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논 문

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

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Abstract - In this paper, a variable structure dynamic output feedback controller with a transformed sliding surface is designed for the improved robust control of a uncertain system under unmatched system uncertainty, matched input matrix uncertainty, and disturbance satisfying some conditions. This paper is extended from the results of the static output feedback VSS in [9]. To effectively remove the reaching phase problems, an initial condition of the dynamic output is determined. The previous some limitations on the dynamic output feedback variable structure controller is overcome in this systematic design. A stabilizing control is designed to generate the sliding mode on the predetermined sliding surface $S=0$ and as a results the closed loop exponential stability is obtained and proved together with the existence condition of the sliding mode on $S=0$ for all unmatched system matrix uncertainties. To show the usefulness of the algorithm, a design example and computer simulations are presented.

Key Words : Dynamic 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][3], static output feedback(SOF)[4]–[9], and dynamic output feedback(DOF)[12]–[20]. The dynamic output feedback is the theme of this paper by means of the variable structure system or sliding mode control.

Using the variable structure system with sliding mode control, the dynamic output feedback controller has been designed recently[14]–[20]. The variable structure system(VSS) can provide the effective and robust means for controlling an uncertain dynamical system[10]. The most distinct feature of the variable structure system is the presence of the sliding mode on the predetermined sliding surface[11]. Concerning on the SOF, in 1985, White first studied the use of output feedback in variable structure system with no uncertainties[5]. 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[6]. In

[7], Kwan extended his results of a SISO VSS in 1996 to linear MIMO systems with global closed loop stability in 2001. It was demonstrated that the numerical methods to design the reaching phase in output feedback sliding mode control are only applicable under certain structural condition. 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[8]. Lee proposed a static output feedback integral variable structure controller for uncertain system with unmatched system matrix uncertainty in 2010 in [9]. Concerning about the DOF, in 1991 and 1992, Diong and Medanic proposed the two type so called compensator type and observer type dynamic output feedback variable structure controllers for MIMO system stabilization based on the simplex method without uncertainty in [14] and [15]. Bag et al. suggested the two robust SOF and DOF sliding mode designs for linear systems with matched uncertainty in [16]. Under the condition of mismatched system matrix uncertainty, a dynamic output feedback variable structure controller was proposed by Shyu, Tsai, and Lai in [17] in 2001, which is modified and extended from the results of [6] and [7] to a class of mismatched uncertain VSS. For linear systems with norm bounded mismatched system matrix uncertainty and matched input matrix uncertainty and disturbance, a compensator type DOF variable structure control was designed by Park, Choi, and Kong in [18] in 2007. Chang suggested a dynamic output integral VSS with a dynamic output integral sliding surface for

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disturbance attenuation and an observer type DOF sliding mode control for uncertain mechanical systems in [19] and in [20], respectively.

Most of the variable structure dynamic output feedback controllers have the reaching phase approaching the sliding surface from a given initial condition. During this phase, the sliding mode does not guarantee[10][11]. The derivative of the sliding surface is a function of the state not the output[6]. Therefore, it is difficult to prove the closed loop stability.

In this paper, a variable structure compensator type dynamic output feedback controller for the improved robust control of an uncertain systems with mismatched uncertainty in the state matrix. This paper is extended from the results of the static output feedback VSS in [9]. The reaching phase problems are completely removed by the special intial condition for the compensator type dynamic output. A stabilizing control is designed to generate the sliding mode on the integral sliding surface $S=0$ and as a results, the closed loop asymptotic 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. Dynamic Output Feedback Variable Structure System

