Research Article

Simplified Stability Criteria for Delayed Neutral Systems

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For a class of linear time-invariant neutral systems with neutral and discrete constant delays, several existing asymptotic stability criteria in the form of linear matrix inequalities (LMIs) are simplified by using matrix analysis techniques. Compared with the original stability criteria, the simplified ones include fewer LMI variables, which can obviously reduce computational complexity. Simultaneously, it is theoretically shown that the simplified stability criteria and original ones are equivalent; that is, they have the same conservativeness. Finally, a numerical example is employed to verify the theoretic results investigated in this paper.

1. Introduction

Some practical systems, such as population ecology, neural networks, heat exchangers, and robots in contract with rigid environments, have been modeled by functional differential equations of neutral type (e.g., [1–6]). Since stability analysis is the primary task of analyzing and synthesizing a system, many researchers have paid more and more attention to establish stability criteria for delayed neutral systems (see [7, 8] and the references therein).

For a class of linear time-invariant neutral systems with neutral and discrete constant delays, both neutral- and discrete-delay-dependent stability criteria have been investigated in [9–27]. Many approaches have been provided for obtaining these stability criteria. Here we mention only some critical and representative approaches. Model transformation approach first transforms the neutral system with discrete delay into the one with distributed delays, and then delay-dependent stability criteria can be obtained by constructing a Lyapunov-Krasovskii functional [9]. However, model transformation approach introduces some additional dynamics, which leads still to conservative results [28]. To overcome this shortage, the so-called descriptor model transformation approach is introduced in [15, 24], which transforms the original system to an equivalent descriptor form. The descriptor model transformation approach will not introduce additional dynamics in the sense defined in [28]. Although

the results obtained from descriptor model transformation approach may be less conservative than some existing ones, they can be improved by employing some other approaches (e.g., free weighting matrix approach [21, 22] and augmented Lyapunov-Krasovskii functional approach [14, 23, 27]) to get a larger bound for discrete delay.

By employing free weighting matrices and the Leibniz-Newton formula, He et al. [21] presented a neutral- and discrete-delay-dependent stability criterion for neutral systems with neutral and discrete constant delays, which reduces the conservativeness of methods involving a fixed model transformation. For the same system models, Qian et al. [27] established neutral- and discrete-delay-dependent stability criteria by constructing a Lyapunov-Krasovskii functional with additional functional parameters and employing free weighting matrices. To the best of our knowledge, the large-scale employment of functional parameters and/or free weighting matrices can cause complex stability criteria, and thereby the computational complexity increases obviously. Therefore, in order to reduce computational complexity, it is necessary to reduce the number of functional parameters and free weighting matrices. This motivates the present study.

The aim of this paper is to simplify several stability criteria proposed by He et al. [21] and Qian et al. [27]. The main contributions of the paper are as follows. (i) In the premise of not increasing conservativeness, a pair of stability criteria proposed in [27, Theorem 1 and Corollary 1] are

simplified by using matrix analysis techniques; (ii) one of the pair of simplified stability criteria is theoretically presented to be less conservative than [26, Corollary 1], and another is theoretically proven to be equivalent to [21, Theorem 1]; and (iii) by one numerical example, our theoretic results are verified to be more effective than many existing results.

2. Problem Statement and Preliminary Results

Consider a class of delayed neutral systems described as

$$\dot{x}(t) - C\dot{x}(t - \eta) = Ax(t) + A_1x(t - \tau), \quad t \geq 0, \quad (1a)$$

$$x(t) = \phi(t), \quad t \in [-\omega, 0], \quad (1b)$$

where $x(t)$ is the n -dimensional state vector, A , A_1 , and C are known real constant matrices with appropriate dimensions, $\omega = \max\{\eta, \tau\}$, $\phi(s)$ is an $\mathbb{R}^n$ -valued continuous initial function defined on $[-\omega, 0]$, and positive scalars η and τ represent the neutral and discrete delays, respectively.

Define $C([- \eta, 0], \mathbb{R}^n)$ as the set of continuous $\mathbb{R}^n$ valued function on the interval $[- \eta, 0]$, and let $x_t \in C([- \eta, 0], \mathbb{R}^n)$ be a segment of system trajectory defined as

$$x_t(\theta) = x(t + \theta), \quad \theta \in [- \eta, 0]. \quad (2)$$

Define an operator $\mathcal{D} : C([- \eta, 0], \mathbb{R}^n) \rightarrow \mathbb{R}^n$ by $\mathcal{D}x_t = x(t) - Cx(t - \eta)$. The definitions on stability of operator $\mathcal{D}$ and systems (1a) and (1b) can be seen in [29].

As mentioned in Introduction, neutral- and discrete-delay-dependent stability criteria for systems (1a) and (1b) have been investigated by He et al. [21] and Qian et al. [27]. In this paper, we will simplify the stability criteria [21, Theorem 1] and [27, Theorem 1 and Corollary 1] in the premise of not increasing conservativeness of stability criteria.

In order to present conveniently our main results, the following lemmas are required.

