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다입출력 불확실 선형 플랜트를 위한 포화함수에 의한 연속 슬라이딩 면 변환 가변구조시스템

(A Continuous Sliding Surface Transformed VSS by Saturation Function for MIMO Uncertain Linear Plants)

이 정 훈*

(Jung-Hoon Lee©)

요 약

본 연구에서는 다입출력 불확실 선형 플랜트를 위한 포화함수에 의한 연속 슬라이딩 면 변환 가변 구조 시스템이 주어진다. 이론적으로 불연속 슬라이딩 면 변환 가변구조 시스템을 제안한다. 사전에 결정된 슬라이딩 면 위에 슬라이딩 모드의 다입출력 존재 조건과 함께 페루프 지수 안정성에 대해 검토한다. 실제 응용을 위하여 포화 함수에 의하여 불연속 가변구조 시스템의 연속 근사화를 이룬다. 실제적인 관점에서 가변 구조 시스템의 내부 특성인 제어입력의 불연속성을 많이 개선한다, 설계 예와 시뮬레이션 연구를 통하여 제안된 연속 변환 가변구조 시스템 제어기의 유용성을 입증한다.

Abstract

In this note, a continuous sliding surface transformed variable structure systems by the saturation function is presented for MIMO uncertain linear plants. A discontinuous sliding surface transformed VSS is proposed theoretically. The closed loop exponential stability together with the MIMO existence condition of the sliding mode on the predetermined sliding surface is investigated. For practical applications, a continuous approximation of the discontinuous VSS is made by means of the saturation function. The discontinuity of the control input as the inherent property of the VSS is much improved in view of the practical aspects. Through a design example and simulation studies, the usefulness of the proposed continuous transformed VSS controller is verified.

Keywords : saturation function, variable structure system, sliding mode control, continuous VSS, sliding surface transformed VSS

Ⅰ. Introduction

The variable structure system(VSS) or sliding mode control(SMC) can provide the effective means to the discontinuous control of uncertain dynamical systems under parameter variations and external disturbances[1~2]. One of its essential advantages is the robustness of the controlled system to matched parameter uncertainties and matched external disturbances in the sliding mode on the predetermined sliding surface, s=0[3~4]. To take the advantages of the sliding mode on the predetermined

* 정회원, 국립경상대학교 제어계측공학과, ERI
(Dept of Control & Instrum. Eng., Gyeongsang National University)
© Corresponding Author(E-mail: wangwang7@naver.com)
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sliding surface, the MIMO precise existence condition of the sliding mode, $s_i \cdot \dot{s}_i < 0,\ i = 1,2,...m$ for the linear MIMO case should be satisfied and proved where s is the sliding surface and s_i is the sub-manifold of the sliding surface. For a linear MIMO case, some design methods were studied, those are the hierarchical control methodology[1~2], transformation (diagonalization) methods[1, 3], simplex algorithm[6], Lyapunov approach[7~9], and so on. In MIMO VSSs, it is difficult to prove the precise existence condition of the sliding mode on the predetermined sliding surface theoretically, but in [7], [8], and [9], only the results that the derivative of the Lyapunov candidate function is negative, i.e. $\dot{V} < 0$ is obtained when $V = 1/2 s^T s$. Without the complete proofs, the two methodologies for SISO plants as well as MIMO plants is presented by Utkin to prove the existence condition of the sliding mode on the sliding surface in 1978[1]. It is so called the invariance theorem, that is the equation of the sliding mode is invariant with respect to the two nonlinear transformation (diagonalization)s. Those are the control input transformation and sliding surface transformation. The essential feature of both methods is conversion of a multi-input design problem into m single-input design problems. Those were only reviewed in [3]. DeCarlo, Zak, and Matthews tried to prove Utkin's invariance theorem. But, the proofs are not clear and not complete. In [8], Su, Drakunov, and Ozguner mentioned the sliding surface transformation, which would diagonalize the control coefficient matrix to the dynamics for the sliding surface s. But they did not prove the MIMO precise existence condition of the sliding mode on the predetermined sliding surface. For MIMO uncertain linear plants, the theorem of Utkin is proved comparatively and completely by Lee[10].

