Design of a Discrete-time Adaptive Output Feedback Control System based on Passivity

（受動性に基づく離散時間適応出力フィードバック制御系の設計）

by

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Contents

Abstract

This thesis addresses the control problem of designing discrete-time adaptive output feedback control systems based on passivity, and it investigates the passivity property in linear systems as well as in non-linear systems. There are several outcomes to be clarified in terms of successful design of adaptive output feedback control systems and verification of the proposed schemes.

The notion of passivity is a fundamental concept in control theory, yet the use of the term has varied. For linear time-invariant (LTI) systems, strict passivity is equivalent to strict positive realness (SPR). It is well recognized that SPR property can be certain to stabilize adaptive control systems based on the Lyapunov function. Therefore, adaptive algorithms are able to be built and thus, the performance can be maintained in the presence of either stationary or non-stationary uncertainties. However, for real-world plants, they are hard to satisfy the SPR conditions. An alternative concept almost strict positive realness (ASPR) is emerged, yet the required conditions to be ASPR are very restrictive. As a result, the parallel feedforward compensator (PFC) is utilized to alleviate such restrictions. This thesis establishes the relationship between the PFC and the direct term d which emerges in the system representation, and the causality problem in discrete-time domain is addressed as well. Additionally, a problem is concerned in terms of tracking

property since the steady state error emerges when the PFC is introduced. The feedforward input is considered to deal with the steady state error, and this thesis discusses the way of generating feedforward input by only considering an integral action. Furthermore, the fictitious reference iterative tuning (FRIT) approach is introduced to optimize the PFC from the practical perspective. As a consequence, for LTI systems discussed in this thesis, there are four outcomes. The first one is that the adaptive output feedback control system is successfully designed; the second one is that the steady state error is removed by introducing the feedforward input; the third one is that the low-order and simpler adaptive controller can be designed with the use of output feedback, and this adaptive controller can handle the system without *priori* information; the last one is that the FRIT is succeeded in applying to the adaptive control system to optimize the PFC. These outcomes are verified through numerical simulations and experiments, which are discussed in this thesis.

For non-linear case, the passivity is discussed in designing the adaptive control system. Since the output feedback is considered, the output feedback strictly passive (OFSP) is investigated. It is well recognized that adaptive control systems based on OFSP can achieve asymptotic stability via static output feedback. However, these conditions are very restrictive. Similarly to the linear case, the idea of introducing PFC to alleviate those restrictions; and the steady state error is removed through the use of feedforward input. At present, researchers are yet to examine a data-driven application adaptive control system based on OFSP. As a consequence, there are two outcomes. The first one is that the steady state error is removed by adding the feedforward input; the second one is that the data-driven approach is successful used to improve the performance in designing an adaptive control system based on OFSP. These outcomes are verified through numerical simulations which demonstrate the effectiveness of the proposed scheme, which is discussed in this thesis.

Chapter 1

Introduction

1.1 Research background

Feedback is the key for automatic control that does not rely on human interference [1]. Generally speaking, the feedback control occurs in the closed-loop control system, in which the output signals are utilized for feedback to generate a control input such that the system uncertainties and effects of disturbance can be reduced. Moreover, from the practical point of view, considering the control design with a relative simple structure by only utilizing the available output signal seems much attractive. Therefore, feedback control has been extensively used and significantly developed in lots of various systems for the past few decades. However, feedback control is merely an impressive control structure, based on which a certain control technique should be applied to deal with sophisticated circumstances.

Adaptive control is based on feedback of signals in a system so as to effectively handle system uncertainties, and it can also provide systematic, flexible approaches to compensate the unanticipated changes. Therefore, adaptive control has been attracting considerable attentions since it appears in the 1950's [2]. A typical adaptive control system consists of a plant to be controlled, a controller with parameters, and an adaptive law to update the controller parameters. The controller parameters, in the conventional methods, can be calculated based on the approximated plant parameters and assumptions, with which some desired system performances are successfully achieved. The practical benefits of adaptive control have been documented in a wide variety of successful industrial applications [5]. In particular, adaptive control offers significant potential benefits for the process control problems where the process is hard to be understood and is changed in unpredicted ways.

Although the impressive achievements of adaptive control design have been obtained, the stability issue has not been taken into much consideration [13]. A typical example is the so-called MIT-rule implemented in adaptive control schemes [19, 20], which has been considered as a clever engineering idea. However, it ended in failure, since there was not very much knowledge of the theoretical guarantee of stability. This unsuccessful example also proved that without guaranteeing stability, the performance cannot even be discussed. The lack of stability of MIT-rule based adaptive control schemes prompted several researchers to develop tools and techniques for rigorous stability analysis. The stability analysis has then become the central point in new developments related to adaptive control. The successful achievements [6, 7, 8, 9, 10, 11, 12] are mainly based on the Lyapunov's stability theory. The Lyapunov's stability theory was established at the beginning of the 19th century, yet it was investigated extensively in 1960's. It can be considered as tool, especially in modern control, for proving convergence in adaptive control schemes [3, 4].

Furthermore, as mentioned earlier, some *priori* information of unknown plant are needed in terms of order of the plant or knowledge of the pole-excess in the plant [13]. Unfortunately, these assumptions or approximation may be inaccurate or be seldom valid in real-world large systems. A simplied adaptive control scheme was developed by Sobel *et al.* [14, 15], Barkana and Kaufman [16, 17] and Iwai and Mizumot [18], and the stability issue was analyzed based on the Lyapunov's stable theory. This approach was influenced by the model reference adaptive control and considered the state as a element to design an adaptive controller. However, practitioners are also interested in designing an adaptive controller only considering the feedforward input signal as well as feedback signal. Thus, the adaptive controller can be implemented potentially in various practical processes.

Additionally, maintaining performance in various operational environments is an attractive idea for control designers, leading to robustness of the adaptive control. An adaptive controller is defined to be robust if it guarantees signals boundedness in the presence of unmodeled dynamics and bounded disturbances as well as the performance error bounded [4, 21]. It is natural to arise a question that what kind of controlled plant can be utilized, in which a adaptive controller is employed to compute the right gains to the right situation such that the performance is obtained while the robust stability is guaranteed. The answer is that the controlled plant is of passivity property, and this property has been attracted attentions of engineers in control fields.

1.2 Concept of passivity

The notion of passivity originates in electrical circuit theory in which the circuits are made up of only passive components, for instance resistor, inductor and capacitor. These circuits are known to be stable and can be regarded as dynamical systems. The property of passivity itself characterizes input-output behavior of a dynamical system from energy-based point of view. In other words, this dynamical system with this property that stores and dissipates energy supplied by the environment without generating its own is passive. The passive system has been studied in literatures [22, 23, 24], the essential result of which is that passive system is stable under certain conditions. The passivity then has been discussed and applied in numerous areas such as chemical processes [25], temperature control in buildings [26], multi-agent systems [27], distributed control systems [28] and large-scale systems [29]. Furthermore, another area has been well studied in the connection with the adaptive control [30, 31, 32]. This useful property allows the proof of stability with adaptive controllers.

The concept of passivity has been widely adopted in the stability analysis of continuous-time systems. Many stability results have been specially developed in the series of papers [33, 34, 35]. In fact, the central result in [33] and [35] could be interpreted as a form of the Kalman-Yacubovitch-Popov (KYP) Lemma, under appropriate hypotheses. In particular, it is easy to examine whether a continuous-time system is passive through the use of the KYP Lemma. The KYP Lemma is a critical link in relating the passivity and the existence of a Lyapunov function, and hence the stability of a dynamical system is assured. This link can be precisely interpreted that by using the KYP Lemma, a positive-definite matrix can be determined satisfying the Lyapunov function which results in a dynamical system is passive. The existence of a positive-definite matrix is assured by the KYP Lemma.

Not only in continuous-time but also in discrete-time are there different versions of the KYP Lemma. Moreover, a lot of practical processing is implemented by sampled-data systems. As a result, researchers are focused on the study of the passivity based on the KYP Lemma in discrete-time in [36, 37, 39]. A significant idea was proposed in [39], in which there were two outcomes. One is that the discrete-time version of the KYP Lemma was proposed. The other one is based on the KYP Lemma, the relative degree of a system should be zero. In other words, it does not make any sense to study passivity of discrete-time systems having relative degree non-zero. This is in sharp contrast with the continuous-time case. The discrete-time systems are dealt with throughout this thesis.

While passivity is typically applied to general nonlinear systems, this thesis also focuses on the linear time-invariant (LTI) case. The foundational relationship is that, for LTI systems, the property of passivity is equivalent to the property of positive realness. Under technical assumptions, these systems are Lyapunov stable [40]. In particular, strict passivity (SP) is equivalent to strict positive realness (SPR). It is should be clear that the plant should be rigorously called SP, while in LTI systems the input-output transfer function should be called SPR.

At present, in modern control theory, the state-space representation is an analytical way to reveal the relationship behind the input and output of a dynamical system. Therefore, the strict passivity is characterized by some relations in the form of state-space representation. These relations are called strict passivity condition which seems to be the most useful for successful proofs of stability using Lyapunov's stability theory [38]. In other words, the strict passivity condition required to guarantee the stability of a adaptive control system is equivalent to the formulation of basic stabilizability properties of a plant.

The strict passivity condition allows the guarantee of stability of an adaptive control; nonetheless, for a certain period of time, the so-called strict passivity condition has been considered very restrictive and for quite some time the adaptive control engineers have been trying to drop the condition. This thesis investigates the way of alleviating the condition by considering "Parallel Feedforward Compensator (PFC)", and a discussion regarding PFC is undertook. Furthermore, a causality problem only appeared in discrete-time domain is also addressed, and answers are provided both in linear systems and in nonlinear systems.

1.3 Objectives and overview

As already mentioned in the previous section, the feedback control is a such attractive structure, and the property of passivity has been studied both in linear and nonlinear cases. Moreover, the output signal is always available from the practical point of view. Thus, the objective of this thesis is to design an adaptive output feedback control system based on the passivity for discrete-time linear systems as well as nonlinear systems. The typical structure of the adaptive output feedback control system is depicted in Fig. 1.1. The $r(k)$ and $y(k)$ are denoted as the reference signal and the output of the plant, respectively. Additionally, the output tracking problem is addressed and discussed in this thesis.

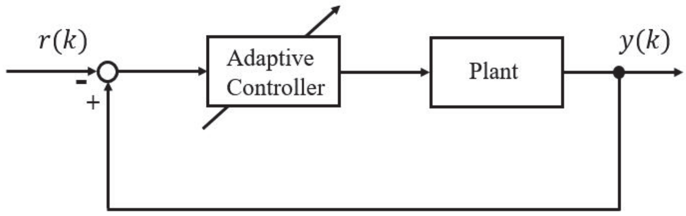

Figure 1.1: A typical structure of adaptive feedback output control system.

The control problem is to design an adaptive controller based on the passivity, consideration should be given to strict passivity condition. As it is aforementioned, the strict passivity condition proposed in [13, 41] seems much too demanding. However, it has been somewhat alleviated even for non-strict passive system if there exists a constant output feedback gain (unknown) such that the resulting closed-loop system is strict passive. Since in this case the original system is only separated from strict passivity by a simple constant output feedback, it is called almost strictly passive (ASP), which results in a new challenge for the researchers. The challenge is that it is unknown for which systems can satisfy the new conditions. Towards to reducing the new conditions, the so-called PFC is proposed such that the augmented system can satisfy the new conditions. As a result, the adaptive output feedback control system based on the passivity is successfully designed.

The brief overview of what each chapter involves is given as follows.

The Chapter 1 discusses the background regarding feedback control and adaptive control. In addition, the introduction of passivity and its use towards to the proof of stability to adaptive control are the good basis, on which the adaptive controller can be designed safely.

The Chapter 2 addresses a dessign problem of an adaptive output feedback control system with a feedforward input. Since the PFC is added to allow the augmented system to satisfy the ASPR condition in LTI system, the steady state error appears. Due to this reason, the feedforward input is introduced to remove the error. The reference signal is utilized as the feedfoward input instead of signals obtained by a complicated algorithm. According to the proposed scheme, the structure of the adaptive controller is not complicated, and it can deal with non-minimum phase systems. Besides, the PFC in the proposed scheme is considered as a constant parameter. Furthermore, the controller in the this proposed schme is low-order, yet it can control the real-world applications with high-order degree. The stability of the proposed scheme is investigated in this chapter. The effectiveness of the proposed scheme was confirmed by employing in pilot-scale temperature control system.

The Chapter 3 introduces the fictitious reference iterative tuning (FRIT) approach which is employed to determine the value of the PFC using one-shot input/output experimental data directly, without a *prior* information about the control system. Since the stability issue has been investigated in the Chapter 2, the FRIT can be utilized with certainty in the theoretical sense. This chapter explains how the FRIT approach is applied in designing an adaptive output feedback control system. The proposed scheme was verified through a motor application, which demonstrated the effectiveness.

The Chapter 4 is devoted to the passivity in nonlinear system. The Output Feedback Strictly Passive (OFSP) is proposed for nonlinear system. The controller in the proposed scheme stabilizes the plant through the use of the PFC, and the feedforward input is utilized in the controller to remove the steady state error. Furthermore, at present, researchers are yet to examine a data-drive approach in an adaptive control system based on OFSP. Once the robust stability of the adaptive control system based on OFSP, the adaptive gains can be updated by the data-driven approach such that the output performance is able to be improved. As a result, there are two outcomes in this Chapter. The first outcome was that the PFC and feedforward input were utilized to design the adaptive controller; the second one was that the data-drive approach succeeded in applying in the adaptive control system based on OFSP. These outcomes were verified through numerical examples which demonstrated the effectiveness of the proposed scheme, which is discussed in this Chapter.

The Chapter 5 concludes the thesis, and outstanding issues are presented. The future works are discussed in several aspects as well.

Chapter 2

Design of ASPR-based adaptive output feedback control system with feedforward input

2.1 Introduction

This chapter discusses the strict passivity property for linear systems. The property of strict passivity is equivalent to the property of the strict positive realness (SPR) for linear time-invariant (LTI) systems. An adaptive output feedback control system based on alomst strict positive realness (ASPR) with feedforward input is presented.

It is well known that SPR property of a closed-loop system can guarantee stability in systems with uncertainty [42] and in adaptive control [43] of linear time-invariant systems. Unfortunately, most real systems are not inherently SPR. However, to be able to utilize the SPR property, Kaufman et al. [41] proved that a system called ASPR can be rendered SPR via constant output feedback gain. Some conditions are imposed for a continuous-time system to be ASPR in technical literatures [44],[45]. Hence, one can design a proper adaptive output feedback control system easily if the conditions are satisfied. However, most real realistic systems do not satisfy those imposed restrictive conditions, which leads the limitation of adaptive output feedback control applications. The crucial issue, therefore, is to realize ingenious methods to alleviate the restrictive conditions. Barkana [45] proposed a significant idea that a non-ASPR system could be rendered ASPR by introducing a parallel feedforward compensator (PFC). Thereafter, the feasibility of adaptive output control to various system was extended, and the successful implementations of this concept for continuous-time systems have been summarized in [47].

In this chapter, the design of an adaptive output feedback control system for the discrete-time domain will be dealt with. Since the majority of practical processes are implemented by sampled data systems, thus, considering a control strategy for discrete-time systems becomes an important issue. The sufficient conditions for a discrete-time ASPR system have been imposed in [48, 46, 49], and they are summarized as follows: (1) the system is minimum-phase, (2) the system has a relative degree of 0, and (3) the high frequency gain of the system is positive. Since most practical systems do not satisfy these conditions, similarly to a solution in continuous-time systems, and introduction of PFC can alleviate the restricions. Therefore, an ASPR-based adaptive output feedback control system in discrete-time domain using a PFC can be designed and the stability of system is also guaranteed.

It should be emphasized that the ASPR conditions can not be satisfied in discrete-time systems unless the system must have nonsingular direct term. In precise, the relative degree of discrete ASPR system is zero. In other words, it does not make sense to study the ASPR property of a discrete-time system without the direct term. As a consequence, the causality problem, which is not considered in continuous-time system, will appear in such discrete ASPR systems. The proposed scheme provides a solution by considering an equivalent controller.

