Robust Control for Time-Delay Singular Systems Based on Passivity Analysis

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Abstract. This paper deals with the problem of robust stability and strictly passive control for a class of uncertain descriptor systems with time-delay. By using Lyapunov method and linear matrix inequality technique, delay-dependent sufficient conditions for the robust stability and strict passivity of the system are derived. In terms of solutions of linear matrix inequalities, the strictly passive state feedback controller of descriptor system is presented by introducing a slack variable. Finally, a numerical example shows the effectiveness of the proposed method.

Keywords: Descriptor system · Time-Delay system · Passive control · Delay-Dependent · Linear matrix inequality (LMI)

1 Introduction

Many practical processes can be modeled as descriptor systems, such as economic systems, electrical network, power systems, chemical processes and so on. In the past several decades, stability and control problems of descriptor systems have been extensively studied due to the fact that the descriptor system better describes physical systems than the state-space systems [1, 2].

Delay is one of the main reasons to cause the system unstable [3, 4]. Stability criterion of systems with time delay can generally be divided into two categories: delay-independent and delay-dependent. Due to many practical systems with time delay is bounded, delay-dependent criteria have less conservativeness relative to the delay-independent criteria. There has been a lot of literature on descriptor system with time delay [5–9]. In the paper [8], an improved delay-dependent stability criterion for the nominal singular time-delay system is established in terms of strict linear matrix inequalities. And the delay-dependent robust stability criteria for two classes of uncertain singular time-delay systems are proposed, which ensure that the systems are regular, impulse free and asymptotically stable for all admissible uncertainties.

On the other hand, the passivity notion has extensive applications in various engineering areas such as electrical circuits, mechanical systems, nonlinear systems and complex networks. For these reasons, the passivity and passive control problems have

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been an active area of research recently. It is noted that these problems have been investigated for a variety of dynamics systems including hybrid systems, networked control systems, signal processing systems and linear time-delay systems. Very recently, the passivity and passive control problems for descriptor systems have been studied in [10–16], we note that delay-dependent conditions was not considered in [12, 13]. Although the delay-dependent passivity was considered in [11], the uncertainty was not considered. So far, to the best of our knowledge, the problems of delay-dependent passivity analysis and passive controller design for uncertain time-delay singular systems have been investigated few in the literature, which are very challenging and of great importance. This motivates the present study.

In this paper, we deal with the robust stability and strictly passive control problem for a class of uncertain singular systems with time delay. Our objective is to design a state-feedback controller such that the resulting closed-loop system is generalized quadratically stable and strictly passive. By using a suitable Lyapunov functional and the recently developed integral inequality, delay-dependent conditions for the existence of the desired controllers are obtained in terms of LMIs. On the basis of these conditions, a controller design procedure is developed. The usefulness of the proposed design method is confirmed by numerical results.

2 Problem Formulation

Consider the following uncertain singular systems with time delay

$$\begin{aligned} E\dot{x}(t) &= (A+\Delta A(t))x(t) + (A_d + \triangle A_d(t))x(t-\tau) \\ &\quad + Bu(t) + A_v v(t) \\ y(t) &= Cx(t) \\ z(t) &= Lx(t) + Du(t) + D_1 v(t) \\ x(t) &= \varphi(t), \quad \forall t \in [-\tau, 0] \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n, u(t) \in \mathbb{R}^m, v(t) \in \mathbb{R}^m, z(t) \in \mathbb{R}^m$ are the state, control input, external disturbance and control output, respectively. $v(t) \in \mathbb{L}_2[0,\infty)$, E, A, A_d, B, A_v, L, D, D_1 are constant matrices with suitable dimension, and $rankE \leq n$. ΔA, ΔA_d are the uncertain parts in the system, and suppose ΔA, ΔA_d satisfy the following formation:

$$[\Delta A \; \Delta A_d] = HF(t)[N_1 \; N_2] \tag{2}$$

where H, N_1, N_2 are known constant matrices, $F(t)$ is unknown Lebesgue measurable function matrix satisfying $F^T(t)F(t) \leq I \cdot \tau > 0$ is the delay constant of the system, $\varphi(t)$ is the continuous vector-valued initial function. The matrices in the system are of appropriate dimensions.