2.1 System Descriptions and Basic Backgrounds

The problem of designing the variable structure dynamic output feedback controller is considered for an mismatched uncertain system:

$$\begin{aligned} \dot{x} &= A(x,t)x + B(x,t)u(t) + \Delta d(x,t), & x(0) \\ &= [A_0 + \Delta A(x,t)]x + [B_0 + \Delta B(x,t)]u(t) \\ &\quad + \Delta d(x,t), & x(0) \\ y &= C \cdot x(t) & y(0) = Cx(0) \end{aligned} \quad (1)$$

where $x \in R^n$ is the state variable, $u(t) \in R$ is the control, $y \in R^q$ is the output, and $A_0 \in R^{n \times n}$, $B_0 \in R^{n \times 1}$, and $C \in R^{q \times n}$ are the nominal system matrix, the nominal input matrix, and output matrix, respectively. A_0 may be unstable. $x(0)$ and $y(0)$ are the initial conditions of the state and output. $\Delta A(t)$, $\Delta B(t)$,and $\Delta d(X,t)$ are the unmatched system matrix uncertainty, the bounded matched input matrix uncertainty, and bounded matched external disturbance. respectively.

Assumption

A1: The pair (A_0, B_0) is stabilizable and the pair (A, C) is observable

A2: $\text{Rank}(B_0) = m = 1$ and $\text{Rank}(C) = q$, $1 = m \leq q < n$.

A3: The unmatched $\Delta A(t)$ is unknown, bounded, and satisfied by the following conditions[9]

$$\Delta A(t) = \Delta A'(t)C^T C = \Delta A''(t)C \quad (2)$$

The relationship of (2) is less restrictive than that in [6].

To introduce extra dynamics to provide additional degree of freedom[14]–[16], consider a dynamic compensator given by

$$\dot{z} = A_1 z + Hy \quad (3)$$

where matrices $A_1 \in R^{q \times q}$ and $H \in R^{q \times q}$ are to be determined. If $A_1 = 0$ and $H = I$, then z is the pure integral state of the output and the main results become those of [9]. Hence the dynamic output feedback is more general than only the integral augmentation in [9].

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

2.2 Dynamic Output Feedback Transformed Sliding Surface

Assumption

A4: $(F_1 C B_0)$ has the inverse for a non zero element row vector F_1 .

$$A5 \quad (F_1 C B_0)^{-1} F_1 C \Delta B = \Delta I < 1 \quad (4)$$

Now, a dynamic output feedback transformed sliding surface[22] is suggested to be

$$S = (F_1 C B)^{-1} F_1 \cdot y + F_0 \cdot z \quad (=0) \quad (5)$$

$$z(0) = -F_0^{-1} (F_1 C B)^{-1} F_1 \cdot y(0) \quad (6)$$

where $F_0^{-1} = (F_0^T W F_0)^{-1} F_0^T W$. In (5), non zero row vector F_1 and F_0 are the design parameters satisfying the following relationship

$$F_0 A_1 = K_0 \quad (7)$$

$$F_0 H C + (F_1 C B_0)^{-1} F_1 C A_0 - K_1 C = C \cong 0 \quad (8)$$

where K_0 is a linear constant dynamic output feedback gain and K_1 is a linear constant output feedback gain and designed in the manner in [9] when the closed loop system matrix $A_C = A_0 - B_0 K_1 C$ is selected in advance. And $z(0)$ becomes the initial condition for the dynamic compensator (3) which stems from [21]. Since the dynamic output feedback transformed sliding surface (5) is zero at $t=0$, there is no reaching phase and the controlled system slides from the beginning[21]. By choosing the design parameters, F_0 , F_1 , and K_1 in (8), one can make the value of C close to zero. From $\dot{S}=0$, the real sliding dynamics is as follows[9]:

$$\begin{aligned} \dot{S} &= (F_1 C B)^{-1} \cdot F_1 C \cdot \dot{x} + F_0 \cdot \dot{z} \\ &= (F_1 C B)^{-1} \cdot F_1 C \cdot [A(x,t)x + B(x,t)u(t) + \Delta d(x,t)] \\ &\quad + F_0 \cdot [A_1 z + Hy] \end{aligned} \quad (9)$$

From (13), the equivalent control is obtained as

$$U_{eq} = -[(F_1 C B)^{-1} F_1 C \cdot [A(x,t)x + B(x,t)u(t) + \Delta d(x,t)] + F_0 \cdot (A_1 z + Hy)] \quad (10)$$

which can not be implemented because of the feedback of the state, the uncertainties, and disturbance.

