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A Static Output Feedback Integral Variable Structure Controller for Uncertain Systems with Unmatched System Matrix Uncertainty

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Abstract - In this paper, an integral variable structure static output feedback controller with an integral-augmented sliding surface is designed for the improved robust control of a uncertain system under unmatched system uncertainty and matched input matrix uncertainty and disturbance satisfying some conditions. To effectively remove the reaching phase problems, an output dependent integral augmented sliding surface is proposed. Its equivalent control and ideal sliding mode dynamics are obtained. The previous some limitations is overcome in this systematic design. A stabilizing control with the closed loop exponential stability is designed for all unmatched system matrix uncertainties and proved together with the existence condition of the sliding mode on $S=0$. To show the usefulness of the algorithm, a design example and computer simulations are presented.

Key Words : Output feedback, Variable structure system, Sliding mode control, Unmatched uncertainties

1. Introduction

The output feedback problem is one of the most important open questions in control engineering when incomplete state is available[1]. The output feedback control is categorized as three problems, i.e., observer(estimator) based[2][13], dynamic output feedback[1][3][17][20], and static output feedback[4][7]-[16]. The static output feedback is the theme of this paper by using the variable structure system.

Using the variable structure system with sliding mode control, the output feedback controller has been designed recently[2][3][7]-[20]. The variable structure system(VSS) can provide the effective and robust means for controlling an uncertain dynamical system[5]. The most distinct feature of the variable structure system is the presence of the sliding mode on the predetermined sliding surface[6]. In 1985, White first studied the use of output feedback in variable structure system with no uncertainties[7]. Emelyanov et al. suggested observer based variable structure controller for a class of uncertain systems[2]. A generalized output tracking design for affine nonlinear system via variable structure system was proposed by Chen et al. in 1992[8]. The robust output tracking control problem of general nonlinear MIMO system via sliding mode technique was discussed by Elmali and Olgac[9]. Variable structure system approach combined with the geometric approach to synthesis of system was employed in robust output feedback stabilization with local stability based on the eigenvector methods by Zak and Hui in 1993[10]. Edwards and Spurgeon proposed that the procedure for the design of the sliding surface used established output feedback eigenvalue assignment for uncertain systems with minimum phase nominal system and provided necessary and sufficient conditions in terms of the system structure for a stable reduced order motion to exist[11]. In [12], El-Khazali and Decarlo investigated static output feedback variable structure control linear state model from the switching surface design to the actual construction of the variable structure controller. Kwan proposed the modification of Zak and Hui's output sliding mode controller for SISO systems which can eliminate the two limitations of Zak and Hui's (a) system uncertainties must be bounded by the output and (b) a requirement of matrix equality[14]. In [15], however, Hsu and Linzarralde pointed out that there is no degree of freedom for choosing the eigenvalues through the coefficient of the sliding surface of Kwan and redesigned the sliding surface by means of VS-MRAC approach. In [16], Kwan extended his results of [14] to linear MIMO systems with global closed loop stability. It was demonstrated that the numerical methods to design the reaching phase in output feedback sliding mode control are only applicable under

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certain structural conditions in [18]. Choi considered the problems of designing a variable structure output feedback control law for a class of uncertain system with mismatched uncertainty in the state matrix based on the LMI.

Most of the variable structure static output feedback controllers have a linear output dependent sliding surface except [3], which has the reaching phase approaching the sliding surface from a given initial condition. During this phase, the sliding mode does not guaranteed[6][21]. The derivative of the sliding surface is a function of the state not the output[10][14][19][20]. Therefore, it is difficult to prove the closed loop stability.

In this paper, an variable structure static output feedback controller with an output dependent integral-augmented sliding surface for the improved robust control of an uncertain systems with mismatched uncertainty in the state matrix. The reaching phase problems are completely removed by an suggested output dependent integral-augmented sliding surface. The previous some limitations mentioned above on the output feedback variable structure controller is overcome in this systematic design. A stabilizing control is designed to generate the sliding mode on the integral sliding surface $S=0$ and as a results, the closed loop exponential stability is obtained for all unmatched system matrix uncertainties, and straightforwardly proved together with the existence condition of the sliding mode on $S=0$. To show the usefulness of the algorithm, a design example and computer simulations are presented.

