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A New Robust Variable Structure Controller with Nonlinear Integral-Type Sliding Surface for Uncertain Systems with Mismatched Uncertainties and Disturbance

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Abstract - In this paper, a new robust variable structure controller based on a nonlinear integral type sliding surface is presented for the control of uncertain systems with mismatched uncertainties and disturbance. A nonlinear integral type sliding surface is suggested for removing the reaching phase. After its ideal sliding dynamics is obtained, the two design methods are presented. A corresponding control input is proposed to satisfy the closed loop stability in the sense of Lyapunov and the existence condition of the sliding mode on the nonlinear integral type sliding surface, which will be investigated in Theorem 1. Through a design example and simulation study, the usefulness of the proposed controller is verified.

Key Words : Variable structure system, Sliding mode control, Nonlinear integral type sliding surface, Mismatched uncertainties

1. Introduction

The sliding mode control(SMC) can provide the effective means to the problem of controlling uncertain dynamical systems under parameter variations and external disturbances[1][2][3]. 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, $s=0$[4]. The proper design of the sliding surface can determine the almost output dynamics and its performances[5]. Many design algorithms including the linear(optimal control[5][6][10][12], geometric approach[8], pole assignment[9], eigenstructure assignment[10], differential geometric approach[11], Lyapunov approach [14][15], integral augmentation[5][12][16][17][22][24][25], Ackermann's formula[20], dynamic sliding surface[23]), and nonlinear[13][19] techniques are reported.

In general, the sliding surface is the linear combination of the full state and fixed in state space being independent of a given initial condition[5]. Hence the reaching phase naturally exists for the initial condition far from the sliding surface. During this phase, the sliding mode does not occur, so the controlled system may be sensitive to the parameter variations and external disturbances. Furthermore, it is difficult to find the designed performance of the sliding surface in the output[5]. In 1992[12], specially, an integral action was augmented to improve the steady state performance against the external disturbances without removing the reaching phase problems. Moreover, introducing the integrator without removing the reaching phase can inevitably result in the overshoot problems because the integral state should be re-regulated to zero in steady state[5]. In 1994, the integral state with special initial condition is augmented to the linear sliding surface for completely removing the reaching phase for the first time[5] and it is designed by the advanced optimal control. In [13], in order to realize the linear controller by the sliding mode, the continuous scalar sliding surface is chosen as a linear time invariant SISO plant, which is input dependent. The linear and nonlinear sliding surfaces having the reaching phase are proposed by Su et al in [15] and designed by the Lyapunov approach. The integral sliding surface is selected as the overall transfer function without removing the reaching phase[16]. Utkin suggested the integral sliding surface with the special initial condition for removing the reaching phase[17]. Chung proposed the general class sliding surface relative degree more than one[19]. Using Ackermann's formula, the integral sliding surface is designed with removing the

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reaching phase[20]. For mismatched uncertainties, the sliding mode control with linear sliding surface is designed in [21]. Park proposed the sliding surface augmented by a virtual state with removing the reaching phase, which is a function of the nominal control and needs more mathematical accuracy[22]. In [23], Acarman designed the dynamic sliding surface and high order sliding mode controller. For unmatched uncertain system, Cao proposed a nonlinear integral-type sliding surface without reaching phase. It is pointed out that the ideal sliding mode dynamics is sensitive to the unmatched uncertainties. In [25], the integral sliding surface is augmented by the linear sliding surface itself and designed based on the LMI for mismatched uncertain systems.

Until now, for uncertain system with the mismatched uncertain and mismatched disturbance, an integral variable structure system is not reported.

In this paper, a new integral variable structure controller(IVSC) with a nonlinear integral type sliding surface is suggested for the control of uncertain general linear systems with mismatched uncertainties and mismatched disturbance which is totally stabilizable. The reaching phase is completely removed by introducing an nonlinear integral-type sliding surface with special non-zero initial value. The two design methods are presented after obtaining the ideal sliding dynamics of the nonlinear integral-type sliding surface. A corresponding control is selected to guarantee the sliding mode on every point of the sliding surface for completely guaranteeing the designed output in the sliding surface from any initial condition to the origin for all the matched parameter variations and matched disturbances. For mismatched uncertainties and disturbance, the controlled system is sensitive however satisfies the closed loop stability in the sense of Lyapunov. Finally, an example is presented to show the effectiveness of the algorithm.