It is important to consider tracking and maintaining a system output against the reference signal because of requirement of high-quality products and low cost in most industrial processes [50]. However, by introducing a PFC, the conventional schemes achieve that the augmented output tracks the given reference signal but not the output of original systems, which implies there is a steady state error between them. Mizumoto and Fujimoto [51] presented an adaptive predictive control strategy that the steady state error can be compensated by employing a feedforward input. The several other related works [52, 53, 54, 55] were published. The feedforward input is obtained based on neural networks or generalized predictive control (GPC), which implies that the control structure is complex, and learning cost is considerable large. Therefore, it might be hard to employ those schemes in the industrial processes. For the sake of simplicity and implementation in most industrial processes, the proposed scheme provides a solution that the reference input is used as feedforward input directly. In precise, the feedforward input is obtained by only considering an integral action. Additionally, the system of industrial processes is generally of high-order degree, whereas, they can be controlled by the low-order controller.

A design scheme of an adaptive output feedback control system with a feedforward input is proposed in this chapter. According to the proposed scheme, there are two main outcomes. The first one was the structure of the adaptive controller was not complicated, and it can deal with non-minimum phase systems. The entire adaptive control system was assured to be stable. The second one was that the reference signal was utilized as the feedfoward input instead of signals obtained by a complicated algorithm. These two outcomes were verified through an numerical simulation. In addition to the simulation, the effectiveness was confirmed by employing in a pilot-scale temperature control system.

This chapter is organized as follows : the problem statement is described in section 2.2; the design of proposed scheme and stability analysis are provided in section 2.3; the section 2.4 illustrates an numerical simulation; the experimental conduction is the main topic of section 2.5, and the section 2.6 concludes this chapter.

Notations. Γ denotes the coefficient contained in the algorithm, and σ literally means σ-term which is to avoid divergence of the integral gains in the presence of disturbances. $\Delta v(k)$ denotes the difference of $v(k)$ and v^*. $\|\cdot\|$ expresses the 2-norm. $\lambda_{min}[\cdot]$ denotes the minimum eigenvalue of a real matrix.

2.2 Problem statement

Consider the following single-input single-output (SISO) discrete-time system with state-space, represented as

$$\boldsymbol{x}(k+1) = A\boldsymbol{x}(k) + \boldsymbol{b}u(k) \tag{2.1}$$

$$y(k) = \boldsymbol{c}^T\boldsymbol{x}(k) \tag{2.2}$$

$$y_a(k) = \boldsymbol{c}^T\boldsymbol{x}(k) + du(k). \tag{2.3}$$

The original system is considered as strictly proper and expressed by (2.1) - (2.2), and the augmented system, which is denoted by (2.1) - (2.3), is proper. $\boldsymbol{x}(k) \in \boldsymbol{R}^n$ represents a state vector, and $u(k)$ and $y(k) \in \boldsymbol{R}$

are input and output of the original system, respectively. $y_a(k)$ denotes the augmented output of the system. It should be noted that as it is stated, the augmented system is proper, the relative degree of which is 0. In particular, the following Lemma is given in terms of the relative degree 0.

Lemma 1. Consider the above minimum-phase augmented system $A, \boldsymbol{b}, \boldsymbol{c}^T, d$ with positive definite d is ASPR, namely it can be stabilize and rendered SPR via constant output feedback.

The proof of this Lemma can be seen in [46, 39]. A specific proof is given in Appendix A. As a matter of fact, the augmented system $A, \boldsymbol{b}, \boldsymbol{c}^T, d$ can never be SPR with $d = 0$, and thus this chapter establish the useful relations between d and the PFC. Therefore, let us surmise that the system satisfies the following assumptions.

Assumption 1. There exists a constant PFC d such that the resulting augmented system (2.1) - (2.3) is ASPR.

Under assumption 1, there exists a static output feedback gain $k_e^* > 0$, such that the virtual closed-loop system shown in Fig. 2.1 is SPR. This im-

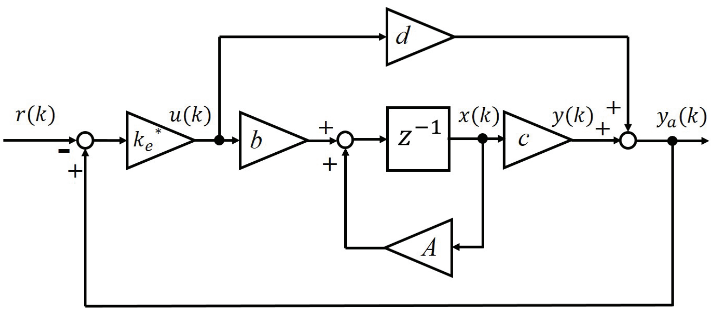

Figure 2.1: Virtual closed-loop system.

plies that for the above system $\{A, \boldsymbol{b}, \boldsymbol{c^T}, d\}$, there exists a positive constant

k_e^* in the control signal

$$\begin{aligned} u(k) &= -k_e^*(y_a(k) - r(k)) \\ &= -k_e^*(\boldsymbol{c}^T\boldsymbol{x}(k) + du(k) - r(k)) \\ &= \frac{-k_e^*\boldsymbol{c^T}x(k) + k_e^*r(k)}{1 + dk_e^*}. \end{aligned} \tag{2.4}$$

Substituting the augmented system (2.1) - (2.3) gives

$$\begin{aligned} \boldsymbol{x}(k+1) &= A_c\boldsymbol{x}(k) + \boldsymbol{b_c}r(k) \\ y_a(k) &= \boldsymbol{C_c^T}\boldsymbol{x}(k) + d_c r(k), \end{aligned} \tag{2.5}$$

where

$$A_c = A - \frac{k_e^*\boldsymbol{b}\boldsymbol{c}^T}{1 + dk_e^*} \tag{2.6}$$

$$\boldsymbol{b_c} = \frac{\boldsymbol{b}k_e^*}{1 + dk_e^*} \tag{2.7}$$

$$\boldsymbol{C_c^T} = \frac{\boldsymbol{c}^T}{1 + dk_e^*} \tag{2.8}$$

$$d_c = \frac{dk_e^*}{1 + dk_e^*}. \tag{2.9}$$

The closed-loop system is strict passive and the augmented system is ASPR. That is, the augmented system is proper, minimum-phase system with a positive definite d.

Remark. It has been clarified in [56, 57] that if the system can be stabilized by a static output feedback, the inverse of a stabilizing gain can be considered to be a PFC. The detail of this clarification is given in Appendix B. The parameter d, which parallels with the original system, is considered as the inverse of a stabilizing constant gain from the (2.5). Therefore, in this chapter, the parameter d can be considered as a constant PFC without dynamic parts.

The block diagram of an adaptive output feedback control system with feedforward input is shown in Fig. 2.2. The following assumption is given as follows.

Assumption 2. There exists an ideal input $v^*(k)$ and ideal state $\boldsymbol{x}^*(k)$

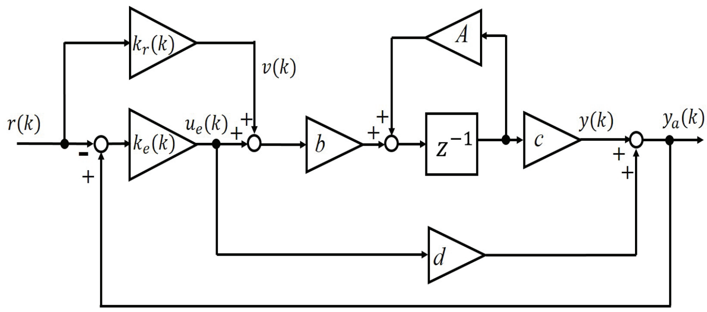

Figure 2.2: Adaptive output feedback control with feedforward input.

such that the output of original plant tracks the given reference signal $r(k)$, under which situation the error included in $u_e(k)$ ends being zero; therefore, $u_e(k)$ ends up with 0. Thus, the following equations hold.

$$\begin{aligned} \boldsymbol{x}^*(k+1) &= A\boldsymbol{x}^*(k) + \boldsymbol{b}v^*(k) \\ y^*(k) &= \boldsymbol{c}^T\boldsymbol{x}^*(k) + du_e(k) \\ &= \boldsymbol{c}^T\boldsymbol{x}^*(k) = r(k). \end{aligned} \tag{2.10}$$

It should be noted that there must be a proper constant d that can achieve the perfect tracking. The ideal state of the augmented system can be represented by

$$\begin{aligned} \boldsymbol{x}^*(k+1) &= A\boldsymbol{x}^*(k) + \boldsymbol{b}v^*(k) \\ y_a^*(k) &= \boldsymbol{c}^T\boldsymbol{x}^*(k) = r(k). \end{aligned} \tag{2.11}$$

The objective in this chapter is to design the adaptive output feedback control system by using a proper constant d, and the feedforward input is considered as well.

2.3 Design of the proposed scheme

This section will contain two main parts: the state error analysis of the system is first considered, and stability analysis is stated in the second subsection.

2.3.1 Controller structure and error system

The implemented adaptive controller is described as

$$u(k) \;=\; u_e(k) + v(k). \tag{2.12}$$

That is

$$u(k) \;=\; -k_e(k)e_a(k) - k_r(k)r(k), \tag{2.13}$$

where

$$e_a(k) \;=\; y_a(k) - r(k), \tag{2.14}$$

and the adaptive gains are given by the following algorithm

$$k_e(k) \;=\; k_e(k-1) - \Gamma_e e_a^2(k) - \sigma_e k_e(k) \tag{2.15}$$

$$k_r(k) \;=\; k_r(k-1) - \Gamma_r e_a(k)r(k) - \sigma_r k_r(k), \tag{2.16}$$

in which $\Gamma_e, \Gamma_r, \sigma_e$, and σ_r are positive constant.

Since the direct term exists in a discrete ASPR augmented system, the control signal (4.16) can not be applied directly because of the causality problem [58]. Thus, the equivalent output feedback control signal is obtained by

$$
\begin{aligned}
u_e(k) &= -k_e(k)e_a(k) \\
&= -k_e(k)(\boldsymbol{c}^T\boldsymbol{x}(k) + du_e(k) - \boldsymbol{c}^T\boldsymbol{x}^*(k)) \\
&= -k_e(k)\frac{\boldsymbol{c}^T\boldsymbol{e_x}(k)}{1 + dk_e(k)} \\
&= -k_e(k)\frac{e(k)}{1 + dk_e(k)}
\end{aligned} \tag{2.17}
$$

with $e(k) = \boldsymbol{c}^T\boldsymbol{e_x}(k)$ and $\boldsymbol{e_x}(k)$ is defined as $\boldsymbol{x}(k) - \boldsymbol{x}^*(k)$.

The state error system between the proposed system and the ideal system can be obtained as follows:

$$
\begin{aligned}
\boldsymbol{e_x}(k+1) &= A\boldsymbol{e_x}(k) + \boldsymbol{b}\{u_e(k) + \Delta v(k)\} \\
&= A\boldsymbol{e_x}(k) + \boldsymbol{b}\left\{u_e(k) + \Delta v(k) + \frac{k_e^* e(k)}{1 + dk_e^*}\right. \\
&\quad \left. -\frac{k_e^* e(k)}{1 + dk_e^*} + \frac{k_e^* e(k)}{1 + dk_e} - \frac{k_e^* e(k)}{1 + dk_e}\right\} \\
&= A_c\boldsymbol{e_x}(k) + \boldsymbol{b}\left\{\widetilde{u}(k) + \Delta v(k) + u_d(k)\right\}
\end{aligned}
$$

where $u_d(k) = \dfrac{k_e^* e(k)}{1 + dk_e^*} - \dfrac{k_e^* e(k)}{1 + dk_e(k)}$, $\Delta v(k) = v(k) - v^*(k)$, and $\widetilde{u}(k) = \dfrac{\Delta k_e(k)e(k)}{1 + dk_e(k)}$ with the definition $\widetilde{k_e}(k) = k_e^* - k_e(k)$.

Thus, the state error system can be represented by

$$
\begin{aligned}
\boldsymbol{e_x}(k+1) &= A_c\boldsymbol{e_x}(k) + \boldsymbol{b}(\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\
e_a(k) &= \boldsymbol{C_c}^T\boldsymbol{e_x}(k) + d(\widetilde{u}(k) + u_d(k)).
\end{aligned} \tag{2.18}
$$

2.3.2 Stability analysis

From the assumptions stated in the preceding section, there exists a positive definite matrices $P = P^T > 0, Q = Q^T > 0$, a vector $\boldsymbol{l}$ and a positive constant w such that the following Kalman-Yakubovich-Popov Lemma (KYP

Lemma) is satisfied.

$$
\begin{aligned}
A_c^T P A_c - P &= -Q - \boldsymbol{l}\boldsymbol{l}^T \\
A_c^T P \boldsymbol{b} &= \boldsymbol{C_c} - \boldsymbol{l} w \\
\boldsymbol{b}^T P \boldsymbol{b} &= 2d - w^2
\end{aligned}
\tag{2.19}
$$

The following positive definite function $V(k)$ is considered.

$$
V(k) \;=\; V_1(k) + (1+\sigma_e)^{-1} V_2(k) + (1+\sigma_r)^{-1} V_3(k),
$$

and every term is defined as

$$
\begin{aligned}
V_1(k) &= \boldsymbol{e_x}(k)^T P \boldsymbol{e_x}(k) \\
V_2(k) &= \Gamma_e^{-1} \widetilde{k_e}^2(k) \\
V_3(k) &= \Gamma_r^{-1} \widetilde{k_r}^2(k).
\end{aligned}
$$

Thus, $\Delta V_1(k)$ can be evaluated by the following equation.

$$
\begin{aligned}
\Delta V_1(k) &= \boldsymbol{e_x}^T(k+1) P \boldsymbol{e_x}(k+1) - \boldsymbol{e_x}^T(k) P \boldsymbol{e_x}(k) \\
&= [A_c \boldsymbol{e_x}(k) + \boldsymbol{b}(\widetilde{u}(k) + \Delta v(k) + u_d(k))]^T P \\
&\quad \times [A_c \boldsymbol{e_x}(k) + \boldsymbol{b}(\widetilde{u}(k) + \Delta v(k) + u_d(k))] \\
&\quad - \boldsymbol{e_x}^T(k) P \boldsymbol{e_x}(k) \\
&= \boldsymbol{e_x}^T(k) A_c^T P A_c \boldsymbol{e_x}(k) + \boldsymbol{e_x}^T(k) A_c^T P \boldsymbol{b} \\
&\quad \times (\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\
&\quad + (\widetilde{u}(k) + \Delta v(k) + u_d(k)) \boldsymbol{b}^T P A_c \boldsymbol{e_x}(k) \\
&\quad + (\widetilde{u}(k) + \Delta v(k) + u_d(k)) \boldsymbol{b}^T P \boldsymbol{b} \\
&\quad \times (\widetilde{u}(k) + \Delta v(k) + u_d(k)) - \boldsymbol{e_x}^T(k) P \boldsymbol{e_x}(k).
\end{aligned}
\tag{2.20}
$$

From KYP Lemma, it follows that

$$\begin{aligned}\Delta V_1(k) &= -\boldsymbol{e}_{\boldsymbol{x}}^T(k)Q\boldsymbol{e}_{\boldsymbol{x}}(k) - \boldsymbol{e}_{\boldsymbol{x}}^T(k)\boldsymbol{l}\boldsymbol{l}^T\boldsymbol{e}_{\boldsymbol{x}}(k) + \boldsymbol{e}_{\boldsymbol{x}}^T(k)\boldsymbol{C_c} \\ &\quad \times(\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\ &\quad -\boldsymbol{e}_{\boldsymbol{x}}^T(k)\boldsymbol{l}w(\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\ &\quad +(\widetilde{u}(k) + \Delta v(k) + u_d(k))\boldsymbol{C_c}^T\boldsymbol{e}_{\boldsymbol{x}}(k) \\ &\quad -(\widetilde{u}(k) + \Delta v(k) + u_d(k))\boldsymbol{l}w\boldsymbol{e}_{\boldsymbol{x}}(k) \\ &\quad +2d(\widetilde{u}(k) + \Delta v(k) + u_d(k))^2 \\ &\quad -(\widetilde{u}(k) + \Delta v(k) + u_d(k))^2 w^2. \end{aligned} \tag{2.21}$$

