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Position Control of an AC Servo Motor Using Sliding Mode Controller with Disturbance Estimator

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ABSTRACT

In this work, a new control methodology to achieve accurate position control of an AC servo motor subjected to external disturbance is proposed. Unlike conventional sliding mode controller which requires a prior knowledge of the upper bound of external disturbance, the proposed technique, called sliding mode controller with disturbance estimator (SMCDE), can offer robust control performances without a prior knowledge of the disturbance bound. The SMCDE is featured by an integrated average value of the imposed disturbance over a certain sampling period. By doing this, undesirable chattering phenomenon in the estimation process can be effectively alleviated. The benefits of the proposed control methodology are empirically demonstrated on AC servo motor and control responses are evaluated through a comparative work between the proposed and conventional control schemes.

Key Words : Sliding Mode Control, Disturbance Estimator, Robust Control, Position Control, AC Servo Motor

1. Introduction

It is well-known that an AC servo motor can be effectively utilized in many position control systems subjected to external disturbances such as friction.[1,2] The conventional PID controller can guarantee robust and favorable control performances if accurate dynamic model and detailed information on the disturbances are acquired. [3,4] However, this assumption is hardly acceptable in practical environment. This leads to use so called robust control techniques such as sliding mode control (SMC). [5-8] The SMC is a special class of non-linear control mechanism characterized by a discontinuous control action which changes the structure upon reaching a set of sliding surfaces. During the motion on the sliding surface (sliding phase), the system has invariance properties, yielding motion that is independent of certain perturbations including external disturbances. In most of the SMC design strategies, the use of over-conservative high feedback gain is inevitable since the upper bound of the perturbation is normally employed to guarantee robust control performance. However, this causes undesirable chatter problem which deteriorates control accuracy. Recently, various techniques for perturbation estimation in SMC, which offer robust control performance without a prior knowledge about the upper bounds of the perturbations, have been proposed to avoid the over-conservative design.[9-13] Kozek et al.[9] proposed a sliding mode controller associated with a linear disturbance observer and proved its effectiveness by applying it to the levitation system of high-speed electromagnetic vehicles. Lu and Chen[10] proposed a perturbation estimator using the theory of the variable structure system to enhance the robustness of a pole placement controller design. Liu and Peng[11] developed a disturbance observer by treating plant non-linearities and parameter variations as a lumped disturbance and showed its superior performance to the standard adaptive control scheme. Elmali and Olgac[12] proposed a very effective methodology, called sliding

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mode control with perturbations estimation (SMCPE), which offers a robust feedback control with much lower gains than its conventional counterparts. This method has been successfully implemented on a two-axis planar SCARA robot.[13] The disturbance estimator proposed in this work has a similar form to the SMCPE. However the proposed one does not include state derivative terms (included in the SMCPE) which may cause undesirable noise and chattering in the estimation process. Instead, the integrated average value of the imposed disturbance is used over a certain sampling period to avoid the noise and chattering phenomena. In order to demonstrate the proposed controller, called sliding mode controller with disturbance estimator (SMCDE), AC servo motor subjected to torque disturbances is adopted and its position control performances are experimentally evaluated through a comparative work between conventional SMC and the proposed SMEDE.

2. Controller Design

The governing equation of the AC servo motor adopted in this work can be expressed as follows:[14]

$$\begin{bmatrix} \dot{\theta}_m \\ \ddot{\theta}_m \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{B}{J} \end{bmatrix} \begin{bmatrix} \theta_m \\ \dot{\theta}_m \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix} T_m(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} d(t) \tag{1}$$

where J is the moment of inertia of the motor, B is the effective viscous damping coefficient, $T_m(t)$ is the input torque and $d(t)$ is the external torque including the friction. In order to formulate the proposed SMCDE, Eq.(1) can be rewritten in a state space form as follows:

$$\begin{aligned} \dot{x}_1(t) &= x_2(t) \\ \dot{x}_2(t) &= -\frac{B}{J}\dot{x}_1(t) + \frac{1}{J}u(t) + d(t) \end{aligned} \tag{2}$$

where $u(t)$ is the input torque to be applied to the motor, and $x_1(t)$ and $x_2(t)$ represent angular displacement and velocity of the motor, respectively. Since the impending control issue is to achieve desired position and velocity of the motor, the tracking errors are defined by

$$\begin{aligned} e_1(t) &= x_d(t) - x_1(t) \\ e_2(t) &= \dot{x}_d(t) - x_2(t) \end{aligned} \tag{3}$$

where $x_d(t)$is the desired angular displacement of the motor. Thus, a sliding surface (in fact, a line in this case) is established in the error state as

$$s(t) = c_1 e_1(t) + e_2(t) = 0 \tag{4}$$

where $c_1(>0)$ is the slope of the sliding surface.