2. An Integral Variable Structure Systems

2.1 Descriptions of Plant

Consider a mismatched uncertain linear system

$$\begin{aligned}\dot{x} &= Ax+Bu+d'(x,t), \qquad x(0) \\ &= (A_0+\triangle A)x+(B_0-\triangle B)u+d'(x,t) \\ &= A_o x+B_o u+d(x,t)\end{aligned} \tag{1}$$

$$d(x,t)=\triangle Ax-\triangle Bu+d'(x,t) \tag{2}$$

where $x\in R^n$ is the state, $x(0)$ is its initial state, $u\in R^1$ 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 mismatched and bounded, and $d'(x,t)$ is mismatched bounded external disturbance, respectively.

Assumption

A1: The pair (A_0,B_0) is stabilizable

A2: The lumped uncertainties $d(x,t)$ is bounded and totally stabilizable

The useful definition is introduced which will be used later in the design of the integral sliding surface

Definition:

It is defined that $R_{B_0N}(\cdot)$ and $R_{B_0}(\cdot)$ are as follows:

$$R_{B_0N}(B_0)\equiv row\ vector\ of\ null\, space\ of\ B_0 \tag{3}$$

$$R_{B_0}(B_0)\equiv row\ vector\ of\, non\, null\, space\, of\, B_0=B_0\ominus R_{B_0N}(B_0) \tag{4}$$

which will be used in this controller design. Hence

$$B_0=R_{B_0}(B_0)\oplus R_{B_0N}(B_0) \tag{5}$$

2.2 Integral Sliding Surface

To control a mismatched uncertain system (1) or (2) with a linear closed loop dynamics, the nonlinear integral-type sliding surface used in this design is proposed as follows:

$$s=C^T\left[x-\int_{-\infty}^{t}A_c x dt\right](=0) \tag{6}$$

where A_c is the closed loop system matrix having a desired performance

$$A_c=A_o-B_oK \tag{7}$$

where K is the state feedback gain, and the initial condition of the integral in the sliding surface is as follows[5][16][17]:

$$\int_{-\infty}^{0}A_c x dt=x(0) \tag{8}$$

Therefore, at $t=0$, this sliding surface is zero so that there is no reaching phase[5]. To design a gain K with the suggested technique, first one designs the stable A_c having a desired performance, then

$$A_c=R_{B_0}(A_c)\oplus R_{B_0N}(A_c) \tag{9}$$

$$A_c=R_{B_0N}(A)\oplus R_{B_0}(A-BK) \tag{10}$$

$$R_{B_0N}(A_c)=R_{B_0N}(A) \tag{11}$$

$$R_{B_0}(A_c)=R_{B_0}(A-BK)=R_{B_0}(A)-R_{B_0}(B)K\ . \tag{12}$$

Finally the stable gain is deigned as

$$\therefore\ K=R_{B_0}^{-}(B)[R_{B_0}(A)-R_{B_0}(A_c)] \tag{13}$$

where $R_{B_0}^{-}(B)=\left[R_{B_0}^T(B)XR_{B_0}(B)\right]^{-1}R_{B_0}^T(B)X$[21]. In (6), C is a non zero element as the design parameter such that the following assumption is satisfied.

Assumption

A3: C^TB and C^TB_0 have the full rank, i.e. are invertible

A4: $C^T\triangle B\left[C^TB_0\right]^{-1}=\triangle I$ diagonal and $|\triangle I|<\delta\leq 1,\ 0<\delta<1.$

The equivalent control input is obtained using $\dot{s}=0$[2] as

$$u_{eq}=-\left[C^TB\right]^{-1}C^T(A-A_c)x-\left[C^TB\right]^{-1}C^Td'(x,t) \tag{14}$$

