1}e_{s2}\begin{bmatrix}(j^{-2}F_\theta(\cos(\hat{x}_{12}))^2(e_{s2}+l_2)-\\ j^{-1}\hat{x}_{22}^2)\hat{\theta}_1+j^{-1}F_x\hat{x}_{21}\hat{\theta}_2+\\ (-j^{-2}F_\theta\hat{x}_{22}(\cos(\hat{x}_{12}))^2+\\ j^{-1}(F_\theta((e_{s2}+l_2)-\hat{x}_{22}))\hat{\theta}_3-\\ \hat{\theta}_4 j^{-1}g+1000\end{bmatrix}\\ \dot{\hat{\theta}}_4=\Gamma_4^{-1}e_{s2}\left[j^{-2}g(\cos(\hat{x}_{12}))^2\hat{\theta}_1+j^{-1}g\hat{\theta}_3+1600\right]\end{cases}\tag{22}$$

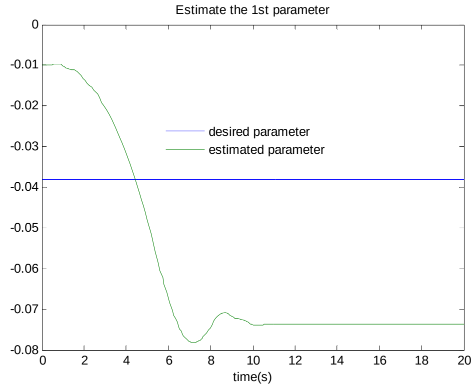
The simulation parameters are:

$\hat{\theta}_1(0)=-0.01$; $\hat{\theta}_2(0)=0$; $\hat{\theta}_3(0)=21$; $\hat{\theta}_4(0)=0.6$; $k_{11}=0.85$; $k_{21}=1$; $k_{12}=0.1$; $k_{22}=0.1$; $\lambda_{11}=\lambda_{12}=\lambda_{21}=10^{-5}$ $\lambda_{22}=-30$; $\Gamma_1^{-1}=-6*10^{-9}$; $\Gamma_2^{-1}=10^{-5}$; $\Gamma_3^{-1}=-10^{-5}$; $\Gamma_4^{-1}=10^{-6}$; $\tau=5.x_{11}(0)=2$; $x_{21}(0)=1$; $x_{12}(0)=10^{-5}$; $x_{22}(0)=0$; $\hat{x}_{11}(0)=2$; $\hat{x}_{21}(0)=3$; $\hat{x}_{12}(0)=10^{-4}$; $\hat{x}_{22}(0)=1$

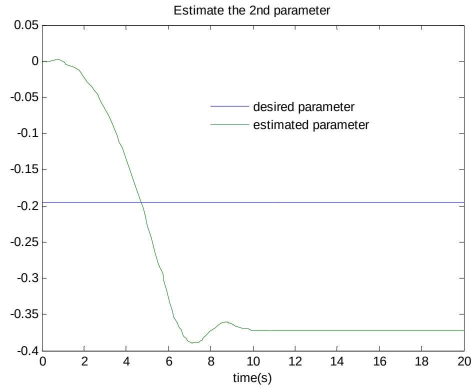
According to the simulation results, the adaptive sliding mode observer having a filtered error as a sliding surface shows the good performances in estimating the angular speed x_{22} (Figure 2.a), whereas the parameters do not converge (Figure 2.b.c.d.e). This result is the same as in [7].



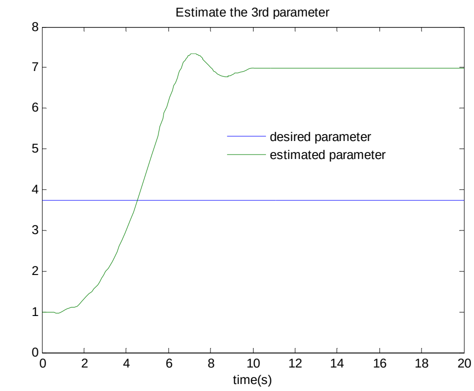
(a) Estimation of the state x_{22}



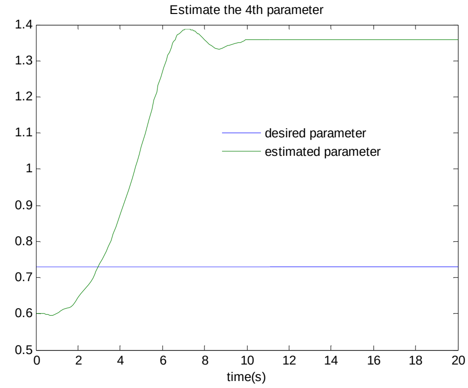
(b) Estimation of the parameter θ_1



(c) Estimation the parameter θ_2



(d) Estimation the parameter θ_3



(e) Estimation of the parameter θ_4

Fig. 2 Estimation of the state and the parameters by an adaptive observer having a filtered error as sliding surface and constant parameters

By comparing this result to the first one, we have shown that the adaptive sliding mode observer having a filtered error is more robust than the adaptive sliding mode observer designed to a lipchitz nonlinear systems to estimate the angular speed of the inverted pendulum. But both are not efficient to estimate all the parameters.

V. Conclusion

In this work, the performances of the two adaptive sliding mode observers are studied through the example of inverted pendulum mounting on a cart. It was shown that the performance of the adaptive sliding mode observer attributed to a lipchitz nonlinear system is modest when the nonlinearity is written in a fractional nonlinear form. An adaptive sliding observer having a filtered error as a sliding surface is applied to a fractional nonlinear system; it gives better performance to estimate the states than the first one. But both architectures of the adaptive observer are not efficient to estimate all the parameters.

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