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Fractional Order Fuzzy Backstepping Torque Control of Electrical Load Simulator

***Abstract**. A novel Fractional order adaptive robust control is proposed for electrical load simulator system (ELS) using fuzzy back stepping method. A fractional order linear sliding surface is constructed and a robust fractional order control law is derived using back stepping method. The control performance of load simulator is affected by extra torque disturbance. Fuzzy logic system is used to estimate extra torque disturbance .A fractional order adaptive law is derived to update fuzzy logic system using Lyapunov theorem. The effectiveness of proposed control scheme is verified using numerical simulations.*

***Streszczenie.** W artykule opisano zastosowanie sterowania FOC (ang. Fractional Order Control) do symulacji obciążenia elektrycznego, z wykorzystaniem sterowania rozmytego z krokiem wstecz. Wyznaczono powierzchnię ślizgową rzędu ułamkowego oraz opracowano reguły dla sterowania rzędu ułamkowego. Zastosowana logika rozmyta pozwala na określenie pojawiających się wahań momentu, co zbadano poprzez zadawanie tego rodzaju zmian. Skuteczność proponowanego rozwiązania poddano weryfikacji w badaniach symulacyjnych. (**Rozmyte sterowanie momentem z ułamkowym krokiem wstecz dla symulatora obciążenia elektrycznego**).*

Keywords: Electrical load simulator, back stepping control, Fuzzy logic system, Fractional Calculus.
Słowa kluczowe: symulator obciążenia elektrycznego, sterowanie z krokiem wstecz, logika rozmyta, rachunek różniczkowy ułamkowy.

Introduction

Load simulators are used to realize aerodynamics loads (torque/forces) on flight actuation system of high dynamics flight vehicles in ground based experiments. Electrical load simulator is a medium range loading hardware in the loop simulator (HIL) system in which PMSM/DC motor is used as loading device.

The control performance of load simulator system is affected by extra torque disturbance which is acting on loading motor due to movement of actuator under test [1]. Different integer order control methods are applied and presented in literaure to compensate extra torque disturbance and formulate torque control [2 -9].

In high performance servo drive it is mandatory to compensate friction phenomena. Friction state observer is proposed for high performance control in [10, 11].

Back stepping is a recursive control method in which virtual control law is derived using Lyapunov theorem for each step, thus it can be used for higher order complex systems. Integer order back stepping method is proposed in [12, 13] for PMSM servo control. Sliding mode controller is proposed for trajectory tracking control of quad rotor aerial vehicle using back stepping method [14] and integral back stepping control method is proposed for under actuated X4 flyer in [15].

All methods discussed above are integer order. The design idea of fractional order controller was first developed by Oustaloup. The first robust fractional order controller CRONE (Commande Robuste d'Ordere Non-Entier) was developed in 1996 [16].Later on the researcher extended the idea and developed PID and adaptive fractional PID controllers[17].Fractional order sliding mode controllers are developed as given in [18, 19, 20].

Based on the above literature survey, this work is focused on developing a fractional order adaptive fuzzy backsteping controller for torque tracking control of ELS simulator. To update fuzzy logic, we propose a fractional order adaptive law derived from Lyapunov theorem.

The paper is organized as follow. In next section basic definition of fuzzy logic system and fractional calculus are presented. In section 3 control problem is formulated. The review of integer order adaptive fuzzy back stepping controller is presented in section 4.The new fractional order adaptive fuzzy backsteping control law is developed in section 5.The simulation results and comparison is made in section 6 and the conclusion is made in section 7.

