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**System identification and control design of a
nonlinear Continuous Stirred Tank Reactor**

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Dedication

I humbly dedicate this work to my dear parents, who have been my pillars, my inspiration, and my motivation throughout this journey. To my father, for his unwavering support, and to the cherished memory of my mother, whose guidance, unconditional love, and endless patience continue to inspire me every day. May God protect and bless them both.

To Dr Menighed Kamel my advisor, whose wise advice, valuable guidance, and constant support have been invaluable in the development of this thesis.

To my brothers and sisters, who have been my confidants, companions, and best supporters. Your presence has been a constant comfort.

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To the entire Petrochemical Department, for the spirit of cooperation and solidarity that united us.

Finally, I dedicate this work to everyone who has loved and supported me, believed in me, and encouraged me. Your faith in me has been my greatest motivation, and I am infinitely grateful to you.

Abstract :

This project explores the application of adaptive control to a Continuous Stirred Tank Reactor (CSTR). A comprehensive MATLAB simulation model was developed to represent the reactor dynamics accurately. The adaptive control system, using the Recursive Least Squares (RLS) algorithm and an RST (Reference Signal Tracking) controller, was implemented to maintain the reactor's temperature at the desired setpoint. The system was tested under various conditions, including the introduction of disturbances and noise. The results demonstrated the robustness and resilience of the adaptive control strategy, maintaining stability and performance despite increased prediction error and parameter variability. This project highlights the effectiveness of adaptive control in managing CSTRs, making it a reliable solution for maintaining process stability in the presence of external disturbances.

Résumé :

Ce projet explore l'application du contrôle adaptatif à un réacteur à cuve agitée continue (CSTR). Un modèle de simulation complet sous MATLAB a été développé pour représenter avec précision la dynamique du réacteur. Le système de contrôle adaptatif, utilisant l'algorithme des moindres carrés récurrents (RLS) et un contrôleur RST (suivi du signal de référence), a été mis en œuvre pour maintenir la température du réacteur au point de consigne souhaité. Le système a été testé dans diverses conditions, y compris l'introduction de perturbations et de bruit. Les résultats ont démontré la robustesse et la résilience de la stratégie de contrôle adaptatif, maintenant la stabilité et la performance malgré l'augmentation de l'erreur de prédiction et la variabilité des paramètres. Ce projet met en évidence l'efficacité du contrôle adaptatif dans la gestion des réacteurs CSTR, en faisant une solution fiable pour maintenir la stabilité des processus en présence de perturbations externes.

ملخص :

يستعرض هذا المشروع تطبيق نظام التحكم التكيفي على مفاعل الخزان المستمر المزود بمقلب (CSTR). تم تطوير نموذج محاكاة شامل باستخدام برنامج MATLAB لتمثيل سلوك المفاعل بدقة عالية. تم تنفيذ نظام التحكم التكيفي باستخدام خوارزمية المربعات الصغرى التكرارية (RLS) ومتحكم RST (تتبع الإشارة المرجعية) للحفاظ على درجة حرارة المفاعل عند نقطة الضبط المحددة. جرى اختبار النظام تحت ظروف مختلفة، بما في ذلك إدخال اضطرابات وضوضاء. أظهرت النتائج فعالية ومتانة استراتيجية التحكم التكيفي، حيث تم الحفاظ على الاستقرار والأداء حتى مع زيادة خطأ التنبؤ وتغير المعلمات. يبرز هذا المشروع كفاءة التحكم التكيفي في إدارة مفاعلات CSTR، مما يجعله حلاً موثوقاً للحفاظ على استقرار العمليات في ظل وجود الاضطرابات الخارجية.

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General Introduction

General introduction

In recent years, automation has experienced significant growth. The development of control laws for systems has been the subject of numerous research works. As the systems to be controlled become increasingly complex, the control laws themselves become complex and sometimes difficult to implement.

In industries like petrochemicals, food processing, pharmaceuticals, and biochemistry, many processes are inherently nonlinear due to the dynamics of chemical reactions, thermodynamic relationships, and other factors. These complexities make these processes challenging to control effectively. One example is the continuously stirred tank reactor (CSTR), which not only exhibits highly nonlinear behavior but also operates at multiple points of operation, adding further complexity to its control. [1]

Using conventional fixed-parameter controllers such as PID controllers doesn't always yield the desired performance. Furthermore, these controllers operate within narrow operating points to avoid instability.

Our goal is twofold:

- Accurately identify the dynamic model of a nonlinear Continuous Stirred Tank Reactor (CSTR).
- Develop an adaptive control strategy tailored to the nonlinear characteristics of the CSTR.
- Evaluate the system's response to disturbances and noise through simulations.
- Demonstrate the effectiveness of adaptive control in improving the efficiency and stability of petrochemical operations.

To achieve this, we will utilize an adaptive controller known as the indirectly self-adjustable regulator. The principle behind these controllers is continuous updating of an

General introduction

identified model of the system being controlled (reactors), which is then used for regulator synthesis. As a result, our reactors maintain stable operation even when subjected to noise and disturbances.