The VSS or SMC has the two main disadvantages of the reaching phase and chattering problems. The reaching phase problems are solved by the integral augmentation with a special initial condition for $s = 0$ at $t = 0$ in [5]. The chattering of the control input is because the VSS or SMC has the discontinuous inherent property resulted from the high frequency switching of the control structure to generate the sliding mode on the predetermined sliding surface so that the controlled system is theoretically robust(insensitive) to the uncertainty and external disturbance in the sliding mode. Because the chattering of the resultant discontinuous input of the VSS or SMC is a harmful factor to real plants, the practically continuous approximation based on the saturation function[11~15], boundary layer methods[16~20], higher order method[21], and etc[22] is essentially necessary in order to have the high potential of the real application of the VSS to the continuous control of real plants. By using the saturation function instead the discontinuous sign function, a continuous approximation is made by Ambrosino, Celentano, and Garofalo in [11]. For the tracking control of robot manipulators, the saturation function is used in [12] and is combined with the disturbance observer in [13] and [14]. For the tracking control of brushless direct drive servo motors(BLDDSM), by using the saturation function, the chattering problems are improved in [14] and [15].

In this note, by using the saturation function, a continuous sliding surface transformed variable structure systems proposed for MIMO uncertain linear plants. After a discontinuous sliding surface transformed VSS is proposed theoretically, the closed loop exponential stability together with the MIMO existence condition of the sliding mode is investigated in Theorem 1. Then, for practical applications, a continuous approximation of the discontinuous VSS is made by using the saturation function. The discontinuity of the control input as the inherent property of the VSS is much improved. Through a design example and simulation studies, the usefulness of the proposed continuous transformed VSS controller is verified. The organization of the this paper is as follows. In section Ⅱ, a descriptions of plants, transformed linear sliding surface, and a corresponding discontinuous and continuous control input with the stability analysis are presented as the main results. A design example and simulation study is carried out in section Ⅲ. Finally some concluding remarks are given in section Ⅳ.

Ⅱ. Continuous Variable Structure Systems

For a MIMO uncertain linear system:

$$\dot{x} = (A_0 + \Delta A)x + (B_0 + \Delta B)u + \Delta D(t) \quad (1)$$

where $x \in R^n$ is the state, $u \in R^m$ is the control input, $A_0 \in R^{n \times n}$ is the nominal system matrix, $B_0 \in R^{n \times 1}$ is the nominal input matrix, $\triangle A$ and $\triangle B$ are the system matrix uncertainty and input matrix uncertainty, those are bounded, and $\Delta D(t)$ is bounded external disturbance, respectively.

The transformed sliding surface $s \in R^m$ is the linear combination of the full state variable as[10]

$$s = (CB_0)^{-1} C \cdot x \quad (2)$$

Assumption 1:

CB_0 has the full rank and its inverse for a coefficient matrix of the sliding surface C.

Assumption 2:

$(CB_0)^{-1} C \triangle B = \triangle I$. $\triangle I$ is diagonal and $|\triangle I_{ii}| \le \rho_i < 1, \quad i = 1,2,...,m$

Now, the suggested VSS control input for the transformed sliding surface is taken as follows:

$$\begin{aligned} u = &- K \cdot x - \Delta K \cdot x - G \cdot s \\ &- \triangle G \cdot sign(s) \end{aligned} \quad (3)$$

where one takes the constant gains as

$$\begin{aligned} &K = (CB_0)^{-1} CA_0 \\ &G = [g_{ii}], \quad g_{ii} > 0, \ i = 1,2,...,m \end{aligned} \quad (4)$$

and takes the switching gains as follows:

$$\triangle k_{ij} = \begin{cases} \ge \dfrac{\max\{(CB_0)^{-1} C \triangle A - \triangle IK\}_{ij}}{\min\{I + \triangle I\}_{ii}} & sign(s_i x_j) > 0 \\ \le \dfrac{\min\{(CB_0)^{-1} C \triangle A - \triangle IK\}_{ij}}{\min\{I + \triangle I\}_{ii}} & sign(s_i x_j) < 0 \end{cases}$$

