New stability conditions of neutral delay systems via free-matrix-based integral inequality

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Abstract

The problem of robust stability of uncertain neutral systems with time-delay is studied in this paper. A new free-matrix-based integral inequality is proposed, which is more tighter than existing ones. By using it to investigate the stability of neutral delay systems, less conservative stability conditions are obtained, which are presented in terms of linear matrix inequalities (LMIs). Two numerical examples are provided to illustrate the effectiveness and the reduced conservativeness of the method. ©2017 All rights reserved.

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1. Introduction

Time delays are frequently encountered in many practical systems, such as chemical engineering systems, inferred grinding model, neural network, nuclear reactor, and population dynamic model [13, 14, 22, 24–26]. In many systems, the models of systems are described by functional differential equations of neutral type, which depend on the delays of state and state derivative. Physical examples of neutral time-delay systems include chemical reactors, distributed networks, dynamic process including steam and water pipes, microwave oscillators, and lossless transmission lines [2, 4, 7, 15]. On the other hand, time delays often cause instability and generation of oscillation. Thus, many approaches have been proposed to deal with the problem of specification requirements of neutral delay systems [10, 17, 19, 23].

There are two main methods for the stability analysis of neutral systems with time delay: the direct Lyapunov method and the input-output approach [5]. The application of the direct Lyapunov method to neutral systems with constant delays requires a well-known assumption on the stability of the difference equation in [6], where necessary and sufficient conditions for the stability of this difference equation are given in the frequency domain. It was shown that the descriptor model transformation approach to

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neutral systems with constant delays implies the stability of the difference equation and thus avoids a verification of the above assumption (see [3]). To reduce the conservativeness of model transformation approach, He et al. proposed a free-weighting matrix approach in [12]. This approach was employed to investigate the stability and stabilization for neutral system with time-delay [17]. The discretized-Lyapunov-functional method (e.g., [9]) is one of the most efficient among them, but it is difficult to extend to the synthesis of a control system.

Using the Lyapunov-Krasovskii functional method to derive delay-dependent conditions, the reduction of conservativeness are from the following two aspects: choosing a suitable functional and obtaining a tighter bound on its derivative. To reduce the conservativeness of a simple Lyapunov-Krasovskii functional, two categories were proposed: (1) an augmented Lyapunov-Krasovskii functional [11] and (2) a delay-partitioning Lyapunov-Krasovskii functional (see [15, 23] and the references therein). The purpose of these two categories is to make a Lyapunov-Krasovskii functional containing more information. In addition, it is indispensable to take the derivative of the functional to derive a stability condition, and the main difficulty lies in the bounds of the integrals that appear in the derivative. Various methods are proposed for handling such integrals. Among them, the integral inequality method has extensively used because it can be applied to deal with the integral directly (see [8, 27]). Recently, a new integral inequality based on the Wirtinger inequality was reported in [16], which uses information not only on the augmented state but also on the integral of the state over the period of the delay. It was proved that this inequality is more tighter than the Jensen inequality. In addition, the free-matrix-based approach is proposed to reduce the conservativeness of the inequality in [20] and [21].

In this study, inspired by [20] and [21], a new free-matrix-based integral inequality is developed. The free matrices provide freedom in reducing the conservativeness of the resulting inequality. The new inequality was used to derive improved delay-dependent stability criteria for neutral delay systems. Two numerical examples are used to demonstrate the effectiveness of the method and its superiority over others.

Throughout this paper, the superscripts ‘ -1 ’ and ‘ T ’ stand for the inverse and transpose of a matrix, respectively; $\mathbb{R}^n$ denotes the n -dimensional Euclidean space; $\mathbb{R}^{n \times m}$ is the set of all $n \times m$ real matrices; $P > 0$ means that the matrix P is symmetric and positive definite; symmetric terms in a symmetric matrix are denoted by ‘ $*$ ’; I is an appropriately dimensioned identity matrix; and $\text{Sym}\{X\} = X + X^T$.

