Speed Control of a DC Motor with Variable Load Using Sliding Mode Control

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Abstract: Sliding mode control method (SMC), which is built on Variable structure control (VSC) theory, is a robust nonlinear control method creating insensibility against to modeling errors, external disturbing effects and parametric change of the system. In this paper, control of a DC Motor used in particularly robots and countless industrial applications is carried out by using SMC and analysis are also performed under load changes. It is desirable that motors operating under load in robotic applications must not be affected by changes depending on loading condition. In this paper, SMC Method is used against to this situation which is affected stability of system and performance of motor. Modeling of a DC motor, designing of its controller and overall analyses are performed by using actual data. When comparisons between proposed method and commonly used PID control are made in terms of performance analyses, it is seen that SMC method produces more successful results.

Key words: Control of DC motor, nonlinear control method, PID, robust control, sliding mode control.

1. Introduction

Numerous mechanical actions which are seen around us are provided by electric motors. They are devices converting electrical energy to mechanical energy. At the end of 1800's, several inventors discovered the first DC (direct current) supplied motors. Due to its high torque in terms of inertia ratio, high efficiency, big power density, successful performance, easy controllability, exact, broad, simple and continuous control characteristic, DC motors are widely used in many industrial applications such as electric cars, electric winches, steelworks, robotic manipulator, paper machines and home applications [1]-[3]. As compared with AC motors, driver modules of DC motors are cheaper and its controllers are easier [1]. According to the type, DC motors are controlled by changing the field current or armature voltage.

Due to easy design, they are commonly controlled by PID controller. To adjust PID parameters, it is required to do some experiment or to determine the best way mathematical model of the system. However, conventional PID does not work attractively in applications of nonlinear, complex and of which system model cannot be defined precisely [4], [5].

Electrical parameters of motor get changed in time as to temperature, current and voltage fluctuations, time varying loading conditions, driving and operating conditions [4]. Loading changes generate fluctuations in speed of rotor [1].

PID controller is affected negatively by external disturbing effects, loading changes and parametric changes which occur depending on its location, so its usage is restricted in applications such as speed

control. Because PID controller with constant coefficient cannot show a good performance, until now, various modified PIDs such as Adaptive and self-tuning have been developed to cope with these effects [4]. Additionally, Fuzzy Logic, Fractional Order PID, Genetic Algorithm and different methods are investigated in applications control of DC motor in order to get a control structure with better performance. Control of a permanent magnet DC motor (PMDC) is realized by using PI and fuzzy logic control in a simulation study [6]. Gowthaman *et al.* in [7] designed a speed controller for a PMDC motor via self-tuning PID control method and also use fuzzy logic for a self-tuning. Velagic *et al.* in [8] carry out speed control of a PMDC motor by fuzzy logic controller. Comparisons are made between PID and fuzzy control under disturbing effect in both simulation and real time application. Kumar *et al.* in [9], speed control of separately excited DC motor performs using various PI, PID and Ziegler Nichols methods. In [10], Ziegler Nichols, modified Ziegler Nichols methods and PI controller which are designed via Particle Swarm Optimization (PSO) are used for speed control of DC motor. In this paper, Sliding mode control as a control method will be used to cope with mentioned effects and analysis will be made under various loading conditions.

2. Sliding Mode Control

Variable structure control (VSC) has been used for the first time by Emelyanov and *et al.*, at the end of 1800's in Russia. Although SMC which is founded on the VSC was unknown until 1977, when Utkin made a study, then, it has been started to use for linear and nonlinear applications in the international communities [11]. SMC, which has low sensitivity against to parametric changes of the system and disturbing effects, is an effective method to control complex and dynamic systems. Moreover it can operate under uncertain conditions which commonly occur in the modern technology [12].

Fig. 1. (a)Phase portrait of sliding mode control, (b) Sliding surface, reaching mode and high frequency switching.

SMC consists of two parts called as reaching mode and sliding mode and its phase portrait is shown like Fig. 1(a). The first of all, a surface is designed for system to be controlled.

As shown Fig. 1(b), control signal switched high frequency slide state trajectories of the system to this surface and this surface is called sliding surface. The movement along this surface represents output action of the system. SMC method tries to pull states of system from sliding surface to origin. Movement in sliding surface signify sliding mode and is stage from starting point to sliding mode called as reaching mode. States of system are insensitive to parametric changes and disturbing effects. The aim of the SMC is that output of system is to tracking to desired reference and to produce signal 'u' which makes minimum to tracking error. System reaches sliding surface by making transitions between stable and unstable trajectories and error converge to zero in sliding surface.

