Applied Mathematics and Computation 339 (2018) 113–131

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Stability analysis for a class of neutral type singular systems with time-varying delay[☆]

Shaohua Long[a,*], Yunlong Wu[b], Shouming Zhong[c], Dian Zhang[d]

[a] School of Science, Chongqing University of Technology, Chongqing 400054, PR China
[b] School of Mathematics and Statistics, Yangtze Normal University, Fuling 408100, PR China
[c] School of Mathematics Science, University of Electronic Science and Technology of China, Chengdu 611731, PR China
[d] College of Automation and Electronic Engineering, Qingdao Universtiy of Science and Technology, Qingdao 266042, PR China

ARTICLE INFO

Keywords:
Singular system
Neutral system
Stability
Time-varying delay
Linear matrix inequality

ABSTRACT

This paper is concerned with the stability problem for a class of neutral type singular systems with time-varying delay. The considered systems contain delays both in their state and in their derivatives of state. Based on the singular system approach and the Lyapunov–Krasovskii functional approach, some sufficient conditions which guarantee the considered systems to be regular, impulse-free and stable are derived. Finally, some numerical examples are provided to show the effectiveness of the presented methods.

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1. Introduction

Singular systems, which can represent physical systems better than regular ones and sometimes are also called differential-algebraic systems, generalized state-space systems, implicit systems, semi-state systems or descriptor systems, have important applications in, e.g., circuit systems, chemical systems and economic systems [1]. Therefore, during the past several decades, many researchers have paid attention to studying the singular systems and a number of important and interesting results have been presented, see, e.g., [2–14]. These papers cover a lot of topics related to the singular systems, including the dissipative fault-tolerant control problem based on slow state feedback [2], slow state variables feedback stabilization problem [3], $L_2 - L_\infty$ synchronization problem [4], stability and stabilization problems [5–8], filtering problem [9–12] and dissipative control problem [13,14].

As is well known, time delay arises frequently in the practical systems and is often the cause of instability and poor performance. Therefore, the stability problem for the systems with time delay has attracted considerable attention in the past several decades, see, e.g., [15–24]. The neutral systems, which contain delays both in their state and in their derivatives of state, are a class of important time delay systems and encountered frequently in many practical systems, such as bipolar dissolving tanks in chemical process, vibrating masses attached to an elastic bar and distributed networks containing lossless transmission lines [25,41]. The stability problem for the neutral systems also has investigated widely in the past several decades, see, e.g., [26–37].

☆ This research was supported by Scientific and Technological Research Program of Chongqing Municipal Education Commission (KJ1500908), Spark Program of Chongqing University of Technology (2014XH01) and Chongqing Research Program of Basic Research and Frontier Technology (cstc2016jcyjA0492, cstc2017jcyjA0923).

* Corresponding author.
E-mail address: longshaohua0732@163.com (S. Long).

https://doi.org/10.1016/j.amc.2018.06.058
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Recently, there has been some interest on the neutral type singular systems(NTSSs). Li et al. [38] gave a solution to the stability problem for the NTSSs with mixed delays. The robust stability problem for uncertain NTSSs was studied in [39]. Wang et al. [40] considered the problems of robust stability and stabilization for uncertain NTSSs. Wang et al. [41] and [42] investigated the PD feedback H_∞ control problem and the output strictly passive control problem for uncertain NTSSs, respectively. It should be pointed out that the results presented in [38] and [39] are invalid if the NTSSs do not satisfy $\|E_1^{-1}C_1\| < 1$ or $\det(C_2) \neq 0$ (for more information, please see Remark 2 in this paper). If the NTSSs do not satisfy $\det(E-C) \neq 0$, the results presented in [40–42] are invalid. In addition, in [38–42], the considered NTSSs are with invariant time delay. The NTSSs with time-varying delay are not investigated in [38–42]. To the best of our knowledge, the stability problem for NTSSs has not been fully studied. If the considered NTSS is with time-varying delay and dose not satisfy $\det(E-C) \neq 0$ (from $\|E_1^{-1}C_1\| < 1$ and $\det(C_2) \neq 0$, it can be deduced that $\det(E-C) \neq 0$), almost no results in the existing literature can be applied to analyzing its stability problem. It is also worth pointing out that the NTSSs have wide applications in the practical systems (please see Remark 1 for some practical applications). Therefore, either in theory or in practice, it is significant and necessary to further study the NTSSs. This motivates the present work of this paper.

