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Journal of ELECTRICAL ENGINEERING, VOL. 66, NO. 4, 2015, 203–213

FUZZY BACKSTEPPING TORQUE CONTROL OF PASSIVE TORQUE SIMULATOR WITH ALGEBRAIC PARAMETERS ADAPTATION

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This work presents fuzzy backstepping control techniques applied to the load simulator for good tracking performance in presence of extra torque, and nonlinear friction effects. Assuming that the parameters of the system are uncertain and bounded, Algebraic parameters adaptation algorithm is used to adopt the unknown parameters. The effect of transient fuzzy estimation error on parameters adaptation algorithm is analyzed and the fuzzy estimation error is further compensated using saturation function based adaptive control law working in parallel with the actual system to improve the transient performance of closed loop system. The saturation function based adaptive control term is large in the transient time and settles to an optimal lower value in the steady state for which the closed loop system remains stable. The simulation results verify the validity of the proposed control method applied to the complex aerodynamics passive load simulator.

K e y w o r d s: passive torque simulator, mathematical modelling, backstepping, fuzzy logic, algebraic parameters adaptation

1 INTRODUCTION

Passive torque simulator is one of the most important equipments in ground based hardware in the loop (HIL) simulation system, which simulates aerodynamics loads torque or forces on flight control system in real time according to the flight conditions. The ground testing enables the designer to qualify the actuators of control surfaces and rudders before conducting actual flight tests [1]. There are three types of load simulators. The electro hydraulic load simulators are used to simulate high loads. Some of the factors that degrade control performance of electro hydraulic load simulators are high maintenance cost, leakage and low power efficiency. Similarly pneumatics simulator can simulate medium range loads on actuators under test [2]. Due to the recent improvements and developments in the electronics drivers and torque motors, the electrical load simulator is the best choice for simulating small and medium range aerodynamics loads. PMSM is a good choice used as a torque loading motor [1, 2]. Since the load simulator is used to test the performance of actuators under test and its qualification for development, so good control performance of load simulator is very crucial and of prime importance. There are many factors that degrade control performance of electrical load simulator. Some of the factors are discussed briefly.

In loading experiment the actuator under test and the loading motor are connected directly through a rigid shaft. The reference position command to the actuator under test will cause the loading motor to move as well even if the input command of the loading motor is zero. This will create additional component of toque in the loading motor which will strongly influence the control performance of torque loading motor. This additional component of torque induced in the loading motor due to the movement of actuator under test is called extra torque [4]. Friction is another nonlinear phenomenon which can lead to very poor control performance, therefore the nonlinear phenomenon must be compensated for good control performance [2].

Unknown or uncertain parameters of a complex electromechanical system lead to model error. It is vital to estimate the unknown parameters online and compensate for modeling error [3]. Most of the past research is focused on analyzing extra torque and its compensation. Since the mathematical model of the whole simulator is very complex. The simple state equation was derived in [1] and fuzzy SMC control scheme was adopted for good tracking performance. The research was further enhanced by considering parametric uncertainties in the model and deriving suitable control scheme for electrical load simulator [3]. Jiao analyzed the basic reason of extra toque generation and used feed forward technique to eliminate extra torque [4]. The velocity synchronization method was proposed in [6] to compensate extra torque.

This work is focused on designing fuzzy backstepping control scheme for torque tracking loop with algebraic parameter adaptation scheme. The complex mathematical model of load simulator is derived in to a simple state model. Backstepping method is used to drive the main feedback loop of the load simulator. Fuzzy logic is used to estimate extra torque and nonlinear friction. Practically the fuzzy estimation error cannot converge to zero; this will lead to tracking error. Secondly since the extra torque is acting on torque loading motor just after the

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DOI: 10.2478/jee-2015-0033, Print ISSN 1335-3632, On-line ISSN 1339-309X

start up of the system, so it is necessary to introduce a control effort component which can compensate for fuzzy estimation error as well improve the transient tracking response. This work proposes saturation function based adaptive law to compensate for the fuzzy estimation error and improve transient response. Furthermore the effect of fuzzy estimation error on the algebraic parameters estimation is analyzed through simulation. The organized of the paper is as follow.

2 PROBLEM FORMULATION

Electrical motor based PTS torque servo system is a coupled electromechanical system which suffers from inherent strong coupling disturbance of the actuator under test. Nonlinear friction is another dominant factor that degrades control performance of PTS. To design a novel controller for good torque tracking performance the following ideas are highlighted. Backstepping control is designed to track the torque reference trajectory in combination of fuzzy logic system. Fuzzy logic is used to estimate the nonlinear friction and extra torque. From the previous section it is concluded that PTS system is influenced by extra torque even in the transient time [4]. Hence fuzzy logic based extra torque estimation is not very good in the transient time due to processing delays which induce transient tracking error. The transient tracking error needs to be addressed for good control performance.

To compensate of transient tracking error we add additional fixed gain robust control component, which compensate for transient tracking error, with chattering in the control signal. Assuming that the parameters of PTS servo system are uncertain and bounded, Algebraic parameters adaptation is used to estimate the uncertainty in the parameters because mismatch state parameters in the controller will lead to poor performance. Fixed gain robust term used to compensate transient tracking error leading to chattering in control signal and noisy measured states will have adverse effect on parameter adaptation algorithm. So the compromise between robustness and accuracy of parameters estimation is hard to balance. To ensure overall good control performance of torque servo system elimination of transient tracking error as well fast and accurate estimation of uncertain state parameters are very crucial.

In the view of above, a novel composite controller is proposed which can compensate for transient tracking error without chattering in the control signal. The fixed robust control term is replaced by adaptive control term. The gain of the adaptive controller is reasonably high at the very start of transient cycle to suppress transient tracking error and it decreases sharply to avoid chattering in the control signal. So it ensures good transient tracking performance as well chattering free control signal available to be used for accurate parameters estimation.

The noisy measured state is low pass filtered. The algebraic parameters adaptation algorithm working in parallel with composite controller can ensure fast and accurate estimation of uncertain parameters. The stability of the closed loop is analyzed.