2.1. Basic Theory

Aim of the SMC is that output of system $y(t)$ is to tracking to desired output $y_d(t)$ and is to produce $u(t)$ which makes minimum to tracking error which is defined in (1). If this equation is generalized as (2), sliding surface is indicated as in (3) and C is Hurwitzian polynomial coefficients. Equation (4) is commonly used for sliding surface.

$$e(t) = y(t) - y_d(t) \quad (1)$$

$$e(t) = [e(t), \dot{e}(t), \dots, e^{(n-1)}(t)]^T \in R \quad (2)$$

$$s(t) = C * e(t) \quad (3)$$

$$s(x, t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} e(t) \quad (4)$$

In design of sliding surface, it is produced homogeny differential equation to be $s(x, t) = 0$ and $e(t) = 0$. Lyapunov function in (5) is commonly used for sliding mode and stability condition of system is obtained by (6), which is shown (7).

$$V = \frac{1}{2} s^2 \quad (5)$$

$$V(0) = 0, \quad s > 0, \quad V(s) > 0 \quad (6)$$

$$\dot{V} = \frac{1}{2} \frac{d}{dt} s^2 \leq -\eta |s| \quad (7)$$

Condition of convergence is acquired as (8) and condition of sliding mode is defined as (9).

$$\begin{aligned} s\dot{s} &\leq -\eta |s| \\ s\dot{s} &\leq -\eta \operatorname{sgn}(s)s \end{aligned} \quad (8)$$

$$\dot{s} \operatorname{sgn}(s) \leq -\eta \quad (9)$$

System reaches to sliding mode if $\eta > 0$. If dynamic equations are continued, signal $u(t)$ can be demonstrated as (10) which are consisted of two parts. The first of part symbolizes equivalent control signal, the other one symbolizes switching control signal which is shown as (10).

$$u(t) = u_{eq}(t) + u_{sw}(t), \quad u_{sw}(t) = K \operatorname{sgn}(s) \quad (10)$$

$$\operatorname{sgn}(s(t)) = \begin{cases} +1, & \text{if } s(t) > 0 \\ 0, & \text{if } s(t) = 0 \\ -1, & \text{if } s(t) < 0 \end{cases} \quad (11)$$

Switching control signal pulls states of system to sliding surface, while $s(t) \neq 0$. After reached sliding surface, switching control signal is disable and equivalent control signal keep stable to system. K in (10) is positive number and $\operatorname{sgn}(\cdot)$ is signum function. They are described as (11).

Disadvantage of SMC method is chattering phenomenon that it happens by high frequency switching and signum function. Chattering can be decreased by altering signum function or using fuzzy logic.

3. Modeling of DC Motor

Equivalent circuit of DC motor to be used in this paper is seen in Fig. (2) and speed control is performed by adjusting voltage of armature in fixed magnetic field. Parametric coefficients of motor are used like in [13]. They are selected as armature resistance (R_a) 7.72 ohm, armature inductance (L_a) 0.1627 Henry, inertia moment (J) 0.0236 kgm²/s², viscous friction (B) 0.003 Nms, Torque coefficient (K_t) and back emk coefficient (K_b) 1.25 Vs/rad.

Fig. 2. Schematic equivalent of DC Motor.

Dynamic equations of DC motor are written as below,

$$e_a(t) - e_b(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} \quad (12)$$

$$e_b(t) = K_b \omega(t) \quad (13)$$

$$\dot{i}_a(t) = \frac{e_a(t)}{L_a} - \frac{K_b}{L_a} \omega(t) - \frac{R_a}{L_a} i_a(t) \quad (14)$$

$$T(t) = T_l + J \frac{d\omega(t)}{dt} + B\omega(t) \quad (15)$$

$$T(t) = K_t i_a(t) \quad (16)$$

and if Laplace transformation is made, is synthesized under condition $T_l = 0$, transfer function of motor can be obtained as in (17).

$$\frac{\omega(s)}{e_a(s)} = \frac{\frac{K_t}{J L_a}}{\left(\left(s + \frac{R_a}{L_a} \right) \left(s + \frac{B}{J} \right) + \frac{K_b K_t}{J L_a} \right)} \quad (17)$$

4. Implementation of PID Control Method

PID is a control method commonly used in terms of basic design and consists of (K_p) proportional, integral (K_i) and derivative (K_d). It is demonstrated as (18) in the time domain. These parameters should be adjusted precisely and exactly to acquire desired performance characteristics of system. Nichols-Ziegler method can be used for adjusting these coefficients [9], [10]. The first values for K_p , K_i and K_d are determined by using Nichols-Ziegler. Then, PID coefficients are tuned the best. If it is not, controllers response is slow, settling time and overflow are increase. In this paper, as more competitive, durability of SMC method will compare to Tuned-PID control which its coefficients are adjusted via the best optimization values and also, analyses will be made in Section 6.

