Design of Adaptive Sliding Mode Control with Fuzzy Controller and PID Tuning for Uncertain Systems

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Abstract – *In this paper, a robust control system with the fuzzy sliding mode controller and sliding mode control with PID tuning method for a class of uncertain system is presented. The goal is to achieve system robustness against parameter variations and external disturbances. A Fuzzy logic controller using simple approach & smaller rule set is proposed. Suitable PID control gain parameters can be systematically on-line computed according to the developed adaptive law. To reduce the high frequency chattering in the switching part of the controller, a boundary layer technique is utilized. The proposed method controller is applied to a brushless DC motor control system.*

Key Words: **PID controller, fuzzy controller, sliding mode control, adaptive control.**

1. INTRODUCTION

The proportional – integral – derivative (PID) controller operates the majority of the control system in the world. It has been reported that more than 95% of the controllers in the industrial process control applications are of PID type as no other controller match the simplicity, clear functionality, applicability and ease of use offered by the PID controller[1,2]. The PID controller is used for a wide range of problems like motor drives, automotive, flight control, instrumentation etc. PID controllers provide robust and reliable performance for most systems if the PID parameters are tuned properly [3].

To control complex systems or imperfectly modeled systems using fuzzy logic, a lot of efforts have been made in the past and these have been fruitful in many areas. However the designing of fuzzy logic controller greatly depends upon the expert's knowledge or trial and errors. Furthermore, fuzzy controller does not guarantee the stability and the robustness due to the linguistic expressions of the fuzzy control. Disadvantage of PID controller is poor capability of dealing with system uncertainty, i.e., parameter variations and external disturbance. Sliding mode control (SMC) is one of the popular strategies to deal with uncertain control systems. The main feature of SMC is the robustness against parameter variations and external disturbances [4].

In this paper, A Fuzzy logic controller using simple approach & smaller rule set is proposed, and the adaptive PID with sliding mode controller is proposed for second-order uncertain systems. In this study, the PID parameters can be systematic ally obtained according to the adaptive law. To reduce the high frequency chattering in the controller, the boundary layer technique is used [5]. The proposed method controller is applied to the brushless DC motor control system. The computer simulation results demonstrate that the chattering is eliminated and satisfactory trajectory tracking is achieved [6-11].

2. SLIDING MODE CONTROL

The robustness to the uncertainties becomes an important aspect in designing any control system. Sliding mode control (SMC) is a robust and simple procedure for the control of linear and nonlinear processes based on principles of variable structure control [12-14]. It is proved to be an appealing technique for controlling nonlinear systems with uncertainties. Figure 1 shows the graphical representation of SMC using phase-plane, which is made up of the error ($e(t)$) and its derivative ($\dot{e}(t)$). It can be seen that starting from any initial condition, the state trajectory reaches the surface in a finite time (reaching mode), and then slides along the surface towards the target (sliding mode).The first step of the SMC design requires the design of a custom made surface. On the sliding surface, the plants dynamics is restricted to the equations of the surface and is robust to match

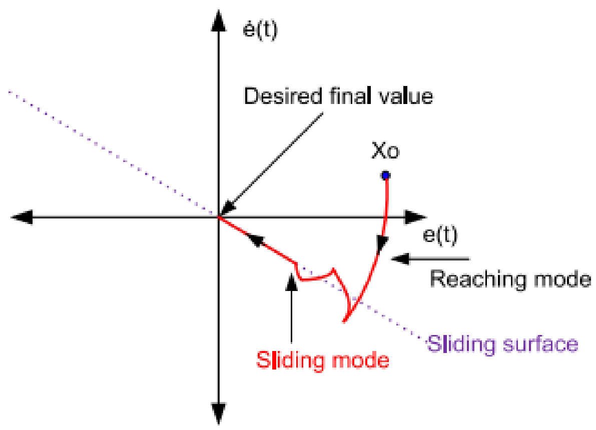

Fig -1: Graphical interpretation of SMC.

plant uncertainties and external disturbances. At the second step, a feedback control law is required to be designed to provide convergence of a systems trajectory to the sliding surface; thus, the sliding surface should be reached in a finite time. The systems motion on the sliding surface is called the sliding mode.

3. DESIGN OF FUZZY LOGIC CONTROLLER (FLC)

The model of the fuzzy controller and the plant with unity feedback is shown in Fig.