It can be seen that the error state converges to zero for any initial conditions provided that a control law $u(t)$ exists in Eq.(2) so as to cause the trajectory $e(t)$ to slide along the surface defined by Eq.(4). This can be achieved by constructing an appropriate SMC to satisfy the sliding mode condition : $s(t)\dot{s}(t) < 0$. To formulate such an SMC, the dynamics of the sliding surface is firstly obtained by

$$\begin{aligned} \dot{s}(t) &= c_1 \dot{e}_1(t) + \dot{e}_2(t) \\ &= c_1 \dot{e}_1(t) + \ddot{x}_d(t) + \frac{B}{J}x_2(t) - \frac{1}{J}u(t) - d(t) \end{aligned} \tag{5}$$

Now, we can construct the following SMC which satisfies the sliding mode condition.

$$\begin{aligned} u(t) &= J(u_{eq} + k\,\mathrm{sgn}(s(t))), \quad k > |d(t)| \\ u_{eq} &= c_1 \dot{e}_1(t) + \ddot{x}_d(t) + \frac{B}{J}x_2(t) \end{aligned} \tag{6}$$

where k is the discontinuous control gain. As we noticed from Eq.(6) that the information on the disturbance $d(t)$ should be known in advance in order to determine an appropriate control gain k . However, an accurate knowledge of the upper bounds of the disturbance may not be easy to obtain in practice. This may yield the over-conservative high feedback gain, which results in undesirable control performances such as high chattering. Consequently, an accurate estimation of the disturbance is necessary to enhance control performances.

In order to design the proposed SMCED, the $s(t)$

dynamics, which includes the disturbance estimator, is arranged as follows:

$$\begin{aligned}\dot{s}(t) &= c_1\dot{e}_1(t)+\dot{e}_2(t)\\ &= c_1\dot{e}_1(t)+\ddot{x}_d(t)+\frac{B}{J}x_2(t)-\\ &\quad u_{eq}(t)-k\,\mathrm{sgn}(s(t))+d_{estimated}(t)-d(t)\end{aligned}\tag{7}$$

The integration of the above equation from $T-\delta$ to T yields

$$\begin{aligned}&\int_{T-\delta}^{T} d(t)\,dt = -\{s(T)-s(T-\delta)\}-\\ &\delta\cdot k\,\mathrm{sgn}(s(T-\delta))+\delta\cdot d_{estimated}(T-\delta)+\\ &\int_{T-\delta}^{T}\left(c_1\dot{e}_1(t)+\ddot{x}_d(t)+\frac{B}{J}x_2(t)-u_{eq}(T-\delta)\right)dt\end{aligned}\tag{8}$$

In the above, δ is the sampling time for the disturbance estimation. Both control and estimation performances, of course, depend upon the sampling time of δ.

A constant, $d_{average}$, is now defined as in the left-hand side of Eq.(8) :

$$\int_{T-\delta}^{T} d_{average}(T)dt = \int_{T-\delta}^{T} d(t)dt \tag{9}$$

The above equation indicates that the integrated value of the disturbance is equal to the integrated value of average disturbance $d_{average}(T)$. Thus, the average disturbance can be expressed by

$$d_{average}(T) = \int_{T-\delta}^{T} d(t)dt \Big/ \delta \tag{10}$$

Substituting Eq.(10) into the left-hand side of Eq.(8) yields the following equation:

$$\begin{aligned}&d_{average}(T) = -\{s(T)-s(T-\delta)\}/\delta-\\ &\quad k\,\mathrm{sgn}(s(T-\delta))+d_{estimated}(T-\delta)+\\ &\left\{\int_{T-\delta}^{T}\left(c_1\dot{e}_1(t)+\ddot{x}_d(t)+\frac{B}{J}x_2(t)-u_{eq}(T-\delta)\right)dt\right\}\Big/\delta\end{aligned}\tag{11}$$