$$i = 1,2,...,m \quad j = 1,2,...,n \quad (5)$$

$$\triangle G_i = \begin{cases} \ge \dfrac{\max\{(CB_0)^{-1} C \Delta D(t)\}_i}{\min\{I + \triangle I\}_{ii}} & sign(s_i) > 0 \\ \le \dfrac{\min\{(CB_0)^{-1} C \Delta D(t)\}_i}{\min\{I + \triangle I\}_{ii}} & sign(s_i) < 0 \end{cases}$$

$$i = 1,2,...,m \quad (6)$$

In the discontinuous control input (3), the transformed sliding surface itself is one of the feedback elements which makes the controlled system be closer to the ideal sliding surface[5]. Then, the real dynamics of the sliding surface by the discontinuous control input, i.e. the time derivative of s becomes

$$\begin{aligned} \dot{s} &= (CB_0)^{-1} \dot{s} = (CB_0)^{-1} C\dot{x} \\ &= (CB_0)^{-1} C(A_0 + \Delta A)x + (CB_0)^{-1} C(B_0 + \Delta B)u \\ &\quad + (CB_0)^{-1} C \Delta D(t) \\ &= (CB_0)^{-1} C(A_0 + \Delta A)x + (I + \Delta I)u + (CB_0)^{-1} C \Delta D(t) \\ &= (CB_0)^{-1} C(A_0 + \Delta A)x \\ &\quad - (I + \Delta I)(Kx + \Delta Kx + Gs + \triangle G sign(s)) \\ &\quad + (CB_0)^{-1} C \Delta D(t) \\ &= (CB_0)^{-1} CA_0 x - Kx + (CB_0)^{-1} C \Delta Ax - \Delta IKx \\ &\quad - (I + \Delta I)\Delta Kx - (I + \triangle I)Gs \\ &\quad + (CB_0)^{-1} C \Delta D(t) - (I + \Delta I)\triangle G sign(s) \end{aligned} \quad (7)$$

From (4), the real dynamics of s becomes

$$\begin{aligned} \dot{s} = &[(CB_0)^{-1} C \Delta A - \Delta IK]x - (I + \Delta I)\Delta Kx \\ &- (I + \Delta I)Gs + (CB_0)^{-1} C \Delta D(t) \\ &- (I + \Delta I)G sign(s) \end{aligned} \quad (8)$$

The closed loop stability with the discontinuous control input (3) together with the existence condition of the sliding mode will be investigated in next Theorem 1.

Theorem 1: If the sliding surface is designed to be stable, the discontinuous control input (3) with the transformed sliding surface (2) satisfies the MIMO existence condition of the sliding mode on the pre-designed sliding surface and exponential stability.

Proof: Take a Lyapunov function candidate as

$$V(s)=\frac{1}{2}s^Ts \tag{9}$$

Differentiating (9) with time leads to and substituting (8) into (10)

$$\begin{aligned}
\dot{V}(x) &= s^T\dot{s} \\
&= s^T(CB_0)^{-1}C\dot{x} \\
&= s^T(CB_0)^{-1}C(A_0+\triangle A)x \\
&\quad + s^T(CB_0)^{-1}C(B_0+\triangle B)u \\
&\quad + s^T(CB_0)^{-1}C\triangle D(t) \\
&= s^T(CB_0)^{-1}C(A_0+\triangle A)x \\
&\quad + s^T(CB_0)^{-1}C\triangle D(t) \\
&\quad - s^T(I+\triangle I)\{Kx+\triangle Kx+Gs+\triangle Gsign(s)\} \\
&= s^T\{(CB_0)^{-1}CA_0-K\}x \\
&\quad + s^T(CB_0)^{-1}C(\triangle A-\triangle IK)x - s^T(I+\triangle I)\triangle Kx \\
&\quad - s^T(I+\triangle I)Gs + s^T(CB_0)^{-1}C\triangle D(t) \\
&\quad - s^T(I+\triangle I)\triangle Gsign(s) \\
&= s^T(CB_0)^{-1}C(\triangle A-\triangle IK)x - s^T(I+\triangle I)\triangle Kx \\
&\quad - s^T(I+\triangle I)Gs + s^T(CB_0)^{-1}C\triangle D(t) \\
&\quad - s^T(I+\triangle I)\triangle Gsign(s)
\end{aligned} \tag{10}$$