After some algebraic calculations, it yields

$$\begin{aligned}\Delta V_1(k) &= -\boldsymbol{e}_{\boldsymbol{x}}^T(k)Q\boldsymbol{e}_{\boldsymbol{x}}(k) \\ &\quad -(\boldsymbol{e}_{\boldsymbol{x}}^T(k)\boldsymbol{l} - (\widetilde{u}(k) + \Delta v(k) + u_d(k)))^2 \\ &\quad +2(\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\ &\quad \times[e_a(k) - d(\widetilde{u}(k) + \Delta v(k))] \\ &\quad +2d(\widetilde{u}(k) + \Delta v(k) + u_d(k))^2. \end{aligned} \tag{2.22}$$

Finally, $\Delta V_1(k)$ can be evaluated by

$$\begin{aligned}\Delta V_1(k) &\leq -\boldsymbol{e}_{\boldsymbol{x}}^T(k)Q\boldsymbol{e}_{\boldsymbol{x}}(k) + (\widetilde{u}(k) + \Delta v(k) + u_d(k)) \\ &\quad \times(2e_a(k) + d\Delta v(k)). \end{aligned} \tag{2.23}$$

Here, taking into account that $e(k) = \boldsymbol{c}^T\boldsymbol{e}_{\boldsymbol{x}}(k)$, and for an appropriate constant $\rho_i > 0$

$$\begin{aligned}\widetilde{u}(k)\Delta v(k) &= \frac{\widetilde{k}_e(k)\widetilde{k}_r(k)r(k)e(k)}{1 + dk_e(k)} \\ &\leq \rho_1|\widetilde{k}_r(k)|\|\boldsymbol{e}_{\boldsymbol{x}}(k)\| \end{aligned} \tag{2.24}$$

from the fact that $\dfrac{\widetilde{k}_e(k)r(k)}{1+dk_e(k)}$ is bounded, and then,

$$\begin{aligned}
\Delta v^2(k) &= \widetilde{k}_r^{\,2}(k)r^2(k) \leq -\rho_2|\widetilde{k}_r(k)|^2 && (2.25)\\
u_d(k)\Delta v(k) &\leq \rho_3|\widetilde{k}_r(k)|\|\boldsymbol{e_x}(k)\| && (2.26)\\
2\widetilde{u}e_a(k) &= \frac{2\widetilde{k}_e(k)e_a(k)}{1+dk_e(k)} = \frac{2\widetilde{k}_e(k)e^2(k)}{(1+dk_e(k))^2} && (2.27)\\
2\Delta v e_a(k) &= \frac{2\widetilde{k}_r(k)r(k)e(k)}{1+dk_e(k)} && (2.28)\\
2e_a(k)u_d(k) &= \frac{2e(k)}{1+dk_e(k)}\left(\frac{k_e^* e(k)}{1+dk_e^*} - \frac{k_e^* e(k)}{1+dk_e}\right) && (2.29)
\end{aligned}$$

For equation (2.29), if $k_e^* > k_e(k)$, $2e_a(k)u_d(k) < 0$ and if $k_e^* \leq k_e(k)$, (2.29) becomes

$$2e_a(k)u_d(k) \leq \frac{2e(k)}{1+dk_e^*(k)}\left(\frac{k_e^* e(k)}{1+dk_e^*} - \frac{k_e^* e(k)}{1+dk_e}\right). \tag{2.30}$$

If the $\dfrac{2}{d}\|C\| < \lambda_{min}[Q]$, the following inequality can be obtained.

$$\begin{aligned}
-\boldsymbol{e}_{\boldsymbol{x}}^T(k)Q\boldsymbol{e_x}(k) + 2e_a(k)u_d(k) &\leq -\boldsymbol{e}_{\boldsymbol{x}}^T(k)Q\boldsymbol{e_x}(k)\\
&\quad + \frac{2k_e^* e^2(k)}{(1+dk_e^*)^2}\\
&\leq -\rho_4\|\boldsymbol{e_x}(k)\|^2. && (2.31)
\end{aligned}$$

Consider the adaptive gain algorithm (4.18),

$$k_e(k) = k_e(k-1) - \Gamma_e\frac{e^2(k)}{(1+dk_e(k))^2} - \sigma_e k_e(k). \tag{2.32}$$

Then

$$(1+\sigma_e)k_e(k) = k_e(k-1) - \Gamma_e\frac{e^2(k)}{(1+dk_e(k))^2}. \tag{2.33}$$

Define $\widetilde{k}_e(k-1) = k_e(k-1) - k_e^*$ and thus,

$$\widetilde{k}_e(k-1) = (1+\sigma_e)\widetilde{k}_e(k) + \sigma_e k_e^* + \Gamma_e\frac{e^2(k)}{(1+dk_e(k))^2}. \tag{2.34}$$

Therefore,

$$\begin{aligned}\Delta V_2(k) &= -2\sigma_e\Gamma_e^{-1}\widetilde{k_e}^2(k) - \Gamma_e^{-1}\sigma_e^2\widetilde{k_e}^2(k) - \\ &\quad 2(1+\sigma_e)\frac{\widetilde{k_e}(k)e^2(k)}{(1+dk_e(k))^2} - \Gamma_e^{-1}(\sigma_e k_e^*)^2 \\ &\quad -\Gamma_e^{-1}\left(\Gamma_e\frac{e^2(k)}{(1+dk_e(k))^2}\right)^2 - 2\sigma_e(1+\sigma_e) \\ &\quad \Gamma_e^{-1}\widetilde{k_e}(k)k_e^* - 2\frac{\sigma_e k_e^* e^2(k)}{(1+dk_e(k))^2} \\ &\leq -2\sigma_e\Gamma_e^{-1}\widetilde{k_e}^2(k) - 2(1+\sigma_e)\frac{\widetilde{k_e}(k)e^2(k)}{(1+dk_e(k))^2} \\ &\quad +2\sigma_e(1+\sigma_e)\Gamma_e^{-1}|\widetilde{k_e}(k)|k_e^*. \end{aligned} \tag{2.35}$$

It is similar for $k_r(k)$ and $\Delta V_3(k)$. Setting

$$k_r(k) = k_r(k-1) - \Gamma_r\frac{r(k)e(k)}{1+dk_e(k)} - \sigma_r k_r(k), \tag{2.36}$$

then $\Delta V_3(k)$ gives

$$\begin{aligned}\Delta V_3(k) &\leq -2\sigma_r\Gamma_r^{-1}\widetilde{k_r}^2(k) - 2(1+\sigma_r)\frac{\widetilde{k_r}(k)r(k)e(k)}{1+dk_e(k)} \\ &\quad +2\sigma_r(1+\sigma_r)\Gamma_r^{-1}|\widetilde{k_r}(k)|k_e^*. \end{aligned} \tag{2.37}$$

Therefore, $\frac{1}{1+\sigma_e}\Delta V_2(k)$ and $\frac{1}{1+\sigma_r}\Delta V_3(k)$ become

$$\begin{aligned}\frac{1}{1+\sigma_e}\Delta V_2(k) &\leq \frac{-2}{1+\sigma_e}\sigma_e\Gamma_e^{-1}\widetilde{k_e}^2(k) \\ &\quad -\frac{2\widetilde{k_e}(k)e^2(k)}{(1+dk_e(k))^2} \\ &\quad +2\sigma_e\Gamma_e^{-1}k_e^*|\widetilde{k_r}(k)| \end{aligned} \tag{2.38}$$

and

$$\begin{aligned}\frac{1}{1+\sigma_r}\Delta V_3(k) &\leq \frac{-2}{1+\sigma_r}\sigma_r\Gamma_r^{-1}\widetilde{k_r}^2(k) \\ &\quad -\frac{2\widetilde{k_e}(k)e(k)r(k)}{1+dk_e(k)} \\ &\quad +2\sigma_r\Gamma_r^{-1}k_e^*|\widetilde{k_r}(k)|. \end{aligned} \tag{2.39}$$

Eventually, $\Delta V(k)$ can be evaluated by

$$\begin{aligned}\Delta V(k) \;\leq\; & d\rho_1|\widetilde{k}_r(k)|\|\boldsymbol{e_x}(k)\| + d\rho_3|\widetilde{k}_r(k)|\|\boldsymbol{e_x}(k)\| \\ & -d\rho_2|\widetilde{k}_r(k)|^2 - \rho_4\|\boldsymbol{e_x}(k)\|^2 \\ & -\frac{2\sigma_e\Gamma_e^{-1}}{1+\sigma_e}\widetilde{k}_e^{\,2}(k) + 2\sigma_e\Gamma_e^{-1}k_e^*|\widetilde{k}_e(k)| \\ & -\frac{2\sigma_r\Gamma_r^{-1}}{1+\sigma_r}\widetilde{k}_r^{\,2}(k) + 2\sigma_r\Gamma_r^{-1}k_e^*|\widetilde{k}_r(k)|. \end{aligned} \tag{2.40}$$

The appropriate constants δ_1, δ_2, and δ_3 are introduced such that

$$\begin{aligned}\Delta V(k) \;\leq\; & -(\rho_4 - \delta_1^2)\|\boldsymbol{e_x}(k)\|^2 - \left(d\rho_2 - \frac{(d\rho_1 + d\rho_3)^2}{4\delta_1^2}\right) \\ & \times|\widetilde{k}_r(k)|^2 - \left(\frac{2\sigma_e\Gamma_e^{-1}}{1+\sigma_e} - \delta_2^2\right)|\widetilde{k}_e(k)|^2 \\ & -\left(\frac{2\sigma_r\Gamma_r^{-1}}{1+\sigma_r} - \delta_3^2\right)|\widetilde{k}_r(k)|^2 \\ & +\frac{(\sigma_e\Gamma_e^{-1})^2}{\delta_2^2} + \frac{(\sigma_r\Gamma_r^{-1})^2}{\delta_3^2}. \end{aligned} \tag{2.41}$$

It is easy to conclude that $V(k)$ satisfies the following inequality.

$$\Delta V(k) \leq -\alpha V(k) + R, \quad \alpha, R > 0. \tag{2.42}$$

The proper Γ, δ can be found to make α, R be positive. In conclusion, all the signals in the proposed adaptive control system were found to be bounded. Thus, for the above adaptive control system with aforementioned assumptions and controller, the following theorem holds.

Theorem: Under the assumptions 1 and 2, the use of control input (4.16) with the adaptive algorithm (4.18) - (4.19) will guaranteed the ultimate boundedness of all signals.

The above theorem clarifies the assumptions 1 and 2 can be satisfied, and, hence, the constant d exists to render the augmented system ASPR.

2.4 Numerical simulation

The effectiveness of the proposed method is examined by performing a numerical simulation.

The following second-order non-minimum phase controlled system is considered.

$$G(z) = \frac{z + 1.1}{z^2 - 0.95z} \tag{2.43}$$

It is easy to see that there is a zero outside of unit circle shown in the Fig. 2.3, in which "$\circ$" denotes zero, and "$\times$" denotes poles. This figure shows the controlled system is non-minimum phase system. In addition to it, the system is strictly proper, which implies it is not an ASPR system.

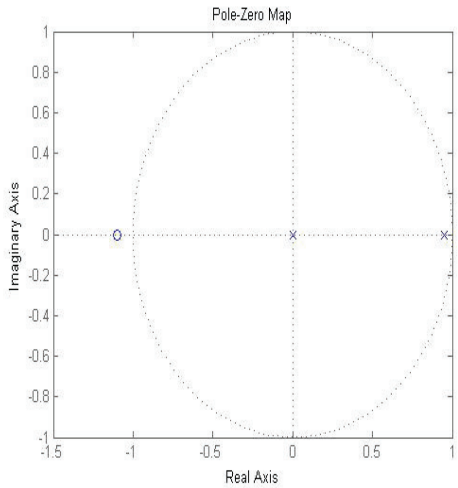

Figure 2.3: Roots of the original system.

Due to this reason, the constant parallel feedforward $d = 10$ is added. The augmented system becomes minimum-phase system from the root-locus diagram shown in Fig. 2.4.

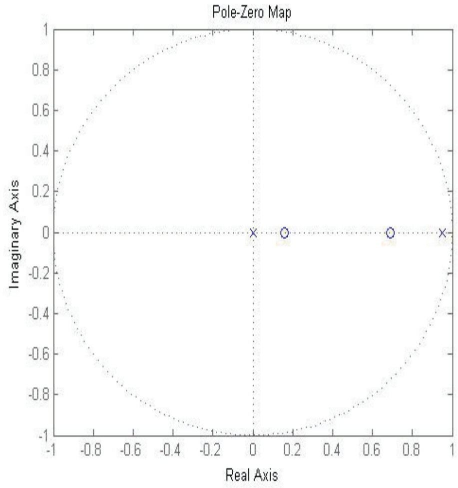

Figure 2.4: Roots of the augmented system.

The design parameters were

$$\Gamma_r = 0.005, \quad \Gamma_e = 0.55, \quad \sigma = 0.0005 \tag{2.44}$$

in the simulation. The simulation results are shown in Fig. 2.5 and Fig. 2.6. From the Fig. 2.5, one can observe that the original output tracks the reference input perfectly. The controller is constructed with a feedforward input to compensate the error between augmented output and original output. The adaptive gains shown in Fig. 2.6 ultimately tend to reach constant values.

2.5 Experimental evaluation

This section presents the experimental evaluation of the proposed scheme. The experiment was conducted in a pilot-scale temperature control system, as shown in Fig. 2.7. The objective of the experiment was to track the specified temperature and observe the robustness when adding the disturbance.

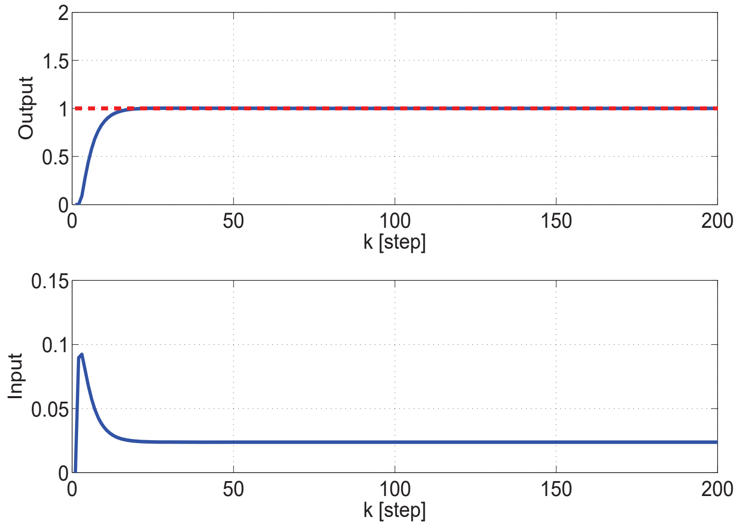

Figure 2.5: Simulation of control result obtained by the proposed scheme.

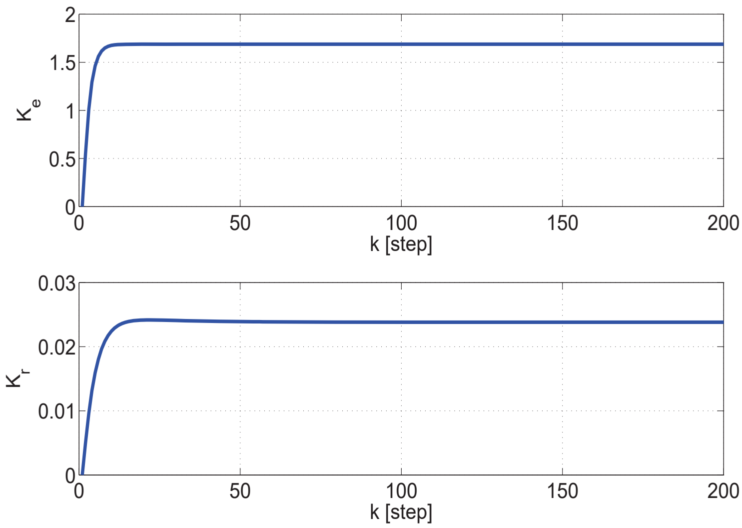

Figure 2.6: Simulation of the trajectories of the adaptive gains.

