Optimal Sliding-mode Control Scheme for the Position Tracking Servo System

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Abstract: - Systems having structural uncertainties or a known complicated structure are difficult to control. Modeling of the uncertainties or handling the deterministic complexity are typical problems frequently encountered in the field of systems and control engineering. The dynamic characteristics of such systems are usually very complex and highly nonlinear. A new design approach of an optimal sliding-mode variable structure controller with integral compensation is presented for the position tracking servo control system in this paper. The method for obtaining switching function, integral gain and control function is also given. It can achieve accurate servo tracking in the presence of the disturbance and the plant parameter variation. Simulation results show that the new control algorithm exhibits the better control performance than the classical control method, and the rapidness and robustness of the system are improved. Moreover, its realization is simple and convenient.

Key-Words: - Nonlinear system, variable structure control, sliding mode, switching function, control function, integral gain.

1 Introduction

Systems having structural uncertainties or a known complicated structure are difficult to control. Modeling of the uncertainties or handling the deterministic complexity are typical problems frequently encountered in the field of systems and control engineering. The dynamic characteristics of such systems are usually very complex and highly nonlinear. For a practical control system, it is usually desired to have a fast accurate response with small overshoot.

In recent years, sliding-mode variable structure control attracts control domain's attentions, and has been widely developed. It has complete self-adaptation and strong robustness for the plant parameter uncertainties. Variable structure control (VSC) with sliding mode was first proposed and elaborated in the early 1950's in the Soviet Union by Emelyanov and several researchers [1, 2, 3]. In their pioneer works, the plant considered was a linear second-order system modeled in phase variable form. Since then, VSC has developed into a general design method being examined for a wide spectrum of system types including nonlinear systems, multi-input/multi-output systems, discrete-time models, large-scale and infinite-dimensional systems, and stochastic systems. In addition, the objectives of VSC have been greatly extended from stabilization to other control functions. The most distinguished feature of VSC is its ability to result in very robust control systems, in many cases invariant control systems result. Loosely speaking, the term "invariant" means that the system is completely insensitive to parametric uncertainty and external disturbances. Today, research and development continue to apply VSC to a wide variety of engineering systems.

The main drawback of sliding-mode control (SMC) is chattering which can excite undesirable high-frequency dynamics. Several methods of chattering reduction have been reported. But many approaches provide no guarantee of convergence to the sliding mode and involve a tradeoff between chattering and robustness. Continuous SMC can exponentially drive the system state to a chattering-free sliding mode but tends to produce conservative designs. This method has the factions of lowering the order and uncoupling. The control law is simple. In the linear and nonlinear system, it still can solve the problem of stability, properties, etc [4, 5,6].

However pure sliding control as limited usage in practice since it requires very fast switching on the input (which cannot be provided by real actuators), is extremely vulnerable to measurement noise (the input depends on the sign of a measured variable which is very close to zero) and employs unnecessarily large control signals. To alleviate these difficulties, several modifications to the original sliding control law have been proposed, the most recent approach being the use of intelligent paradigms, such as fuzzy logic and neural networks in solving the engineering problems of sliding mode controllers [7-15].

2 Variable Structure Control

2.1 The Basic Theory of VSC

The basic idea of VSC was originally illustrated by a second-order system, similar to the following

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= 2y - x + u \\ u &= -\psi x \end{aligned} \tag{1}$$

where

$$\begin{aligned} \psi &= 4 \qquad when\ s(x,y) > 0 \\ \psi &= -4 \qquad when\ s(x,y) < 0 \end{aligned} \tag{2}$$

and

$$s(x,y) = x\sigma, \quad \sigma = 0.5x + y \tag{3}$$

A block diagram of the system is shown in Fig.1 . The variable $s(x,y)$ in (3) is the product of two functions

$$s(x,y) = x\sigma, \quad \sigma = 0.5x + y \tag{4}$$

The functions describe lines dividing the phase plane (xy plane) into regions where $s(x,y)$ has different sign as shown in Fig. 2. As such, the lines (4) are often called switching lines and $s(x,y)$ is called a switching function. The lines also define the set of points in the phase plane where $s(x,y)$ = 0. This set of points is known as the switching surface, despite the fact that the set composed of two lines is not a surface in the strict sense. All of these terms are more carefully defined and used later.