2. Static Output Feedback Variable Structure System with an Integral-Augmented Sliding Surface

2.1 System Descriptions and Basic Backgrounds

The problem of the designing the variable structure static output feedback controller with an output dependent integral -augmented sliding surface is considered for an uncertain system:

$$\begin{aligned}\dot{X} &= A(X,t)X + B(X,t)U(t) + d(X,t), \qquad X(0)\\ &= (A+\triangle A)X + (B+\triangle B)U(t) + d(X,t), \quad X(0)\\ Y &= C\cdot X(t) \qquad\qquad Y(0)=CX(0)\end{aligned} \tag{1}$$

where $X \in R^n$ is state variable, $U(t) \in R$ is the control, $Y \in R^q$ is the output, and $A \in R^{n\times n}$, $B \in R^{n\times 1}$, and $C \in R^{q\times n}$ are the nominal system matrix, the nominal input matrix, and output matrix respectively. $X(0)$ and $Y(0)$ are the initial conditions of the state and output. $\triangle A(t)$, $\triangle B(t)$,and $d(X,t)$ are the unmatched system matrix uncertainty, the matched input matrix uncertainty, and matched external disturbance. respectively.

Assumption

A1: The pair (A,B) is stabilizable and the pair (A,C) is observable

A2: $Rank(B)=m=1$ and $Rank(C)=q$, $1=m\le q<n$.

A3:unmatched $\triangle A(t)$, matched $\triangle B(t)$,and matched $d(X,t)$ are unknown and bounded and are satisfied by the following conditions

$$\triangle A(t) = \triangle A'(t)C^T C = \triangle A''(t)C \tag{2a}$$

$$\triangle B(t) = BB^T\triangle B'(t) = B\triangle I, \quad |\triangle I| \le p < 1, \quad 1 > p > 0 \tag{2b}$$

$$d(X,t) = BB^T d'(X,t) = Bd''(X,t) \tag{2c}$$

which means that $\triangle A'(t)$, $\triangle B'(t)$, and $d'(X,t)$ exist such that (2a)-(2c) are satisfied. The relationship of (2a) is less restrictive than [10]. The following definition is introduced

Definition 1:

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

$$R_{BN}(\cdot) \equiv row\ vector\ of\ null\ space\ of\ B \tag{3}$$

$$R_B(B) \equiv row\ vector\ of\ non\ null\ space\ of\ B = B \ominus R_{BN}(B) \tag{4}$$

which will be used later in this design. Hence, the following property is obtained

Property 1:

P1: $A = R_B(A) \oplus R_{BN}(A)$

P2: $R_B(A_1 \pm A_2) = R_B(A_1) \pm R(A_2)$

P3: $R_B(BK) = R_B(B)K$

The design goal in this paper is to control the output of the uncertain system (1) to the integral sliding surface from a given initial condition to zero with the sliding mode from the beginning.

2.2 Integral-Augmented Sliding Surface

Assumption

A4: $(F_1 CB)$ has the inverse for some non zero row vector F_1.

Now, an integral sliding surface is suggested be[3][21][22]

$$S = (F_1 CB)^{-1}(F_1\cdot Y + F_0\cdot Y_0)(=0) \tag{5}$$

$$Y_0 = \int_0^t A_0\cdot Y(\tau)d\tau + Y_0^0, \qquad Y_0^0 = -F_0^- F_1\cdot Y(0) \tag{6}$$

where $F_0^- = (F_0^T W F_0)^{-1}F_0^T W$ and A_0 is appropriately dimensioned without loss of generality, $A_0 = I$. In (5), non zero row vector F_1 and F_0 are the design parameters satisfying the following relationship

$$F_1 C(A - BKC) + F_0 C = F_1 C A_C + F_0 C = 0 \tag{7}$$

where closed loop system matrix $A_C = A - BKC$ and K is a linear constant output feedback gain and designed following manner when A_C is selected in advance.

$$A_c = R_B(A_c) \oplus R_{BN}(A_c) \tag{8}$$

$$A_c = R_{BN}(A) \oplus R_B(A_C) = R_{BN}(A) \oplus R_B(A - BKC) \tag{9}$$

$$R_{BN}(A_c) = R_{BN}(A) \tag{10}$$

$$R_B(A_c) = R_B(A - BKC) = R_B(A) - R_B(B)KC. \tag{11}$$

Finally the stable output gain is satisfied as

$$\therefore KC = R_B^-(B)[R_B(A) - R_B(A_c)] \tag{12}$$

where $R_B^-(B) = \left[R_B^T(B)WR_B(B)\right]^{-1}R_B^T(B)W$

Because the integral sliding surface (5) is zero at $t=0$, there is no reaching phase and the controlled system slides from the beginning. From $\dot{S}=0$, the real sliding dynamics is as follows[5]:

$$\begin{aligned}\dot{S}&=(F_1CB)^{-1}\cdot[F_1C\cdot\dot{X}+F_0\cdot Y] \\ &=(F_1CB)^{-1}\cdot[F_1C\cdot A(X,t)X+F_1C\cdot B(X,t)U(t) \\ &\qquad +F_1C\cdot d(X,t)+F_0\cdot Y]\end{aligned} \tag{13}$$

