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A Speed Control of AC Servo Motor with Sliding Mode Controller

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Abstracts In this paper, a sliding mode controller (SMC) which can be characterized by high accuracy, fast response and robustness is applied to speed control of AC-SERVO motor. The control input is changed to continuous one in the boundary layer to reduce the chattering phenomenon, and the boundary layer converges to zero when the state variables of system reach to steady state values. The integral compensator is added to reduce steady state error and to provide the continuous torque reference. The acceleration which is necessary to get the sliding plane is estimated by an observer. Sliding surface is included in control input to enhance the robustness and transient response without increasing sliding mode controller gain. The proposed controller is implemented by DSP(digital signal processor). The effectiveness of the proposed control scheme for speed controller is shown by the real-time experimental results in the paper.

Keywords SMC, AC-SERVO motor, Speed control

1. INTRODUCTION

Recently, AC servo motor system is extensively applied to robot manipulator, computer numeric control machine(CNC) and other industrial areas. Generally, servo system requires fast accurate response without overshoot. The SMC have been several difficulties to implement for chattering and fast switching. But evolution of power semiconductor device and microprocessor technology have greatly influenced on the performances of the SMC. However, the SMC still has some weak points such as sensitivity to parameter variation and chattering of state path caused by discontinuous input. A number of authors have researched and analyzed to improve the performance of SMC[1][2][3]. Harashima[4][5] reduced the sensitivity by means of changing slope of the sliding surface. Hashimoto[6] removed the reaching mode dividing the sliding surface into three sections, and suggested time varying sliding surface for the motor control, which makes initial state exist on the sliding surface. In order to reduce chattering, Slotine[7] set up the boundary layer parallel with the sliding surface, which can alter discontinuous input into continuous one within layer.

In this paper, a modified SMC which may be characterized by fast response and robustness is applied to speed control of AC servo motor system. Boundary layer is added to the sliding surface to eliminate steady state error. The control input converges to zero when the state of the system reach at steady state. The chattering can be reduced by changing discontinuous input to continuous one in the boundary layer. Additionally, a new control method is also suggested which can improve robustness to sudden disturbance. Especially, the friction torque, which has inherent nonlinear characteristics, causes inaccuracy in the servo system performance. So, we have to model the nonlinear friction torque to compensate. Most of sliding mode control algorithm are applied to position control. The information needed in position control includes position, speed and acceleration. Speed and position informations can be easily obtained through sensors but acceleration gives some difficulty in measuring because it has high frequency components. That is why we employ an observer to get accurate acceleration information.

In this experiment, TMS320C31 control board is used as most parts of the controller are implemented with software in order to improve reliability.

2. NONLINEAR SERVO SYSTEM MODELLING

It is important to treat uncertainty of servo system in speed and position control. Friction is one of the uncertain nonlinear terms because it many change with speed and lubrication condition. The friction torque is a nonlinear function of speed, rotating direction, which effects in the performance of the control. System modelling to be compensated is shown in (1). Fig. 1 illustrates the friction torque model.

$$T_f(\cdot) = \begin{cases} \alpha_1\omega + \beta_1 & \omega(t) > 0 \\ \alpha_2\omega + \beta_2 & \omega(t) < 0 \end{cases} \tag{1}$$

The parameter α, β in (1) are viscous, coulomb torque constant respectively and ω is angular speed.

They can be obtained through experiment by means of varying input. Equation (2) shows the dynamic state equation of the servo system including friction torque. However, load disturbance torque and coupling of motor are ignored.

$$\begin{bmatrix} \frac{d\theta(t)}{dt} \\ \frac{d\omega(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & -\frac{\alpha_i}{J} \end{bmatrix} \begin{bmatrix} \theta(t) \\ \omega(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J} \end{bmatrix} \left[\ T_g(t) - \beta_i sgn(\omega)\ \right] \tag{2}$$

Where T_g is the generated torque.

$$\alpha_i, \beta_i, \begin{cases} i = 1 & \omega(t) > 0 \\ i = 2 & \omega(t) < 0 \end{cases}$$

Fig. 2 shows the simple block diagram of servo system controller, which includes torque controller and acceleration observer. On outer loop the speed controller, the command torque which is proportional to the error between actual speed and command speed, and command torque is sent to torque controller. The acceleration needed the speed controller is estimated at every sampling instants.