From the inequalities in (5) and (6), one can obtain the following equation

$$\begin{aligned}
\dot{V}(x) &\le -\epsilon s^TGs, \quad \epsilon=\min\{I_{ii}+\triangle I_{ii}\} \\
&= -\sum_{i=1}^{m}(1-\rho_i)g_{ii}s_i^2
\end{aligned} \tag{11}$$

From (11), the following equation is obtained

$$s_i \cdot \dot{s}_i < (1-\rho_i)g_{ii}s_i^2, \quad i=1,2,...,m \tag{12}$$

The MIMO existence condition of the sliding mode on the predetermined transformed sliding surface by the control input is proved theoretically. From (11), the following equation is obtained.

$$\begin{aligned}
\dot{V}(x) &\le -\epsilon g_{iim}s^Ts, \quad g_{iim}=\min\{g_{ii}\} \\
&= -2\epsilon g_{iim}V(x)
\end{aligned} \tag{13}$$

From (13), the following equation is obtained

$$\begin{aligned}
&\dot{V}(x)+2\epsilon g_{iim}V(x) \le 0 \\
&V(t) \le V(0)e^{-2\epsilon g_{iim}t}
\end{aligned} \tag{14}$$

which completes the proof of Theorem 1.

The high frequency switching of the discontinuous part of the control input (3) results in the chattering problems because of the switching of the sign function in (3) according to the value of the sliding surface which may be harmful to practical real plants. Hence, the continuous approximation of the discontinuous VSS is essentially necessary for practical applications without a severe performance loss. Using the saturation function, therefore, the continuous VSS is proposed as

$$\begin{aligned}
u &= -K\cdot x - G\cdot s \\
&\quad -\left\{\sum_{j=1}^{n}|\Delta k_{ij}\cdot x_j| + |\triangle g_{ij}\cdot sign(s_j)|\right\}\left\{\frac{s_i}{|s_i|+\delta_i}\right\}
\end{aligned} \tag{15}$$

Ⅲ. Design Example and Simulation Studies

Consider a fifth-order system with the two inputs described by the state equation which is slightly modified from that in [23]

$$\begin{aligned}
\dot{x} &= \begin{bmatrix} 0.0 & 1.0 & 0.0 & 3.20 & 1.98 \\ 0.0 & 0.0 & 1.0 & -14.72 & 0.49 \\ -8.86 & 8.0 & 9.36 & -7.92 & 36.01 \\ 1.69 & 1.26 & 0.08 & 0.0 & 1.0 \\ -7.52 & -5.23 & -0.45 & 32.32 & -1.36 \end{bmatrix} x \\
&\quad + \begin{bmatrix} 0.0 & 0.0 \\ 0.0 & 0.0 \\ 2.0\pm 0.1 & 0.0 \\ 0.0 & 0.0 \\ 0.0 & 2.0\pm 0.2 \end{bmatrix} u + \begin{bmatrix} 0.0 & .0.0 \\ 0.0 & 0.0 \\ \pm 3.0 & 0.0 \\ 0.0 & 0.0 \\ 0.0 & \pm 5.0 \end{bmatrix}
\end{aligned} \tag{16}$$

where the nominal parameter A_0 and B_0, matched uncertainties $\triangle A$ and $\triangle B$, and disturbance $\triangle D(t)$ are