3 SYSTEM DYNAMICS AND MATHEMATICAL ANALYSIS

The overall block diagram of load simulator is shown in Fig. 1. Mathematical model of passive torque simulator is very complex and needs to be analyzed deeply. Before deriving simple state model, S domain model is analyzed to understand the factors influencing control performance of passive torque simulator. The voltage and torque equations of torque motor can be described as

$$U = iR + L\frac{\mathrm{d}i}{\mathrm{d}t} + K_b w_m\,, \tag{1}$$

$$T_e = K_t i = J\frac{\mathrm{d}w_m}{\mathrm{d}t} + Bw_m + T_f + T_L\,, \tag{2}$$

$$T_L = K_s(\theta_m - \theta_a)\,. \tag{3}$$

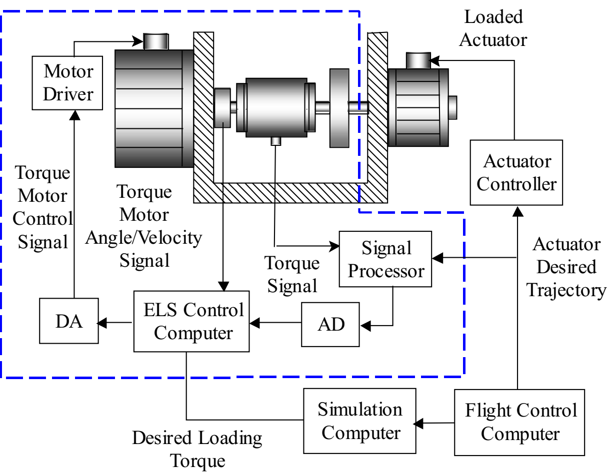

Fig. 1. Block diagram of passive torque simulator

T_f is the the nonlinear friction.In this work we will use the simplified stribeck friction model to simulate the effect of friction. In (3) T_L is the loading torque applied on actuator under test .The loading torque consist of actual loading torque and the extra torque component to be discussed later. Equation (3) represents the simplified dynamics of torque sensor assuming that inertia and damping coefficient of torque sensor is negligible as compared to the whole system.

Parameter K_s is the stiffness of torque sensor. Parameters θ_m and θ_a represent the motor and actuator position. J, B, K_b and K_t are the mechanical parameters, R and L are the electrical parameters of the system. According to [1] the relation of loading torque is given by

$$T_L = \frac{K_v K_i K_t V - S[(LS+R)(JS+B) + K_b K_t]K_s\theta_a}{D(S)}\,. \tag{4}$$

Here K_v and $K_i$are the voltage and current amplifier gain. From (4) it is clear that loading torque consist of two components. The first component is due to the reference command V, and the second term is due to the movement of actuator command θ_a.

3.1 Mathematical formulations and PTS state model derivation

To design a good control system, the complex model should be simplified because it is very difficult to design a good control system with very complex model and understand its all aspect. Consider Fig. 2 as a reference diagram for deriving the simplified mathematical model. PTS is connected through a stiff shaft to the actuator with the torque sensor in the middle. The state model is derived in [1, 3]. Here we derive the model in more detail.

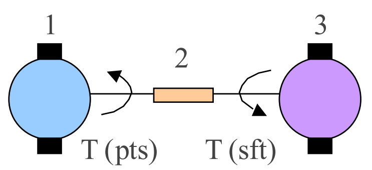

Fig. 2. 1 — torque motor, 2 — sensor, 3 — actuator

Case 1. We assume that the reference command input to the PTS is zero. In that case if the actuator moves with a reference command, PTS has to move and act as a generator. As a result back emf will be generated and current will flow throw the winding and hence will cause an electromagnetic torque. This torque as referred as the extra torque in the case when reference torque of PTS is zero. So (1) and (2) can be represented as

$$-K_b w_m^* = i^* R + L\frac{\mathrm{d}i^*}{\mathrm{d}t}\,. \tag{5}$$

PTS will act as generator with no load. w_m^* is the PTS motor velocity due the actuator effect. Parameter i^* is the current flowing in PTS motor winding due to the actuator effect. Similarly torque balance equation can be written as

$$T_{sft} - T_e^* = -J\frac{\mathrm{d}w_m^*}{\mathrm{d}t} - Bw_m^*\,. \tag{6}$$

In (6) T_{sft} is the mechanical shaft torque which is responsible for moving the PTS torque motor. We assume that the PTS motor will follow the actuator speed so we have $w_m* \approx w_a$.

Case 2. When the PTS torque motor reference command is not zero and it applies loading torque on actuator under test so the voltage and torque balance equations of the PTS system will also have the additional terms as given in (5) and (6). So the resultant equations can be written as

$$u = (i - i^*)R + L\frac{\mathrm{d}(i - i^*)}{\mathrm{d}t} + K_b(w_m - w_a)\,, \tag{7}$$

$$T_e - T_e^{*'} = J(\ddot\theta_m - \ddot\theta_a) + B(\dot\theta_m - \dot\theta_a) + T_{sft} + T_f + T_L\,. \tag{8}$$

Assuming that the electrical dynamics of PTS system is faster than the mechanical dynamics thus ignoring the term $L\frac{\mathrm{d}i+i^*}{\mathrm{d}t}$ the resultant equations can be expressed as

$$(i - i^*) = \frac{u - K_b(w_m - w_a)}{R}\,. \tag{9}$$

$$(i - i^*)k_t = J(\ddot\theta_m - \ddot\theta_a) + B(\dot\theta_m - \dot\theta_a) + T_{sft} + T_f + T_L\,. \tag{10}$$

after some manipulation we get

$$\ddot T_L = \frac{K_s k_t u}{JR} - \frac{k_t k_b}{JR}\dot T_L - \frac{B}{J}\dot T_L - \frac{K_s}{J}T_{sft} - \frac{K_s}{J}T_f - \frac{K_s}{J}T_L\,. \tag{12}$$

Where $\dot T_L = K_s(\dot\theta_m - \dot\theta_a)$ and $\ddot T_L = K_s(\ddot\theta_m - \ddot\theta_a)$ and represents the first and second derivative of load torques.

$$\ddot T_L = \frac{K_s k_t u}{JR} - \Big(\frac{k_t k_b}{JR}\Big)\dot T_L - \frac{K_s}{J}T_{sft} - \frac{K_s}{J}T_f - \frac{K_s}{J}T_L\,, \tag{13}$$

$$\ddot T_L = -a\dot T_L + bu - c\big(T_{sft} + T_f + T_L\big)\,. \tag{14}$$

According to assumption 1, let ΔJ, ΔB and ΔK_t, ΔR and ΔK_s is the bounded uncertainty in the parameters of PTS system then (14) can be represented as

$$\ddot T_L = -(a + \Delta a)\dot T_L + (b + \Delta b)u - (c + \Delta c)(T_{sft} + T_f + T_L)\,, \tag{15}$$

$$\ddot T_L = -\hat a\dot T_L + \hat b u - \hat c(T_{sft} + T_f + T_L)\,, \tag{16}$$

$$\ddot T_L = -\hat a\dot T_L + \hat b u - \hat c T_L - f(T - \text{extra}, T_f)\,. \tag{17}$$

4 FUZZY BACKSTEPPING CONTROL

Backstepping control technique is a step wise recursive control design methodology which ensures high tracking performance as well as stability of the closed loop of nonlinear complex electromechanical systems. PTS torque servo system is strongly influenced by extra torque generated due to the movement of actuator under test. A method based on velocity synchronization for compensation of extra torque is proposed in [7], in which the instantaneous velocity of loaded actuator is calculated from nominal model and a suitable control term is designed to compensate for the velocity difference of PTS motor and loaded actuator. Since the parameters of actual loaded actuator may have uncertainty so this method cannot efficiently cancel the effect of extra torque. We propose Fuzzy logic for estimation purpose. Using fuzzy logic as estimator, we do not need dedicated encoder sensor for measurement of the angular position of loaded actuator to calculate the velocity instead the torque sensor output signal and its derivate is used as input to fuzzy logic. At this stage we ignore sensor noise which can affect the estimation algorithm. Since the output signal of torque sensor include all the dynamics including the actual loading torque and extra torque, so fuzzy logic is superior to use because the estimation can be accurately interpreted even in the case when the loaded actuator parameters are uncertain. Let T_L be output load torque and T_r be the desired torque signal, we define

$$e_1 = T_L - T_r\,, \qquad \dot{e}_1 = \dot{T}_L - \dot{T}_r\,. \tag{18}$$

Let $\dot{e}_1 = \alpha_1 - \dot{T}_r$. We choose Lyapunov function as

$$V_1 = \frac{1}{2}e_1^2\,, \qquad \dot{V}_1 = e_1(\alpha_1 - \dot{T}_r)\,. \tag{19}$$

