Design of a Sliding Mode Controller with Self-tuning Boundary Layer

경계층이 자동으로 조정되는 슬라이딩 모우드 제어기의 설계

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ABSTRACT

Sliding mode controller(SMC) is a simple but powerful nonlinear controller, because it guarantees the stability and the robustness. However, it leads to the high frequency chattering of the control input. Although the phenomenon can be avoided by introducing a thin boundary layer to the sliding surface, the method results in a steady state error proportional to the boundary layer thickness.

In this paper, we proposed a new sliding mode controller with self-tuning the thickness of a boundary layer. It uses a fuzzy rule base for tuning the thickness of a boundary layer. That is, the thickness is increased to some degree to reject a discontinuous control input at the initial state and then it is decreased as the states approaches to the steady states for improving the tracking performance. In order to assure the control performance, we performed the computer simulation using an inverted pendulum system as a controlled plant.

요 약

탁월한 비선형 제어 특성을 가지고 있는 슬라이딩 모우드 제어기는 제어 대상 플랜트의 모델링 과정에서 발생하는 부정확성과 각종 외란등으로 인하여 제어 입력 신호가 매우 높은 주파수의 비연속적인 특성을 가진다. 이를 방지하기 위하여 슬라이딩 평면에 얇은 경계층을 도입하는 방법을 많이 사용하고 있지만 이 경우에는 원하지 않는 정상 상태 오차가 유발될 수도 있다. 이때의 정상 상태 오차는 경계층의 폭에 비례해서 증가하는 특성이 있다. 본 논문에서는 정상 상태 오차와 제어 입력 신호의 불연속성 사이에서 구해지는 경계층의 폭을 정상 상태에 접근할수록 퍼지 규칙 베이스에 의해 자동으로 감소시키는 자기동조형 경계층을 가지는 슬라이딩 모우드 제어기를 제안하였다. 그리고 제안된 알고리즘의 성능을 역진자 계통의 추적 제어 시뮬레이션을 통하여 입증하였다.

Keywords : sliding mode control, sliding surface, fuzzy control, fuzzy rule base, self-tuning

I. Introduction

Sliding mode controller(SMC) is a powerful nonlinear controller. It has been used for the control of imprecise non-linear plants. In SMC, the control input is allowed to change its structure, that is, to switch at

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any instant from one to another member, according to continuous functions of the state. It is based on the control law with a sliding regime that not only is independent of changes in the plant parameters and the external disturbances but also has the property of the reduction of a system order [1]. While in the sliding mode, accordingly, this control algorithm guarantees the stability and the robustness in itself. However, it has several drawbacks. One of them is the high frequency chattering of the control input. The chattering phenomenon is generally undesirable in practice, because it involves extremely high control activity, and further it may excite high frequency dynamics neglected in the course of modeling [2]. Many approaches that alleviate this chattering phenomenon has been proposed. In particular, the chattering magnitude can be alleviated by an equivalent control input. Furthermore, the phenomenon can be avoided by introducing the thin boundary layer to a sliding surface. This method called the boundary layer approach generates the continuous control input. In consequence, the method can eliminate the chattering by smoothing out the control discontinuity in a thin boundary layer neighboring the switching surface. Unfortunately the boundary layer method leads to a steady state error, and the error increases with the extension of a boundary layer thickness [2][3].

Since L. Zadeh had introduced the fuzzy set theory in 1965, this theory has been applied to many areas. Fuzzy control has emerged as one of the most active and fruitful areas for research in the application of fuzzy set theory. Fuzzy controller has been successfully applied to many plants that are mathematically poorly understood. In recent, the fuzzy logic theory in the control areas is used to improve the overall performance of conventional control algorithms such as PID control, adaptive control, neuro control, and so on. Furthermore, it has been used in many self-tuning techniques like the adjustment of several control parameters of a conventional PID controller.

In this paper, we proposed new sliding mode controller with self-tuning boundary layer thickness. The controller uses a fuzzy rule base to tune the varying boundary layer thickness. That is, the thickness is increased to some degree to reject of a discontinuous control input at the initial state and then to improve the tracking performance, it is decreased as the states approaches the steady state. As a result, a sliding mode controller with self-tuning boundary layer thickness makes the control input continuous as well as greatly decreases the steady state error. To assure the control performance, we performed the computer simulation using an inverted pendulum system as a controlled plant.