The following definitions and lemmas could be used in the rest of the paper. The system $E\dot{x}(t) = Ax(t)$ is often denoted as the pair (E, A).

Definition 1 [1]

(i) A pencil $sE - A$ (or a pair (E, A)) is regular if $\det(sE - A)$ is not identically zero.

(ii) For a regular pencil $sE - A$, the finite eigenvalues of $sE - A$ are said to be the finite modes of (E, A). Suppose that $Ev_1 = 0$, then the infinite eigenvalues associated with the generalized principal vectors v_k satisfying $Ev_k = Av_{k-1}$, $k = 2, 3, 4, \ldots$, are impulse modes of (E, A).

(iii) A pair (E, A) is admissible if it is regular and has neither impulse modes nor unstable finite modes.

Definition 2 System (1) is called generalized quadratically stable if the system is regular, impulse free and stable for all the admissible uncertainties which satisfying $F^T(t)F(t) \le I$.

Definition 3 System (1) with $u(t) = 0$ is said to be robust passive if there exists the semi-positive function $V(x(t))$ such that the following inequality

$$\int_0^T v^T(t)z(t)dt \geq V(x(T)) - V(x(0)), \forall T \geq 0 \tag{3}$$

holds for all admissible uncertainties. When the inequality holds strictly, the system is said to be robust strictly passive.

Lemma 4: [17] *If the pair (E, A) is regular, impulse free, then the solution of the singular time-delay system $E\dot{x}(t) = Ax(t) + A_d x(t - \tau)$ is exist and unique.*

Lemma 5: [2] *If the pairs (E, A) and $(E, A + A_d)$ are regular and impulse free, then the system $E\dot{x}(t) = Ax(t) + A_d x(t - \tau)$ is regular and impulse free.*

Lemma 6: [18] Given appropriate dimensional matrices Q, H, M, where Q is symmetric, then

$$Q + HFM + M^T F^T H^T < 0$$

holds for F satisfying $F^T F \le I$ if and only if there exists a scalar $\varepsilon > 0$ such that

$$Q + \varepsilon HH^T + \varepsilon^{-1} M^T M < 0.$$

3 Strict Passivity Analysis

At first, the problem of the delay-dependent strict passive control for system (1) with $u(t) = 0$ is considered, and the following theorem could be obtained.

Theorem 7 *If there exist the scalars $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, nonsingular matrix P, and symmetric definite matrices W, N, such that the following LMIs hold*:

$$E^T P = P^T E \geq 0 \tag{4}$$

$$\Theta_1 = \begin{bmatrix} \Phi_1 & \Phi_2 & \Phi_3 & \tau A^T N & N_1^T & \tau N_1^T \\ * & \Phi_4 & 0 & \tau A_d^T N & N_2^T & \tau N_2^T \\ * & * & \Phi_5 & \tau A_v^T N & 0 & 0 \\ * & * & * & \Phi_6 & 0 & 0 \\ * & * & * & * & -\varepsilon_1 I & 0 \\ * & * & * & * & * & -\varepsilon_2 I \end{bmatrix} < 0 \tag{5}$$

where

$$\begin{aligned} \Phi_1 &= A^T P + P^T A + W - E^T NE + \varepsilon_1 P^T HH^T P \\ \Phi_2 &= P^T A_d + E^T NE \\ \Phi_3 &= P^T A_v - L^T \\ \Phi_4 &= -W - E^T NE \\ \Phi_5 &= -D_1^T - D_1 \\ \Phi_6 &= -N + \varepsilon_2 NHH^T N \end{aligned}$$

Then system (1) with $u(t) = 0$ is generalized quadratically stable and robust strictly passive.

