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Fault detection for singular multiple time-delay systems with application to electrical circuit

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Abstract

In this paper, an H_-/H_∞ fault detection (FD) filter is designed for linear singular systems with multiple state delays. System faults and unknown disturbances are assumed to reside in finite frequency ranges. By combining the Parseval theorem and the strict S-procedure, both time domain and frequency domain approaches are used to formulate a new delay-dependent finite frequency bounded real lemma (BRL), which includes some existing results as special cases. Based on the obtained BRL, convex FD filter design conditions are derived in terms of solving a set of linear matrix inequalities (LMIs). The effectiveness of the proposed finite frequency FD method is illustrated through a simulation example on the electrical circuit.

1. Introduction

Due to the increasing demand for reliability and safety in industrial processes, FD has been the subject of intensive research and a lot of model based FD approaches have been reported in the literature. Among these approaches, the celebrated H_-/H_∞ FD scheme is accepted as a popular and useful one. For instance, a weighting matrix is introduced in [1,2] to transform the fault sensitivity performance into an H_∞ constraint; in [3–5], the H_∞ and H_- indexes are used to directly measure the fault sensitivity performance and the disturbance attenuation performance, respectively.

On another research front, singular systems have a strong practical background, and they are always encountered in chemical and mineral industries, mechanical and aerospace systems, as

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well as electronic and electrical circuits. Just as pointed out in [6], singular systems provide a more general representation than standard state-space systems in the sense of modeling. Many fundamental system theories developed for state-space systems have been successfully generalized to their counterparts for singular systems, for example, controllability and observability [7], filter design [8–12], observer design [13], stability analysis [14,15] and fault tolerant control [16,17], etc. Especially, the fault detection problems for singular systems have been studied in [18–23]. To reflect the frequency characterizations of external disturbances and fault signals, the FD performance requirements over a finite frequency range have been translated into an H_∞ tracking problem in [19,20] by introducing a weighting matrix. Although the weighting based method has been proven useful in practice, the process of selecting appropriate weights can be time-consuming, and the additional weights tend to increase the complexity of FD systems.

To solve these problems, the generalized Kalman–Yakubovic–Popov (GKYP) lemma [24] based FD methods [25–28] have been developed for linear time-invariant (LTI) systems, where the exact LMI conditions for guaranteeing disturbance attenuation and fault sensitivity requirements in finite frequency ranges are derived without resorting to any frequency weighting matrix. In fact, the GKYP lemma includes a finite frequency BRL as a special case, and this finite frequency BRL has been used in [25–28] for the purpose of FD, while it has not been established for linear singular systems with state delays. Note that control or filtering of time-delay systems is a subject with both practical and theoretical importance, and a lot of methods have been given to study this problem, for example, the delay-slope-dependent based method [29], augmented Lyapunov function method [30,31], piecewise Lyapunov function method [32], and so on. Moreover, the linear singular system with multiple delays includes the one with single delay as a special case, then it is able to characterize a wide class of practical systems. With these observations, it is necessary to generalize the result in [24] to linear singular system with multiple delays and further formulate solvable finite frequency FD system design conditions, which motivates our investigation.

In this paper, an H_-/H_∞ FD scheme is firstly established in finite frequency ranges for linear singular systems with multiple state delays. By combining time domain and frequency domain approaches, a new delay-dependent finite frequency BRL is obtained within the framework of the Parseval theorem [33] and the strict S-procedure [34]. It is shown that this BRL includes some existing results as special cases. In addition, based on the obtained BRL, convex FD filter design conditions are derived through constructing a hyperplane tangent to a ball, and the FD filter parameters are also presented by solving a set of LMIs. Finally, a simulation example on an electrical circuit system is given to show the validity and applicability of the proposed finite frequency FD method.

The rest of this paper is organized as follows: in Section 2, the design objectives and preliminary results are presented. The FD filter analysis and design conditions are given in Section 3. The FD threshold and simulation results are given in Section 4 and Section 5, respectively.

The following notations are used throughout this paper. A block diagonal matrix with matrices $X_1, X_2, \ldots X_n$ on its main diagonal is denoted as $diag(X_1, X_2, \ldots X_n)$. For a symmetric matrix Ξ, $\Xi > 0$ and $\Xi < 0$ denote positive definiteness and negative definiteness. The symmetric terms in a symmetric matrix are denoted by $\star$. For a matrix A, its complex conjugate transpose is denoted by A^*, and $He(A) \triangleq A + A^*$. The set of matrices $N = N^* \leq 0$ is denoted by $\mathbf{N}$. The symbol $\mathbf{H_n}$ stands for the set of $n \times n$ Hermitian matrices. $\overline{\sigma}(\cdot)$ and $\underline{\sigma}(\cdot)$ denote maximum and minimum singular values of a transfer function matrix, respectively, I denotes the identity matrix with an