The last term of the above equation compensates for the correction of the error which may be caused by an assumption ; $u_{eq}(T-\delta)=c_1\dot{e}_1(t)+\ddot{x}_d(t)+\frac{B}{J}x_2(t)$. In computation, it is hard to accurately calculate this term. Thus, the following approximation is used :

$$X_c(T) = -\left(u_{eq}(T)-u_{eq}(T-\delta)\right)/2 \tag{12}$$

Now, by substituting Eq.(12) into Eq.(11) we can obtain a final from of the average disturbance as follows:

$$\begin{aligned}d_{average}(T) &= -\{s(T)-s(T-\delta)\}/\delta-\\ &\quad k\,\mathrm{sgn}(s(T-\delta))+d_{estimated}(T-\delta)-\\ &\quad X_c(T)\end{aligned}\tag{13}$$

The calculated value for Eq.(13) is the average disturbance integrated from $T-\delta$ to T , and the disturbance estimation is fed back for the next step of control input. In computer realization, the disturbance estimation $d_{estimated}(t)$ can be obtained by the Taylor series as

$$d_{estimated}(t) = \sum_{i=0}^{n}\delta^i\cdot d_{average}^{(i)}(T)\big/i! \tag{14}$$

where i is the design of time derivative. Thus, the SMCDE proposed in this work can be expressed by

$$u(t) = J\{u_{eq}(t)+k\,\mathrm{sgn}(s(t))-d_{estimated}(t)\} \tag{15}$$

Consequently, the realization of the proposed SMCDE can be achieved by combining Eqs.(13), (14) and (15).

3. Control Results

In order to demonstrate the effectiveness and superior performance of the proposed SMCDE, an experimental apparatus has been established as shown in Fig.1. The angular displacement of the motor is measured by the optical encoder and fed back to the microprocessor (IBM PC). On the other hand, the angular velocity of the motor, which is required for the controller implementation, is numerically obtained by tracking time derivative of the angular displacement. Both the displacement and velocity signals are fed back to the microprocessor via the A/D converter. And the control input determined from the SMCDE given by Eq.(15) is supplied to the motor via the D/A converter. It is to be noted that actual input to the motor is not voltage, but current into which voltage is converted through the servo drive board of the motor. The model parameters and controller gains employed in this work are given as follows : $J = 0.00268 kg \cdot m^2$, $B = 0.0347568 Nm \cdot s$, $c = 0.29481$, $k = 0.2$, $\delta = 0.001$ *sec*. For the dynamic motion, the motor shaft initially positioned at 0° was rotated to the position of 45° and steadily regulated. It is here remarked that the disturbance torque is augmented to the input torque during control action.

Figure 2 presents the simulated control responses when the external disturbance , $0.02\sin(9.5Hz\ t)$, is imposed on the input torque. It is clearly seen that the imposed disturbance is accurately estimated by the proposed SMCDE, and this results in superior control performance to the conventional SMC. Figure 3 presents the measured control responses under the same conditions imposed on the results shown in Fig.2. It is observed that the small magnitude of the estimation error has been occurred at the peak of the sinusoidal trajectory. This is due to system uncertainties including the motor friction. Despite the error, the regulating control performances of the proposed SMCDE guarantees acceptable position accuracy.

In order to investigate the effect of the disturbance dynamics on control responses, the following two disturbances ; $0.02\sin(30Hz\ t)$ and $0.02\sin(60Hz\ t)$ are imposed and control results are presented in Fig.4 and 5, respectively. It is also observed that the proposed SMCDE provides more accurate control responses than conventional SMC under relatively high frequency of the external disturbance. As mentioned earlier, control response of the proposed SMCDE depends upon the sampling time for the estimation. Table 1 presents the