Here's how this project is organized:

- The first chapter will provide a brief overview of the various types of chemical reactors, focusing on the presentation of the CSTR chemical reactor.
- In the second chapter, we will present the modeling of the CSTR chemical bioreactor, along with linearizing the obtained model around an operating point. Additionally, we will simulate it in open-loop manner .
- In the third chapter, we will explore the parametric estimation algorithm utilizing the recursive least squares method. This will be followed by an examination of the pole placement method (employing the RST controller) for its use in indirect adaptive control. Subsequently, we will apply these techniques to a continuous stirred-tank reactor (CSTR).
- In the fourth and last chapter, we will present our simulation results along with their interpretation. We will analyze the data and discuss the implications of the findings. This chapter will conclude our study by providing insights based on the simulations.

Chapter 1 : Overview of Chemical Reactors

1.1.Introduction

Chemical engineering can be seen as the engineering discipline dedicated to the optimal execution of physicochemical and/or biological processes for converting raw materials into functional products. A significant aspect of chemical engineering is reaction engineering, focusing on the rational implementation methods of chemical transformations, especially within the apparatus where reactions occur: chemical reactors.

In this chapter, we will explore the realm of chemical reactors. Our discussion will begin with a concise introduction to chemical reactors, their classification criteria, and various types. Subsequently, we will outline the primary characteristics of a well-agitated reactor.

1.2.Description of a process from the automation engineer's point of view

From an automation perspective, describing a process involves detailing its operational aspects, control requirements, and instrumentation. Automaticians focus on designing, implementing, and optimizing control systems for processes. This includes: [2]

- **Process Overview:** Understanding the process flow, inputs, outputs, and key variables.
- **Instrumentation:** Identifying sensors and actuators used to measure and control process variables.
- **Control Strategy:** Developing a control strategy that defines how the system will respond to changes and disturbances.
- **Control System Design:** Designing and implementing controllers (such as PID controllers) to regulate process variables.

- Safety Systems: Implementing safety measures and emergency shutdown systems to prevent accidents.
- Data Acquisition: Setting up data acquisition systems to collect real-time data for monitoring and analysis.
- Optimization: Continuously optimizing the control system to improve efficiency, stability, and performance.
- Human-Machine Interface (HMI): Creating interfaces for operators to monitor the process, set parameters, and respond to alarms.

In essence, automaticians play a crucial role in ensuring that processes run smoothly, efficiently, and safely through the design and implementation of automated control systems.

1.3. Definition of a chemical reactor

A chemical reactor is a device designed to facilitate a chemical reaction, transforming molecular species into other chemical species with the purpose of producing one or more specific chemical compounds or removing one or more compounds from a mixture. This definition excludes systems that perform chemical reactions for other purposes, such as energy production. [3]

1.4. Uses of chemical reactors

Chemical reactors serve as the central components in chemical manufacturing units, found across refineries, metallurgical complexes, chemical plants, and related industries. Within these industrial settings, reactors are typically surrounded by equipment placed upstream and downstream, facilitating the physical treatment of raw materials and reaction products. Furthermore, pollution control installations often incorporate additional reactors designed for chemically purifying various influents.

In today's diverse landscape of chemical manufacturing facilities, observers focus on pinpointing the specific equipment where chemical transformations occur. The wide range of shapes and sizes of these apparatuses ranging from furnaces, boilers, tanks, columns, balloons, mixers, rotary kilns, blast furnaces, to simple tubes may lead some to believe that attempting to classify chemical reactors is futile, as each encountered piece of equipment appears to represent a unique case.

However, all these devices share a common objective: to facilitate chemical transformations. By referring to the fundamental characteristics of a chemical reaction, we can establish several criteria for classifying these reactors.

1.5. Criteria for classification of chemical reactors [3]

The classification of chemical reactors is based on criteria defined among all these characteristics; we will primarily focus on the nature of the phases present, followed by the operating mode.

1.5.1. Number of phases present

- Single-phase systems: The reaction medium can either be a gas phase (for example, ethylene chlorination, steam cracking) or a liquid phase (for example, ethyl acetate from $\text{CH}_3\text{COOH} + \text{C}_2\text{H}_5\text{OH}$).
- Poly-phasic or heterogeneous systems: These are typically made up of the following combinations:
 - ✓ Liquid-liquid mixture (like sulfonation or nitration of aromatics)
 - ✓ Gas-liquid system (such as oxidation, hydrogenation, or chlorination of an organic reagent in a liquid phase)
 - ✓ Gas-solid system (for instance, coal combustion or pyrite roasting)

- ✓ Gas-solid system (catalyst) (such as NH₃ synthesis)
- ✓ Gas-liquid-solid system (like the Fischer-Tropsch reaction, coal liquefaction, or hydrodesulfurization of a petroleum cut).

1.5.2. Operating mode [2]

This criterion is determined by the practical needs of operating the chemical process. We distinguish between two distinct operating modes.