2.2 Stabilizing Control

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

$$u(t) = -K_0 z - \Delta K_0 z - K_1 y - \Delta K_1 y - K_2 \cdot S - \Delta K_2 \text{sign}(S) \quad (11)$$

where K_0 is the linear constant compensator state feedback gain identical to that in (7), K_1 is the linear constant output feedback gain identical to that in (8), and K_2 is the linear constant feedback gain of the sliding surface, ΔK_0 , ΔK_1 and ΔK_2 are switching gains, those are selected as follows:

$$K_2 > 0 \quad (12)$$

$$\Delta K_{0i} = \begin{cases} > \frac{\max\{\Delta I F_0 A_1\}_i}{\min\{I + \Delta I\}_i} & \text{for } (S \cdot z_i) > 0 \\ < -\frac{\min\{\Delta I F_0 A_1\}_i}{\min\{I + \Delta I\}_i} & \text{for } (S \cdot z_i) < 0 \\ i = 1, 2, \dots, q \end{cases} \quad (13)$$

$$\Delta K_{1i} = \begin{cases} > \frac{\max\{(F_1 C B_0)^{-1} F_1 C \Delta A'' - \Delta I K_1\}_i}{\min\{I + \Delta I\}_i} & \text{for } (S \cdot y_i) > 0 \\ < -\frac{\min\{(F_1 C B_0)^{-1} F_1 C \Delta A'' - \Delta I K_1\}_i}{\min\{I + \Delta I\}_i} & \text{for } (S \cdot y_i) < 0 \\ i = 1, 2, \dots, q \end{cases} \quad (14)$$

$$\Delta K_2 > \frac{\max\{C x + (F_1 C B_0)^{-1} \Delta d(t)\}}{\min\{I + \Delta I\}} \quad (15)$$

If $\|x\|$ is bounded, then one can find ΔK_2 . C should be small near to zero to be small ΔK_2 . By this corresponding stabilizing control input with the dynamic output feedback transformed sliding surface, 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 (11) 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

$$V = 1/2 S \cdot S \quad (16)$$

From (9) and (11)–(15), the derivative of S becomes

$$\begin{aligned} \dot{S} &= (F_1 C B)^{-1} \cdot [F_1 C \cdot (A_0 + \Delta A)x + F_1 C \cdot (B_0 + \Delta B)u(t) \\ &\quad + F_1 C \cdot \Delta d(x)] + F_0[A_1 z + H y] \\ &= (F_1 C B)^{-1} \cdot [F_1 C \cdot (A_0 + \Delta A)x] + [I + \Delta I]u(t) \\ &\quad + (F_1 C B)^{-1} F_1 C \cdot \Delta d(x) + F_0[A_1 z + H y] \\ &= F_0 A_1 z + F_0 H y + (F_1 C B)^{-1} F_1 C \cdot A_0 x - K_0 z - K_1 y \\ &\quad - \Delta I K_0 z - \Delta I K_1 y + (F_1 C B)^{-1} F_1 C \cdot \Delta A x - [I + \Delta I] \Delta K_0 z \\ &\quad - [I + \Delta I] \Delta K_1 y + (F_1 C B)^{-1} F_1 C \cdot \Delta d(x, t) - [I + \Delta I] K_2 S \\ &\quad - [I + \Delta I] \Delta K_2 \text{sgn}(S) \end{aligned} \quad (17)$$

