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Application of ICC LPV control to a blended-wing-body airplane with guaranteed $\mathcal{H}_\infty$ performance

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ABSTRACT

This paper addresses the Input Covariance Constraint (ICC) control problem with guaranteed $\mathcal{H}_\infty$ performance for continuous-time Linear Parameter-Varying (LPV) systems. The upper bound of the output covariance is minimized subject to the constraints on input covariance and $\mathcal{H}_\infty$ output performance. This problem is an extension of the mixed $\mathcal{H}_2/\mathcal{H}_\infty$ LPV control problem, in that the resulting gain-scheduling controllers guarantee not only closed-loop system robustness in terms of $\mathcal{H}_\infty$ norm bound but also output covariance performance over the entire scheduling parameter space. It can be shown that this problem can be efficiently solved by utilizing the convex optimization of Parameterized Linear Matrix Inequalities (PLMIs). The main contributions of this paper are to characterize the mixed ICC/$\mathcal{H}_\infty$ LPV control problem using PLMIs and to develop the optimal state-feedback gain-scheduling controllers, while satisfying both input covariance and $\mathcal{H}_\infty$ constraints. The effectiveness of the proposed control scheme is demonstrated through vibration suppression of a blended-wing-body airplane model.

1. Introduction

Linear Parameter-Varying (LPV) modeling and control have gained significant interest from the control community over the past two decades [1–4]. The main benefit of LPV control is that the varying nature of system dynamics can be captured by the LPV model with its linear system matrices dependent on scheduling parameter. LPV controllers can be designed with its gain scheduled based on scheduling parameters measured in real-time.

A systematic LPV modeling approach was proposed in our previous publication [5,6] for developing reduced-order LPV models for flexible aerospace structures. The sub-sequential LPV control design based on developed LPV models is presented in this article. The mainstream approach of LPV gain-scheduling control design is to formulate control synthesis conditions in terms of Linear Matrix Inequalities (LMIs) or Parameterized Linear Matrix Inequalities (PLMIs) [1,7,8]. Numerically tractable optimization methods, such as convex optimization, can then be applied to solve for feasible or optimal LPV gain-scheduling controllers. LPV control designs with guaranteed $\mathcal{H}_2$ and/or $\mathcal{H}_\infty$ performance have been intensively studied in the literature [9–12]. However, in practical aerospace structural control applications, control inputs are often hard-constrained and modeling error is unavoidable. Therefore, how to achieve optimal output performance when subject to constrained control input and bounded modeling error is a critical control design problem, but conventional LPV control design technique cannot handle such a design problem. Therefore, mixed Input Covariance Constraint (ICC) and $\mathcal{H}_\infty$ LPV control is proposed in this paper to deal with this multi-objective optimal control problem.

As an extension of $\mathcal{H}_2$ control, the ICC control problem is to minimize the output covariance performance subject to the multiple constraints on input covariance. The ICC control plays an especially important role for systems with hard constraints on control authority [13,14]. In practical applications, actuators are utilized to drive the mechanical systems to achieve desired output performance, and these actuators typically have limited capacity. Therefore, it is critical to incorporate these actuator constraints during control design, however, this has not been considered in the traditional LPV control formulation. In addition, the existing optimization formulation for conventional LPV controller design often leads to high-gain controllers, due to the optima-seeking nature of the optimization process. These high-gain controllers would inevitably tend to drive the actuators beyond their physical limitations and could also degrade or even destabilize closed-loop systems [15]

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when the modeling error becomes significant. Furthermore, for multiple exogenous input scenarios, the problem of LPV control design to achieve the best possible performance is still an open research problem.

The dual of ICC problem is the Output Covariance Constraint (OCC) control problem, which is to minimize the control input covariance subject to the constraints on output covariance. Both ICC and OCC control problems for linear systems have been studied extensively in the past. For instance, a linear quadratic control problem minimizing control energy subject to output covariance constraints was first considered in Hsieh et al. [16]. In Zhu et al. [17] an algorithm with guaranteed convergence was proposed, in which the OCC problem was solved by optimally selecting the output weighting matrix and solving the Riccati equation iteratively. After the LMI technique was introduced, both ICC and OCC problems have subsequently been converted into the convex optimization problems with LMI constraints [18,19], and they were solved using convex optimization tools. Al-Jiboory et al. [19] utilized the linear time-invariant (LTI) ICC control design approach to optimize the system performance, in terms of output covariance with given actuator constraints, for both state and output feedback cases. An application of the control synthesis LMI conditions can be found in Al-Jiboory et al. [18]. It should be emphasized that the OCC and ICC control problems mentioned above were all for LTI systems, and only a single $\mathcal{H}_2$ performance constraint was considered. In other words, there was no guaranteed robust performance for closed-loop systems when subject to modeling errors.

To meet multiple performance requirements, a mixed $\mathcal{H}_2/\mathcal{H}_\infty$ LPV control strategy has been proposed with two separate performance channels for $\mathcal{H}_2$ and $\mathcal{H}_\infty$ performance specifications. Scherer et al. [20] formulated an $\mathcal{H}_2/\mathcal{H}_\infty$ problem for LPV systems and provided the associated solution by solving the algebraic LMIs. In Scherer et al. [21] a solution to the output-feedback mixed $\mathcal{H}_2/\mathcal{H}_\infty$ LPV control problem was presented. Apkarian et al. [22] developed a tractable and practical LMI formulation for the multi-objective LPV control problem using Linear Fractional Transformation (LFT) representations. All these studies treat the mixed performance control problem without including control input and output performance constraints. Recently, White et al. [3,23] formulated PLMI conditions to solve this multi-objective problem for polytopic discrete-time LPV systems, and provided a solution that guarantees $\mathcal{L}_2$ to $\mathcal{L}_\infty$ gain and performance. Zhang et al. [24] designed a multi-objective LPV controller for an electronic throttle, and showed that the multi-objective LPV controller is able to improve closed-loop system performance over the baseline PID controller.