The brief introduction of the operational mechanism of the pilot-scale temperature control system is described in the following. There are two heaters securing on a steel plate, and they work simultaneously. The tem-

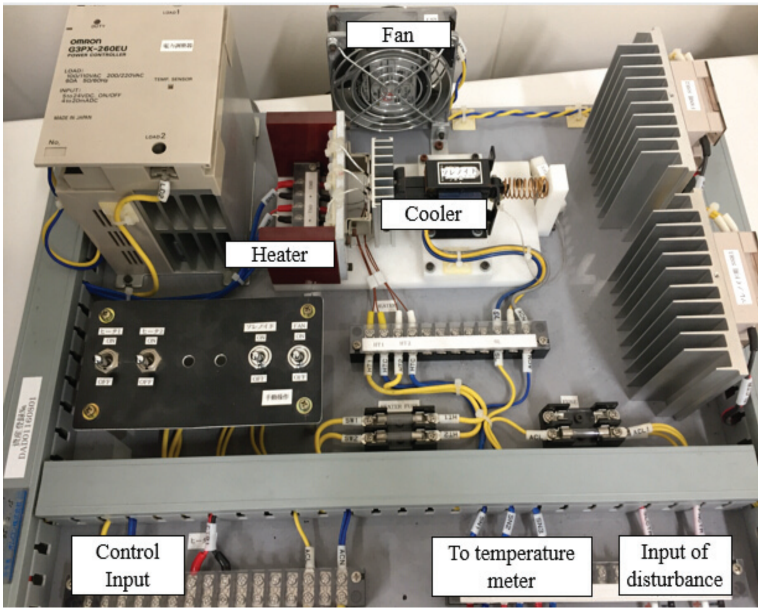

Figure 2.7: Appearance of the pilot-scale temperature control system.

perature of the steel plate could be measured by a thermo-couple that is fastened to it. The measured signal, as a system output signal, is in the analog form and sent to the D/A converter. Subsequently, the control signal is computed by the proposed scheme after receiving a digital error signal, and eventually it is converted to an analog signal by the A/D converter. The sampling time (T_s) of the system was set to 1 s.

It should be noted that many practical systems are expressed by (2.1) - (2.2), which does not include the direct term. Therefore, it is reasonable to assume that the pilot-scale temperature control system does not satisfy the ASPR condition. For the sake of designing a stable adaptive output feedback control system, a proper PFC (i.e. the constant control parameter d stated in the preceding remark) is required. The user-specified parameter d is set to 1. The next chapter would investigate a optimal way of determining it by adopting an algorithm. The control results are eventually shown in Fig. 2.8

when the related parameters are given as follows.

$$\Gamma_r = 1.5 \times 10^{-5}, \quad \Gamma_e = 0.3, \tag{2.45}$$

$$\sigma_e = 5 \times 10^{-6}, \quad \sigma_r = 5 \times 10^{-6}. \tag{2.46}$$

The adaptive gains are plotted in Fig. 2.9. It was obvious to observe that the disturbance was happened at approximately 210 step; therefore, the adaptive gains changed to a large value to negate the disturbance. The merit of adaptive control was also illustrated from the performance. The adaptive gains ultimately tended to reach constant values. The effectiveness and convergence were finally confirmed through these results.

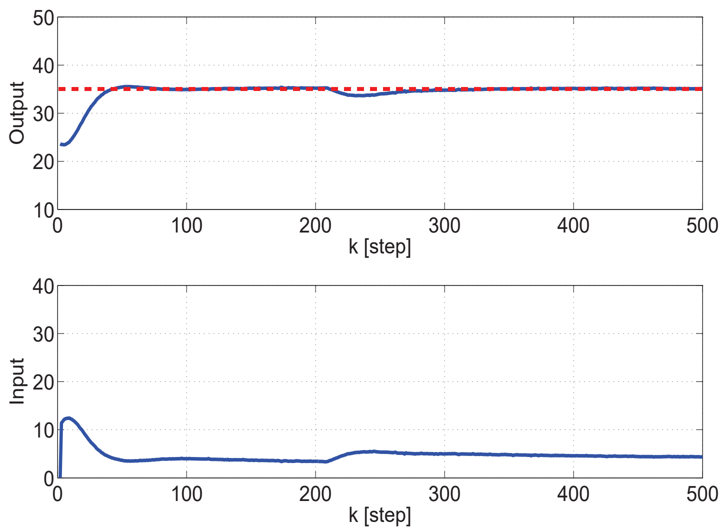

Figure 2.8: Control result obtained by the proposed scheme.

Moreover, the comparative study was conducted, the results of which were shown in Fig. 2.10 and Fig. 2.11, respectively. In this case, d was set as 5, whereas, other conditions remained the same. It can be seen that from (2.17) the control input could be decreased if d was enlarged such that the effect of suppressing the overshoot was restrained.

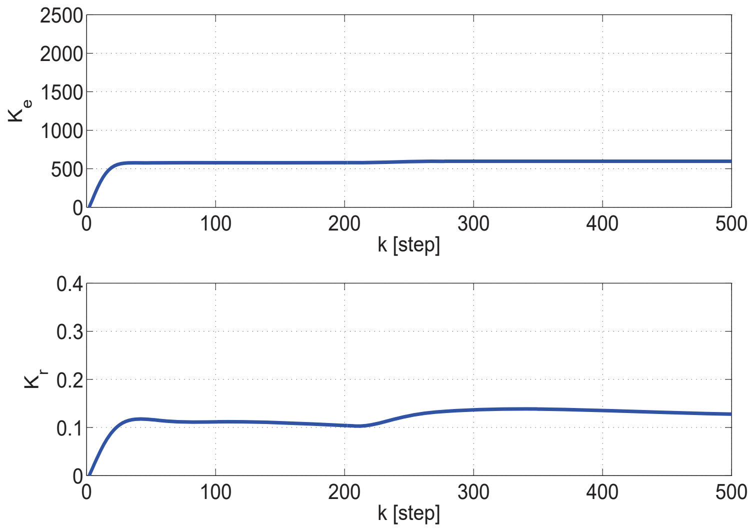

Figure 2.9: Trajectories of adaptive gains in the proposed scheme.

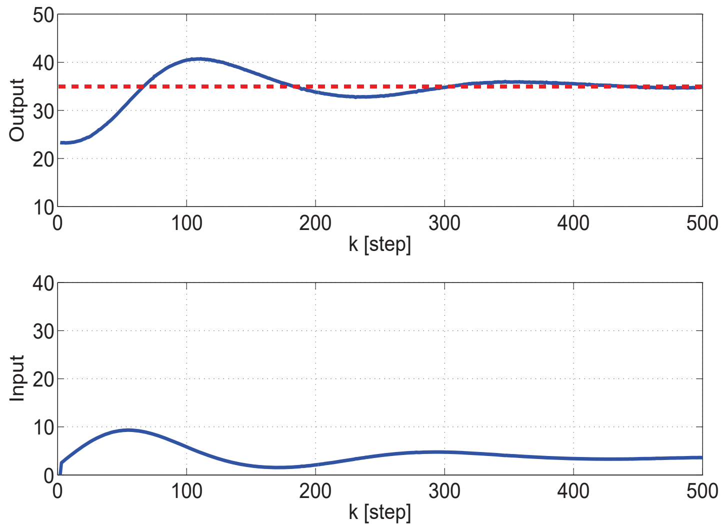

Figure 2.10: Control result obtained in the comparative study.

2.6 Conclusion

In this chapter, the design of an adaptive output feedback control system with a feedforward input was presented. The relationship between the PFC

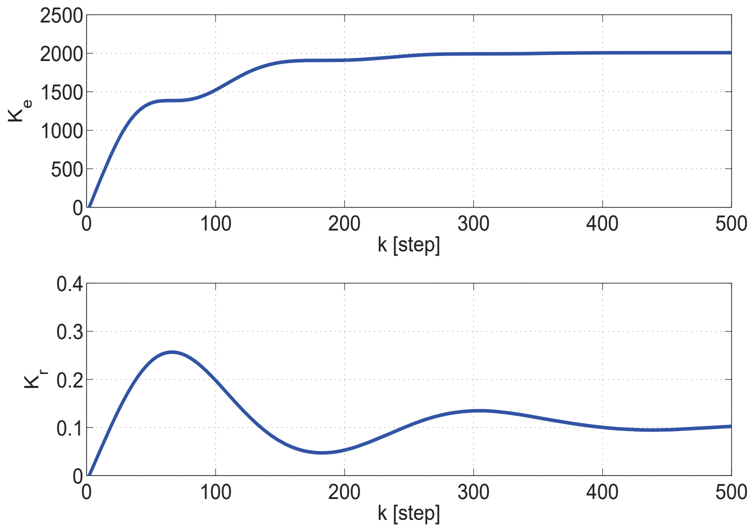

Figure 2.11: Trajectories of adaptive gains in the comparative study.

and the direct term d was also addressed. That is the parameter d could be considered as a PFC without dynamic parts, based on which the constant PFC d was properly designed to make the augmented system ASPR. Therefore, the stability of the proposed adaptive output feedback control system was guaranteed. In addition, the feedforward input was utilized to remove the steady state error, and the feedforward input was obtained by only considering the integral action. Compare to other methods of generating the feedforward input, the simpler structure in the proposed scheme reduced the cost. Furthermore, the low-order controller could control the industrial processes with high-order degree even in the presence of uncertainties. This chapter also showed the rigorous proof of convergence of the adaptive output feedback control system. The proposed scheme was verified through a numerical simulation and by employing in a pilot-scale temperature control system. The control results demonstrated the effectiveness and robustness of the proposed scheme. The adaptive gains ultimately reached a constant value both in numerical simulation and in experimental evaluation.

The performance obtained from the proposed scheme was superior to that from the comparative study. This resulted in that the constant PFC (i.e. the constant value of d in this chapter parameters) existed a optimal value. Therefore, the topic regarding to the determination of proper parameter d by adopting an algorithm will be investigated in the next chapter.

Appendix 2.A The proof of the Lemma

For the minimum-phase augmented system (2.1) - (2.3), the zero-dynamics of this system is given in the following when the output at zero in spite of the presence of input commands.

$$y_a(k) = \boldsymbol{c}^T \boldsymbol{x}(k) + du(k) \tag{2.47}$$

that gives

$$u(k) = -d^{-1}\boldsymbol{c}^T \boldsymbol{x}(k). \tag{2.48}$$

Substituting in (2.1) gives the zero-dynamics equation

$$\boldsymbol{x}(k+1) = A_z \boldsymbol{x}(k) \tag{2.49}$$

where, $A_z = A - \boldsymbol{b}d^{-1}\boldsymbol{c}^T$ is the system matrix for the zero-dynamics. The system is minimum-phase; thus, there exist two positive matrices, P and Q such that

$$A_z^T P A_z - P = Q. \tag{2.50}$$

Furthermore, for the augmented system (2.1) - (2.3), if a positive definite output feedback gain k_e^* is utilized, the system matrix is given in the form of (2.6). For the sake of simplicity, the following expression is considered in the appendix.

$$\frac{k_e^*}{1 + dk_e^*} = \bar{k_e}^* = (k_e^{*-1} + d)^{-1} \leq d^{-1}. \tag{2.51}$$

Therefore, the (2.6) can be expressed by

$$A_c = A - \boldsymbol{b}\bar{k_e}^* \boldsymbol{c}^T. \tag{2.52}$$

As a result,

$$A_c^T P A_c - P \tag{2.53}$$

$$
\begin{aligned}
=&(A - \boldsymbol{b}\bar{k_e}^* \boldsymbol{c}^T + \boldsymbol{b} d^{-1} \boldsymbol{c}^T)^T P (A - \boldsymbol{b}\bar{k_e}^* \boldsymbol{c}^T + \boldsymbol{b} d^{-1} \boldsymbol{c}^T) - P \\
=&A^T P A - P - A^T P \boldsymbol{b} d^{-1} \boldsymbol{c}^T + A^T P \boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T - (\boldsymbol{b} d^{-1} \boldsymbol{c}^T) P A \\
&- (\boldsymbol{b} d^{-1} \boldsymbol{c}^T)^T P \boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T + (\boldsymbol{b} d^{-1} \boldsymbol{c}^T)^T P \boldsymbol{b} d^{-1} \boldsymbol{c}^T \\
&+ (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P A - (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b} d^{-1} \boldsymbol{c}^T \\
&+ (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b}(\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T) \\
=&-Q + A^T P \boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T + (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P A \\
&+ (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b}(\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T) - (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b} d^{-1} \boldsymbol{c}^T \\
&- (\boldsymbol{b} d^{-1} \boldsymbol{c}^T)^T P \boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T \\
\leq&-Q + A^T P \boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T + (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P A \\
&+ (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b}(\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T) \\
&- (\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T)^T P \boldsymbol{b}(\boldsymbol{b}(d^{-1} - \bar{k_e}^*)\boldsymbol{c}^T) \\
=&-Q - A^T P \boldsymbol{b}(\bar{k_e}^* - d^{-1})\boldsymbol{c}^T - (\boldsymbol{b}(\bar{k_e}^* - d^{-1})\boldsymbol{c}^T)^T P A.
\end{aligned} \tag{2.54}
$$

It can be seen that the above inequality is to be negative if the feedback gain k_e^* is sufficiently large, and thus $\bar{k_e}^*$ is sufficiently large. The proof of the Lemma is completed.

Appendix 2.B The detail of the clarification

In general, the practical system is strictly proper; thus, the system (2.1) - (2.2), which is denoted as $G : \{A, \boldsymbol{b}, \boldsymbol{c^T}, 0\}$ in this Appendix, is given. The following theorem is imposed with respect to the system G.

Theorem. Assume that there exists a proper, static or dynamic, stabilizing feedback configuration $H : \{A_H, \boldsymbol{b}_H, \boldsymbol{c}_H^T, d_H\}$ such that the closed-loop system is asymptotically stable. The augmented system $G_a = G + H^{-1}$ is proper and strictly minimum-phase and is therefore ASPR.

Proof.

The state-space representation of the feedback controller H can be expressed by :

$$\boldsymbol{x}_H(k+1) = A_H \boldsymbol{x}_H(k) + \boldsymbol{b}_H y(k) \tag{2.55}$$

$$y_H(k) = \boldsymbol{c}_H^T \boldsymbol{x}_H(k) + d_H y(k). \tag{2.56}$$

The control signal is given as follows.

$$u(k) = -y_H(k). \tag{2.57}$$

The closed-loop system shown in the Fig. 2.12 with $u(k) = -y_H(k)$ as the control input can be represented in the following. It should be mentioned that the input signal is considered as zero in this case.

$$\boldsymbol{x}_z(k+1) = \boldsymbol{A}_z \boldsymbol{x}_z(k), \tag{2.58}$$

where

$$\boldsymbol{x}_z = \begin{bmatrix} \boldsymbol{x}(k) \\ \boldsymbol{x}_H(k) \end{bmatrix}$$

$$\boldsymbol{A}_z = \begin{bmatrix} A - \boldsymbol{b} d_h^{-1} \boldsymbol{c}_H^T & -\boldsymbol{b}\boldsymbol{c}_H^T \\ \boldsymbol{b}_H \boldsymbol{c}^T & A_H \end{bmatrix}$$

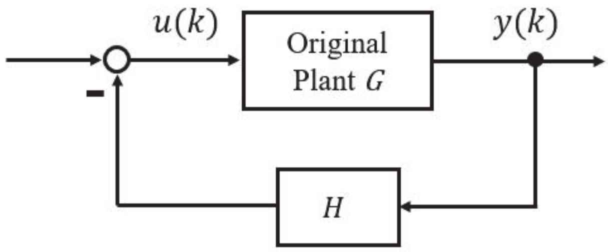

Figure 2.12: Closed-loop system with controller H

This matrix $\boldsymbol{A}_z$ is Hurwitz, which represents the close-loop system is asymptotically stable.