This control input can not be implemented because of the uncertainties, but used to obtaining the ideal sliding dynamics. The ideal sliding mode dynamics of the sliding surface (4) can be derived by the equivalent control approach[20] as

$$\dot{x}_s = \left[A_0 - B_0(C^T B_0)^{-1} C^T (A - A_c)\right] x_s, \quad x_s(0) = x(0) \tag{15}$$

$$\dot{x}_s = A_c x_s, \qquad x_s(0) = x(0) \tag{16}$$

The solution of (15) or (16) identically defines the sliding surface (6) $s=0$. Hence to design the sliding surface as stable, this ideal sliding dynamics (16) is designed to be stable[5]. To choose the stable gain based on the Lyapunov stability theory, the ideal sliding dynamics of (6) is represented by the nominal plant of (2) as

$$\begin{aligned} \dot{x}_s &= A_0 x_s + B_0 u, \qquad u = -K x_s \\ &= A_c x_s, \qquad A_c = A_0 - B_0 K \end{aligned} \tag{17}$$

To select the stable gain based on the Lyapunov second method, take a Lyapunov function candidate as[15]

$$V(x) = \frac{1}{2} x^T P x, \qquad P > 0 \tag{18}$$

The derivative of (10) becomes

$$\dot{V}(x) = x^T \left[A_0^T P + P A_0\right] x + u^T B_0^T P x + x^T P B_0 u \tag{19}$$

If one take the control input as[15]

$$u = -B_0^T P x \tag{20}$$

and $Q>0$ is

$$A_0^T P + P A_0 = -Q \tag{21}$$

then

$$\begin{aligned} \dot{V}(x) &= -x^T Q x - 2x^T P B_0 B_0^T P x \\ &= -x^T \left[Q + 2PB_0 B_0^T P\right] x \\ &= -x^T \left[A_c^T P + P A_c\right] x \\ &= -x^T Q_c x, \qquad Q_c = A_c^T P + P A_c > 0 \\ &\le -\lambda_{\min}\{Q_c\} x^2 \\ &\le 0 \end{aligned} \tag{23}$$

Therefore the stable gain is chosen as

$$K = B_0^T P \tag{24}$$

2.3 Control Input

The corresponding control input is proposed as follows:

$$u = -Kx - \triangle K x - K_1 s - K_2 sign(s) \tag{25}$$

where K is a feedback gain equal to (13) or (24), $\triangle K$ is a state dependent switching gain, K_1 is a feedback gain of the sliding surface, and K_2 is a switching gain, respectively as

$$\therefore\ K = R_{B_0}^{-1}(B)[R_{B_0}(A) - R_{B_0}(A_c)] \ \text{ or } \ K = B_0^T P \tag{26}$$

$$\triangle K = \left[C^T B_0\right]^{-1} \triangle K' \tag{27}$$

$$\triangle k'_j = \begin{cases} \ge \dfrac{\max\{C^T \triangle A - C^T \triangle BK\}_j}{\min\{I - \triangle I\}} & sign(s x_j) > 0 \\ \le \dfrac{\min\{C^T \triangle A - C^T \triangle BK\}_j}{\min\{I - \triangle I\}} & sign(s x_j) < 0 \end{cases} \quad j = 1, \ldots, n \tag{28}$$

$$K_1 = \left[C^T B_0\right]^{-1} K_1', \qquad K_1' > 0 \tag{29}$$

$$K_2 = \left[C^T B_0\right]^{-1} K_2' \tag{30}$$

$$K'_2 = \frac{\max\{C^T d'(x,t)\}}{\min\{I - \triangle I\}} \tag{31}$$

The real sliding dynamics by the proposed control (25) with the nonlinear integral-type integral sliding surface (6) is obtained as follows:

$$\begin{aligned} \dot{s} &= C^T \dot{x} - C^T A_c x \\ &= C^T A_0 x - C^T \triangle A x + C^T (B_0 - \triangle B) u \\ &\quad + C^T d'(x,t) - C^T A_c x \\ &= C^T A_0 x - C^T \triangle A x - C^T B_0 K x - C^T \triangle B K x \\ &\quad - C^T (B_0 - \triangle B) \triangle K x - C^T (B_0 - \triangle B) K_1 s \\ &\quad - C^T (B_0 - \triangle B) K_2 sign(s) + C^T d'(x,t) - C^T A_c x \\ &= - C^T \triangle A x - C^T \triangle B K x - C^T (B_0 - \triangle B) \triangle K x \\ &\quad - C^T (B_0 - \triangle B) K_1 s - C^T (B_0 - \triangle B) K_2 sign(s) \\ &\quad + C^T d'(x,t) \end{aligned} \tag{32}$$

The closed loop stability by the proposed control input with sliding surface together with the existence condition of the sliding mode will be investigated in next Theorem 1.