Choosing the first virtual control we get

$$\begin{aligned} &\alpha_1 = -c_1 e_1 + \dot{T}_r\,,\\ &\dot{V}_1 = e_1(-c_1 e_1 + \dot{T}_r - \dot{T}_r) = -c_1 e_1^2\,. \end{aligned} \tag{21}$$

By choosing proper value of $c-1>0$ we can easily prove that $\dot{V}_1 < 0$. Now we define the second tracking error and its derivative as

$$e_2 = \dot{T}_L - \alpha_1\,, \qquad \dot{e}_2 = \ddot{T}_L - \dot{\alpha}_1\,. \tag{22}$$

Subtitling (17) into (22) we get

$$\dot{e}_2 = -\hat{a}\dot{T}_L + \hat{b}u - \hat{c}T_L - f\big(T_{\text{extra}}, T_f\big) - \dot{\alpha}_1\,. \tag{23}$$

Using (21) and (23)

$$\dot{\alpha}_1 = -c_1\dot{e}_1 + \ddot{T}_r\,. \tag{24}$$

$$\dot{e}_2 = -\hat{\alpha}\dot{T}_L + \hat{b}u - \hat{c}T_L - f\big(T_{\text{extra}}, T_f\big) - \big(c_1\dot{e}_1 + \ddot{T}_r\big). \tag{25}$$

Choose Lyapunov function as

$$V_2 = V_1 + \frac{1}{2}\Big(e_2^2 + \sum_{i=1}^{n}\eta_i\tilde{\theta}_i^2\Big). \tag{26}$$

After differentiating it and using (25)

$$\begin{aligned} \dot{V}_2 = -c_1 e_1^2 + e_2\big(&-\hat{a}\dot{T}_L + \hat{b}u - \hat{c}T_L - f(T_{\text{extra}}, T_f)\\ &+ c_1\dot{e}_1 - \ddot{T}_r\big) = \sum_{i=1}^{n}\eta_i\tilde{\theta}_i\dot{\tilde{\theta}}_i\,. \end{aligned} \tag{28}$$

We choose control law as

$$\begin{aligned} u = \frac{1}{\hat{b}}\big(&-c_2 e_2 + \hat{a}\dot{T}_L + \hat{c}T_L + \hat{f}\big(T_{\text{extra}}, T_f|\theta\big) - c_1\dot{e}_1 + \ddot{T}_r\big)\\ &- K_1(e_1 + \psi e_2) - K_2\,\text{sgn}(e_1 + \psi e_2)\,. \end{aligned} \tag{29}$$

To prove the stability of the whole closed loop we put (29) in (28)

$$\begin{aligned} \dot{V}_2 = -c_1 e_1^2 + e_2\big[&-c_2 e_2 - f\big(T_{\text{extra}}, T_f\big) + \hat{f}\big(T_{\text{extra}}, T_f|\theta\big)\\ - K_1(e_1 + \psi e_2) - K_2\,\text{sgn}(e_1 + \psi e_2)\big] &+ \sum_{i=1}^{n}\eta_i\tilde{\theta}_i\dot{\tilde{\theta}}_i\,. \end{aligned} \tag{31}$$

From [21] we define

$$\begin{aligned} e_f &= f\big(T_{\text{extra}}, T_f\big) - \hat{f}\big(T_{\text{extra}}, T_f\big)/\theta^*\\ \tilde{\theta}_i\xi_i(\dot{\theta}) &= \hat{f}\big(T_{\text{extra}}, T_f\big)/\theta - \hat{f}\big(T_{\text{extra}}, T_f\big)/\theta^*\,. \end{aligned} \tag{32}$$

Add and subtract $\tilde{f}\big(T_{\text{extra}}, T_f\big)/\theta^*$ in (31) and simplifying we get

$$\begin{aligned} \dot{V}_2 = -c_1 e_1^2 - c_2 e_2^2 - e_2\big[&-e_f - K_1(e_1 + \psi e_2)\\ &- K_2\,\text{sgn}(e_1 + \psi e_2)\big] + \Big[e_2\tilde{\theta}_i\xi_i(\dot{\theta}) + \sum_{i=1}^{n}\tilde{\theta}_i\dot{\tilde{\theta}}_i\Big]. \end{aligned} \tag{33}$$

We define adaptive law to cancel the effect of last term in (33) as given by the following equation

$$\dot{\tilde{\theta}}_i = -\eta_i^{-1}e_2\xi_i(\dot{\theta})\,. \tag{34}$$

Ideally we assume that $e_f \approx 0$ and replacing (34) in (33) we get the simplified equation as

$$\dot{V}_2 = -c_1 e_1^2 - c_2 e_2^2 - e_2\big[-K_1(e_1 + \psi e_2) - K_2\,\text{sgn}(e_1 + \psi e_2)\big]. \tag{35}$$

By selecting optimum values of $c_1 > 0, c_2 > 0$, $K_1 > 0$ and $K_2 > 0$ it is easy to prove that

$$\dot{V}_2 < 0\,.$$

Thus the hybrid control law given in (29) can make the closed loop tracking error minimum with stable operation. The uncertainty in the parameters of the PTS system will be adopted using Algebraic parameters adaptation algorithm which will be derived and discussed in the next section.

