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뉴트럴 시간지연 시스템의 강인 지연의존 안정성 해석을 위한 새로운 리아프노프 함수법

A New Augmented Lyapunov Functional Approach to Robust Delay-dependent Stability Analysis for Neutral Time-delay Systems

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Abstract - This paper propose a new delay-dependent stability criterion of neutral time-delay systems. By employing double-integral terms in augmented states and constructing a new Lyapunov-Krasovskii's functional, a delay-dependent stability criterion is established in terms of Linear Matrix Inequality. Through numerical examples, the validity and improvement results obtained by applying the proposed stability criterion will be shown.

Key Words : Neutral systems, Time-delay, Stability, Lyapunov method, Linear Matrix Inequality(LMI).

1. Introduction

During the last two decades, the stability analysis of time-delay systems has been given a great interest and many important methods have been proposed since time-delay occurs in various systems such as chemical processes, large-scale systems, neural networks, synchronization between two chaotic systems, networked control systems, and so on. For examples, see [1]-[17] and references therein. In the field of stability analysis of time-delay systems, one of the most important methods used to check the stability of time-delay systems is Lyapunov-Krasovskii's functional approach, which is a natural generalization of the classical Lyapunov stability theory for ordinary systems to the case of time-delay systems. These methods can be classified into two types: delay-dependent stability and delay-independent one. Recently, delay-dependent stability criteria have been paid more attraction than delay-independent ones because in general delay-dependent stability criteria, which include the information of the size of time-delay, provide a larger feasible region than delay-independent ones when the size of time-delay is small. Therefore, how to choose Lyapunov-Krasovskii's functionals and augmented variables and how to utilize appropriate bounding techniques play important roles to improve the feasible region of stability for time-delay systems.

In this regard, bounding technique of cross terms [3], descriptor system approach [4], neutral model transformation [5], free-weighting matrix techniques [6]-[7], augmented Lyapunov functional approach [12]-[13], [16]-[17] have given major contributions in this field.

Recently, triple-integral terms in the Lyapunov -Krasovskii's functionals were introduced in [13] and showed the improvement of feasible region of delay bounds. In [13], one-integral terms were included in augmented variables. If double-integral terms are used in augmented variables, can the results be improved? Also, to include double-integral terms in augmented variables, how to choose Lyapunov-Krasovskii's functionals?

With the motivation discussed above, in this paper, a new delay-dependent stability criterion for uncertain neutral time-delay systems, which have delays in both its state and the derivatives of the state, is proposed. By including double-integral terms in augmented variables and constructing a new Lyapunov-Krasovskii's functional, an improved delay-dependent stability criterion is derived in terms of LMI which can be solved efficiently by using various optimization algorithms such as interior-point ones [16]. Through two numerical examples, the effectiveness and improvement of proposed stability criterion is shown.

Throughout this paper, ★ represents the elements below the main diagonal of a symmetric matrix. The notation $X > Y$, where X and Y are matrices of same dimensions, means that the matrix $X - Y$ is positive definite, I denotes the identity matrix whose dimensions can be determined from the context. R^n is the n-dimensional Euclidean space, $R^{m \times n}$ denotes the set of $m \times n$ real matrix.

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2. Problem Statements

Consider the following neutral time-delay systems:

$$\dot{x}(t) - C\dot{x}(t-h) = (A+\Delta A(t))x(t) + (A_d + \Delta A_d(t))x(t-h), \quad x(s) = \phi(s), \quad \forall s \in [-h, 0], \tag{1}$$

where $x(t) \in \boldsymbol{R}^n$ is the state vector, A, $A_d, C \in \boldsymbol{R}^{n \times n}$ are known constant matrices with appropriate dimensions, $\phi(s) \in \boldsymbol{C}_{n,h}$ is a given continuous vector-valued initial function, h is a constant time-delay, $\Delta A(t)$ and $\Delta A_d(t)$ are the system uncertainties of the form

$$[\Delta A(t) \quad \Delta A_d(t)] = DF(t)[E_1 \quad E_2] \tag{2}$$

in which D, E_1, E_2 are known constant matrices and the time-varying nonlinear function $F(t)$ satisfies

$$F^T(t)F(t) \le I, \ \forall t \ge 0. \tag{3}$$

We assume that the spectral radius of the matrix C is less than one.
Now, the system (1) can be rewritten as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + A_d x(t-h) + C\dot{x}(t-h) + Dp(t), \\ p(t) &= F(t)q(t), \\ q(t) &= E_1 x(t) + E_2 x(t-h). \end{aligned} \tag{4}$$

The goal of this paper is to investigate a delay-dependent stability analysis of system (4) with time-invariant delay.