Theorem 1: *If the sliding surface is designed in the stable, i.e. stable design of K, the proposed input with Assumption A1-A4 satisfies the existence condition of the sliding mode on the nonlinear integral-type sliding surface and the stability in the sense of Lyapunov for all mismatched uncertainties and mismatched disturbance.*

Proof; Take a Lyapunov function candidate as

$$V(x) = \frac{1}{2} s^T s \tag{33}$$

Differentiating (33) with respect to time leads to and substituting (32) into (34)

$$\begin{aligned} \dot{V}(x) &= s^T \dot{s} \\ &= s^T C^T \triangle A x - s^T C^T \triangle B K x - s^T [I - \triangle I] C^T B_0 \triangle K x \\ &\quad - s^T [I - \triangle I] C^T B_0 K_1 s + s^T C^T d'(x,t) \\ &\quad - s^T [I - \triangle I] C^T B_0 K_2 sign(s) \\ &\le -\epsilon K_1' \|s\|^2, \qquad \epsilon = \|(I - \triangle I)\| \end{aligned} \tag{34}$$

which completes the proof of Theorem 1.

3. Design Example and Simulation Studies

Consider a second order uncertain system with mismatched uncertainties and disturbance

$$\begin{aligned} \dot{x}_1 &= -x_1 + x_1 \sin^2(x_1) + x_2 + 0.02\sin(x_1) u - d_1'(x,t) \\ \dot{x}_2 &= x_2 + x_2 \sin^2(x_2) + (2 + 0.5\sin(2t)) u - d_2'(x,t) \end{aligned} \tag{35}$$

$$d_1'(x,t) = 0.5\sin(x_1) + 0.9\sin(x_2) + 0.02(x_1^3 + x_2^2) + 1.5\sin(3t) \tag{36}$$

$$d_2'(x,t) = 0.7\sin(x_1) - 0.8\sin(x_2) + 0.2(x_1^2 + x_2^2) + 2\sin(2t) + 3.0$$

where the nominal parameter A_0 and B_0 and matched uncertainties $\triangle A$ and $\triangle B$ are

$$A_0 = \begin{bmatrix} -1 & 1 \\ 0 & 1 \end{bmatrix}, B_0 = \begin{bmatrix} 0 \\ 2 \end{bmatrix}, \triangle A = \begin{bmatrix} 0 & 0 \\ 0 & x_2 \sin^2(x_2) \end{bmatrix}$$

$$\triangle B = \begin{bmatrix} 0 \\ 0.5\sin(2t) \end{bmatrix} \tag{37}$$

and

$R_{B_0}(B_0) = 2,\ R_{B_0N}(B_0) = 0,\ R_{B_0}(A) = [0\ \ -1]$, and

$$R_{B_0N}(A) = [-1\ \ 1]. \tag{38}$$

To compare matched uncertainties, the mismatched uncertainties and disturbance are as follows:

$$\triangle A = \begin{bmatrix} x_1\sin^2(x_1) & 0 \\ 0 & x_2\sin^2(x_2) \end{bmatrix},\ \triangle B = \begin{bmatrix} 0.02\sin(x_1) \\ 0.5\sin(2t) \end{bmatrix}, \text{ and } \begin{bmatrix} d_1'(x,t) \\ 0 \end{bmatrix} \tag{39}$$

which satisfies Assumption A2. To design the nonlinear integral type sliding surface, A_c is selected as

$$A_c = A_0 - B_0K = R_{B_0N}(A) \oplus R_{B_0}(A - BK) = \begin{bmatrix} -1 & 1 \\ -100 & -21 \end{bmatrix} \tag{40}$$

in order to have the double poles at -11. The coefficient of the nonlinear integral type sliding surface is determined as

$$C = [1\ \ 1]^T \tag{41}$$

which satisfy the Assumption A3-A4. The designed nonlinear integral type sliding surface becomes

$$s = \begin{bmatrix} 1 \\ 1 \end{bmatrix}^T \left\{ x - \int_0^t \begin{bmatrix} -1 & 1 \\ -100 & -21 \end{bmatrix} x dt \right\} = 0 \tag{42}$$