Now, let us consider the inverse system of H with $u(t)$ as the input and $y_h(k) = -y(k)$ as the output. The inverse system can be expressed by :

$$\boldsymbol{x}_h(k+1) = \left(A_H - \boldsymbol{b}_H d_H^{-1} \boldsymbol{c}_H^T\right) \boldsymbol{x}_h(k) - d_H^{-1} \boldsymbol{b}_H u(k) \tag{2.59}$$

$$y_h(k) = d_H^{-1} \boldsymbol{c}_H^T \boldsymbol{x}_h(k) + d_H^{-1} u(k). \tag{2.60}$$

The augmented system with the inverse system shown in Fig. 2.13 is then expressed by :

$$\boldsymbol{x}_a(k+1) = A_a x_a(k) + \boldsymbol{b}_a u(k) \tag{2.61}$$

$$y_a(k) = \boldsymbol{c}_a^T \boldsymbol{x}_a(k) + d_a u(k), \tag{2.62}$$

where,

$$\boldsymbol{x}_a = \begin{bmatrix} \boldsymbol{x}(k) \\ \boldsymbol{x}_h(k) \end{bmatrix}$$

$$A_a = \begin{bmatrix} A & 0 \\ 0 & A_H - \boldsymbol{b}_H d_H^{-1} \boldsymbol{c}_H^T \end{bmatrix}$$

$$\boldsymbol{b}_a = \begin{bmatrix} \boldsymbol{b} \\ -d_H^{-1} \end{bmatrix}$$

$$\boldsymbol{c}_a^T = \begin{bmatrix} \boldsymbol{c}^T \\ d_H^{-1}\boldsymbol{c}^T \end{bmatrix}$$

$$d_a = d_H^{-1}$$

The zero dynamics of the augmented system can be obtained when the $y_a(k)$

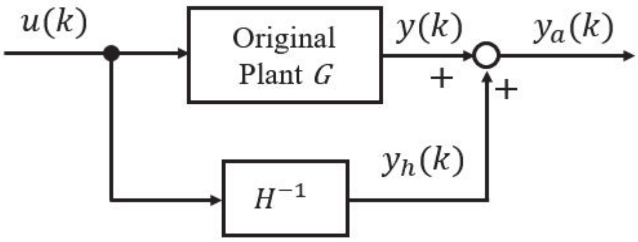

Figure 2.13: Augmented system with a configuration H^{-1}

is expected to zero. The system matrix of the augmented system $\boldsymbol{A}_{az}$ is given by :

$$\boldsymbol{A}_z = \boldsymbol{A}_{az} = \begin{bmatrix} A - \boldsymbol{b}d_h^{-1}\boldsymbol{c}_H^T & -\boldsymbol{b}\boldsymbol{c}_H^T \\ \boldsymbol{b}_H\boldsymbol{c}^T & A_H \end{bmatrix}$$

The system matrix of the augmented system has the same structure as the matrix $\boldsymbol{A}_z$; therefore, the zero dynamics of the augmented system can be stabilized by the inverse of the feedback configuration.

This theorem indicates that the PFC can be designed as the inverse of the feedback configuration. Furthermore, it is reasonable to design a constant PFC from the relation $d_a = d_H^{-1}$ without a dynamics part.

Chapter 3

Design of ASPR-based adaptive output feedback control system using FRIT

3.1 Introduction

This chapter provides a strategy to the problem mentioned in the previous conclusion. The Fictitious Reference Iterative Tuning (FRIT) approach is employed to determine the value of constant PFC d by the use of one-shot input/output experimental data directly in the SPR system. The notion of FRIT is as one of the data-oriented controller tuning methods.

The data-oriented approach to the design of a controller has been attracted considerable attentions in the recent years and is considered as one of the effective ways for the desired performance. In conventional controller design methods, the calculation of control parameters for a system necessitates *priori* information such as the order and/or the relative degree of the system. The process of obtaining such a *priori* information is inevitably time- and cost-consuming. Though the controller is designed based on the approximated information, a disaster performance is easy to be emerged. Therefore, lots of researchers focus on the data-oriented controller design method, and some successful achievements are presented in literatures [59, 60, 61, 62, 63, 64, 65, 66, 67, 68].

In order to achieve a desired tracking output, the Iterative Feedback tuning (IFT) is proposed in [69], in which the cost function to be minimized directly was represented. However, it costs considerable expense because of the iteration of experiments. As an alternative data-oriented approach without iteration, FRIT is originally developed in the literature [70]. The FRIT approach only considers one-shot input/output experimental data; thus, it is significant in practical sense that the approach enables practitioners design the controller without a mathematical model. As a result, the FRIT approach is extensively investigated in [73, 74, 75, 76, 77, 78].

However, there is an important problem remained in [71, 72]. The problem is that the stability is yet to be clarified. Though, the data-oriented approach is hard to be described in terms of mathematical model for analysis of stability, the controller based on the data-oriented approach in the SPR system should be stable. In the previous chapter, the proposed adaptive control system, that is SPR system, has been proved stable with positive value PFC d; therefore, in such system, the FRIT approach is safely to be applied. As a consequence, the FRIT approach is able to be adopted in the stable adaptive system and optimize the control parameter d.

This chapter is organized as follows : the problem is stated in section 3.2; the proposed scheme is explained in section 3.3; the numerical simulation and analysis are presented in section 3.4, and the chapter is concluded in section 3.5.

3.2 Problem statement

The constant PFC d is considered as the ASPR configuration while the feedforward input is utilized to remove the steady state error, which is concluded in the previous chapter. The basic idea here focuses on optimization of the value d; thus, the feedforward input is yet to be under consideration when the initial data is obtained.

Consider the original SISO system (2.1) - (2.2) with an equivalent controller $C(d)$, as shown in Fig. 3.1. The equivalent controller is formulated based on the (2.17) as follows

$$C(d) = \frac{k_e}{1 + dk_e}. \tag{3.1}$$

The symbol $u_{e0}(k)$ and $y_0(k)$ are denoted as the respective initial input and output, and $r(t)$ is the reference signal.

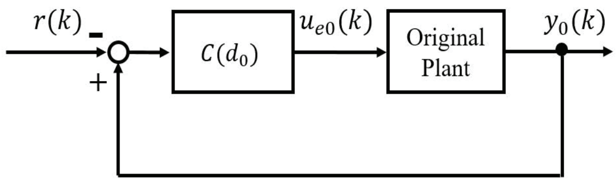

Figure 3.1: The closed-loop system.

Here, it is assumed that one can obtain an input/output data $\{u_{e0}(k), y_0(k)\}$ for an initial appropriate parameter d_0. The objective is to obtain an optimal constant PFC d_m through the use of FRIT approach by utilizing this set of data.

3.3 Design of the proposed scheme

The proposed scheme is given detail in this section. The first subsection addresses a problem in terms of the stability issue. The second subsection is shown the block diagram and the mechanism of the FRIT applied to the adaptive output feedback control system.

3.3.1 Stability analysis

The literature [71] has documented a remark in terms of the stability issue. The remark is that the issue with respect to whether the closed-loop is stable or not is not clarified in the design of a controller. In other words, if the stability can not be guaranteed, the discussion of applying the FRIT does not make sense. The theorem in the previous chapter has clarified that under certain assumptions, the constant d exists to render the augmented system ASPR, which implies the system is stable via constant feedback gain. The FRIT can be applied to design the constant d which is contained in this stable system, which results in the proposed scheme below.

3.3.2 Fictitious reference iterative tuning for the PFC design

The details of the proposed scheme are given in this section. As seen equivalent control signal represented in (2.17), the control parameter d is incorporated in the signal and determined by the FRIT approach. Fig. 3.2 presents the block diagram of the FRIT approach as applied to the proposed scheme.

As shown in the block diagram, $u_{e0}(k)$ and $y_{e0}(k)$ express the initial input and output, respectively. $r(k)$ denotes the given reference signal, $\tilde{u}_e(k)$

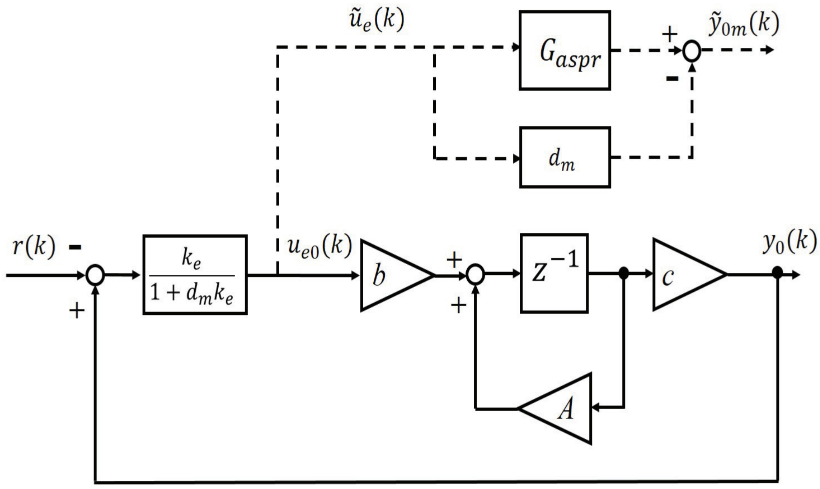

Figure 3.2: Block diagram of the FRIT approach as applied to the proposed scheme.

represents the fictitious input signal, and $\tilde{y}_{0m}(k)$ represents the fictitious output signal. G_{aspr} represents the given ASPR systems, and the constant PFC d_m is the optimal control parameter to be determined.

From the Fig. 3.2, the fictitious input signal is derived as follows

$$\tilde{u}_e(k) = \frac{k_e}{1 + d_m k_e}\{r(k) - y_0(k)\}. \tag{3.2}$$

Therefore, the fictitious output can be obtained as follows.

$$\tilde{y}_{0m}(k) = \tilde{u}(k)G_{aspr} - d_m \tilde{u}_e(k) \tag{3.3}$$

The following cost function, related to the proposed scheme, is described by

$$J(d_m) = \|\tilde{y}_{0m}(d_m) - y_0\|^2. \tag{3.4}$$

Under these settings, $J(d_m)$ is to be minimized using different d_m and the optimal control parameter can therefore be determined.

$$d_m = \arg\min_{d_m} J(d_m). \tag{3.5}$$

3.4 Numerical simulation

The effectiveness of the proposed scheme is verified through a numerical simulation.

Consider the following second-order non-minimum phase plant which is presented as :

$$G(z) = \frac{z+1.5}{z^2-0.7z} \tag{3.6}$$

It is apparent to see that there is a zero outsider of the unit circle, yet it is stable from the transfer function. Additionally, in the mathematical sense, the degree of denominator is larger than that of numerator, which results in the strictly proper of this system. The controlled plant is yet to satisfy the ASPR conditions mentioned in the previous chapter. As a consequence, the constant PFC d is needed to configure the ASPR condition; therefore, the stability of the adaptive system is under guarantee. Thus, the initial data are certain to be obtained when the parameters are set as follows :

$$r = 1, \quad d_0 = 2, \quad k_e = 0.5 \tag{3.7}$$

where r denotes the reference signal; d_0 is the initial user-specified parameter, and k_e is the constant feedback gain that is utilized to stabilize the controlled plant. The simulation of the initial data is shown in Fig. 3.3 where the steady state error emerged because of not use of the feedforward input.

It should be emphasized that the feedforward input is for the tracking issue, while the stability of the adaptive system should be guaranteed primarily when the initial data is obtained.

For the sake of implementation of FRIT approach to this scheme, the

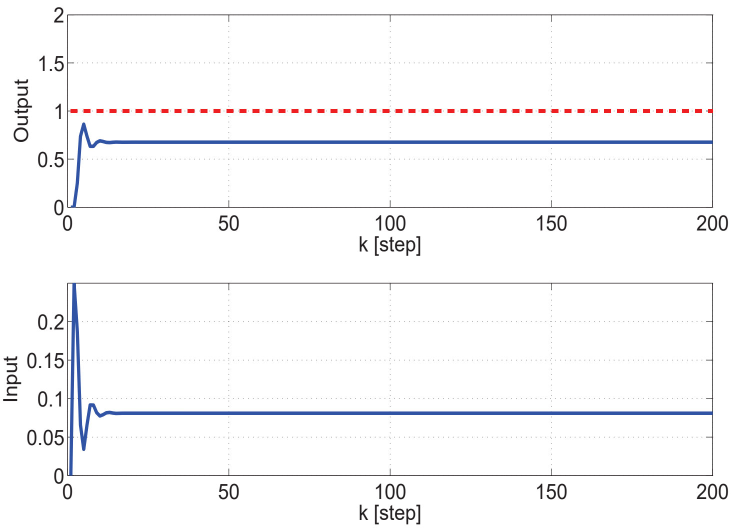

Figure 3.3: The simulation of initial data for the FRIT approach.

ASPR system should be given in the following.

$$G_{aspr} = \frac{5z - 2.9}{z - 0.9}. \tag{3.8}$$

By considering the equations (3.2) - (3.4), the optimal parameter is expressed as d_m and is shown as follows.

$$d_m = 5. \tag{3.9}$$

As a consequence, the optimal parameter d_m is applied to the adaptive control system which results in the Fig. 3.4. The adaption coefficients were set by

$$\Gamma_r = 0.04, \quad \Gamma_e = 0.7. \tag{3.10}$$

The adaptive gains are depicted in Fig. 3.5 which shows they ultimately tend to reach constant values.

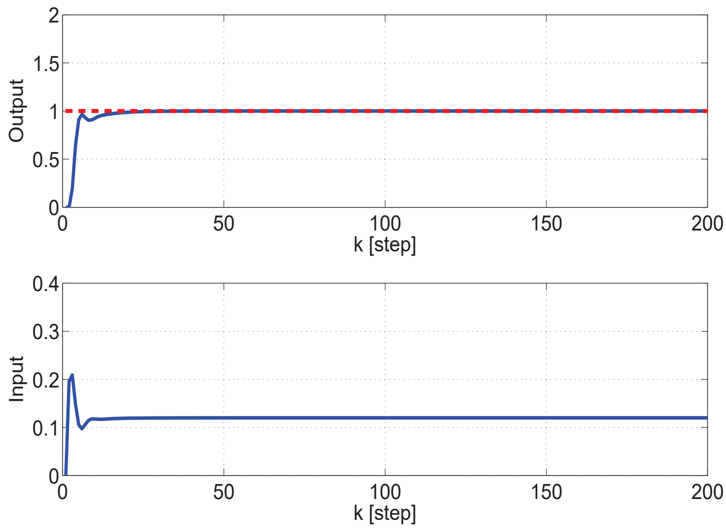

Figure 3.4: Simulation of control result obtained by the proposed scheme.

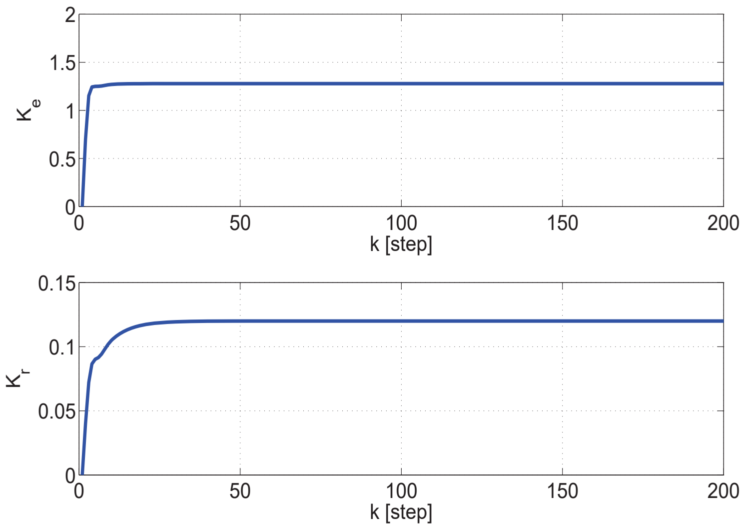

Figure 3.5: Simulation of trajectories of control gains.

The comparative study was simulated under the same condition except the parameter d. The parameter d was set as 2, and the control result is shown in Fig. 3.6. The overshoot in the output emerged, which is caused by the unsuitable d. The trajectories of adaptive gains are plotted in Fig. 3.7. To achieve the better performance, the optimal parameter d_m should be obtained.

