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論 文
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A New Improved Integral Variable Structure Controller for Uncertain Linear Systems

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Abstract - In this paper, a new variable structure controller is designed for the tracker control of uncertain general plants so that the output of plants can controlled to a given arbitrary point in state space. By using the error between the steady state value of the output and the given reference, the sliding surface is defined, in advance, the surface from an initial state to the given reference without any reaching phase. A corresponding control input to satisfy the existence condition of the sliding mode is suggested to control the output on the predefined surface. Therefore the output controlled by the proposed controller is completely robust and identical to that of the sliding surface. Through an example, the usefulness is verified.

Key Words : Interal variable structure system, sliding mode control, strong robustness, tracker control problems

1. Introduction

The theory of the variable structure system (VSS) or sliding mode control (SMC) can provide the effective means to the problem of controlling uncertain dynamical systems under parameter variations and external disturbances[1-5,23]. One of its essential advantages is the invariance of the controlled system to variations of parameters and disturbances in the sliding mode on the predetermined sliding surface, $s(t)=0$. The proper design of the sliding surface can determine the almost output dynamics and its performances. Many design algorithms including the linear(optimal control[6,7], eigenstructure assignment[8,9], geometric approach[10], differential geometric approach[11], Lyapunov approach[29]) and nonlinear[12,22] techniques are reported. Moreover, an integral action have been augmented by the two groups [7,13-15]. One is to improve the steady state performance [7,13,14] against the external disturbances possibly in the digital implementation of the VSS, and the other aims to reduce the chattering problems by means of filtering the discontinuous input through the integral action[15].

Unfortunately, most of these existing VSS's have the reaching phase and are applied to canonical plants. During the reaching phase, the controlled systems may be sensitive to the parameter variations and disturbances because the sliding mode can not be realized [18]. And it is difficult to find the designed performance from real output, that is, the output is not predictable in the design stage. Moreover, introducing the integral to the VSS without removing the reaching phase can inevitably cause overshoot problems.

One alleviation method for the reaching phase problems is the use of the high-gain feedback[1]. This has the drawbacks related to the high-gain feedback, for example sensitivity to the unmodelled dynamics and actuator saturation[18]. The adaptive rotating or shifting of the sliding surface is suggested to reduce the reaching phase problems in [2,20], and the segmented sliding surface connected from a given initial condition to origin is also suggested in [21]. But these changing techniques and segmented sliding surfaces are applicable to only a second order system and those outputs are not predictable. In [22,23], the exponential term is added to the conventional linear sliding surface in order to make the sliding surface be zero at $t=0$. But, its resultant sliding dynamics becomes nonlinear. In [30], Park attempted to remove the reaching phase problems for general uncertain systems. However, the developed algorithms for regulation problems use a complex sliding surface including the control term and need mathematical accuracy in the formulation of the algorithm.

In this paper, a new integral variable structure controller(IVSC) is suggested for the tracker control[32]

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of uncertain general linear systems to an any given point with predetermination/prediction of output response. The reaching phase is completely removed by only introducing an integral of state error with special non-zero initial value to the sliding surface. After obtaining the dynamic representation of the integral sliding surface, its coefficent are designed by the tracker control design. A corresponding control is proposed to completely guarantee the designed output in the sliding surface from any initial condition to a given desired point for all the parameter variations and disturbances. The advantages obtained after removing the reaching phase are discussed. Finally, an example is presented to show the effectiveness of the algorithm compared with the typical VSS having the conventional linear sliding surface.

2. Integral-Augmented Variable Structure Systems

2.1 Description of plants

An n-th order uncertain non-canonical linear system is described by

$$\dot{X}(t) = (A+\Delta A)X(t) + (B+\Delta B)u(t) + Df(t), \quad X(t_0)$$
$$y = EX(t) \tag{1}$$

where $X(\cdot) \in R^n$, $u \in R$, and $f \in R^r$ are the state, control, disturbance, $\Delta A, \Delta B, D$ are the bounded uncertainties and the disturbance matrix and satisfying the matching condition:

$$\Re(\Delta A),\ \Re(\Delta B),\ \text{and}\ \Re(D) \in \Re(B) \tag{2}$$

The purpose of the controller design is to control the output(state) of a plant (1) to track the predetermined intermediate dynamics finally to any value y_r ($X_r, y_r = Ex_r$) for all the uncertainties and disturbances by using the integral sliding mode control. Generally, this type tracker control of following a non zero reference command signal [32]. By state transformation, $z = Px$ a canonical form of (1) is obtained as,

$$\dot{Z}(t) = \Lambda Z(t) + \Gamma u(t) + \Gamma h(t), \quad Z(t_0) \tag{3}$$
$$y = EP^{-1}Z(t)$$

where

$$\Lambda = PAP^{-1} = \begin{bmatrix} 0 & 1 & 1 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -\alpha_1 & -\alpha_2 & -\alpha_3 & \cdots & -\alpha_n \end{bmatrix} \text{ and } \Gamma = PB = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \tag{4}$$

$Z(t_0)$ and $h(t)$ are a transformed initial condition and lumped uncertainty in transformed system, respectively.

2.2 Design of Integral Sliding Surfaces

To design the IVSC, the sliding surface in error coordinate system is suggested to the following form having an integral of state errors as

$$\begin{aligned} S_p(Z,t) &= C_{Z0}[\textstyle\int_0^t (Z-Z_r)dt + \int_{-\infty}^0 (Z-Z_r)dt] \\ &\quad + c_1(z_1(t)-z_{1r}) + \cdots + c_n(z_n(t)-z_{nr}) \\ &= C_{Z0}[\textstyle\int_0^t (Z-Z_r)dt + \int_{-\infty}^0 (Z-Z_r)dt] \\ &\quad + C_{Z1}(Z(t)-Z_r) = 0 \end{aligned} \tag{5}$$

$$\begin{aligned} S_p(X,t) &= C_{X0}[\textstyle\int_0^t (X-X_r)dt + \int_{-\infty}^0 (X-X_r)dt] \\ &\quad + C_{X1}(X(t)-X_r) = 0 \end{aligned} \tag{6}$$

where coefficient matrices, initial condition for the integral states, and the reference command are expressed as shown

$$C_{Z1} = [c_1 \ \ c_2 \ \ \cdots \ \ c_n] \in \aleph^{1\times n}, \ c_n = 1$$
$$C_{X0} = C_{Z0}P, \quad C_{X1} = C_{Z1}P \in R^{1\times n} \tag{7}$$
$$\textstyle\int_{-\infty}^0 (z_i - z_{ir})dt] = C_{Z1i}\{Z_r - Z(t_0)\}/C_{Z0i},$$
$$\textstyle\int_{-\infty}^0 (x_i - x_{1r})dt] = C_{X1i}\{X_r - X(t_0)\}/C_{X0i} \tag{8}$$

The initial condition (8) for the integral state in (5) and (6) are selected so that those are zeros at $t=0$ for removing the reaching phase from the beginning as (6). From $\dot{S}_p(Z,t)=0$, (3), and (5), the differential equation for $z_n(t)$ is obtained

$$\begin{aligned} \dot{z}_n(t) &= -C_{Z0}(Z-Z_r) - [0 \ \ c_1 \ \ \cdots \ \ c_{n-1}]\cdot Z(t) \\ &= -C_Z Z(t) + C_{Z0}Z_r \end{aligned} \tag{9}$$

where

$$C_Z = [c_{z1} \ \ c_{z2} \ \ \cdots \ \ c_{zn}] = C_{Z0} + [0 \ \ c_{z1} \ \ \cdots \ \ c_{zn-1}] \tag{10}$$