Proof At first we prove system (1) with $u(t) = 0$, $v(t) = 0$ is generalized quadratically stable. For simple, the following notation will be used in the paper:

$$\begin{aligned} \bar{A} &= A + \triangle A(t) \\ \bar{A}_d &= A_d + \triangle A_d(t) \\ f_1(t) &= \bar{A}x(t) + \bar{A}_d x(t-\tau) \end{aligned}$$

Since $rankE \leq n$, two nonsingular matrices G, H could be found such that

$$GEH = \begin{bmatrix} I_r & 0 \\ 0 & 0 \end{bmatrix},$$

Let

$$GAH = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix}], G^{-T} PH = \begin{bmatrix} \bar{P}_1 & \bar{P}_2 \\ \bar{P}_3 & \bar{P}_4 \end{bmatrix}.$$

According to (4), $\bar{P}_2 = 0$ could be easily obtained. Left and right multiplying Φ_1 by H^T, H respectively, then

$$A_4^T \bar{P}_4 + \bar{P}_4^T A_4 < 0,$$

Therefore A_4 is nonsingular, matrix pair (E, A) is regular and impulse free.

Choose the Lyapunov function as follows:

$$\begin{aligned} V_1(t) &= x^T(t)E^TPx(t) + \int_{t-\tau}^{t} x^T(\xi)Wx(\xi)d\xi \\ &+ \tau \int_{-\tau}^{0}\int_{t+\eta}^{t} f_1^T(\xi)Nf_1(\xi)d\xi d\eta \end{aligned} \tag{6}$$

where

$$E^TP = P^TE \geq 0, W = W^T > 0, N = N^T > 0.$$

The derivative of the Lyapunov function along system (1) with $u(t) = 0$, $v(t) = 0$ is

$$\begin{aligned} \dot{V}_1(t) =& f_1^T(t)Px(t) + x^T(t)P^Tf_1(t) + x^T(t)Wx(t) \\ &- x^T(t-\tau)Wx(t-\tau) + \tau^2 f_1^T(t)Nf_1(t) \\ &- \tau \int_{t-\tau}^{t} f_1^T(\xi)Nf_1(\xi)d\xi \end{aligned} \tag{7}$$

By using of Jensen integral inequality [3], it is easily obtained that

$$-\tau \int_{t-\tau}^{t} [E\dot{x}(\xi)]^T N[E\dot{x}(\xi)]d\xi \leq \begin{bmatrix} x(t) \\ x(t-\tau) \end{bmatrix}^T \begin{bmatrix} -E^TNE & E^TNE \\ E^TNE & -E^TNE \end{bmatrix} \begin{bmatrix} x(t) \\ x(t-\tau) \end{bmatrix}$$

Then

$$\dot{V}_1(t) \leq \xi_1^T(t)\Theta_2\xi_1(t)$$

where

$$\xi_1^T(t) = \begin{bmatrix} x^T(t) & x^T(t-\tau) \end{bmatrix}$$

$$\Theta_2 = \begin{bmatrix} \Phi_7 & \Phi_8 \\ * & \Phi_9 \end{bmatrix} \tag{8}$$

and

$$\begin{aligned} \Phi_7 &= \bar{A}^TP + P^T\bar{A} + W - E^TNE + \tau^2\bar{A}^TN\bar{A} \\ \Phi_8 &= P^T\bar{A}_d + E^TNE + \tau^2\bar{A}^TN\bar{A}_d \\ \Phi_9 &= -W - E^TNE + \tau^2\bar{A}_d^TN\bar{A}_d \end{aligned}$$