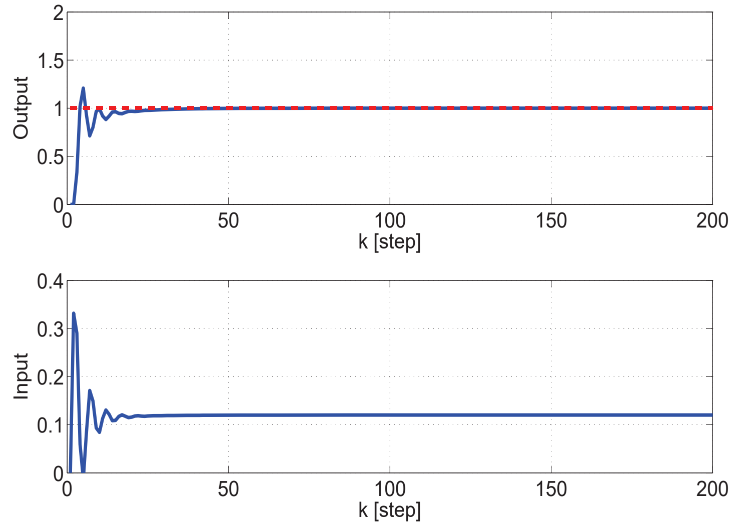

Figure 3.6: Simulation of control result in comparative study.

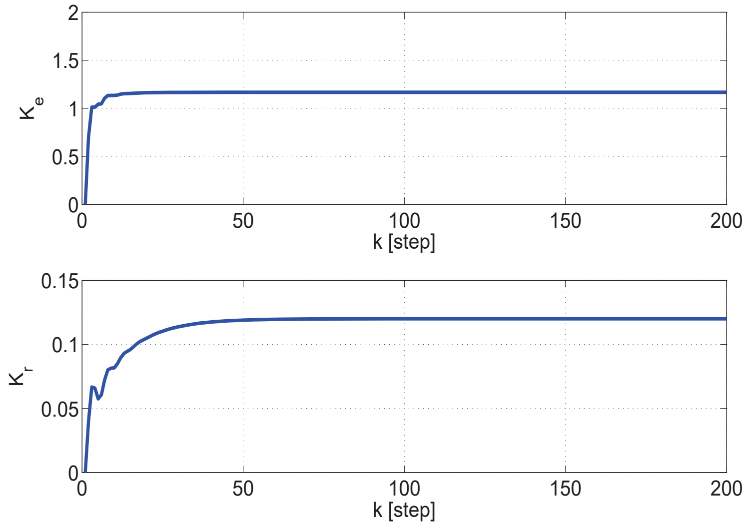

Figure 3.7: Simulation of trajectories of control gains in comparative study.

3.5 Experimental evaluation

This section presents the experimental evaluation of the proposed scheme. The experiment was conducted using a motor application, the image of which is shown in Fig. 3.8. The schematic diagram of the equipment is shown in Fig. 3.9. The objective of the experiment was to maintain the disk at the same rotational speed (unit: [rad/s]) as the one specified by the reference signal.

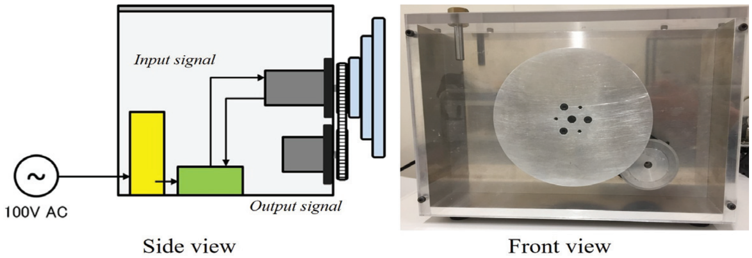

Figure 3.8: Picture of motor application.

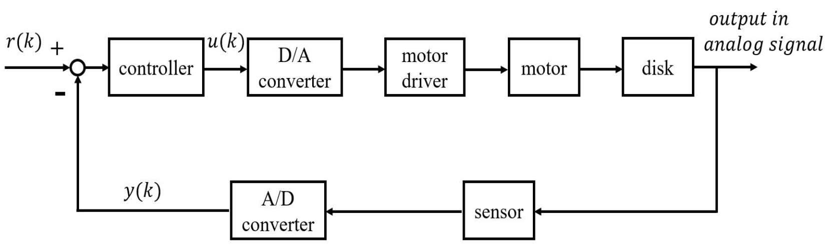

Figure 3.9: Block diagram of motor application.

The operational mechanism of the motor application used in the experiment is introduced briefly in the following section. The rotational speed of the disk was measured by a sensor. The measured signal was in the analog form and therefore sent to the D/A converter. Subsequently, the controller received a digital error signal such that the control signal was computed by an algorithm. The A/D converter converted the digital signal to an analog signal. The function of the motor driver was to amplify the signal, which was then used to operate the motor to allow rotation of the disk. It should be emphasized that the operation voltage in this experiment was limited to a value between 0 V and 24 V. The sampling time (Ts) of the system was set to 0.02 s.

Many practical systems do not include the direct term; therefore, it is reasonable to assume that the motor application can be presented as (2.1) - (2.2). For the purpose of designing a stable adaptive output feedback control system, the PFC d needed to be calculated. In this experiment, the initial input/output data was obtained first, by setting the related parameters as shown below, in order to apply the FRIT approach.

$$r = 1000, \quad d_0 = 5, \quad k_e = 10 \tag{3.11}$$

where r is the value of reference signal, d_0 is a user-specified initial parameter, and k_e is a constant that could stabilize the motor application. From Fig. 3.10, it is seen that the final steady output could not reach the given reference value, since the feedforward input was not implented. As explained in the previous section, the purpose of this step is to obtain the stable initial input/output data so as to proceed the FRIT to the next step in motor application.

The given ASPR system was set to the following configuration in the second step.

$$G_{aspr} = \frac{5z - 1.7}{z - 0.9}. \tag{3.12}$$

Here, d was reasonably restricted to a value in the range between 0

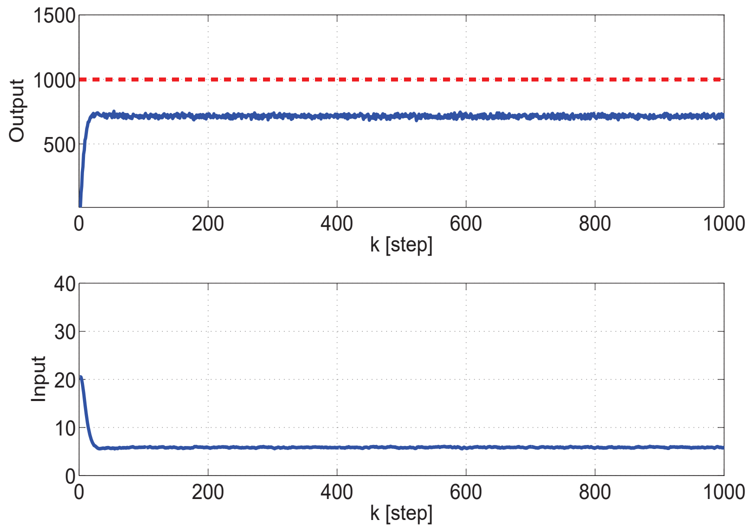

Figure 3.10: Initial data for the FRIT approach.

and 20. By using (3.2) to (3.4), the proper control parameter d_m can be represented as follows.

$$d_m = 9.2. \tag{3.13}$$

Eventually, Fig. (3.12) shows the control output when the related parameters were set as

$$\Gamma_r = 4 \times 10^{-6}, \quad \Gamma_e = 6 \times 10^{-4}. \tag{3.14}$$

The adaptive gains are plotted in Fig. (3.11).

The disturbance in Fig. (3.12) was introduced at approximately 500 step, and the adaptive gains appeared to change to large values trying to negate the disturbance. As time advanced by 120 steps, the output attained the reference value again. This fact reflected the advantage of adaptive control. The adaptive gains ultimately tended to reach a constant value. These results verified the effectiveness of the proposed scheme and the convergence was also illustrated.

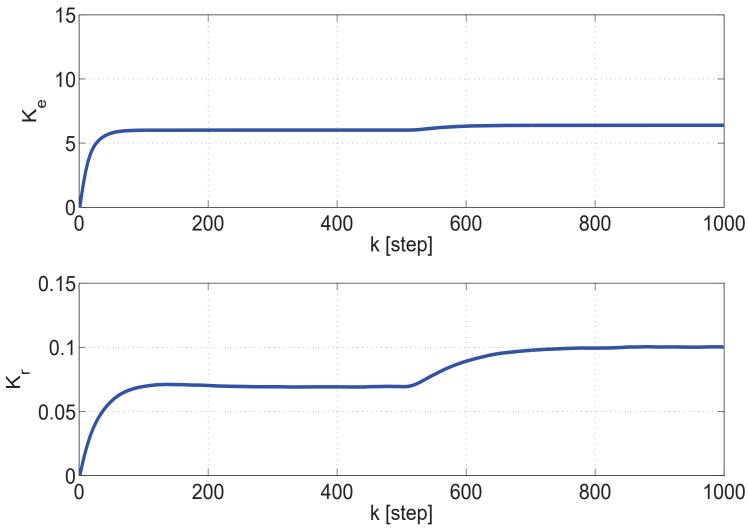

Figure 3.11: Trajectories of control parameters in the proposed scheme.

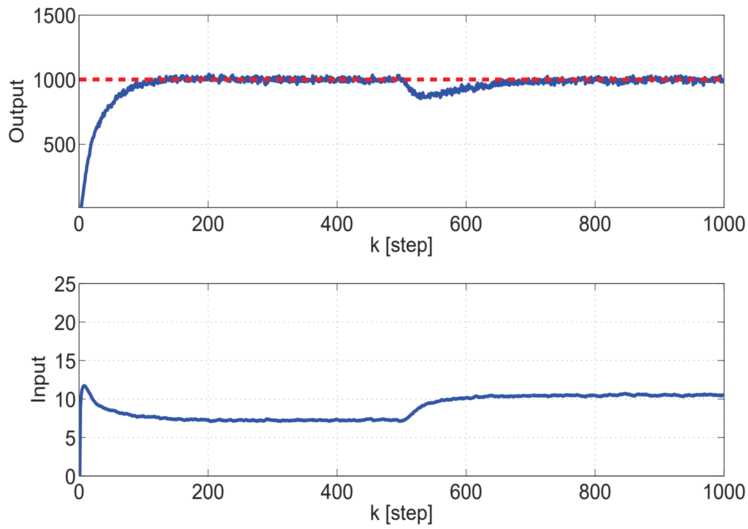

Figure 3.12: Control result obtained by the proposed scheme.

Additionally, a controlled comparative study was executed in terms of the proposed scheme. All the conditions remained the same, except for d, which in this case was set to 20. From (2.17), it could be seen that a larger value of d led to a decrease in the control input, which implies that the control input can-not effectively and timely suppress the output. The overshoot finally appears in Fig. 3.13, and the adaptive gains in the comparative study are depicted in Fig. 3.14

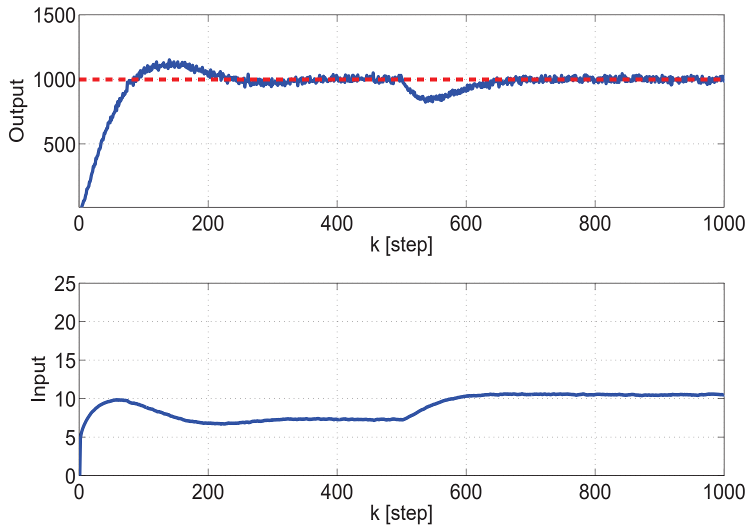

Figure 3.13: Control result in comparative study.

Remark. The experimental evaluation was conducted only under the consideration of input/output data. The controller was able to be designed based on the output signal. All the signals in the adaptive control system were bounded, which confirmed the theorem. The proper value of d was determined by the FRIT approach.

3.6 Conclusion

In this chapter, the design of an adaptive output feedback control system with a feedforward input by applying the FRIT approach was presented. A rigorous proof of convergence regarding to the adaptive control system was

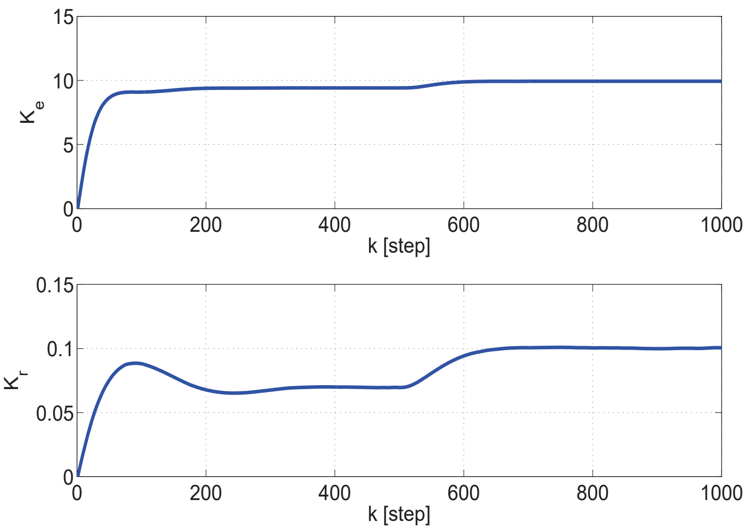

Figure 3.14: Trajectories of control parameters in comparative study.

provided in the previous chapter. The proof indicated that the d could be designed safely. As a result, the FRIT approach was able to be applied to optimize the parameter d, and this chapter explained the implementation of the FRIT approach in the proposed scheme. The major feature of the proposed scheme was that the proper constant PFC d was determined by using one-shot experimental input/output data with no mathematical model. This was significant from the practical point of view since the accurate model was hard to be estimated, and the potential use of the proposed scheme should be focused on. The steady state error was eliminated and the output of the original plant was found to track the reference value.

An experiment was conducted in a motor system to confirm the effectiveness of the proposed scheme. According to the control results, the proposed scheme negated the implanted disturbances, which shows the power of adaptive control. The comparative experiment was also studied in terms of different parameter d, which confirmed that the parameter d determined by the FRIT approach was the optimal one.

The passivity property, which is equivalent to SPR in LTI systems, was discussed in this and previous chapters while the passivity property in nonlinear systems would be addressed in the next chapter.

Chapter 4

Design of OFSP-based adaptive output feedback control for non-linear systems using data-driven approach

4.1 Introduction

This chapter investigates the passivity property in nonlinear systems. Moreover, the data-driven approach is adopted as a tool to perform the update of adaptive gains rapidly.

Researchers have focused their attention on approaches to deal with nonlinear systems, since the majority of practical processes contain non-linearities. One particular interest of those approaches is a controller design based strict passivity property for discrete-time nonlinear systems. The strict passivity property has played an important role in assuring stability in adaptive control systems, and it has been characterized by some relations in the form of state-space representation. These relations are called strict passivity condition based on which the stability of an adaptive control system can be assured by using Lyapunov's stable theory.

A discrete-time version Kalman-Yacubovitch-Popov (KYP) Lemma proposed in [39] plays a crucial role in establishing a relationship between strict passivity and Lyapunov function. That is a positive-definite matrix can be determined by using the KYP Lemma such that the matrix satisfies the Lyapunov function. As a result, a strict passive system, which is of the strict passivity property, can be obtained.

In this chapter, the output feedback strict passive is discussed. A dynamical system that needs an output feedback to become strictly passive has been called output feedback strictly passive (OFSP) [79, 80, 90, 91]. Researchers can easily design an adaptive control system based on OFSP such that the augmented system has robustness against disturbances and uncertainties. The issue of stability of adaptive output feedback control based on OFSP for nonlinear systems has been investigated in [80, 13, 85]. Once the stability of the adaptive control systems can be guaranteed, the adaptive gains can be varied in a bounded range to minimize the tracking error.

The sufficient conditions required for a discrete-time system to be OFSP have been presented in the technical literature [80]. However, since most practical systems do not satisfy OFSP conditions, it is unsuitable to render the adaptive output feedback method for use in practical applications. One of the significant ideas was proposed in [45, 80], wherein a parallel feedforward compensator (PFC) was considered to alleviate the restrictive conditions. Additionally, it should be noted that the strict passive system must have a direct term, which results in the relative degree zero [39]. However, under this condition, the causality problem emerges in the controller design in discrete-time domain. The equivalent controller is considered in the proposed scheme to address this problem.