$$A_0 = \begin{bmatrix} 0.0 & 1.0 & 0.0 & 3.20 & 1.98 \\ 0.0 & 0.0 & 1.0 & -14.72 & 0.49 \\ -8.86 & 8.0 & 9.36 & -7.92 & 36.01 \\ 1.69 & 1.26 & 0.08 & 0.0 & 1.0 \\ -7.52 & -5.23 & -0.45 & 32.32 & -1.36 \end{bmatrix},$$

$$B_0=\begin{bmatrix}0.0 & 0.0\\ 0.0 & 0.0\\ 2.0 & 0.0\\ 0.0 & 0.0\\ 0.0 & 2.0\end{bmatrix},$$

$$\triangle A=0, \triangle B=\begin{bmatrix}0.0 & 0.0\\ 0.0 & 0.0\\ \pm 0.1 & 0.0\\ 0.0 & 0.0\\ 0.0 & \pm 0.2\end{bmatrix}, \&$$

$$\triangle D(t)=\begin{bmatrix}0.0 & .0.0\\ 0.0 & 0.0\\ \pm 3.0 & 0.0\\ 0.0 & 0.0\\ 0.0 & \pm 5.0\end{bmatrix} \tag{17}$$

The stable coefficient matrix of the sliding surface is determined as

$$C=\begin{bmatrix}-0.436 & 1.802 & 1.0 & -14.568 & 0.0\\ 1.010 & 0.505 & 0.0 & 1.616 & 0.5\end{bmatrix} \tag{18}$$

and the equations in Assumption 1 are calculated as

$$CB_0=\begin{bmatrix}2 & 0\\ 0 & 1\end{bmatrix} \text{ and } (CB_0)^{-1}=\begin{bmatrix}0.5 & 0\\ 0 & 1\end{bmatrix} \tag{19}$$

By letting the gain

$$\begin{aligned}K&=(CB_0)^{-1}CA_0\\ &=\begin{bmatrix}0.5 & 0.0\\ 0.0 & 1.0\end{bmatrix}\begin{bmatrix}-33.4799 & -10.7917 & 9.966 & -35.8406 & 21.4617\\ -1.0290 & 0.4312 & 0.4093 & 11.9584 & 3.1833\end{bmatrix}\\ &=\begin{bmatrix}-16.7400 & -5.3958 & 4.9983 & -17.9203 & 10.7309\\ -1.0290 & 0.4312 & 0.4093 & 11.9584 & 3.1833\end{bmatrix}\end{aligned} \tag{20}$$

and $\triangle I$ in Assumption 2 is

$$\triangle I=(CB_0)^{-1}C\triangle B=\begin{bmatrix}0.5 & 0.0\\ 0.0 & 1.0\end{bmatrix}\cdot$$

$$\begin{bmatrix}-0.436 & 1.802 & 1.0 & -14.568 & 0.0\\ 1.010 & 0.505 & 0.0 & 1.616 & 0.5\end{bmatrix}\begin{bmatrix}0.0 & 0.0\\ 0.0 & 0.0\\ \pm 0.1 & 0.0\\ 0.0 & 0.0\\ 0.0 & \pm 0.2\end{bmatrix}$$

$$=\begin{bmatrix}\pm 0.05 & 0.0\\ 0.0 & \pm 0.1\end{bmatrix} \tag{21}$$

If one take the switching gains as follows:

$$\Delta k_{11}=\begin{cases}1.2 & \text{if } s_1x_1>0\\ -1.2 & \text{if } s_1x_1<0\end{cases}, \quad \Delta k_{12}=\begin{cases}4.2 & \text{if } s_1x_2>0\\ -4.2 & \text{if } s_1x_2<0\end{cases},$$

$$\Delta k_{13}=\begin{cases}3.5 & \text{if } s_1x_3>0\\ -3.5 & \text{if } s_1x_3<0\end{cases} \quad \Delta k_{14}=\begin{cases}6.5 & \text{if } s_1x_4>0\\ -6.5 & \text{if } s_1x_4<0\end{cases}$$

$$\Delta k_{15}=\begin{cases}6.5 & \text{if } s_1x_5>0\\ -6.5 & \text{if } s_1x_5<0\end{cases}, \quad \triangle g_{11}=\begin{cases}1.8 & \text{if } s_1>0\\ -1.8 & \text{if } s_1<0\end{cases} \tag{22}$$