According to (5) and Lemma 3,

$$\begin{bmatrix} \Phi_{10} & P^T\bar{A}_d + E^T NE & \Phi_3 & \tau\bar{A}^T N \\ * & \Phi_4 & 0 & \tau\bar{A}_d^T N \\ * & * & \Phi_5 & \tau A_v^T N \\ * & * & * & -N \end{bmatrix} < 0 \tag{9}$$

where

$$\Phi_{10} = \bar{A}^T P + P^T \bar{A} + W - E^T NE$$

Left and right multiplying inequality (9) by $diag\{I, I, 0, 0, 0\}$ and its transpose, then

$$P^T(\bar{A} + \bar{A}_d) + (\bar{A} + \bar{A}_d)^T P < 0.$$

Combining (4), matrix paris $(E, \bar{A} + \bar{A}_d)$ is regular and impulse free, and P is nonsingular. Therefore, system (1) with $u(t) = 0$, $v(t) = 0$ is regular and impulse free.

Considering Schur complement, it's easily obtained that Θ_2 is less than zero, that is $\dot{V}_1(t) < 0$. Then the system is stable for all the admissible uncertainties, and the generalized quadratical stability is completed.

Next we will prove that system (1) with $u(t) = 0$ is strict passive.

Let

$$f_2(t) = \bar{A}x(t) + \bar{A}_d x(t-\tau) + A_v v(t)$$

By introducing the Lyapunov function:

$$\begin{aligned} V_2(t) = {} & x^T(t)E^T Px(t) + \int_{t-\tau}^{t} x^T(\xi)Wx(\xi)d\xi \\ & + \tau \int_{-\tau}^{0}\int_{t+\eta}^{t} f_2^T(\xi)Nf_2(\xi)d\xi d\eta \end{aligned} \tag{10}$$

As to arbitrary nonzero $v(t)$, the derivative of Lyapunov function $V_2(t)$ along system (1) is

$$\begin{aligned} \dot{V}_2(t) = {} & f_2^T(t)Px(t) + x^T(t)P^T f_2(t) + x^T(t)Wx(t) \\ & - x^T(t-\tau)Wx(t-\tau) + \tau^2 f_2^T(t)Nf_2(t) \\ & - \tau \int_{t-\tau}^{t} f_2^T(\xi)Nf_2(\xi)d\xi \end{aligned} \tag{11}$$

By using of Jensen integral inequality, it holds that

$$\dot{V}_2(t) \le \xi_2^T(t)\Theta_4\xi_2(t),$$

where

$$\xi_2^T(t) = \begin{bmatrix} x^T(t) & x^T(t-\tau) & v^T(t) \end{bmatrix}$$

$$\Theta_4 = \begin{bmatrix} \Phi_7 & \Phi_8 & P^TA_v + \tau^2\bar{A}^TNA_v \\ * & \Phi_9 & \tau^2\bar{A}_d^TNA_v \\ * & * & \tau^2A_v^TNA_v \end{bmatrix}$$

then

$$\dot{V}_2(t) - z^T(t)v(t) - v^T(t)z(t) \le \xi_2^T(t)\begin{bmatrix} \Phi_7 & \Phi_8 & \Phi_{11} \\ * & \Phi_9 & \tau^2\bar{A}_d^TNA_v \\ * & * & \tau^2A_v^TNA_v - D_1^T - D_1 \end{bmatrix}\xi_2(t)$$

where

$$\Phi_{11} = P^TA_v + \tau^2\bar{A}^TNA_v - L^T$$

Using (9) and Schur complement,

$$\dot{V}_2(t) - z^T(t)v(t) - v^T(t)z(t) \le 0.$$

Let $V(t) = 2V_2(t)$, according to the definition, the proof is completed.

