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Fuzzy singularly perturbed modeling and composite controller design for nonlinear multiple time-scale systems with time-delay

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Abstract

This paper investigates the problems of modeling and robust controller design for nonlinear multiple time-scale systems (MTSSs) with time-delay. An uncertain standard discrete-time fuzzy singularly perturbed model (FSPM) with time-delay is firstly constructed to estimate the considered system. Based on a matrix spectral norm approach, robust composite controllers with or without time-delay are designed respectively. They are composed by a slow-state-variables feedback controller and an output integrator. The controller's gains are obtained by solving a set of ε-independent linear matrix inequalities (LMIs) such that the ill-conditioned problems caused by ε can be easily avoided. The designed control laws not only can stabilize resulting closed-loop systems but also can overcome external disturbances. Finally, simulation results for CE150 helicopter system illustrate the effectiveness of the proposed approaches. In contrast to the existing results, the proposed methods have the following advantages: i) They have better practical value since parameter uncertainty, external disturbances and the problem that the state variables are not fully measurable are considered. ii) A high accurate control performance can be achieved. iii) External disturbances can be effectively reduced.

Keywords: Uncertain singularly perturbed systems (SPSs); Discrete-time systems; Linear matrix inequality (LMI); Spectral norm; Time-delay; Robust control

1. Introduction

Time-delay, nonlinear and multiple time-scale characteristics often coexist in many practical systems, such as metallurgical systems, aircraft systems, biological systems, network systems, and nuclear reactors, etc., and cause instability, in which the multiple time-scale characteristic is a dynamic feature that the state variables of systems occur in the slow and fast dynamical phenomena. The systems with the above three characteristics are called nonlinear multiple time-scale systems (NMTSSs) with time-delay. The control problems in these systems are more complex than in conventional systems due to coexistence of many features. Most of the existing control theory results [1–9] for complex systems considered only one or two characteristics coexistence problems. For example, [1–3] investigated the

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control problems of conventional linear systems with time-delay. Nonlinear systems with or without time-delay were considered in [4–9]. Linear multiple time-scale systems with or without time-delay [10–13] and NMTSSs without time-delay [14–29] were investigated by using singular perturbation techniques. Specially, [14–17] used conventional nonlinear singularly perturbed modeling and controller design approaches based on an integral manifold to deal with the problems of stabilization and robust control for NMTSSs without time-delay. However, they require complex derivation and some assumptions for the systems architecture. In order to solve this problem, [18–30] presented fuzzy singularly perturbed modeling and control methods for continuous-time [18–25] and discrete-time [18,26–30] NMTSSs without time-delay, in which [26,29,30] considered uncertain parameters cases. However, the high accuracy control performances cannot be obtained if the above results would be applied directly to NMTSSs with time-delay because they ignored the time-delay problem of three coexistence characteristics. In recent years, in order to deal with the problem of three characteristics coexistence, modeling and control methodologies for NMTSSs with time-delay have been in some progress, but they considered only continuous-time cases [31–33], which cannot be used directly to discrete-time NMTSSs with time-delay. To the authors' best knowledge, the control problems of discrete-time NMTSSs with time-delay have not been addressed yet. In addition, the sampling periods of most practical NMTSSs with time-delay are greater than 0.05. Therefore, it is very necessary that time-delay standard discrete-time fuzzy singularly perturbed modeling and control are investigated to solve the high accuracy control problem of NMTSSs with time-delay. Because of that standard discrete-time fuzzy singularly perturbed model (FSPM) with time-delay can describe the dynamics of time-delay NMTSSs with larger sampling periods under a unified model framework.

This paper focuses on the problems of modeling and robust controller design for NMTSSs with time-delay based on a standard discrete-time FSPM with parameter uncertainty. The sufficient conditions for the existence of robust controllers with and without time-delay are derived by employing a matrix spectral norm approach. Simulation results for CE150 helicopter system confirm the effectiveness of the presented methods.

The rest of this paper is organized as follows. In Section 2, an uncertain standard discrete-time fuzzy singularly perturbed model is constructed for nonlinear MTSSs with time-delay. The main results are given in Section 3 where the robust controllers with and without time-delay design problems are reduced to the feasibilities of a set of ε-independent LMIs via a matrix spectral norm approach. The validity of this method is demonstrated by a CE150 helicopter system provided in Section 4. Section 5 concludes this paper.

The notations used throughout this paper are quite standard. In symmetric block matrices, we use "*" as an ellipsis for the terms that are introduced by symmetry. $I_{n\times n}$ is an $n\times n$ identity matrix, $0_{n\times n}$ is an $n\times n$ zeros matrix.

2. Fuzzy singularly perturbed modeling for nonlinear MTSSs with time-delay

Linear SPSs can be described by both standard and nonstandard discrete-time singularly perturbed models according to their sampling rates. In terms of some linear discrete-time SPSs theories, this paper constructs uncertain standard discrete-time fuzzy singularly perturbed models with time-delay for nonlinear MTSSs with slow sampling rates and design controllers with or without time-delay, which are composed by slow-state-variables feedback controllers and output integrators.

The considered nonlinear MTSSs are described by the following uncertain standard discrete-time fuzzy singularly perturbed model with time-delay:

Plant rule i:

If $\xi_1(t)$ is ϕ_{i1} and ... and $\xi_g(t)$ is ϕ_{ig}, then

$$\begin{aligned} x(k+1) &= E_\varepsilon(A_i+\Delta A_i)x(k)+E_\varepsilon(A_{di}+\Delta A_{di})x(k-\tau)+E_\varepsilon B_i u(k)+E_\varepsilon D_i w(k) \\ y(k) &= Cx(k) \end{aligned} \tag{1}$$

where

$$E_\varepsilon=\begin{bmatrix} I_{n\times n} & 0 \\ 0 & \varepsilon I_{m\times m}\end{bmatrix},\qquad x(k)=\begin{bmatrix} x_s(k) \\ x_f(k)\end{bmatrix},$$

$x_s(k)\in R^n$ is slow-state-vector, $x_f(k)\in R^m$ is fast-state-vector, $u(k)\in R^{q\times 1}$ is control input vector, $w(k)\in R^{q\times 1}$ is external disturbance vector, $y(k)\in R^{l\times 1}$ is measurable output, ϕ_{ij} $(j=1,2,\dots g)$ is fuzzy sets, $\xi_1(k),\dots,\xi_g(k)$ are