Finally combing (9) with the first n-1 differential equation in the systems (3) leads to the ideal sliding dynamics:

$$\dot{Z}_s(t) = \Lambda_c Z_s(t) + \Gamma C_{Z0}Z_r, \qquad Z_s(t_0) = Z(t_0) \tag{11}$$

and

$$\dot{X}_s(t) = P^{-1}\Lambda_c P X_s(t) + P^{-1}\Gamma C_{Z0}PX_r, \ X_s(t_0) = X(t_0) \tag{12}$$

where

$$\Lambda_c = \begin{bmatrix} O^{(n-1)\times 1} & I^{(n-1)\times(n-1)} \\ & -C_Z \end{bmatrix} \tag{13}$$

which can be considered as a dynamic representation of the sliding surface (5) or (6). Because of the reference command in the system (11), the design problems becomes the tracker control design also[32]. In order to apply the well-studied linear regulator theories to choosing the coefficient of the integral sliding surfaces, (11) and (12) are transformed to the nominal from of (1)

$$\dot{Z}_s(t) = \Lambda Z_s(t) + \Gamma u_s(Z_s, t) + \Gamma C_{Z0}Z_r$$
$$u_s(Z_s, t) = -GZ_s(t) \tag{14}$$

where

$$\Lambda_c = \Lambda - \Gamma G \quad (15)$$

and expressed with the original state as

$$\dot{X}_s(t) = AX_s(t) + Bu_s(X_s, t) + BC_{Z0}PX,$$
$$u_s(X_s, t) = -GPX_s(t) = -KX_s(t) \quad (16)$$

where

$$P^{-1}\Lambda_c P = A - BK$$

When one determines the continuous gain, the condition on the gain should be satisfied to be $y = y_r$ in steady state

$$\Gamma G = \Lambda + \Gamma C_{Z0} \quad \text{and} \quad BK = A + BC_{Z0}P \quad (17)$$

After determining K or G to have a desired ideal sliding dynamics, the coefficient matrix of the new surface (5) or (6) can be directly determined from the relationship:

$$\begin{aligned} C_Z &= \begin{bmatrix} c_{Z0_1} & c_{Z0_2} + c_{Z1} & \cdots & c_{Z0_n} + c_{Z1_{n-1}} \end{bmatrix} \\ &= \begin{bmatrix} \alpha_1 & \alpha_2 & \cdots & \alpha_n \end{bmatrix} + G \\ &= \begin{bmatrix} \alpha_1 & \alpha_2 & \cdots & \alpha_n \end{bmatrix} + KP^{-1} \end{aligned} \quad (18)$$

$$C_{Z0} = C_Z \quad (19)$$

which is derived from (15) and (17). If the tracker control using the nominal plant (14) or (16) is designed, then the sliding surface having exactly the same output performance can be effectively chosen using (18) or (19). As a consequence, the output of (14) or (16) becomes the state set of the chosen sliding surface, called as the ideal sliding output meaning the nominal output design in the sliding surface or desired performance design.

2.3 Control Inputs and Stability Analysis

Now, as the second design phase of the IVSC, a following control input to generate the sliding mode on the selected sliding surface is proposed as composing of the continuous and switching term

$$\begin{aligned} u(t) = &-(C_{X1}B)^{-1}[C_{X0}(X - X_r) + C_{X1}AX(t)] \\ &-(C_{X1}B)^{-1}[\sum_{i=1}^{n}\rho_{1i}|x_i - x_{i_r}| + \rho_2\|X\| + \rho_3]\text{sgn}(S_p) \end{aligned} \quad (20)$$

with the positive constant gains satisfying the inequalities:

$$\rho_{1i} > |c_{X0i}|\frac{\max\{|C_{X1}\Delta B|\}}{1 - \max\{|C_{X1}\Delta B|\}/|C_X B|}, \quad i = 1,2 \ldots, n$$
$$\rho_2 > \frac{\max\{|C_{X1}\Delta A|\}}{1 - \max\{|C_{X1}\Delta B|\}/|C_{X1}B|} \quad (21)$$
$$\rho_3 > \frac{\max\{|C_{X1}Df(t)|\}}{1 - \max\{|C_{X1}\Delta B|\}/|C_{X1}B|}$$

The continuous term (20) is directly determined according to the choosing the sliding surface. Only the switching gains are the design parameters for the robustness. As a result, the controller design is separated into the performance design and robustness design. Because of the feasibility of the control, the necessary constraint is imposed on the uncertain bound of $\Delta B(t)$ with respect to the coefficient C_{X1} and the nominal input matrix B.

$$1 > \max\{|C_{X1}\Delta B|\}/|C_{X1}B| \quad (22)$$

By means of the derived algorithm until now, the obtainable performance including the stability of the closed loop systems can be stated in next theorem.