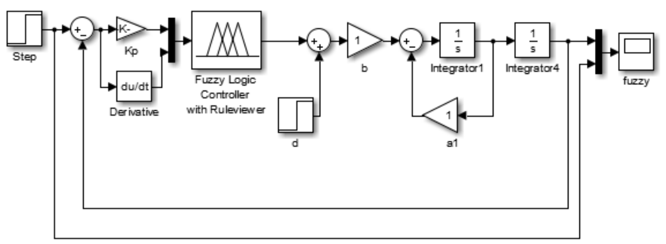

Fig -2: model of the fuzzy controller

For a two input fuzzy controller, 3,5,7,9 or 11 membership functions for each input are mostly used. In this paper, only two fuzzy membership functions are used for the two inputs error e and the derivative of error as shown. The fuzzy membership functions for the output parameter are shown in Fig, here N means Negative, Z means Zero and P means Positive.

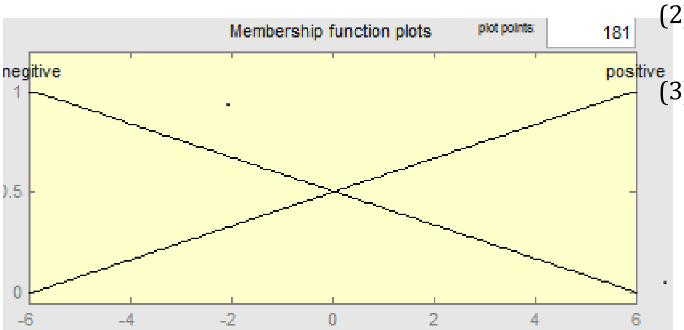

Fig -3: Membership functions for two inputs

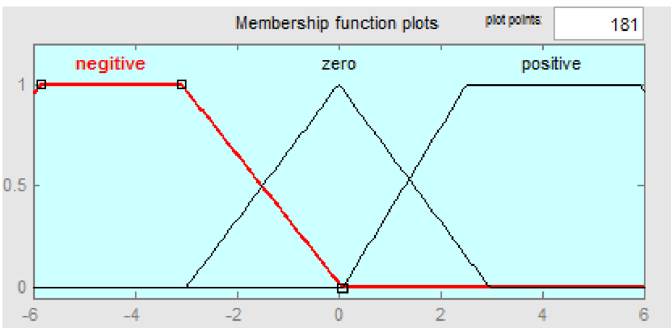

Fig -4: Membership functions for output

The system response can be divided in two phases. Phase A - System output is below the set point. Phase B - System output is above the set point. Depending upon whether the output is increasing or decreasing, 4 rules were derived for the fuzzy logic controller (Table I). These four rules are sufficient to cover all possible situations.

u		ė	
		N	P
e	N	N	Z
	P	Z	P

Table.1: Fuzzy rules

4. DESIGN OF SLIDING MODE CONTROLLER WITH PID TUNING:

4.1 Definition of the problem

Consider a second-order uncertain system which as shown below

$$\dot{x}_1(t) = x_2(t) \quad (1)$$

$$\dot{x}_2(t) = f(x_1, x_2, t) + \nabla f(x_1, x_2, t) + d(t) + bu \quad (2)$$

$$y(t) = x_1(t) \quad (3)$$

where $x_1(t)$ and $x_2(t)$ are measurable states, u is the input, y is the output, b is the input gain, $f(\cdot)$ is nominal parameter of plant, $\Delta f(\cdot)$ is the plant uncertainty applied to the system, and $d(t)$ denotes the external disturbance. It is assumed that there exist two positive upper bounds, g and α satisfying $\Delta f(\cdot) \le g$ and $d(t) \le \alpha$. Let e be the error between the desired trajectory y_d and the output y, i.e.

$$e = y_d - y \quad (4)$$

4.2 Design of the controller

The new reference signal is defined as

$$\dot{x}_r = \ddot{y}_d + k_1 e + k_0 e \quad (5)$$

Where k_1 and k_0 are chosen by the designers such that the roots of $s^2 + k_1 s + k_0 = 0$ are in the open left-half complex plane.

