Robust H^∞ Control for Delayed System with Time-Varying Norm-Bounded Parameter Uncertainty

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Abstract

In this paper, we present a robust H^∞ control design method for parameter uncertain systems that have delay in both state and control input. Through a certain algebraic Riccati inequality approach, a state feedback controller is obtained. The proposed state feedback controller stabilizes parameter uncertain delay systems and guarantees disturbance attenuation within a prescribed level. An illustrative example is given to demonstrate the results of the proposed method.

I. Introduction

Many researchers have considered the problem of robust H^∞ control with parameter uncertainty [4, 10, 11, 12]. Petersen [8] proposed an algorithm which was dealt with the disturbance attenuation and H^∞ optimization design method which was based on the algebraic Riccati equation. And Doyle *et al.* [3] presented the state-space solutions to standard H^2 and H^∞ control problems. However, there are a few studies on parameter uncertain system with delay [2, 6, 7, 9]. Since the time delay is encountered in many control problems, the analysis of the parameter uncertain systems with delay is important issue. Recently, Lee *et al.* [6] proposed the state-space H^∞ controller design method which has been extended to state delayed linear time-invariant systems. But one can not directly obtain the memoryless H^∞ controller for parameter uncertain systems with delay in both state and control. Mahmoud *et al.* [7] presented related method, but they did not deal with the disturbance attenuation.

In this paper, we give a control law which satisfies a stability for parameter uncertainties and delay terms in both state and control input and guarantees disturbance attenuation within a prescribed level. With the proposed method, one can easily obtain the control law using a certain algebraic Riccati inequality approach and appropriate manipulations. Our method is simpler than any other works.

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II. Problem Formulation

Consider a parameter uncertain delayed system with exogenous input

$$\begin{aligned} \dot{x}(t) &= [A_1+\triangle A_1(t)]x(t)+[A_2+\triangle A_2(t)]x(t-d_1(t)) \\ &\quad +[B_1+\triangle B_1(t)]u(t)+[B_2+\triangle B_2(t)]u(t-d_2(t))+B_3 w(t) \\ z(t) &= Cx(t)+Du(t) \\ x(t) &= 0,\ t<0 \end{aligned} \tag{1}$$

where $x(t)$ is the state, $u(t)$ is the control input, $d_1(t)$ and $d_2(t)$ are the delay terms, $w(t)$ is the exogenous input, $z(t)$ is the controlled output, all matrices have proper dimensions, and the parameter uncertainties are defined as follows:

$$\begin{aligned} &\triangle A_1(t)=H_1F(t)E_1,\ \ \triangle A_2(t)=H_2F(t)E_2, \\ &\triangle B_1(t)=H_3F(t)E_3,\ \ \triangle B_2(t)=H_4F(t)E_4, \end{aligned} \tag{2}$$

where H_i and E_i, $i=1,2,3,4$, are known real matrices and $F(t)$ is an unknown matrix function which is bounded by

$$F(t)\in\Omega:=\{\ F(t):\ F(t)^TF(t)\le I,\ \text{ the elements of } F(t) \text{ are Lebesgue measurable}\ \}. \tag{3}$$

And the delay terms are defined

$$0\le d_1(t),\ d_2(t)<\infty,\ \ \dot{d}_1(t)\le\beta_1<1,\ \ \dot{d}_2(t)\le\beta_2<1, \tag{4}$$

where β_1 and β_2 are the upper bound of derivative of delay terms. For simplicity, we define some parameters as follows:

$$
\begin{aligned}
A(t) &= A_1+\triangle A_1(t), \quad B(t) = B_1+\triangle B_1(t), \\
A_d(t) &= A_2+\triangle A_2(t), \quad B_d(t) = B_2+\triangle B_2(t), \\
q_1(t) &= x(t-d_1(t)), \quad q_2(t) = x(t-d_2(t)), \\
\hat{R} &= (1-\beta_1)R, \qquad \hat{S} = (1-\beta_2)S^{-1}, \\
\alpha_1 &= \|E_2 \hat{R}^{-1} E_2^T\|, \quad \alpha_2 = \|E_4 \hat{S}^{-1} E_4^T\|,
\end{aligned} \tag{5}
$$

where, $\|\cdot\|$ means standard Euclidean norm. Now, consider a linear state feedback control law with constant gain matrix

$$u(t) = -S^{-1}B_1^T P x(t), \tag{6}$$

where S and P are positive-definite matrices. It is assumed that plant state is available for state feedback.