Theorem 1: *The proposed feasible variable structure controller with the input (20) and the modified sliding surface (6) can exhibit the asymptotic stability and the ideal output of the sliding mode dynamics for all the uncertainties, (14) or (16), exactly defined by the modified sliding surface (6).*

Proof: Take a Lyapunov candidate function as

$$V(t) = \frac{1}{2}S_p^2(X,t) \quad (23)$$

Differentiating (23) with time leads to

$$\dot{V}(t) = S_p(X,t)\dot{S}_p(X,t) \quad (24)$$

Now, the real dynamics of the sliding surface by the new control input can be obtained as

$$\begin{aligned} \dot{S}_p(X,t) &= C_{X0}(X - X_r) + C_{X1}\dot{X} = C_0(X - X_r) \\ &+ C_{X1}\{(A + \Delta A)X(t) + (B + \Delta B)u(t) + Df(t)\} \end{aligned} \quad (25)$$

Substituting (20) into (25) leads to

$$\begin{aligned} \dot{S}_p(X,t) &= C_{X1}\Delta AX(t) - C_{X1}\Delta B(C_{X1}B)^{-1}[C_0(X - X_r) \\ &+ C_{X1}AX(t)] - C_{X1}(B + \Delta B)(C_{X1}B)^{-1}[\sum_{i=1}^{n}\rho_{1_i}(x_i - x_{i_r}) \\ &+ \rho_2\|x\| + \rho_3]\text{sgn}(S_p) + C_{X1}Df(t) \\ &= -C_{X1}\Delta B(C_{X1}B)^{-1}C_0(X - X_r) - C_X\Delta AX(t) \\ &- C_{X1}(B + \Delta B)(C_{X1}B)^{-1}\sum_{i=1}^{n}\rho_{1_i}(x_i - x_{i_r})\text{sgn}(S_p) \\ &- C_{X1}(B + \Delta B)(C_{X1}B)^{-1}\rho_2\|X\|\text{sgn}(S_p) \\ &- C_{X1}Df(t) - C_{X1}(B + \Delta B)(C_{X1}B)^{-1}\rho_3\,\text{sgn}(S_p) \end{aligned} \quad (26)$$

To stabilize the dynamics of the sliding surface in (26), the condition (22) is naturally necessary. By menas of the inequalities of gain (21) and (22), it can be easily shown that the derivative of the Lyapunov candidate function (24) and the existence condition of the sliding mode

$$S_p(X,t)\cdot\dot{S}_p(X,t) < 0 \quad (27)$$

is satisfied, which completes the proof.

From the above theorem, the control in this paper can generate the sliding mode at every point on the modified sliding surface. Therefore, the output trajectory by the proposed controller can be identical to that of the ideal sliding mode dynamics from a given initial state to origin identically defined by the new sliding surface because of the insensitivity of the controlled system to uncertain parameters and disturbances in the sliding mode[31].

3. Design Examples and Simulation Studies

Consider the following plant with uncertainties and disturbance

$$\dot{x}_1(t) = (-2 + \Delta a_1)x_1(t) + (1 + \Delta b_1(t))u(t) + f(t)$$
$$\dot{x}_2(t) = \Delta a_1 x_1(t) - 3x_2(t) + (1 + \Delta b_2(t))u(t) + f(t)$$
$$y = [2 \quad 1][x_1 \quad x_2]^T \tag{28}$$

where

$$\Delta a_1(t) = 3\sin(8t),\ \Delta b_1(t) = \Delta b_2(t) = 0.3\cos(5t),\ f(t) = 0.5\cos(6t)$$
$$|\Delta a_1(t)| \le 3,\ |\Delta b_1(t)| = |\Delta b_2(t)| \le 0.3,\ |f(t)| \le 0.5. \tag{29}$$

The controller is aim to drive the output of the plant (28) to any given y_r. In the steady state, the state should be $Z_r = [1 \quad 0]^T y_r$ and $X_r = [3/8 \quad 1/4]^T y_r$ due to the steady state condition. The transformation matrix to a controllable canonical form and the resultant transformed system matrices are

$$P = \begin{bmatrix} 1 & -1 \\ -2 & 3 \end{bmatrix} \quad \Lambda = \begin{bmatrix} 0 & 1 \\ -6 & -5 \end{bmatrix} \quad \Gamma = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{30}$$