In Section Ⅱ, we give a short review of the sliding mode control. We explain in detail the boundary layer method and the self-tuning boundary layer thickness that is the heart of our study in Section Ⅲ. Also we described the results of a computer simulation using the proposed algorithm in Section Ⅳ, which demonstrates the improved control performance. Finally conclusions are followed in Section Ⅴ.

Ⅱ. Sliding Mode Control

The central idea of SMC is switching to a different structure at each side of a given switching surface. So, originally this algorithm is called the variable structure control (VSC). The term SMC is used for emphasizing the importance of the sliding mode or the sliding regime [5]. The salient feature of VSC is that the sliding mode occurs on the switching surface and while in this mode the system remains insensitive to parameter uncertainties and external disturbances [6]. Hence, SMC guarantees the stability and the robustness in itself. Recently the objectives of SMC has been greatly extended to stabilize other control algorithms that are difficult to prove the stability.

General classes of nonlinear dynamic systems can be transformed into the following class [2].

$$x^{(n)} = f(\mathrm{x}, t) + u(t) + d(t) \tag{1}$$

In this paper, we use the second order system for simplicity as follows

$$\ddot{x}(t) = f(\mathrm{x}, t) + u(t) + d(t), \tag{2}$$

where $\mathrm{x} = [x, \dot{x}]^T$ is the state vector, and $d(t)$ and $u(t)$ are the disturbance and the control input, respectively. The function $f(\mathrm{x}, t)$ (in general nonlinear) is not exactly known, but the extent of the imprecision on $f(\mathrm{x}, t)$ is upper bounded by a known continuous function of x. Similarly, the disturbance $d(t)$ is bounded by a known continuous function of x,

$$\begin{aligned} |\Delta f(\mathrm{x}, t)| &\le F(\mathrm{x}, t) \\ |d(t)| &\le D(\mathrm{x}, t), \end{aligned} \tag{3}$$

where the model uncertainty $\Delta f(\mathrm{x}, t)$ is expressed as follows

$$\Delta f(\mathrm{x}, t) = f(\mathrm{x}, t) - \hat{f}(\mathrm{x}, t), \tag{4}$$

where $\hat{f}(\mathrm{x}, t)$ represents the estimation of $f(\mathrm{x}, t)$.

Let $e(t)$ be the tracking error of a state x.

$$e(t) = x(t) - x_d(t). \tag{5}$$

Furthermore, let us define a surface $s(t)$ in the state-space R^2 by the scalar equation $s(\mathrm{x}, t) = 0$, where

$$s(\mathrm{x}, t) = (\frac{d}{dt} + \lambda)\, e(t) = \dot{e}(t) + \lambda e(t), \tag{6}$$

and λ is a strictly positive constant and the surface $s(\mathrm{x}, t) = 0$ is called the sliding surface. Then the control problem is for the state x to track the desired state $\mathrm{x}_d(t)$ even under the model uncertainties and the disturbances. The problem of tracking a 2-dimensional vector $\mathrm{x}_d(t)$ can in effect be replaced by a first-order stabilization problem in s. That is, the tracking control is to place the error $s(t)$ on the sliding surface. The control input is made to satisfy the following sliding condition,

$$\frac{1}{2}\frac{d}{dt}[s^2(\mathrm{x}, t)] \le \eta |s|, \ \eta \ge 0. \tag{7}$$

Let the control input be

$$u = \hat{u} - K(\mathrm{x}, t)\, sgn(s) \tag{8}$$

$$sgn(s) = \begin{cases} 1 & \text{for } s \ge 0 \\ -1 & \text{for } s < 0. \end{cases} \tag{9}$$

From the sliding condition, we get

$$s\dot{s} = s(f(\mathrm{x}, t) + u + d - \ddot{x}_d(t) + \lambda \dot{e}) \le \eta |s|. \tag{10}$$

that is, in order to satisfy above sliding mode, despite uncertainties on the dynamics $f(\mathrm{x}, t)$ and the disturbances $d(t)$, K has to satisfy the following condition

$$K(\mathrm{x}, t) \ge F(\mathrm{x}, t) + D(\mathrm{x}, t) + \eta. \tag{11}$$

In equation (8), an equivalent control law $\hat{u}$ is computed by (i.e., $f = \hat{f}$, $d = 0$) as follows

$$\hat{u} = \ddot{x}_d(t) - \hat{f}(\mathrm{x}, t) - \lambda \dot{e}. \tag{12}$$

$\hat{u}$ is the nominal compensation term that can be interpreted as our best estimate, and plays the important role of decreasing a chattering amplitude. Namely, the chattering magnitude of a control input is reduced as much as a prior knowledge of the function $f(\mathrm{x}, t)$.