From (13), the equivalent control is obtained as

$$\begin{aligned}U_{eq}=&-\left[(F_1CB)^{-1}FCB(X,t)\right]^{-1}[(F_1CB)^{-1}F_1CA(X,t)X \\ &+(F_1CB)^{-1}F_0Y+(F_1CB)^{-1}F_1Cd(X,t)]\end{aligned} \tag{14}$$

which can not be implemented because of feedback of the state, the uncertainties, and disturbance. The theoretical ideal sliding dynamics is derived as follows[6][24]:

$$\begin{aligned}\dot{X}_s&=\left[A-B(F_1CB)^{-1}F_1CA-B(F_1CB)^{-1}F_0C\right]X_s \\ &=A_cX_s, \quad X_s(0)=X(0)\end{aligned} \tag{15a}$$

$$Y_s=C\cdot X_s \tag{15b}$$

which solution of (15a) is equivalent to the surface that the output dependent integral sliding surface defines $S=0$ from a given initial condition to origin.

2.3 Stabilizing Control

As the second phase, the corresponding control input to generate the sliding mode on the pre-selected integral sliding surface will be designed. To generate the sliding mode on $S=0$, the following class of output feedback control is employed as

$$U(t)=-K\cdot Y-K_1\cdot S-\triangle K\cdot Y-K_2sign(S) \tag{16}$$

where K is the linear constant output feedback gain identical to that in (7) and (12), K_1 is the linear constant feedback gain of the sliding surface, $\triangle K$ and K_2 are switching gains, those are as follows:

$$KC=(F_1CB)^{-1}(F_1CA+F_0C) \tag{17a}$$
$$\text{or } F_1C(A-BKC)+F_0C=F_1CA_C+F_0C=0$$

$$K_1>0 \tag{17b}$$

$$\triangle K_i=\begin{cases} > \dfrac{\max\{(F_1CB)^{-1}F_1C\triangle A''-\triangle IK\}_i}{\min\{I-\triangle I\}_i} & \text{for } (S\cdot Y_i)>0 \\ <-\dfrac{\min\{(F_1CB)^{-1}F_1C\triangle A''-\triangle IK\}_i}{\min\{I-\triangle I\}_i} & \text{for } (S\cdot Y_i)<0\end{cases}, \quad i=1,2,\ldots,q \tag{17c}$$

$$K_2>\frac{\max\{d''(X,t)\}}{\min\{I-\triangle I\}} \tag{17d}$$

If only $U(t)=-KY$ is applied to the nominal system of (1) without uncertainties and disturbance, the closed loop system equals to the theoretical ideal sliding dynamics (15). By this control input, the existence of the sliding mode on every point of $S=0$ and closed loop stability will be investigated in next Theorem.

Theorem 1: The closed loop system, (1) with (5) and (16) is globally exponentially stable with respect to $S=0$, eventually to the origin of q-th order output space provided that $S=0$ is asymptotically stable.

Proof: Take Lyapunov candidate function as

$$V=1/2S\cdot S \tag{18}$$

From (13) and (16)-(17), the derivative of S becomes

$$\begin{aligned}\dot{S}=&(F_1CB)^{-1}\cdot[F_1C\cdot(A+\triangle A)X+F_1C\cdot(B+\triangle B)U(t) \\ &+F_1C\cdot d(X,t)+F_0\cdot Y] \\ =&(F_1CB)^{-1}\cdot[F_1C(A-BKC)+F_0C]X \\ &+(F_1CB)^{-1}\cdot F_1C\triangle A''(t)Y \\ &-\triangle I\cdot KY-(I-\triangle I)\triangle KY-(I-\triangle I)K_1S \\ &+d''(X,t)-(I-\triangle I)K_2sign(S)\end{aligned} \tag{19}$$