Before deriving our main results, we give the following useful lemmas.

Lemma 1 (Finsler's Lemma). [19] Let $\zeta \in R^n$, $\Phi = \Phi^T \in R^{n \times n}$, and $B \in R^{m \times n}$ such that $rank(B) < n$. The following statement is equivalent:

i) $\zeta^T \Phi \zeta < 0, \forall B\zeta = 0, \ \zeta \ne 0$,

ii) $(B^{\perp})^T \Phi B^{\perp} < 0$

where $B^{\perp}$ is a right orthogonal complement of B.

Lemma 2. [20] For any constant matrix $M \in \boldsymbol{R}^{n \times n}$, $M = M^T > 0$, a scalar $\gamma > 0$ and a vector function $x : [0, \gamma] \to \boldsymbol{R}^n$ such that the integrations concerned are well defined, then

$$\gamma \int_0^{\gamma} x^T(s) M x(s) ds \ge \left(\int_0^{\gamma} x(s) ds \right)^T M \left(\int_0^{\gamma} x(s) ds \right) \tag{5}$$

Lemma 3. From Lemma 1, the following integral inequalities can be easily obtained:

$$\begin{aligned} &(h^2/2) \int_{t-h}^{t} \int_s^t x^T(u) G x(u) du ds \\ &\ge \left(\int_{t-h}^{t} \int_s^t x(u) du ds \right)^T G \left(\int_{t-h}^{t} \int_s^t x(u) du ds \right) \end{aligned} \tag{6}$$

and

$$\begin{aligned} &(h^3/6) \int_{t-h}^{t} \int_s^t \int_u^t x^T(v) M x(v) dv du ds \\ &\ge \left(\int_{t-h}^{t} \int_s^t \int_u^t x(v) dv du ds \right)^T M \left(\int_{t-h}^{t} \int_s^t \int_u^t x(v) dv du ds \right) \end{aligned} \tag{7}$$

where G and M are positive definite matrices.

3. Main Results

In this section, we propose a new delay-dependent stability criterion for time-delay system (4). Before introducing our main results, the notations of several matrices are defined for the sake of simplicity:

$$\begin{aligned}
&\Sigma = [\Sigma^{(i)}_{(m,n)}], \ m = 1, \ldots, 7, \ n = 1, \ldots, 7, \\
&\Sigma_{(1,1)} = N_{11} + N_{23} + N_{23}^T - (h^2/2)^2 G + (h^2/2)^2 Q_{11} - h^2 Q_{22} + \varepsilon E_1^T E_1, \\
&\Sigma_{(1,2)} = -N_{23}^T + \varepsilon E_1^T E_2, \qquad \Sigma_{(1,3)} = R_{11} + N_{12} + (h^2/2)^2 Q_{12}, \\
&\Sigma_{(1,4)} = R_{12}, \quad \Sigma_{(1,5)} = N_{13}^T + hQ_{22}, \quad \Sigma_{(1,6)} = N_{33}^T - hQ_{12}^T + (h^2/2)G, \\
&\Sigma_{(1,7)} = 0, \qquad \Sigma_{(2,2)} = -N_{11} + \varepsilon E_2^T E_2, \qquad \Sigma_{(2,3)} = R_{12}^T, \\
&\Sigma_{(2,4)} = R_{22} - N_{12}, \quad \Sigma_{(2,5)} = -N_{13}, \quad \Sigma_{(2,6)} = 0, \quad \Sigma_{(2,7)} = 0, \\
&\Sigma_{(3,3)} = N_{22} + (h^2/2)^2 Q_{22} + (h^3/6)^2 G, \quad \Sigma_{(3,4)} = 0, \quad \Sigma_{(3,5)} = 0, \\
&\Sigma_{(3,6)} = 0, \quad \Sigma_{(3,7)} = 0, \quad \Sigma_{(4,4)} = -N_{22}, \quad \Sigma_{(4,5)} = -N_{23}, \quad \Sigma_{(4,6)} = 0, \\
&\Sigma_{(4,7)} = 0, \Sigma_{(5,5)} = -N_{33} - Q_{22}, \qquad \Sigma_{(5,6)} = Q_{12}^T, \qquad \Sigma_{(5,7)} = 0, \\
&\Sigma_{(6,6)} = -Q_{11} - G, \ \Sigma_{(6,7)} = 0, \ \Sigma_{(7,7)} = -\varepsilon I, \\
&\Gamma = [A \quad A_d \quad -I \quad C \quad 0 \quad 0 \quad D], \\
&\zeta^T(t) = \Big[x^T(t) \quad x^T(t-h) \quad \dot{x}^T(t) \quad \dot{x}^T(t-h) \quad \int_{t-h}^{t} x^T(s) ds \\
&\qquad \int_{t-h}^{t} \int_s^t x^T(u) du ds \quad p^T(t) \Big], \\
&\alpha^T(t) = [x^T(t) \quad x^T(t-h)], \\
&\beta^T(t,s) = \left[x^T(s) \quad \dot{x}^T(s) \quad \int_s^t x^T(u) du \right], \\
&\gamma^T(t) = [x^T(t) \quad \dot{x}^T(t-h)]
\end{aligned} \tag{8}$$