By choosing K to be large enough so an equation (11) is satisfied, sliding condition is proved. The control discontinuity K across $s = 0$ increases with the extent of parameter uncertainties and disturbances. As we explained before, SMC results in chattering due to $Ksgn(s)$. The chattering phenomenon of a control input means high frequency oscillation with a certain magnitude, which is undesirable in practice.

Ⅲ. Continuous Control Law with Self-tuning Boundary Layer

3.1 Boundary layer Method for Continuous Control Law

Good performance of SMC is obtained at the price of extremely high control activity. And in order to compensate the effect of modeling imprecision and of disturbances, the control law has to be discontinuous across the sliding surface. Since the implementation of associated control switchings is necessarily imperfect due to the presence of delays and hysteresis in switchings, this causes the trajectory to chatter along the sliding surface. So, a rapid time-varying control input signal will be accompanied. The chattering phenomenon is undesirable in practice, because it implies extremely high control activity, and further may excite unmodelled high frequency dynamics. Therefore the discontinuous control law $u(t)$ must be suitably smoothed out. To avoid this undesirable phenomenon, some researchers proposed the so-called the boundary layer method that generates a continuous control law in place of a discontinuous one. In this method, the saturation function is used instead of the sign function for a conventional sliding mode control. As a result, the control law (8) is changed to following equations (13) and (14).

$$u = \hat{u} - K(\mathrm{x}, t)\, sat\left(\frac{s}{\Phi}\right) \tag{13}$$

$$sat\left(\frac{s}{\Phi}\right) = \begin{cases} \dfrac{s}{\Phi} & \text{for } |s| \le \Phi \\ sgn\left(\dfrac{s}{\Phi}\right) & \text{for } |s| < \Phi, \end{cases} \tag{14}$$

where Φ represents the boundary layer thickness that is well described in Fig. 1. That is, the discontinuity of the control law is smoothed out in a thin boundary layer $B(t)$ neighboring the sliding surface (Fig. 1).

$$B(t) = \{\mathrm{x},\ |s(\mathrm{x};t)| \le \Phi\},\ \Phi > 0 \tag{15}$$

At the outside of the boundary layer a control input $u(t)$ is chosen as before, and at its inside a control input $u(t)$ is interpolated as equation (13).

The boundary layer width, here, ε is introduced, and we can see the fact that it represents the maximum value of a tracking error from the followings.

The limitations on s can be immediately translated into the limitations on the tracking error vector x_e, that is,

$$|s(t)| \le \Phi, \rightarrow |\mathrm{x}_e| \le \varepsilon, \tag{16}$$

where

$$\Phi > 0,\ \varepsilon = \frac{\Phi}{\lambda^{n-1}}. \tag{17}$$

By definition of a switching surface, a tracking error x_e is obtained from s through a sequence of first-order filters as shown in Fig. 3, where $p = \frac{d}{dt}$ is the Laplace variable. Let v_1 be the output of the first filter as follows

$$v_1(t) = \int_0^t e^{-\lambda(t-\tau)} s(\tau)\, d\tau \tag{18}$$

From $|s| \le \Phi$, we obtain the following.

$$|v_1(t)| \le \Phi \int_0^t e^{-\lambda(t-\tau)} s(\tau)\, d\tau = \frac{\Phi}{\lambda}(1 - e^{-\lambda t}) \le \frac{\Phi}{\lambda} \tag{19}$$

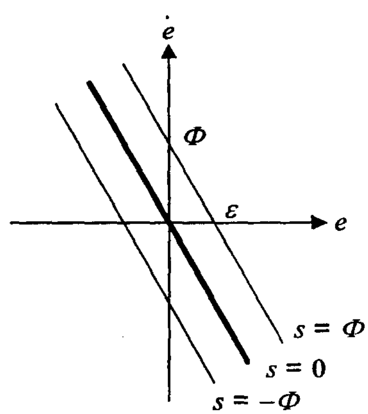


Fig. 1. The boundary layer with thickness Φ.

