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A descriptor system approach to the delay-dependent exponential stability analysis for switched neutral systems with nonlinear perturbations

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ABSTRACT

In this paper, the problem of exponential stability analysis for switched neutral systems with mixed time-delays and nonlinear perturbations based on descriptor system approach is addressed. Delay-dependent exponential stability results are derived in terms of linear matrix inequalities based on piecewise descriptor type Lyapunov–Krasovskii functional. Average dwell time approach is used to analyze switched neutral systems. In addition convex combination, delay decomposition and free-weighting matrix approaches have been employed to derive less conservative results. Further, numerical examples are illustrated to demonstrate the effectiveness and less conservativeness of the derived theoretical results.

1. Introduction

Switched dynamical system is a two level system in which the lower level is described by differential and/or difference equations and the upper level is governed by the switch among the modes. They admit continuous state space which takes value from a vector space and discrete state which takes values from a discrete index set with finite number of elements. The interactions between the continuous and discrete states make the switched dynamical systems to behave more complicated. Frequently time-delays occur in many practical systems, such as manufacturing systems, telecommunication and economic systems, and are the major cause of instability and poor performance (see [1–3]). Hence switched dynamical systems with time-delays have received much attention during the recent decades because of their wider applications in many real world systems such as robot systems, and networked control systems (for more details see [4–11] and references therein).

Systems which can be formulated as a set of coupled differential and algebraic equations are called singular systems. These systems include information on the static as well as dynamic constraints of a real plant. Singular systems are also referred to as generalized systems, descriptor systems, implicit systems, differential–algebraic systems, or semi-state systems (see [12]). They do not belong to the class of ODEs since an ODE does not have any underlying algebraic constraints on its variables. Also they contain the state-space form as a special case and thus can represent a much wider class of systems than its state-space counterpart. Further, the study of time-delay phenomena for singular systems is more complicated than the state space time-delay systems since it requires considering not only stability, but also regularity and absence of impulses for continuous-time descriptor systems and causality for discrete-time descriptor systems at the same time (see [13,14]).

Under arbitrary switching, a common Lyapunov–Krasovskii functional (LKF) is utilized to derive stability conditions but most of the switched systems do not possess a common LKF. An efficient tool to overcome this difficulty is average dwell

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time technique in which the piecewise LKF is utilized. The switching signal $\sigma(t),\ t \in [0, \infty)$ is said to have dwell time T_d if $t_{i+1} - t_i \geq T_d$ for any two consecutive jump times t_i and t_{i+1}. Let $\mathcal{S}(T_d)$ denote the set of all switching signals satisfying the above property. In the existing literature, it is shown that the switched system is exponentially stable for any switching signal belonging to $\mathcal{S}(T_d)$ by choosing T_d sufficiently large. In [15], the above concept was extended to the average dwell time approach with the condition that the average time interval between any two consecutive switchings is not less than some specific constant T_a. Further in [15], it is proved that if T_a is sufficiently large then the switched system is exponentially stable. Hence average dwell time technique has attracted many researchers during the recent decades (for example see [16,15,17–19] and references therein).

Neutral time-delay systems are time-delay systems in which the time-delay depends not only on its state but also on the derivative of its state. Stability issues of these systems are proved to be more complex and hence a lot of research has been done in the field of neutral systems (for details see [20,2,3,21,22] and references therein). These kinds of systems can be found in many physical systems such as the partial element equivalent circuit in large-scale integrated circuit, the cutting operation of big devices, the switch between controllers of automatic control system, and the motion and walking of a robot (see [23]). Also the presence of nonlinear perturbations will affect the stability of the system. Due to the above factors neutral systems with nonlinear perturbations have been studied by many researchers in the recent years (for details see [24–28]). Switched neutral system is a switched system in which the subsystems are neutral systems. Many systems can be modeled as switched neutral systems if switched behavior and neutral time-delays exist simultaneously during the operation of system and the transmission of signal (for details one can refer to [17,29,30]).