By means of Ackermanns formula, the gain is obtained

$$K = [0.75 \quad 0.25] \text{ and } G = [1.75 \quad 1.00] \tag{31}$$

so that the closed loop eigenvalues of Λ_c are located at *-2.5* and *-3.5*. By the relationship (18) and (19), the coefficient of the new sliding surface directly becomes

$$\begin{aligned} C_n &= [\alpha_1 \quad \alpha_2] + G = [6 \quad 5] + [1.75 \quad 1.00] \\ &= [8.75 \quad 6.00] = C_{z0} \end{aligned} \tag{32}$$

$$C_{Z0} = [8.75 \quad 6],\quad C_{z1} = [0 \quad 1],$$
$$C_{X0} = C_{Z0}P = [-3.25 \quad 9.25],\ C_{X1} = C_{Z1}P = [-2 \quad 3] \tag{33}$$

As a result, a new sliding surface becomes

$$\begin{aligned} S(X,t) = &-3.25[\textstyle\int_0^t (x_1 - x_{1r})dt + (2/3.25)(x_{1r} - x_1(0))] \\ &+ 9.25[\textstyle\int_0^t (x_2 - x_{2r})dt + (3/9.25)(x_{2r} - x_2(0))] \\ &- 2(x_1 - x_{1r}) + 3(x_2 - x_{r2}) \end{aligned} \tag{34}$$

For the second design phase of the IVSC,

$$C_{X1}B = 1,\quad C_{X1}\Delta B = 0.3\cos(5t)$$
$$1 - \max\{C_{X1}\Delta B\} / |C_{X1}B| = 0.7 \tag{35}$$

are calculated. The condition (22) is satisfied in this design. The inequalities for the switching gains in discontinuous input term, (21) becomes

$$\rho_{11} > |c_{X0_1}| \frac{\max\{|C_{X1}\Delta B\}}{1 - \max\{|C_{X1}\Delta B|\} / |C_{X1}B|} = 3.25\frac{0.3}{0.7} = 1.393$$

$$\rho_{12} > |c_{X0_2}| \frac{\max\{|C_{X1}\Delta B\}}{1 - \max\{|C_{X1}\Delta B|\} / |C_{X1}B|} = 9.25\frac{0.3}{0.7} = 3.964$$

$$\rho_2 > \frac{\max\{|C_{X1}\Delta A\}}{1 - \max\{|C_{X1}\Delta B|\} / |C_{X1}B|} = \frac{3}{0.7} = 4.286 \tag{36}$$

$$\rho_3 > \frac{\max\{|C_X Df(t)|\}}{1 - \max\{|C_X\Delta B|\} / |C_X B|} = \frac{0.5}{0.7} = 0.714$$

The selected control gains are

$$\rho_{11} = 2 \quad \rho_{12} = 5 \quad \rho_2 = 7 \text{ and } \rho_3 = 4 \tag{37}$$

