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A descriptor-system approach for finite-frequency H_∞ control of singularly perturbed systems☆

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ABSTRACT

This paper investigates the robust control for a class of singularly perturbed systems in the presence of actuator saturation. The controller design problem is cast as a convex optimization formulation, and the descriptor-system approach and the finite-frequency control technique are used to alleviate the ill-conditioning of the systems and reduce the conservatism of control system specifications. A parameter-dependent Lyapunov function approach is used to study the stability of the closed-loop system, and time-domain constraints are then formulated to enhance the safe operation of the systems subject to actuator saturations. We characterize the disturbance attenuation capability from external disturbances to measurement outputs in concerned frequency ranges such that the numerical stiffness can be avoided by specifying the unknown matrices in the singularly perturbed form. The finite-frequency descriptor-system control method is applied to an armature-controlled DC motor system to verify its effectiveness and merits.

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1. Introduction

Two-time-scale behaviors in physical systems are characterized by the simultaneous presence of slow and fast transients in the system's response to external inputs [5,12,20,21]. Such two-time-scale systems are customarily referred to as singularly perturbed systems (SPSs). Generally, some small "parasitic" elements in control systems, such as high frequency parasitics in electronic circuits and small time-delays in industrial processes, are the source of singular perturbation phenomena [1,2,12]. Singular perturbation techniques (SPTs) aim at alleviating the numerical stiffness resulted from weak coupling among system dynamics [3,18,19,21,22], which can generally be classified as parameter-dependent and parameter-independent methods. Many existing parameter-independent SPTs use the slow-fast decomposition methods such that a full-order feedback design problem can then be decomposed into two parameter-independent slow and fast sub-problems [4,17,25]. Such decomposition methods, however, sacrifice a considerable amount of model accuracy for lower computation complexity, and can only be applied in standard SPSs with an invertible fast system matrix [12]. As for the parameter-dependent SPTs, some descriptor-system approaches based on matrix theory have been introduced to find new synthesis

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approaches for nonstandard SPSs [6,7,26,30,31]. The key feature of such methods is to solve the singularly-perturbed problem through investigating its analogous problem for a descriptor system. The relationship between the regulator problem for an SPS and its corresponding descriptor system was discussed in [26]. Controllers were designed based on the structure of descriptor system, which led the full-order SPS to the near-optimal performance in [6]. Descriptor-system approaches were designed for near-optimal control of nonstandard SPSs in [31], which is a significant achievement over the two-stage design procedure for the parameter-independent composite controller in [12,14].

Another major problem in system theory and control applications is how to enhance the robustness of various control system performances to external disturbances in the system model. In this sense, factors such as disturbance attenuation, measurement limitation, and actuator saturation should be considered in the system analysis and controller design. Considering that control systems usually operate over finite frequency ranges rather than the entire frequency range, each design specification is often given for certain frequency ranges of interest to reduce the conservatism in the dynamic state feedback controller design. Moreover, the two-frequency-scale nature of SPSs mean that their slow and fast dynamics are sensitive to low-frequency and high-frequency external disturbances, respectively, which can lead to the application of finite-frequency techniques. Recently, some important works have addressed the finite-frequency control issues [8,16,23,24,27–29,32]. In [23], the problem of finite-frequency H_∞ control was proposed for active vehicle suspension systems. However, the existing finite-frequency techniques fail to be directly used in SPSs because of the numerical stiffness caused by the weak coupling effects in SPSs. To the best of the authors' knowledge, only a few attempts have been made to address the finite-frequency robust control problem of SPSs, which motivates this study.

In this work, a parameter-independent state feedback controller is designed to attenuate the ill-conditioning of SPSs and enhance the robustness of finite-frequency control specifications. Integrating descriptor-system approaches with finite-frequency control techniques, we cast the controller design into a convex multi-objective optimization problem, which can then be solved using linear matrix inequalities (LMIs). First, we investigate the stability properties of SPSs under the performance constraints, and a parameter-dependent Lyapunov function is employed to formulate LMI-based sufficient conditions for the existence of the stabilizing controller. Then, the disturbance attenuation capability of SPSs is characterized by the less conservative finite-frequency bounded-real property. Through specifying the unknown variables in parameter-dependent form, the numerical stiffness in the equivalent LMI can be alleviated.

To the best of the authors knowledge, this is the first attempt of the matrix inequality techniques to investigate the finite-frequency robust properties and alleviate the ill-conditioning of SPSs in the literature. The usefulness of classical parameter-independent SPTs is limited because a variety of engineering applications are in the nonstandard singularly perturbed form. The proposed method can be applied to both standard and nonstandard SPSs, thus it has a wide range of practical applications. It is also simple and intuitive. The main contributions of this paper are summarized as follows:

1. The proposed control design method can be used in both standard and nonstandard SPSs;
2. Both parameter-dependent and parameter-independent state feedback controllers are designed. By solving a specific formulation of the matrix, the numerical stiffness in the LMI-based sufficient conditions can be overcome with both the computation complexity and approximation accuracy taken into account;
3. The proposed controller design method is applicable to more sophisticated systems that exhibit multi-time-scale characteristics, and hence broadening the application prospects.

Notation. Throughout this paper, R^n and $\mathrm{R}^{n \times m}$ denote the n-dimensional Euclidean space and the set of all $n \times m$ real matrices, respectively. H_n stands for the set of $n \times n$ Hermitian matrices. $A \otimes B$ stands for the Kronecker product of matrices A and B. The superscripts "T", "†", and "⊥" denote the matrix transpose, the Moore-Penrose inverse, and the orthocomplement of a matrix, respectively. The Hermitian part of a square matrix M is denoted by $\mathrm{He}(M) = M + M^T$. The symbol "det(M)" is the determinant of matrix M. In symmetric block matrices and complex matrix expressions, we use the symbol $\star$ to represent a term that is induced by symmetry, and a block-diagonal matrix is denoted by diag{...}. For $G \in \mathrm{C}^{n \times m}$, a function σ is defined by

$$\sigma(G, \Pi) = \begin{bmatrix} G \\ I_m \end{bmatrix}^T \Pi \begin{bmatrix} G \\ I_m \end{bmatrix}.$$

The notation $\|G\|_\infty$ denotes the H_∞ norm of the transfer function matrix $G(s)$. The matrices, unless explicitly stated, are assumed to have compatible dimensions.

2. Problem formulation and preliminaries

Consider a class of standard SPSs with distinctive slow and fast dynamics,

$$\begin{aligned} \dot{x}_1 &= A_{11}x_1 + A_{12}x_2 + B_{u1}u + B_{w1}w, \\ \epsilon\dot{x}_2 &= A_{21}x_1 + A_{22}x_2 + B_{u2}u + B_{w2}w, \\ z &= C_1x_1 + C_2x_2 + D_uu + D_ww, \end{aligned} \tag{2.1}$$

where $x_i \in \mathrm{R}^{n_i}$, $i = 1, 2$, are, respectively, slow and fast state vectors with $n = n_1 + n_2$ denoted as the system dimension, $u \in \mathrm{R}^{n_u}$ is the control input, $w \in \mathrm{R}^{n_w}$ is the external disturbance, and $z \in \mathrm{R}^{n_z}$ is the measurement output. The small positive parameter ϵ is the perturbation parameter to characterize the separation in "speed" of slow and fast dynamics.

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