$$\Delta k_{21}=\begin{cases}5.2 & \text{if } s_2x_1>0\\ -5.2 & \text{if } s_2x_1<0\end{cases}, \quad \Delta k_{22}=\begin{cases}4.2 & \text{if } s_2x_2>0\\ -4.2 & \text{if } s_2x_2<0\end{cases},$$

$$\Delta k_{23}=\begin{cases}3.5 & \text{if } s_2x_3>0\\ -3.5 & \text{if } s_2x_3<0\end{cases} \quad \Delta k_{24}=\begin{cases}6.5 & \text{if } s_2x_4>0\\ -6.5 & \text{if } s_2x_4<0\end{cases},$$

$$\Delta k_{25}=\begin{cases}6.5 & \text{if } s_2x_5>0\\ -6.5 & \text{if } s_2x_5<0\end{cases}, \quad \triangle g_{22}=\begin{cases}5.8 & \text{if } s_2>0\\ -5.8 & \text{if } s_2<0\end{cases}$$

$$g_{11}=1.0 \quad g_{22}=1.0 \tag{23}$$

then

$$s_1\cdot\dot{s}_1<-1.9s_1^2 \text{ and } s_2\cdot\dot{s}_2<-0.8s_2^2 \tag{24}$$

The simulation is carried out under $0.1[msec]$ sampling time and with $x(0)=[2\ 0\ 0\ -1.5\ 0]^T$ initial condition. Fig. 1 shows the five state output responses, x_1 and x_2 in a top figure, x_3 in a middle figure, x_4 and x_5 in a bottom figure by the discontinuous control input. The two real trajectories and two ideal trajectories are shown Fig. 2, x_1-x_2 plane trajectories in a upper figure and x_4-x_5 plane trajectories in a lower figure. The two sliding surfaces and two discontinuous control inputs are depicted in Fig. 3 and Fig.4, respectively. As can be seen, the large chattering of the two discontinuous control inputs is shown which results in the

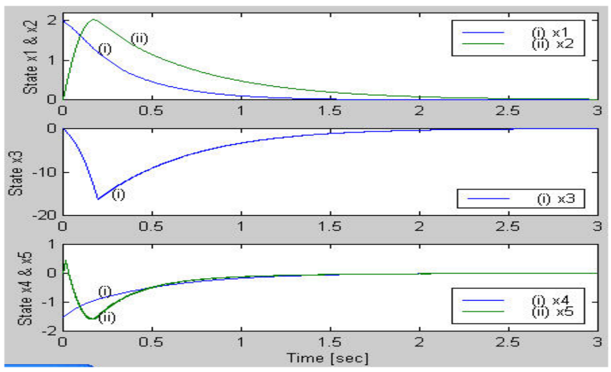

그림 1. 불연속 제어입력에 의한 5개의 상태변수 응답 (x_1과 x_2는 제일 윗 그림에, x_3는 중간 그림에, x_4과 x_5는 제일 아래 그림에)

Fig. 1. Five state output responses, x_1 and x_2 in a top figure, x_3 in a middle figure, x_4 and x_5 in a bottom figure by discontinuous control input.

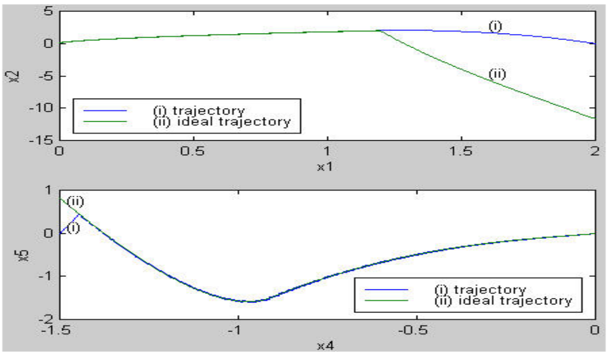

그림 2. 두 실제 궤적과 두 이상 궤적(x_1-x_2 평면은 윗 그림에, x_4-x_5 평면은 아래 그림에)

Fig. 2. Two real trajectories and two ideal trajectories (x_1-x_2 plane in a upper figure and x_4-x_5 plane in a lower figure).