Lemma 1 (Schur complement lemma [30]). *Given constant matrices Ω_1 , Ω_2 , and Ω_3 of appropriate dimensions, where $\Omega_1^T = \Omega_1$ and $\Omega_2^T = \Omega_2$, then*

$$\Omega_1 + \Omega_3^T \Omega_2^{-1} \Omega_3 < 0 \quad (3)$$

if and only if

$$\begin{bmatrix} \Omega_1 & \Omega_3^T \\ \Omega_3 & -\Omega_2 \end{bmatrix} < 0 \quad \text{or} \quad \begin{bmatrix} -\Omega_2 & \Omega_3 \\ \Omega_3^T & \Omega_1 \end{bmatrix} < 0. \quad (4)$$

Lemma 2 (see [31]). *Given a real symmetric matrix Ψ and a pair of real matrices P and Q , the following LMI problem*

$$\Psi + P^T X^T Q + Q^T X P < 0 \quad (5)$$

is solvable with respect to decision variable X if and only if

$$\mathcal{N}_P^T \Psi \mathcal{N}_P < 0, \quad \mathcal{N}_Q^T \Psi \mathcal{N}_Q < 0, \quad (6)$$

where $\mathcal{N}_P$ and $\mathcal{N}_Q$ are matrices whose columns form a basis of the right null spaces of P and Q , respectively.

3. Several Stability Criteria in the Literature

In this section we introduce several existing stability criteria for systems (1a) and (1b), which will be useful to present conveniently the main results of this paper in the next section.

Proposition 3 (see [21, Theorem 1]). *For given scalars $\tau > 0$ and $\eta > 0$, systems (1a) and (1b) are asymptotically stable, if the operator $\mathcal{D}$ is stable and there exist real $n \times n$ matrices $P^T = P > 0$, $Q_i^T = Q_i > 0$ ($i = 1, 2$), $R^T = R > 0$, $\check{X}_{ii}^T = \check{X}_{ii}$, $\check{Y}_{ii} = \check{Y}_{ii}$ ($i = 1, \dots, 5$), $\check{X}_{ij}$, and $\check{Y}_{ij}$ ($1 \leq i < j \leq 5$) such that the following LMIs are feasible:*

$$\begin{bmatrix} \check{X} & \check{X}_5^T \\ \check{X}_5 & \check{X}_{55} \end{bmatrix} \geq 0, \quad \begin{bmatrix} \check{Y} & \check{Y}_5^T \\ \check{Y}_5 & \check{Y}_{55} \end{bmatrix} \geq 0, \quad (7)$$

$$\begin{bmatrix} \check{\Phi} + \tau \check{X} + \eta \check{Y} + \check{\Phi}_X + \check{\Phi}_Y & \check{A}^T S \\ S \check{A} & -S \end{bmatrix} < 0, \quad (8)$$

where

$$\begin{aligned} \check{X} &= \begin{bmatrix} \check{X}_{11} & \check{X}_{12} & \check{X}_{13} & \check{X}_{14} \\ \check{X}_{12}^T & \check{X}_{22} & \check{X}_{23} & \check{X}_{24} \\ \check{X}_{13}^T & \check{X}_{23}^T & \check{X}_{33} & \check{X}_{34} \\ \check{X}_{14}^T & \check{X}_{24}^T & \check{X}_{34}^T & \check{X}_{44} \end{bmatrix}, \\ \check{Y} &= \begin{bmatrix} \check{Y}_{11} & \check{Y}_{12} & \check{Y}_{13} & \check{Y}_{14} \\ \check{Y}_{12}^T & \check{Y}_{22} & \check{Y}_{23} & \check{Y}_{24} \\ \check{Y}_{13}^T & \check{Y}_{23}^T & \check{Y}_{33} & \check{Y}_{34} \\ \check{Y}_{14}^T & \check{Y}_{24}^T & \check{Y}_{34}^T & \check{Y}_{44} \end{bmatrix}, \\ \check{X}_5 &= [\check{X}_{15}^T \quad \check{X}_{25}^T \quad \check{X}_{35}^T \quad \check{X}_{45}^T], \\ \check{Y}_5 &= [\check{Y}_{15}^T \quad \check{Y}_{25}^T \quad \check{Y}_{35}^T \quad \check{Y}_{45}^T], \end{aligned} \quad (9)$$

$$\check{\Phi}_X = \check{X}_5^T \Pi_1 + \Pi_1^T \check{X}_5, \quad \check{\Phi}_Y = \check{Y}_5^T \Pi_2 + \Pi_2^T \check{Y}_5,$$

$$\Pi_1 = [I_n \quad -I_n \quad 0 \quad 0],$$

$$\Pi_2 = [I_n \quad 0 \quad -I_n \quad 0], \quad S = R + \tau \check{X}_{55} + \eta \check{Y}_{55},$$

$$\check{A} = [A \quad A_1 \quad 0 \quad C],$$

$$\check{\Phi} = \begin{bmatrix} \check{\Phi}_{11} & PA_1 & -A^T PC & 0 \\ A_1^T P & -Q_1 & -A_1^T PC & 0 \\ -C^T PA & -C^T PA_1 & -Q_2 & 0 \\ 0 & 0 & 0 & -R \end{bmatrix},$$