2. Preliminaries

Consider the following neutral system, Σ , with time-varying structured uncertainties.

$$\Sigma : \begin{cases} \dot{x}(t) - (C + \Delta C(t))\dot{x}(t-h) = (A + \Delta A(t))x(t) + (A_d + \Delta A_d(t))x(t-h), & t > 0, \\ x(t) = 0, & t \in [-h, 0], \end{cases} \quad (2.1)$$

where $x(t) \in \mathbb{R}^n$ is the state vector; A, A_d and C are constant matrices with appropriate dimensions. The delay, $h > 0$, is assumed to be a constant satisfying $h \in [h_{\min}, h_{\max}]$. The uncertainties are of the form

$$[\Delta C(t) \ \Delta A(t) \ \Delta A_d(t)] = HF(t)[E_c \ E_a \ E_{ad}],$$

where H, E_c, E_a , and E_{ad} are appropriately dimensioned constant matrices, and $F(t)$ is an unknown real and possibly time-varying matrix with Lebesgue-measurable elements satisfying

$$\|F(t)\| \leq I, \quad \forall t,$$

where $\|\cdot\|$ is the Euclidean norm.

First, the nominal system, Σ_0 , of Σ is discussed. It is given by

$$\Sigma_0 : \begin{cases} \dot{x}(t) - C\dot{x}(t-h) = Ax(t) + A_dx(t-h), & t > 0, \\ x(t) = 0, & t \in [-h, 0]. \end{cases} \quad (2.2)$$

The following lemma is used to deal with a system with time-varying uncertainties.

Lemma 2.1 ([18]). Given matrices $Q = Q^T$, H , E , and $R = R^T > 0$ with appropriate dimensions,

$$Q + HF(t)E + E^T F^T(t)H^T < 0$$

for all $F(t)$ satisfying $F^T(t)F(t) \leq R$, if and only if there exists a scalar $\varepsilon > 0$ such that

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

To obtain the main results of this paper, the following improved free-matrix-based integral inequality is developed.

Lemma 2.2. Let $x : [\alpha, \beta] \rightarrow \mathbb{R}^n$ be a differentiable function. For symmetric matrices $R \in \mathbb{R}^{n \times n}$, and $Z_{11}, Z_{22}, Z_{33} \in \mathbb{R}^{4n \times 4n}$, and any matrices $Z_{12}, Z_{13}, Z_{23} \in \mathbb{R}^{4n \times 4n}$, and $N_1, N_2, N_3 \in \mathbb{R}^{4n \times n}$ satisfying

$$\bar{\Phi} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & N_1 \\ * & Z_{22} & Z_{23} & N_2 \\ * & * & Z_{33} & N_3 \\ * & * & * & R \end{bmatrix} \geq 0,$$

the following inequality holds:

$$-\int_{\alpha}^{\beta} \dot{x}^T(s) R \dot{x}(s) ds \leq \vartheta^T \bar{\Omega} \vartheta, \quad (2.3)$$

where

$$\bar{\Omega} = \tau(Z_{11} + \frac{1}{3}Z_{22} + \frac{6}{5}Z_{33} - Z_{13} - Z_{13}^T) + \text{Sym}\{N_1 \bar{\Pi}_1 + N_2 \bar{\Pi}_2 + N_3 \bar{\Pi}_3\},$$

$$\bar{\Pi}_1 = \bar{e}_1 - \bar{e}_2,$$

$$\bar{\Pi}_2 = \bar{e}_1 + \bar{e}_2 - 2\bar{e}_3,$$

$$\bar{\Pi}_3 = 6\bar{e}_4 - 6\bar{e}_3,$$

$$\bar{e}_1 = [I \quad 0 \quad 0 \quad 0],$$

$$\bar{e}_2 = [0 \quad I \quad 0 \quad 0],$$

$$\bar{e}_3 = [0 \quad 0 \quad I \quad 0],$$

$$\bar{e}_4 = [0 \quad 0 \quad 0 \quad I],$$

$$\vartheta = \left[x^T(\beta) \quad x^T(\alpha) \quad \frac{1}{\tau} \int_{\alpha}^{\beta} x^T(s) ds \quad \frac{2}{\tau^2} \int_{\alpha}^{\beta} \int_{\alpha}^s x^T(u) du ds \right]^T, \quad \tau = \beta - \alpha.$$