Rearranging (17) with (7) and (8), it follows

$$\begin{aligned} \dot{S} &= -\Delta I K_0 z - [I + \Delta I] \Delta K_0 z + (F_1 C B)^{-1} F_1 C \cdot \Delta A' y \\ &\quad - \Delta I K_1 y - [I + \Delta I] \Delta K_1 y - [I + \Delta I] K_2 S \\ &\quad + C x + (F_1 C B_0)^{-1} F_1 C \Delta d(x, t) - [I + \Delta I] \Delta K_2 \text{sgn}(S) \end{aligned} \quad (18)$$

The derivative of (16) with respect to time leads to and substituting (18) into (19)

$$\begin{aligned} \dot{V} &= S^T \dot{S} = -S^T \Delta I K_0 z - S^T [I + \Delta I] \Delta K_0 z \\ &\quad + S^T (F_1 C B)^{-1} F_1 C \cdot \Delta A' y - S^T \Delta I K_1 y \\ &\quad - S^T [I + \Delta I] \Delta K_1 y - S^T [I + \Delta I] K_2 S \\ &\quad + S^T C x + S^T (F_1 C B_0)^{-1} F_1 C \Delta d(x, t) \\ &\quad - S^T [I + \Delta I] \Delta K_2 \text{sgn}(S) \end{aligned} \quad (19)$$

$$\begin{aligned} &\leq -\epsilon K_2 S^2 \quad \epsilon = \|I + \Delta I\| \\ &= -2\epsilon K_2 V \end{aligned} \quad (20)$$

From (20), the following equation is obtained a

$$\dot{V} + 2\epsilon K_2 V \leq 0 \quad (21)$$

$$V(t) \leq V(0) e^{-2\epsilon K_2 t} \quad (22)$$

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 $S=0$ from a given initial condition to the origin. 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 bounded uncertainties and disturbance satisfying A3, and the reachability of the controlled system does not need to be considered. 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, matched input matrix uncertainties, and matched disturbance, which is modified from that of [9]

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -1 - 0.02 \sin^2 x_2 & 1 & 0 \\ \sin^2(x_2) & -1 & 1 \\ 1 + \sin^2 x_3 & 0.4 \sin^2 x_3 & 2 + 0.4 \sin^2 x_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (23)$$

$$+ \begin{bmatrix} 0 \\ 0 \\ 2 + 0.3 \sin(2t) \end{bmatrix} u + \begin{bmatrix} 0 \\ 0 \\ d_1(x, t) \end{bmatrix}$$

$$y = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T \quad (24)$$

$$d_1(x, t) = 0.7 \sin(x_1) - 0.8 \sin(x_2) + 0.2(y_1^2 + y_3^2) + 2.0 \sin(2t) + 20.0 \quad (25)$$

where the nominal matrices A_0 , B_0 and C , the unmatched system matrix uncertainties, matched input matrix uncertainties, and matched disturbance are

$$A_0 = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & 2 \end{bmatrix}, \quad B_0 = \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix} \quad (26)$$

$$\Delta A = \begin{bmatrix} -0.02\sin^2 x_2 & 0 & 0 \\ 0.3\sin^2 x_2 & 0 & 0 \\ 1.0\sin^2 x_2 & 0.4\sin^2 x_3 & 0.4\sin^2 x_3 \end{bmatrix} \quad (27)$$

$$\Delta B = \begin{bmatrix} 0 \\ 0 \\ 0.3\sin(2t) \end{bmatrix}, \Delta d(X,t) = \begin{bmatrix} 0 \\ 0 \\ d_1(X,t) \end{bmatrix}$$

The eigenvalues of open loop system matrix A_0 are 2.1038 and $\pm j0.5652$, hence A_0 is unstable. The unmatched system matrix uncertainties satisfies Assumption A3 as

$$\Delta A'' = \begin{bmatrix} 0 & -0.02\sin^2 x_2 \\ 0 & 0.3\sin^2 x_2 \\ 0.4\sin^2 x_3 & \sin^2 x_2 \end{bmatrix} \quad (28)$$