4 State Feedback Passive Control

In this section, we will design the controller

$$u(t) = Kx(t)$$

such that the closed-loop system

$$\begin{aligned} E\dot{x}(t) &= (\bar{A} + BK)x(t) + \bar{A}_dx(t-\tau) + A_vv(t) \\ z(t) &= (L + DK)x(t) + D_1v(t) \end{aligned} \tag{12}$$

is delay-dependent passive. Following Theorem 7, the existing condition for the controller is presented as follows:

Theorem 8 Given the scalar $\lambda > 0$, if there exist scalars $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, positive definite matrices X, $\bar{W}$ and matrix Y such that

$$EX = X^T E^T \geq 0 \tag{13}$$

$$\begin{bmatrix} \Phi_{12} & \Phi_{13} & \Phi_{14} & \Phi_{15} & XN_1^T & \tau XN_1^T \\ * & \Phi_{16} & 0 & \tau\lambda XA_d^T & XN_2^T & \tau XN_2^T \\ * & * & \Phi_5 & \tau\lambda A_v^T & 0 & 0 \\ * & * & * & \Phi_{17} & 0 & 0 \\ * & * & * & * & -\varepsilon_1 I & 0 \\ * & * & * & * & * & -\varepsilon_2 I \end{bmatrix} < 0 \tag{14}$$

where

$$\begin{aligned} \Phi_{12} &= X^T A^T + AX + Y^T B^T + BY + \bar{W} - \lambda EX^T E^T + \varepsilon_1 HH^T \\ \Phi_{13} &= A_d X + \lambda EX^T E^T \\ \Phi_{14} &= A_v - X^T L^T - Y^T D^T \\ \Phi_{15} &= \tau\lambda(AX + BY)^T \\ \Phi_{16} &= -\bar{W} - \lambda EX^T E^T \\ \Phi_{17} &= -\lambda X + \varepsilon_2 \lambda^2 HH^T \end{aligned}$$

Then $u(t) = Kx(t)$ is the passive controller for system (1), and the controller gain is $K = YX^{-1}$.

Proof According to Theorem 7, if system (12) is robust stable and strictly dissipative, then it satisfies that the inequality (4) and the following LMI:

$$\begin{bmatrix} \Phi_{18} & P^T \bar{A}_d + E^T NE & \Phi_{19} & \tau(\bar{A} + BK)^T N \\ * & \Phi_4 & 0 & \tau \bar{A}_d^T N \\ * & * & \Phi_5 & \tau A_v^T N \\ * & * & * & -N \end{bmatrix} < 0 \tag{15}$$

where

$$\begin{aligned} \Phi_{18} &= (\bar{A} + BK)^T P + P^T(\bar{A} + BK) + W - E^T NE \\ \Phi_{19} &= P^T A_v - (L + DK)^T \end{aligned}$$

The uncertainties is contained in the inequality (15), next we will deal with the uncertainties. According to Lemma 6 and Schur complement, inequality (15) is equal to the inequality (16) as follows:

$$\begin{bmatrix} \Phi_{20} & \Phi_2 & \Phi_{19} & \Phi_{21} & N_1^T & \tau N_1^T \\ * & \Phi_4 & 0 & \tau A_d^T N & N_2^T & \tau N_2^T \\ * & * & \Phi_5 & \tau A_v^T N & 0 & 0 \\ * & * & * & \Phi_{22} & 0 & 0 \\ * & * & * & * & -\varepsilon_1 I & 0 \\ * & * & * & * & * & -\varepsilon_2 I \end{bmatrix} < 0 \tag{16}$$

where

$$\begin{aligned}\varPhi_{20} &= A^T P + P^T A + K^T B^T P + P^T BK + W \\ &\quad - E^T NE + \varepsilon_1 P^T HH^T P \\ \varPhi_{21} &= \tau(A + BK)^T N \\ \varPhi_{22} &= -N + \varepsilon_2 NHH^T N\end{aligned}$$

Let $N = \lambda P$, and $\lambda > 0$ is the scalar parameter. Left and right multiplying the inequality (16) by the matrix $diag\{P^{-T}, P^{-T}, I, I, P^{-T}, I, I\}$ and $diag\{P^{-1}, P^{-1}, I, I, P^{-1}, I, I\}$, respectively. Then let

$$X = P^{-1}, Y = KX, \bar{W} = X^T WX \tag{17}$$

By using of inequality (13) and simple computation, inequality (14) is easily obtained. Therefore, the controller gain is $K = YX^{-1}$.