- Continuous operation: Equipment operating continuously, referred to as open systems, have one or more inputs for introducing reactants, as well as one or more outputs for removing reaction products. Thus, the two operating modes described above differ in that the discontinuous system operates in a non-stationary manner, whereas the continuous system is designed to operate in a steady-state regime.
- Discontinuous operation: These devices are sometimes referred to as closed systems because during the reaction period, there is no flow of material entering or leaving the system. This type of equipment is often favored by industry for operations considered delicate or for small-scale production.
- Semi-continuous operation: In some polyphasic systems, semi-continuous regimes are observed. An operation is considered semi-continuous when there is periodic loading of raw materials and periodic emptying of the equipment, but there is also continuous removal of a product or by-product, allowing for the addition of new quantities of raw materials over an extended period. The reactor in semi-continuous mode is primarily distinguished from the discontinuous mode by its auxiliary equipment. [3]

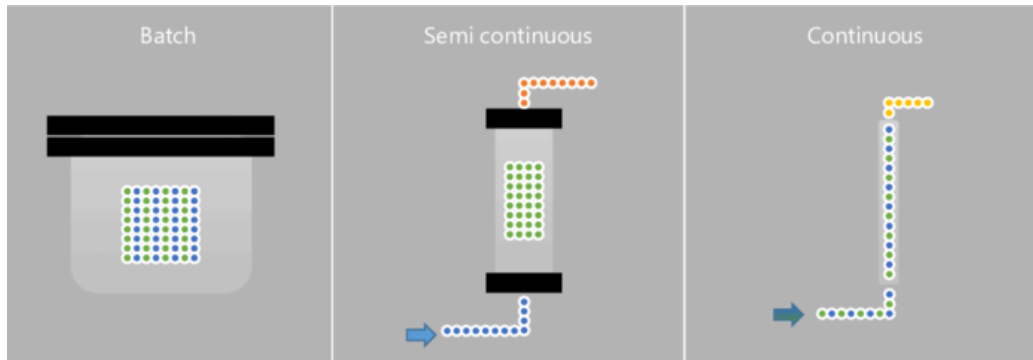


Figure 1.1 : Diagram of the different types of reactors

1.5.3. *In geometry*

Two main categories of reactors are distinguished:

- **Stirred Tank Reactor:** this is a vessel where a fluid is agitated using a mechanical system consisting of a rotating shaft supporting an agitator. Stirred tank reactors are operated in both continuous and batch modes.
- **Tubular Reactor:** this is simply a pipeline, typically quite long (up to several tens of meters). By nature, it is operated in continuous mode.

1.5.4. *In thermal regime*

- **Isothermal Reactor:** is achieved when using a perfectly stirred continuous reactor in steady-state operation, although it represents an ideal limit when considering a tubular reactor type. Again, assimilating a practical case to an ideal and isothermal tubular reactor can sometimes be an acceptable approximation.
- **Non-Isothermal Reactor:** corresponds to a variable operating temperature over time. It is used in the case of starting up a continuous stirred reactor and in the case of a batch stirred reactor.

- Adiabatic Reactor: on the other hand, simply represents a special case of the general case corresponding to zero heat exchange.

1.6. Application areas of chemical reactors

The majority of industrial reactors operate continuously instead of in batch mode because continuous reactors yield more products using lighter equipment, requiring less labor and maintenance, and often delivering superior quality control. Although starting and stopping continuous processes is more complex than with batch reactors, they generate products without interruption for batch changes and require minimal labor.

Batch processes can be adapted to produce small product quantities when necessary. They are also beneficial for measuring rates and kinetics to model continuous processes: obtaining information quickly without generating multiple discarded products. In pharmaceuticals, batch processes are sometimes preferred for quality control: each batch can be analyzed and certified or rejected, unlike continuous processes where contamination inevitably leads to numerous discarded products before purity can be restored. Food and beverage production often relies on batch processes due to the unpredictable nature of biological reactions.

1.7. Types of ideal reactors

Based on the criteria mentioned, the various reactors encountered in practice can be classified according to two main characteristics: the nature of the phases involved and the operating mode of the reactor. [3]

1.7.1. Tubular plug flow reactor

The plug flow reactor serves as an ideal model for the real tubular reactor, where the reactive mixture moves in parallel slices.

1.7.2. Uniform closed reactor

This apparatus involves introducing the reactants at the beginning of the operation; once they are brought to the required temperature and pressure, the reaction proceeds until the desired conversion rate is achieved.

1.7.3. *Perfectly stirred continuous reactor*

Such a reactor (figure 1.2) essentially consists of a tank equipped with an agitation system, a feeding tube, and a withdrawal tube. The operation of a perfectly stirred reactor is straightforward; it is assumed that at every point in such equipment, intensive variables such as concentration or temperature have the same value.