5 ALGEBRAIC PARAMETERS ADAPTATION

Case 1. *Parameters Adaptation with noise and chattering free control signal.*

In this section we derive the detailed algorithm for parameters adaptation. Ideally we assume that the load toque measured is noise free as well control signal chattering is negligible. Consider equation (17) and follow the steps as given in [5].

$$\ddot{T}_L = -\hat{a}\dot{T}_L + \hat{b}T_L - \hat{c}T_L - f\big(T_{\text{extra}}, T_f\big). \tag{36}$$

We assume that ideally $\hat{f}\big(T_{\text{extra}}, T_f|\theta\big)$ of (27) will cancel out the $f\big(T_{\text{extra}}, T_f\big)$ term in (36) so the simplified form is given by

$$\ddot{T}_L + \hat{a}\dot{T}_L + \hat{c}\dot{T}_L = \hat{b}u\,. \tag{37}$$

Equation (37) has three unknown parameters so we derive the adaptation algorithm. The Laplace transform of (37) multiplied by s will give

$$\begin{aligned} \big(s^3T_L(s) - s^2T_L(0) - s\dot{T}_L(0)\big) + \hat{a}\big(s^2T_L(s) - sT_L(0)\big) +&\\ s\hat{c}T_L(s) = s\hat{b}u(s)\,.& \end{aligned} \tag{39}$$

Table 1. State Representation of Coefficient Matrix

$A_{11} = x_1$	$A_{12} = a_1$	$A_{13} = d_1$
$\dot{x}_1 = -t^3T_L + x_2$	$\dot{a}_1 = a_2$	$\dot{d}_1 = d_2$
$\dot{x}_2 = 6t^2T_L + x_3$	$\dot{a}_2 = t^3u + a_3$	$\dot{d}_2 = -t^3T_L + d_3$
$\dot{x}_3 = -6tT_L$	$\dot{a}_3 = -3t^2u$	$\dot{d}_3 = +3t^2T_L$
$A_{21} = y_1$	$A_{22} = b_1$	$A_{23} = e_1$
$\dot{y}_1 = y_2$	$\dot{b}_1 = b_2$	$\dot{e}_1 = e_2$
$\dot{y}_2 = -t^3T_L + y_3$	$\dot{b}_2 = b_3$	$\dot{e}_2 = e_3$
$\dot{y}_3 = 6t^2T_L + y_4$	$\dot{b}_3 = t^3u + b_4$	$\dot{e}_3 = -t^3T_L + e_4$
$\dot{y}_4 = -6tT_L$	$\dot{b}_4 = -3t^2u$	$\dot{e}_4 = +3t^2T_L$
$A_{31} = z_1$	$A_{32} = c_1$	$A_{33} = f_1$
$\dot{z}_1 = z_2$	$\dot{c}_1 = c_2$	$\dot{f}_1 = f_2$
$\dot{z}_2 = z_3$	$\dot{c}_2 = c_3$	$\dot{f}_2 = f_3$
$\dot{z}_3 = -t^3T_L + z_4$	$\dot{c}_3 = c_4$	$\dot{f}_3 = f_4$
$\dot{z}_4 = 6t^2T_L + z_5$	$\dot{c}_4 = t^3u + c_5$	$\dot{f}_4 = -t^3T_L + f_5$
$\dot{z}_5 = -6tT_L$	$\dot{c}_5 = -3t^2u$	$\dot{f}_5 = +3t^2T_L$

Table 2. State Representation of B Matrix

$B_1 = g_1 + t^3T_L$	$B_2 = h_1$	$B_3 = k_1$
$\dot{g}_1 = -9t^2T_L + g_2$	$\dot{h}_1 = t^3T_L + h_2$	$\dot{k}_1 = k_2$
$\dot{g}_2 = 18tT_L + g_3$	$\dot{h}_2 = -9t^2T_L + h_3$	$\dot{k}_2 = t^3T_L + k_3$
$\dot{g}_3 = -6T_L$	$\dot{h}_3 = 18tT_L + h_4$	$\dot{k}_3 = -9t^2T_L + k_4$
	$\dot{h}_4 = -6T_L$	$\dot{k}_4 = 18tT_L + k_5$
		$\dot{k}_5 = -6T_L$

Taking 3rd derivative of (39) with respect to s yields

$$\frac{\mathrm{d}^3}{\mathrm{d}s^3}\big(s^3T_L(s) - s^2T_L(0) - s\dot{T}_L(0)\big) + \hat{a}\frac{\mathrm{d}^3}{\mathrm{d}s^3}\big(s^2T_L(s) - sT_L(0)\big) + \hat{c}\frac{\mathrm{d}^3}{\mathrm{d}s^3}\big(sT_L(s)\big) = \hat{b}\frac{\mathrm{d}^3}{\mathrm{d}s^3}\big(su(s)\big). \quad (40)$$

Expanding the terms in (40) and multiplying it by s^{-3}, the resultant equation can be written as

$$\Big(\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 9s^{-1}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 18s^{-2}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s) + 6s^{-3}T_L(s) + \hat{a}\Big(s^{-1}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 6s^{-2}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 6s^{-3}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s)\Big) + \hat{c}\Big(s^{-2}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 3s^{-3}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s)\Big) = \hat{b}\Big(s^{-2}\frac{\mathrm{d}^3}{\mathrm{d}s^3}u(s) + 3s^{-3}\frac{\mathrm{d}^2}{\mathrm{d}s^2}u(s)\Big). \quad (42)$$

Multiply (42) by s^{-1} and s^{-2} to get another two equations as

$$\Big(s^{-1}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 9s^{-2}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 18s^{-3}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s) + 6s^{-4}T_L(s)\Big) + \hat{a}\Big(s^{-2}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 6s^{-3}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 6s^{-4}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s)\Big) + \hat{c}\Big(s^{-3}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 3s^{-4}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s)\Big) = \hat{b}\Big(s^{-3}\frac{\mathrm{d}^3}{\mathrm{d}s^3}u(s) + 3s^{-4}\frac{\mathrm{d}^2}{\mathrm{d}s^2}u(s)\Big), \quad (43)$$

$$\Big(s^{-2}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 9s^{-3}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 18s^{-4}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s) + 6s^{-5}T_L(s)\Big) + \hat{a}\Big(s^{-3}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 6s^{-4}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s) + 6s^{-5}\frac{\mathrm{d}}{\mathrm{d}s}T_L(s)\Big) + \hat{c}\Big(s^{-4}\frac{\mathrm{d}^3}{\mathrm{d}s^3}T_L(s) + 3s^{-5}\frac{\mathrm{d}^2}{\mathrm{d}s^2}T_L(s)\Big) = \hat{b}\Big(s^{-4}\frac{\mathrm{d}^3}{\mathrm{d}s^3}u(s) + 3s^{-5}\frac{\mathrm{d}^2}{\mathrm{d}s^2}u(s)\Big). \quad (44)$$

Re arranging (42), (43) and (44)

$$\begin{aligned} \hat{a}A_{11} + \hat{b}A_{12} + \hat{c}A_{13} &= B_1\,, \\ \hat{a}A_{21} + \hat{b}A_{22} + \hat{c}A_{23} &= B_2\,, \\ \hat{a}A_{31} + \hat{b}A_{32} + \hat{c}A_{33} &= B_3\,. \end{aligned} \quad (45)$$

Equation (45) can be represented in matrix form as

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix}. \quad (46)$$

And from theory of linear algebra we can find the solution as

$$\hat{a} = \frac{\begin{vmatrix} B_1 & A_{12} & A_{13} \\ B_2 & A_{22} & A_{23} \\ B_3 & A_{32} & A_{33} \end{vmatrix}}{\begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix}}, \quad \hat{b} = \frac{\begin{vmatrix} A_{11} & B_1 & A_{13} \\ A_{21} & B_2 & A_{23} \\ A_{31} & B_3 & A_{33} \end{vmatrix}}{\begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix}}, \quad \hat{c} = \frac{\begin{vmatrix} A_{11} & A_{12} & B_1 \\ A_{21} & A_{22} & B_2 \\ A_{31} & A_{32} & B_3 \end{vmatrix}}{\begin{vmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{vmatrix}}. \quad (47)$$

In (47) the coefficient of 3×3 matrix can be written as

$$\begin{aligned} A_{k1} &= -\int^{k} t^3T_L + 6\int^{k+1} t^2T_L - 6\int^{k+3} tT_L\,, \\ A_{k2} &= \int^{k+1} t^3u - 3\int^{k+2} t^2u\,, \\ A_{k3} &= -\int^{k+1} t^3T_L + 3\int^{k+2} t^2T_L\,, \end{aligned} \quad (48)$$

$$B_k = \int^{k-1} t^3T_L - 9\int^{k} t^2T_L + 18\int^{k+1} tT_L - 6\int^{k+2} T_L\,.$$

where $\int^0 f \equiv f$.