Fractional Calculus & Fuzzy Logic System Basic Definitions

Let the fractional operator is defined as aD_t^{λ} [17, 18, 19, 20]

$$aD_t^{\lambda} \triangleq D^{\lambda} = \begin{cases} \frac{d^{\lambda}}{dt^{\lambda}} & R(\lambda) > 0 \\ 1 & R(\lambda) = 0 \\ \int_a^t (d\tau)^{-\lambda} & R(\lambda) < 0 \end{cases} \tag{1}$$

where a and t are the limits of operation and λ is the order of fractional operator. Now αth-order Riemann–Liouville fractional derivative of function $f(t)$ with respect to t and the terminal value t_0 is given by [21].

$$D^{\alpha} f(t) = \frac{d^{\alpha} f(t)}{dt^{\alpha}} = \frac{1}{\Gamma(m-\alpha)} \frac{d^m}{dt^m} \int_{t_0}^{t} \frac{f(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau \tag{2}$$

Riemann–Liouville formula of the αth -order fractional integration can be written as [21].

$$I^{\alpha} f(t) = \frac{1}{\Gamma(\alpha)} \int_{t_0}^{t} \frac{f(\tau)}{(t-\tau)^{1-\alpha}} d\tau \tag{3}$$

where m is the first integer larger than α, i.e. $m-1 \le \alpha < m$ and Γ is the gamma function. The Caputo fractional derivative expression of a continuous function $f(t)$ is expressed as.

$$D^{\alpha} f(t) = \begin{cases} \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^m(\tau)}{(t-\tau)^{\alpha-m+1}} d\tau & (m-1 \le \alpha < m) \\ \frac{d^m}{dt^m} f(t) & \alpha = m \end{cases} \tag{4}$$

where m is the first integer larger than α.If anti differentiation of a fractional derivative of a function $f(t)$ exits then

$$aI_t^{\alpha}(aD_t^{\alpha} f(t)) = f(t) - \sum_{J=1}^{k} \left[aD_t^{\alpha-J} f(t)\right]_{t=a} \frac{(t-a)^{\alpha-J}}{\Gamma(\alpha-J+1)} \tag{5}$$

To approximate a continuous unknown function, fuzzy logic system is proposed. The output of SISO fuzzy logic system with centre average defuzzifier, product inference and singleton fuzzifier is given by following relation [22].

$$y_j = \frac{\sum_{l=1}^{M} (u_{Ai}^{(x)}) y_j^{-l}}{\sum_{l=1}^{M} (u_{Ai}^{(x)})} \quad j = 1,2,\dots\dots,m \tag{6}$$

x_i is the input parameter vector and y_j is the output parameter vector. *M* is the total number of rules. $u_{A_i^l}(x_i)$ is the membership function vector. Eq.6 can be simplified as

(7) $$y_j = \theta_j \xi(x) \;\; j = 1,2, \dots \dots m$$

θ_j , called the parameter vector which is adaptive term. $\xi(x)$ is fuzzy bases function vector. y_j^{-l} is a free parameter.

Problem Formulation

The mathematical model and detailed analysis of ELS system is given as in [23]. The state model can be written as

(8) $$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -ax_2 + bu - cf(T_{extra}) \end{aligned}$$

Where $[x_1 \; x_2]$ represents system states, u is the control effort, $f(T_{extra})$ is the extra torque disturbance and the state parameters are represented as $a = \left(\frac{k_t k_b}{JR}\right)$,$b = \frac{K_s k_t}{JR}$ and $c = \frac{K_s}{J}$.

Assumption1. System states are measurable and noise free.

Assumption2. System parameters are known and time invariant.

The control objective is to get ELS torque motor to track a desired reference loading torque command vector $[x_r \; \dot{x}_r]$ where the state error vector can be defined as

(9) $$e_1 = x_1 - x_r \, , e_2 = x_2 - \dot{x}_r$$

The goal of this work is to design adaptive robust fuzzy fractional order backstepping controller for torque tracking loop of ELS system.