The feedback gain ψ is switched according to (2), i.e., the sign of $s(x,y)$. Therefore, the system (1, 2) is analytically defined in two regions of the phase plane by two different mathematical models:

In region Ⅰ where $s(x,y)$ = xu > 0, model is

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= 2y - x - 4x = 2y - 5x \end{aligned} \tag{5}$$

In region Ⅱ where $s(x,y)$ = xu < 0, model is

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= 2y - x + 4x = 2y + 3x \end{aligned} \tag{6}$$

The phase plane trajectories for (5) and (6) are shown as portrait in Fig.3 and Fig.4. The equilibrium point of (5) is an unstable focus at the origin. The equilibrium point of (6) is a saddle at the origin; the saddle point is also unstable.

The phase portrait for the system (1, 2) is formed by drawing the portrait for (4) in region I of the phase plane and drawing the portrait for (5) in region Ⅱ. The resultant portrait is shown in Fig.5. To obtain the complete phase portrait, the trajectory of the system on the set $s(x,y)$ = 0 must be described. On the line x = 0, the phase trajectories of regions Ⅰ and Ⅱ are just joined together without any ambiguity. On the line

$$\sigma = 0.5x + y = 0 \tag{7}$$

which itself is a dynamical equation, the phase portrait is a trajectory along the switching line σ = 0 as shown in Fig.5.

The complete phase portrait of the system shows that there are no unusual motion characteristics on the line x = 0 other than possible discontinuities on motion direction. However, the line σ = 0 contains only endpoints of those trajectories coming from both sides of the line. These points constitute a special trajectory along the σ = 0 line, representing motion called a sliding mode. Thus, a phase trajectory of this system generally consists of two parts, representing two modes of the system. The first part is the reaching mode, also called nonsliding mode, in which the trajectory starting from anywhere on the phase plane moves toward a switching line and reaches the line in finite time. The second part is the sliding mode in which the trajectory asymptotically tends to the origin of the phase plane, as defined by the differential equation (7). Four basic notions of this example VSC system should be observed:

1) Since the origin of the phase plane represents the equilibrium state of the system, the sliding mode represents the behavior of the system during the transient period. In other words, the line that describes σ = 0 defines the transient response of the system during the sliding mode.
2) During the sliding mode, trajectory dynamics (7) are of a lower order than the original model (1).
3) During the sliding mode, system dynamics are solely governed by the parameters that describe the line σ = 0.
4) The sliding mode is a trajectory that is not inherent in either of the two structures defined by (4) or (5).

During the control process, the structure of the control system (1), (2) varies from one structure (4) to another (5), thus earning the name variable structure control. To em- phasize the important role of the sliding mode, the con- trol is also often called sliding mode control. It should be noted that a variable structure control system can be devised without a sliding mode, but such a system does not possess the associated merits.

Fig. 1 System model

Fig. 2 Regions defined by the switching logic

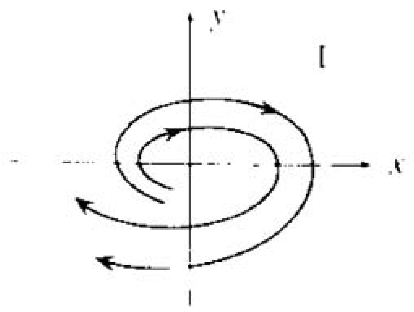

Fig.3 Phase portraits for system (5).

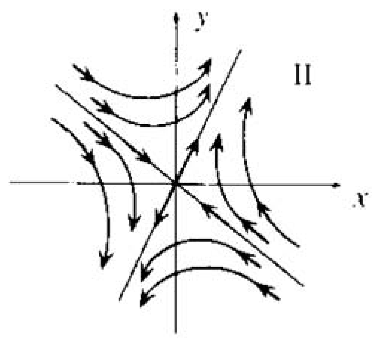

Fig.4 Phase portraits for system (6)