$$\check{\Phi}_{11} = PA + A^T P + Q_1 + Q_2.$$

Proposition 4 (see [27, Theorem 1]). *For given scalars $\tau > 0$ and $\eta > 0$, systems (1a) and (1b) are asymptotically stable, if*

the operator $\mathcal{D}$ is stable and there exist real $n \times n$ matrices U , $P^T = P$, $W^T = W$, $Q_k^T = Q_k$, $N_k^T = N_k$, $R_k^T = R_k$, $T_k^T = T_k$, M_k , Z_k ($k = 1, 2$), E_i , F_i , H_i , Y_{ij} ($i = 1, \dots, 5$), and Y_{ij} ($1 \leq i < j \leq 5$) such that the following LMIs are feasible:

$$\begin{bmatrix} R_2 & Z_2 \\ Z_2^T & T_2 \end{bmatrix} \geq 0, \quad (10)$$

$$Q_k \geq 0, \quad k = 1, 2, \quad (11)$$

$$W > 0, \quad \begin{bmatrix} R_1 & Z_1 \\ Z_1^T & T_1 \end{bmatrix} > 0, \quad (12)$$

$$\begin{bmatrix} P & M_1 & M_2 \\ M_1^T & \tau^{-1}Q_1 + N_1 & U^T \\ M_2^T & U & \eta^{-1}Q_2 + N_2 \end{bmatrix} > 0, \quad (13)$$

$$\Xi := \begin{bmatrix} \Phi + \eta Y & \tau G_1 & -\tau F \\ \tau G_1^T & -\tau R_1 & -\tau Z_1 \\ -\tau F^T & -\tau Z_1^T & -\tau T_1 \end{bmatrix} < 0, \quad (14)$$

$$\Omega := \begin{bmatrix} Y & -G_2 & H \\ -G_2^T & R_2 & Z_2 \\ H^T & Z_2^T & T_2 \end{bmatrix} \geq 0, \quad (15)$$

where

$$\Phi = \begin{bmatrix} \Phi_{11} & \cdots & \Phi_{15} \\ \cdots & \cdots & \cdots \\ \Phi_{15}^T & \cdots & \Phi_{55} \end{bmatrix}, \quad Y = \begin{bmatrix} Y_{11} & \cdots & Y_{15} \\ \cdots & \cdots & \cdots \\ Y_{15}^T & \cdots & Y_{55} \end{bmatrix},$$

$$F = \begin{bmatrix} F_1 \\ \vdots \\ F_5 \end{bmatrix}, \quad H = \begin{bmatrix} H_1 \\ \vdots \\ H_5 \end{bmatrix},$$

$$\begin{aligned} \Phi_{11} &= PA + A^T P + Q_1 + Q_2 + \tau R_1 + \eta R_2 \\ &\quad + M_1 + M_1^T + M_2 + M_2^T + F_1 + F_1^T \\ &\quad + H_1 + H_1^T - E_1 A - A^T E_1^T, \end{aligned}$$

$$\Phi_{12} = PA_1 - M_1 + H_2^T - A^T E_2^T + F_2^T - F_1 - E_1 A_1,$$

$$\begin{aligned} \Phi_{13} &= -A^T PC - M_1^T C - M_2^T C - M_2 \\ &\quad - H_1 + H_3^T + F_3^T - A^T E_3^T, \end{aligned}$$

$$\Phi_{14} = -A^T E_4^T + E_1 + F_4^T + H_4^T + \tau Z_1 + \eta Z_2,$$

$$\Phi_{15} = -A^T E_5^T + F_5^T + H_5^T - E_1 C,$$

$$\Phi_{22} = -Q_1 - E_2 A_1 - A_1^T E_2^T - F_2 - F_2^T,$$

$$\Phi_{23} = -A_1^T PC + M_1^T C - H_2 - F_3^T - A_1^T E_3^T,$$

$$\Phi_{24} = E_2 - A_1^T E_4^T - F_4^T, \quad \Phi_{25} = -E_2 C - A_1^T E_5^T - F_5^T,$$

$$\Phi_{33} = -Q_2 + C^T M_2 + M_2^T C - H_3 - H_3^T,$$

$$\Phi_{34} = E_3 - H_4^T,$$

$$\Phi_{35} = -E_3 C - H_5^T, \quad \Phi_{44} = E_4 + E_4^T + W + \tau T_1 + \eta T_2,$$

$$\Phi_{45} = -E_4 C + E_5^T, \quad \Phi_{55} = -W - E_5 C - C^T E_5^T,$$

$$G_1 = [N_1 + U^T \quad -N_1 \quad -U^T \quad M_1^T \quad -M_1^T C]^T,$$

$$G_2 = [N_2 + U \quad -U \quad -N_2 \quad M_2^T \quad -M_2^T C]^T.$$

(16)