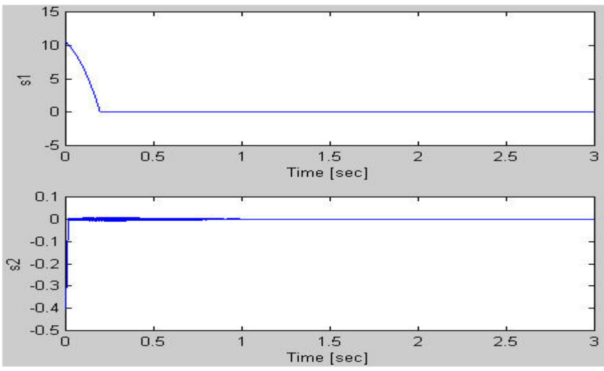

그림 3. 두 슬라이딩 면

Fig. 3. Two sliding surfaces.

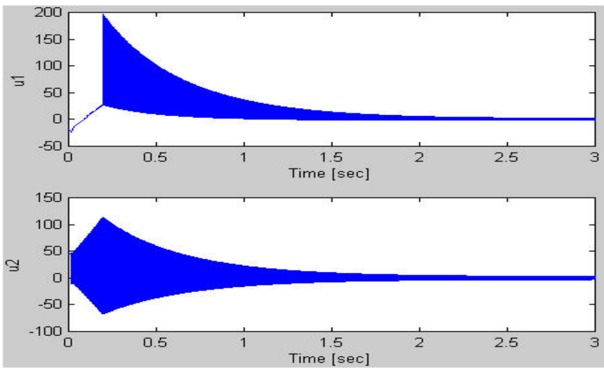

그림 4. 두 불연속 제어입력

Fig. 4. Two discontinuous control inputs.

chattering problems and may be harmful to real plants. For the continuous approximation by the continuous control inputs (15) with proper $\delta_1=\delta_2=0.008$, Fig. 5 shows the five state output responses, x_1 and x_2 in a top figure, x_3 in a middle

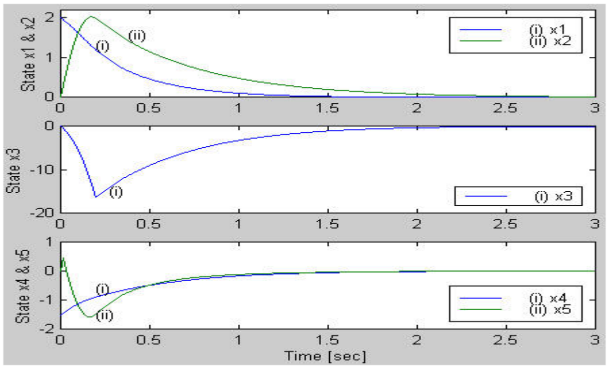

그림 5. $\delta_1=\delta_2=0.008$인 연속 제어입력에 의한 5개의 상태변수 응답(x_1과 x_2는 제일 윗 그림에, x_3는 중간 그림에, x_4과 x_5는 제일 아래 그림에)

Fig. 5. Five state output responses, x_1 and x_2 in a upper figure, x_3 in a middle figure, x_4 and x_5 in a lower figure by continuous input with $\delta_1=\delta_2=0.008$.