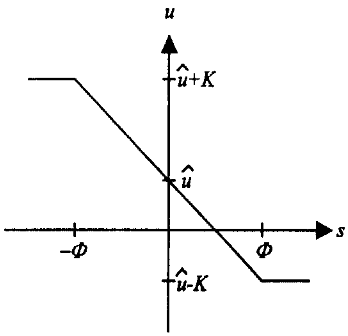


Fig. 2. The relation between the control input and the sliding surface.

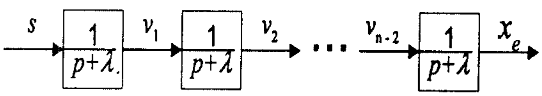


Fig. 3. The sequence of first-order filters for computing bounds on x_e.

We can apply the reasoning of a equation (19) to the second filter, and so on, until $v_{n-1}=x_e$. Then we have the following result.

$$|x_e| \le \frac{\Phi}{\lambda^{n-1}} = \varepsilon \tag{20}$$

□

From the above result, the more the boundary layer thickness increases, the more the tracking precision degrades. Further the more the boundary layer thickness decreases, the more the chattering possibility increases. Thus an control law $u(t)$ requires the trade-off between the tracking performance and the chattering phenomenon.

3.2 Fuzzy Logic-based Self-tuning Boundary Layer

In this section, we find the method that the varying boundary layer thickness is automatically adjusted without the chattering phenomenon. Here, we use the fuzzy logic that is much closer in spirit to human thinking and natural language than the traditional logic systems.

Fuzzy rules for the self-tuning of a varying boundary layer thickness are as follows

$$\text{R}_i : e \text{ is } \tilde{A}_i \text{ and } \dot{e} \text{ is } \tilde{B}_i, \text{ then } \Phi \text{ is } \tilde{C}_i,\ i=1, 2, \cdots, n.$$

where Ri is the i-th rule, n is the number of rules, and e, $\dot{e}$, and Φ are linguistic variables representing two state variables and one tuning variable, respectively; $\tilde{A}_i$, $\tilde{B}_i$, and $\tilde{C}_i$ are linguistic values of the linguistic variables e, $\dot{e}$, and Φ, respectively.

Now these rules have to be inferred by an proper reasoning method. Among several reasoning methods, we use Mamdani's MIN operation that is the most common method. The fuzzy rule(R_i) is represented on the spaces of $E \times \dot{E} \times \Phi$ as follows.

$$R_i = (\tilde{A}_i \times \tilde{B}_i) \times \tilde{C}_i \tag{21}$$

Total rule(R) is summarized to the following equation.

$$\text{R} = R_1 \cup R_2 \cup \cdots \cup R_n = \bigcup_{i=1}^{n} R_i \tag{22}$$

If fuzzy inputs are $\tilde{A}^0(e)$, $\tilde{B}^0(\dot{e})$, then the fuzzy output is:

$$\tilde{C}^0(\Phi) = Max_{e,\dot{e}}[\text{R}(e, \dot{e}, \Phi) \wedge \tilde{A}^0(e) \wedge \tilde{B}^0(\dot{e})]. \tag{23}$$

But, e $\dot{e}$, generally, are observed by explicit values, so $\tilde{A}^0$, $\tilde{B}^0$ can be represented as follows.

$$\tilde{A}^0(e) = \begin{cases} 1 & e = e^0 \\ 0 & e \ne e^0 \end{cases} \tag{24}$$

$$\tilde{B}^0(\dot{e}) = \begin{cases} 1 & \dot{e} = \dot{e}^0 \\ 0 & \dot{e} \ne \dot{e}^0 \end{cases} \tag{25}$$

Also equation (23) is simplified to equation (26).