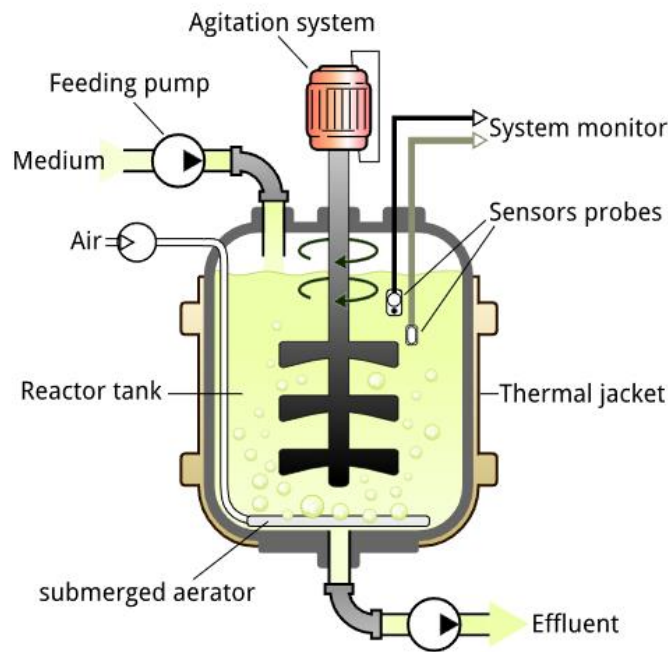


Figure 1.2 : Continuous stirred chemical reactor.

There are three types of perfectly stirred reactors defined as follows :

- Non-Isothermal Perfectly Stirred Continuous Reactor

In this mode, temperature changes over time, typically during reactor startup or when operating near an unstable point. To avoid unusual operation, such reactors require heat exchange surfaces and temperature regulation systems. [3]

- Isothermal Perfectly Stirred Continuous Reactor

This describes steady-state reactor operation where temperature and other variables remain constant.

- Adiabatic Perfectly Stirred Reactor

An adiabatic reactor operates without exchanging heat with the surroundings, as seen in adiabatic reactions.

1.7.4. Catalytic reactors (multiphase)

Catalytic reactors are the most prevalent among multiphase reactors. They stand out due to their heating mode, operating mode (continuous, periodic, cyclic), the catalyst's nature (solid, liquid), and the catalyst's recovery or regeneration method. In this study, our focus is solely on examining the perfectly stirred reactor among the various reactors mentioned.

1.8. Perfectly stirred continuous reactor

The model proposed (Figure 1.3) consists of a cooling system in the form of a coil that carries the coolant liquid with a flow rate q_c at an inlet temperature T_{c0} . It is worth noting that inside the reactor, an exothermic chemical reaction takes place (which releases energy in the form of heat).



Figure 1.3 : Perfectly stirred CSTR reactor

In mechanical settings, superbly mixed reactors are direct round and hollow holders fitted with an compelling inner tumult instrument, along side gulf and outlet tubes for presenting and evacuating the response blend containing the items of the response. These reactors are characterized by a uniform composition and momentary state of the response blend all through their volume. This basis is met when the included reactants are blended momentarily. [4]

In this reactor type, the reaction mixture is either stirred by external circulation or mechanical agitation methods :

- External circulation agitation: Mixing the reactants with the reaction medium is achieved through external circulation using a pump.
- Mechanical agitation: The cylindrical tank is equipped with a rotating agitator, typically with a vertical motor axis introduced from the top. This rotating agitator, driven by a motor through a shaft, imparts a rotational movement to an agitating

element that stirs the fluid. The agitators vary based on the shape of the agitating element, which must be tailored to each specific case.

1.9.Characteristics of the CSTR chemical reactor

The characteristics of a Continuous Stirred Tank Reactor (CSTR) in chemical engineering include: [3]

- **Operational Flexibility:** CSTRs can operate across a wide range of temperatures and pressures, making them versatile for various reaction conditions.
- **Self-Thermal Regulation:** They offer self-thermal regulation benefits where the heat produced by the reaction can be directly utilized without the need for external heat exchange.
- **Uniformity:** CSTRs provide uniform temperature and concentration throughout the reaction volume, ensuring consistent reaction conditions.
- **Suitability for Liquid-Phase Reactions:** They are well-suited for liquid-phase reactions, especially those with moderate to low reaction rates.
- **Residence Time Control:** The reaction time in a CSTR is controlled by the residence time of the reaction mixture within the reactor, typically falling within a manageable range.
- **Mixing Efficiency:** CSTRs ensure efficient mixing of reactants and products due to continuous stirring, promoting effective mass transfer and reaction kinetics.
- **Scalability:** They are scalable for both laboratory and industrial applications, allowing for easy adaptation to different production scales.

- Process Control: CSTRs are amenable to process control strategies, facilitating precise control of reaction parameters such as temperature, pressure, and feed rates.

These characteristics collectively make CSTRs a widely used and versatile choice in chemical processing industries for various types of chemical reactions.