The feedback gain is

$$\begin{aligned} \therefore\ K &= R_{B_0}^{-1}(B)[R_{B_0}(A) - R_{B_0}(A_c)] \\ &= 2^{-1}\{[0\ \ 1] - [-100\ \ -21]\} \\ &= 2^{-1}[100\ \ 22] \\ &= [50\ \ 11] \end{aligned} \tag{43}$$

Another Lyapunov design method is as follows. The P in (18) is chosen as

$$P = \begin{bmatrix} 150 & 25 \\ 25 & 5.5 \end{bmatrix} > 0 \tag{44}$$

so as that

$$A_c^T P + PA_c = \begin{bmatrix} -5300 & -950 \\ -950 & -181 \end{bmatrix} < 0 \tag{45}$$

Hence, the continuous feedback gain is chosen as

$$K = B_0^T P = [50\ \ 11] \tag{46}$$

which is identical to (43). The selected gains in the control input are as follows:

$$\triangle k_1 = \begin{cases} 26.5 & \text{if } sx_1 > 0 \\ -26.5 & \text{if } sx_1 < 0 \end{cases},\ \triangle k_2 = \begin{cases} 10 & \text{if } sx_2 > 0 \\ -10 & \text{if } sx_2 < 0 \end{cases} \tag{48}$$

$$K_1 = 5 \tag{49}$$

$$K_2 = 16.5 + 0.5(x_1^2 + x_2^2) \tag{50}$$

The simulation is carried out under 1[msec] sampling time and with $x(0) = [10\ \ 5]^T$ initial state. Fig. 1 shows the three case output responses of (i) ideal sliding output, i.e. solution of (16), (ii) output with no uncertainty and no disturbance, and (iii) output with matched uncertainty and matched disturbance. As can be seen, the tree case outputs are identical and insensitive to only matched uncertainty and matched disturbance. In Fig. 2, the phase trajectories of (i) ideal sliding phase trajectory, (ii) phase trajectory with no uncertainty and no disturbance, and (iii) phase trajectory with matched uncertainty and matched disturbance are depicted. There is no reaching phase only the controlled system slides from the initial state. Fig. 3 shows the sliding surfaces with (i) no uncertainty and no disturbance and (ii) matched uncertainty and disturbance. The two case control inputs with (i) no uncertainty and no disturbance and (iii) matched uncertainty and disturbance are depicted in Fig. 4. Fig. 5 shows the four case output responses with (i) ideal sliding output, i.e. solution of (16), (ii) output with no uncertainty and no disturbance, (iii) output with matched uncertainty and matched disturbance, and (iv) mismatched uncertainties and mismatched disturbance. The output with (iv) mismatched uncertainty and mismatched disturbance is different from the other three case outputs. The output with mismatched uncertainties and disturbance satisfies the stability in the sense Lyapunov, however, the output is sensitive to mismatched uncertainties and disturbance, which is pointed out by Cao[24]. Fig. 6 shows the two case phase trajectories (i) mismatched uncertainties and mismatched disturbance and (ii) ideal sliding phase trajectory. The sliding surface and control input with (i) mismatched uncertainties and mismatched disturbance are depicted in Fig. 7 and Fig. 8, respectively. From the simulation studies, the effectiveness of the proposed SMC is proven.

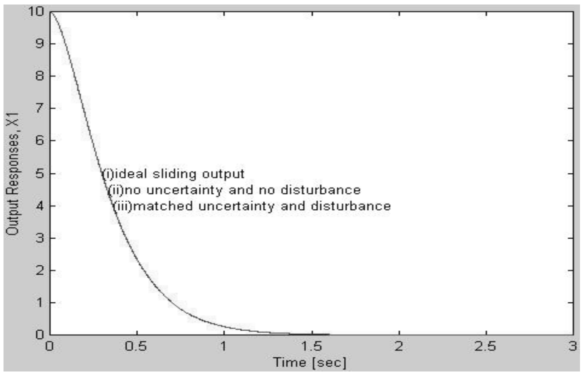

Fig. 1 Three case output responses of (i) ideal sliding output, (ii) output with no uncertainty and no disturbance, and (iii) output with matched uncertainty and matched disturbance.