To design the dynamic compensator in this consideration, the A_1 and H in (3) are selected as follows

$$A_1 = \begin{bmatrix} -5 & 0 \\ 0 & -5 \end{bmatrix} \text{ and } H = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} \quad (29)$$

to have open loop stable double pole at -5 . To choose the dynamic output transformed sliding surface, F_0 and F_1 are designed as

$$F_0 = [1.4 \ 1.4] \text{ and } F_1 = [0.5 \ 1] \quad (30)$$

hence, in Assumption 4 $F_1 C B_0 = 1$ and in Assumption 5, $(F_1 C B_0)^{-1} F_1 C \Delta B = \Delta I = 0.15\sin(2t) < 1$. Both assumptions are satisfied. By the relationship of (7) and (8), K_0 and K_1 are chosen as

$$K_0 = F_0 A_1 = [-7 \ -7] \text{ and } K_1 = [3.55 \ 2.55] \quad (31)$$

such that

$$A_C = A_0 - B_0 K_1 C = \begin{bmatrix} -1.0 & 1.0 & 0.0 \\ 0.0 & -1.0 & 1.0 \\ -2.1 & -7.1 & -5.1 \end{bmatrix} \quad (32)$$

has the stable poles at -1.3664 and $-2.8668 \pm j1.4990$ and

$$F_0 H C + (F_1 C B_0)^{-1} F_1 C A_0 - K_1 C = C = [0 \ -0.5 \ 0] \cong 0 \quad (33)$$

The control gains in (11), (12)–(15) are selected as follows:

$$K_2 = 5.0 \quad (34a)$$

$$\Delta k_{01} = \begin{cases} 4.5 & \text{if } Sz_1 > 0 \\ -4.5 & \text{if } Sz_1 < 0 \end{cases} \quad (34b)$$

$$\Delta k_{02} = \begin{cases} 3.4 & \text{if } Sz_2 > 0 \\ -3.4 & \text{if } Sz_2 < 0 \end{cases} \quad (34c)$$

$$\Delta k_{11} = \begin{cases} 3.5 & \text{if } Sy_1 > 0 \\ -3.5 & \text{if } Sy_1 < 0 \end{cases} \quad (34d)$$

$$\Delta k_{12} = \begin{cases} 3.3 & \text{if } Sy_2 > 0 \\ -3.3 & \text{if } Sy_2 < 0 \end{cases} \quad (34e)$$

$$K_2 = 15.5 + 0.3(y_1^2 + y_2^2) \quad (34f)$$

The simulation is carried out under 1[msec] sampling time and with $X(0) = [-6 \ 3 \ 5]^T$ initial state, and $y(0) = Cx(0) = [8 \ -6]^T$ and $z(0) = [-2.85714 \ 4.28571]^T$. Fig. 1 shows the two case output responses of y_1 and y_2 (i) without uncertainties and disturbance and (ii) with uncertainties 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) in advance. Fig 2 shows the phase trajectories with and without uncertainties and disturbance. The dynamic outputs z_1 and z_2 of the compensator are depicted in Fig. 3. Both outputs converge to zeros in steady state from the initial $z(0) = [-2.85714 \ 4.28571]^T$. Fig. 4 shows the sliding surface 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 controlled system slides from the beginning. The control input with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance is depicted in Fig. 5. 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 easily for practical application a

$$U(t) = -K_0 z - K_1 y - K_2 \cdot S - [\Delta K_0 z + \Delta K_1 y + \Delta K_2 \text{sign}(S)] \frac{S}{|S| + \delta} \quad (35)$$

The outputs and almost continuous control input are depicted in Fig. 6 and Fig. 7 for $\delta = 0.2$, respectively. As can be seen in Fig 7, the discontinuity of control input of Fig. 5 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 systematic design of variable structure dynamic output feedback controller with an dynamic output feedback transformed surface is presented for the improved robust control of an uncertain systems with mismatched uncertainty in the state matrix satisfying A3. This paper is extended from the results of the static output feedback VSS of [9]. A dynamic output feedback transformed sliding surface is proposed in order to remove the reaching phase by means of the special initial condition for the dynamic compensator, and its equivalent control is derived. A stabilizing control is designed to generate the sliding mode on the integral sliding surface $S=0$ from the initial state to the origin and as a results, the closed loop exponential stability is obtained for all unmatched system matrix uncertainties, and proved together with the existence condition of the sliding mode on $S=0$. Through a given systematic design example and computer simulations, the usefulness of the algorithm is demonstrated.