1.10. Uses of the CSTR chemical reactor

The Continuous Stirred Tank Reactor (CSTR) is used in chemical engineering for homogeneous reactions, biological processes, continuous production, gas-liquid reactions, process development, and research/education purposes. It's valued for its versatility, efficiency, and scalability in a wide range of chemical processes.

1.11. Conclusion

This chapter provides the different types of chemical reactors and their classification criteria. Indeed, these criteria define several categories of ideal reactors used to model the behavior of real reactors. The perfectly stirred reactor, which is the focus of our study, has been introduced. This understanding will facilitate modeling the reactor and establishing control laws for improved management.

Chapter 2 : Modeling of CSTR system

2.1.Introduction

Understanding and effectively managing dynamic systems is essential for optimizing industrial processes, particularly in the complex realm of petrochemical operations. This chapter delves into the critical aspects of modeling and controlling these dynamic systems, which are pivotal for ensuring smooth process operation and achieving desired outcomes.

The chapter begins by laying down fundamental concepts related to modeling and control within systems. It explores the diverse forms and types of models used, tailored to the specific behaviors exhibited by different processes within the industry.

A focal point of this chapter is the detailed exploration of modeling a perfectly stirred reactor. Through a comprehensive breakdown of the reactor's characteristics and behavior, readers will gain insights into the intricacies of creating mathematical models that accurately represent real-world processes. Specifically, the chapter will introduce the mathematical model of the reactor without control, setting the stage for deeper discussions on control strategies in subsequent sections.

By delving into these topics, this chapter aims to equip professionals and researchers in the petrochemical industry with the knowledge and tools necessary to effectively model and control dynamic systems, thereby enhancing process efficiency and overall operational performance.

2.2.Interest in modeling and simulation

The value of modeling and simulation lies in exploring processes through their mathematical representations. Creating a mathematical model not only deepens our understanding of a system but also encourages questioning that drives progress in grasping the underlying phenomena. Models play a crucial educational role in this regard.

Having a mathematical model of a specific unit operation enables the calculation of parameters that are challenging to measure directly or are inaccessible. This ability also allows for extrapolation, facilitating the testing of extreme operating conditions that may be impractical or impossible to implement in real-world settings. Furthermore, models can be utilized in equipment design and ensuring process safety, enhancing their practical utility across various aspects of industrial operations. [5]

2.3. Open-loop CSTR reactor modeling

The reactor we're investigating is designed to operate under ideal conditions, where we assume everything from fluid dynamics to physical properties align perfectly. This type of reactor serves as a simplified representation of real-world industrial reactors and forms the backbone of our modeling approach.

Before we delve into the mathematical intricacies of the reactor model, it's important to paint a clear picture of how this reactor operates within our system. This description lays the groundwork for understanding its behavior and the key variables influencing its performance in our simulations. [6]

2.4. Process Description

The process under consideration involves a continuously stirred tank reactor (CSTR) with dual cooling jackets for temperature control. Within this reactor, an irreversible and exothermic first-order chemical reaction occurs, converting substance A into substance B at a specific reaction rate.

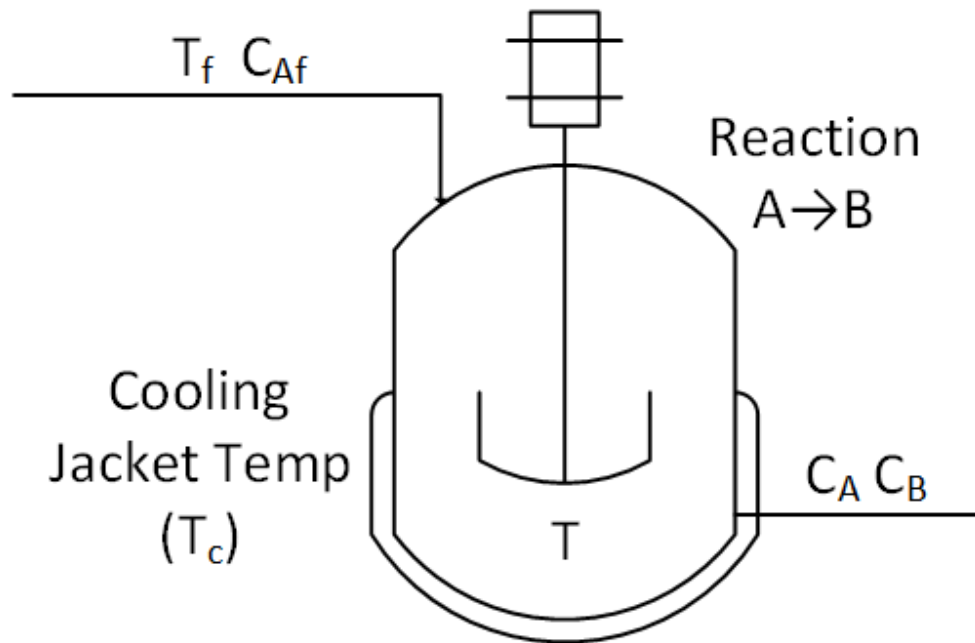


Figure 2.1 : Continuous stirred-tank reactor with cooling in the jacket

This continuous stirred-tank chemical reactor operates with an exothermic reaction of first order, converting A into B and releasing heat ΔH . Reactant A enters the reactor continuously at a consistent flow rate q , maintaining an initial concentration C_{A0} and temperature T_0 .

