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State Observer based Adaptive Fuzzy Backstepping Compensation Control of Passive Torque Simulator

***Abstract**. Passive Torque Simulator (PTS) is an important ground based hardware tester simulator used for qualification of flight actuation system under aerodynamics torque loading .In this work extra torque disturbance due to actuator motion under test is analyzed and fuzzy Backstepping control with online parameters tuning scheme is proposed. Since extra torque affects both transient and steady state performance of the control loop, high gain adaptive control is investigated to improve the transient response of PTS torque tracking. Finally fuzzy Back stepping control with online parameters tuning scheme is proposed to improve torque tracking performance of load simulator both in transient and steady state. Simulations results show the validity of proposed control.*

***Streszczenie.** W artykule przedstawiono analizę wpływu ruchu siłownika w czasie testu, na zakłócenia pomiaru momentu obciążenia na potrzeby symulatora obciążenia aerodynamicznego w systemie siłowników (ang. Passive Torque Simulator). W algorytmie wykorzystano sterowanie oparte na logice rozmytej z krokiem wstecz i parametrami dobieranymi online. (**Kompensujące sterowanie adaptacyjne rozmyte z krokiem wstecz dla symulatora momentu pasywnego – obserwator stanu**).*

Keywords:. PTS, Observer, Transient Performance, Backstepping Control, Extra Torque, Fuzzy Logic.
Słowa kluczowe: PTS, obserwator, odpowiedź impulsowa, sterowanie z krokiew wstecz, moment, logika rozmyta.

Introduction

Actuation system of High maneuverable flight vehicles are under aerodynamics loading which may vary depending on angle of attack, Mach number and air speed. Qualification of actuation systems for such flight vehicles may require excessive flight test which is costly and time consuming. Passive torque simulator (PTS) is ground based hardware in the loop simulator which can be used for applying medium range aerodynamics loads on actuation system of flight vehicles in real time according to flight trajectory. In medium range aerodynamics load simulators, electrical motor is used as loading device to generate desired loading torque to be applied on actuator under test. The Loading motor and actuator under test are directly connected through a rigid shaft. For measurement of loading torque a torque sensor is mounted the middle [1].

Control performance of PTS is influenced by nonlinear factors such as friction, external disturbance and unmodeled dynamics. Actuator under test follows the desired input position command, causing PTS motor to move because of direct connectivity. So PTS torque motor is influenced with strong position disturbance which is acting on it even when its input command is zero. The torque produced due to the position coupling is called as extra torque [1-2].

Many techniques are presented in the literature to compensate extra torque disturbance such as feed forward compensation, fuzzy sliding mode control ,velocity synchronization control, disturbance observer , robust H infinity and optimal sliding mode control [1],[5-7],[15].

Friction is another nonlinear phenomenon which can degrade control performance. Adaptive robust controller with friction compensation was proposed for linear electrical loading system in [2].The parameters of nonlinear friction model may not be accurately known with uncertainty in friction modeling. Friction observer with NN network is proposed to observe the immeasurable state of the Lugre friction model and compensate the model uncertainty [3].

Back stepping control is a recursive nonlinear control design method which has been successfully applied to many nonlinear systems in the past decade. But for many practical systems with strong nonlinear effects like friction and other disturbances back stepping control alone cannot guarantee good control performance. Back stepping control with robust friction state observer and recurrent fuzzy neural networks is proposed to compensate the nonlinear friction as in [4].

Uncertain and time varying parameters of complex electromechanically driven system are estimated online for good control performance. Enhanced model reference back stepping control is proposed for Permanent magnet synchronous generator (PMSG) equipped wind energy conversion system with electrical parameters uncertainty in [16] with robustness and performance property under the influence of wind disturbance. A robust model reference adaptive back stepping controller is proposed for direct torque control of PM synchronous motor. The simulation results show that the proposed controller is robust to uncertainties and all the control variables are globally asymptotically stable. The control performance of the proposed scheme is discussed as given in [17]. For PMSM motor under strong nonlinear coupling of external load a velocity control using model reference dynamic inversion concept is proposed in [18]. Performance improvement control algorithm is proposed for PMSM machines using exponential weighted functional model predictive control in [19]. Adaptive robust control with μ modification is presented in [20].