Proof. Define

$$f_1(s) = \frac{2s - \beta - \alpha}{\beta - \alpha}, \quad f_2(s) = \frac{6[s^2 - (\beta + \alpha)s + \beta\alpha]}{(\beta - \alpha)^2}, \quad \zeta(s) = [\vartheta^T \quad f_1(s)\vartheta^T \quad f_2(s)\vartheta^T \quad \dot{x}^T(s)]^T.$$

It is easy to see that

$$\zeta^T(s) \bar{\Phi} \zeta(s) \geq 0. \quad (2.4)$$

Integrating the left-hand side of (2.4) from α to β yields

$$\begin{aligned} \int_{\alpha}^{\beta} \zeta^T(s) \bar{\Phi} \zeta(s) ds &= (\beta - \alpha) \vartheta^T Z_{11} \vartheta + \frac{\beta - \alpha}{3} \vartheta^T Z_{22} \vartheta + \frac{6(\beta - \alpha)}{5} \vartheta^T Z_{33} \vartheta - 2(\beta - \alpha) \vartheta^T Z_{13} \vartheta + 2 \vartheta^T N_1 (\bar{e}_1 - \bar{e}_2) \vartheta \\ &\quad + 2 \vartheta^T N_2 (\bar{e}_1 + \bar{e}_2 - 2\bar{e}_3) \vartheta + 2 \vartheta^T N_3 (6\bar{e}_4 - 6\bar{e}_3) \vartheta + \int_{\alpha}^{\beta} \dot{x}^T(s) R \dot{x}(s) ds. \end{aligned}$$

To sum up, we have

$$-\int_{\alpha}^{\beta} \dot{x}^T(s) R \dot{x}(s) ds \leq (\beta - \alpha) \vartheta^T Z_{11} \vartheta + \frac{\beta - \alpha}{3} \vartheta^T Z_{22} \vartheta + \frac{6(\beta - \alpha)}{5} \vartheta^T Z_{33} \vartheta - 2(\beta - \alpha) \vartheta^T Z_{13} \vartheta + 2\vartheta^T N_1 (\bar{e}_1 - \bar{e}_2) \vartheta \\ + 2\vartheta^T N_2 (\bar{e}_1 + \bar{e}_2 - 2\bar{e}_3) \vartheta + 2\vartheta^T N_3 (6\bar{e}_4 - 6\bar{e}_3) \vartheta = \vartheta^T \bar{\Omega} \vartheta.$$

This completes the proof. $\square$

Remark 2.3. The free-matrix-based integral inequality is firstly proposed in [20], which is shown less conservative than the Wirtinger inequality given in [16]. However, the inequality derived in this paper achieves some improvement over [20]. The double integral term of state are taken into consideration in (2.3). In addition, it is easy to prove that the inequalities presented in [16, 20] are special cases of (2.3).

3. Main results

This section presents new stability criteria derived using the new free-matrix-based integral inequality. The following nomenclature for vectors and matrices simplifies the representation.

$$v_1(t) = \int_{t-h}^t x(s) ds, \\ v_2(t) = \int_{t-h}^t \int_{t-h}^s x(u) du ds, \\ \eta_1(t) = [x^T(t) \ x^T(t-h) \ v_1^T(t) \ v_2^T(t)]^T, \\ \eta_2(t) = [x^T(t) \ \dot{x}^T(t)]^T, \\ \eta_3(t) = [x^T(t) \ x^T(t-h) \ \frac{1}{h} v_1^T(t) \ \frac{2}{h^2} v_2^T(t)]^T, \\ \xi(t) = [\eta_3^T(t) \ \dot{x}^T(t) \ \dot{x}^T(t-h)]^T, \\ e_i = [0_{n \times (i-1)n} \ I_n \ 0_{n \times (6-i)n}]^T, \quad i = 1, 2, \dots, 6.$$

Now, we present our first stability criterion.