Inside the reactor, a motorized agitator ensures thorough mixing of the reactor contents. A continuous output stream containing a mixture of reactant A and product B is then withdrawn from the reactor at the same flow rate q , with compositions C_A and C_B , and temperature T .

To manage the heat produced by the exothermic reaction, the reactor is enclosed in a double jacket, featuring a heat exchange area A and constant volume V . This jacket circulates a cooling fluid, typically water, at a variable flow rate q_j and a constant inlet temperature T_{C0} .

Our study adopts reactor parameters and operating conditions in line with Luyben's specifications. With this detailed reactor description, our focus now shifts to developing its mathematical model. [7] [8]

2.5. Nonlinear mathematical model of CSTR

The mathematical framework we're constructing integrates differential terms that encapsulate the reactor's dynamic responses.

This model acts as a dynamic monitor, tracing the evolution of reactor variables such as concentrations, reaction volume, and temperature over time, under the influence of operating conditions and reaction kinetics. The set of equations governing the perfectly stirred reactor's balances represents a nonlinear system of differentials, illustrating how five essential parameters change with time:

- the concentration of reactant A (C_a)
- reactor temperature (T)
- double jacket temperature (T_j)
- the volume of the reaction mixture (v).

To depict the dynamic behavior of a reactor (CSTR), the initial step involves establishing mass and energy balances : [8]

- Mass balance:

$$\frac{dC_a}{dt} = \frac{q}{v} (C_{a0} - C_a(t)) - k_0 C_a(t) \exp\left(\frac{-E}{RT(t)}\right) \quad (2.1)$$

- Energy balance:

$$\frac{dT}{dt} = \frac{q}{v} (T_0 - T(t)) - k_1 C_a(t) \exp\left(\frac{-E}{RT(t)}\right) + k_2 q_c(t) \left(1 - \exp\left(\frac{-k_3}{q_c(t)}\right)\right) (T_{c0} - T(t)) \quad (2.2)$$

$$\text{With : } k_1 = \frac{\Delta H k_0}{\rho C_p}, k_2 = \frac{\rho_c C_{pc}}{\rho C_p v}, k_3 = \frac{h_A}{\rho_c C_{pc}}$$

2.6.Characteristics of the chemical reactor (CSTR)

The parameters of this reactor are represented in the following table:

Symbols	Setting	Values
C_{A0}	Concentration of A	1 mol/l
q_c	Process Flow Rate	100 l/min
T_0	Supply temperature	350 K
T_{c0}	Refrigerant inlet temperature	350 K
v	Reactor volume	100 l
h_A	Heat transfer coefficient	$7.5 * 10^5 \text{ cal}/(\text{min K})$
k_0	Exponential factor	$7.2 * 10^{10} \text{ min}^{-1}$
E/R	Activation energy	10000 K
ΔH	The heat of the reaction	$2e5 \text{ cal /mol}$
ρ, ρ_c	Liquid densities	$1 * 10^3 \text{ g /l}$
C_p, C_{pc}	Specific heats	$1 \text{ cal /}(gK)$

Table 2.1 : Summary of the CSTR parameters reactor

2.7.State representation of the CSTR

The state, input and output variables of the CSTR are represented as follows:

$$x(t) = [x_1(t), x_2(t)]^T = [C_a(t), T(t)]^T, u(t) = q_c(t), y(t) = C_a(t)$$

The equations (2.1) and (2.2) can be written as follows: [9]

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t)) \\ &= \begin{bmatrix} 1 - x_1(t) - k_0 x_1(t) \exp\left(\frac{-10^4}{x_2(t)}\right) \\ 350 - x_2(t) - k_1 x_1(t) \exp\left(\frac{-10^4}{x_2(t)}\right) + k_2 u(t) \left(1 - \exp\left(\frac{-k_3}{u(t)}\right)\right) (350 - x_2(t)) \end{bmatrix} \\ y(t) &= h(x(t)) = x_1(t) \end{aligned} \quad (2.3)$$

It can be noted that the model is not in affine form because the control variable $u(t)$ does not appear linearly in equation (2.3).