Stability and L_2-gain analysis for switched neutral systems with mixed time-varying delays have been investigated in [17] while the authors in [26] have investigated the problem of delay-dependent exponential stability criteria for neutral systems with interval time-varying delays and nonlinear perturbations using the delay-partitioning and reciprocal convex combination approaches. The problem of exponential stability analysis for neutral switched systems with interval time-varying mixed delays and nonlinear perturbations has been investigated in [30]. In the existing literature different kinds of approaches such as free weighting matrix, convex combination, reciprocal convex combination, and delay decomposition are used to reduce conservatism on time-delay. Authors in [31] have employed free weighting matrix and convex combination approaches to derive less conservative results.

In [32,13,33], the authors have used descriptor system approach to establish the stability conditions for time-delay systems and especially authors in [34,35] have used this approach to derive the stability conditions for neutral systems. In [18], the authors have analyzed the exponential stability criteria of switched neutral systems with nonlinear perturbations with application to the drilling system. However to the best of authors' knowledge, the problem of switched neutral systems with nonlinear perturbations based on descriptor system approach has not been investigated in the existing literature.

Motivated by the above discussions, in this paper, the problem of delay-dependent exponential stability analysis of switched nonlinear neutral systems with mixed time-delays based on descriptor system approach is investigated. The main contribution of this paper can be summarized as follows: sufficient delay-dependent exponential stability conditions are derived by using Lyapunov stability theory and LMI technique; the delay interval is decomposed into two equal subintervals and a descriptor type LKF is constructed by choosing different weight matrices on different subintervals; average dwell time approach is used to analyze switched neutral systems; using Newton–Leibnitz rule some free-weighting matrices are introduced to obtain less conservative results; stability results are derived as a convex combination of terms involving time-delays. Derived results are formulated in terms of LMIs which can be solved by using MATLAB LMI solvers. Finally, the effectiveness and less conservativeness of the derived theoretical results are validated through numerical examples.

The rest of this paper is organized as follows. Section 2 states the problem description and preliminaries. In Section 3, exponential stability results for switched neutral systems based on descriptor system approach are investigated. Section 4 provides the robust stability results for switched neutral systems through average dwell time approach. In Section 5, numerical examples are given to show the effectiveness of the derived results and Section 6 concludes the paper.

Notations: Throughout this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote, respectively, the n-dimensional Euclidean space and the set of all $n \times m$ real matrices. For symmetric matrices X and Y, the notation $X \geq Y$ ($X > Y$) means that $X - Y$ is positive semi-definite (positive-definite), G^T denotes the transpose of the matrix G. I denotes the identity matrix with appropriate dimension and $\mathcal{C}^1 = \mathcal{C}^1([-h, 0], \mathbb{R}^n)$ denotes the family of continuously differentiable functions from $[-h, 0]$ to $\mathbb{R}^n$, where $h > 0$. Further $\lambda_{\max}(A)$, $\lambda_{\min}(A)$ denote the maximum and minimum eigen values of the matrix A respectively. Matrices, if not explicitly stated, are assumed to have compatible dimensions.

2. Problem description and preliminaries

Consider the switched neutral system with mixed time-delays and nonlinear perturbations as follows:

$$\dot{x}(t) = A_{\sigma(t)}x(t) + B_{\sigma(t)}x(t-\tau(t)) + C_{\sigma(t)}\dot{x}(t-d) + f_{1\sigma(t)}(t, x(t)) + f_{2\sigma(t)}(t, x(t-\tau(t))) + f_{3\sigma(t)}(t, \dot{x}(t-d)), \quad (1)$$
$$x(t) = \phi(t), \quad \forall t \in [-h, 0],$$

where $x(t) \in \mathbb{R}^n$ is the state of the system, the initial condition $\phi(\cdot)$ is continuously differentiable on $[-h, 0]$, $h = \max\{\tau_2, d\}$. The discrete time-varying delay $\tau(t)$ is assumed to satisfy

$$0 \leq \tau(t) \leq \tau_2, \quad \dot{\tau}(t) \leq \mu_1 < \infty, \quad (2)$$