Then, we have the following theorem.

Theorem 1. For a given positive scalar h, the system (4) is asymptotically stable if there exist positive matrices $\boldsymbol{R} = [R_{ij}]_{2 \times 2}$, $\boldsymbol{N} = [N_{ij}]_{3 \times 3}$, $\boldsymbol{Q} = [Q_{ij}]_{2 \times 2}$, G, and positive scalar ε satisfying the following LMI:

$$(\Gamma^{\perp})^T \Sigma \Gamma^{\perp} < 0 \tag{9}$$

where Σ and Γ are defined in (8), and $\Gamma^{\perp}$ is the right orthogonal complement of Γ.

Proof. For positive definite matrices $\boldsymbol{R} = [R_{ij}]_{2 \times 2}$ $\boldsymbol{N} = [N_{ij}]_{3 \times 3}$, $\boldsymbol{Q} = [Q_{ij}]_{2 \times 2}$, and G, let us choose the following Lyapunov-Krasovskii's functional candidate:

$$V(t) = \sum_{i=1}^{4} V_i(t) \tag{10}$$

where

$$\begin{aligned}
V_1(t) &= \alpha^T(t) \boldsymbol{R} \alpha(t),, \\
V_2(t) &= \int_{t-h}^{t} \beta^T(t,s) \boldsymbol{N} \beta(t,s) ds, \\
V_3(t) &= (h^2/2) \int_{t-h}^{t} \int_s^t \int_u^t \gamma^T(v) \boldsymbol{Q} \gamma(v) dv du ds, \\
V_4(t) &= (h^3/6) \int_{t-h}^{t} \int_s^t \int_u^t \int_v^t \dot{x}^T(\lambda) G \dot{x}(\lambda) d\lambda dv du ds,
\end{aligned} \tag{11}$$

and $\alpha(t)$, $\beta(t)$, and $\gamma(t)$ are defined in (8).