Theorem 3.1. For given a scalar $h > 0$, the system (2.1) is asymptotically stable if there exist $P(\in \mathbb{R}^{4n \times 4n}) > 0$, $Q(\in \mathbb{R}^{2n \times 2n}) \geq 0$, and $R(\in \mathbb{R}^{n \times n}) > 0$, symmetrical matrices $Z_{11}, Z_{22}, Z_{33} \in \mathbb{R}^{4n \times 4n}$, and any matrices $Z_{12}, Z_{13}, Z_{23}, \in \mathbb{R}^{4n \times 4n}$ and $N_1, N_2, N_3 \in \mathbb{R}^{4n \times n}$, $U_1, U_2 \in \mathbb{R}^{n \times n}$, such that the following LMIs are feasible,

$$\Xi = \Xi_1 + \Xi_2 < 0, \quad (3.1)$$

$$\Phi = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & N_1 \\ * & Z_{22} & Z_{23} & N_2 \\ * & * & Z_{33} & N_3 \\ * & * & * & R \end{bmatrix} \geq 0, \quad (3.2)$$

where

$$\Xi_1 = \text{Sym}\{\Pi_1^T P \Pi_2\} + \Pi_3^T Q \Pi_3 - \Pi_4^T Q \Pi_4 + h e_5^T R e_5, \\ \Xi_2 = h \Pi_5^T (Z_{11} + \frac{1}{3} Z_{22} + \frac{6}{5} Z_{33} - Z_{13} - Z_{13}^T) \Pi_5 + \text{Sym}\{\Pi_5^T N_1 \Pi_6 + \Pi_5^T N_2 \Pi_7 + \Pi_5^T N_3 \Pi_8 + \Pi_9^T \Pi_{10}\}, \\ \Pi_1 = [e_1^T \ e_2^T \ h e_3^T \ \frac{h^2}{2} e_4^T]^T,$$

$$\begin{aligned}
\Pi_2 &= [e_5^T \quad e_6^T \quad e_1^T - e_2^T \quad he_3^T - he_2^T]^T, \\
\Pi_3 &= [e_1^T \quad e_5^T]^T, \\
\Pi_4 &= [e_2^T \quad e_6^T]^T, \\
\Pi_5 &= [e_1^T \quad e_2^T \quad e_3^T \quad e_4^T]^T, \\
\Pi_6 &= e_1 - e_2, \\
\Pi_7 &= e_1 + e_2 - 2e_3, \\
\Pi_8 &= 6e_4 - 6e_3, \\
\Pi_9 &= [e_1^T U_1 + e_5^T U_2]^T, \\
\Pi_{10} &= Ae_1 + A_d e_2 + Ce_6 - e_5.
\end{aligned}$$

Proof. Choose the following Lyapunov-Krasovskii functional candidate

$$V(x_t) = \eta_1^T(t) P \eta_1(t) + \int_{t-h}^t \eta_2^T(s) Q \eta_2(s) ds + \int_{-h}^0 \int_{t+\theta}^t \dot{x}^T(s) R \dot{x}(s) ds d\theta.$$

The derivative of $V(x_t)$ is

$$\begin{aligned}
\dot{V}(x_t) &= \xi^T(t) [\text{Sym}\{\Pi_1^T P \Pi_2\} + \Pi_3^T Q \Pi_3 - \Pi_4^T Q \Pi_4 + he_5^T R e_5] \xi(t) - \int_{t-h}^t \dot{x}^T(s) R \dot{x}(s) ds \\
&= \xi^T(t) \Xi_1 \xi(t) - \int_{t-h}^t \dot{x}^T(s) R \dot{x}(s) ds.
\end{aligned} \tag{3.3}$$

On the other hand, for any matrices U_1 and U_2 with appropriate dimensions, it is true that

$$\begin{aligned}
0 &= 2[x^T(t)U_1 + \dot{x}^T(t)U_2][Ax(t) + A_d x(t-h) + C\dot{x}(t-h) - \dot{x}(t)] \\
&= 2\xi^T(t) \Pi_9^T \Pi_{10} \xi(t).
\end{aligned} \tag{3.4}$$