Definition 1. Let a constant $\gamma > \gamma_o$ be prescribed where γ_o is a infimum value of γ and assume $\gamma^2 I-D^T D > 0$. The system (1) is quadratically stable with disturbance attenuation γ, if the following is fulfilled for all $F(t)\in\Omega$:

(i) There exist a positive-definite matrix P and a scalar $\mu > 0$ such that Lyapunov functional $L(x(t),t)$ satisfie

$$\frac{dL(x(t),t)}{dt} < -\mu\|x(t)\|^2, \quad x(t)\neq 0,$$

(ii) On the assumption of zero initial condition, the controlled output $z(t)$ satisfies

$$\|z(t)\|_2 < \gamma\|w(t)\|_2$$

where $\|\cdot\|_2$ means 2-norm. □

Therefore, the objectives of this paper are designing a state feedback controller (6) which stabilizes system (1) in the presence of time-varying parameter uncertainties and time-varying delay terms and guarantees disturbance attenuation of closed loop system from $w(t)$ to $z(t)$ within a γ.

III. Main Results

The approach adopted in this paper to solve the robust H^{∞} control problem involves solving a Riccati inequality. For this objective, definition 1 should be satisfied. We show the proofs of conditions of definition 1 in this section. Lemma 1 is related to (i) of definition 1. Theorem 1 shows satisfaction of the condition (ii) in definition 1.

Lemma 1. Consider the system (1) and suppose that the exogenous input is zero for all time. Let S and R be given positive-definite matrices and suppose there exists a positive constant ε such that the Riccati inequality

$$
\begin{aligned}
A_1^T P+PA_1-PB_1S^{-1}B_1^T P+PA_2\hat{R}^{-1}A_2^T P+PB_2\hat{S}^{-1}B_2^T P+ \\
R+\frac{1}{\varepsilon}E_1^T E_1+PMP < 0
\end{aligned} \tag{7}
$$

has a popsitive-definite matrix P, where

$$
\begin{aligned}
M = \;& \varepsilon[H_1H_1^T+H_2H_2^T+H_3H_3^T+H_4H_4^T] \\
&+\frac{1}{\varepsilon}[B_1S^{-1}E_3^T E_3 S^{-1}B_1^T+B_2\hat{S}^{-1}E_4^T E_4\hat{S}^{-1}B_2^T+ \\
&A_2\hat{R}^{-1}E_2^T E_2\hat{R}^{-1}A_2^T]+\alpha_1 H_2H_2^T+\alpha_2 H_4H_4^T.
\end{aligned} \tag{8}
$$

Then the parameter uncertain delayed system (1)~(5) is asymptotically stabilizable for zero exogenous input.

Proof. Suppose (7) has a solution P and $u(t)$ is given by (6). For the Lyapunov functional which is positive-definite for all $x(t)\neq 0$

$$
\begin{aligned}
L(x(t),t) = x(t)^T Px(t)+\int_{t-d_1(t)}^{t} x(\tau)^T Rx(\tau)\,d\tau+ \\
\int_{t-d_2(t)}^{t} x(\tau)^T PB_1S^{-1}B_1^T Px(\tau)\,d\tau.
\end{aligned} \tag{9}
$$

Lyapunov derivative of (9) is given by

$$
\begin{aligned}
& dL(x(t),t)/dt= \\
& x(t)^T A(t)^T Px(t)+q_1(t)^T A_d(t)^T Px(t)-x(t)^T PB_1S^{-1}B(t)^T Px(t) \\
& -q_2(t)^T PB_1S^{-1}B_d(t)^T Px(t)+x(t)^T PA(t)x(t)+x(t)^T PA_d(t)q_1(t) \\
& -x(t)^T PB(t)S^{-1}B_1^T Px(t)-x(t)^T PB_d(t)S^{-1}B_1^T Pq_2(t)+x(t)^T Rx(t) \\
& -(1-\dot{d}_1(t))q_1(t)^T Rq_1(t)+x(t)^T PB_1S^{-1}B_1^T Px(t) \\
& -(1-\dot{d}_2(t))q_2(t)^T PB_1S^{-1}B_1^T Pq_2(t).
\end{aligned} \tag{10}
$$