This paper deals with the stability problem for a class of NTSSs with time-varying delay. By using the singular system method and the Lyapunov–Krasovskii functional method, sufficient conditions are presented to guarantee the considered system to be regular, impulse-free and stable. The main contributions of this paper can be summarized as follows. First, the NTSSs considered in [38–42] are with constant time delay, while the NTSSs considered in this paper are with time-varying delay, which is a more general time delay case. Second, Li et al. [38], Wang and Xue [39], and Wang et al. [40–42] employed the operator $\Im(x_t) = Ex(t) - Cx(t-\tau)$ to study the NTSSs. However, if the considered NTSSs do not satisfy $\det(E-C) \neq 0$, the results presented in [38–42] are invalid. In this paper, we use the singular system method and the obtained results can be applied to analyzing the NTSSs which do not satisfy $\det(E-C) \neq 0$. Third, some numerical examples illustrate the less conservatism of the obtained results of this paper compared with those of [38–42].

Notations: In the whole paper, $\|\cdot\|$ stands for the Euclidean norm for a vector. R^n denotes the n-dimensional Euclidean space. $R^{m\times n}$ is the set of all $m \times n$ real matrices. For a real symmetric matrix X, $X > 0 (X \geq 0)$ means that X is positive definite (semi-positive definite). I is the identity matrix of appropriate dimensions. The symbol "$*$" denotes the symmetric elements in a symmetric matrix. $\det(X)$ means the determinant of the matrix X. The superscript "T" stands for the transpose of a matrix or a vector. $\mathrm{diag}\{\cdots\}$ denotes a block-diagonal matrix. $\rho(\cdot)$ means the spectral radius of a matrix. $\lambda_{\max}(\cdot)$ and $\lambda_{\min}(\cdot)$ mean the largest eigenvalue and the smallest eigenvalue of a matrix, respectively.

2. Preliminaries

Consider a class of neutral type singular systems with time-varying delay as follows:

$$\begin{cases} E\dot{x}(t) - C\dot{x}(t-\tau(t)) = Ax(t) + A_d x(t-\tau(t)), \\ \quad x(\theta) = \varphi(\theta), \quad \theta \in [-\tau_2, 0], \end{cases} \tag{1}$$

where $x(t) \in R^n$ represents the state vector of the system. The matrices $E \in R^{n\times n}$, $C \in R^{n\times n}$, $A \in R^{n\times n}$ and $A_d \in R^{n\times n}$ are known real constant matrices. We assume that E is singular and satisfies $0 < \mathrm{rank}(E) = q < n$. $\tau(t)$ denotes the time-varying delay and satisfies

$$0 < \tau_1 \leq \tau(t) \leq \tau_2, \qquad h_1 \leq \dot{\tau}(t) \leq h_2 < 1, \tag{2}$$

where τ_1, τ_2, h_1 and h_2 are known real constant scalars. We suppose that $\tau_2 > \tau_1$, $h_2 \geq 0$ and $h_1 \leq 0$. $\varphi(\theta)$ $(\theta \in [-\tau_2, 0])$ is a continuous vector valued initial function and we assume that its derivative is also continuous.

Without loss of generality, we suppose that $E = \begin{bmatrix} I_q & 0 \\ 0 & 0 \end{bmatrix}$ in this paper (see Remark 1 of [43]).

To facilitate the following discussion, we introduce some definitions that are related to singular systems and will be used later.

Definition 1 [12]**.** (i) The pair (E, A) is said to be regular if $\det(sE - A)$ is not identically zero.

(ii) The pair (E, A) is said to be impulse-free if it is regular and $\deg(\det(sE - A)) = \mathrm{rank}(E)$.

Definition 2 [12]**.** (i) System $E\dot{x}(t) = Ax(t) + A_d x(t-\tau(t))$ ($\tau(t)$ satisfies (2)) is said to be regular and impulse-free, if the pair (E, A) is regular and impulse-free.

(ii) System $E\dot{x}(t) = Ax(t) + A_d x(t-\tau(t))$ ($\tau(t)$ satisfies (2)) is said to be stable, if for any $\varepsilon > 0$, there exists a scalar $\delta(\varepsilon) > 0$ such that, for any compatible initial conditions $\varphi(t)$ satisfying $\sup_{-\tau_2 \leq t \leq 0} ||\varphi(t)|| \leq \delta(\varepsilon)$, its solution $x(t)$ satisfies $||x(t)|| \leq \varepsilon$. Furthermore, $x(t) \to 0$ as $t \to \infty$.

(iii) System $E\dot{x}(t) = Ax(t) + A_d x(t-\tau(t))$ ($\tau(t)$ satisfies (2)) is said to be admissible, if it is regular, impulse-free and stable.

Some lemmas that will be used in the proof of our main results should be introduced first.

Lemma 1 [38]**.** *The linear matrix inequality* $\begin{bmatrix} H & P^T \\ P & R \end{bmatrix} > 0$ *is equivalent to* $R > 0, \quad H - P^T R^{-1} P > 0.$

Lemma 2 [38]**.** *For any real matrices* W_1, W_2 *and* $Q > 0$ *of appropriate dimensions, the inequality* $W_1^T W_2 + W_2^T W_1 \leq W_1^T Q W_1 + W_2^T Q^{-1} W_2$ *holds.*

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