Since the term $E^T NE$ is contained in the inequality (16). the controller gain could not easily obtained by left and right multiplying (16) with some nonsingular matrices directly. The controller could be presented well by introducing $N = \lambda P$, which will be shown in the following simulation example. The slack variable λ is of some flexibility, the obtained maximum time-delay is changed by λ. And the conservativeness is reduced in some degree, which could be illustrated in the following section.

5 Numerical Examples

To demonstrate the effectiveness and applicability of the proposed method, a simple example is presented in this section. Attention is focused on the controller synthesis for the uncertain time-delay descriptor systems.

Consider time-delay system (1) with the following parameters:

$$E = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, A = \begin{bmatrix} 7 & -2.3 \\ 4 & 2 \end{bmatrix}, A_d = \begin{bmatrix} 2.4 & 1 \\ 4.1 & 0.6 \end{bmatrix}, A_v = \begin{bmatrix} 0.6 & 1.4 \\ -1.8 & 2 \end{bmatrix},$$

$$B = \begin{bmatrix} 5 & 8 \\ 2 & -6 \end{bmatrix}, D = \begin{bmatrix} 8 & 2 \\ -4 & 3.5 \end{bmatrix}, D_1 = \begin{bmatrix} 0.4 & 2.3 \\ -1.6 & 0.5 \end{bmatrix}, L = \begin{bmatrix} 1.5 & 0.7 \\ 3 & 2 \end{bmatrix},$$

$$H = \begin{bmatrix} 0.1 & 0 \\ 0.5 & 0.1 \end{bmatrix}, N_1 = \begin{bmatrix} 0.5 & -1 \\ 0 & 0.6 \end{bmatrix}, N_2 = \begin{bmatrix} 0.2 & 1 \\ 1 & 0.3 \end{bmatrix}.$$

The objective here is to design a set of state feedback controllers such that the closed-loop system is robust stable and strictly dissipative for all admissible uncertainties. Here, assume that $\lambda = 0.1$, using the LMI toolbox of Matlab to solve the inequalities (13), (14), the maximum time-delay $\tau = 0.32$ could be obtained, and

$$X = \begin{bmatrix} 0.0789 & 0 \\ 0 & 0.4730 \end{bmatrix}, Y = \begin{bmatrix} -0.0754 & -0.1322 \\ -0.2300 & 0.3297 \end{bmatrix}, \bar{W} = \begin{bmatrix} 00050 & -0.0051 \\ -0.0051 & 0.0079 \end{bmatrix},$$
$$\varepsilon_1 = 0.0151, \varepsilon_2 = 0.0550.$$

Then the corresponding passive controller is:

$$u(t) = Kx(t) = \begin{bmatrix} -0.9563 & -0.2795 \\ -2.9156 & 0.6971 \end{bmatrix} x(t). \tag{18}$$

In order to see the relationship between the maximum time-delay and the slack variable λ, we solve the convex optimization problem (13), (14) using different values of λ, which is shown in Table 1.

It shows in Table 1 that the different τ could be obtained by choosing different λ, and the smaller with λ, the bigger with τ.

Table 1. τ using different λ

λ	0.01	0.05	0.1	0.2	0.5
τ	0.87	0.44	0.32	0.22	0.14

6 Numerical Examples

Delay-dependent strictly passive control problem has been studied for a class of uncertain descriptor systems. By using the linear matrix inequality and integral inequality techniques, sufficient condition for system to be generalized quadratically stable and strictly passive has been derived. And the sufficient condition is composed of a set of delay dependent linear matrix inequality. By introducing a slack invariable, the corresponding strictly passive state feedback controller is designed. The numerical example illustrates that different λ could get different maximum delay upper bound.

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