First, the time-derivative of V_1 can be calculated as

$$\dot{V}_1 = 2\alpha^T(t)\boldsymbol{R}\alpha(t). \tag{12}$$

Second, the time-derivative of V_2 can be obtained as

$$\begin{aligned}\dot{V}_2 =\ & \beta^T(t,t)\boldsymbol{N}\beta(t,t) - \beta^T(t,t-h)\boldsymbol{N}\beta(t,t-h) \\ & + \int_{t-h}^{t} \frac{\partial}{\partial t}\{\beta^T(t,s)\boldsymbol{N}\beta(t,s)\}ds \\ =\ & \beta^T(t,t)\boldsymbol{N}\beta(t,t) - \beta^T(t,t-h)\boldsymbol{N}\beta(t,t-h) \\ & + \int_{t-h}^{t} 2\beta^T(t,s)\boldsymbol{N}\frac{\partial}{\partial t}\beta(t,s)ds \\ =\ & \beta^T(t,t)\boldsymbol{N}\beta(t,t) - \beta^T(t,t-h)\boldsymbol{N}\beta(t,t-h) \\ & + 2\left(\int_{t-h}^{t} x(s)ds\right)N_{13}x(t) \\ & + 2(x(t)-x(t-h))^T N_{23}x(t) \\ & + 2\left(\int_{t-h}^{t}\int_{s}^{t} x(u)duds\right)^T N_{33}x(t).\end{aligned} \tag{13}$$

Third, calculating the time-derivative of V_3 leads to

$$\begin{aligned}\dot{V}_3 =\ & (h^2/2)^2\gamma^T(t)\boldsymbol{Q}\gamma(t) - (h^2/2)\int_{t-h}^{t}\int_{s}^{t}\gamma^T(u)\boldsymbol{Q}\gamma(u)duds \\ \le\ & (h^2/2)^2\gamma^T(t)\boldsymbol{Q}\gamma(t) - \begin{bmatrix}\int_{t-h}^{t}\int_{s}^{t} x(u)duds \\ \int_{t-h}^{t}\int_{s}^{t}\dot{x}(u)duds\end{bmatrix}^T \\ & \times\boldsymbol{Q}\begin{bmatrix}\int_{t-h}^{t}\int_{s}^{t} x(u)duds \\ \int_{t-h}^{t}\int_{s}^{t}\dot{x}(u)duds\end{bmatrix} \\ =\ & (h^2/2)^2\gamma^T(t)\boldsymbol{Q}\gamma(t) - \begin{bmatrix}\int_{t-h}^{t}\int_{s}^{t} x(u)duds \\ hx(t) - \int_{t-h}^{t} x(s)ds\end{bmatrix}^T \\ & \times\boldsymbol{Q}\begin{bmatrix}\int_{t-h}^{t}\int_{s}^{t} x(u)duds \\ hx(t) - \int_{t-h}^{t} x(s)ds\end{bmatrix}.\end{aligned} \tag{14}$$

Finally, the time-derivative of V_4 can be obtained as

$$\begin{aligned}\dot{V}_4 =\ & (h^3/6)^2\dot{x}^T(t)G\dot{x}(t) - (h^3/6)\int_{t-h}^{t}\int_{s}^{t}\int_{u}^{t}\dot{x}^T(v)G\dot{x}(v)dvduds \\ \le\ & (h^3/6)^2\dot{x}^T(t)G\dot{x}(t) - \left(\int_{t-h}^{t}\int_{s}^{t}\int_{u}^{t}\dot{x}(v)dvduds\right)^T \\ & \times G\left(\int_{t-h}^{t}\int_{s}^{t}\int_{u}^{t}\dot{x}(v)dvduds\right) \\ =\ & (h^3/6)^2\dot{x}^T(t)G\dot{x}(t) - \left((h^2/2)x(t) - \int_{t-h}^{t}\int_{s}^{t} x(u)duds\right)^T \\ & \times G\left((h^2/2)x(t) - \int_{t-h}^{t}\int_{s}^{t} x(u)duds\right)\end{aligned} \tag{15}$$

Since the following inequality holds from (3) and (4),

$$p^T(t)p(t) \le q^T(t)q(t), \tag{16}$$

there exists a positive scalar ε, satisfying the following inequality

$$\varepsilon\left[q^T(t)q(t) - p^T(t)p(t)\right] \ge 0. \tag{17}$$

From (10)-(17) and by the application of S-procedure [18], an upper bound of $\dot{V} = \sum_{i=1}^{4}\dot{V}_i$ can be obtained as

$$\dot{V} \le \zeta^T(t)\Sigma\zeta(t), \tag{18}$$

where $\zeta(t)$ and Σ are defined in (8).