Let $\xi = [x(t)^T \; q_1(t)^T \; (B_1^T Pq_2(t))^T]^T$, the (10) is transformed into

$$
\xi^T Q\xi := \xi^T \begin{bmatrix} \tilde{A}(t) & PA_d(t) & -PB_d(t) \\ A_d(t)^T P & -(1-\dot{d}_1(t))R & 0 \\ -B_d(t)^T P & 0 & -(1-\dot{d}_2(t))S^{-1} \end{bmatrix} \xi, \tag{11}
$$

where, $\tilde{A}(t) = A(t)^T P+PA(t)-PB_1S^{-1}B(t)^T P-PB(t)S^{-1}B_1^T P+PB_1S^{-1}B_1^T P+R$. (11) is negative-definite when the matrix

$$
\begin{aligned}
\Pi :=\;& \\
& A(t)^T P+PA(t)-PB_1S^{-1}B(t)^T P-PB(t)S^{-1}B_1^T P+PB_1S^{-1}B_1^T P+R \\
& +PA_d(t)\hat{R}^{-1}A_d(t)^T P+PB_d(t)\hat{S}^{-1}B_d(t)^T P < 0.
\end{aligned} \tag{12}
$$

This relation is derived by [5]. It should be remarked that verifying (12) would lead to constructing an upper bound for the Lyapunov derivative in (10). To do this, we expand Π and rearrange the respective terems into

$$x(t)^T\Pi x(t)=$$
$$x(t)^T\{[A_1^TP+PA_1-PB_1S^{-1}B_1^TP+R+PA_2\hat{R}^{-1}A_2^TP+PB_2\hat{S}^{-1}B_2^TP]$$
$$+[E_1^TF(t)^TH_1^TP+PH_1F(t)E_1]$$
$$+[PB_1\hat{S}^{-1}E_3^TF(t)^TH_3^TP+PH_3F(t)E_3\hat{S}^{-1}B_1^TP]$$
$$+[PH_2F(t)E_2\hat{R}^{-1}A_2^TP+PA_2\hat{R}^{-1}E_2^TF(t)^TH_2^TP]$$
$$+[PH_4F(t)E_4\hat{S}^{-1}B_2^TP+PB_2\hat{S}^{-1}E_4^TF(t)^TH_4^TP]$$
$$+[PH_2F(t)E_2\hat{R}^{-1}E_2^TF(t)^TH_2^TP+PH_4F(t)E_4\hat{S}^{-1}E_4^TF(t)^TH_4^TP]\}x(t). \tag{13}$$

Using (3) and $2(x^TPDFEx)\le\varepsilon(x^TPDD^TPx)+\frac{1}{\varepsilon}(x^TE^TEx)$, the right side terms of (13) can be written as

$$x(t)^T[PH_1F(t)E_1+E_1^TF(t)^TH_1^TP]x(t)=2x(t)^TPH_1F(t)E_1x(t)$$
$$\le\varepsilon x(t)^TPH_1H_1^TPx(t)+\frac{1}{\varepsilon}x(t)^TE_1^TE_1x(t),$$

$$x(t)^T[PH_3F(t)E_3\hat{S}^{-1}B_1^TP+PB_1\hat{S}^{-1}E_3^TF(t)^TH_3^TP]x(t)$$
$$=2x(t)^TPH_3F(t)E_3\hat{S}^{-1}B_1^TPx(t)$$
$$\le\varepsilon x(t)^TPH_3H_3^TPx(t)+\frac{1}{\varepsilon}x(t)^TPB_1\hat{S}^{-1}E_3^TE_3\hat{S}^{-1}B_1^TPx(t),$$

$$x(t)^T[PH_2F(t)E_2\hat{R}^{-1}A_2^TP+PA_2\hat{R}^{-1}E_2^TF(t)^TH_2^TP]x(t)$$
$$=2x(t)^TPH_2F(t)E_2\hat{R}^{-1}A_2^TPx(t)$$
$$\le\varepsilon x(t)^TPH_2H_2^TPx(t)+\frac{1}{\varepsilon}x(t)^TPA_2\hat{R}^{-1}E_2^TE_2\hat{R}^{-1}A_2^TPx(t),$$

$$x(t)^T[PH_4F(t)E_4\hat{S}^{-1}B_2^TP+PB_2\hat{S}^{-1}E_4^TF(t)^TH_4^TP]x(t)$$
$$=2x(t)^TPH_4F(t)E_4\hat{S}^{-1}B_2^TPx(t)$$
$$\le\varepsilon x(t)^TPH_4H_4^TPx(t)+\frac{1}{\varepsilon}x(t)^TPB_2\hat{S}^{-1}E_4^TE_4\hat{S}^{-1}B_2^TPx(t),$$