Based on the above literature survey, this work is focused on designing back stepping control scheme for PTS torque control system with adaptive parameters tuning law and fuzzy compensation control. Since extra torque disturbance is affecting PTS motor control performance in the transient state, high gain adaptive controller cannot be used to compensate extra torque because high frequency oscillations are induced in the control signal. Fuzzy back stepping controller guarantees good steady state response but the transient response is poor. A fuzzy back stepping controller is proposed with online adaptive parameters tuning. The parameters tuning law is derived from the error dynamics between PTS plant and the observer. The paper is arranged as follow. In section II detailed mathematical model is discussed. Sections III is focused on fuzzy back stepping control law design and analyze its stability. Section IV discusses the simulations results and Conclusion.

Mathematical Model

The working diagram of PTS system is shown in fig.1.PTS motor and actuator under aerodynamics torque loading test are directly connected through a stiff shaft. Due to direct connectivity the mechanical rotation of actuator severely affect the torque tracking control loop of PTS system. The dynamics of PTS can be written as

(1) $$T_L = K_s(\theta_m - \theta_a)$$

(2) $$u = iR + L\frac{di}{dt} + K_b w_m$$

(3) $$T_e = K_t i = J\frac{dw_m}{dt} + Bw_m + T_f + T_L$$

Eq. (1) represents the dynamics of torque sensor with K_s being the total stiffness of torque senor and connecting shaft.

Here $[\theta_m \ \theta_a]$ is angular position vector of PTS motor and actuator, $[K_t \ K_b]$ represents PTS motor torque constant and back emf constant, $[L \ R]$ represents inductance and resistance of PTS motor and $[T_e \ T_f \ T_L]$ represents the electromagnetic torque, friction torque and the load torque of PTS motor. We consider the following two steps in formulation of state model.

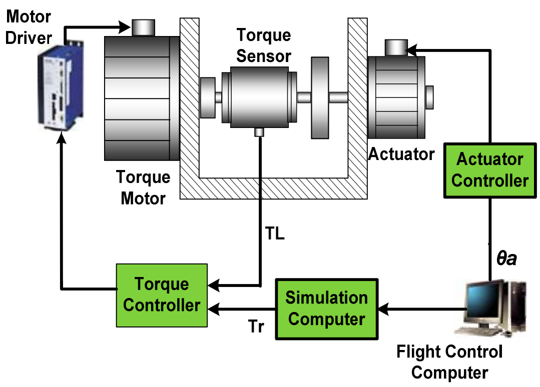


Fig.1 .PTS System Functional Diagram

Step1. From fig.1 when actuator controller command signals $\theta_a \neq 0$ and PTS motor reference command signal $u = 0$. The actuator will follow the reference command issued by flight control computer, so the PTS will follow the actuator motion as both are connected directly through a stiff shaft. Eq. (2) And Eq. (3) can be written as

(4) $$-K_b {w_m}^* = i^* R + L\frac{di^*}{dt}$$

(5) $$T_{sft} - {T_e}^* = -J\frac{d{w_m}^*}{dt} - B{w_m}^*$$

Here T_{sft} is the mechanical torque of actuator acting directly on PTS motor. All other variable parameters with '*' marked are the induced parameters due to actuator effect.

Step2. If control command signals of both PTS motor and actuator are not zero, then the dynamics of the system can be represented as

(6) $$u = (i - i^*)R + L\frac{d(i-i^*)}{dt} + K_b(w_m - w_a)$$

(7) $$T_e - {T_e}^{*\prime} = J(\ddot{\theta}_m - \ddot{\theta}_a) + B(\dot{\theta}_m - \dot{\theta}_a) + T_{sft} + T_f + T_L$$

Solving Eq. (6) in term of $(i - i^*)$ according to assumption that electrical dynamics of PTS motor is faster than the mechanical dynamics, hence $L\frac{d(i-i^*)}{dt} = 0$ and replacing the resultant equation in Eq. (7) .After simplifying the resultant equation can be written as given in [21].