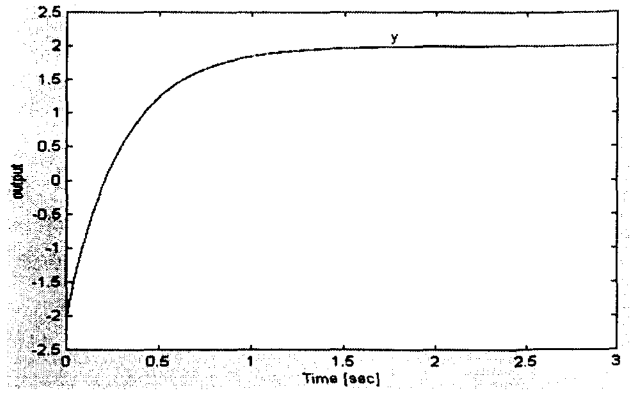

그림 1 이상 출력과 실제 출력 응답
Fig. 1 Ideal and real output responses

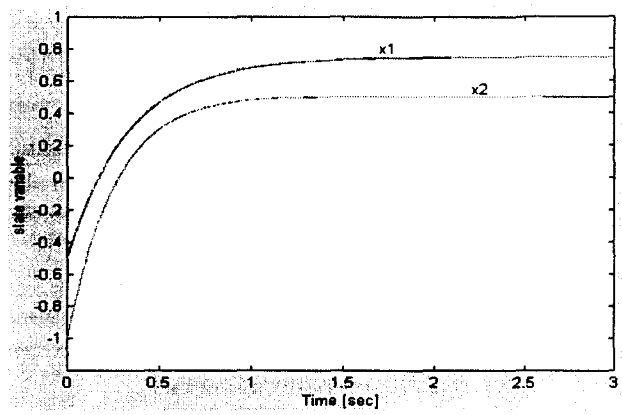

그림 2 이상 상태변수과 실제 상태변수 응답
Fig. 2 Ideal and real state responses

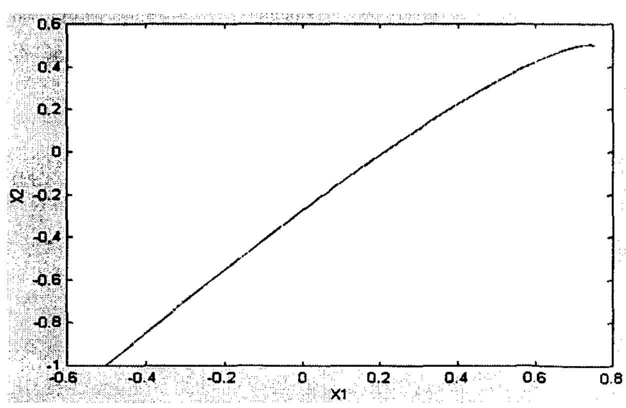

그림 3 상 응답
Fig. 3 Phase portrait

and finally, the following control input is obtained to satisfy the existence condition of the sliding mode (27) as

$$\begin{aligned} u(t) = &-[-3.25(x_1 - x_{1r}) + 9.25(x_2 - x_{2r}) + 4x_1 - 9x_2] \\ &-[2|x_1 - x_{1r}| + 5|x_2 - x_{2r}| + 7\|X\| + 4]\mathrm{sgn}(S_p) \end{aligned} \tag{38}$$

Fig. 1 shows the ideal output and real output from an initial condition $y(0) = -2 = [2 \quad 1][-0.5 \quad -1]^T$ to a given