3. SLIDING MODE CONTROL STRATEGY FOR SPEED CONTROL

The sliding mode control can be achieved if there exists a control law such that the condition $s\dot{s} < 0$ is satisfied. Sliding surface(s) of servo system (3) is introduced by (2).

$$\begin{aligned} s &= C\epsilon_\omega(t) + \dot{\epsilon}_\omega(t) \\ &= -(C - \frac{\alpha_1}{J})\omega(t) + C\omega_r - \frac{1}{J}(T_g(t) - \beta_1 sgn(\omega)) \quad (3) \end{aligned}$$

Where $\epsilon_\omega = \omega_r - \omega$ is the speed tracking error. C is positive real constant. Control input $u(t)$ is expressed by derivative of generate torque as (4).

$$u(t) = \dot{T}_g(t) \quad (4)$$

When the states reach sliding surface, the control input should make the derivative of sliding surface equal zero.

$$\dot{s} = -(C - \frac{\alpha_1}{J})\dot{\omega}(t) - \frac{1}{J}u(t) \quad (5)$$

And $u_{eq}(t)$ can be obtained from the condition $\dot{s}(\epsilon_\omega, u) = 0$.

$$u_{eq}(t) = -J(C - \frac{\alpha_1}{J})\dot{\omega}(t) \quad (6)$$

The control input $u_{eq}(t)$ in (6) makes ϵ_ω and $\dot{\epsilon}_\omega$ which are sliding mode state variables converge to the stable point. The control input needed that the state reaches the sliding surface should be signum function including $u_{eq}(t)$, as shown in (7).

$$u(t) = u_{eq}(t) + K_1 sgn(s) \quad (7)$$

In (7) K_1 is positive real number and constant value adjusted by $u_{eq}(t)$. The signum function which is the second term in (7) is expressed in more detail by gains determining state variable and their signs as following equation.

$$u(t) = \psi_1 \epsilon_\omega + \psi_2 \dot{\epsilon}_\omega \quad (8)$$

The term ψ_1, ψ_2 in (8) is a commutation function with high frequency component which satisfies system state with sliding conditions. The other words, the state trajectory for shows chattering during the reaching $s(\epsilon_\omega) = 0$ condition. To reduce the chattering effect, we establish the boundary layer so as converging to "0" when the system state reaches steady state. The control input to change a discontinuous into continuous one is represented by a continuos function $1/(\lambda N(E))$. and the signum function in (7) is modified as (9).

$$u(t) = u_{eq}(t) + K_1 sat(\frac{s}{\lambda N(E)}) \quad (9)$$

where.

$$sat(\frac{s}{\lambda N(E)}) = \begin{cases} \frac{s}{\lambda N(E)}, & \text{if } |\frac{s}{\lambda N(E)}| < 1 \\ sgn(\frac{s}{\lambda N(E)}), & \text{if } |\frac{s}{\lambda N(E)}| \geq 1 \end{cases}$$

$$N(E) = |\epsilon_\omega| + |\dot{\epsilon}_\omega|$$

λ is a constant number determining layer boundary. The whole system response gets slow if λ is too large, which makes sliding gain small. So, λ should be chosen so that it does not affect the response time. The control input are adjusted such that the condition for existing sliding is satisfied, and then all of the system states heading the boundary layer, after that, the state moves on the bounding layer. Disturbance means an external action to the speed control operation. Popular approaches of the robustness to disturbance include SMC. Especially, speed SMC controller with high gain is known to overcome unknown disturbance, even though controlled variable reaches steady state, and chattering occurs. The pulsation effect in torque command is unavoidable. We include sliding surface term(s) in the control input, and put $K_d s$ again as shown by (10).

$$u(t) = \psi_1 \epsilon_\omega + \psi_2 \dot{\epsilon}_\omega + K_d s \quad (10)$$

The control input in (10) acts like the control input in (9) excluding "$K_d s$" when state exists in the boundary layer, and the control input including "$K_d s$" when the system state escapes from the bound, which helps the system recovery in the case of sudden variation by disturbance. Because it can be insensitive to sudden disturbance with the same gain. With the control input, we should obtain the condition that makes all the system states head to stable point of sliding surface. The state trajectory reaches the sliding surface according as the system state using above conditions. The input $u(t)$ obtained from controller should pass through an integral compensator in order to make the torque command. The torque command, with sliding control input, can reduce steady state error.

It is necessary to have accurate speed and acceleration in the SMC. However, it is difficult to measure acceleration directly because the measured signals contain high harmonic noises. That is why we employ an observer to estimate acceleration in this paper[12]. The observer is described as

$$\begin{aligned} \begin{bmatrix} \frac{d\hat{\omega}(t)}{dt} \\ \frac{d\hat{\dot{\omega}}(t)}{dt} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ 1 & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} \hat{\omega}(t) \\ \hat{\dot{\omega}}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J} \end{bmatrix} u(t) \\ &+ \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} (\omega - \hat{\omega}) \quad (11) \end{aligned}$$

It is essential to determine observer gain l_1, l_2 by the observer theory.