According to [5], it is better to write (48) in state form for implementation, so the resultant state equations can be written as given in Tabs. 1 and 2.

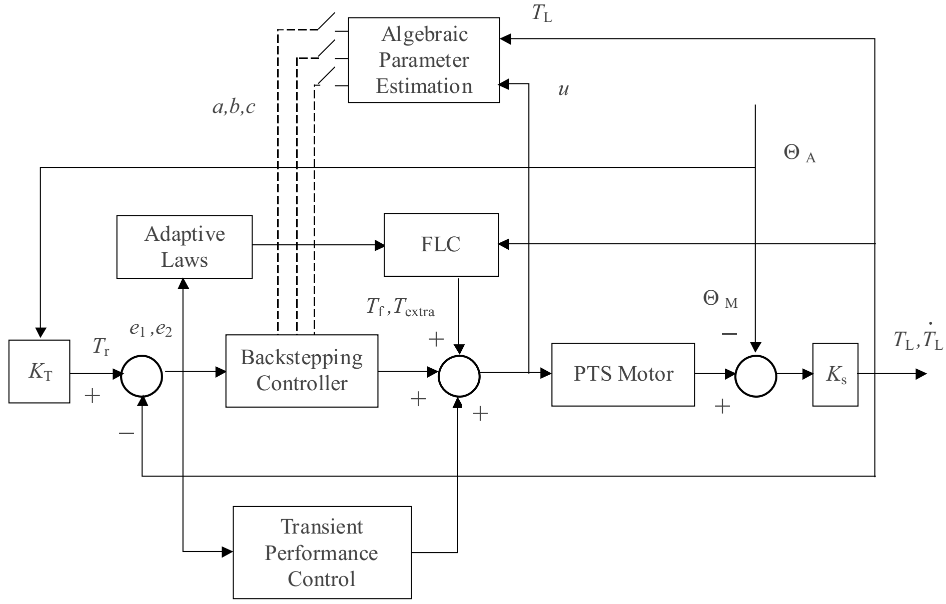

Fig. 3. PTS Torque Controller with Algebraic Parameters Estimation

Case 2. *Parameters Adaptation with noise and chattering in control signal.*

In the previous analysis we assumed that the measured signal at the output of torque sensor is noise free .Also the control signal was assumed to be chattering free. But practically the sensor noise is always present. So considering the two effects, the state equation can be represented as

$$\ddot{T}_L = -\hat{a}(\dot{T}_L + \dot{\eta}_s) + \hat{b}\overset{*}{u} - \hat{c}(T_L + \eta_s)\,. \tag{49}$$

In (49) n_s and n_s is the sensor noise and its derivate associated with T_L measurement from torque sensor, $\overset{*}{u}$ is the control signal with severe chattering.

For Accurate and fast parameters estimation the two effects in (49) needs to be addressed. Sensor noise can be suppressed using appropriate filter. For filtering noise we use integrator as low pass filter and the resulting equations can be written as

$$\hat{p} = \frac{(1/s^2) * |p|}{(1/s^2) * |A|}\,. \tag{50}$$

Here $\hat{p}$ is the estimated parameter, $|p$ is the determinant of the coefficient matrix after replacing the appropriate column vector and $|A|$ is the determinant of coefficient matrix.

The control signal chattering is associated with improvement of transient performance of torque controller when the robust control term is large and fixed. To solve chattering problem we use adaptive law based control, which ensures elimination of transient tracking error and chattering problems.

6 DESIGN OFADAPTIVE LAW FOR IMPROVING TRANSIENT RESPONSE AND ELIMINATION OF CHATTERING.

Figure 3 shows the overall control scheme with algebraic parameters estimation algorithm. The Control law defined in (29) as written as

$$u = u_m + u_{(\text{Extra,friction})} + u_r\,. \tag{51}$$

$$U_m = \frac{1}{\hat{b}}\big(-c_2e_2 + \hat{a}\dot{T}_L + \hat{c} - c_1\dot{e}_1 + \ddot{T}_r\big),$$

$$u_{(\text{Extra,friction})} = \frac{1}{\hat{b}}\big(\hat{f}(T_{\text{extra}}, T_f|\theta)\big),$$

$$u_r = -K_1\big(e_1 + \psi e_2\big) - K_2\,\mathrm{sgn}\big(e_1 + \psi e_2\big)\big)$$

u_m represents model based control and $u_{(\text{Extra,friction})}$ is the fuzzy compensation for the extra torque and friction.

In [4] the generation mechanism of extra torque is deeply analyzed. The extra torque is present even the control input to PTS is zero.

As we are using Fuzzy logic to estimate the extra torque which has some processing delays for estimation any function. So in the transient time the fuzzy compensation control for extra torque and friction is not very good, which leads to transient tracking error. So to cancel the transient error and other external disturbances a fixed gain control term u_r is added in (51). The transient tracking error is eliminated but the control signal suffers from severe chattering problem. Control signal with chattering is not feasible to be used for parameters estimation algorithm. For chattering free control signal and elimination of transient tracking error at the same time we propose adaptive law based control as given below.

$$\hat{u}_r = \mathrm{sat}(\hat{k}_1) * (e_1 + \psi e_2) + \mathrm{sat}(k_2) * \int (e_1 + \psi e_2)\,. \tag{52}$$