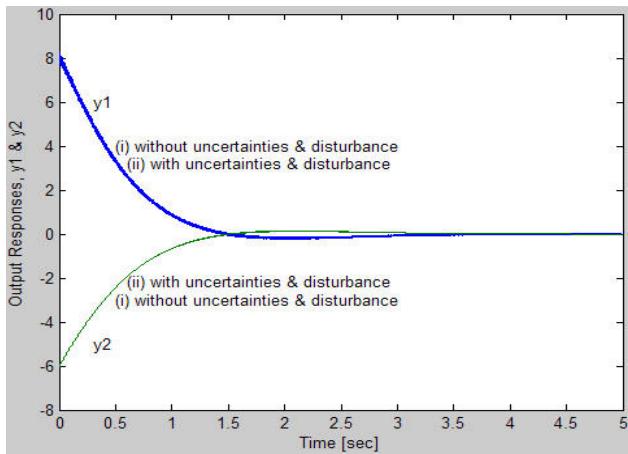


Fig. 1 Two case output responses of y_1 and y_2 (i) without and (ii) with unmatched system matrix uncertainty and matched input matrix uncertainty and disturbance.

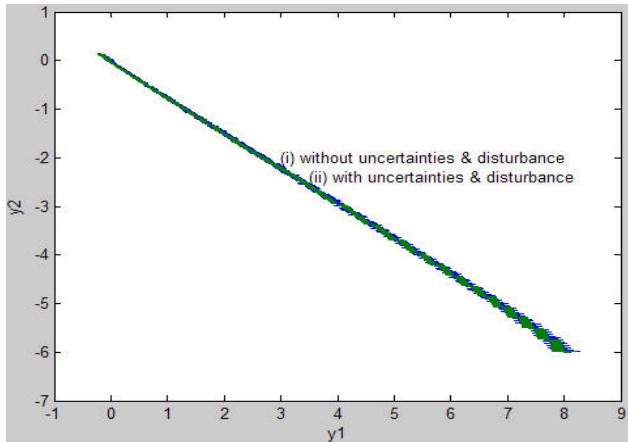


Fig. 2 Trajectories (i) without and (ii) with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance

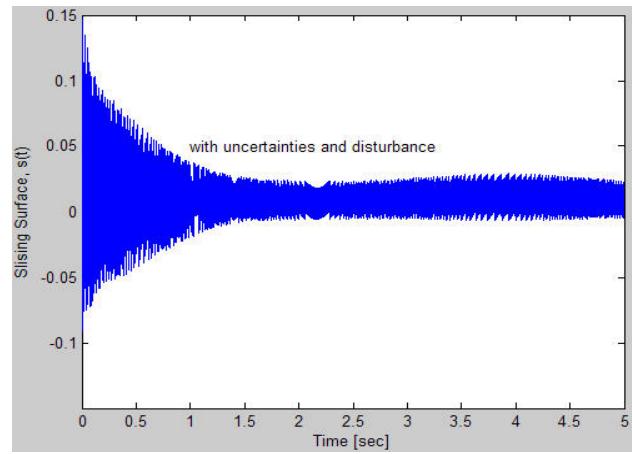


Fig. 4 Sliding surface with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance

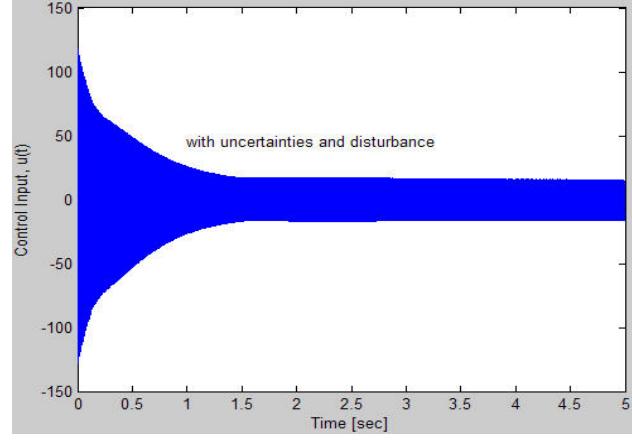


Fig. 5 Corresponding control input with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance.

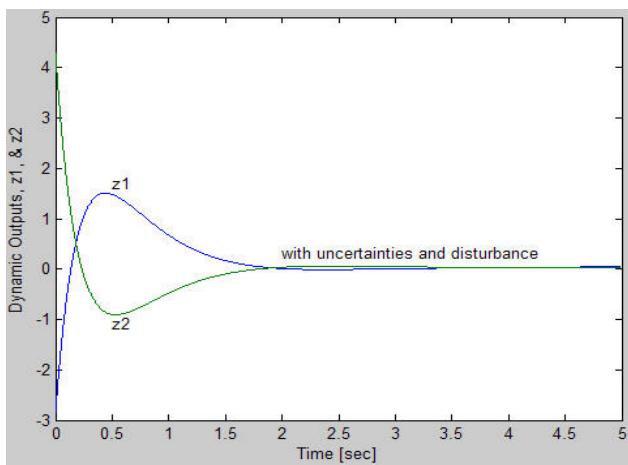


Fig. 3 Dynamic Outputs z_1 and z_2 of the compensator with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance

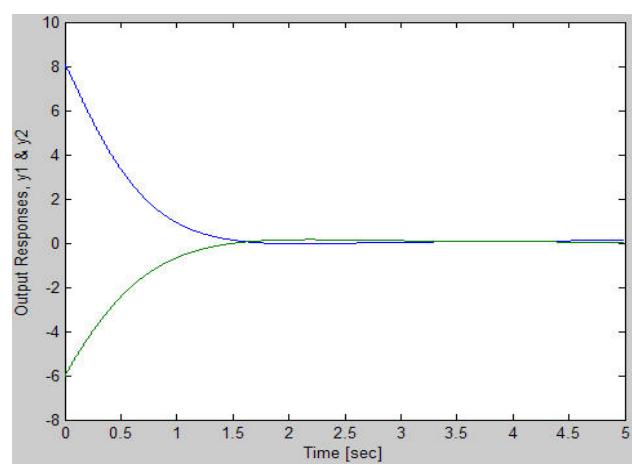


Fig. 6 Output responses of y_1 and y_2 by continuous control input with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance.

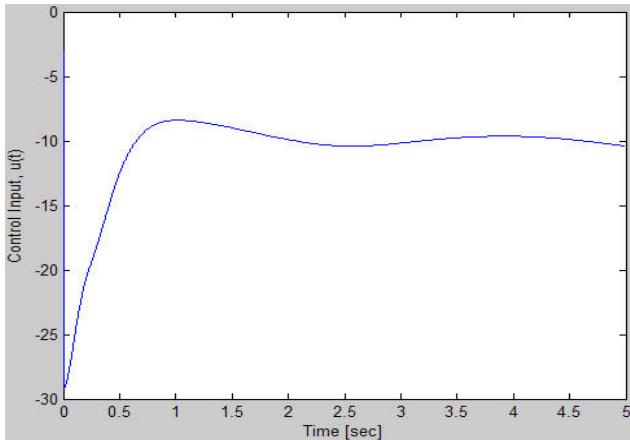


Fig. 7 Continuous control input with unmatched system matrix uncertainty, matched input matrix uncertainty, and disturbance for $\delta=0.2$.

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