Fig. 3 represents the proposed system block diagram which consists of sliding speed controller, integral compensator, torque controller and acceleration observer.

4. EXPERIMENTAL RESULTS

Experimental motor is AC servo 200W include optical encoder (1024 pulse/rev.).

The controller is implemented on a TMS320c31 board with 32K words memory, A/D, D/A converts and 33.3 MHz system clock. Fig. 4 shows the entire hardware system. Equation (12) represents the full order observer with actual system parameters.

$$\begin{bmatrix} \frac{d\hat{\omega}(t)}{dt} \\ \frac{d\hat{\dot{\omega}}(t)}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & -166.67 \end{bmatrix} \begin{bmatrix} \hat{\omega}(t) \\ \hat{\dot{\omega}}(t) \end{bmatrix}$$

$$+ \begin{bmatrix} 0 \\ 294 * 10^3 \end{bmatrix} u(t) + \begin{bmatrix} 11 * 10^3 \\ 1018 * 10^3 \end{bmatrix} (\omega - \hat{\omega}) \quad (12)$$

The sampling frequency of the speed controller is 10KHz. The frequency of current control loop is 33KHZ. The experimental result illustrates the performance of the controller comparing the proposed controller with a conventional one. Fig. 5 expresses each sliding surface of a conventional method(a) and the proposed one(b). In this figure, the proposed method reduces chattering at $\lambda = 0.27$.

Fig. 6 and Fig. 7 illustrates the speed response(a), control input(b) and torque command (c) of the conventional and proposed method respectively. Actual speed tracks a speed command without overshoot, when the speed command is 200[rad/sec], Its steady state reaching time and steady state error rate are 0.24[sec] and 0.42% respectively. We can see that the torque command which is the output of the integral compensator has a lot of pulsation in Fig. 6(c). It improves the steady state reaching time 0.232[sec] and the steady state error rate 0.41% in Fig. 7. The amount of the control input decrease in the proposed control by 83.42% as compared with that of the can conventional method.

Fig. 8 (a) shows the speed response when a step load impact, 46% of motor rated torque is applied to the motor shaft. Fig. 8(a) is the speed response to the case of a control input without sliding surface term, the speed falls downs to 33[rad/sec] at the moment of the load impact, and its recovering time is 0.31[sec]. On the other hand, Fig. 8(b) shows the case of including sliding surface term($K_d = 0.2$), and it recovers fast. The speed falls down to 25[sec] and the recovering time is 0.23[sec]. It shows that rate of recovering time of the proposed method can be improved than without sliding surface term.

5. CONCLUSIONS

We employ an observer to estimate acceleration from actual speed and an integral compensator. And adding sliding surface to the control input results in insensitivity to sudden change of load. This paper presents a modified SMC strategy is applied to the speed control of the AC servo motor. From the results of simulation and experiment, we verify that speed response has less chattering to the load variation.

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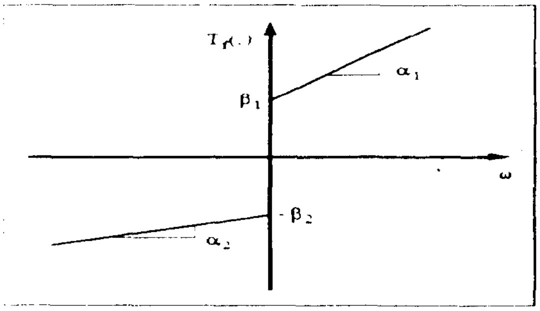