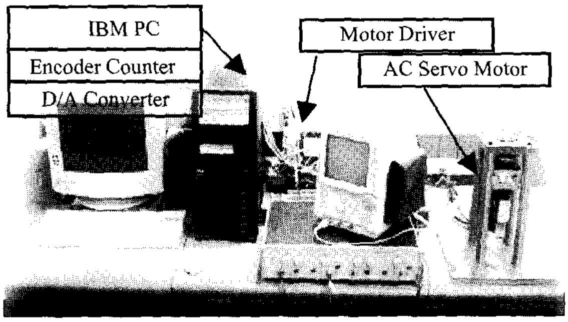

Fig. 1 Photograph of an experimental apparatus

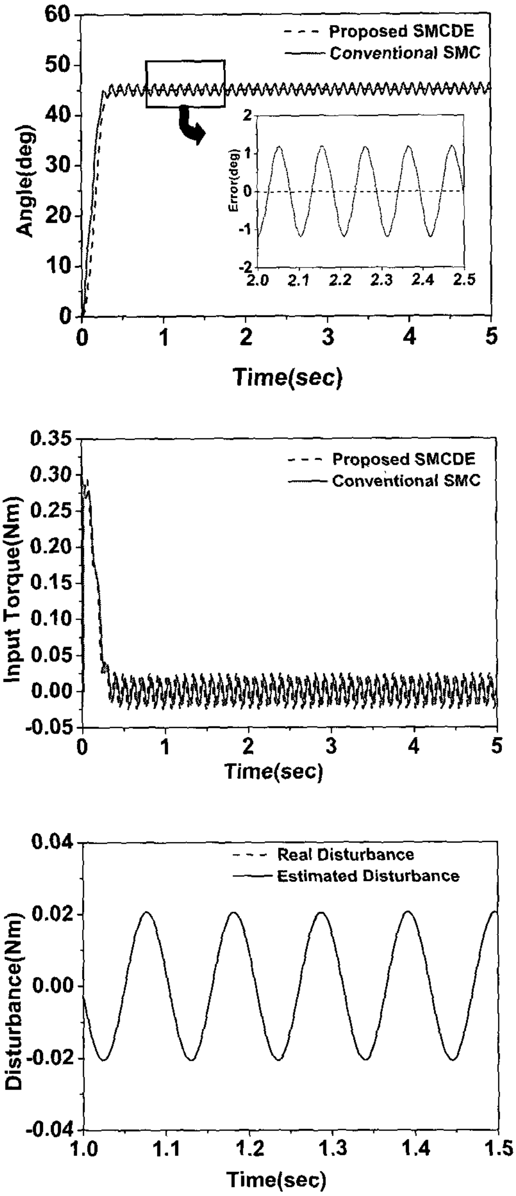

Fig. 2 Simulated control responses in the presence of the torque disturbance (9.5Hz)

average disturbance error with several different sampling times. As expected, the estimation error increases as the sampling time increases. This directly indicates that the higher resolution of the microprocessor yields the higher accuracy of the position control.

4. Conclusions

In this work, a new type of sliding mode controller with disturbance estimator (SMCDE) was proposed and applied to the position control of AC servo motor. After explaining the salient feature of the SMCDE, a controller to achieve accurate position of the servo motor has been designed in a sequential manner. The controller was then experimentally realized with respect to different disturbance frequency components and sampling times for the estimation. It has been demonstrated that control responses of the SMCDE are far superior to those

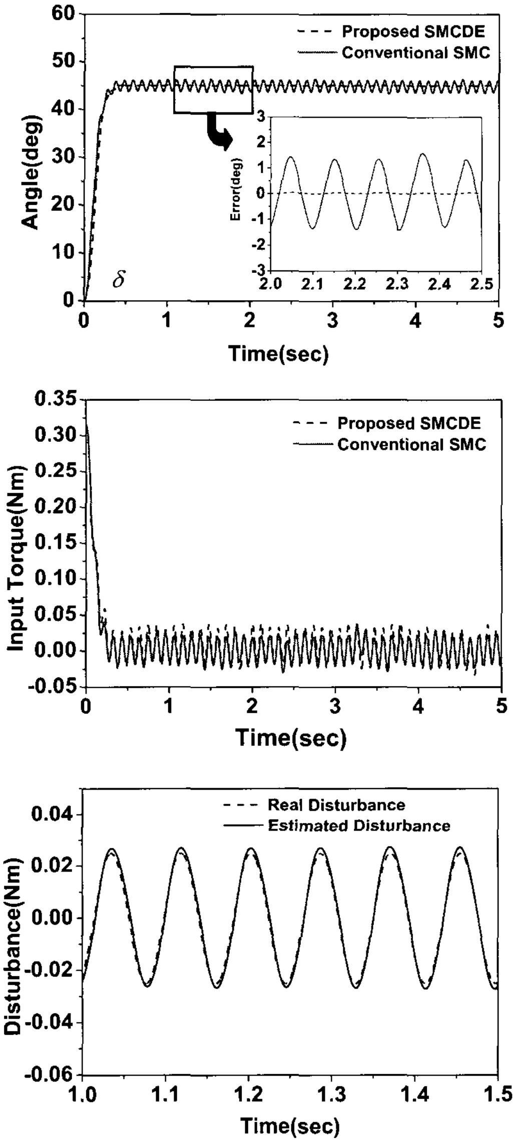

Fig. 3 Measured control responses in the presence of the torque disturbance (9.5Hz)