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} + K_i \int e(t) dt \quad (18)$$

5. Implementation of SMC Method

If simplifications are made in (19) by using (17), (20) is obtained. If descriptions of state for SMC is made as in (21), (22) is obtained. Moreover, equation of sliding surface is acquired as in (23).

$$A_1 = \frac{K_t}{J L_a}, \quad A_2 = \frac{R_a}{L_a}, \quad A_3 = \frac{B}{J}, \quad A_4 = \frac{K_b K_t}{J L_a} \quad (19)$$

$$\ddot{\omega} + (A_2 + A_3)\dot{\omega} + (A_2 A_3 + A_4)\omega = e_a A_1 \quad (20)$$

$$X_1 = \omega(t), \quad X_2 = \dot{X}_1 = \dot{\omega}(t), \quad \dot{X}_2 = \ddot{\omega}(t), \quad Y = X_1 = \omega(t), \quad u = e_a(t) \quad (21)$$

$$\dot{X}_2 = \ddot{\omega}(t) = -(A_2 + A_3)\dot{\omega} - (A_2 A_3 + A_4)\omega + e_a A_1 \quad (22)$$

$$s = C X_1 + X_2 = C e + \dot{e} = C(\omega_r - \omega) + \dot{\omega}_r - \dot{\omega} \quad (23)$$

$$\dot{s} = C(\dot{\omega}_r - \dot{\omega}) + \ddot{\omega}_r - \ddot{\omega} = 0 = -K \operatorname{sgn}(s) \quad (24)$$

If (22) is substituted in (24) and parametric data of used motor, which are seen in Section 3, is also substituted in (25), $u(t)$ control signal will produced as in (26).

$$u(t) = \frac{1}{A_1} [(A_2 + A_3 - C)\dot{\omega} + (A_2 A_3 + A_4)\omega + K \operatorname{sgn}(s)] \quad (25)$$

A change in signum function as shown in (27) is done to reduce processing load and relieve chattering.

$$u(t) = \frac{1}{325.484} [(47.567 - C)X_2 + (412.88)X_1 + K \operatorname{sgn}(s)] \quad (26)$$

$$u(t) = \frac{1}{325.484} \left[(47.567 - C)X_2 + (412.88)X_1 + K \left(\frac{s}{|s| + \delta} \right) \right], \quad 0 < \delta < 1 \quad (27)$$

6. Simulation Result and Comparisons

According to (23), (24) and (27), block scheme of SMC and simulation scheme of control system are introduced in Fig. 3. Sliding mode control of DC motor is carried out both without any loading and loading. Performance analyses are shown Fig. 4 and Fig. 5.

Fig. 3. (a) Block schema of SMC, (b) Overall simulation scheme.

Fig. 4. (a) . Change of angular velocity for PID and SMC, (b) Change of control signal $u(t)$.

Fig. 5. (a) Change of sliding surface, (b) Change of phase portrait according to error and derivative of error.

0.1Nm torque is loaded after 2.sec as disturbing effect on DC motor system. In Fig. 4(a), it is seen comparison graph of between PID and SMC in terms of transient analysis, steady state and loading change. According to this graph, SMC has a better performance due to less overshoot and quick come again to reference under loading. When variations of load are occurred or increased by continuing analysis, it can be seen that difference of performance is increasing. Produced control signals, switching and equivalent control signals, are seen in Fig. 4(b). Furthermore, it seen that $u_{sw}(t)$ is cut out from 0.18s in this graph. This means that to system output reaches to desired value. In Fig. 5(a), it is shown that sliding surface is converging to zero. Change of error and its derivative are demonstrated in Fig. 5(b). This is means that error in max value is converging to zero and it does little loop again under change of load. Comparison of performance of controllers is given in Table 1. According to performance criteria, it is shown that SMC has a better performance.

Table 1. Comparison of Controllers

Criteria	Expression	PID	SMC
T_r	Rising Time (s)	0.076	0.097
T_s	Settling Time (s)	0.32	0.18
Overshoot	Overshoot (%)	7.7	0
e_{ss}	Steady state error	0	0
Overshoot	Overshoot in loading (%)	-16.8	-1.8
Δt	Time difference for settling in loading (s)	0.3	0.05

7. Conclusion

In this paper, SMC and PID control method is used speed control of DC motor, which is an important issue in control systems, and analysis are made by comparing performance of designed controllers. Also, a change is made for chattering in SMC method. First of all, analysis are performed without disturbing effect, and then performed according to variable loading conditions. It seen that SMC give successful results in terms of settling time, state-state error and rapid response to disturbance. Moreover, SMC tolerates more successfully for particularly transient analysis. To use the SMC provide an advantage in applications which doesn't effect changes by depending on loading condition of motors operated especially under the load in robotic applications.

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