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L_2 bumpless transfer control for switched linear systems with almost output regulation[☆]

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HIGHLIGHTS

- Bumpless transfer control issue with almost output regulation is firstly studied.
- A output bumpless transfer performance concept is proposed.
- Switching law design is firstly used to realize the bumpless transfer performance.
- Under the same switching law, the almost output regulation property is ensured.
- The switching law allows each subsystem not to have both properties.

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ABSTRACT

In this paper, the issue of L_2 bumpless transfer control for switched linear systems with almost output regulation property is investigated. First, a description of the L_2 bumpless transfer performance for a category of switched linear systems is given to measure the output bumpless transfer levels of the systems. Then, a compensator and a switching law are designed via a multiple Lyapunov functions strategy. Under the designed compensator and switching law, a sufficient condition guaranteeing the L_2 bumpless transfer property and the almost output regulation property of the systems is presented. Furthermore, the sufficient condition allows each subsystem not to have both properties. At last, an example showing the effectiveness of the proposed control scheme is offered by controlling a turbofan model.

1. Introduction

A switched system is a special hybrid system whose dynamics change among finite different modes [1]. Numerous practical processes can be modeled as switched systems, such as DC/DC power converters [2], network systems [3], electronic systems [4] and so on. The design of switching laws is a typical feature of switched systems [5], since a switched system can satisfy a certain property which is not owned by subsystems by designing a switching rule [6]. However, unexpected transient responses may be brought by unappropriate switchings. Subsequently, a question is: how to decrease or suppress those undesirable transient behaviors induced by switchings?

Bumpless transfer (BT) control provides an answer to the above question [7]. The first representative design method on BT control is a conditioning transfer scheme [8]. An *LQ* BT control strategy was introduced by [9]. [10] optimized the output response after a known switching instant. Whereas, only one switching is considered in the BT control issue settled by [8–10]. For the BT control issue with more than one switchings, few achievements are made. Two main difficulties need to be mentioned. The first one is the intrinsic nature of switched systems, that is, the information of switching signals is usually unknown in prior in practice [6]. The other difficulty is how to pursue better transient behaviors and maintain original steady-state properties of switched systems owing to the identical importance of stable-state properties and transient properties [11]. The *LQ* BT control scheme [9] was applied to solve the stabilization problem [12], output tracking problem [13], [14] and output regulation problem [15]. A slow–fast controller decomposition approach and a gain constrained method were given by [16] and [17], respectively. Whereas, almost

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all works on the BT control problem focus on modifying the predesigned controllers. This leads to the fact that the advantages of the design of switching laws for switched systems are not fully exploited.

Turning to the classical output regulation issue, a limitation is the accurate known dynamics of the controlled systems and exosystems [18–20]. This limitation is a little ambitious owing to the fact that some un-modeled disturbances inevitably affect the systems in practice [21]. To remove the limitation, the almost output regulation problem was proposed by [22], being an output regulation problem of systems with un-modeled disturbances which do not severely affect the original output regulation property of the systems. Especially, when the un-modeled disturbances do not exist, the almost output regulation property degrades into the classical output regulation property [23]. However, few works have been reported on the almost output regulation problem of systems, especially of switched systems. [24,25] offered solutions to the almost output regulation problem of impulsive systems and switched systems, respectively. It is worth noting that the issue of almost output regulation for switched systems without solvability of the problem for subsystems has not been considered. Moreover, the BT control problem of switched systems with almost output regulation property has not been considered yet.

In fact, to address the almost output regulation problem of switched systems with an assumption on the possible unsolvability of the problem for subsystems, the design of switching laws is often considered. This implies that the switching signals need to be unknown in advance. While, the switching signals are assumed to be known in most existing research results on the BT control problem. Accordingly, another question arises: whether a switching rule can be designed to enforce the almost output regulation property and the L_2 BT property of a switched system to be satisfied simultaneously? This paper aims to offer a positive answer to the above question.

Specifically, in this paper, the L_2 BT control problem of switched linear systems with almost output regulation property is studied via a multiple Lyapunov functions strategy. Compared with most existing works on the BT control problem, this paper has three main features: (i) We describe the output BT performance of a class of switched linear systems by a group of L_2-gain indexes. The description of the BT performance is a generalization of that in [10]. Through the multiple Lyapunov functions scheme, a switching law and a compensator is designed to achieve the L_2 BT performance of the systems. The design of the switching law adds an additional degree of freedom for the L_2 BT control design. While, the existing main BT control strategies are based on modifying the predesigned controllers only [9,13]. (ii) With the designed switching law and the compensator, the almost output regulation property is ensured even if each subsystem does not possess the almost output regulation property. This makes our control scheme useful to solve the almost output regulation problem for a more general class of switched systems [25]. in more general cases than the method of (iii) The presented control strategy is used to tackle the L_2 BT control problem of a turbofan model with the almost output regulation property.