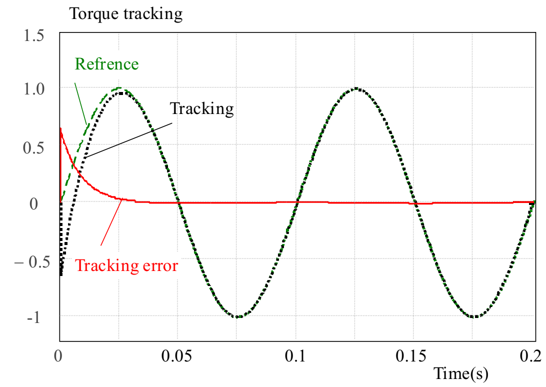

Fig. 4. Toque tracking performance case 1

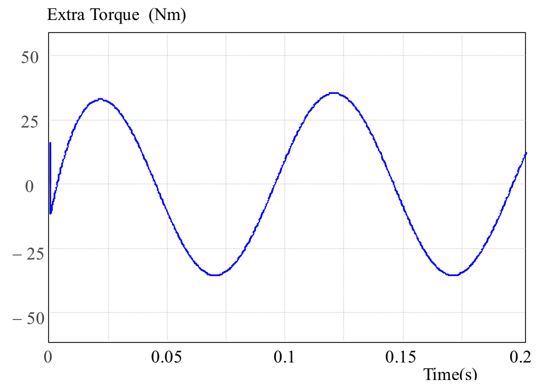

Fig. 5. Extra torque estimation

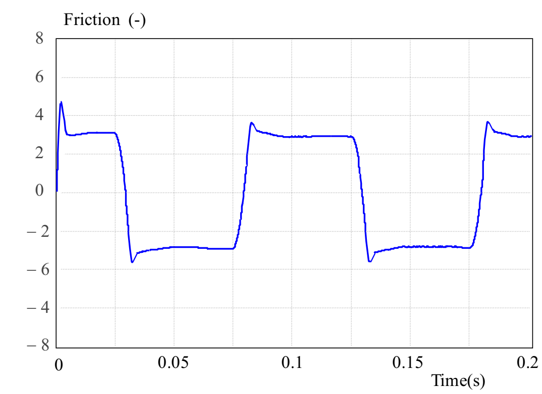

Fig. 6. Continuous friction estimation and compensation

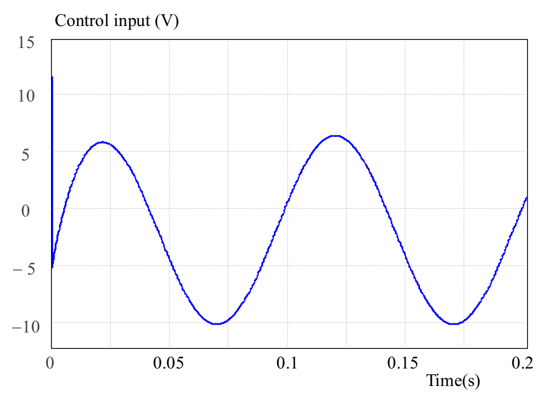

Fig. 7. Control input to PTS Motor case 1

Let $s = e_1 + \psi e_2$. Adaptive law to update $\hat{k}_1$ and $\hat{k}_2$ is given as in [22]

$$\dot{\hat{k}}_1 = -\gamma_1 * s * e_1\,, \quad \dot{\hat{k}}_2 = -\gamma_2 * s * \int (e_1)\,. \qquad (53)$$

The constant γ_1 and γ_2 are the estimation learning rate, the adaptive control gain will be large in the transient time and will settle to a minimum optimum value as the error and derivative of error decreases in the steady state. As a result the transient tracking error is compensated without chattering in the control signal. Further the control signal is useable at the input of algebraic parameter estimator.

6.1 Critical Analysis on stability of closed loop with adaptive controller

The adaptive controller derived in (52) is used to eliminate the transient tracking error as well as decrease the chattering in control. Since the gain of the controller is initial set to some large optimum value which will account for the transient tracking error and after a very small time interval the gain sharply decrease to lower optimum value to account for chattering in control signal.

A saturation function is used to restrict the gain $\hat{h}_1$ and $\hat{k}_2$ to the initial lower optimum values for which the closed loop stability was guaranteed. Without restricting the values to their optimum values the closed loop stability of the torque servo system cannot be guaranteed and the relation in equation (35) does not remain valid.

The possible reason for system instability is the nature of update laws as given (53). Let we suppose that the adaptive gain converges from initial value to a lower optimum value and the closed loop system is stable without saturation function, at that instant a small perturbation on the system can introduce a tracking error. So without saturation function the adaptive gain will further decrease below the optimum lower values and the loop will be unstable.

7 SIMULATION RESULTS AND DISCUSSION

For simulations and validity of proposed control scheme the following parameters are used. The PTS and the actuator system parameters are given as

Total inertia of the system is given as $J = 0.04$, resistance $R = 7.5$, PTS motor torque constant $Km = 5.732$, Back emf constant $Ke = 5.732$, viscous coefficient $B = 0.244$, torque sensor stiffness $Ks = 950$, static friction $Fs = 3$ Nm, Coulomb friction $Fc = 2.7$ N and Stribeck velocity $alfa = 0.01$.

The parameters of the controller are given as fuzzy learning rate $\eta_i = 0.0001$, amplifier gain $Ku = 10$, $C_1 = 117$, $C_2 = 110$, $K_1 = 1.5$, $K_2 = 0.5$.