In addition, the system (4) can be rewritten as $\Gamma\zeta(t) = 0$ where Γ is defined in (8). By lemma 1, the inequality $\zeta^T(t)\Sigma\zeta(t) < 0$ with $\Gamma\zeta(t) = 0$ is equivalent to the inequality $(\Gamma^{\perp})^T\Sigma\Gamma^{\perp} < 0$. Therefore, if the LMI (9) holds for all $\zeta(t)$ such that $\Gamma\zeta(t) = 0$, then the system (4) is asymptotically stable. This completes our proof. ■

Remark 1. Recently, triple-integral form of Lyapunov-Krasovskii's functional $V_3(t)$ in Eq. (11) was proposed in [13]. However, unlike Eq. (6) in [13], the double-integral of Lyapunov-Krasovskii's functional is not considered in this paper. Instead, more information which includes double integral term $\int_{t-h}^{t}\int_{s}^{t} x(u)duds$ was utilized in the proposed augmented variable $\zeta(t)$. Also, quadrable-integral form of Lyapunov-Krasovskii's functional is proposed for the first time. With the augmented variable $\zeta(t)$ in Eq. (8), the proposed Lyapunov-Krasovskii's functional has not been considered up to now. Through numerical examples, Theorem 1 can provide less conservative results than the one by Theorem 1 in [13].

4. Numerical Examples

In this section, we provide two examples to show the less conservativeness of the proposed new stability criterion in this paper.

Example 1. Consider a practical example of Partial Element Equivalent Circuit (PEEC) model which can be represented by

$$\dot{x}(t) = Ax(t) + A_d x(t-h) + C\dot{x}(t-h) \tag{19}$$

with

$$A = 100\times\begin{bmatrix}\beta & 1 & 2 \\ 3 & -9 & 0 \\ 1 & 2 & -6\end{bmatrix},\ A_d = 100\times\begin{bmatrix}1 & 0 & -3 \\ -0.5 & -0.5 & -1 \\ -0.5 & -1.5 & 0\end{bmatrix},$$

$$C = \frac{1}{72}\times\begin{bmatrix}-1 & 5 & 2 \\ 4 & 0 & 3 \\ -2 & 4 & 1\end{bmatrix}.$$

For $\beta = -2.105, -2.103$, and -2.1, the maximum delay bounds for guaranteeing system (19) asymptotically stable were investigated in [12]. Also, by Theorem 1 of [13], the maximum delay bounds can be obtained and are listed in Table 1. From Table 1, the results obtained by Theorem 1 of this paper provide larger delay bounds than those obtained by Theorem 1 [12] and [13].

표 1 예제 1에서 다양한 β 값에 따른 h의 상한 값

Table 1 Upper bounds of time-delay with different β (Example 1).

β	-2.105	-2.103	-2.1
Ref. [12]	1.3075	0.4440	0.2902
Ref. [13]	1.4483	0.4917	0.3214
Theorem 1	1.4839	0.5028	0.3281

Example 2. Consider the following system

$$\dot{x}(t) - C\dot{x}(t-h) = (A + \Delta A(t))x(t) + (A_d + \Delta A_d(t))x(t-h), \quad (20)$$

where

$$A = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix}, \ A_d = \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix}$$

$$C = \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}, \quad D = I, \quad E_1 = E_2 = 0.2I.$$

When c is 0, 0.1, 0.2, 0.3, and 0.4, maximum delay bounds obtained by the previous results [14]-[17] and our results are listed as Table 2. From Table 2, one can see that Theorem 1 provides larger delay bounds than the other ones in [14]-[17].

표 2 예제 2에서 다양한 c 값에 따른 h의 상한 값

Table 2 Upper bounds of time-delay with different c(Example 2).

c	0	0.1	0.2	0.3	0.4
Ref. [14]	2.39	1.89	1.48	1.15	0.87
Ref. [15]	2.39	2.06	1.76	1.48	1.22
Ref. [16]	2.43	2.24	2.03	1.78	1.50
Ref. [17]	2.475	2.281	2.047	1.790	1.508
Theorem 1	2.7822	2.5423	2.2669	1.9594	1.6245

5. Conclusions

In this paper, a new delay-dependent stability criterion for neutral time-delay systems was proposed. By introducing double integral terms of states, a new augmented Lyapunov-Krasovskii's functional was proposed and the stability criterion was derived in terms of LMI. Through two numerical examples, our results gives larger delay bound than the recent existing ones.

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