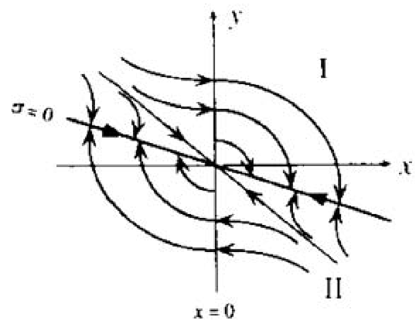

Fig.5 Phase portraits for system (1,2)

2.2 The Strategy of Sliding-mode VSC

For a given control system represented by the state equation

$$\dot{x} = f(x,u,t) \qquad (8)$$
$$x \in R^n, u \in R^m, t \in R$$

We find

1) m switching functions, represented in vector form as $s(x)$,

2) a variable structure control

$$u_i(x) = \begin{cases} u_i^+(x) & |s_i(x) > 0 \\ u_i^-(x) & |s_i(x) < 0 \end{cases},$$

such that the reaching modes satisfy the reaching condition, namely, reach the set $s(x)$ = 0 (switching surface) in finite time[16].

The physical meaning of above statement is as follows:

1) Design a switching surface $s(x)$ = 0 to represent a desired system dynamics, which is of lower order than the given plant.
2) Design a variable structure control $u(x,t)$ such that any state x outside the switching surface is driven to reach the surface in finite time. On the switching surface, the sliding mode takes place, following the desired system dynamics. In this way, the overall VSC system is globally asymptotically stable.

2.3 Brief Theoretical Background

Before the emergence of the early stages of VSC development, its foundation had already been laid. Elements of the foundation consist of the theory of oscillation and the qualitative theory of differential equations. Brief discussions of these elements are given below.

2.3.1 Phase Plane Method

As a powerful graphical tool for studying second-order dynamic systems, the phase plane method was well established in the realm encom-passing the qualitative (geometric) theory of differential equations and oscillation theory. The classical literature of Andronov et al. [17] and Flugge-Lotz [18] cited many early works in these areas. In their outstanding works, two contributions provided the foundation for the emergence of VSC:

1) Regionwise linearization of nonlinear dynamic systems in which linearization of nonlinear systems was applied in partitioned regions of the phase plane. This gave the initial prototype VSC systems.
2) The sliding mode motion, a term first used by Nikol- ski [19]. This was the first concept of sliding mode control.

2.3.2 Theory of Differential Equations

Theory of Differential Equations with a Nonanalytic Right-Hand Side: Two kinds of nonanalyticity are of importance with respect to VSC:

1) Finite discontinuous right-hand side, which is the relay type discontinuity,
2) Double-valued right-hand side, which is the relay type discontinuity with hysteresis.

The problem is that a differential equation is not defined at the point where the right-hand side of the equation is not analytic because the existence and uniqueness of the solutions at these points are not guaranteed. Hence, the phase plane method cannot give a complete solution without defining an auxiliary equation at these points. The auxiliary equation is the model of switching that occurs in VSC systems with discontinuous control. Five methods have been suggested to define the differential equation for the system at points of discontinuous dynamics [20].

3 Optimal Sliding-Mode VSC

The system using VSC with integral compensation is desired as

$$\begin{aligned} \dot{x}_i &= x_{i+1} \qquad i = 1, 2, \cdots, n-1 \\ \dot{x}_n &= -\sum_{i=1}^{n} a_i x_i + bu - f \\ \dot{x}_0 &= x_d - x_1 \end{aligned} \tag{9}$$

where x_1 is the output, x_d is the expectated input, a_i and b are the plant parameters, f is the disturbance, and u is a piecewise linear control function of the form

$$u = \begin{cases} u^+(x,t), & if \quad \sigma > 0 \\ u^-(x,t), & if \quad \sigma < 0 \end{cases} \tag{10}$$

where σ is the switching function given by

$$\sigma = c_1(x_1 - k_I x_0) + \sum_{i=2}^{n} c_i x_i \tag{11}$$

$$c_n = 1$$

In which k_1 is the integral control gain and c_i are constants.

Design of such a system involves (9) the determination of the control function u to guarantee the existence of a sliding mode, (10) the determination of the switching function and σ the integral control gain k_I such that the system has an optimal motion with respect to a quadratic performance index, and (11) the elimination of chattering of the control input.