(8) $$\ddot{T}_L = -a\dot{T}_L + bu - c(T_{sft} + T_f + T_L)$$

(9) $$\ddot{T}_L = -a\dot{T}_L + bu - cf(T_{extra}, T_f) - cT_L$$

In Eq. (9) $a = (\frac{k_t k_b}{JR} + \frac{B}{J})$, $b = \frac{K_s k_t}{JR}$ and $c = \frac{K_s}{J}$. Eq. (9) with parametric uncertainty can be represented as

(10) $$\ddot{T}_L - (a + \Delta a)\dot{T}_L + (b + \Delta b)u(c + \Delta c)f(T_{extra}, T_f) - (c + \Delta c)T_L$$

(11) $$\ddot{T}_L = -a\dot{T}_L + bu - cf(T_{extra}, T_f) - cT_L + \Delta d$$

Here Δd is represents the model error due to parametric uncertainty. Simplifying Eq. (11) we get

(12) $$\ddot{T}_L = -a\dot{T}_L + bu - D(T_{extra}, \Delta d) - cT_L - cT_f$$

In Eq. (12) $D(T_{extra}, \Delta d)$ represents total disturbance due to extra torque and parametric uncertainty. The state observer is proposed in Eq. (13).

(13) $$\hat{\ddot{T}}_L = -a\hat{\dot{T}}_L + bu - c\,\hat{T}_L - (\tilde{D}(T_{extra}, \Delta d) + K_{obs}E_1$$

In Eq. (13) E_1 is the tracking error.

Controller Design

From the above section it is clear that extra torque is the inherent disturbance which is acting on PTS motor even the input command of PTS motor is zero. Friction is another nonlinear phenomenon which severely affects control performance. In this paper we use Lugre model to simulate the effect of friction. Friction torque is compensated using friction observer. The proposed controller is shown in fig.2

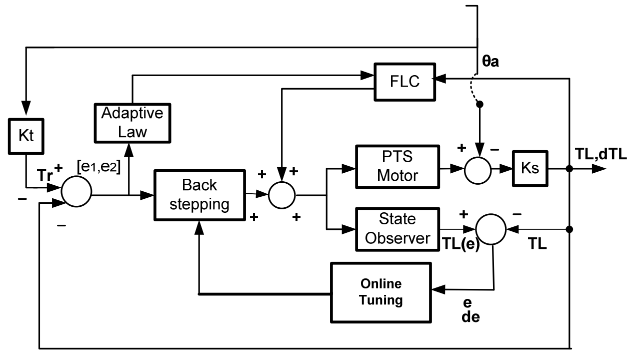


Fig. 2. PTS Controller

A. Adaptive Backstepping controller

Let T_L be output load torque and T_r be the desired torque signal, we define error and derivative of error as

(14) $$E_1 = T_L - T_r$$
$$\dot{E}_1 = \dot{T}_L - \dot{T}_r$$

As shown in fig.2 the state observer is used to estimate the system states. The error dynamics between the actual plant and the state observer is given as

(15) $$\dot{E} = \hat{\ddot{T}}_L - \ddot{T}_L = -a\dot{E} - cE + (\tilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d)$$

where

(16) $$E = \hat{T}_L - T_L$$
$$\dot{E} = \hat{\dot{T}}_L - \dot{T}_L$$

Eq. (14) can be expressed as

(17) $$\dot{E}_1 = \alpha_1 - \dot{T}_r$$

We choose Lyapunov function and its derivative as

(18) $$V_1 = \frac{1}{2}E_1^2$$

(19) $$\dot{V}_1 = E_1\dot{E}_1$$

Substituting $\dot{E}_1$ from Eq. (17) into Eq. (19) we get

(20) $$\dot{V}_1 = E_1(\alpha_1 - \dot{T}_r)$$

Choosing the first virtual control as given in Eq. (21) and replacing in Eq. (20) we get Eq. (23)