2.8.CSTR simulation in open loop

We consider q_c and $C_a(t)$ as the input and output of the CSTR system, respectively. The simulation of the open-loop system in Matlab/Simulink, with the initial conditions:

$$q_{c-init} = 97 \text{ l/min}, C_{a-init} = 0.1 \text{ mol/l}, T = 443.31 \text{ K}$$

At steady state, we have $\frac{dC_a}{dt} = 0$ and $\frac{dT}{dt} = 0$, so the equations (2.1) and (2.2) become: [10]

$$\frac{q}{V} (C_{A0} - C_A) - K_0 C_A \exp\left(\frac{E}{RT}\right) = 0 \quad (2.4)$$

$$\frac{q}{V}(T_0 - T) - \left(\frac{\Delta H}{\rho C_p}\right) K_0 C_p \exp\left(\frac{-E}{RT}\right) + \left(\frac{\rho_c C_{pc}}{\rho C_p V}\right) q_c \left[1 - \exp\left(\frac{-hA}{q_c \rho_c C_{pc}}\right)\right] (T_{C0} - T) = 0 \quad (2.5)$$

For our simulation, we will use excitation values :

$$q_c = 97 \text{ l/min}$$

$$C_a = 0.09 \text{ mol/l}$$

$$T = 443.31 \text{ K}$$

The response of the open loop system is given as follows:

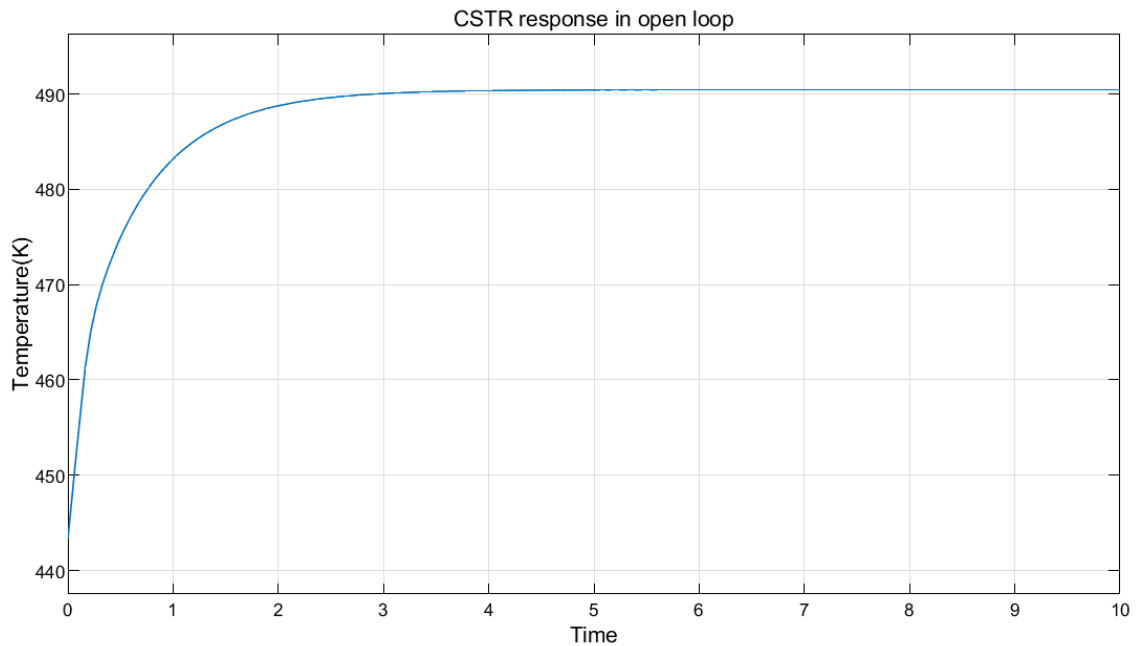


Figure 2.2 : CSTR response in open loop (temperature rate)

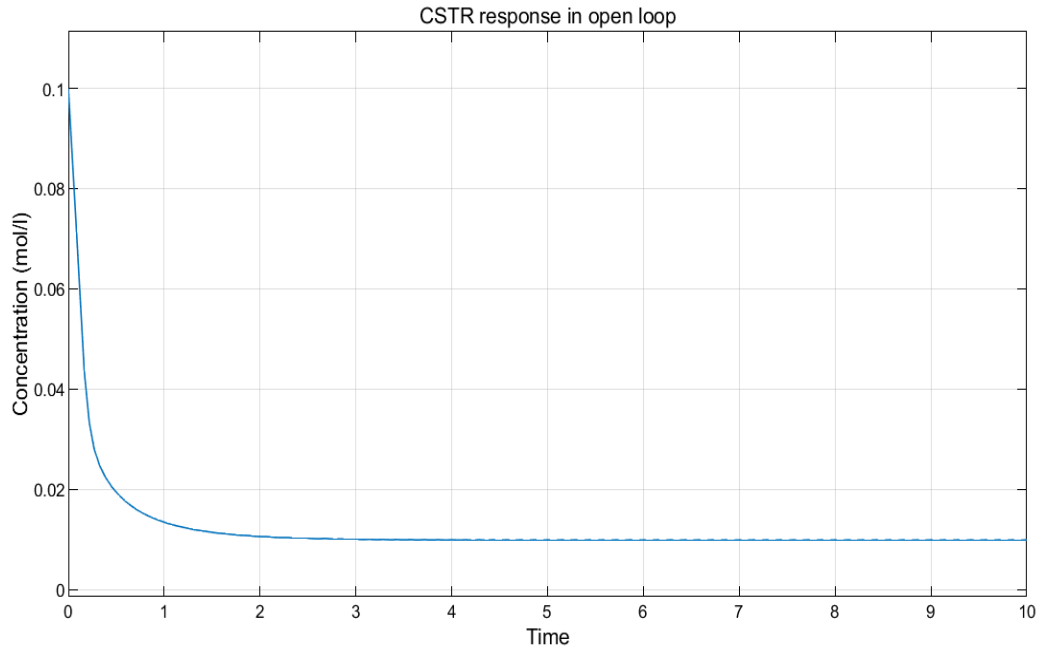


Figure 2.3 : CSTR response in open loop (concentration rate)