3.1 Determination of Control Function

From (9) and (11), one obtains

$$\dot{\sigma} = c_1[x_2 - k_I(r - x_1)] + \sum_{i=2}^{n-1} c_i x_{i+1} + (-\sum_{i=1}^{n} a_i x_i + bu - f) \quad (12)$$

Let

$$a_i = \hat{a}_i + \Delta a_i, \quad i=1\cdots n$$

$$b = \hat{b} + \Delta b$$

where $\hat{a}_i$ and $\hat{b}$ are nominal values of a_i and b, and Δa_i and Δb are the deviations, respectively.

Let the control function u be decomposed into

$$u = u_{eq} + \Delta u \quad (13)$$

where u_{eq} ,called the equivalent control, is defined as the solution of the equation $\dot{\sigma} = 0$ under f=0, $a_i = \hat{a}_i$ and $b = \hat{b}$, that is

$$u_{eq} = [c_1 k_I (x_d - x_1) - \sum_{i=2}^{n} c_{i+1} x_i + \sum_{i=1}^{n} \hat{a}_i x_i] / \hat{b} \quad (14)$$

The function Δu is used to eliminate the influence due to the presence of Δa_i, Δb and f so as to guarantee the existence of a sliding mode. This function is constructed as

$$\Delta u = \Psi_1(x_1 - k_I x_0) + \sum_{i=2}^{n} \Psi_i x_i + \Phi \quad (15)$$

Where

$$\Psi_1 = \begin{cases} \alpha_1, & (x_1 - k_I z)\sigma > 0 \\ \beta_1, & (x_1 - k_I z)\sigma < 0 \end{cases}$$

$$\Psi_i = \begin{cases} \alpha_i, & x_i\sigma < 0 \\ \beta_i, & x_i\sigma < 0 \end{cases} \qquad i = 2, \cdots, n$$

and

$$\Phi = \begin{cases} \gamma, & \sigma > 0 \\ \delta, & \sigma < 0 \end{cases}$$

It is known that the condition for the existence and accessibility of a sliding motion is [21]

$$\sigma\dot{\sigma} < 0 \quad (16)$$

Substitution of (13) into (14) yields

$$\sigma\dot{\sigma} = (-\Delta a_1 + \hat{a}_1 \Delta b / \hat{b} + b\Psi_1)(x_1 - k_I x)\sigma + \sum_{i=2}^{n} [(-\Delta a_i + \hat{a}_i \Delta b / \hat{b} - c_{i-1}\Delta b / \hat{b} + b\Psi_i) x_i \sigma] + [b\Phi + N(t)]\sigma$$

where

$$N(t) = \{-k_I z(\Delta a_1 - \hat{a}_1 \Delta b / \hat{b}) + [c_1 k_I (x_d - x_1)]\Delta b / \hat{b} - f\}$$

Thus, the conditions of satisfying the inequality (15) are

$$\Psi_i = \begin{cases} \alpha_i < (\Delta a_i - \hat{a}_i \Delta b / \hat{b} + c_{i-1}\Delta b / \hat{b}) / b \\ \beta_i > (\Delta a_i - \hat{a}_i \Delta b / \hat{b} + c_{i-1}\Delta b / \hat{b}) / b \end{cases}$$

$$c_0 = 0 \qquad i = 1, 2, \cdots, n$$

and

$$\Phi = \begin{cases} \gamma < -N(t)/b \\ \delta > N(t)/b \end{cases}$$

3.2 Determination of Switching Function and Integral Control Gain

Under sliding motion, the system described by (9) can be reduced to

$$\begin{aligned} \dot{x}_i &= x_{i+1} \qquad i = 1, 2, \cdots, n-2 \\ \dot{x}_{n-1} &= -\sum_{i=1}^{n-1} c_i x_i + c_1 k_I x_0 \\ \dot{x}_0 &= x_d - x_1 \end{aligned} \quad (17)$$

or, in the matrix form[19]

$$\dot{X} = AX + BV + Er$$

$$V = GX$$

where

$$X = \begin{bmatrix} z \\ x_1 \\ \vdots \\ x_{n-1} \end{bmatrix}_{n\times 1} \qquad A = \begin{bmatrix} 0 & -1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & & & & \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{n\times l}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{bmatrix}_{n\times 1} \qquad E = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{n\times 1}$$

and

$$G = \begin{bmatrix} c_1 k_I & -c_1 & -c_2 & \cdots & -c_{n-1} \end{bmatrix}_{1\times n}$$