The structure of this paper is arranged as: Section 2 gives the formulation of L_2 BT transfer control problem for switched linear systems with almost output regulation property. In Section 3, we offer a solution to the problem. An example used to text the effectiveness of the provided control strategy is given in Section 4. Section 5 concludes this paper.

Notation: R^n refers to the n-dimension real space. N and S represent the sets of nonnegative integers and positive integers, respectively. $|\cdot|$ denotes the magnitude of a vector. $L_2^n[0, \infty)$ is the space of n-dimension square integrable function vectors over $[0, \infty)$. $\lambda_{\max}(P)$ is the largest eigenvalue of the matrix P.

2. Problem formulation and preliminaries

Consider a class of continuous-time linear systems given by

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Ew(t) + Gd(t), \\ e(t) &= C_2x(t) + Du(t) + Fw(t) + Hd(t), \\ y(t) &= C_1x(t), \end{aligned} \tag{1}$$

where $x(t) \in R^n$, $u(t) \in R^m$, $e(t) \in R^p$, $y(t) \in R^l$, $d(t) \in L_2^n[0, \infty)$ denote the state, control input, regulated output, measurement output, and un-modeled external disturbance input, respectively, $w(t) \in R^r$ standing for the reference input and/or external disturbance input is generated by the disturbed exosystem

$$\dot{w}(t) = Sw(t) + Td(t). \tag{2}$$

In addition, some bounded control input signal $\tilde{u}(t)$ is initially utilized by the system (1) and must be replaced by a switched controller

$$\begin{aligned} \dot{\xi}(t) &= F_{c\sigma(t)}\xi(t) + G_{c\sigma(t)}u_\xi(t), \\ y_\xi(t) &= H_{c\sigma(t)}\xi(t) + L_{c\sigma(t)}u_\xi(t) \end{aligned} \tag{3}$$

through the interconnection equations

$$u(t) = \begin{cases} \tilde{u}(t), & t < \tilde{t}, \\ y_\xi(t) + v_1(t), & t \geq \tilde{t}, \end{cases} \tag{4}$$

$$u_\xi(t) = y(t) + v_2(t), \quad t \geq 0 \tag{5}$$

at a given instant $\tilde{t}$, where $\xi(t) \in R^q$ stands for the state of the controller (3), $\sigma(t) : [t_0, \infty) \to S = \{1, 2, \ldots, s\}$ refers to the switching signal to be chosen with s being the number of sub-controllers, $v_1(t)$ and $v_2(t)$ represent the amendations of the controller (3). The specific forms of $v_1(t)$ and $v_2(t)$ will be given later. The switching signal $\sigma(t)$ can be expressed by a sequence $\{x_0, (i_0, t_0), (i_1, t_1), \ldots, (i_k, t_k), \ldots | i_k \in S, k \in N\}$ with x_0, $t_0 = \tilde{t}$ and t_k denoting the initial state, initial time and kth switching instant, respectively. Also, the i_kth sub-controller of (3) is in operation whenever $\sigma(t) = i_k$. Suppose that the switching signal $\sigma(t)$ has a finite number of switchings over any finite time interval.

Remark 1. It should be noted that when the interconnection equations between the system (1) and the controller (3) are expressed as

$$u(t) = \begin{cases} \tilde{u}(t), & t < \tilde{t}, \\ y_\xi(t), & t \geq \tilde{t}, \end{cases} \tag{6}$$

$$u_\xi(t) = y(t), \quad t \geq 0, \tag{7}$$

the controller (3) is interconnected with the system (1) without any amendations. Under this situation, each sub-controller of (3) can deal with the almost output regulation problem of the systems (1), (2) but cannot achieve the bumpless transfer goal by the same measurement way and modification method of [10]. In order to solve the trouble, it is necessary to design the switching signal $\sigma(t)$. Similar design ideas can be founded in [26,27].

Nevertheless, the design of the switching signal $\sigma(t)$ causes some troubles. On the one hand, the bumps occur at not only the instant $\tilde{t}$ but also new switching instants t_k, $k \in N$ induced by the switching signal $\sigma(t)$. All bumps are needed to be handled. On the other hand, the almost output regulation problem of the systems (1)–(3) with the interconnection equations (6), (7) may be unsolvable under the designed switching rule $\sigma(t)$.

To address the above situation, firstly, a description of the BT performance with possible multiple switchings for the systems (1)–(3) is needed. Before proceeding, we introduce a reference system to quantify the BT performance. The reference system refers to a system composed of (1)–(3) with $u(t) = y_\xi(t)$, $u_\xi(t) = y(t)$.