Since $\Phi \geq 0$, from Lemma 2.2, we have

$$\begin{aligned}
& - \int_{t-h}^t \dot{x}^T(s) R \dot{x}(s) ds \\
& \leq \xi^T(t) \left\{ h \Pi_5^T (Z_{11} + \frac{1}{3} Z_{22} + \frac{6}{5} Z_{33} - Z_{13} - Z_{13}^T) \Pi_5 + \text{Sym}\{\Pi_5^T N_1 \Pi_6 + \Pi_5^T N_2 \Pi_7 + \Pi_5^T N_3 \Pi_8\} \right\} \xi(t).
\end{aligned} \tag{3.5}$$

Adding the right side of (3.4) to (3.3) and applying (3.5) yield

$$\dot{V}(x_t) \leq \xi^T(t) (\Xi_1 + \Xi_2) \xi(t).$$

If $\Xi_1 + \Xi_2 < 0$, then $\dot{V}(x_t) < 0$. So, the system (2.2) is asymptotically stable. This completes the proof. $\square$

Extending Theorem 3.1 to a neutral system with time-varying structured uncertainties yields the following delay-dependent robust stability criterion.

Theorem 3.2. For given a scalar $h > 0$, the system (2.1) is asymptotically stable if there exist $P(\in \mathbb{R}^{4n \times 4n}) > 0$, $Q(\in \mathbb{R}^{2n \times 2n}) \geq 0$, and $R(\in \mathbb{R}^{n \times n}) > 0$, symmetrical matrices $Z_{11}, Z_{22}, Z_{33} \in \mathbb{R}^{4n \times 4n}$, and any matrices

$Z_{12}, Z_{13}, Z_{23} \in \mathbb{R}^{4n \times 4n}$, $N_1, N_2, N_3 \in \mathbb{R}^{4n \times n}$, $U_1, U_2 \in \mathbb{R}^{n \times n}$, and a scalar $\varepsilon > 0$, such that LMIs (3.2) and (3.6) are feasible,

$$\tilde{\Xi} = \begin{bmatrix} \Xi + \varepsilon \Theta_2^T \Theta_2 & \Theta_1^T \\ \Theta_1 & -\varepsilon I \end{bmatrix} < 0 \quad (3.6)$$

where $\Theta_1 = [e_1^T U_1 H + e_5^T U_2 H]^T$, $\Theta_2 = [e_1^T E_a^T + e_2^T E_{ad}^T + e_6^T E_c^T]^T$, and Ξ is defined in Theorem 3.1.

Proof. Replacing $C + HF(t)E_c$, $A + HF(t)E_a$, and $A_d + HF(t)E_{ad}$ for C , A , and A_d in (3.1), and applying Lemma 2.1 and the Schur complement [1] yields (3.6) and this ends the proof. $\square$

4. Numerical examples

Two numerical examples in this section illustrate the effectiveness and superiority of our method.

Example 4.1. Consider the following nominal neutral system, Σ_0 .

$$A = \begin{bmatrix} -2 & 0 \\ 0 & -0.9 \end{bmatrix}, \quad A_d = \begin{bmatrix} -1 & 0 \\ -1 & -1 \end{bmatrix}, \quad C = \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix}, \quad 0 \leq c < 1,$$

This example was discussed in [4, 7, 17]. In our method, all the free-matrices are determined by solving the corresponding LMIs. Table 1 summarizes the maximum upper bound computed by Theorem 3.1 for different c and those obtained by other methods. It is obvious that our method produces significantly better results than the others.

Table 1: Maximum upper bound of h .

c	0	0.1	0.3	0.5	0.7	0.9
Fridman's paper [4]	4.47	3.49	2.06	1.14	0.54	0.13
Han's paper [7]	4.35	4.33	4.10	3.62	2.73	0.99
Wu's paper [17]	4.47	4.35	4.13	3.67	2.87	1.41
Theorem 3.1	6.16	6.03	5.54	4.73	3.50	1.57

Remark 4.2. The free-weighting matrices approach proposed in [12] and [17], was regarded as an effective approach to derive delay-dependent condition. It is shown in this example that the approach proposed in this paper obviously outperforms that given in [17].