In order to find the optimal gain matrix G by means of the optimal linear regulator technique, the quadratic index I as shown in the following equation must be minimized:

$$I = \frac{1}{2}\int_{t_s}^{\infty} (X^T Q^T X + V^T RV) \tag{18}$$

where $Q = Q^T > 0$ and $R = R^T > 0$ are weighting matrices and t_s is the time from which the sliding mode begins. The weighting matrix Q can be chosen as $Q = D^T D$, where D is a $1\times n$ vector and the pair (A,D) is observable [22].

Then the optimal gain matrix G is given by

$$G = -R^{-1} B^T P$$

where P is the solution of the matrix Riccati equation

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{19}$$

3.3 Chattering Considerations

For the control law given by (13), if Φ and Ψ_i are chosen as

$$\Phi = \gamma = -\delta,$$

$$\Psi_i = \alpha_i = -\beta_i,$$

$$i = 1, \cdots, n$$

then the control function u can be represented as

$$\begin{aligned} u = {} & [c_1 k_I (x_d - x_1) - \sum_{i=2}^{n} c_{i-1} x_i + \sum_{i=1}^{n} \hat{a}_i x_i] / \hat{b} \\ & + (\Psi_1 |x_1 - k_I x_0| + \sum_{i=2}^{n} \Psi_i |x_i| + \Phi) \operatorname{sgn}(\sigma) \end{aligned} \tag{20}$$

Since the control u contains the sign function $\operatorname{sgn}(\sigma)$, direct application of such a control signal to the plant may give rise to chattering[23], [24]. To obtain a continuous control signal, the discontinuous function $\operatorname{sgn}(\sigma)$ in (20) can be replaced by a proper continuous function as

$$S_\delta(\sigma) = \frac{\sigma}{|\sigma| + \delta}$$

where δ is positive. If it is too small, the chattering phenomenon may not be effectively suppressed, and if it is too large, the sliding action may be slow so that the advantage of robustness of VSC is lost[25].

For improving the result, the value of δ is therefore chosen as a function of $|x_1 - x_d|$ as

$$\delta = \delta_0 + \delta_1 |x_1 - x_d|$$

where δ_0 and δ_1 are positive constants, and the proper continuous function is modified as

$$M_\delta(\sigma) = \frac{\sigma}{|\sigma| + \delta_0 + \delta_1 |x_1 - x_d|}$$

4 Application

4.1 Model of the System

Considering a position tracking servo system, in this case, the system includes a casement, a reducer and an electromotor. The moment of inertia that converted into the motor's axis is J =0.00657 Kgm^2. The torque coefficient of the electromotor is C_M, and its counter electromotive force voltage coefficient is C_e. The resistance of the armature loop is $R = 3\Omega$. The decelerating ratio is $i = 1670$. The maximum of the Coulomb friction torque has been given. The maximum value of the load disturbance f_d is 9.8 Nm. The gain is K = 304. $N(A)$ is the backlash characteristic, and the transmission clearance is

2.5 mil . In addition, the fluctuation of the system's parameters is 10%. Fig. 6 shows the structure of the system.

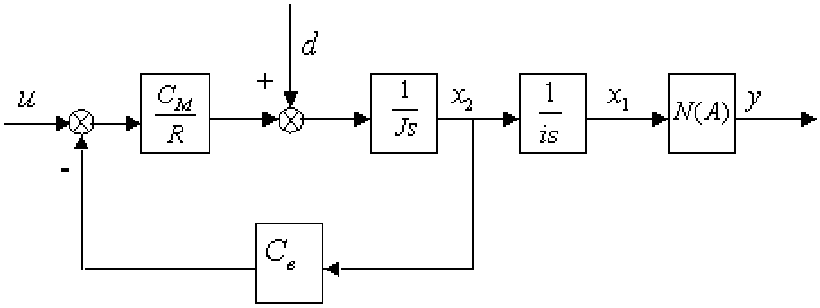

Fig. 6 Structure of the tracking servo system

The system's performances have been given. The transition time of the step response is t_s =1.6s. The overshoot is less than 17 percent. The steady-state error of unit step input is zero.