Integer Order Adaptive Fuzzy Backstepping Control

Let a linear integer order sliding surface is defined as

(10) $$s = ce_1 + e_2$$

(11) $$\dot{s} = c\dot{e}_1 + \dot{e}_2$$

where $c > 0$, differentiating Eq. 9

(12) $$\dot{e}_1 = \alpha_1 - \dot{x}_r, \;\; \dot{e}_2 = \dot{x}_2 - \dot{\alpha}_1$$

To calculate first virtual control α_1, the Lyapunov function is $V_1 = \frac{1}{2}e_1^2$. So the virtual control is given as

(13) $$\alpha_1 = -c_1 e_1 + \dot{x}_r$$

Using Eq. 9, Eq.12 and Eq. 13 the error dynamics can be written as [24].

(14) $$\dot{e}_1 = -c_1 e_1 + e_2$$

Eq. 12 can be written as

(15) $$\dot{e}_2 = -ax_2 + bu - cf(T_{extra}) - \dot{\alpha}_1$$

Substitute Eq. 14 and Eq. 15 in Eq.11

(16) $$\dot{s} = c(-c_1 e_1 + e_2) + (-ax_2 + bu - cf(T_{extra}) - \dot{\alpha}_1)$$

We choose control law as

(17) $$u = \frac{1}{b}\left(c(c_1 e_1 - e_2) + ax_2 + c\tilde{f}(T_{extra}) + \dot{\alpha}_1 - k_1 s - k_2 sign(s)\right)$$

We choose Lyapunov function as

(18) $$\begin{aligned} V &= \frac{1}{2}\left(s^2 + \textstyle\sum_{i=1}^{n} \eta_i \tilde{\theta}^2{}_i\right) \\ \dot{V} &= s\dot{s} + \textstyle\sum_{i=1}^{n} \eta_i \tilde{\theta}_i \dot{\tilde{\theta}}_i \end{aligned}$$

Introducing Eq. 16 -Eq. 17 into Eq. 18 and simplifying the resultant equation we get the adaptive law as given in [23].

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

Replacing Eq. 19, Eq. 17 into Eq. 18 and we choose $k_1 > 0$, $c_1 > 0$ and $k_2 > 0$ such that $\dot{V} < 0$

Fractional Order Adaptive Fuzzy Backstepping Control

Let a fractional order linear sliding surface and its first derivative is defined as

(20) $$\begin{aligned} s &= cD^{\alpha-1}e_1 + e_2 \\ \dot{s} &= cD^{\alpha-1}\dot{e}_1 + \dot{e}_2 \end{aligned}$$

Here α is the degree of fractional operator. Substitute Eq. 14 and Eq. 15 in Eq.20

(21) $$\dot{s} = c(-c_1 e_1 + e_2) + D^{\alpha-1}(-ax_2 + bu - cf(T_{extra}) - \dot{\alpha}_1)$$

We choose control law as

(22) $$u = \frac{1}{b}\left(-cD^{\alpha-1}(-c_1 e_1 + e_2) + ax_2 + c\tilde{f}(T_{extra}) + \dot{\alpha}_1 - k_1 s - k_2 sign(s)\right)$$

Fractional Order Adaptive Fuzzy logic system

To derive fractional order adaptive law for fuzzy logic system and prove the stability of whole closed loop we Introducing Eq. 21 and Eq. 22 into Eq. 18, the simplified relation can be written as

(23) $$\dot{V} = s\left[[c\tilde{f}(T_{extra}) - cf(T_{extra}) \;\; - k_1 s - k_2 sign(s)]\right] + \textstyle\sum_{i=1}^{n} \eta_i \tilde{\theta}_i \dot{\tilde{\theta}}_i$$

Eq. (23) can be simplified as

(24) $$\dot{V} = s\left[c\tilde{f}(T_{extra}) - cf(T_{extra})\right] + s[-k_1 s - k_2 sign(s)] + \textstyle\sum_{i=1}^{n} \eta_i \tilde{\theta}_i \dot{\tilde{\theta}}_i$$