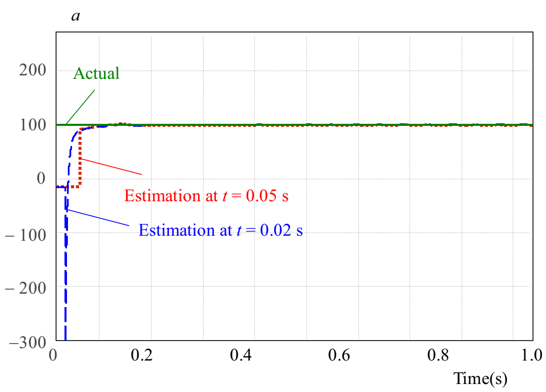

Fig. 8. Estimation of state parameter a

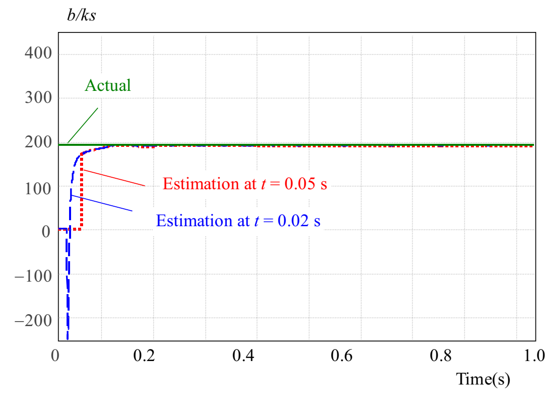

Fig. 9. Estimation of state parameter b/ks

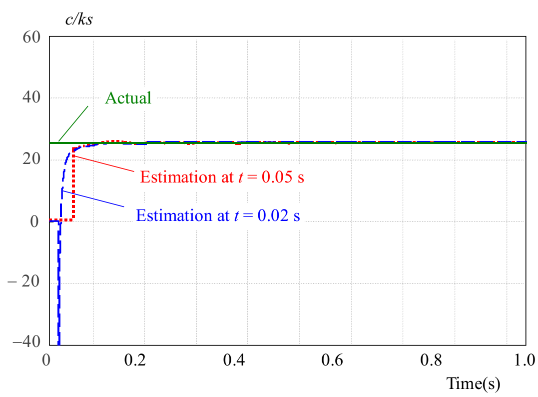

Fig. 10. Estimation of state parameter c/ks

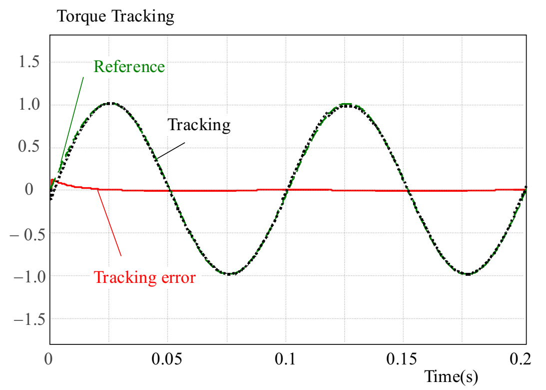

Fig. 11. Toque tracking performance case 2

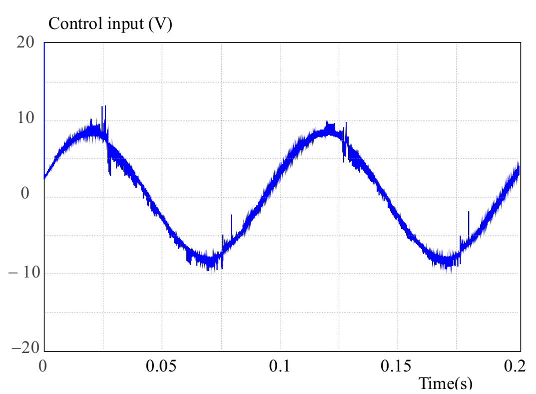

Fig. 12. Control input to PTS Motor case 2

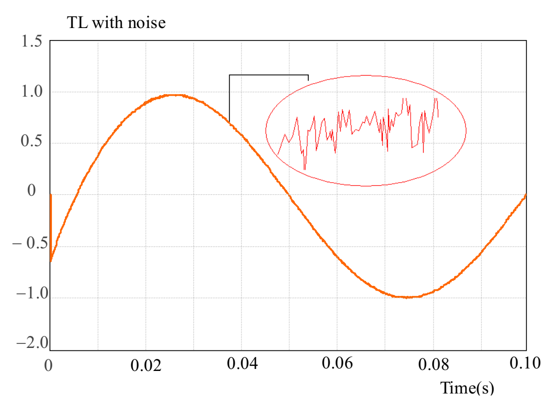

Fig. 13. T_L with sensor noise

7.1 Parameters Adaptation with Tracking error in the transient response and without sensor noise and chattering in control signal

Torque tracking performance is shown in Fig. 4. The transient tracking error is $50\,\%$. In the steady state the closed loop torque controller tracking error is less than $1\,\%$.

Figures 5 and 6 show the estimation of extra torque and nonlinear friction. Figure 7 is the voltage control signal applied at the input of current driver of PTS motor. The control signal is chattering free because the robust term in the torque controller is set to a minimum optimum value to avoid chattering and let the transient tracking error be there to analyze the parameters adaptation algorithm.

Figures 8, 9 and 10 show the estimation of state parameters a, $\frac{b}{k_s}$ and $\frac{c}{k_s}$. The parameters adaptation switch is closed at 0.02 sec and 0.05 sec respectively. The estimation of parameters is very accurate even in the presence of transient tracking error $(t = 0.02)$ but with a large negative peek. The convergence time of parameters to their final values is about 0.08 sec. compared to the results of estimation at $t = 0.05$, the estimation of all parameters is very fast and converge fastly because at $t = 0.05$, the torque tracking error is very small and the transient error is averaged out.

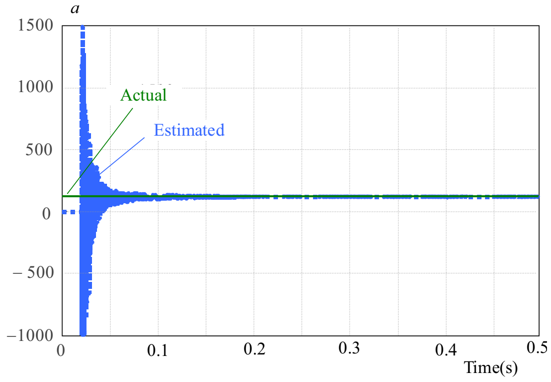

Fig. 14. Estimated a with sensor noise and control signal chattering

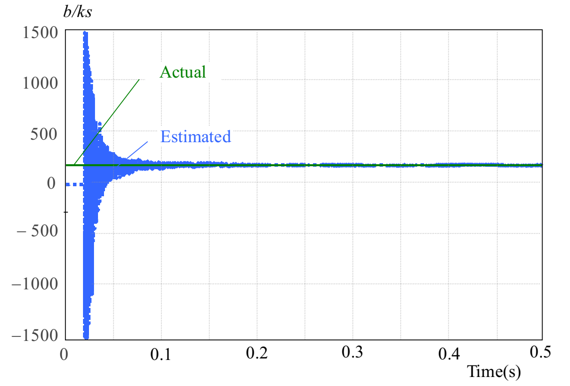

Fig. 15. Estimated b/ks with sensor noise and control signal chattering

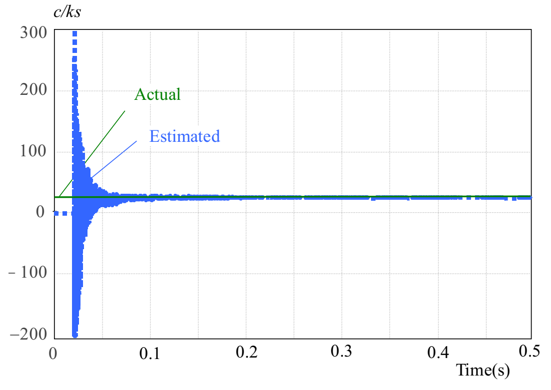

Fig. 16. Estimated c/ks with sensor noise and control signal chattering

7.2 Parameters adaptation with elimination of transient tracking error and with sensor noise and control signal chattering.

To eliminate the transient tracking error and to analyze the effect of chattering and sensor noise on parameters adaptation we modify the robust term gain as $K_1 = 4.5$, $K_2 = 1.5$. Moreover to study the effect of sensor noise on parameters adaptation algorithm we add some noise to the loading torque as

$$\overset{*}{T}_L = T_L + \beta * randn(10 * t)\,. \tag{54}$$

Where β is the amplitude of high frequency random noise, for simulating the effect of noise we choose, $\beta = 0.003$.

Figure 11 shows the torque tracking performance under large robust gain. The transient tracking error is almost eliminated with severe chattering in the control signal as shown in Fig. 12.

Figure 13 shows the noisy output signal which serves as input to the parameters estimation algorithm. The second input to the estimation algorithm is the control signal with severe chattering as shown in Fig. 12.

Figures 14, 15 and 16 shows effect of chattering and sensor noise on Parameters adaptation of PTS system. From the simulations results it is clear that in presence of noise and chattering the convergence time of parameters to their final values is larger with a large peaks both in negative and positive direction. This can cause system instability and can lead to poor control performance of the closed loop system.