According to the system's requirement, we can neglect the backlash characteristic here. As shown in Fig. 6, suppose that the casement rotational angle is x_1, the angular velocity is x_2 , $y = x_1$, then the state equation of the control system is

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0.0006 \\ 0 & -3.107 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 3778.79 \end{bmatrix} u + \begin{bmatrix} 0 \\ 152.207 \end{bmatrix} d \tag{21}$$
$$y = [1 \quad 0]\, x$$

where u is the control input, and d is the total disturbance.

4.2 Controller Design

According to optimal sliding-mode variable structure control strategy, in order to obtain zero steady-state error with step input, sliding mode must include the integral of $x_d - x_1$, as following

$$\dot{x}_0 = x_d - x_1 \tag{22}$$

where x_d is the instruction signal.

$$\begin{bmatrix} \dot{x}_0 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 0.0006 \\ 0 & 0 & -3.107 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 3778.79 \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ 152.207 \end{bmatrix} d + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} x_d \tag{23}$$
$$y = [0 \quad 1 \quad 0]\, x$$

Following the design procedure above, we can obtain the control function

$$u = [c_1 k_I (x_1 - x_d) - c_1 x_2 + \hat{a}_2 x_2] / \hat{b} + (\Psi_1 |-x_1 - k_I x| + \Psi_2 |x_2| + \Phi) M_\delta(\sigma)$$

with

$$\Psi_i < -\left|\Delta a_i - \hat{a}_i \Delta b / \hat{b}\right| / b$$

$$i = 1, 2 \quad c_0 = 0$$

and

$$\Phi < -|N(t)| / b$$

where

$$N(t) = \{-k_I x_0 (\Delta a_1 - \hat{a}_1 \Delta b / \hat{b}) + [c_1 k_I (-x_d + x_1)] \Delta b / \hat{b} - f\}$$

The σ function is obtained from (3) as

$$\sigma = c_1(-x_1 - k_I x_0) + x_2$$

and, by suitably choosing, we can obtain Q=diag(100,

3) and R=0.01. Then, from (20), the optimal gain matrix can be obtained as

$$G = [\ -0.02436\ \ -0.00087]$$

so that $k_I = 28$, $c_1 = 0.00087$.

Gains Ψ_1, Ψ_2 and Φ must be chosen to satisfy the above forms, and based on simulations, we choose

$$\Psi_1 = -1,\ \Psi_2 = -0.0002,\ \Phi = -0.005.$$

This VSC with integral compensation approach gives a control function

$$u = -0.00000645(x_d - x_1) - 0.00000023x_2 - 0.00082x_2 + (-|x_1 - k_I x_0| - 0.0002|x_2| - 0.005)M_\delta(\sigma)$$

Where

$$\sigma = -0.00087(x_1 - K_I x_0) + x_2,$$

$$\delta = 0.000364|x_1 - x_d| + 0.00605.$$

4.3 Simulation

According to the real time control requirement, under Matlab 6.0 environment, we adopt the fixed step-size arithmetic and simulate on the computer.

Fig. 7 shows the tracking of a step input with optimal SMC. Its transition time is 1.07s, and the overshoot is zero. Fig. 8 shows the response under the same condition using SMC. It is obviously that the performance of fast tracking and a significant reduction of chattering are obtained by introducing the integral compensation.