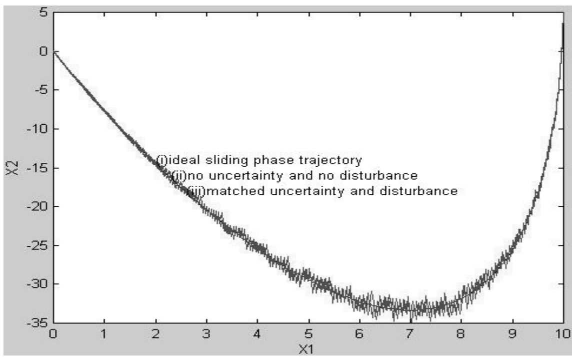

Fig. 2 Three case phase trajectories of (i) ideal sliding trajectory, (ii) trajectory with no uncertainty and no disturbance, and (iii) trajectory with matched uncertainty and matched disturbance.

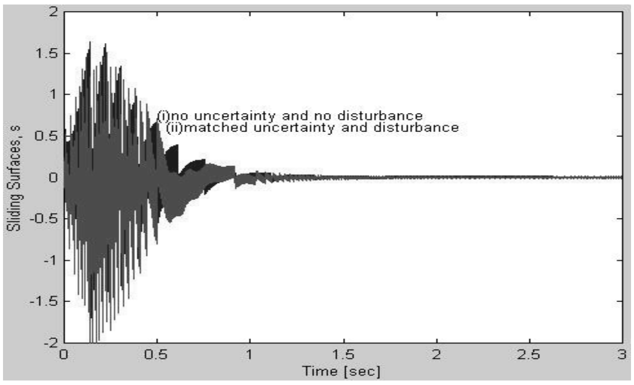

Fig. 3 Two case sliding surfaces of (i) no uncertainty and no disturbance and (ii) matched uncertainties and disturbance

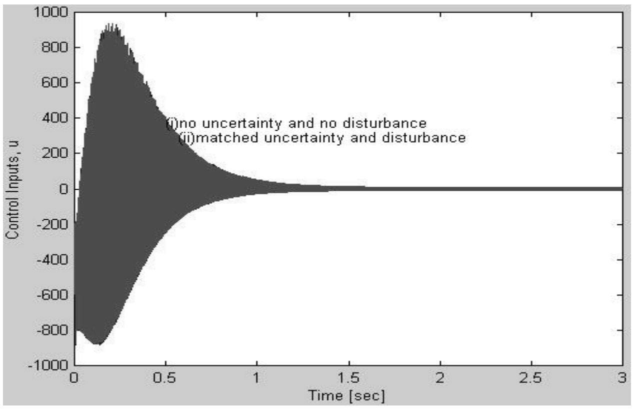

Fig. 4 Two case control inputs of (i) no uncertainty and no disturbance and (ii) matched uncertainties and disturbance

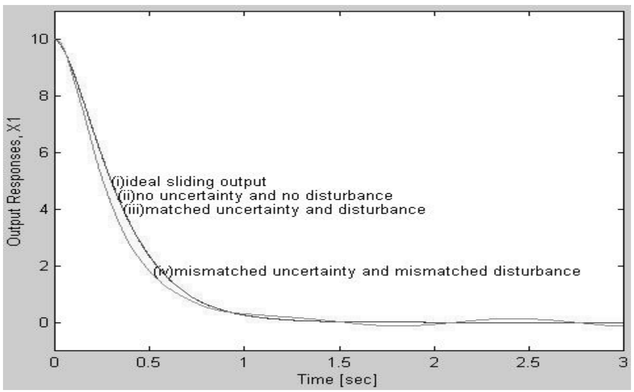

Fig. 5 Four output responses of (i) ideal sliding trajectory, (ii) trajectory with no uncertainty and no disturbance, (iii) trajectory with matched uncertainty and matched disturbance, and (iv) mismatched uncertainty and mismatched disturbance