$$\begin{aligned} \tilde{C}^0(\Phi) &= R(e^0, \dot{e}^0, \Phi) \\ &= R_1(e^0, \dot{e}^0, \Phi) \vee \cdots \vee R_n(e^0, \dot{e}^0, \Phi), \end{aligned} \tag{26}$$

where

$$R_1(e^0, \dot{e}^0, \Phi) = \widetilde{A}_i(e^0) \wedge \widetilde{B}_i(\dot{e}^0) \wedge \widetilde{C}_i(\Phi)$$
$$= w_i \wedge \widetilde{C}_i(\Phi) \quad (27)$$
$$w_i = \widetilde{A}_i(e^0) \wedge \widetilde{B}_i(\dot{e}^0). \quad (28)$$

Thus, the result of inference is

$$\widetilde{C}^0(\Phi) = [w_1 \wedge \widetilde{C}_1(\Phi)] \vee [w_2 \wedge \widetilde{C}_2(\Phi)] \vee \cdots \vee [w_n \wedge \widetilde{C}_n(\Phi)]$$
$$= \vee_{i=1}^{n} [w_i \wedge \widetilde{C}_n(\Phi)]. \quad (29)$$

But, $\widetilde{C}^0(\Phi)$ that is obtained by a fuzzy inference is a fuzzy number. This fuzzy number can not be directly used to an input to the plant. It must be transformed to an explicit value. This transformation is called a defuzzification. In this paper we use the Center Of Gravity(COG) method for a defuzzification that is expressed in equation (30). That is, a crisp value for a boundary layer thickness is obtained from the following equation.

$$\Phi^0 = \frac{\int \widetilde{C}^0(\Phi)\Phi d\Phi}{\int \widetilde{C}^0(\Phi)\Phi d\Phi} \quad (30)$$

Figures 4, 5, and 6 represent the fuzzy membership functions for inputs $|e|$, $|\dot{e}|$, and an output Φ, respectively. Namely, all the membership functions are isosceleses triangles for simplicity. And the fuzzy rule base that relates $|e|$ and $|\dot{e}|$ to Φ is given by table 1. That is, table 1 is the summary of the fuzzy rule base for self-tuning of a boundary layer thickness. Here, the boundary layer thickness Φ is not fixed by an arbitrary value but self-tuned by some fuzzy rules with the following knowledge: in the initial state the thickness has a few large value for compensating the chattering phenomenon, and then the more the states approach the steady states, the more the boundary layer thickness decreases within the limits of no chattering phenomenon. In other words, if both $|e|$ and $|\dot{e}|$ have small values, namely, the states approach near by the steady states, then the rule decreases the thickness for improving the tracking performance. Similarly, if $|e|$ or $|\dot{e}|$ has a large value, namely, the states are far away from the steady states, then the rule increases the thickness for alleviating the chattering phenomenon. Consequently, we design a new VSC with a varying boundary layer of which the thickness is thicken in the initial states and thinned in the steady states. Also we use only 16 rules for ensuring the effect of a proposed scheme. The abbreviations that are used at table 1 mean as follows : BiG(BG), MeDium(MD), SMall(SM), ZeRo(ZR).

Fig. 7 represents the overall structure of the proposed control system, which consists of conventional SMC with boundary layer and fuzzy rule base tuning the thickness of a boundary layer.

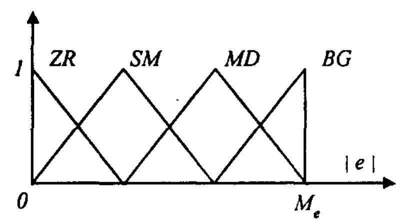


Fig. 4. The Membership function for $|e|$.

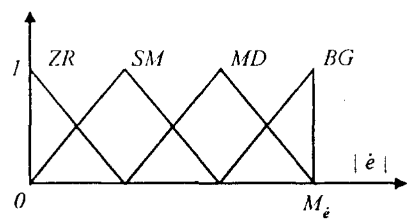


Fig. 5. The Membership function for $|\dot{e}|$.

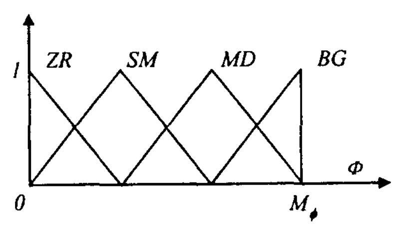


Fig. 6. The Membership function for Φ.

Table 1. Fuzzy Rule Table for Self-tuning Boundary Layer.