$$x(t)^T[PH_2F(t)E_2\hat{R}^{-1}E_2^TF(t)^TH_2^TP+PH_4F(t)E_4$$
$$\hat{S}^{-1}E_4^TF(t)^TH_4^TP]x(t)\le\alpha_1x(t)^TPH_2H_2^TPx(t)+$$
$$\alpha_2x(t)^TPH_4H_4^TPx(t),$$

then (7) is obtained. □

Lemma 1 shows the stability of closed loop system using Lyapunov functional and appropriate manipulations. Now consider the Riccati inequality

$$A_1^TP+PA_1-PB_1S^{-1}B_1^TP+PA_2\hat{R}^{-1}A_2^TP+PB_2\hat{S}^{-1}B_2^TP$$
$$+R+\frac{1}{\varepsilon}E_1^TE_1+PMP+2C^TC+\rho\gamma^2PB_3B_3^TP \tag{14}$$
$$+2PB_1S^{-1}D^TDS^{-1}B_1^TP<0$$

where γ is a prescribed level and ρ is a positive constant.

Definition 2. From the (7), (12), and (13), we can define the derivative of Lyapunov functional as

$$\dot{L}_1(x,t)=$$
$$x(t)^T(A_1^TP+PA_1-PB_1S^{-1}B_1^TP+PA_2\hat{R}^{-1}A_2^TP+PB_2\hat{S}^{-1}B_2^TP$$
$$+R+\frac{1}{\varepsilon}E_1^TE_1+PMP)x(t)$$
$$<-x(t)^T(2C^TC+\rho\gamma^2PB_3B_3^TP+2PB_1S^{-1}D^TDS^{-1}B_1^TP)x(t). \tag{15}$$

□

Theorem 1. Suppose S and R are given positive-definite matrices, γ is a positive prescribed level, and ρ and ε are positive constant. If there exists a positive-definite solution P such that (14) holds, then an H^∞ norm of the closed loop system from $w(t)$ to $z(t)$ of (1) is less than equal to γ.

Proof. In order to establish the upper bound $\gamma\|w(t)\|_2$ for $\|z(t)\|_2$, we assume $x(0)=0$ and let us introduce

$$J=\int_0^\infty(z(t)^Tz(t)-\gamma^2w(t)^Tw(t))\,dt. \tag{16}$$

If $J<0$, the proof is completed. For any nonzero $w(t)\in L_2[0,\infty]$, using (15) and the cost function

$$J_a=\int_0^\infty(z(t)^Tz(t)-\gamma^2w(t)^Tw(t)+\dot{L}_1(x(t),t))\,dt \tag{17}$$

we can get

$$J_a<-\int_0^\infty\{\;x(t)^TC^TCx(t)+x(t)^TC^TDS^{-1}B_1^TPx(t)$$
$$+x(t)^TPB_1S^{-1}D^TCx(t)+x(t)^TPB_1S^{-1}D^TDS^{-1}B_1^TPx(t)$$
$$+\rho\gamma^2x(t)^TPB_3B_3^TPx(t)+\gamma^2w(t)^Tw(t)\;\}\,dt \tag{18}$$

$$=-\int_0^\infty\{\;(Cx(t)+DS^{-1}B_1^TPx(t))^T(Cx(t)+DS^{-1}B_1^TPx(t))$$
$$+\rho\gamma^2(B_3^TPx(t))^TB_3^TPx(t)+\gamma^2w(t)^Tw(t)\}\,dt\le0.$$

By (17), (18) means

$$J_a=\int_0^\infty(z(t)^Tz(t)-\gamma^2w(t)^Tw(t)+\dot{L}_1(x(t),t))dt<0, \tag{19}$$

and (19) is equal to

$$\int_0^\infty z(t)^Tz(t)dt<\int_0^\infty\gamma^2w(t)^Tw(t)dt-\int_0^\infty\dot{L}_1(x(t),t)dt. \tag{20}$$

The last term of right side of (20) is

$$\int_0^\infty\dot{L}_1(x(t),t)dt=L_1(x(\infty),\infty)-L_1(x(0),0). \tag{21}$$

With (15) and $x(0)=0$, the second term of right side of (21) $L_1(x(0),0)=0$. Using this fact, (21) can be written as

$$\int_0^\infty\dot{L}_1(x(t),t)dt=L_1(x(\infty),\infty)>0,\ \textbf{for all}\ x(t)\neq0. \tag{22}$$