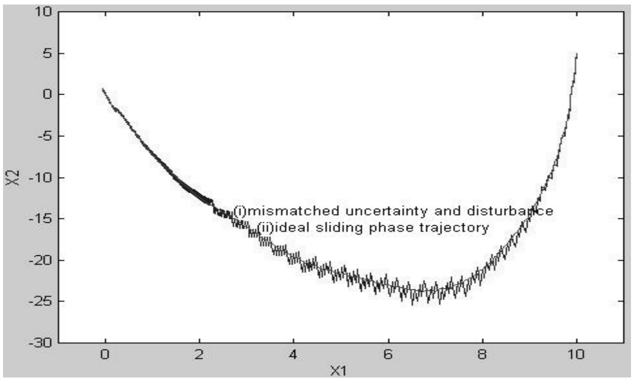

Fig. 6 Two case phase trajectories of (i) mismatched uncertainty and mismatched disturbance and (ii) ideal sliding phase trajectory

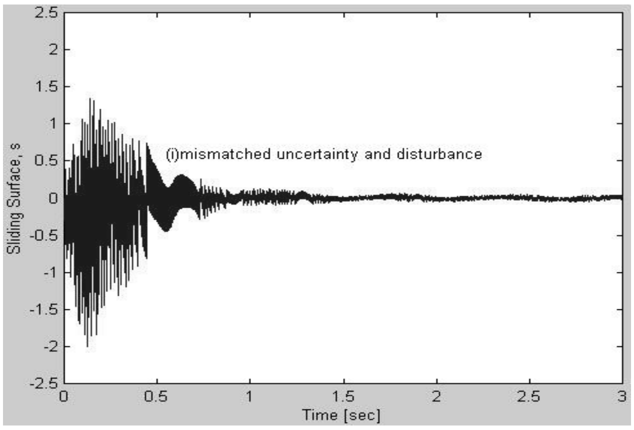

Fig. 7 Sliding surface (i) mismatched uncertainties and mismatched disturbance

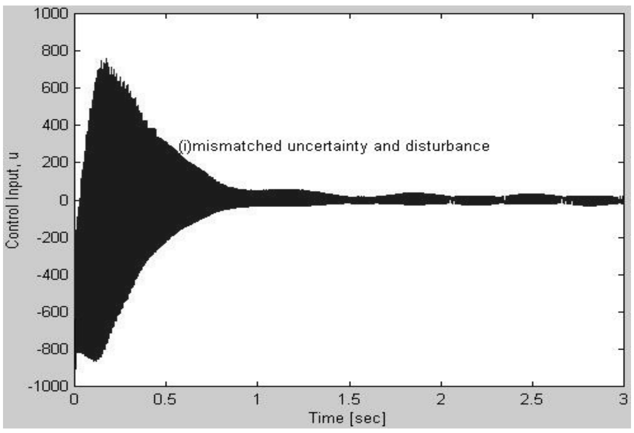

Fig. 8 Control input (i) mismatched uncertainties and mismatched disturbance

4. Conclusions

In this note, a new robust variable structure controller based on nonlinear integral type sliding surface is presented for the control of uncertain systems with mismatched uncertainties and mismatched disturbance which is totally stabilizable. By means of a proposed nonlinear integral-type sliding surface, the reaching phase problems are removed. The useful definition of the two row vectors of the null space and non null space of B is introduced for the design of the constant feedback gain. The two design methods to choose the nonlinear integral-type sliding surface is presented after its ideal sling dynamics is obtained. A corresponding control input is proposed also. The closed loop stability in the sense of Lyapunov by the proposed control input with nonlinear integral-type sliding surface together with the existence condition of the sliding mode on the selected nonlinear integral-type sliding surface will be investigated in Theorem 1 for all mismatched uncertainties and mismatched disturbance. For matched uncertainties and matched disturbances, the output of the controlled system by the proposed algorithm coincides the output of the ideal sliding mode dynamics as designed. For mismatched uncertainties and mismatched disturbances, the controlled system is sensitive to those mismatched uncertainties and mismatched disturbances, but satisfies the closed loop stability in the sense of Lyapunov. Through a design example and simulation studies, the usefulness of the proposed controller is verified.

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