Example 4.3. Consider a partial element equivalent circuit model of neutral type given in [10, 19, 23], which is expressed as an uncertain system, Σ with

$$A = 100 \times \begin{bmatrix} \beta & 1 & 2 \\ 3 & -9 & 0 \\ 1 & 2 & -6 \end{bmatrix}, \quad A_d = 100 \times \begin{bmatrix} 1 & 0 & -3 \\ -0.5 & -0.5 & -1 \\ -0.5 & -1.5 & 0 \end{bmatrix}, \quad C = \frac{1}{72} \times \begin{bmatrix} -1 & 5 & 2 \\ 4 & 0 & 3 \\ -2 & 4 & 1 \end{bmatrix},$$

$$D = 0.2I, \quad E_a = I, \quad E_{ad} = I, \quad E_c = 0.$$

The maximum upper bounds calculated by Theorem 3.2 for different β are listed in Table 2, along with the results provided by other methods. It is clear that the method in this paper provides less conservative results than existing ones. It should be pointed out that our results have small conservatism than those based on the delay-partitioning approach [23], even if the partitioning number $q = 5$.

Remark 4.4. The delay-partitioning approach is widely used to reduce the conservativeness of delay-dependent conditions and less conservative results can be obtained by the increase of the partitioning number. However, increasing the partitioning number results in the increase of dimension of LMIs. When the partitioning number is large, the computational burden increase sharply.

Table 2: Maximum upper bound of h .

β	-2.105	-2.103	-2.1
Han's paper [10]	0.3651	0.2522	0.1906
Yue's paper [19]	0.4064	0.2783	0.2079
Zhang's paper (q=2) [23]	0.5499	0.3835	0.2877
Zhang's paper (q=3) [23]	0.5830	0.4061	0.3044
Zhang's paper (q=5) [23]	0.6004	0.4180	0.3131
Theorem 3.1	0.7808	0.4412	0.3191

5. Conclusion

The stability of neutral system with time delay has been investigated in this paper. A new free-matrix-based integral inequality has been developed that yields new less-conservative stability criteria for neutral delay systems. They were derived by employing an augmented Lyapunov-Krasovskii functional and utilizing the new inequality to bound its derivative. Numerical examples show the effectiveness of the method and its superiority over others.

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References

- [1] S. Boyd, L. El Ghaoui, E. Feron, V. Balakrishnan, *Linear matrix inequalities in system and control theory*, SIAM Studies in Applied Mathematics, Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, (1994). 3
- [2] W.-H. Chen, W. X. Zheng, *Delay-dependent robust stabilization for uncertain neutral systems with distributed delays*, Automatica J. IFAC, **43** (2007), 95–104. 1
- [3] E. Fridman, *New Lyapunov-Krasovskii functionals for stability of linear retarded and neutral type systems*, Systems Control Lett., **43** (2001), 309–319. 1
- [4] E. Fridman, U. Shaked, *Delay-dependent stability and H_∞ control: constant and time-varying delays*, Internat. J. Control, **76** (2003), 48–60. 1, 4, 1
- [5] K. Gu, V. L. Kharitonov, J. Chen, *Stability of time-delay systems*, Control Engineering. Birkhäuser Boston, Inc., Boston, MA, (2003). 1
- [6] J. K. Hale, S. M. Verduyn Lunel, *Introduction to functional-differential equations*, NApplied Mathematical Sciences, Springer-Verlag, New York, (1993). 1
- [7] Q.-L. Han, *Robust stability of uncertain delay-differential systems of neutral type*, Automatica J. IFAC, **38** (2002), 719–723. 1, 4, 1
- [8] Q.-L. Han, *Absolute stability of time-delay systems with sector-bounded nonlinearity*, Automatica J. IFAC, **41** (2005), 2171–2176. 1
- [9] Q.-L. Han, *On stability of linear neutral systems with mixed time delays: a discretized Lyapunov functional approach*, Automatica J. IFAC, **41** (2005), 1209–1218. 1
- [10] Q.-L. Han, *Stability analysis for a partial element equivalent circuit (PEEC) model of neutral type*, Int. J. Circ. Theory Appl., **33** (2005), 321–332. 1, 4.3, 2
- [11] Y. He, Q.-G. Wang, L.-H. Xie, C. Lin, *Further improvement of free-weighting matrices technique for systems with time-varying delay*, IEEE Trans. Automat. Control, **52** (2007), 293–299. 1
- [12] Y. He, M. Wu, J.-H. She, G.-P. Liu, *Delay-dependent robust stability criteria for uncertain neutral systems with mixed delays*, Systems Control Lett., **51** (2004), 57–65. 1, 4.2
- [13] S. I. Niculescu, *On delay-dependent stability under model transformations of some neutral linear systems*, Internat. J. Control, **74** (2001), 609–617. 1