By (22), (20) means

$$\int_0^\infty z(t)^Tz(t)dt<\int_0^\infty\gamma^2w(t)^Tw(t)dt. \tag{23}$$

This (23) implies that $\|z(t)\|_2<\gamma\|w(t)\|_2$. Consequently by definition 1, the system (1) is quadratically stable with disturbance attenuation γ. □

Therefore the state feedback controller obtained from (6) and (14) stabilizes parameter uncertain delayed systems and guarantees disturbance attenuation within a prescribed level. To solve (14), we choose the values of R, S, ρ, and ε.

Adding a certain positive-definite matrix X in left side of (14), the algebraic Riccati inequality is transformed into the algebraic Riccati equation. Therefore (14) is rewritten as

$$A_1^TP+PA_1-PB_1S^{-1}B_1^TP+PA_2\ \hat{R}^{-1}A_2^TP+PB_2\ \hat{S}^{-1}B_2^TP+R$$
$$+\frac{1}{\varepsilon}E_1^TE_1+PMP+2C^TC+\rho\gamma^2PB_3B_3^TP+2PB_1S^{-1}D^TDS^{-1}B_1^TP$$
$$+X=0. \tag{24}$$

From (6) and (24), one can easily obtain a control law. Therefore, our results generalizes the existing works for the following reason:

- The restrictions of H_1 and H_3 [9, 11] are not necessary, in other words, the matching condition (2) is less restrictive. In practical design, our results are more effective.
- The delays in both state and control are considered simultaneously. If $B_3=0$, $C=0$, and $D=0$, our works are extension of [7] with respect to including control input delay also. And we deal with disturbance attenuation with in a prescribed level.
- The state feedback control method is much simpler than existing works.

IV. Illustrative Example

Consider a system with

$$A_1=\begin{bmatrix}-3 & 2\\ 0 & 1\end{bmatrix}, A_2=\begin{bmatrix}-0.3 & 0.2\\ 0 & 0.1\end{bmatrix}, B_1=\begin{bmatrix}0\\ 1\end{bmatrix}, B_2=\begin{bmatrix}0\\ 0.1\end{bmatrix}, B_3=\begin{bmatrix}1\\ 1\end{bmatrix}$$
$$C=[1\ 0], D=0.1,$$
$$H_1=H_2=H_3=H_4=\begin{bmatrix}0.1\\ 0.1\end{bmatrix}, E_1=E_2=[1\ 1], E_3=E_4=1,$$
$$F(t)=\sin t,$$

and delay terms are

$$d_1(t) = 5+0.5\cos t,\ d_2(t) = 2+0.1\sin t.$$

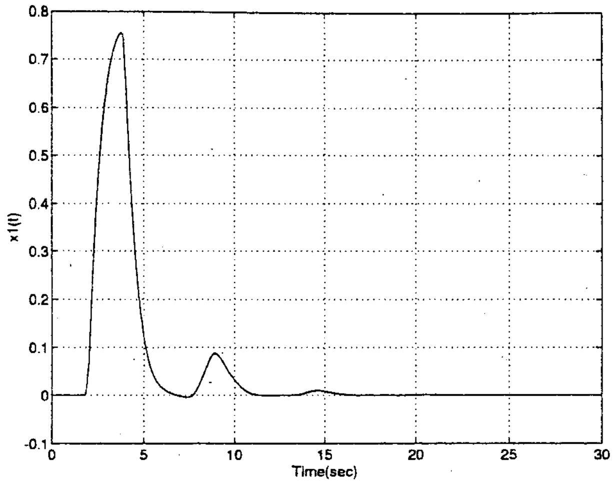
If we take $R=I$, $S=1$, $X=5I$, $\varepsilon=1$, $\rho=1$, and $\gamma=1$, we obtain the solution P of Riccati equation (24) as