The sliding mode surface is defined so that in the sliding mode the system behaves equivalently as a linear system

$$\sigma = x_2 - x_r. \quad (6)$$

When the sliding mode occurs, σ goes to zero or

$$x_2 = x_r \quad (7)$$

From, the following equation is obtained:

$$\ddot{e} + k_1\dot{e} + k_0 e = 0 \quad (8)$$

This shows when time goes to infinite then the tracking error will be zero.
let the control input u be

$$u = u_{pid} + u_s \quad (9)$$

where

$$u_{pid} = \frac{1}{b}[k_p e + k_i \int edt + k_d \dot{e}] \quad (10)$$

$$u_s = -\frac{1}{b}(|f| + g + \alpha + |\dot{x}_r| + k_2)\,\mathrm{sgn}(\sigma) \quad (11)$$

where the k_2 is scalar and sgn(.) is sign function. i.e.,

$$\mathrm{sgn}(\sigma) = \begin{cases} +1, & \sigma > 0 \\ -1, & \sigma < 0 \end{cases} \quad (12)$$

The three PID controller gains, K_P, K_I, and K_D, are on-line computed, not fixed at all time, by the following adaptive laws,

$$\dot{k}_p = -\eta_1 \sigma e, \quad (13)$$

$$\dot{k}_i = -\eta_2 \sigma \int edt, \quad (14)$$

$$\dot{k}_d = -\eta_3 \sigma \dot{e} \quad (15)$$

where $\eta_i > 0$ is defined as the learning rate, i = 1, 2, 3.
In order to prove the stability, let the Lyapunov function be

$$v = \frac{\sigma^2}{2} \quad (16)$$

Taking derivative $\dot{v} = \sigma\dot{\sigma}$, (17)

$$\dot{v} \le 0, \quad (18)$$

$$\sigma[f + \nabla f + d + b(u_{pid} + u_s) - \dot{x}_r] \le 0 \quad (19)$$

By the above adaptive laws(13)-(15) and control law (9)-(12), guarantee that the reaching and sustaining of the sliding mode.

In general, the inherent high-frequency chattering of the control input may limit the practical application of the developed method. We further replace the $\mathrm{sgn}(\sigma)$ in (11)by the saturation function $sat(\frac{\sigma}{\delta})$ as i.e.

$$\mathrm{sat}(\frac{\sigma}{\delta}) = \begin{cases} 1, & \frac{\sigma}{\delta} \ge 1 \\ \frac{\sigma}{\delta}, & -1 < \frac{\sigma}{\delta} < 1 \\ -1, & \frac{\sigma}{\delta} \le -1 \end{cases} \quad (20)$$

δ is boundary layer width by replacing that, the sliding surface function σ with arbitrary initial value will reach and stay within the boundary layer $|s| \le \delta$.

5. SIMULATION RESULTS

In the computer simulation, by applying this controller to the permanent magnet brushless DC motor with unknown but bounded parameter variations and external disturbance. The dynamics of the brushless DC motor system is described as [11]

$$\ddot{\theta} + a_1\dot{\theta} = b(u + d). \quad (21)$$

Where

θ is the position angle, $\dot{\theta}$ is the angular velocity, $a_1 = \frac{B}{J}$ is composed of the viscous-friction coefficient B and an unknown but bounded J consisting of the rotor inertia and load, and $b = \frac{k_t k_c}{J}$ factors in the motor torque coefficient k_t and the PWM inverter current coefficient k_c. The control input u is the voltage input. Let $x_1 = \theta$ and $x_2 = \dot{\theta}$ therefore, the state-space equation of the brushless DC motor can be obtained as

$$\dot{x}_1 = x_2,$$
$$\dot{x}_2 = -a_1 x_2 + b(u + d), \quad (22)$$
$$y = x_1.$$

The limited bounds on the uncertain parameters and disturbances of the brushless DC motor were applied. The desired trajectory is shown below.

The control input can be implemented by using adaptive laws We choose damping ratio $\zeta = 1$ and natural frequency $w_n = 7$ so that roots of $s^2 + k_1 s + k_0 = 0$ are in the open left-half complex plane with k_1 =14 and k_0 = 49. Three PID controller gains, k_p, k_i, and k_d, with initial values are $k_p(0) = 0$, $k_i(0) = 0$, and $k_d(0) = 0$. The learning rate η_i is 1, i = 1, 2, 3, boundary layer δ = 0.1 as taken.

The simulation results are shown in Figs. 5 to 10. The sampling time is equal to 0.001 sec. The initial condition is $x_1(0) = x_2(0) = 0$. In Figs. 1 and 2, trajectory tracking results show that the output y converges to the desired trajectory y_d. From the Fig.3, it is obvious that chattering of the control input is eliminated by using boundary layer technology. Three PID controller gains are obtained by adaptive laws as shown in Fig. 8-10.