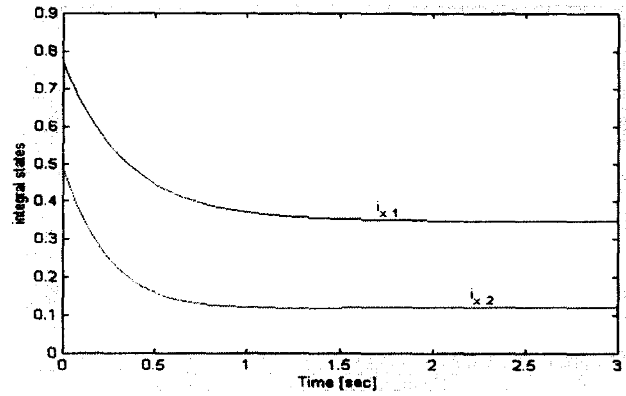

그림 4 적분 상태변수 응답
Fig. 4 Integral state

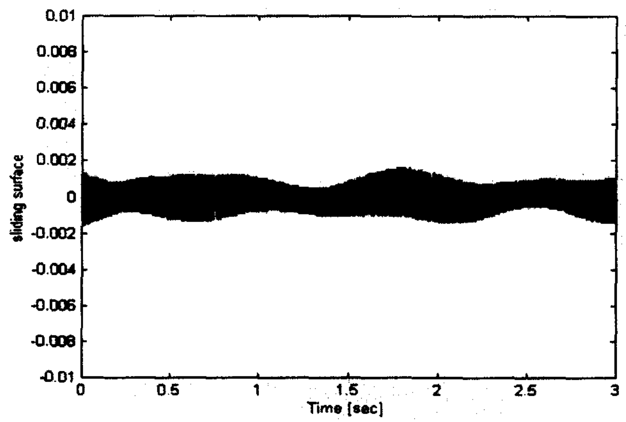

그림 5 슬라이딩 면 응답
Fig. 5 Sliding surface

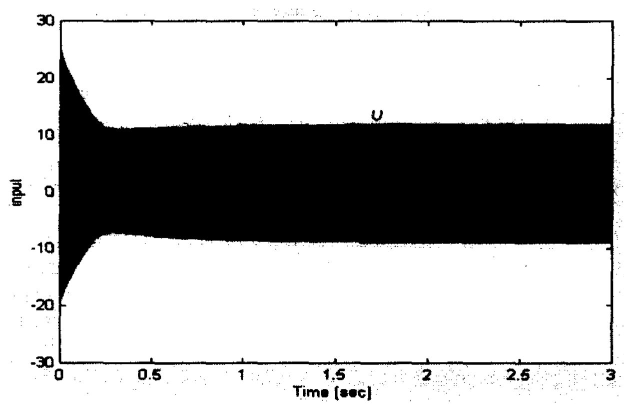

그림 6 제어입력
Fig. 6 Control inputt

command $y_r = 2$. The ideal and real state responses by the proposed SMC are shown in Fig. 2. As can be seen, the trajectories identically equal to those of the ideal sliding output. The phase portrait from $[-0.5 \quad -1]^T$ to $[3/4 \quad 1/2]^T$ is presented in Fig. 3. There is no reaching phase. The integral state of output error is depicted in Fig. 4. The fact of no reaching phase can be also found

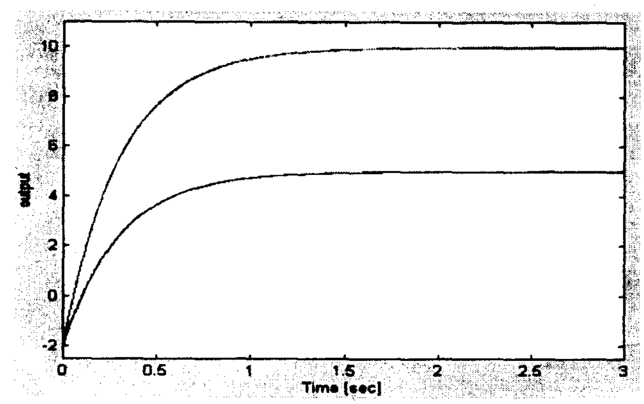

그림 7 2가지 명령에 대한 2가지 출력
Fig. 7 Two outputs for different commands

in Fig. 5 showing that the value of the new sliding surface chatters from the beginning without any reaching action. And this is fundamentally resulted from the switching of the implemented control input from the initial time as shown in Fig. 6 as designed. Fig.7 shows the output responses to the two different commnads, $y_r = 5 \text{ and } 10$.

3. Conclusions

In this paper, a design of an IVSC is presented for the tracker control of uncertain linear systems under persistent disturbances. This algorithm basically concerns with removing the reaching phase and application to the tracker control problem of uncertain non-canonical linear systems. To successfully remove the reaching phase problems, a sliding surface is augmented by an integral of the state error in order to define the hyper plane from any given initial condition. And for its design, the system is transformed to a canonical form and the ideal sliding dynamics is obtained in form of the nominal system. After choosing the desired output performance by means of the tracker control design with the nominal system, the coefficient of the integral sliding surface is determined effectively. A corresponding control input is also designed for completely guaranteeing the ideal sliding output in spite of the uncertainties and disturbances. The robustness of the ideal sliding output itself is proved under all the persistent disturbances in Theorem 1 together with the existence condition of the sliding mode of the IVSC and the asymptotic stability of the proposed IVSC. Therefore, the designed controller can drive uncertain systems to any arbitrary desired value with the predetermined identical sliding output as designed in the sliding surface. The two design concepts of the performance and robustness are perfectly separated in the suggested tracker IVSC. In the tracker control area, the robustness problem is completely solved. Through simulation studies, the usefulness of the proposed controller is verified.

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