- [14] N. Olgac, R. Sipahi, *An exact method for the stability analysis of time-delayed linear time-invariant (LTI) systems*, IEEE Trans. Automat. Control, **47** (2002), 793–797. [1](#)
- [15] R. Sakthivel, K. Mathiyalagan, S. M. Anthoni, *Robust stability and control for uncertain neutral time delay systems*, Internat. J. Control, **85** (2012), 373–383. [1](#)
- [16] A. Seuret, F. Gouaisbaut, *Wirtinger-based integral inequality: application to time-delay systems*, Automatica J. IFAC, **49** (2013), 2860–2866. [1](#), [2.3](#)
- [17] M. Wu, Y. He, J.-H. She, *New delay-dependent stability criteria and stabilizing method for neutral systems*, IEEE Trans. Automat. Control, **49** (2004), 2266–2271. [1](#), [4](#), [1](#), [4.2](#)
- [18] L.-H. Xie, *Output feedback H_∞ control of systems with parameter uncertainty*, Internat. J. Control, **63** (1996), 741–750. [2.1](#)
- [19] D. Yue, Q.-L. Han, *A delay-dependent stability criterion of neutral systems and its application to a partial element equivalent circuit model*, IEEE Trans. Circuits Syst. II, Exp. Briefs, **51** (2004), 685–689. [1](#), [4.3](#), [2](#)
- [20] H.-B. Zeng, Y. He, M. Wu, J.-H. She, *Free-matrix-based integral inequality for stability analysis of systems with time-varying delay*, IEEE Trans. Automat. Control, **60** (2015), 2768–2772. [1](#), [2.3](#)
- [21] H.-B. Zeng, Y. He, M. Wu, J.-H. She, *New results on stability analysis for systems with discrete distributed delay*, Automatica J. IFAC, **60** (2015), 189–192. [1](#)
- [22] H.-B. Zeng, Y. He, M. Wu, S.-P. Xiao, *Stability analysis of generalized neural networks with time-varying delays via a new integral inequality*, Neurocomputing, **161** (2015), 148–154. [1](#)
- [23] X.-M. Zhang, Q.-L. Han, *A new stability criterion for a partial element equivalent circuit model of neutral type*, IEEE Trans. Circuits Syst. II, Exp. Briefs, **56** (2009), 798–802. [1](#), [4.3](#), [4](#), [2](#)
- [24] C.-K. Zhang, Y. He, L. Jiang, M. Wu, *An improved summation inequality to discrete-time systems with time-varying delay*, Automatica J. IFAC, **74** (2016), 10–15. [1](#)
- [25] C.-K. Zhang, Y. He, L. Jiang, M. Wu, H.-B. Zeng, *Delay-variation-dependent stability of delayed discrete-time systems*, IEEE Trans. Automat. Control, **61** (2016), 2663–2669.
- [26] C.-K. Zhang, Y. He, L. Jiang, M. Wu, H.-B. Zeng, *Stability analysis of systems with time-varying delay via relaxed integral inequalities*, Systems Control Lett., **92** (2016), 52–61. [1](#)
- [27] X.-M. Zhang, M. Wu, J.-H. She, Y. He, *Delay-dependent stabilization of linear systems with time-varying state and input delays*, Automatica J. IFAC, **41** (2005), 1405–1412. [1](#)