Rearranging (19), it follows

$$\begin{aligned}\dot{S}=&[(F_1CB)^{-1}\cdot F_1C\triangle A''(t)-\triangle I\cdot K]Y \\ &-(I-\triangle I)\triangle KY-(I-\triangle I)K_1S \\ &+d''(X,t)-(I-\triangle I)K_2sign(S)\end{aligned} \tag{20}$$

In (20), the derivative of S is not a function of the state but a function of the output because of the relationship of (7) or (17a) and Assumption A3. In the previous works[10][14][19][20], it is difficult to prove the closed loop stability because the derivative of S is a function of the state in output feedback control. The derivative of (18) with respect to time leads to and substituting (20) into (21)

$$\begin{aligned}\dot{V}=&S\cdot\dot{S} \\ =&S[(F_1CB)^{-1}\cdot F_1C\triangle A''(t)-\triangle I\cdot K]Y \\ &-S(I-\triangle I)\triangle KY-SI-\triangle I)K_1S \\ &+Sd''(X,t)-S(I-\triangle I)K_2sign(S) \\ \le&-\epsilon K_1S^2 \qquad \epsilon=\|(I-\triangle I)\| \\ =&-2\epsilon K_1V\end{aligned} \tag{21}$$

From (21), the following equation is obtained as

$$\dot{V}+2\epsilon K_1V\le 0 \tag{22}$$

$$V(t)\le V(0)e^{-2\epsilon K_1t} \tag{23}$$

which completes the proof of Theorem 1.

The results of Theorem 1 implies that the proposed algorithm can guarantee the sliding mode at the every point on the integral sliding surface $S=0$. Therefore, the motion equations in the sliding mode on the proposed sliding surface is invariant from a given initial condition to the origin without reaching phase and the controlled system is exponentially stable to $S=0$ naturally including the origin. The performance designed in the integral sliding surface is guaranteed for all uncertainties and disturbance satisfying A3, and the reachability of the controlled system does not need to be considered. The zero dynamics of $S=0$ is automatically stable if the ideal sliding dynamics (15a) is stable, in other words, K in (7) is stable for appropriate F_1 and F_0 satisfying (7).

To show the effectiveness of the algorithm, an example will be presented.

3. Illustrative Example

Consider a third order uncertain linear system with unmatched system matrix uncertainties and matched input matrix uncetainties and disturbance, which is modified from that of [19]

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}=\begin{bmatrix}-3-3\sin^2 x_1 & 1 & 0\\ 0 & -2 & 1\\ 1+.5\sin^2 x_2 & 0 & 2+0.4\sin^2 x_3\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 2+0.3\sin(2t)\end{bmatrix}u+\begin{bmatrix}0\\ 0\\ d_1(X,t)\end{bmatrix} \tag{24a}$$

$$Y=\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x_1 & x_2 & x_3\end{bmatrix}^T \tag{24b}$$

$$d_1(X,t)=0.7\sin(x_1)-0.8\sin(x_2) +0.2(x_1^2+x_3^2)+1.5\sin(2t)+1.5 \tag{25}$$

where the nominal matrices A, B and C, the unmatched system matrix uncertainties and matched imput matrix uncertainties and matched disturbance are

$$A=\begin{bmatrix}-3 & 1 & 0\\ 0 & -2 & 1\\ 1 & 0 & 2\end{bmatrix},\ B=\begin{bmatrix}0\\ 0\\ 2\end{bmatrix},\quad C=\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 1\end{bmatrix}$$

$$\triangle A=\begin{bmatrix}-3\sin^2 x_1 & 0 & 0\\ 0 & 0 & 0\\ 0.5\sin^2 x_2 & 0 & 0.4\sin^2 x_3\end{bmatrix},\ \triangle B=\begin{bmatrix}0\\ 0\\ 0.3\sin(2t)\end{bmatrix} \tag{26}$$

$$d(X,t)=\begin{bmatrix}0\\ 0\\ d_1(X,t)\end{bmatrix}$$

The eigenvalues of open loop system matrix A are -2.6920, -2.3569, and 2.0489, hence A is unstable. The unmatched system matrix uncertainties and matched input matrix uncertainties and matched disturbance satisfy the assumption A3 as

$$\triangle A''=\begin{bmatrix}-3\sin^2 x_1 & 0\\ 0 & 0\\ 0.5\sin^2 x_2 & 0.4\sin^2 x_3\end{bmatrix} \text{ and } d''(X,t)=1/2d_1(X,t) \tag{27}$$