$\lvert e\rvert$ \ $\lvert\dot{e}\rvert$	BG	MD	SM	ZR
BG	BG	BG	BG	BG
MD	BG	MD	MD	SM
SM	BG	MD	SM	ZR
ZR	BG	SM	ZR	ZR

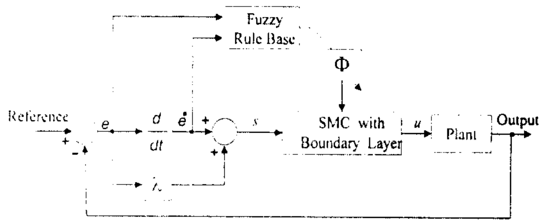


Fig. 7. The structure of overall control system.

Ⅳ. Simulation

In order to investigate the effect due to the addition of the proposed algorithm we performed a computer simulation. The plant to be controlled is an inverted pendulum system. Fig. 8 shows the plant that consists of a pole and a cart. The cart moves on the rail tracks to the horizontal direction left or right. The control objective is to balance the pole starting from arbitrary conditions by supplying a suitable force to the cart. The plant dynamics is expressed as

$$\ddot{\theta} = \frac{g\sin\theta + a\cos\theta - \mu_p w^2\, l\cos\theta\sin\theta}{l(4/3 - \mu_p\cos^2\theta)} \tag{31}$$

$$\mu_p = \frac{m_p}{m_p + m_c},\ a = \frac{F}{m_p + m_c}, \tag{32}$$

where g is an acceleration due to gravity($=9.8\ m/\mathrm{sec}^2$), and F is the applied force. $m_c(=1.0\mathrm{kg})$ and m_p $(=0.1\mathrm{kg})$ are masses and $l(=0.5\mathrm{m})$ is the pole length.

λ that determines the sliding line is given by the following condition [2].

$$\lambda = \frac{1}{5} f_s \tag{33}$$

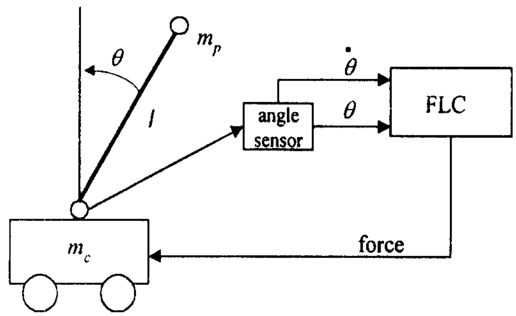
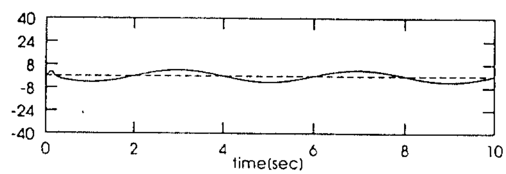
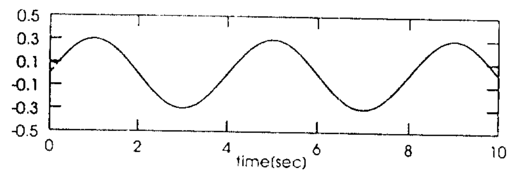


Fig. 8. The inverted pendulum system.

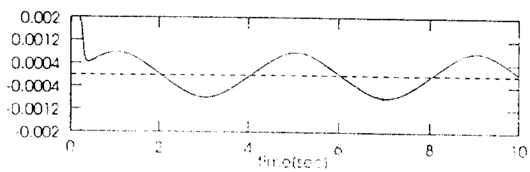
where f_s is the sampling frequency and is 100[Hz] in our simulation. M_e, $M_{\dot{e}}$, and M_Φ that decide the maximum range of membership functions are 1.0, 1.0, and 2.5, respectively. Then the responses of the control input, the plant output, and the tracking error are shown in Fig. 9.



(a) The control input.



(b) The plant output.

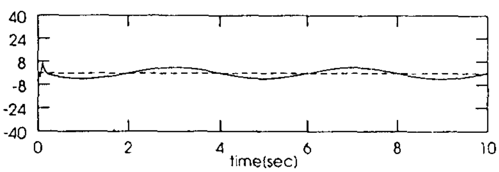


(c) The tracking error.