(21) $$\alpha_1 = -c_1E_1 + \dot{T}_r$$

(22) $$\dot{V}_1 = E_1(-c_1E_1 + \dot{T}_r - \dot{T}_r)$$

(23) $$\dot{V}_1 = -c_1{E_1}^2$$

Choosing optimum 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

(24) $$E_2 = \dot{T}_L - \alpha_1$$
$$\dot{E}_2 = \ddot{T}_L - \dot{\alpha}_1$$

Substituting Eq. (12) into Eq. (24) we get

(25) $$\dot{E}_2 = -a\dot{T}_L + bu - D(T_{extra}, \Delta d) - cT_L - cT_f - \dot{\alpha}_1$$

From [21]

(26) $$\dot{\alpha}_1 = -c_1\dot{E}_1 + \ddot{T}_r$$

Substituting Eq. (26) in Eq. (25)

(27) $$\dot{E}_2 = -a\dot{T}_L + bu - D(T_{extra}, \Delta d) - cT_L - cT_f + c_1\dot{E}_1 - \ddot{T}_r$$

Choose Lyapunov function as

(28) $$V_2 = V_1 + \frac{1}{2}E_2^2 + \frac{c}{2}E^2 + \frac{1}{2}\dot{E}^2 + \frac{1}{2\gamma}((\widetilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d))^2$$

Lyapunov function given in Eq. (28) includes error dynamics of observer and PTS plant. Differentiating Eq. (28)

(29) $$\dot{V}_2 = \dot{V}_1 + E_2\dot{E}_2 + cE\dot{E} + \ddot{E}E + \frac{1}{\gamma}((\widetilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d))\frac{d\widetilde{D}(T_{extra},\Delta d)}{dt}$$

Replacing Eq. (27) and Eq. (15) into Eq. (29) and simplifying

(30) $$\dot{V}_2 = -c_1{E_1}^2 + E_2\left(-a\dot{T}_L + bu - D(T_{extra}, \Delta d) - cT_L - cT_f + c_1\dot{E}_1 - \ddot{T}_r\right) + cE\dot{E} + \dot{E}\left(-a\dot{E} - cE + \left(\widetilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d)\right)\right) + \frac{1}{\gamma}((\widetilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d))\frac{d\widetilde{D}(T_{extra},,\Delta d)}{dt}$$

The control law is chosen as given in Eq. (31)

(31) $$u = \frac{1}{b}\left(-c_2E_2 + a\dot{T}_L + cT_L + c\widetilde{T}_f + \widetilde{D}(T_{extra}, \Delta d) - c_1\dot{E}_1 + \ddot{T}_r\right)$$

Put Eq. (31) in Eq. (30) and simplifying the resultant relation

(32) $$\dot{V}_2 = -c_1{E_1}^2 - c_2{E_2}^2 - a\dot{E}^2 + (E_2 + \dot{E} + \frac{1}{\gamma}\frac{d\widetilde{D}(T_{extra},\Delta d)}{dt})\left(\widetilde{D}(T_{extra}, \Delta d) - D(T_{extra}, \Delta d)\right)$$

We choose the following adaptive law to estimate extra torque and disturbances due to parametric uncertainties as

(33) $$\dot{\hat{D}}(T_{extra}, \Delta d) = -\gamma(E_2 + \dot{E})$$

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

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

Eq. (31) represents Backstepping controller with adaptive law for compensation of extra torque as shown in Eq. (33).

A.1 Lugre Model Friction Compensation

The control law given in Eq. (31) consist of friction compensation control term $\tilde{T}_f$ .In this work we use Lugre model observer for compensating friction torque.The parameters of lugre friction model are shown in table 1. The compensation control is given as in [3].