Fig. 1 Friction torque model

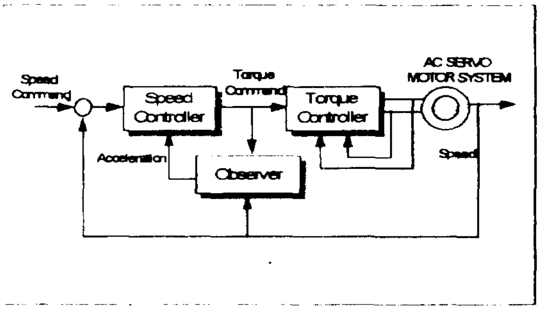


Fig. 2 Block diagram of servo speed control

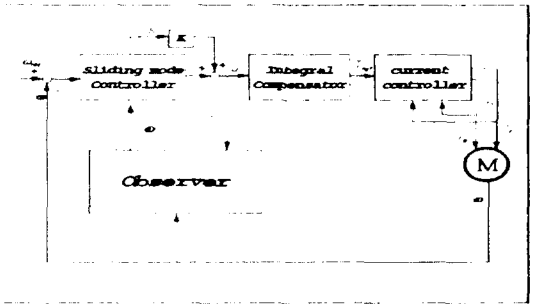


Fig. 3 Block diagram of sliding mode speed controller

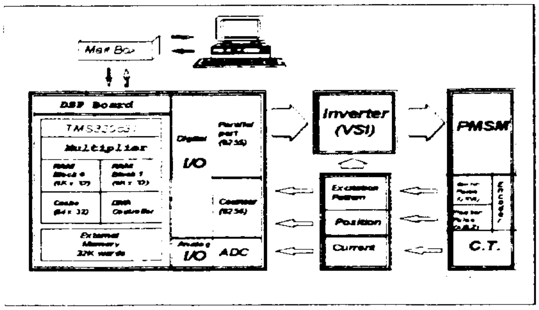
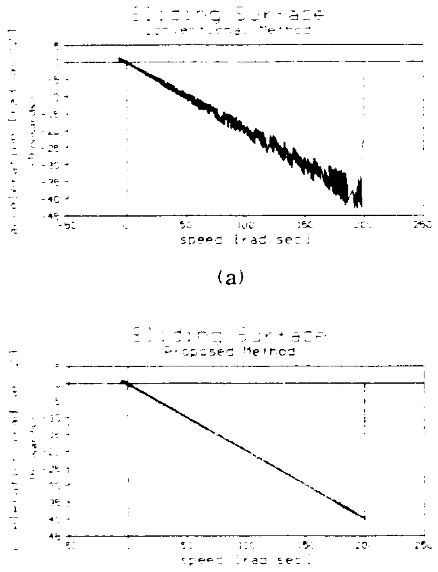


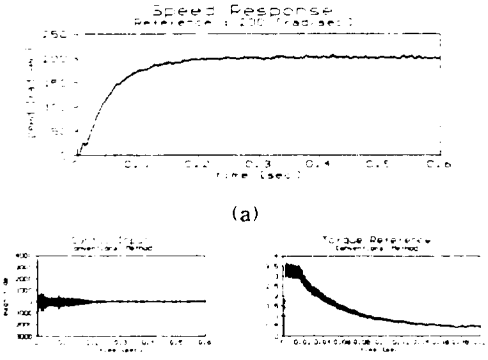
Fig. 4 Scheme of entire hardware system



(a)

(b)

Fig. 5 Comparing sliding surface of conventional(a) and proposed (b) method

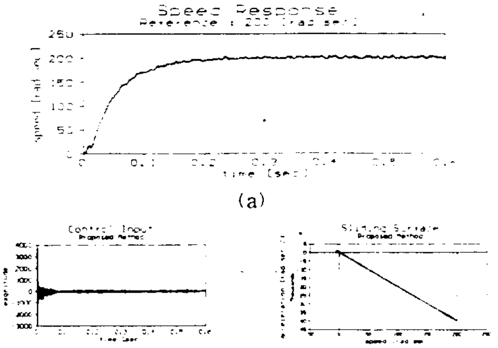


(a)

(b)

(c)

Fig. 6 Speed response of conventional method
(a) Speed response (Reference speed : 200 [rad sec])
(b) Control input (c) Torque reference

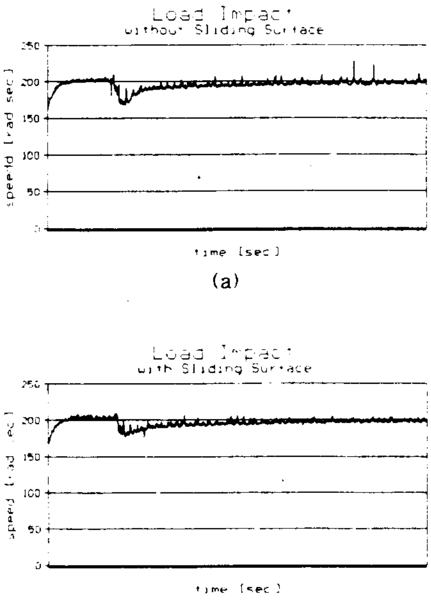


(a)

(b)

(c)

Fig. 7 Speed response of proposed method
(a) Speed response (Reference speed : 200 [rad sec])
(b) Control input (c) Torque reference



(a)

(b)

Fig. 8 Speed characteristic for momentary load impact
(a) Control input without sliding surface term
(b) Control input with sliding surface term