Proposition 5 (see [27, Corollary 1]). When $\eta = \tau$, for a given scalar $\tau > 0$, systems (1a) and (1b) are asymptotically stable, if the operator $\mathcal{D}$ is stable and there exist real $n \times n$ matrices $W^T = W > 0$, $Q_1^T = Q_1 > 0$, $P^T = P$, $N_1^T = N_1$, $R_1^T = R_1$, $T_1^T = T_1$, M_1 , Z_1 , E_i , and F_i ($i = 1, 2, 4, 5$) such that the following LMIs are feasible:

$$\begin{bmatrix} R_1 & Z_1 \\ Z_1^T & T_1 \end{bmatrix} > 0, \quad \begin{bmatrix} P & M_1 \\ M_1^T & \tau^{-1}Q_1 + N_1 \end{bmatrix} > 0, \quad (17)$$

$$\begin{bmatrix} \Pi_{11} & \Pi_{12} & \Pi_{13} & \Pi_{14} & \tau N_1 & -\tau F_1 \\ \Pi_{12}^T & \Pi_{22} & \Pi_{23} & \Pi_{24} & -\tau N_1 & -\tau F_2 \\ \Pi_{13}^T & \Pi_{23}^T & \Pi_{33} & \Pi_{34} & \tau M_1 & -\tau F_4 \\ \Pi_{14}^T & \Pi_{24}^T & \Pi_{34}^T & \Pi_{44} & -\tau C^T M_1 & -\tau F_5 \\ \tau N_1 & -\tau N_1 & \tau M_1^T & -M_1^T C & -\tau R_1 & -\tau Z_1 \\ -\tau F_1^T & -\tau F_2^T & -\tau F_4^T & -\tau F_5^T & -\tau Z_1^T & -\tau T_1 \end{bmatrix} < 0, \quad (18)$$

where

$$\begin{aligned} \Pi_{11} &= PA + A^T P + M_1 + M_1^T + Q_1 + \tau R_1 \\ &\quad + F_1 + F_1^T - E_1 A - A^T E_1^T, \end{aligned}$$

$$\begin{aligned} \Pi_{12} &= PA_1 - A^T PC - M_1 - M_1^T C \\ &\quad - A^T E_2^T - E_1 A_1 + F_2^T - F_1, \end{aligned}$$

$$\Pi_{13} = -A^T E_4^T + E_1 + F_4^T + \tau Z_1,$$

$$\Pi_{14} = -A^T E_5^T + F_5^T - E_1 C,$$

$$\begin{aligned} \Pi_{22} &= -Q_1 - A_1^T PC - C^T PA_1 + C^T M_1 + M_1^T C \\ &\quad - E_2 A_1 - A_1^T E_2^T - F_2 - F_2^T, \end{aligned}$$

$$\Pi_{23} = E_2 - A_1^T E_4^T - F_4^T, \quad \Pi_{24} = -E_2 C - A_1^T E_5^T - F_5^T,$$

$$\Pi_{33} = E_4 + E_4^T + \tau T_1 + W, \quad \Pi_{34} = -E_4 C + E_5^T,$$

$$\Pi_{44} = -E_5 C - C^T E_5^T - W.$$

(19)

Remark 6. Proposition 3 simplifies the notations in [21, Theorem 1].

Remark 7. Propositions 4 and 5 correct some slips of the pen in [27, Theorem 1 and Corollary 1]. After [27, Theorem 1] is amended as in Remark 7, [27, Theorem 2] will be correct.

4. Simplified Stability Criteria

In this section we will simplify the stability criteria introduced in the previous section. Firstly, the stability criterion presented in Proposition 4 can be simplified by the following theorem.

Theorem 8. For given scalars $\tau > 0$ and $\eta > 0$, systems (1a) and (1b) are asymptotically stable, if the operator $\mathcal{D}$ is stable and one of the following cases, (i)–(iv), holds.

- (i) There exist real $n \times n$ matrices $U, P^T = P, W^T = W, Q_k^T = Q_k, N_k^T = N_k, R_k^T = R_k, T_k^T = T_k, M_k, Z_k (k = 1, 2), E_i, F_i, H_i, Y_{ii} (i = 1, \dots, 5),$ and $Y_{ij} (1 \leq i < j \leq 5)$ such that the LMIs (10)–(15) hold.
- (ii) There exist real $n \times n$ matrices $U, P^T = P, W^T = W, Q_k^T = Q_k, N_k^T = N_k, R_k^T = R_k, T_k^T = T_k, M_k, Z_k (k = 1, 2), E_i, F_i, H_i, Y_{ii} (i = 1, \dots, 5),$ and $Y_{ij} (1 \leq i < j \leq 5)$ such that the LMIs (11)–(15) and the following LMI (20) hold:

$$\begin{bmatrix} R_2 & Z_2 \\ Z_2^T & T_2 \end{bmatrix} > 0. \quad (20)$$

- (iii) There exist real $n \times n$ matrices $U, P^T = P, W^T = W, Q_k^T = Q_k, N_k^T = N_k, R_k^T = R_k, T_k^T = T_k, M_k,$ and $Z_k (k = 1, 2)$ such that the LMIs (11), (12), and (13) and the following LMI (21) hold:

$$\begin{bmatrix} \Phi & \tau G_1 & -\tau F & -\eta G_2 & \eta H \\ \tau G_1^T & -\tau R_1 & -\tau Z_1 & 0 & 0 \\ -\tau F^T & -\tau Z_1^T & -\tau T_1 & 0 & 0 \\ -\eta G_2^T & 0 & 0 & -\eta R_2 & -\eta Z_2 \\ \eta H^T & 0 & 0 & -\eta Z_2^T & -\eta T_2 \end{bmatrix} < 0. \quad (21)$$

