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Parameter-dependent H_∞ filter design for LPV systems and an autopilot application

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ABSTRACT

This paper considers the design problem of parameter dependent H_∞ filters for linear parameter varying (LPV) systems whose parameters are measurable. Conditions for existence of parameter-dependent Lyapunov function are proposed via parametrical linear matrix inequality (LMI) constraints. Based on the solutions to the LMIs, an algorithm for the gain matrices of LPV filter is presented. The design method is applied to a missile system to demonstrate the effectiveness.

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1. Introduction

LPV systems are a class of linear systems whose state-space matrices depend on time-varying parameters. LPV systems are widely used for describing practical systems such as missiles [1–3], aircrafts and spacecrafts [4–6], energy production systems [7–9], inverted pendulum [10], and automated vehicles [11]. Filter analysis and design in LPV systems have attracted considerable investigation over the last decade and several methods of designing filters have been proposed [12–15]. At early stage, parameter-independent Lyapunov function is presented [16]. Later, parameter-dependent Lyapunov function method is proposed to achieve less conservatism for the LPV systems whose parameters vary in a polytopic domain using parametrically affine Lyapunov function method [12,14,17]. Extension research for LPV filter in [17,18] studies reduced-order filtering. Result in [19] presents an improved filtering method for discrete-time systems.

Parameters in LPV systems can be viewed as parametric uncertainty or parameters which can be measured in real time during system operation [20]. In [13,14], the parameters are considered as uncertainty and the parameter-dependent LMI conditions for the existence of parametrically affine and parameter-independent Lyapunov function are presented if the parameters vary in polytopic region. In [21], the parameters are assumed to be measured and an H_∞ controller is designed for the LPV system, but no filter is designed.

Unlike in [13,14] where parameters are required to be in a polytopic region, here we only need parameters to be in a compact set. In this paper, an H_∞ filter is designed for an LPV system. Conditions of existence of parameter-dependent Lyapunov function are formulated via LMI constraints and an algorithm for LPV filter gain matrices based on the solutions to the LMI conditions is presented. Then we demonstrate the effectiveness of our method in designing an LPV filter for a missile pitch-axis autopilot model which needs state estimation to design controller. For the same missile system, a non-LPV filter is designed with no stability analysis given in [2], and we provide an LPV filter design method.

The rest of this paper is organized as follows. Section 2 presents the preliminaries. Section 3 gives the main results for the LPV filter design. An application of the proposed design method to the missile pitch-axis autopilot model is given in Section 4. Section 5 contains conclusion.

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Notation: I and 0 denote the identity matrix and zeros matrix with proper dimensions. $*$ denotes the symmetric part in a matrix. $Ker(\cdot)$ is the manipulation of solving the null matrix.

2. Preliminaries

Consider the following LPV system

$$\begin{aligned}\dot{x} &= A(\rho)x + B_1(\rho)w,\\ z &= C_1(\rho)x + D_{11}(\rho)w,\\ y &= C_2(\rho)x + D_{21}(\rho)w,\end{aligned} \tag{1}$$

where $x \in \mathbb{R}^n$ is the state with $x = 0$ at $t = 0$, $y \in \mathbb{R}^{n_y}$ is the measured output, $z \in \mathbb{R}^{n_z}$ is the signal to be estimated, $w \in \mathbb{R}^{n_w}$ is the disturbance input and $w \in L_2$. $\rho = [\rho_1, \ldots, \rho_s]^T$ is assumed to lie in a compact set $\mathcal{P} \subset \mathbb{R}^s$ with its parameter variation rate bounded by $\underline{v}_k \leqslant \dot{\rho}_k \leqslant \overline{v}_k, k = 1, 2, \ldots, s$, i.e., $\dot{\rho} \in \mathcal{P}_d$.

A full order parameter-dependent filter to be designed is of the form:

$$\begin{aligned}\dot{x}_f &= A_f(\rho)x_f + B_f(\rho)y,\\ z_f &= C_f(\rho)x_f + D_f(\rho)y,\end{aligned} \tag{2}$$

where $x_f \in \mathbb{R}^n$ is the filter state with $x_f = 0$ at $t = 0$ and $z_f \in \mathbb{R}^{n_z}$ is the estimated signal of z.

Given (1) and (2), the connected system in Fig. 1 is expressed as:

$$\begin{aligned}\dot{\sigma} &= \widehat{A}(\rho)\sigma + \widehat{B}(\rho)w,\\ e &= \widehat{C}(\rho)\sigma + \widehat{D}(\rho)w,\end{aligned} \tag{3}$$

where $\sigma = \begin{bmatrix} x^T & x_f^T \end{bmatrix}^T, e = z - z_f$ and

$$\widehat{A}(\rho) = \begin{bmatrix} A(\rho) & 0 \\ B_f(\rho)C_2(\rho) & A_f(\rho) \end{bmatrix}, \quad \widehat{B}(\rho) = \begin{bmatrix} B_1(\rho) \\ B_f(\rho)D_{21}(\rho) \end{bmatrix},$$

$$\widehat{C}(\rho) = [\, C_1(\rho) - D_f(\rho)C_2(\rho) \quad -C_f(\rho)\,], \quad \widehat{D}(\rho) = D_{11}(\rho) - D_f(\rho)D_{21}(\rho).$$

The filtering problem to be dealt with is stated as follows:

Problem 1. Find $A_f(\rho)$, $B_f(\rho)$, $C_f(\rho)$, $D_f(\rho)$ of the filter (2) such that the estimation error system (3) is quadratically stable when $w = 0$, and an upper bound γ to the H_∞ estimation error performance is assured, i.e.,

$$\sup_{w \in L_2, w \neq 0} \frac{\|e\|_2}{\|w\|_2} < \gamma, \quad \rho \in \mathcal{P}, \quad \dot{\rho} \in \mathcal{P}_d. \tag{4}$$

We now split Problem 1 into the following two subproblems:

Subproblem 1. Propose the conditions for the existence of parameter-dependent Lyapunov function $x^T P(\rho) x$ and H_∞ performance index γ such that system (3) is quadratically stable when $w = 0$ and (4) is satisfied.

Subproblem 2. According to the solved parameter-dependent matrix $P(\rho)$ and the index γ, find $A_f(\rho)$, $B_f(\rho)$, $C_f(\rho)$, $D_f(\rho)$ of the filter (2).

The following lemmas are required when dealing with the problem above.

Lemma 1 (Bounded Real Lemma [21]). *If there exist a positive definite matrix $P(\rho)$ and a positive number γ such that*

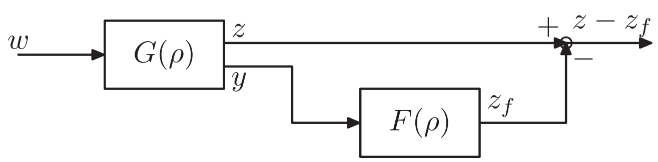

Fig. 1. Block diagram of LPV filter $F(\rho)$ for an LPV system $G(\rho)$.

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