(34) $$\tilde{T}_f = \sigma_0 z + \sigma_1\dot{z} + \sigma_2 v$$

(35) $$\dot{z} = v - \frac{\sigma_0|v|}{g(v)}$$

(36) $$g(v) = f_c + (f_c - f_s)e^{-(\frac{v}{v_s})^2}$$

Here $g(v)$ is the Stribeck effect,v_s is the Stribeck velocity,f_c is coulomb friction,f_{s_c} is static friction,z is the average bristle defection,σ_0 is the stiffness of the bristles,σ_1 is the damping term and σ_2 is the viscous friction coefficiet.

B. Fuzzy Backstepping controller with Adaptive online parameters tuning

Control law derived as shown in Eq. (31) use adaptive compensation control for extra torque disturbance and other uncertainties. Fast adaptive control in absence of suitable filter cannot guarantee robustness as well transient performance [22]. so the control law in Eq. (31) cannot guarantee transient performance with slow adaptation rate, while fast adaptation rate will affect the robustness property. We propose a novel fuzzy back stepping torque controller with adaptive online parameters tuning method. Eq. (11) can be written as

(37) $$\ddot{T}_L = -a\dot{T}_L + bu - cf\left(T_{extra}, T_f\right) - cT_L + \Delta d$$

In Eq. (37) the term $f\left(T_{extra}, T_f\right)$ is estimated using fuzzy logic. $\Delta\tilde{d}$ is derived using lyapunov function from the error dynamics between PTS plant and observer. Based on above analysis error dynamics between PTS plant and observer can be written as

(38) $$\ddot{E} = \ddot{\hat{T}}_L - \ddot{T}_L = -a\dot{E} - cE + (\Delta\tilde{d} - \Delta d)$$

Replacing Eq. (37) and Eq. (26) in Eq. (24) we get

(39) $\dot{E}_2 = -a\dot{T}_L + bu - cf(T_{extra}, T_f) - cT_L + \Delta d + c_1\dot{E}_1 - \ddot{T}_r$

Lyapunov function and its derivative given in Eq. (28) can be modified as

(40) $V_2 = V_1 + \frac{1}{2}\left(E_2^2 + \sum_{i=1}^{n} \eta_i \tilde{\theta}^2{}_i\right) + \frac{c}{2}E^2 + \frac{1}{2}\dot{E}^2 + \frac{1}{2\gamma}(\Delta\tilde{d} - \Delta d)^2$

(41) $\dot{V}_2 = \dot{V}_1 + E_2\dot{E}_2 + \sum_{i=1}^{n} \eta_i \tilde{\theta}_i\dot{\tilde{\theta}}_i + cE\dot{E} + \ddot{E}E + \frac{1}{\gamma}(\Delta\tilde{d} - \Delta d)\frac{d(\Delta\tilde{d})}{dt}$

From Eq. (38) and Eq. (39) replacing $\ddot{E}$ and $\dot{E}_2$ in Eq. (41) .After simplifying we get

(42) $\dot{V}_2 = -c_1{E_1}^2 + E_2\big(-a\dot{T}_L + bu - cf(T_{extra}, T_f) - cT_L + \Delta d + c_1\dot{E}_1 - \ddot{T}_r\big) + \sum_{i=1}^{n} \eta_i \tilde{\theta}_i\dot{\tilde{\theta}}_i + cE\dot{E} + \dot{E}\big(-a\dot{E} - cE + (\Delta\tilde{d} - \Delta d)\big) + \frac{1}{\gamma}(\Delta\tilde{d} - \Delta d)\frac{d(\Delta\tilde{d})}{dt}$

The control law is chosen as given in Eq. (43)

(43) $u = \frac{1}{b}\big(-c_2E_2 + a\dot{T}_L + cT_L + c\tilde{f}(T_{extra}, T_f) - \Delta\tilde{d} - c_1\dot{E}_1 + \ddot{T}_r\big) + \frac{\tilde{k}_d}{b}sign(E_2)$

Replacing *u* from Eq. (43) into Eq. (42) and simplifying the resultant equation is