- (iv) There exist real $n \times n$ matrices $U, P^T = P, W^T = W, Q_k^T = Q_k, N_k^T = N_k, R_k^T = R_k, T_k^T = T_k, M_k,$ and $Z_k (k = 1, 2)$ such that the LMIs (11), (12), (13), and (20) and the following LMI (22) hold:

$$\tilde{\Sigma} := \begin{bmatrix} \tilde{\Phi} & \tilde{G}_1 & \tilde{G}_2 \\ \tilde{G}_1^T & -\tau R_1 & 0 \\ \tilde{G}_2^T & 0 & -\eta R_2 \end{bmatrix} < 0, \quad (22)$$

where

$$\tilde{\Phi} = \begin{bmatrix} \tilde{\Phi}_{11} & \tilde{\Phi}_{12} & \tilde{\Phi}_{13} & \tilde{\Phi}_{14} \\ \tilde{\Phi}_{12}^T & \tilde{\Phi}_{22} & \tilde{\Phi}_{23} & A_1^T S C \\ \tilde{\Phi}_{13}^T & \tilde{\Phi}_{23}^T & \tilde{\Phi}_{33} & 0 \\ \tilde{\Phi}_{14}^T & C^T S A_1 & 0 & C^T S C - W \end{bmatrix},$$

$$\begin{aligned} \tilde{\Phi}_{11} &= P A + A^T P + Q_1 + Q_2 + \tau R_1 + \eta R_2 + M_1 + M_1^T \\ &+ M_2 + M_2^T + A^T S A + \tau A^T Z_1^T + \tau Z_1 A \\ &+ \eta A^T Z_2^T + \eta Z_2 A - \tau^{-1} T_1 - \eta^{-1} T_2, \end{aligned}$$

$$\tilde{\Phi}_{12} = P A_1 - M_1 + \tau Z_1 A_1 + \eta Z_2 A_1 + A^T S A_1 + \tau^{-1} T_1,$$

$$\tilde{\Phi}_{13} = -A^T P C - M_1^T C - M_2^T C - M_2 + \eta^{-1} T_2,$$

$$\tilde{\Phi}_{14} = \tau Z_1 C + \eta Z_2 C + A^T S C,$$

$$\tilde{\Phi}_{22} = -Q_1 - \tau^{-1} T_1 + A_1^T S A_1, \quad \tilde{\Phi}_{23} = -A_1^T P C + M_1^T C,$$

$$\tilde{\Phi}_{33} = -Q_2 + C^T M_2 + M_2^T C - \eta^{-1} T_2,$$

$$S = W + \tau T_1 + \eta T_2,$$

$$\tilde{G}_1 = \begin{bmatrix} \tau N_1^T + \tau U - Z_1^T + \tau A^T M_1 \\ -\tau N_1^T + Z_1^T + \tau A_1^T M_1 \\ -\tau U \\ 0 \end{bmatrix},$$

$$\tilde{G}_2 = \begin{bmatrix} -\eta N_2^T - \eta U^T + Z_2^T - \eta A^T M_2 \\ \eta U^T - \eta A_1^T M_2 \\ \eta N_2^T - Z_2^T \\ 0 \end{bmatrix}.$$

(23)

Proof. Due to Proposition 4, it suffices to show that the conditions (i)–(iv) are equivalent.

(i) $\Rightarrow$ (ii) Since the eigenvalues of a matrix are continuous functions of its elements, it follows from (i) that there exists a sufficiently small positive scalar ϵ such that

$$\Xi + \text{diag}(\eta \epsilon I, 0, 0, \eta \epsilon I, 0, 0, 0) < 0,$$

$$\Omega + \text{diag}(0, \epsilon I, \epsilon I) \geq 0,$$

$$\begin{bmatrix} R_2 + \epsilon I & Z_2 \\ Z_2^T & T_2 + \epsilon I \end{bmatrix} > 0.$$

(24)

Therefore, the LMIs (11)–(15) and (20) are feasible.

(ii) $\Rightarrow$ (i) The proof is very easy, and hence it is omitted.

(ii)⇒(iii) By Lemma 1, it follows from (20) and (15) that

$$Y \geq [-G_2 \ H] \begin{bmatrix} R_2 & Z_2 \\ Z_2^T & T_2 \end{bmatrix}^{-1} [-G_2 \ H]^T. \quad (25)$$

This, together with (14) and Lemma 1, implies that (21) holds.

(iii)⇒(ii) It follows from (21) and Lemma 1 that (20) holds and

$$\begin{bmatrix} \Phi + \eta Y & \tau G_1 & -\tau F \\ \tau G_1^T & -\tau R_1 & -\tau Z_1 \\ -\tau F^T & -\tau Z_1^T & -\tau T_1 \end{bmatrix} < 0, \quad (26)$$

where

$$Y = [-G_2 \ H] \begin{bmatrix} R_2 & Z_2 \\ Z_2^T & T_2 \end{bmatrix}^{-1} [-G_2 \ H]^T, \quad (27)$$

and hence (ii) holds.