The data-driven approach is one of the control strategies applied in nonlinear systems, and it can adjust the control parameters rapidly at each equilibrium point. This approach can be adopted as a tool to accelerate the convergence of adaptive gains when the nonlinearity of a system is strong. Moreover, the data-driven approach is able to optimize the control parameters by utilizing the database generated from input/output data without *priori* information of the controlled system. Furthermore, the control parameters are manipulated in a local bounded neighbor data. Successful implementations of the data-driven approach have been presented in technical literatures [81, 82, 83, 84]. However, the stability of the data-driven approach applied in those mentioned literatures has not been investigated. Therefore, the stability issue is discussed and explained in this chapter. The proposed scheme is employed in a numerical simulation to assess the performance.

This chapter is organized as follows : the problem is stated in section 4.2; the proposed scheme is examined in section 4.3; Section 4.4 provides the simulation and analysis, and the paper is concluded in section 4.5.

4.2 Problem statement

Consider the following single-input single-output (SISO) discrete-time nonlinear system with state-space, represented as

$$\boldsymbol{x}(k+1) = f(\boldsymbol{x})\boldsymbol{x}(k) + g(\boldsymbol{x})u(k) \tag{4.1}$$

$$y(k) = h(\boldsymbol{x})\boldsymbol{x}(k) \tag{4.2}$$

$$y_a(k) = h(\boldsymbol{x})\boldsymbol{x}(k) + du(k). \tag{4.3}$$

The original system is considered as strictly proper and denoted by (4.1) - (4.2), and the augmented system is expressed by (4.1) - (4.3). $\boldsymbol{x}(k) \in \boldsymbol{R}^n$

is a state vector, and $u(k)$ and $y(k) \in \boldsymbol{R}$ are the input and output of the original of the original system, respectively. $f(\boldsymbol{x}(k)) : \boldsymbol{R}^n \to \boldsymbol{R}^n$, $g(\boldsymbol{x}(k)) : \boldsymbol{R}^n \to \boldsymbol{R}^n$, and $h(\boldsymbol{x}(k)) : \boldsymbol{R}^n \to \boldsymbol{R}^n$ are smooth in $\boldsymbol{x}(k)$. $y_a(k)$ denotes the augmented output of the system.

Definition. The system represented by (4.1) - (4.3) is said to be OFSP if there exists a positive definite output feedback gain θ_e^* such that the resulting closed-loop system shown in Fig. 4.1 is strict passive.

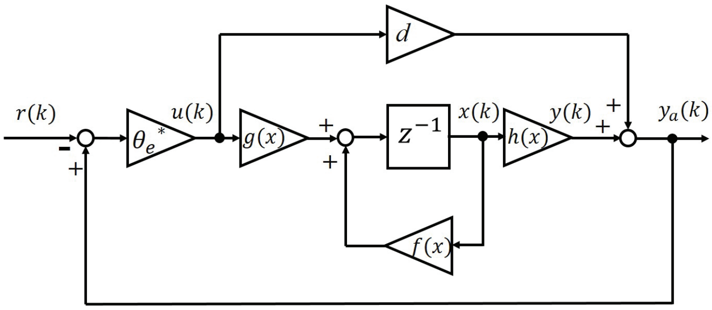

Figure 4.1: Passive system.

It is easy to utilize the controller

$$
\begin{aligned}
u(k) &= -\theta_e^*(y_a(k) - r(k)) \\
&= -\theta_e^*(h(\boldsymbol{x})\boldsymbol{x}(k) + du(k) - r(k)) \qquad (4.4)\\
&= -\frac{\theta_e^*}{1 + d\theta_e^*}(h(\boldsymbol{x})\boldsymbol{x}(k) - r(k)) \\
&= -\bar{\theta}_e^*(h(\boldsymbol{x})\boldsymbol{x}(k) - r(k)),
\end{aligned}
$$

where,

$$\bar{\theta}_e^* = \frac{-\theta_e^*}{1 + d\theta_e^*},$$

such that the augmented system gives

$$\boldsymbol{x}(k+1) = f_a(\boldsymbol{x})\boldsymbol{x}(k) + g_a(\boldsymbol{x})\boldsymbol{x}(k)r(k) \qquad (4.5)$$

$$y_a(k) = h_a(\boldsymbol{x})\boldsymbol{x}(k) + d_a r(k) \qquad (4.6)$$

with

$$f_a(\boldsymbol{x}) = f(\boldsymbol{x}) - \bar{\theta}_e^* g(\boldsymbol{x})h(\boldsymbol{x}) \tag{4.7}$$

$$g_a(\boldsymbol{x}) = -\bar{\theta}_e^* g(\boldsymbol{x})r(k) \tag{4.8}$$

$$h_a(\boldsymbol{x}) = (1 - d\bar{\theta}_e^*)h(\boldsymbol{x}) \tag{4.9}$$

$$d_a = d\bar{\theta}_e^*. \tag{4.10}$$

That is the resulting closed-loop system is proper and minimum-phase after adding the positive d compared to the original system.

Remark 1. It has been clarified in [80, 13, 85] that the stability of a nonlinear adaptive control system is guaranteed if the inverse of the feedback gain is used as PFC to augment the plant to be controlled, and it is reasonable to design a constant PFC in the nonlinear adaptive control system. From the definition aforementioned, in the system (4.1) - (4.3), d can be regarded as parallel feedforward with the original system and is considered to be a PFC.

However, unfortunately, the steady state error exists after introducing the PFC. In order to eliminate the steady state error between the augmented system and the reference signal in the control results, the literatures [86, 87] has proposed a scheme, in which the feedforward input was utilized. Based on this achievement, the following assumption is imposed.

Assumption. Considering the output of the original system is expected to track the reference value, there exists an ideal feedforward input v^* such that the following equations hold.

$$\boldsymbol{x}^*(k+1) = f(\boldsymbol{x}^*)\boldsymbol{x}(k) + g(\boldsymbol{x}^*)\boldsymbol{x}(k)v^* \tag{4.11}$$

$$y^*(k) = h(\boldsymbol{x}^*) = r(k) \tag{4.12}$$

$$y_a^* = h(\boldsymbol{x}^*) + du_e(k) \tag{4.13}$$

$$= y^*(k) = r(k). \tag{4.14}$$

Therefore, under the assumption, the objective of this study is to design an adaptive output feedback control system by applying the data-driven approach. As a result, the optimal adaptive gains can be updated rapidly, and the output of the original system can track the reference value. The block diagram of the proposed scheme is depicted in Fig. 4.2.

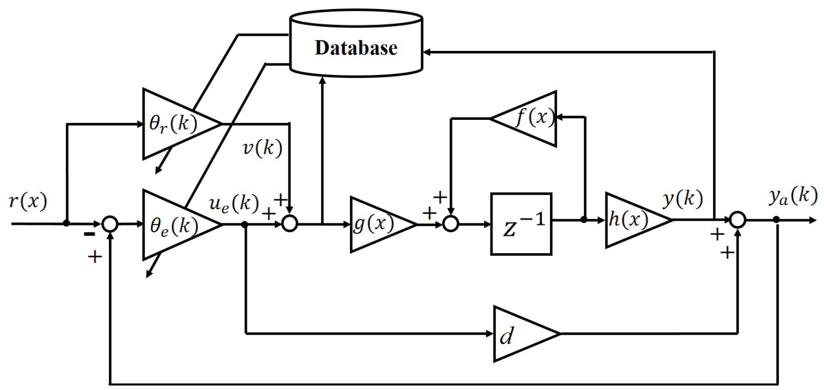

Figure 4.2: Block diagram of the proposed adaptive control system.

4.3 Design of the proposed scheme

This section discusses the design scheme in terms of three aspects. The controller structure is described in the first subsection. The detail of the data-driven approach employed in the proposed scheme is given in the second subsection. The third subsection gives the stability statement of the proposed scheme.

4.3.1 Controller structure

The implemented adaptive controller is described as

$$u(k) = u_e(k) + v(k), \tag{4.15}$$

That is

$$u(k) = -\theta_e(k)e_a(k) - \theta_r(k)r(k), \tag{4.16}$$

where

$$e_a(k) = y_a(k) - r(k), \tag{4.17}$$

and the adaptive gains are generated by the following algorithm

$$\theta_e(k) = \theta_e(k-1) - \Gamma_e e_a^2(k) \tag{4.18}$$

$$\theta_r(k) = \theta_r(k-1) - \Gamma_r e_a(k)r(k), \tag{4.19}$$

where Γ_e and Γ_r are positive constants.

The direct term in parallel with the system is required for an OFSP discrete-time system. Therefore, the control signal (4.16) can not be implemented directly because the current step $e_a(k)$ is not available owing to the causality problem. To solve this problem, the equivalent control input is considered and obtained from the following equation.

$$\begin{aligned} u_e(k) &= -\theta_e(k)e_a(k) \\ &= -\theta_e(k)(h(\boldsymbol{x}(k)) + du_e(k) - r(k)) \\ &= -\theta_e(k)\frac{e(k)}{1 + dk_e(k)}, \end{aligned} \tag{4.20}$$

where $e(k)$ is the error between the output of the original system and the reference signal.

4.3.2 Data-driven approach application

The mechanism of the data-driven approach is reviewed in this subsection. Several mathematical explanations must be considered firstly. The historical data from output of original system and control input construct a vector called information vector which is defined by the following equation:

$$\phi(k-1) := [y(k-1), \cdots, y(k-n_y), u(k-1), \cdots, u(k-n_u)] \tag{4.21}$$

where n_y and n_u are the order of the system output and control input, respectively.

It should be noted that, the output from the original system is considered. It is apparent that the information of controlled system can be indicated by those elements included in $\phi(k-1)$. Furthermore, the data in the form of the information vector expressed in (4.21) is stored in the database. The procedures of the data-driven approach are stated in the following.

[STEP 1] Generate the initial database

The data-driven approach can not work unless the initial database is generated by the historical data. The parameter d is required in order to facilitate the robust implementation of the adaptive output feedback control system. After the stability is guaranteed, the initial control parameters expressed in (4.18) - (4.19), input/output data and the reference signal $r(k)$ are stored in the database indicated by $\Phi(j)$ as follows:

$$\Phi(j) := [\bar{\phi}(k_j), \Theta(k_j)], \quad j = 1, 2, \cdots, N, \tag{4.22}$$

where N denotes the dimension of the initial database, and $\bar{\phi}(k_j)$ and $\Theta(k_j)$ have the form

$$\begin{aligned}\bar{\phi}(k_j) :=& [r(k_j+1), r(k_j), y(k_j), \cdots, y(k_j - n_y + 1), \\ & u(k_j - 1), \cdots, u(k_j - n_u + 1)],\end{aligned} \tag{4.23}$$

$$\boldsymbol{\Theta}(k_j) = [\theta_e(k_j), \theta_r(k_j)]. \tag{4.24}$$

[STEP 2] Calculate the distance and select the neighbors

The query $\bar{\phi}(k)$ which presents the information vector in the current step, is introduced firstly. The distance between the query and the information vector $\bar{\phi}(k_j)$ is calculated by the following $\mathcal{L}_1$-norm with some weights:

$$d(\bar{\phi}(k), \bar{\phi}(k_j)) = \sum_{l=1}^{n_y+n_u+1} \left| \frac{\bar{\phi}_l(k) - \bar{\phi}_l(k_j)}{\max_m \bar{\phi}_l(m) - \min_m \bar{\phi}_l(m)} \right|, \quad j = 1, 2, \cdots, N(k) \tag{4.25}$$

where $N(k)$ denotes the dimension of the database, $\overline{\phi}_l(k)$ denotes the lth element of the query at current step k, and $\bar{\phi}_l(k_j)$ expresses the lth element of the jth information vector. Moreover, $\max \overline{\phi}_l(m)$ is the maximum element among all lth element of all information vector, and the similar explanation with $\min \overline{\phi}_l(m)$. Therefore, the database is arranged by an ascended order based on the calculated distance, and then the q-pieces neighbors can be selected.

[STEP 3] Re-calculate the adaptive gains

From the database selected in the previous step, the suitable control parameters $\boldsymbol{\Theta}(k_j)$ can be calculated around the query by the following equation:

$$\boldsymbol{\Theta}^{old}(k) = \sum_{i=1}^{q} w_i \boldsymbol{\Theta}(i), \quad \sum_{i=1}^{q} = 1, \tag{4.26}$$

where

$$w_i = \frac{\exp(-d_i)}{\sum\limits_{i=1}^{q} \exp(-d_i)}. \tag{4.27}$$

[STEP 4] Updata the adaptive gains

It is necessary to update the calculated adaptive gains such that the better performance can be obtained. The following steepest descent method is considered.

$$\boldsymbol{\Theta}^{new}(k) = \boldsymbol{\Theta}^{old}(k) - \eta \frac{\partial J(k+1)}{\partial \boldsymbol{\Theta}(k)}, \tag{4.28}$$

where $\eta = [\eta_{k_e}, \eta_{k_r}]$ denotes the learning coefficient, and $J(k+1)$ is defined by the following criterion.

$$J(k+1) := \frac{1}{2}\varepsilon(k+1)^2, \tag{4.29}$$

$$\varepsilon(k) := y_r(k) - y(k). \tag{4.30}$$

The output $y_r(k)$ is obtained from a reference model given by:

$$y_r(k) = \frac{z^{-1}P(1)}{P(z^{-1})} r(k), \tag{4.31}$$

$$P(z^{-1}) = 1 + p_1 z^{-1} + p_2 z^{-2}, \tag{4.32}$$

$$\left.\begin{aligned} p_1 &= -\exp\left(-\frac{\rho}{2\mu}\right)\cos\left(\frac{\sqrt{4\mu - 1}}{2\mu}\rho\right) \\ p_2 &= \exp\left(-\frac{\rho}{\mu}\right) \\ \rho &= T_s/\alpha \\ \mu &= 0.25(1-\beta) + 0.51\delta \end{aligned}\right\}, \tag{4.33}$$

where T_s is the sampling time, α indicates the rising time, and β denotes the decreasing parameter.

Furthermore, the partial differential term of (4.28) is expanded in the form

$$\left.\begin{aligned} \frac{\partial(k+1)}{\partial k_e(k)} &= \frac{\partial(k+1)}{\varepsilon(k+1)} \frac{\varepsilon(k+1)}{\partial y(k+1)} \frac{\partial y(k+1)}{\partial u(k)} \frac{\partial u(k)}{\partial k_e(k)} \\ &= \varepsilon(k+1) \frac{e(k)}{1 + dk_e(k)} \frac{\partial y(k+1)}{\partial u(k)} \\ \frac{\partial(k+1)}{\partial k_r(k)} &= \frac{\partial(k+1)}{\varepsilon(k+1)} \frac{\varepsilon(k+1)}{\partial y(k+1)} \frac{\partial y(k+1)}{\partial u(k)} \frac{\partial u(k)}{\partial k_r(k)} \\ &= \varepsilon(k+1) r(k) \frac{\partial y(k+1)}{\partial u(k)} \end{aligned}\right\}. \tag{4.34}$$

It should be noted that $\partial y(k+1)/\partial u(k)$ is required to calculate (4.34). The literatures [81, 88] have been stated that it is reasonable to assume that the $|\partial y(k+1)/\partial u(k)|$ is included in η.

The proposed scheme then can be summarized briefly as follows:

[step 1] Apply the conventional method to obtain the data that is stored in the initial database

[step 2] Acquire the query $\overline{\phi}(k)$, and calculate the distance by (4.25)

[step 3] Sort the database in a ascended order based on the distance, and select the neighbor data

[step 4] Re-calculate the control parameters by (4.26)

[step 5] Update the calculated adaptive gains based on (4.28), (4.31) and (4.34)

[step 6] Send the updated control parameters into database, and iterate the above steps.

The adaptive gains can be optimized by the above procedures such that the better performance is attained.

4.3.3 Stability analysis

The stability is the first condition in controller design for an adaptive system, especially for a nonlinear system. In the literature [56], the passivity based adaptive output feedback control design for a discrete-time nonlinear system was investigated. The very important achievement was to clarify a discrete-time nonlinear version of the Kalman-Yakubovich-Popov Lemma, and the rigorous proof was given in adaptive feedback control system design for discrete-time nonlinear systems. The adaptive gains and control output can be guaranteed boundedness.