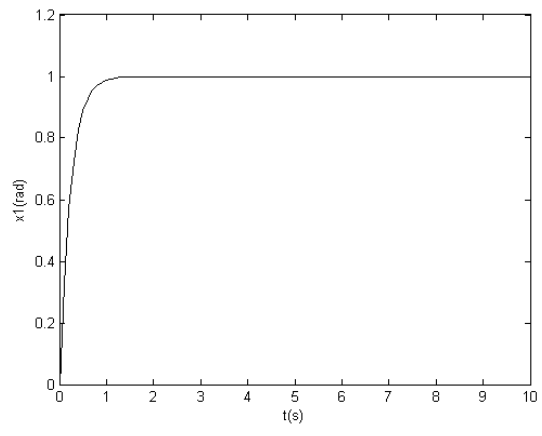

Fig. 7 Step response of SMC

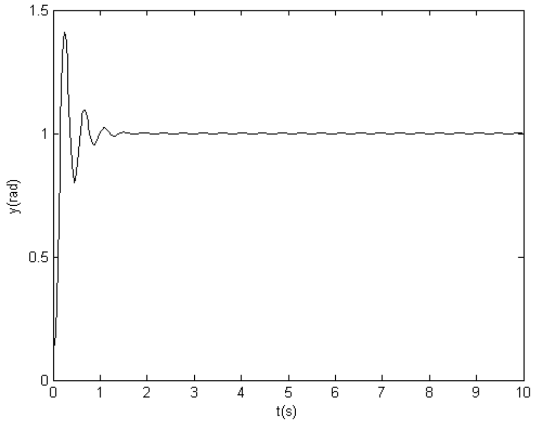

Fig. 8 Step response of the classical control

Fig. 9 shows the ramp input response of the SMC system. It shows that output can follow the input smoothly when the slope is half of the requirement (0.04rad/s). Fig. 10 shows the classical control system cannot follow smoothly with the same input signal.

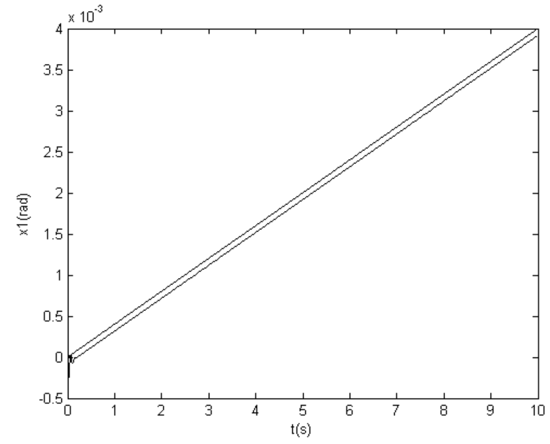

Fig. 9 Ramp response of SMC

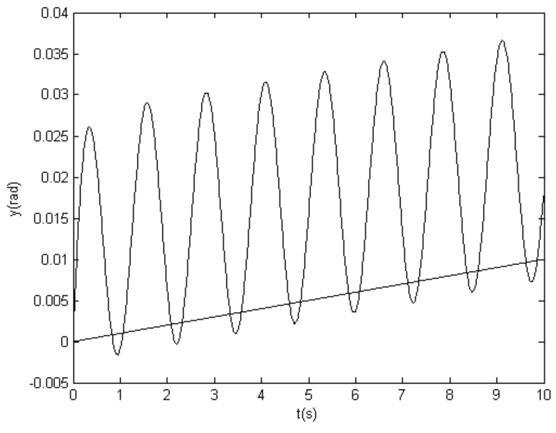

Fig. 10 Ramp response of the classical control

5 Conclusion

Systems having structural uncertainties or a known complicated structure are difficult to control. Modeling of the uncertainties or handling the deterministic complexity are typical problems frequently encountered in the field of systems and control engineering. The dynamic characteristics of such systems are usually very complex and highly nonlinear. For a practical control system, it is usually desired to have a fast accurate response with small overshoot.

In this paper, a new technique of optimal sliding-mode variable structure control with integral compensation for the position tracking servo control system has been discussed. The method for obtaining switching function, integral gain and control function is also given. It can achieve accurate servo tracking in the presence of the disturbance and the plant parameter variation. Inorder to reducing chattering, the related continuous function is considered in the control algorithm. Simulation results show that the new control algorithm exhibits the better control performance than the classical control method, and the rapidness and robustness of the system are improved. Moreover, its realization is simple and convenient.

References:

[1] S. V. Emelyanov, *Variable Structure Control Systems.* Moscow: Nauka (in Russian), 1967.

[2] Y. Itkis, *Control Systems* of *Variable Structure.* New York: Wiley, 1976.

[3] G. Ambrosino, G. Celentano, and E. Garofalo, Variable structure model reference adaptive control systems, *Int. J. Contr.,* Vol. 39, No. 6, pp. 1339-1349.