7.3 Parameters adaptation with adaptive law based control and filtered sensor output signal

Figure 17 shows the variation of adaptive gain. In the transient time the gain decreases sharply and settles to an optimum value in steady state. Figure 18 is the control

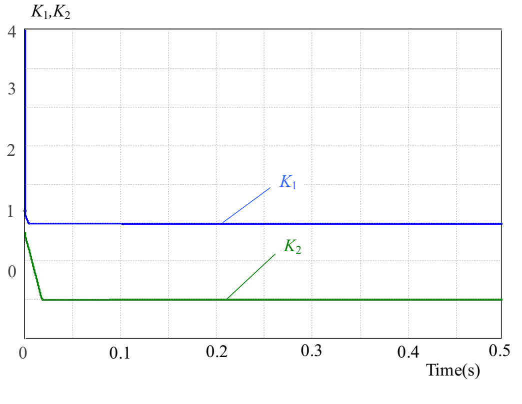

Fig. 17. Adaptive gain K_1, K_2 tuning

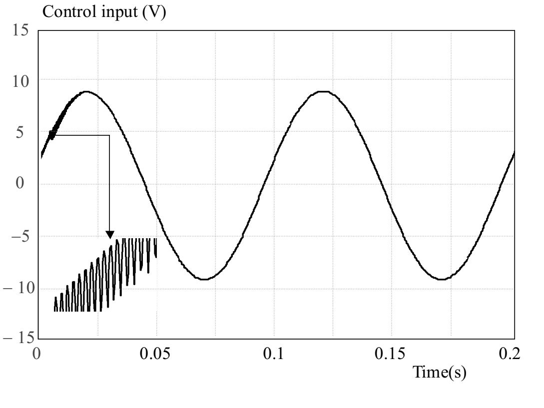

Fig. 18. Chattering elimination using adaptive gain tuning

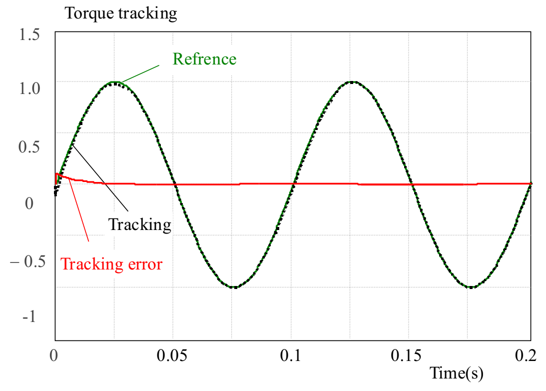

Fig. 19. Toque tracking performance case 3

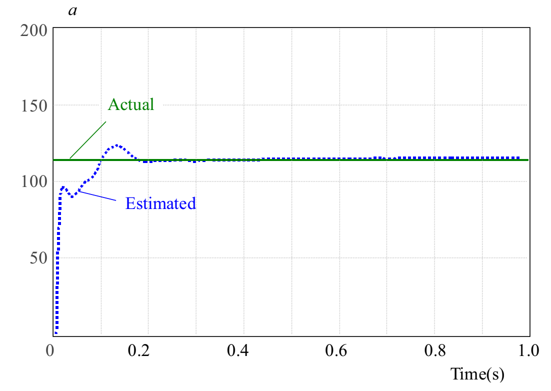

Fig. 20. Estimated a without sensor noise and adaptive law

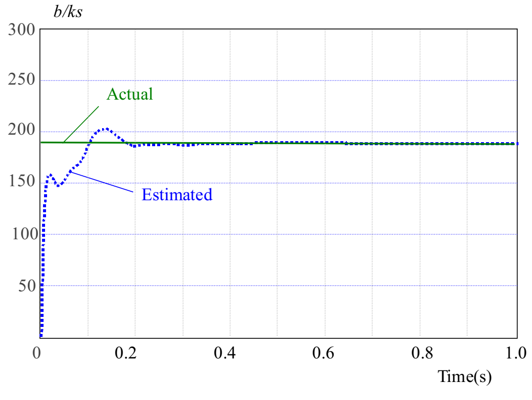

Fig. 21. Estimated b/ks without sensor noise and adaptive law

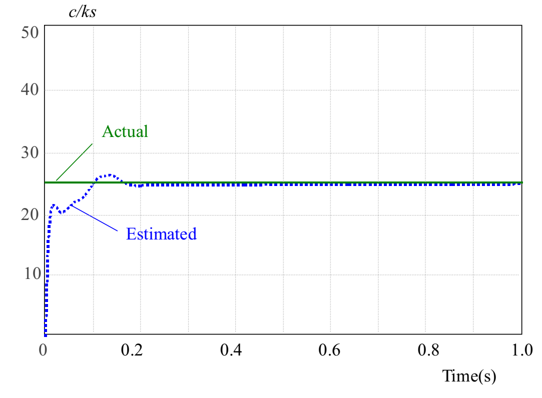

Fig. 22. Estimated c/ks without sensor noise and adaptive law

signal free of chattering. The small amount of chattering only exits in the very start of the transient period and then varnishes

Figure 19 is the torque tracking response under adaptive gain controller. The torque tracking performance is satisfactory and transient tracking is eliminated.

Figures 20, 21 and 22 show the parameters estimation result under the extra adaptive law based control. Since the transient tracking error as well chattering is eliminated, the estimation result is of uncertain parameters converge to their original values smoothly. The estimation error in the transient time is less than 2 % with a sudden peak. The peak appears because of the chattering in the control in the very start of transient cycle as shown in Fig. 18. Since the chattering is significantly decreased after a small interval the peaking error in the parameters estimation also settles down nearly to zero and the true parameters are estimated.

8 CONCLUSIONS

Adaptive fuzzy backstepping torque control for PTS simulator with algebraic parameters estimation is implemented assuming that the state parameters are unknown and uncertain but bounded. For simulations nominal values are used for torque controller initially and updated soon after the estimation. From simulations results it is concluded that fuzzy logic based compensation introduce transient tracking error greater than 50 %. With same transient error the parameters adaptation is reasonably good. For good control performance the transient tracking error was compensated using high robust term, with severe chattering in control signal. Chattering and sensor noise on parameters adaptation has significant effect on convergence time of parameters adaptation with noise spikes in the estimated results. To ensure minimum transient tracking error, chattering free control signal and smooth parameters estimation, the high gain fixed robust term in the control law was replaced with adaptive law of variable gain. The adaptive law gain is large in the start to compensate the transient error and settles to the optimum values initially selected. Chattering was almost eliminated except for the very small interval in transient time .To suppress the sensor noise a double integrator low pass filter was introduced in the numerator and denominator of estimating algorithm. The transient tracking error was decreased to 1 % with smooth parameters estimation.

Acknowledgements

In this research work a new saturation function based adaptive transient performance controller was derived to compensate for transient tracking error without chattering in control signal and adapting uncertain state parameters smoothly. The stability of the closed loop system was analyzed with newly introduced saturation function based law. The authors would like to appreciate the support of Program 111 of China, 863 Hi-Tech program (2009AA04Z412) and BUAA Fund of Graduate Education and Development. References

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Received 4 March 2012

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