$$\triangle I=0.15\sin(2t)\le 0.15<1$$

To design the integral sliding surface, A_c is designed as

$$A_c=A-BKC=R_{BN}(A)\oplus R_B(A-BKC)=\begin{bmatrix}-3 & 1 & 0\\ 0 & -2 & 1\\ -199 & 0 & -200\end{bmatrix}$$

in order to assign the three stable pole to A_c at -200.0051 and $-24974\pm i0.8704$. The constant feedback gain is designed as

$$\begin{aligned}KC&=R_B^-(B)[R_B(A)-R_B(A_c)]\\ &=2^{-1}\{[1\quad 0\quad 2]-[-199\quad 0\quad -200]\}\\ &=[100\quad 0\quad 101]\end{aligned} \tag{28}$$

$$\therefore K=[100\quad 101] \tag{29}$$

Then, one find $F_1=[f_{11}\quad f_{12}]$ and $F_0=[f_{01}\quad f_{02}]$ which satisfy the relationship (7) as

$$\therefore f_{11}=0,\quad f_{01}=199f_{12},\quad f_{02}=200f_{12} \tag{30}$$

One select $f_{12}=10$ and $f_{01}=1990$ and $f_{02}=2000$. Hence $F_1CB=2f_{12}=20$ is a non zero satisfying A4. The resultant integral sliding surface becomes

$$S=\frac{1}{20}\left\{[0\quad 10]\begin{bmatrix}y_1\\ y_2\end{bmatrix}+[1990\quad 2000]\begin{bmatrix}y_{01}\\ y_{02}\end{bmatrix}\right\}(=0) \tag{31}$$

where

$$y_{01}=\int_0^t y_1(\tau)d\tau \tag{32}$$

$$y_{02}=\int_0^t y_2(\tau)d\tau+1/200 \tag{33}$$

The control gains in (16), (17b)-(17d) are selected as folows:

$$K_1=5.0 \tag{34a}$$

$$\triangle k_1=\begin{cases}1.4 & \text{if } Sy_1>0\\ -1.4 & \text{if } Sy_1<0\end{cases} \tag{34b}$$

$$\triangle k_2=\begin{cases}1.5 & \text{if } Sy_2>0\\ -1.5 & \text{if } Sy_2<0\end{cases} \tag{34c}$$

$$K_2=2.7+0.12(y_1^2+y_2^2) \tag{34d}$$

The simulation is carried out under 1[msec] sampling time and with $X(0)=[1\ -2\ \ 1]^T$ initial state. Fig. 1 shows the two case output responses of y_1 and y_2 (i) ideal sliding output, i.e. solution of closed loop nominal system with only $U(t)=-KY$ and (ii) output by (16) with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance. As can be seen, the two case outputs are identical and insensitive to unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance. The output can be predicted by means of (i) ideal sliding output in advance. Fig. 2 shows the sliding surface time trajectory of (5) or (31) with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance. The chattering of sliding surface takes place from $t=0$. There is no reaching phase. The control input time trajectory of (16) with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance is depicted in Fig. 3. The control input chatters from the beginning without reaching phase. The control input chattering may be harmful to the dynamic plant. Hence using the saturation function, one make the input be continuous for practical application as

$$U(t)=-K\cdot Y-K_1\cdot S -(\triangle K\cdot Y+K_2 sign(S))\frac{S}{|S|+\delta} \tag{35}$$

For $\delta=0.5$, the output by (35) with the same gains above and almost continuous control input of (35) are depicted in Fig. 4 and Fig. 5, respectively. The outputs of y_1 and y_2 are almost the same of those of Fig. 1 without the performance loss. As can be seen in Fig. 5, the discontinuity of control input of Fig. 3 is dramatically improved without output performance deterioration.

From the above simulation studies, the proposed algorithm has superior performance over the previous methods in view of the no reaching phase, predetermined output dynamics, robustness, and feasibility of the output prediction.

4. Conclusions

In this paper, a straightforward systematic design of

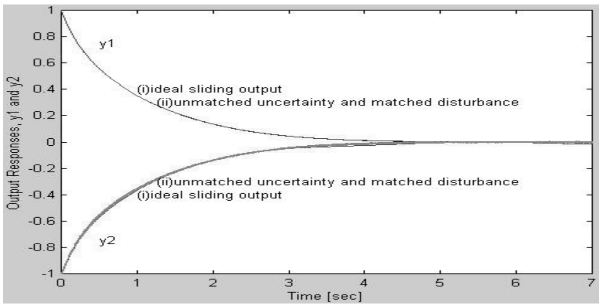

Fig. 1 Two case output responses of y_1 and y_2 (i) ideal sliding output and (ii) output with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance.