$$P=\begin{bmatrix}1.1628 & -0.2853\\ -0.2853 & 2.4992\end{bmatrix},$$

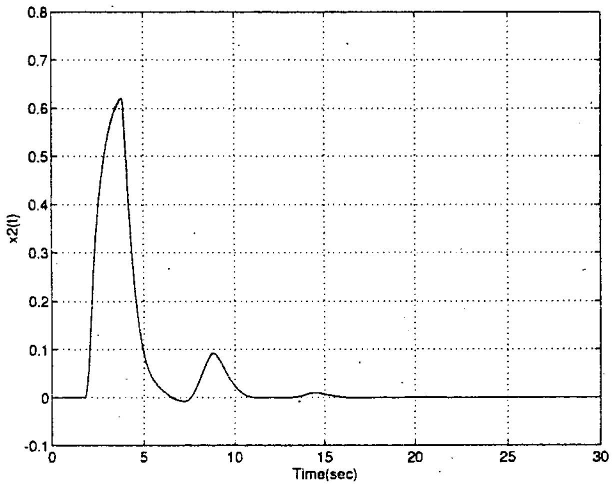
and the control law, $u(t)=0.2853x_1(t)-2.4992x_2(t)$, is guaranteeing disturbance attenuation ($\|T_{zw}\|_\infty\le 1$). If the initial values of all states are zero and the value of $w(t)$ is defined by

$$w(t)=\begin{cases}1, & 1\sec\le t\le 3\sec\\ 0, & otherwise\end{cases},$$

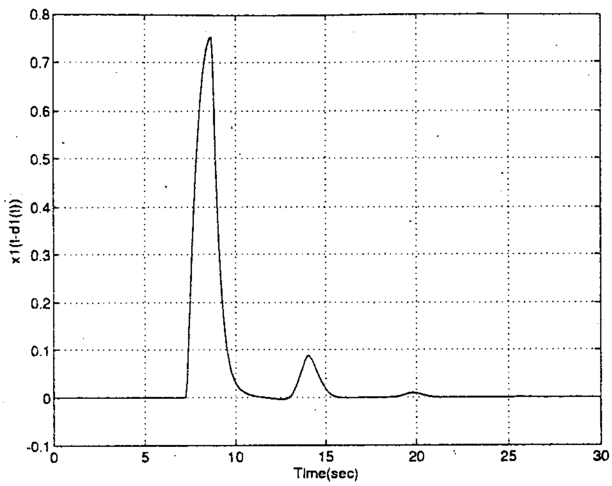
then the trajectories of states, control input and controlled output are given in Fig. 1. which shows the closed loop system is asymptotically stable.