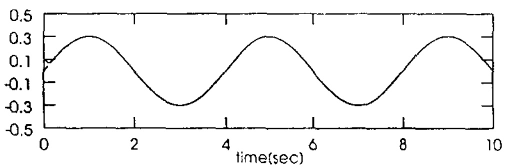
Fig. 9. The responses of the proposed system with a self-tuning boundary layer thickness.

In order to compare the results of our simulation with those of conventional SMC with a thin boundary, we simulate the conventional SMC with arbitrary boundary layer thickness. Fig. 10 shows the results with thickness of 0.5. Fig. 10(a) is similar to Fig. 9(a), which shows that the control inputs are almost the same in both cases. However, from the responses of error we can see the fact that the response of our controller is a little better. Fig. 11 shows that the response of our controller is much better than that of fixed thickness of 0.1. Consequently, as we expected, our algorithm has a good effect on the tracking performance as well as the response of a control input.

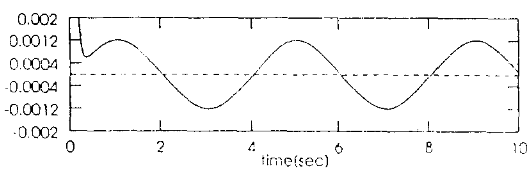
Fig. 12 represents the boundary layer thickness being self-tuned. The thickness, in the initial state, is a little large, but as the states approach the steady state the thickness is reduced to a small value(about 0.28). Unfortunately the thickness is not zero even in the final state because the zero boundary layer thickness leads to the chattering phenomenon of a control input.



(a) The control input.

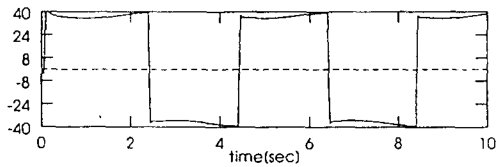


(b) The plant output.

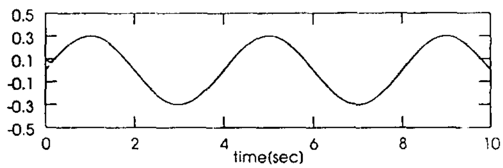


(c) The tracking error.

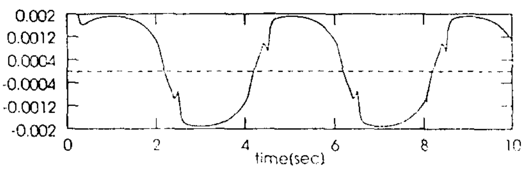
Fig. 10. The responses of the conventional system with the thickness of 0.5.



(a) The control input.



(b) The plant output.



(c) The tracking error.

Fig. 11. The responses of the conventional system with the thickness of 0.1.

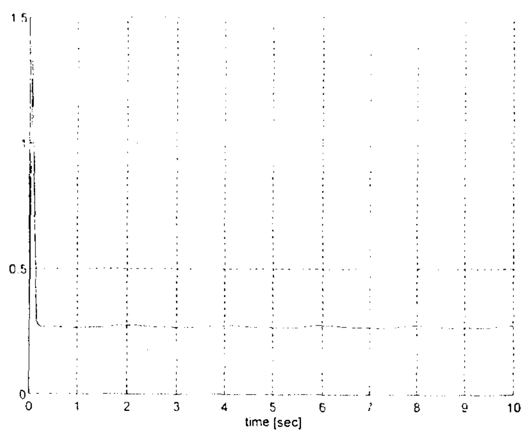


Fig. 12. The response of the boundary layer thickness for the proposed system.

V. Conclusions

We proposed a new sliding mode controller with a self-tuning boundary layer thickness. The proposed controller uses 16 fuzzy rules for tuning the thickness of a boundary layer. Those fuzzy rules are based on both the tracking error and its derivative. Namely in the incipient stage that the error or its derivative is probably large the thickness maintains a little bulky, but it is little by little thinned as the states approach the equilibrium points. That is, the thickness is thinned in the steady states. By adding these fuzzy rules, the conventional boundary layer approach for the continuous control input of a sliding mode controller is greatly improved in view of the tracking performance. It is demonstrated by a computer simulation for the tracking control of an inverted pendulum system.

As a result, since a new proposed sliding mode controller tunes the boundary layer thickness automatically, it not only improves the tracking performance, but also alleviates the chattering phenomenon.

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