(iii)⇔(iv) Let

$$\tilde{F} = [F \ H \ E], \quad E = [E_1^T \ E_2^T \ E_3^T \ E_4^T \ E_5^T]^T,$$

$$K = [e_1^T \ e_2^T \ e_3^T \ e_4^T \ e_5^T]^T,$$

$$L = [(e_1 - e_2 - \tau e_7)^T \ (e_1 - e_3 + \eta e_9)^T \ \tilde{A}^T]^T, \quad (28)$$

$$\tilde{A} = [-A \ -A_1 \ 0 \ I \ -C \ 0_{n \times 4n}],$$

$$e_i = [0_{n \times (i-1)n} \ I \ 0_{n \times (9-i)n}]^T, \quad i = 1, 2, \dots, 9.$$

Then LMI (21) can be written as

$$\Phi_1 + K^T \tilde{F} L + L^T \tilde{F}^T K < 0, \quad (29)$$

where the matrix Φ_1 is obtained from the matrix on the left of (21) by deleting all parts containing one of F , H , and E (e.g., the (5, 5)th subblock of Φ_1 equals $-W$, which is obtained from Φ_{55} by deleting $-E_5 C - C^T E_5^T$). Choose

$$\mathcal{N}_K = [e_6^T \ e_7^T \ e_8^T \ e_9^T]^T, \quad (30)$$

$$\mathcal{N}_L = \begin{bmatrix} e_1 + A^T e_4 + \tau^{-1} e_7 - \eta^{-1} e_9 \\ e_2 + A_1^T e_4 - \tau^{-1} e_7 \\ e_3 + \eta^{-1} e_9 \\ C^T e_4 + e_5 \\ e_6 \\ e_8 \end{bmatrix}^T.$$

Noting that $\mathcal{N}_K^T \Phi_1 \mathcal{N}_K < 0$, one can derive from (12) and Lemma 2 that the LMI (29) (i.e., (21)) is feasible if and only if LMIs (22) and (20) are feasible.

The proof is completed. $\square$

Clearly, the stability condition (iv) in Theorem 8 is more simpler than (i) in Theorem 8 (i.e., Proposition 4). By a process similar to investigating Theorem 8, one can easily obtain the following theorem which simplifies the stability criterion presented in Proposition 5.

Theorem 9. When $\eta = \tau$, for a given scalar $\tau > 0$, systems (1a) and (1b) are asymptotically stable, if the operator $\mathcal{D}$ is stable, and one of the following cases, (i)-(ii), holds.

(i) There exist real $n \times n$ matrices $W^T = W > 0$, $Q_1^T = Q_1 > 0$, $P^T = P$, $N_1^T = N_1$, $R_1^T = R_1$, $T_1^T = T_1$, M_1 , Z_1 , E_i , and F_i ($i = 1, 2, 4, 5$) such that the LMIs (17) and (18) hold.

(ii) There exist real $n \times n$ matrices $W^T = W > 0$, $Q_1^T = Q_1 > 0$, $P^T = P$, $N_1^T = N_1$, $R_1^T = R_1$, $T_1^T = T_1$, M_1 , and Z_1 such that (17) and the following LMI (31) hold:

$$\begin{bmatrix} \tilde{\Pi}_{11} & \tilde{\Pi}_{12} & \tilde{\Pi}_{13} & \tilde{\Pi}_{14} \\ \tilde{\Pi}_{12}^T & \tilde{\Pi}_{22} & \tilde{\Pi}_{23} & \tilde{\Pi}_{24} \\ \tilde{\Pi}_{13}^T & \tilde{\Pi}_{23}^T & \tilde{\Pi}_{33} & 0 \\ \tilde{\Pi}_{14}^T & \tilde{\Pi}_{24}^T & 0 & -\tau R_1 \end{bmatrix} < 0, \quad (31)$$

where

$$\begin{aligned} \tilde{\Pi}_{11} &= PA + A^T P + M_1 + M_1^T + Q_1 + \tau R_1 \\ &\quad + \tau Z_1 A + \tau A^T Z_1^T + A^T S_0 A - \tau^{-1} T_1, \end{aligned}$$

$$\begin{aligned} \tilde{\Pi}_{12} &= PA_1 - A^T P C - M_1 - M_1^T C \\ &\quad + \tau Z_1 A_1 + A^T S_0 A_1 + \tau^{-1} T_1, \end{aligned}$$

$$\tilde{\Pi}_{13} = \tau Z_1 C + A^T S_0 C, \quad \tilde{\Pi}_{14} = \tau N_1 + \tau A^T M_1 - Z_1^T,$$

$$\begin{aligned} \tilde{\Pi}_{22} &= -Q_1 - A_1^T P C - C^T P A_1 + C^T M_1 \\ &\quad + M_1^T C + A_1^T S_0 A_1 - \tau^{-1} T_1, \end{aligned}$$

$$\tilde{\Pi}_{23} = A_1^T S_0 C, \quad \tilde{\Pi}_{24} = -\tau N_1 + \tau A_1^T M_1 + Z_1^T,$$

$$\tilde{\Pi}_{33} = C^T S_0 C - W, \quad S_0 = W + \tau T_1.$$

(32)

Remark 10. Theorems 8 and 9 indicate that, without increasing conservativeness of stability criteria, the free weighting matrices required in Propositions 4 and 5 (i.e., [27, Theorem 1 and Corollary 1]) can be eliminated. This will obviously reduce the computational complexity, and hence the stability conditions (iv) of Theorem 8 and (ii) of Theorem 9 are more effective.