Moreover, the data-driven approach has been an effective method for nonlinear systems, and it can adjust the obtained parameters by steepest descent method. The [89] documented that the convergent of steepest descent method is proved. As a result, the stability of the proposed scheme can be guaranteed.

Remark 2. Under the assumption in the aforementioned section and the above statement, it is apparent that the objective of the proposed scheme can be achieved in a theoretical sense. All the signals in the initial database are bounded, and then are updated by the data-driven technique.

4.4 Numerical simulation

A numerical simulation is implemented to verify the effectiveness of the proposed scheme in nonlinear systems. The Hammerstein models [81] are considered and are given in the following form.

System 1

$$\left.\begin{aligned} y(k) =& 0.6y(k-1) - 0.1y(k-2) \\ & + 1.2x(k-1) - 0.1x(k-2) + \xi(k) \\ x(k) =& u(k) - u^2(k) + u^3(k) \end{aligned}\right\}, \tag{4.35}$$

System 2

$$\left.\begin{aligned} y(k) =& 0.6y(k-1) - 0.1y(k-2) \\ & + 1.2x(k-1) - 0.1x(k-2) + \xi(k) \\ x(k) =& 1.5u(k) - 1.5u(k)^2 + 0.5u(k)^3 \end{aligned}\right\}, \tag{4.36}$$

where $\xi(k)$ is the white Gaussian noise with zero mean and variance of 0.01^2. The static property of the above systems are depicted in Fig. 4.3. The

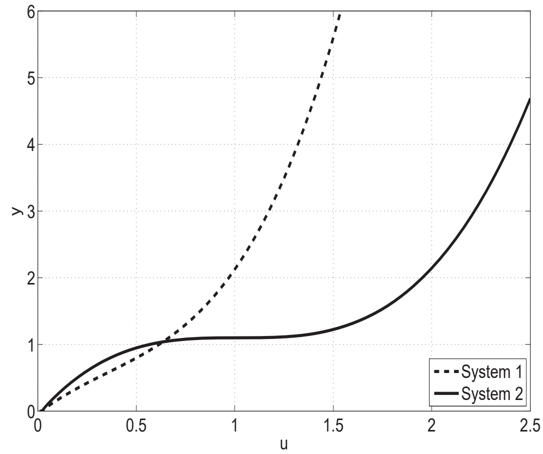

Figure 4.3: Static property of System 1 and System 2.

reference signal values are set as follows:

$$r(k) = \begin{cases} 1(0 \leq k < 50) \\ 0.8(50 \leq k < 100) \\ 1.5(100 \leq k < 150) \\ 1(150 \leq k < 200) \end{cases}. \tag{4.37}$$

The data-driven approach can work only if the initial database is generated. Therefore, the conventional adaptive output feedback control is applied in the model, and the related parameters are set in Table 4.1. It should be

Table 4.1: User-specified parameters for obtaining initial database

System configuration d	5
Sampling interval [s]	1.0[s]
Coefficients	$\Gamma_e = 0.05$
	$\Gamma_r = 0.05$

noted that in the first 200 steps, the System 1 is as the controlled object;

whereas, the System 2 is considered in the rest of the steps. The control results are shown in the Fig. 4.4 and Fig. 4.5, respectively. It is apparent to see that the rising time is large when the reference signal is changed. Moreover, from the static property of the System 2, the nonlinearity is strong in the case where the output equals to 1 such that the tracking error can not be eliminated after 300 step.

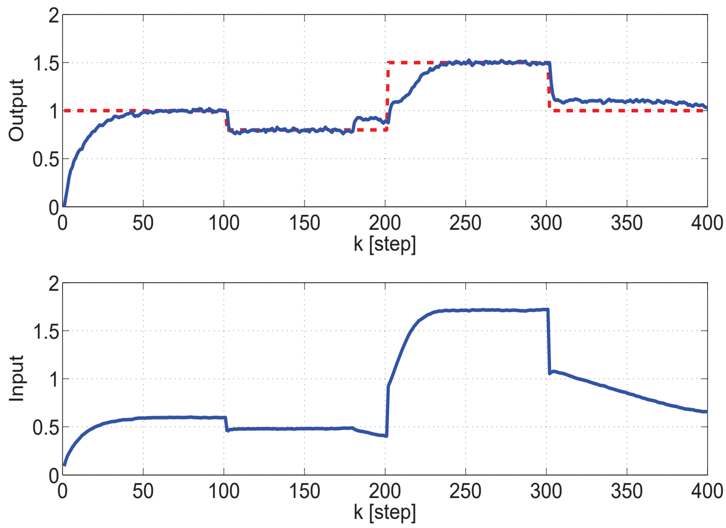

Figure 4.4: Control result obtained by the conventional method.

The results show the stability, and the initial database then is generated by the obtained data in Fig. 4.4 and Fig. 4.5. The related parameters required in this approach are summarized in Table 4.2. The polynomial $P(z^{-1})$ included in the reference model was designed as:

$$P(z^{-1}) = 1 - 0.5896z^{-1} + 0.0183z^{-2}. \tag{4.38}$$

As a result, Fig. 4.6 shows the output of the system and the control input, and Fig. 4.7 illustrates the trajectories of the adaptive gains adjusted

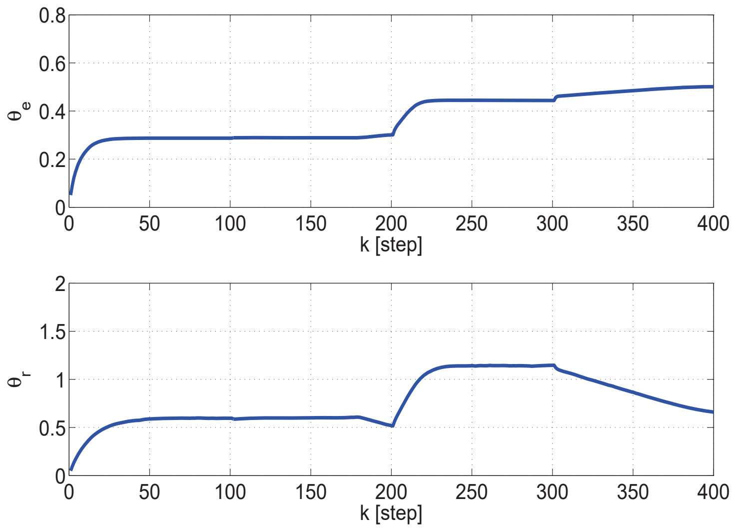

Figure 4.5: Trajectories of adaptive gains.

Table 4.2: User-specified parameters for the proposed scheme

Order of the information vector	$n_y = 2$
	$n_u = 2$
Numbers of neighbors	$q = 10$
	$\Gamma_r = 0.05$
Learning rates	$\eta_{k_e} = 2$
	$\eta_{k_r} = 2$

by the data-driven approach. The rising time in Fig. 4.6 is improved, which occurred both at approximatedly 10 step and 200 step, since the adaptive gains were increased rapidly by data-driven approach. Furthermore, the control performance is maintained after 300 step in the proposed scheme, since the adaptive gains were decreased rapidly to reach the optimal value. The data-driven approach is adopted to update the adaptive gains rapidly to fit the right gains to the righ situation, and the approach also demonstrated

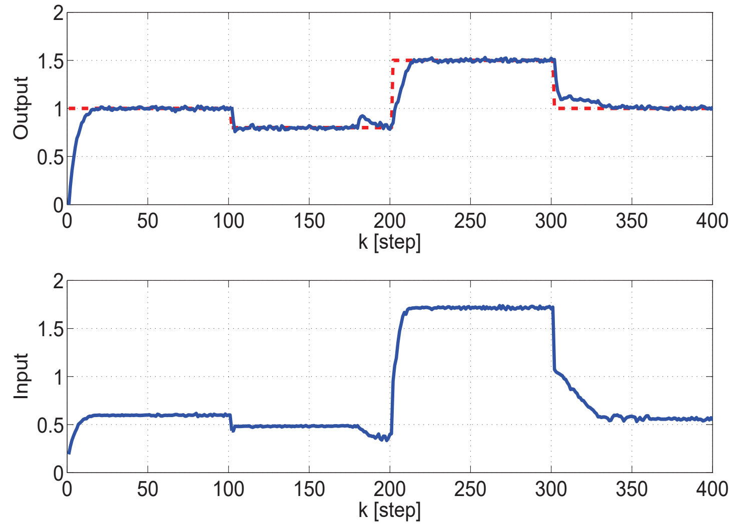

Figure 4.6: Control result obtained by the proposed scheme.

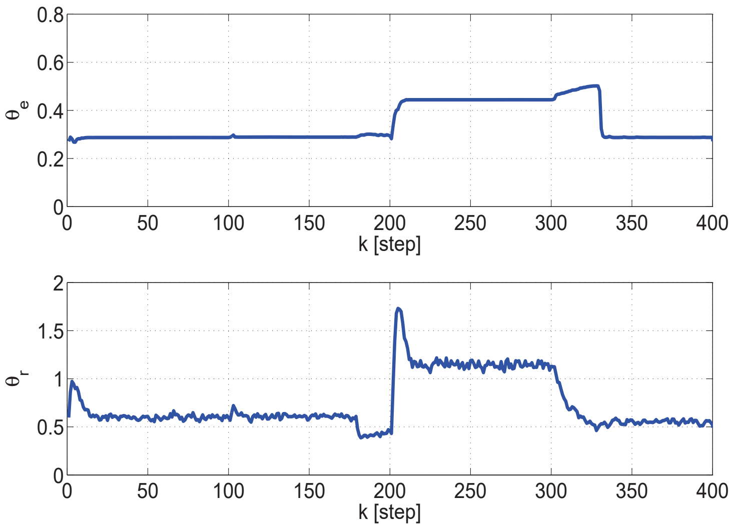

Figure 4.7: Trajectories of adaptive gains in the proposed scheme.

a characteristic that is against the nonlinearity of the system.

Remark 3. The controller design in the proposed scheme only considered the output of the system. All the signals are bounded from the control results, which confirmed the stability of the proposed scheme. The control results obtained by updated control parameters outperformed the one which obtained by the conventional method.

4.5 Conclusion

In this chapter, the design of a data-driven adaptive output feedback control based on the OFSP was presented. In the proposed scheme, the PFC was considered to configure the plant such that the OFSP conditions could be satisfied. Moreover, it was reasonable to assume constant d as a direct term in the propose scheme for non-linear system, and the constant d could be considered as a PFC. Additionally, the feedforward input was utilized so as to remove the steady state error for a nonlinear system. The stability statement was provided, and control parameters were adjusted based on the database such that desired performance could be attained. Furthermore, only the input and output data were utilized in the proposed scheme without the mathematical model. The effectiveness of the proposed scheme was verified analytically through a numerical simulation. The response of the output was improved in terms of rising time, and the tracking error was eliminated. The better performance was maintained even though the system changed. The control parameters ultimately converged to a constant value in the proposed scheme.

Chapter 5

Conclusion

In this thesis, the control problem regarding the design of a adaptive output feedback control system based on passivity was addressed. Both linear systems and non-linear systems were studied in terms of the passivity property. The tracking problem was also addressed and the feedforward input was introduced to remove the steady state error. This thesis clarified the relationship between the PFC and the direct term d, that is, the direct term d could be considered as the constant PFC. Several algorithms for optimizing the parameter d and facilitating the update of adaptive gains were proposed. The efficacies of the proposed schemes were verified analytically through numerical examples and experimental evaluations. The brief summarizations were as follows:

(i) ASPR-based adaptive output feedback control system was designed with feedforward input;

(ii) The FRIT approach was applied to optimize the constant PFC in terms of the adaptive output feedback control system;

(iii) The data-driven approach was considered for OFSP-based adaptive output feedback control system.

In Chapter 1, the research background was introduced in terms of adaptive output feedback control. The stability issue was not taken into consideration until the MIT-rule ended in failure. The introduction of passivity and its use towards to guaranteeing the stability of the adaptive control system are the good basis, on which the adaptive algorithm can be built. The objective of this thesis was briefly summarized as well.

In Chapter 2, the design of an adaptive output feedback control system with a feedforward input was addressed. The relationship between the PFC and direct term d was also clarified, and that was the d could be considered as the PFC without dynamic parts in the proposed scheme. The PFC was properly designed to make the augmented system ASPR such that the stability was guaranteed. Additionally, the feedforward input was utilized to remove the steady state error, and the feedforward input was obtained by only considering the integral action. The simpler structure was superior over other methods with respect to the learning cost. The proposed low-order controller was certain to control the industrial processes with high-order degree even in the presence of uncertainties. The rigorous proof of convergence was also shown in terms of the proposed adaptive output feedback control system. Furthermore, the proposed scheme was verified through a numerical simulation and was employed in the pilot-scale temperature control system. The control results confirmed the effectiveness and robustness of the proposed scheme.

In Chapter 3, the problem regarding to the design optimal parameter d was addressed. Therefore, the design of an adaptive output feedback control system with a feedforward input by applying the FRIT approach was proposed. The parameter d was able to be designed safely, which was proved in the previous chapter. Due to this reason, the FRIT war certain to be applied to optimize the parameter d under the stable adaptive control system. The implementation of the FRIT approach in the proposed scheme was also explained in detail. The major feature of the proposed scheme was that the proper constant PFC d was determined by using one-shot experimental input/output data without mathematical model. This was significant from the practical point of view since the accurate model was hard to be estimated. In the practical sense, the use of FRIT in the proposed scheme widened the range of applications potentially. Moreover, the steady state error was eliminated, and the output of the original plant was found to track the reference value. To assess the performance of the proposed scheme, an experiment was conducted in a motor system. According to the control results, the proposed scheme could negate the implanted disturbance. The comparative experiment was also studied under the same condition except a different parameter d. The control results from comparative study showed oscillation; therefore, the d determined by the FRIT approach was the optimal one.

In Chapter 4, the passivity property was discussed in terms of non-linear system. The design of a data-driven adaptive output feedback control based on OFSP was presented. Similarly to the previous, the PFC was considered to parallel a plant such that OFSP conditions could be satisfied. Moreover, this chapter clarified that it was reasonable to assume constant d as the direct term in this proposed scheme for non-linear system, and the constant d could be considered as a PFC. The stability statement was provided, and control parameters were adjusted based on the database such that desired performance could be attained. Additionally, only the input and output data were utilized in the proposed scheme without a mathematical model. A numerical simulation was shown to confirm the effectiveness of the proposed scheme. The response of the output was improved, and the tracking error was eliminated. Moreover, the better performance was maintained even though the system changed. The adaptive gains ultimately reached a constant value in the proposed scheme.

The future works are discussed in several aspects as follows.

The schemes presented in this thesis can be extended to a linear time-variant system as well as a multiple-input-multiple-output (MIMO) system. A crucial problem should be addressed, that is the use of right form of the Kalman-Yacubovitch-Popov (KYP) Lemma. The KYP Lemma has been recognized as a basic tool of stability proof in system theory, and it varies regarding to different system. This lemma and its applications have been investigated in lots of literatures [41, 80, 92, 93, 94, 95]. It should be careful to utilized the right form of the KYP Lemma to prove the stability issue in various systems.

This thesis provided a approach to optimize the parameter d based on stable adaptive output feedback control system. Once the control system is certain to be stabilized under certain conditions, various algorithms can be developed. Thus, this work can be extended in developing new algorithms that are practically implementable and applicable in real world.

Considering time-delay in the proposed schemes is still an open problem to be addressed. Time-delay occurs frequently in chemical, biological and mechanical systems. Therefore, it is of significant concern when one tries to apply the proposed scheme to practical plants with time-delay. The literatures [96, 97, 98] have investigated the case where one can design a stable adaptive output feedback based output tracking control system for single input single output system in continuous-time domain. Time-delay is handled in these literatures by considering the Pade approximation with relative degree zero. As a consequence, time-delay can be considered in the proposed schemes for discrete-time system. The relative degree of Pade approximation is zero, based on which the SPR conditions may not be hard to be satisfied.

The data-driven approach applied in adaptive output feedback system has been verified analytically through simulation. This work can be extended by adopting the proposed scheme into practical applications so as to contribute to control community.

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