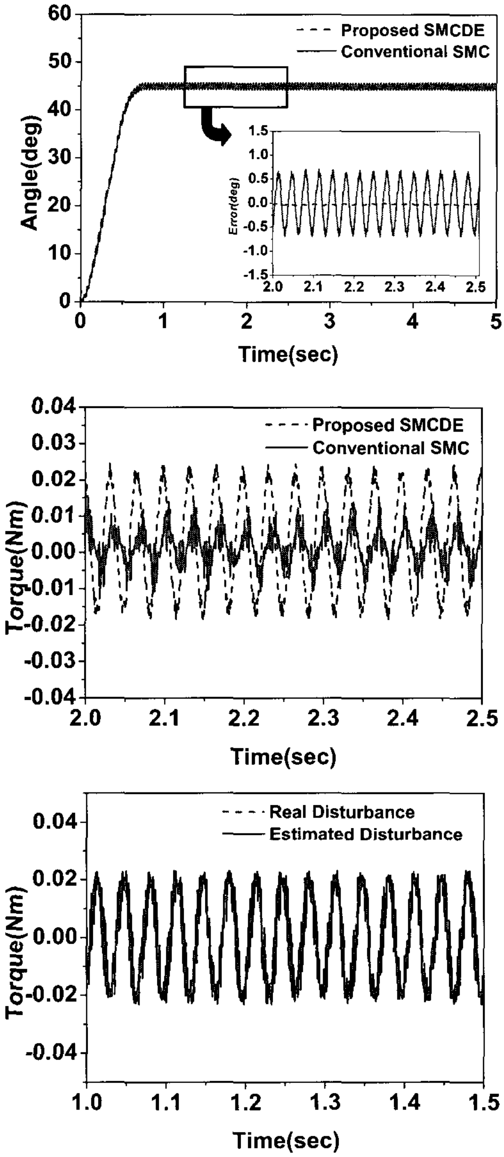

Fig. 4 Measured control responses with different disturbance frequencies(30Hz)

Table 1 Average disturbance error for each sampling time

Sampling Time(δ)	0.0005	0.001	0.005	0.01
Average Disturbance Error(%)	0.000003 %	0.01 %	0.06%	0.5%

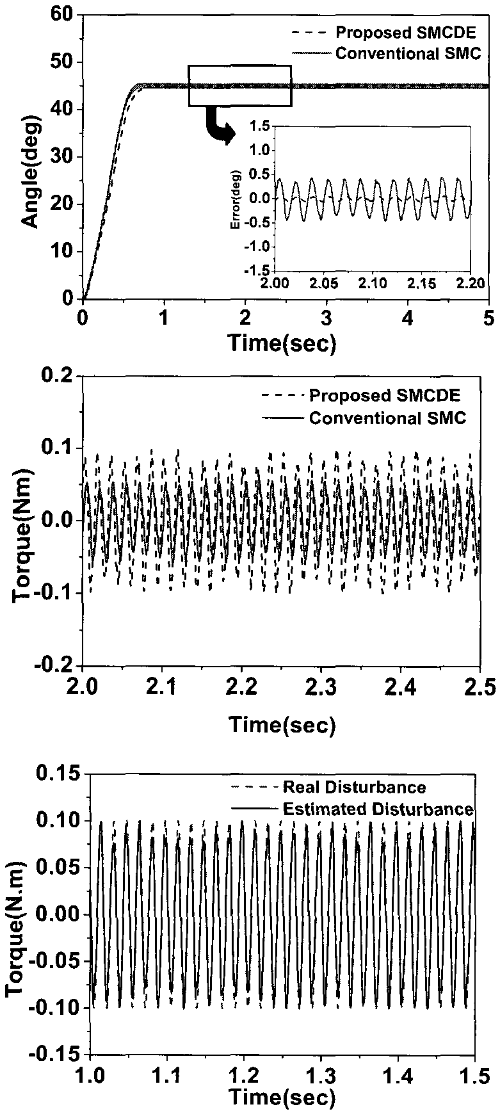

Fig. 5 Measured control responses with different disturbance frequencies (60Hz)

obtained from the conventional sliding mode controller which does not have the disturbance estimator. It has also been investigated that control accuracy of the SMCDE is sensitive to the estimation sampling time. It is finally remarked that the proposed control methodology can be directly applied to various control systems (for example, robotic system) subjected to external disturbances or uncertainties.

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