The proposed controller is shown in fig.1

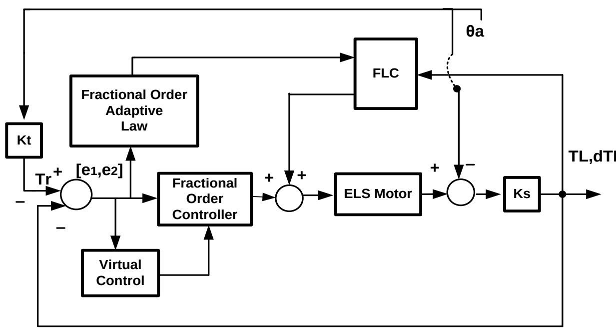

Fig.1. Fractional order controller for ELS system

Using procedure adapted in [23], the following fractional order adaptive fuzzy update law is derived

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

Replace Eq.25 in Eq. 24 and choose $k_1 > 0$, $k_2 > 0$ we get the following simplified relation

$$\dot{V} = s[-k_1 s - k_2 sign(s)]$$

After simplifying the above relation can be written as

$$\dot{V} \leq s[-k_1 s] - k_2|s| < 0$$

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 ELS Motor and Controller

ELS Parameters	Value	Controller Parameters	Value
J	*0.04 kg/m2*	c_1	*10*
R	*7.5Ω*	k_1	*1.5*
Km, Ke	*5.732Nm/v*	k_2	*0.5*
B	*0.244Nm/rad /s*	η_i	*0.0001*
Ks	*950Nm/rad*	*c*	*200*

A. Tracking Performance Comparison

The reference command of ELS torque motor is $T_r = 10\,.sin(2.(\pi).f.t)$ with frequency 10 Hz. The initial conditions for state vector are$[x_{10}\; x_{20}]^T = [28 \quad 500]^T$.The integer order and fractional order control tracking performance are compared in fig. 2. From fig. 2 we conclude that as we decrease order of fractional operator alpha tracking error due to initial conditions converge quickly towards equilibrium point. Best tracking performance is acheived using fractional order alpha=0.7 . Transient tracking error is reduced by approximately 50%.

