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A novel method for fault detection in singularly perturbed systems via the finite frequency strategy

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Abstract

This paper addresses the fault detection synthesis for a class of linear singularly perturbed systems with unknown disturbances. The observer is designed via a novel method, in which singularly perturbed systems could be processed within a uniform framework instead of using the classical slow–fast decomposition. The problem of robust fault detection can be converted into a standard H_∞ model-matching. Based on the generalized Kalman–Yakubovich–Popov lemma and parameter-dependent Lyapunov functions, a full-order observer is designed such that the corresponding error dynamic system is asymptotically stable and satisfies a prescribed finite-frequency H_-/H_∞ performance index. A novel three-step design procedure is then proposed to extract the fault feature from strong background disturbances. An illustrative example is given to demonstrate the validity and applicability of the proposed approaches in the simulation part.

1. Introduction

Singular perturbation phenomena are commonly encountered in many physical systems and engineering plants including aircraft and racket systems, power systems and nuclear reactor systems. In the past decades, a great deal of interest has been devoted to stability analysis and control synthesis for singularly perturbed systems (SPSs). The dynamics of SPSs contain the interaction of slow and fast phenomena such that feedback design often suffers from high dimensionality and ill-conditioning [1,2]. To alleviate the numerical stiffness, engineers usually

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use singular perturbation approaches and time-scale techniques in analytical investigations of system properties. Singularly perturbed models are usually simplified by neglecting the fast part, and the approximation is improved by reintroducing their effects as boundary layer corrections in separate time-scales [1,3,4]. In this sense, stability and control specifications of the original SPS can be inferred from the analysis of lower-order systems in separate time-scales. Despite the great practical significance, there are still restrictions and limitations with classical methods because only a small group of SPSs are capable for slow–fast decomposition. Contrast with the existing methods, novel approaches in singular systems are introduced, which can easily be applied into both standard and nonstandard SPSs. Nowadays, the theory of singular systems is well developed to find a new synthesis approach for SPSs. In [5,6], many results previously known only for regular state-space systems have been extended to singular systems, and increasingly more advances in singular systems have made use of the matrix inequality machinery. It has been pointed out that the limiting model of SPSs is the form of singular systems. Via survey of the algebraic condition that the limiting solution is available to approach that of SPSs, the limiting models are employed to design controllers for the original SPSs. In [7], robust stability analysis and robust stabilization for a class of linear SPSs with norm-bounded time-varying uncertainties are considered with aid of existing results for singular systems under certain conditions. Singular system approaches for nonlinear singularly perturbed optimal control problem have been proposed in [8–12], which also illustrate that the optimal (ϵ-independent) regulators for singular systems are near-optimal regulators for corresponding SPSs.

On the other hand, advanced supervision and fault detection play a critical role in enhancing reliability and safety of modern complex dynamic systems during technical processes [13]. A fault is defined as an unpermitted deviation of at least one characteristic property of a variable from an acceptable behavior, which tends to degrade the overall system performance [14]. The aim of fault detection (FD) is, therefore, to detect faults even in the presence of unknown disturbances. Compared with normal behaviors, analytic symptoms are generated to alarm the occurrence of fault. Nominally, the residual process is nonzero when a fault has occurred, and is zero at other times. Various methods of FD are taken into consideration, which extract features from measured signals based on process and signal models. In the literature, FD observers, depending on using particular type of state observers to produce detection residuals, are usually chosen to detect faults [15]. In [16], a general approach is presented to design robust FD filters for linear time-invariant uncertain systems under feedback control. H_∞ norm optimization techniques play a leading role in the analysis of the disturbance attenuation ability subject to both input constraints and exogenous disturbances. Simultaneously, the H_- method has been introduced to measure the worst-case fault sensitivity performance of a FD observer [14,15,17–19]. The papers present a straightforward procedure for designing an unknown input observer for a linear system subject to uncertain disturbances by using the framework of the general structured observer [20–22].

Due to the wide existence of singular perturbed phenomena in engineering applications, researches and applications in the field of fault detection for SPSs have attracted considerable attention in recent years. Considering the special frequency characteristics of SPSs, design specifications for the H_-/H_∞ control in the entire frequency spectrum can be simplified into the finite-frequency cases. Dynamics of SPSs, comprising of slow "phugoid" modes and fast "short-period" modes, are more sensitive to low- and high-frequency external inputs rather than middle-frequency ones. Advantage is thereby taken of the frequency nature of SPSs to design a well-conditioned FD observer to solve the original ill-conditioned problem within a specified accuracy. In this paper, finite-frequency system specifications, customarily referred to as the window H_-/H_∞ performance index, can be converted into frequency domain inequalities