(44) $\dot{V}_2 = -c_1{E_1}^2 - c_2{E_2}^2 - a\dot{E}^2 + \left(E_2 + \dot{E} + \frac{1}{\gamma}\frac{d\Delta\tilde{d}}{dt}\right)(\Delta\tilde{d} - \Delta d) + \sum_{i=1}^{n} \eta_i \tilde{\theta}_i\dot{\tilde{\theta}}_i + E_2[c\tilde{f}(T_{extra}, T_f) - cf(T_{extra}, T_f)] + \tilde{k}_d sign(E_2)$

From [23] we define

(45) $e_f = f(T_{extra}, T_f) - \tilde{f}(T_{extra}, T_f)\,/\theta^*$

(46) $\tilde{\theta}_i\xi_i(\dot{\theta}) = \hat{f}(T_{extra}, T_f)/\theta - \tilde{f}(T_{extra}, T_f)\,/\theta^*$

Add and subtract $c\tilde{f}(T_{extra}, T_f)\,/\theta^*$ in Eq. (44), the simplified equation is given as

(47) $\dot{V}_2 = -c_1{E_1}^2 - c_2{E_2}^2 - a\dot{E}^2 + \left(E_2 + \dot{E} + \frac{1}{\gamma}\frac{d\Delta\tilde{d}}{dt}\right)(\Delta\tilde{d} - \Delta d) - E_2e_f + [E_2\tilde{\theta}_i\xi_i(\dot{\theta}) + \sum_{i=1}^{n} \eta_i \tilde{\theta}_i\dot{\tilde{\theta}}_i] + \tilde{k}_d sign(E_2)$

From Eq. (47) we derive the following adaptive laws

(48) $\dot{\tilde{\theta}}_i = -{\eta_i}^{-1}E_2\xi_i(\dot{\theta}$

(49) $\frac{d(\Delta\tilde{d})}{dt} = -\gamma(E_2 + \dot{E})$

With adaptive laws given in Eq. (48) and Eq. (49) simplified relation for $\dot{V}_2$ can be written as

(50) $\dot{V}_2 = -c_1{E_1}^2 - c_2{E_2}^2 - a\dot{E}^2 + \tilde{k}_d sign(E_2)$

By selecting optimum values of $c_1 > 0, c_2 > 0$ and $\tilde{k}_d > 0$ it is easy to prove that $\dot{V}_2 < 0$

B.1 Online parameter Tuning

The proposed torque controller is given in Eq. (43).The last term of control law consist of discontinuous signum function in which gain $\tilde{k}_d$ is adustusted online. First a lower optimum value of $\tilde{k}_d$ is chosen such that closed loop feedback controller is stable and chattering in control signal is minmum or almost zero. In a situation where $\tilde{k}_d$ is large, transient tracking error can be eliminated at the cost of chattering in control signal. So to eliminate transient tracking error as well as minimizing chattering in control signal we propose the following adaptive law for tuning of parameter $\tilde{k}_d$.

(51) $\tilde{k}_d = sat(\Delta\tilde{d}) = sat_{\tilde{k}_{dL}}^{\tilde{k}_{dH}}(-\gamma\int(E_2 + \dot{E}))$

Here $\tilde{k}_{dH}$ and $\tilde{k}_{dL}$ represents upper and lower level of gain $\tilde{k}_d$ .The upper level gain is selected such that transient tracking error is eliminated. After that $\tilde{k}_d$ will decrease and will be restricted using saturation function to a lower optimum value at which the closed loop system is stable and steady state error is minimum. This will ensure chattering free signal in the steady state. The learning rate γ is used to adjust the decay rate of gain $\tilde{k}_d$ to the lower optimum value.

Simulation Results and Discussions

To verify the proposed control scheme we use the following parameters for simulation as given in table 1.