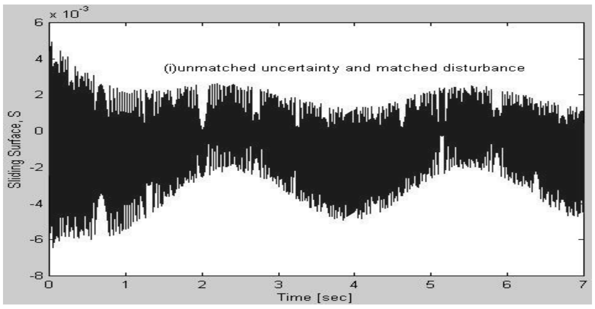

Fig. 2 Sliding surface time trajectory with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance.

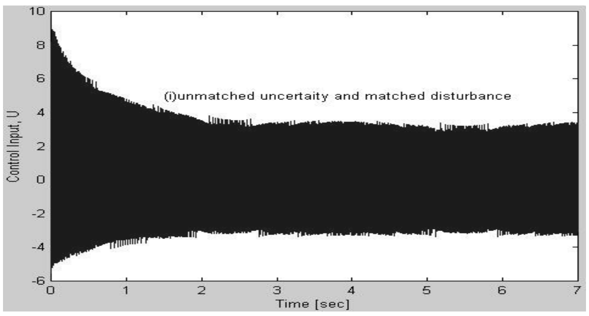

Fig. 3 Corresponding control input time trajectory

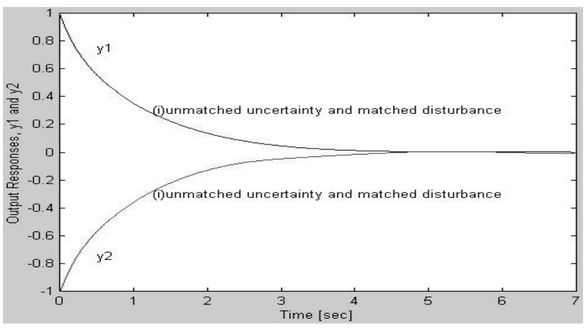

Fig. 4 Output responses of y_1 and y_2 by continuous control input (36) with (i) unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance.

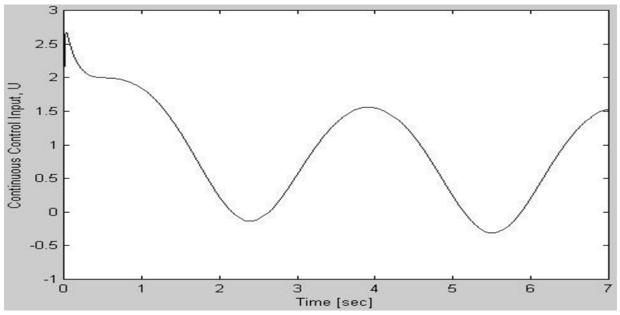

Fig. 5 Almost continuous control input time trajectory by (36) with (i) unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance for $\delta = 0.5$.

variable structure static output feedback controller with an output dependent integral-augmented sliding surface is presented for the improved robust control of an uncertain systems with mismatched uncertainty in the state matrix satisfying Assumption A3, which is first included to this design. The definition of the two row vector of the null space and non null space of B is introduced for the design of the constant output feedback gain. An output dependent integral-augmented sliding surface is proposed in order to remove the reaching phase, and its equivalent control and ideal sliding dynamics from a given initial condition to origin are derived. A simple design procedure of the continuous constant output feedback gain is presented. The previous limits on the output feedback variable structure controller is improved in this systematic design. A corresponding stabilizing control input is designed to exhibit the sliding mode on the integral sliding surface $S=0$ and hence the closed loop exponential stability is proved for all unmatched system matrix uncertainties, and proved together with the existence condition of the sliding mode on $S=0$ first. The performance designed in the output feedback integral sliding surface is exponentially stably guaranteed for all uncertainties and disturbance satisfying A3. Through a given systematic design example and computer simulations, the usefulness of the algorithm is demonstrated in view of the no reaching phase, predetermined output dynamics, robustness, and feasibility of the output prediction.

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