[4] F. Boudjema, and J. L.-Abatut, 1990, Sliding mode - A new way to control series resonant converters, *Proc. I990 IEEE Ind.Electron. Conf.*, 1990, pp. 938-943.

[5] Jiang Jing, Sliding-mode Variable Structure Control for the Position Tracking servo System. *WSEAS Transactions on Systems*, Vol.6, No.2, 2007, pp. 294-297.

[6] Hu Yueming, *Theory and Application for Variable Structure Control*. Science Press, Beijing, 2003.

[7] Zhang Changfan, Wang Yaonan, *Intelligent Control and its Application Based on Sliding Mode Variable Structure Control.* Chinese Journal of Electrical Machine Engineering , Vol. 21, No. 3, 2001, pp. 27-29.

[8] Naji Al-Musabi, Zakariya Al-Hamouz, Hussain Al-Duwaish, Design of Variable Structure Stabilizer for a Nonlinear Model of SMIB System: Particle Swarm Approach. *WSEAS Transactions on Power Systems*, Vol.1, No.2, 2006, pp. 311-316.

[9] Wang Zhujiong, Zhang Zhihui, Sliding Mode Control Design Method Based on Fuzzy Logic. *Control Engineering*, Vol.10, No.6, 2003, pp. 536-538.

[10] Lu Yusheng, Chen jianshiang, A Self-organizing Fuzzy Sliding-mode Controller Design for a Class of Nonlinear Servo Systems. *IEEE Trans Ind Electron*, Vol. 41, No. 5, 1994, pp. 492-502.

[11] Wang Shunyuan, Liu Chunchang, Yang Weitzen, Design of a Static Reactive Power Compensator using Fuzzy Mode Control. *Int J Contrl*, Vol. 63, No.2, 1996, pp. 393-412.

[12] Liu Hongling, Jiang Chuanwen, Zhang Yan, Hussain Al-Duwaish, Design of PID Parameters Self-Tuning Fuzzy Control System and its Application in Hydroelectric System. *WSEAS Transactions on Circuits and Systems*, Vol.5, No.5, 2006, pp. 646-651.

[13] Ha Q P, Rye D C, Durrant-Whyte H F. Fuzzy Moving Sliding Mode Control with Application to Robotic Manipulators. *Automatica*, Vol.35, No. 4, 1999, pp. 607-614.

[14] G. C. Hwang, S.C.Lin. A Stability Approach to Fuzzy Control Design for Nonlinear Systems. *Fuzzy Sets Syst.* Vol. 48, 2001, pp. 279-287.

[15] W. B. Gao, *Fundamentals* of *Variable Structure Control Theory*. Press of Science and Technology in China (in Chinese), Beijing, 1990.

[16] A. A. Adronov, A. A. Vitt, S. E. Khaikin, *Theory of Oscillation.* Moscow: Fizmatgiz. (in Russian), 1959.

[17] I. Flugge-Lotz, *Discontinuous Automatic Control.* Princeton, NJ: Princeton University Press, 1989.

[18] G. N. Nikolski, On automatic stability of ship on given course, *Proc. Central Communication Lab.*. 1934, No. I, pp. 34-75. (in Russian).

[19] John Y. Hung, Weibing Gao, James *C.* Hung. Variable Structure Control: A Survey. *IEEE Transactions on Industrial Electronics*, Vol.40, No.1, 1993, pp. 2-22.

[20] Gu Lijun. *Optimal control system*. Water Power Press, Beijing,1993.

[21] W. B. Gao and M. Cheng, On the quality control of variable structure systems, *Contr. Decision,* Vol. 4, No. 4, 1989, pp.1-6.

[22] Gao Weibing, *Theory and Design Method for Variable Structure Control*. Science Press, Beijing, 1996.

[23] Yi Jikai, Jiangxiangxian, Hou Yuanbin, *Electrical Driving Automatic control Theory and Design*, Beijing Technical University Press, Beijing, 1993.
[24] W. B. Gao and J. C. Hung, Variable Structure Control of nonlinear systems: A new approach. *IEEE Trans. Ind. Electron.*, Vol. 40, 1993, pp. 45-55.
[25] Zhou F, Fisher D G. Continuous Sliding Mode Control. *Int. J.Control,* Vol. 55, 1992, pp. 313-327.