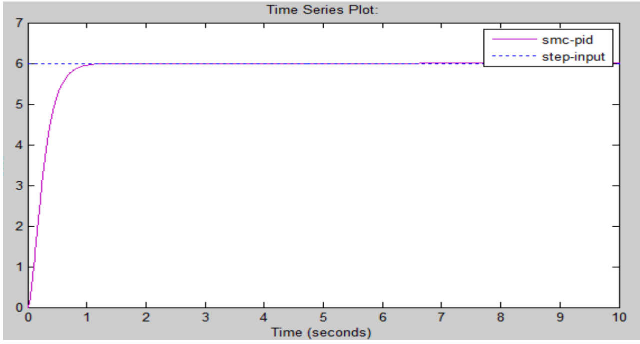

Fig -5: output response

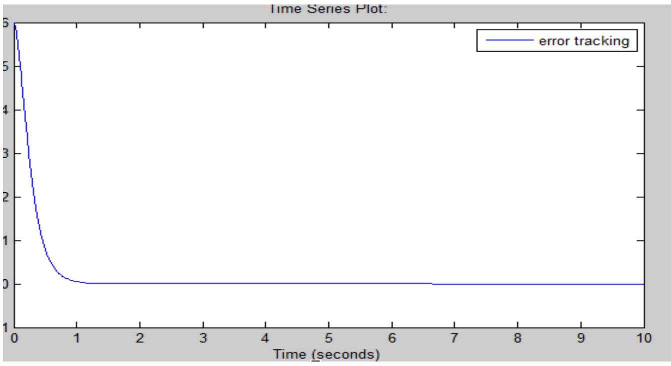

Fig -6: tracking error

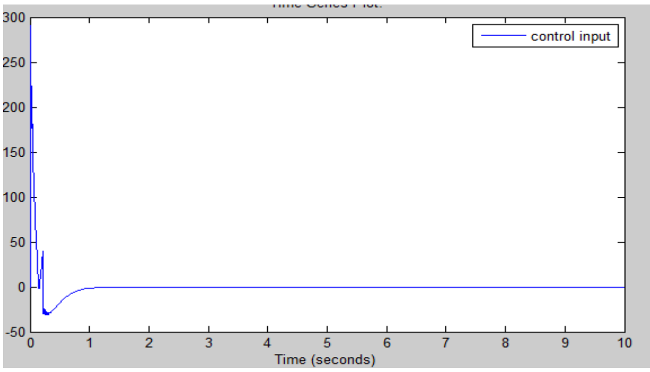

Fig -7: control input

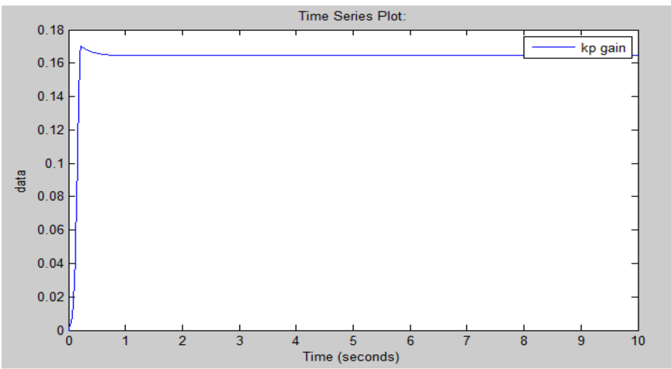

Fig -8: controller gain k_P

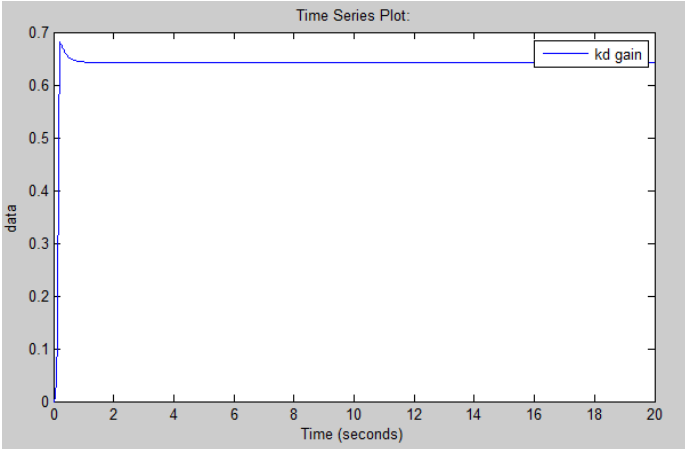

Fig -9: controller gain k_D

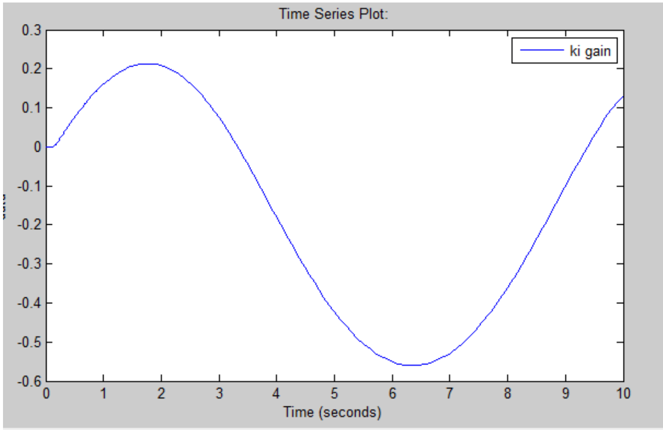

Fig -10: controller gain k_I

The response of the various methods is shown below in Fig.7 and the Fig.8 shows the zoomed view of Fig.7 to measure time response parameters as shown below.

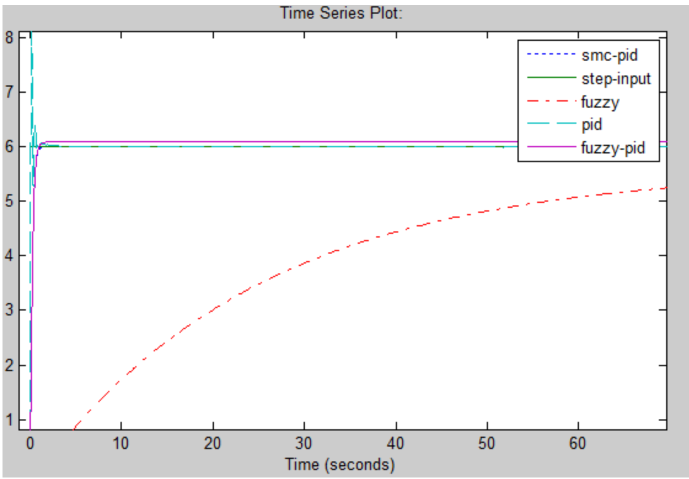

Fig -11: response of various controllers

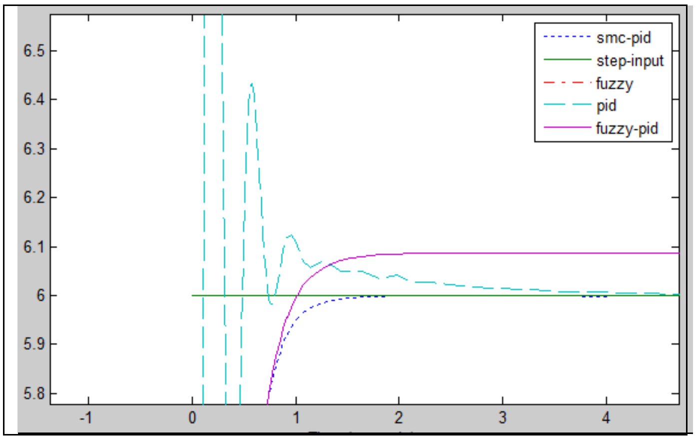

Fig -12: transient response of the controllers

The time response parameters percent overshoot (Mp), settling time (ts) and steady state error (e_{ss}) for PID controller (PID), fuzzy controller (FUZZY) ,Sliding mode control using fuzzy logic controller (SMFLC) and sliding mode PID controller (SMPIDC) for the higher order system are presented in table.2.

Table.2 Time response parameters

	M_p(%)	t_s(sec)	e_{ss}(%)
PID	41	2.3	0
FUZZY	0	49	0
SMFLC	0	1.65	1.667
SMPIDC	0	1.85	0

6. CONCLUSIONS

In this paper PID, fuzzy, sliding mode controller design for uncertain systems is designed. The PID and fuzzy are simple but they have poor capability of dealing with parameter variations and external disturbances. But sliding mode controller with control law consists of a continuous adaptive PID control part and a discontinuous switching control input. The proposed method is simple and the three PID controller gains can be systematically obtained by adaptive laws. The high frequency chattering in the control input is eliminated by using boundary layer technology. The computer simulation results demonstrate that the chattering is eliminated and satisfactory trajectory tracking can be achieved.

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