Remark 11. In the special case that $M_1 = 0$, $N_1 = 0$, $Z_1 = 0$, and $R_1 = \epsilon I_n$ (ϵ is a sufficiently small positive number), Theorem 9 reduces to [26, Corollary 1]. So, by choosing suitable M_1 , N_1 , Z_1 , and R_1 , Theorem 9 could reduce the conservativeness of [26, Corollary 1], by which the improvement over [26, Corollary 1] is theoretically demonstrated.

If we choose $U = 0$, $M_i = 0$, $N_i = 0$, $Z_i = 0$, and $R_i = \epsilon I_n$ (ϵ is a sufficiently small positive number) ($i = 1, 2$) in Theorem 8, the following corollary can be easily derived.

Corollary 12. *For given scalars $\tau > 0$ and $\eta > 0$, systems (1a) and (1b) are asymptotically stable, if the operator $\mathcal{D}$ is stable and there exist real $n \times n$ matrices $P^T = P > 0$, $W^T = W > 0$, $Q_k^T = Q_k > 0$, and $T_k^T = T_k > 0$ ($k = 1, 2$) such that LMI (33) holds:*

$$\widehat{\Phi} := \begin{bmatrix} \widehat{\Phi}_{11} & \widehat{\Phi}_{12} & \widehat{\Phi}_{13} & A^T S C \\ \widehat{\Phi}_{12}^T & \widehat{\Phi}_{22} & \widehat{\Phi}_{23} & A_1^T S C \\ \widehat{\Phi}_{13}^T & \widehat{\Phi}_{23}^T & \widehat{\Phi}_{33} & 0 \\ C^T S A & C^T S A_1 & 0 & C^T S C - W \end{bmatrix} < 0, \quad (33)$$

where

$$\begin{aligned} \widehat{\Phi}_{11} &= P A + A^T P + Q_1 + Q_2 + A^T S A - \tau^{-1} T_1 - \eta^{-1} T_2, \\ \widehat{\Phi}_{12} &= P A_1 + A^T S A_1 + \tau^{-1} T_1, \quad \widehat{\Phi}_{13} = -A^T P C + \eta^{-1} T_2, \\ \widehat{\Phi}_{22} &= -Q_1 - \tau^{-1} T_1 + A_1^T S A_1, \quad \widehat{\Phi}_{23} = -A_1^T P C, \\ \widehat{\Phi}_{33} &= -Q_2 - \eta^{-1} T_2, \quad S = W + \tau T_1 + \eta T_2. \end{aligned} \quad (34)$$

Next we will show that the pair of stability criteria presented in Proposition 3 (i.e., [21, Theorem 1]) and Corollary 12 have the same conservativeness. However, the stability criterion presented in Corollary 12 is more simpler than the one in Proposition 3 (i.e., [21, Theorem 1]), which reduces greatly the computational complexity.

Theorem 13. *For given scalars $\tau > 0$ and $\eta > 0$, LMIs (7) and (8) are feasible if and only if the LMI (33) is feasible.*

Proof. The “Only If” Part. It follows from (7) and (8) that

$$\begin{aligned} \check{X} &\geq \check{X}_5^T \check{X}_{55}^{-1} \check{X}_5, \quad \check{Y} \geq \check{Y}_5^T \check{Y}_{55}^{-1} \check{Y}_5, \\ \check{\Phi} + \tau \check{X} + \eta \check{Y} + \check{\Phi}_X + \check{\Phi}_Y + \check{A}^T S \check{A} &< 0, \end{aligned} \quad (35)$$

and hence

$$\check{\Phi} + \tau \check{X}_5^T \check{X}_{55}^{-1} \check{X}_5 + \eta \check{Y}_5^T \check{Y}_{55}^{-1} \check{Y}_5 + \check{\Phi}_X + \check{\Phi}_Y + \check{A}^T S \check{A} < 0. \quad (36)$$

Noting that

$$\begin{aligned} \tau \check{X}_5^T \check{X}_{55}^{-1} \check{X}_5 + \check{\Phi}_X + \tau^{-1} \Pi_1^T \check{X}_{55} \Pi_1 &\geq 0, \\ \eta \check{Y}_5^T \check{Y}_{55}^{-1} \check{Y}_5 + \check{\Phi}_Y + \eta^{-1} \Pi_2^T \check{Y}_{55} \Pi_2 &\geq 0, \end{aligned} \quad (37)$$

one can conclude from (36) that

$$\check{\Phi} - \tau^{-1} \Pi_1^T \check{X}_{55} \Pi_1 - \eta^{-1} \Pi_2^T \check{Y}_{55} \Pi_2 + \check{A}^T S \check{A} < 0, \quad (38)$$

TABLE 1: The maximum allowable bounds of $\tau = \eta$.