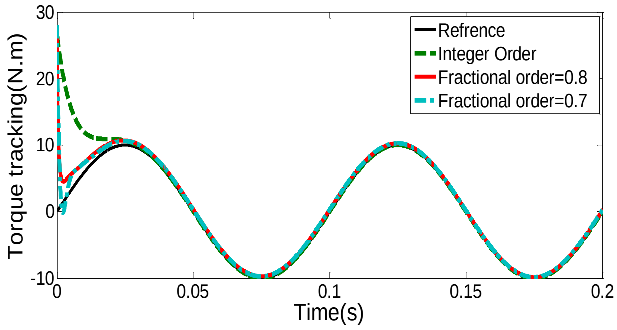

Fig.2. Tracking Performance Comparison

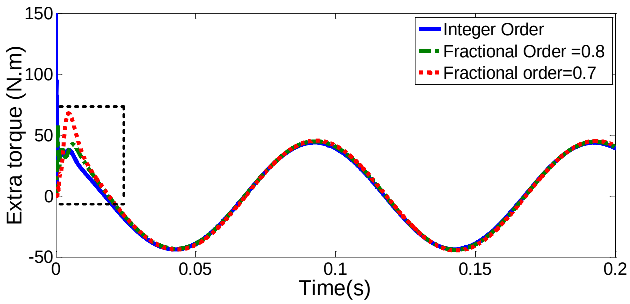

Fig.3. Estimated extra torque Comparison

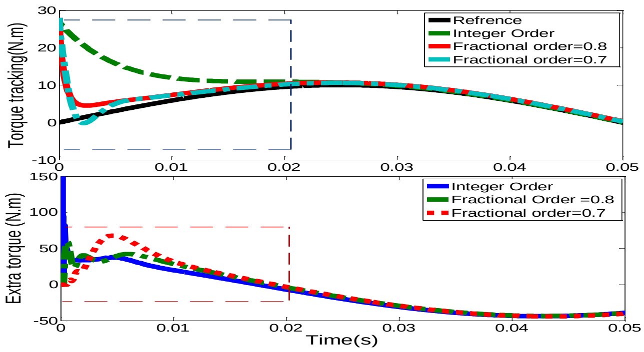

Fig.4. Zoom view of transient response

The estimated extra torque is shown in fig. 4.From simulation results it is clear that as we decrease order of fractional order operator alpha , the overshoot in the estimated extra torque increases. The maximum overshoot is approximately 65 N.m. The enlarged view of fig. 2 and fig. 3 is presented in fig. 4.From fig. 4 it is clear that as we decresae the order of fractional controller , the overshoot in the estimated extra torque component increases.The overshoot represents extra control effort which compensates error due initial conditions.The control effort overshoot occurs at t=0.005 sec. State x_1 reach in the vicinity of its equilibrium point at time t=0.02 sec.

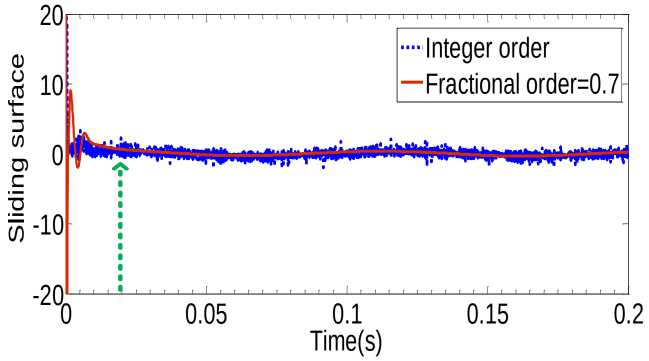

Fig.5. Sliding surface “S” Comparison

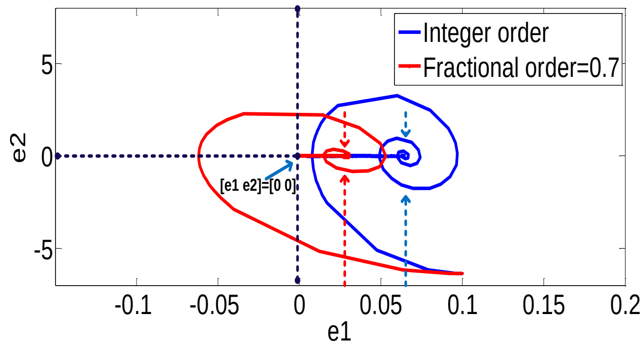

Fig.6. Phase trace of comparison

Fractional and integer order sliding surfaces are compared in fig. 5.There is an overshoot in the fractional order sliding surafce in the transient time. After time t=.02sec , fractional order sliding surface reach in the vicinity of zero. Morever chattering effect is minimized as compared to integer order.

B. Phase Trace Comparison

The reference command of ELS torque motor is $T_r = 1\,.sin(2.(\pi).f.t)$ with frequency 10 Hz. The initial conditions for state vector are $[x_{10}\; x_{20}]^T = [0.1 \quad 58]^T$.The phase trace comparison is given in fig. 6.From simulations result is clear that phase trace of proposed controller with fractional order alpha=0.7 reach equilibrium quikly as compared to integer order.

Remark.1. From simulations results it clear that choice of fractional cofficient alpha is an important factor for improving tracking performance.In this work fractional cofficient is selected using hit and trail method. More precise results can be achieved if alpha is selected using some optimization technique.

Conclusions

Fractional Order adaptive robust controller is proposed using fuzzy backstepping method for ELS system. From numerical simulations it is concluded that the proposed fractional order controller is superior to integer order one for torque tracking loop of ELS system subject to extra torque and non zero initial conditions. Fractional order controller offer more degree of freedom ,so it is easy to acheive tracking objective by choosing a proper fractional order .

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