The primary objective of this paper is to formulate the continuous-time mixed ICC and $\mathcal{H}_\infty$ control problem by utilizing PLMIs for the state-feedback case. To the best of authors' knowledge, the gain-scheduling state-feedback robust ICC problem with guaranteed $\mathcal{H}_\infty$ performance for continuous-time LPV systems has never been explored in the past. One of the great advantages of the proposed approach is that it provides an effective way of designing a family of LPV controllers with varying gains, allowing to tune the controller gains for LPV systems, which is a capability of great practical significance. To illustrate the benefits of the proposed approach, a blended-wing-body airplane model is considered for vibration suppression. Although a full state-feedback controller has limited practical application, nonetheless it serves as a good basis for formulating the dynamic output feedback controllers.

The rest of paper is organized as follows. Section 2 formulates the mixed ICC and $\mathcal{H}_\infty$ (or robust ICC) control problem, and Section 3 provides LPV modeling of linear systems and introduces affine to multi-simplex transformation. Then, the control synthesis conditions in terms of PLMIs are provided in Section 4, and the numerical simulations for the blended-wing-body model are conducted in Section 5. The conclusions are in Section 6.

2. Problem formulation

Consider the following affine LPV systems,

$$\Sigma(\theta):\begin{cases}\dot{x}(t) = A(\theta(t))x(t) + B_\infty(\theta(t))w_\infty(t)\\ \qquad\quad + B_2(\theta(t))w_2(t) + B_u(\theta(t))u(t)\\ z_\infty(t) = C_\infty(\theta(t))x(t) + D_\infty(\theta(t))w_\infty(t)\\ \qquad\quad + E_\infty(\theta(t))u(t)\\ z_2(t) = C_2(\theta(t))x(t)\end{cases} \tag{1}$$

where $\theta(t) = \left[\theta_1(t), \theta_2(t), \ldots, \theta_q(t)\right]^T$ denotes the scheduling parameter vector of q elements, $x(t) \in R^{n_x}$ denotes the state, $w_\infty(t) \in R^{n_{w\infty}}$ the $\mathcal{H}_\infty$ disturbance input due to modeling error, $w_2(t) \in R^{n_{w2}}$ the $\mathcal{H}_2$ disturbance input, $u(t) \in R^{n_u}$ the control input, $z_\infty(t) \in R^{n_{z\infty}}$ the $\mathcal{H}_\infty$ controlled output, and $z_2(t) \in R^{n_{z2}}$ the $\mathcal{H}_2$ performance output. All system matrices are assumed to have compatible dimensions and in affine parameter-dependent form. For example, $A(\theta)$ can be described by

$$A(\theta(t)) = A_0 + \sum_{i=1}^{q} A_i\theta_i\ , \tag{2}$$

where A_0 and A_i, $i = 1, 2, \ldots, q$, are constant matrices. It is assumed that the scheduling parameters are measurable in real-time, and their magnitude and variational rate are bounded. Specifically, the scheduling parameter set is formulated as:

$$\theta \in \Theta = \left\{\underline{\theta}_i \le \theta_i(t) \le \bar{\theta}_i, -\nu_{\theta_i} \le \dot{\theta}_i(t) \le \nu_{\theta_i}\right\}, \tag{3}$$

where $i \in [1, 2, ..., q]$. In this paper, we propose the gain-scheduling state-feedback controllers of the form

$$u(t) = K(\theta(t))x(t), \tag{4}$$

where $K(\theta)$ is the parameter-dependent control gain matrix. Note that $u(t)$ can be partitioned as $u(t) = \left[u_1(t), u_2(t), \ldots, u_{n_u}(t)\right]^T$. Then, substituting (4) into (1) yields the closed-loop LPV system described by

$$\Sigma_{cl}(\theta):\begin{cases}\dot{x}(t) = A_{cl}(\theta)x(t) + B_\infty(\theta)w_\infty(t) + B_2(\theta)w_2(t);\\ z_\infty(t) = C_{cl,\infty}(\theta)x(t) + D_\infty(\theta)w_\infty(t)\\ z_2(t) = C_2(\theta)x(t)\end{cases} \tag{5}$$

where $A_{cl}(\theta) = A(\theta) + B_u(\theta)K(\theta)$, $C_{cl,\infty}(\theta) = C_\infty(\theta) + E_\infty(\theta)K(\theta)$. Throughout this paper, we make use of the following standard definition of $\mathcal{L}_2$ and $\mathcal{L}_\infty$ norms on $x(t) \in R^n$ for all $t \ge 0$,

$$\|x\|_2^2 := \int_0^\infty x^T(t)x(t)dt\ , \quad \|x\|_\infty^2 := \sup_{t\ge0} x(t)^T x(t)\,.$$

2.1. System performance

It should be noted that there are two separate input and output pairs defined in (5), and they are specifically designated for assessing the closed-loop LPV system performances, as shown in Fig. 1. The LPV system $\Sigma(\theta)$ is controlled by the gain-scheduling state-feedback controller (4), to achieve best $\mathcal{H}_2$ performance while subject to $\mathcal{H}_\infty$ performance requirements and control input constraints. Note that the interconnection of Δ in Fig. 1 is to capture the model uncertainties in $\Sigma(\theta)$. The definitions of $\mathcal{H}_\infty$ and $\mathcal{H}_2$ performances are given below.

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