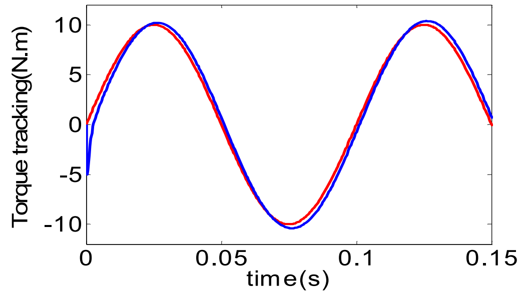
Table 1. The parameters of PTS Motor and Controller

PTS Parameters	Value	Controller Parameters	Value
J	*0.04 kg/m2*	*C1,C2*	*117,110*
R	*7.5Ω*	*KdH*	*5.5*
Km, Ke	*5.732Nm/v*	*KdL*	*1.2*
B	*0.244Nm/rad /s*	η_i	*0.0001*
Ks	*950Nm/rad*	γ_L	*50*
Ts, Tc	*3Nm,2.7Nm*	γ_H	*1500*
$\boldsymbol{\sigma_0}$	*200Nm/rad*	*Vs*	*0.01rad/s*
$\boldsymbol{\sigma_1, \sigma_2}$	*2.5,0.02 Nm-s/rad*		

A. Torque tracking simulations with adaptive Backstepping controller

The reference command of PTS torque motor is $T_r = 10\,.sin(2.(\pi).f.t)$ where frequency is 10 Hz. Tracking Performance of adaptive Backstepping controller with adaptive learning rate $\gamma = 500$ is shown in fig .3a.Transient tracking error is about 4.3N.m and steady state error is 1.5N.m. If the adaptive learning rate is increased to $\gamma = 1500$, then the tracking error is minimized both in transient and steady state time as shown in fig.3b .The transient tracking error is about 1N.m and steady state tracking error is 0.8N.m. The tracking error comparsion for low and high adaptive gain is shown in fig .3c.

Fig .3d shows the estimated extra torque disturbance using adaptive law . Using high adaptaion gain ,transient tracking error can be minimized as shown in fig.3c but at the same time robustness proporty of the proposed controller is affected by high frequency oscillations in the control signal as shown in fig.3e



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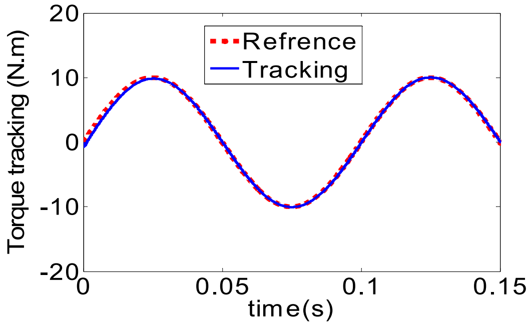

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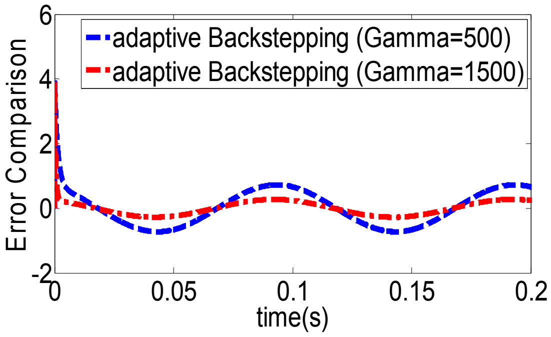

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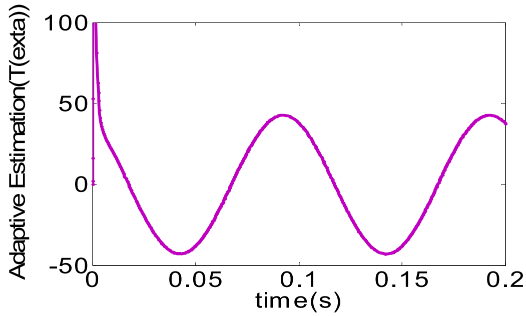

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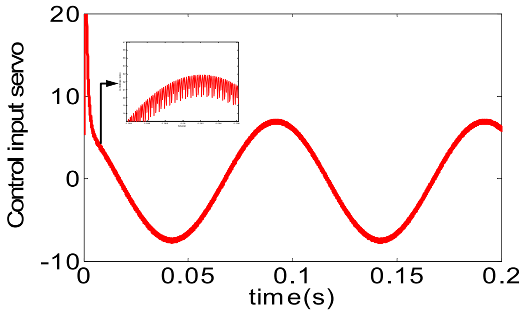


e)