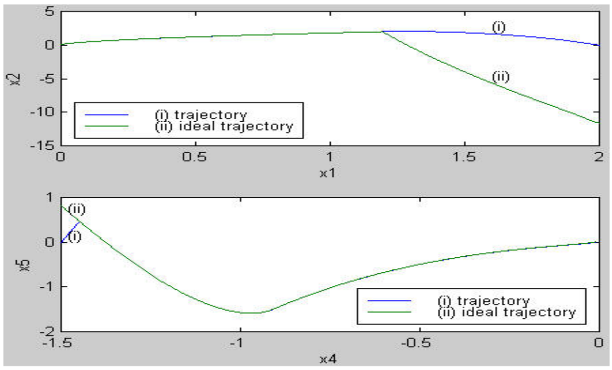

그림 6. 두 실제 궤적과 두 이상 궤적(x_1-x_2 평면은 윗 그림에, x_4-x_5 평면은 아래 그림에)

Fig. 6. Two real trajectories and two ideal trajectories (x_1-x_2 plane in a upper figure and x_4-x_5 plane in a lower figure)

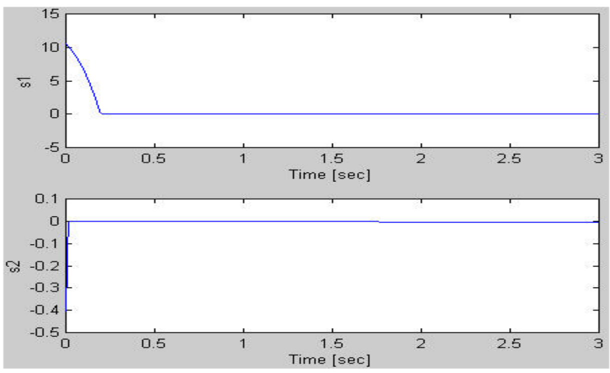

그림 7. 두 슬라이딩 면

Fig. 7. Two sliding surfaces.

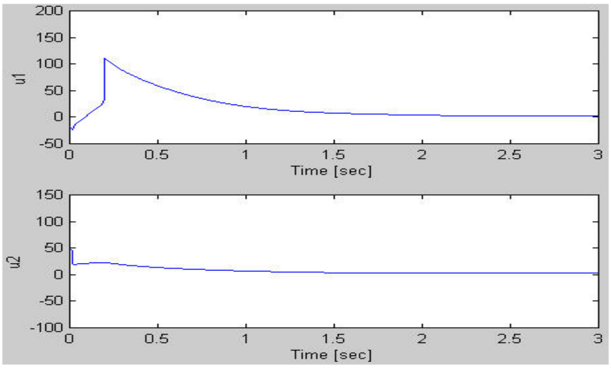

그림 8. $\delta_1 = \delta_2 = 0.008$인 두 연속 제어입력
Fig. 8. Two continuous inputs for $\delta_1 = \delta_2 = 0.008$.

figure, x_4 and x_5 in a bottom figure. The two real trajectories and two ideal trajectories are shown Fig. 6, $x_1 - x_2$ plane trajectories in a upper figure and $x_4 - x_5$ plane trajectories in a lower figure. The two sliding surfaces and two continuous control inputs are depicted in Fig. 7 and Fig. 8, respectively. As can be seen, the large chattering of the two control inputs is much improved with almost the same output performance as that of the discontinuous VSS.

Ⅳ. Conclusions

In this note, a MIMO discontinuous sliding surface transformed VSS with the feedback of the sliding surface itself is proposed. The closed loop exponential stability together with the MIMO existence condition of the sliding mode on the selected sliding surface by the proposed control input is investigated in Theorem 1 for all matched uncertainties and matched disturbance. For practical application of the proposed VSS to real plants, the harmful chattering of the discontinuous input is effectively much improved without severe performance loss by means of the saturation function. Through a design example and simulation studies, the usefulness of the proposed continuous VSS controller is verified. Theoretically the discontinuous input is considered and practically the continuous VSS based on the saturation function method can be applicable to the continuous control of the real plant.

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저 자 소 개

이 정 훈(정회원)
1988년 경북학교 전자공학과 학사 졸업.
1990년 한국과학기술원(KAIST) 전기및전자공학과 석사졸업.
1995년 한국과학기술원(KAIST) 전기및전자공학과 박사 졸업.
1995년～현재 국립 경상대학교 제어계측공학과 교수, 공학연구원 연구원
<주관심분야 : 가변구조제어이론의 개발과 전동기, 로봇 등 모션제어응용, 비선형제어>