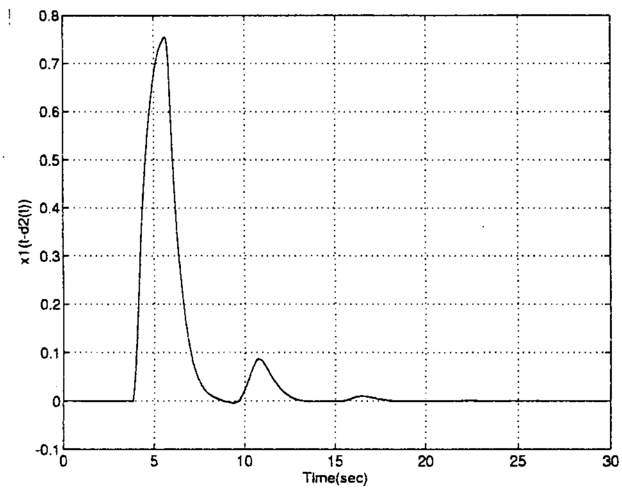
(a) $x_1(t)$



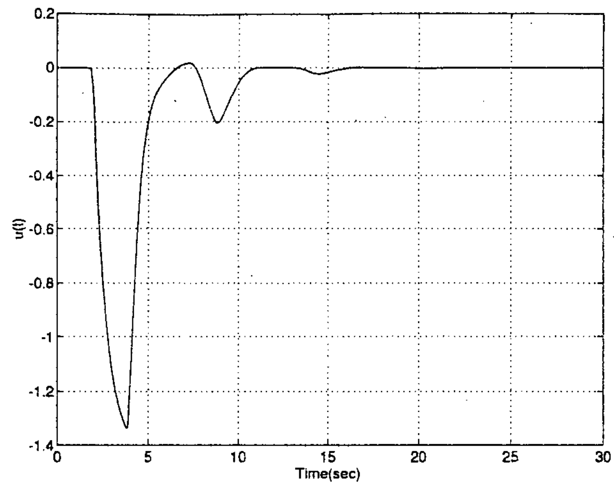
(b) $x_2(t)$



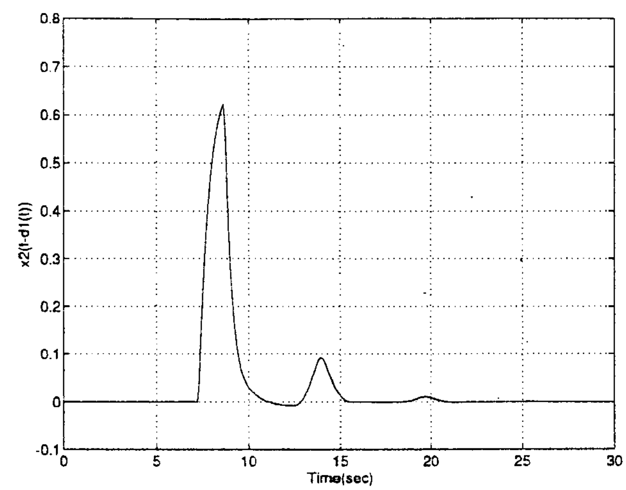
(c) $x_1(t-d_1(t))$



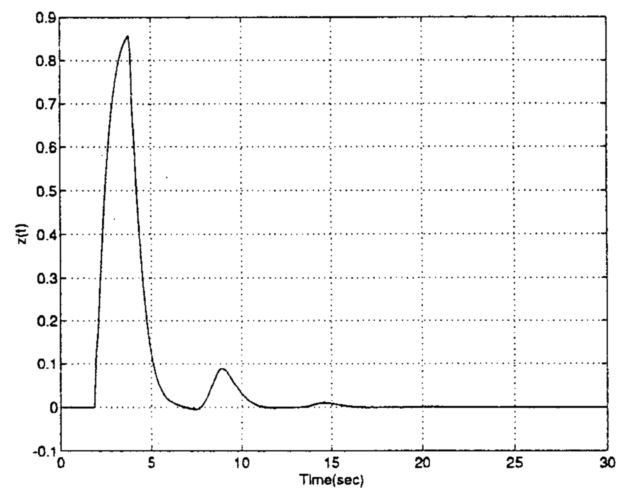
(d) $x_1(t-d_2(t))$



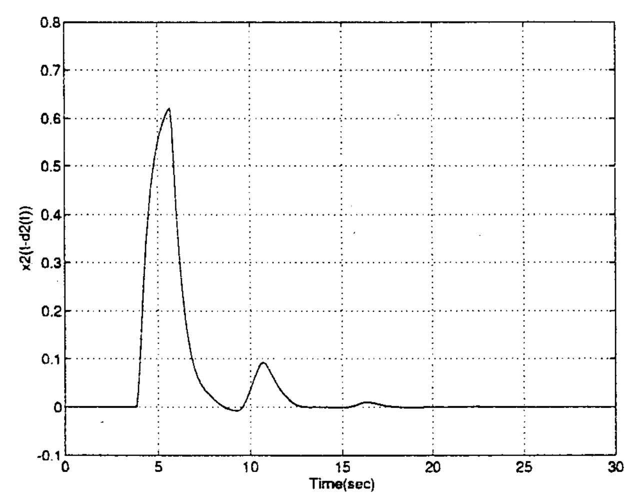
(e) $x_2(t-d_1(t))$



(f) $x_2(t-d_2(t))$



(g) $u(t)$



(h) $z(t)$

Fig. 1. The Trajectories of states, control input, and controlled output.

V. Conclusion

In this paper, we propose a robust H^∞ state feedback control method for time-varying norm-bounded parameter uncertain delayed systems. Based on the notion of quadratically stabilization with H^∞ norm bound, the state feedback gain has been obtained. A complete control law was given in terms of a certain algebraic Riccati equation. The proposed controller stabilizes system with parameter uncertain delays in both state and control input and guarantees disturbance attenuation of closed loop system from $w(t)$ to $z(t)$ within a γ. Moreover the merits of our control method are given. A future research would be to develop output feedback case. Maybe this problem will be addressed in the near future.

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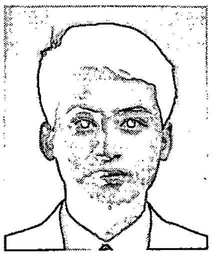

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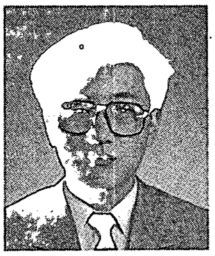

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