Method	max τ
[9]	0.3
[10]	0.5658
[11]	0.5937
[12]	0.6054
[13]	0.6612
[14]	0.7039
[15]	0.74
[16]	0.8844
[17]	1.0402
[18]	1.3718
[19]	1.6014
[20]	1.61
[21]	1.6527
[22]	1.7191
[23]	1.7220
[24]	1.78
[25]	1.7844
[26, Corollary 1]	1.7856
[27] and Theorem 9	1.7890

which becomes LMI (33) by letting $W = R$, $T_1 = \check{X}_{55}$, and $T_2 = \check{Y}_{55}$. That is, LMI (33) is feasible.

The “If” Part. Since LMI (33) is feasible, there exist real $n \times n$ matrices $P^T = P > 0$, $W^T = W > 0$, $Q_k^T = Q_k > 0$, and $T_k^T = T_k > 0$ ($k = 1, 2$) such that LMI (33) is satisfied. Set $R = W$, $\check{X}_{55} = T_1$, and $\check{Y}_{55} = T_2$. Then it follows from (33) and Lemma 1 that

$$\begin{bmatrix} \check{\Phi} - \tau^{-1} \Pi_1^T \check{X}_{55} \Pi_1 - \eta^{-1} \Pi_2^T \check{Y}_{55} \Pi_2 & \check{A}^T S \\ S \check{A} & -S \end{bmatrix} < 0. \quad (39)$$

Let

$$\begin{aligned} \check{X}_5 &= -\tau^{-1} \check{X}_{55} \Pi_1, \quad \check{X} = \check{X}_5^T \check{X}_{55}^{-1} \check{X}_5, \\ \check{Y}_5 &= -\eta^{-1} \check{Y}_{55} \Pi_2, \quad \check{Y} = \check{Y}_5^T \check{Y}_{55}^{-1} \check{Y}_5. \end{aligned} \quad (40)$$

Then LMI (7) holds, and

$$\begin{aligned} \tau \check{X}_5^T \check{X}_{55}^{-1} \check{X}_5 + \check{\Phi}_X + \tau^{-1} \Pi_1^T \check{X}_{55} \Pi_1 &= 0, \\ \eta \check{Y}_5^T \check{Y}_{55}^{-1} \check{Y}_5 + \check{\Phi}_Y + \eta^{-1} \Pi_2^T \check{Y}_{55} \Pi_2 &= 0. \end{aligned} \quad (41)$$

Furthermore, LMI (8) is derived from (39).

The proof is completed. $\square$

5. Numerical Comparisons of Stability Criteria

In this section we will present one example to demonstrate effectiveness of the theoretic results described above.

TABLE 2: The maximum allowable bounds of τ for different η .

Method	η	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	10000	100000
[21] and Corollary 12	τ	1.7100	1.6987	1.6883	1.6792	1.6718	1.6664	1.6624	1.6591	1.6563	1.6543	1.6531	1.6527	1.6527	1.6527	1.6527	1.6527	1.6527
[25]	τ	1.7844	1.7757	1.7669	1.7581	1.7495	1.7413	1.7338	1.7273	1.7226	1.7201	1.7193	1.7191	1.7191	1.7191	1.7191	1.7191	1.7191
[27] and Theorem 8	τ	1.8305	1.8174	1.8038	1.7897	1.7755	1.7616	1.7484	1.7366	1.7272	1.7213	1.7202	1.7202	1.7202	1.7202	1.7202	1.7193	1.7193

Example 1. Consider the stability of systems (1a) and (1b) with

$$A = \begin{bmatrix} -0.9 & 0.2 \\ 0.1 & -0.9 \end{bmatrix}, \quad A_1 = \begin{bmatrix} -1.1 & -0.2 \\ -0.1 & -1.1 \end{bmatrix}, \quad (42)$$

$$C = \begin{bmatrix} -0.2 & 0 \\ 0.2 & -0.1 \end{bmatrix}.$$

Case 1 ($\tau = \eta$). The upper bounds on the delay τ under which robust stability of this system can be guaranteed using the methods in [9–27] and Theorem 9 of this paper are listed in Table 1. It is clear that our results are significantly better than those in [9–26] because our allowable maximum time delay τ is larger.

Case 2 ($\tau \neq \eta$). For different values of η , Table 2 lists the maximum allowable bounds on τ that guarantee the stability of the system. It can be seen that the maximum allowable bound on τ decreases as η increases when η is small but that τ remains almost unchanged when η increases to certain extent.

6. Conclusions

By using matrix analysis techniques, several stability criteria (i.e., [21, Theorem 1] and [27, Theorem 1 and Corollary 1]) for delayed neutral systems have been simplified. The numbers of LMI variables in [21, Theorem 1] and [27, Theorem 1 and Corollary 1] are reduced into the simplified ones, which can obviously reduce computational complexity. Furthermore, it is theoretically proven that the simplified stability criteria have the same conservativeness as the original ones. A numerical example is given to illustrate the theoretic results investigated in this paper.

Extending the idea of this paper to other system models, including singular delayed systems [32–35], stochastic systems [36], Markovian jump systems [37, 38], and genetic regulatory networks [39–41], is under consideration.

Conflict of Interests

The authors declare that there is no commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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