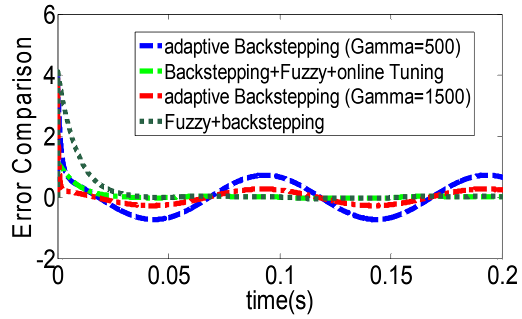
Fig.3. Torque Tracking Simulations with Adaptive Backstepping Controller

B. Torque tracking simulations with Fuzzy back stepping controller and online parameter tuning

To verify the effectivness of proposed controller ,the reference command of PTS torque motor is $T_r = 10\,.sin(\,2.(\pi).f.t)$ with frequency of 10 Hz. Tracking error comparison of fuzzy backstepping controller with online parameters tuning is shown in fig. 4a. As compared to fuzzy backstepping control without online tuning ,transient tracking error for proposed scheme is 0.8N.m and steady state error is 0.1N.m.

Fig. 4b shows Control input of PTS motor . As compared to high gain adaptive backstepping method chattering in control signal is minimized.

Fig. 4c shows friction compensation using proposed observer.The compensation error is less then 1%.Fig .4d represents online tunig of gain $\tilde{k}_d$. The initial transient value of gain is 5 ,and lower value is saturated at 0.8.



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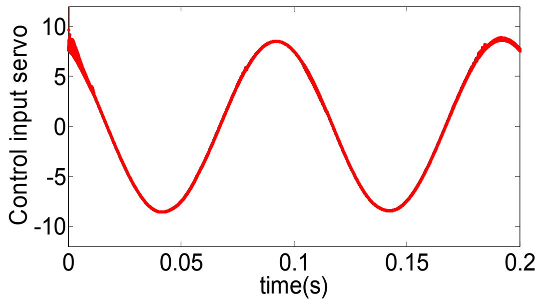

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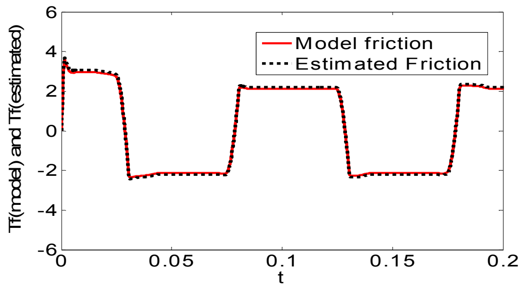

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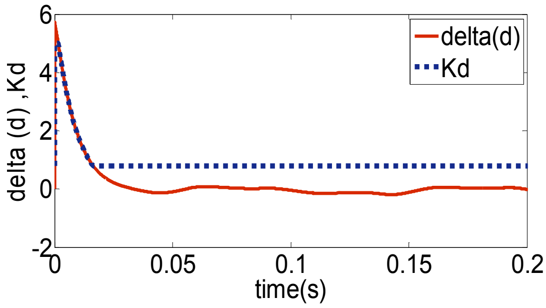

d)

Fig.4. Torque Tracking Simulations with online parameter tuning of Fuzzy Backstepping Controller

Conclusions

Adaptive backstepping torque controller for PTS system is invistigated to improve transient performance of the system under the influence of extra torque and friction nonlinearities. From simualtion results it is concluded that low gain adaptive backstepping control cannot eliminate trasnient tracking error. The problem was rectified using high gain adaptive backstepping control but at cost of high frequency chattering in control signal . A novel fuzzy backstepping controller is proposed with online parameter tuning based on the error dynamics between PTS and observer to rectify both problems. The error comparison simulation verifies the effeciency of the proposed control scheme.

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