2.9. Linearization of the nonlinear CSTR model

Nonlinear equations are linearized and converted to state variable form as follows:

$$\begin{cases} \dot{x}(t) = A x(t) + B u(t) \\ y(t) = C x(t) + D u(t) \end{cases} \quad (2.6)$$

The matrices A and B correspond to the Jacobian matrices at the nominal values of the state and input variables, while x , u , and y denote the deviation variables. The output matrix is denoted by C . [11]

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} C_A - C_{AS} \\ T - T_S \end{bmatrix} \quad (2.7)$$

- C_{AS} : Balance values of concentration in A
- T_S : reactor temperature

The Jacobean matrix A is given by:

$$A = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} \end{pmatrix} \quad (2.8)$$

Where :

$$A_{11} = -\frac{q}{v} - K_0 \exp\left(-\frac{E}{RT_s}\right) \quad (2.9)$$

$$A_{12} = -C_{AS} K_0 \exp\left(-\frac{E}{RT_s}\right) \quad (2.10)$$

$$A_{21} = -\left(\frac{\Delta H}{\rho C_p}\right) K_0 \exp\left(-\frac{E}{RT_s}\right) \quad (2.11)$$

$$A_{22} = -\frac{q}{v} - \frac{UA}{V_p C_p} K_0 \exp\left(-\frac{E}{RT}\right) * \left(\frac{E}{RT^2}\right) C_A \quad (2.12)$$

So, the system's state matrix is:

$$A = \begin{pmatrix} -\frac{q}{v} - K_0 \exp\left(-\frac{E}{RT_s}\right) & -K_0 \exp\left(-\frac{E}{RT}\right) * \left(\frac{E}{RT^2}\right) C_A \\ -\left(\frac{\Delta H}{\rho C_p}\right) K_0 \exp\left(-\frac{E}{RT_s}\right) & -\frac{q}{v} - \frac{UA}{V_p C_p} K_0 \exp\left(-\frac{E}{RT}\right) * \left(\frac{E}{RT^2}\right) C_A \end{pmatrix} \quad (2.13)$$

The Jacobean matrix B is given by:

$$B = \begin{pmatrix} B_{11} \\ B_{21} \end{pmatrix} = \begin{pmatrix} \frac{\partial f_1}{\partial u_1} \\ \frac{\partial f_2}{\partial u_1} \end{pmatrix} \quad (2.14)$$

Where :

$$B_{11} = \frac{\partial f_1}{\partial u_1} = \frac{\partial f_1}{\partial T_j} = 0 \quad (2.15)$$

$$B_{21} = \frac{\partial f_2}{\partial u_1} = \frac{\partial f_2}{\partial q} = \frac{UA}{V_p C_p} \quad (2.16)$$

Using the previously noted parameters in Table 2.1 and the resulting values :

$$T = 441.1475 \text{ K}, q_c = 98 \text{ l/min}, C_A = 0.09 \text{ mol/l}$$

we obtain:

$$A = \begin{pmatrix} -21.53 & -9.4030 \\ 1 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$C = (1.5030 \quad 18.26)$$

$$D = 0$$

Using this state space representation we can get our second order transfer function:

$$G(s) = \frac{1.503 s + 18.26}{s^2 + 21.53 s + 9.403} \quad (2.17)$$

Because the discrete-time transfer function is necessary for our adaptive control, we obtained the following function with a sample time of 0.2 seconds :

$$G(z) = \frac{0.1935 z^{-1} - 0.03022 z^{-2}}{1 - 0.9294 z^{-1} + 0.01349 z^{-2}} \quad (2.18)$$

Using those results we can build a model in Matlab/Simulink that can give us the step response of our CSTR in linear state :

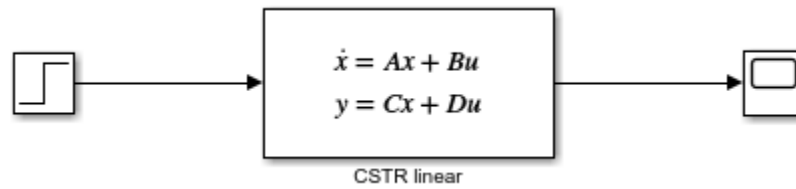


Figure 2.4 : CSTR linear model implemented Matlab/Simulink

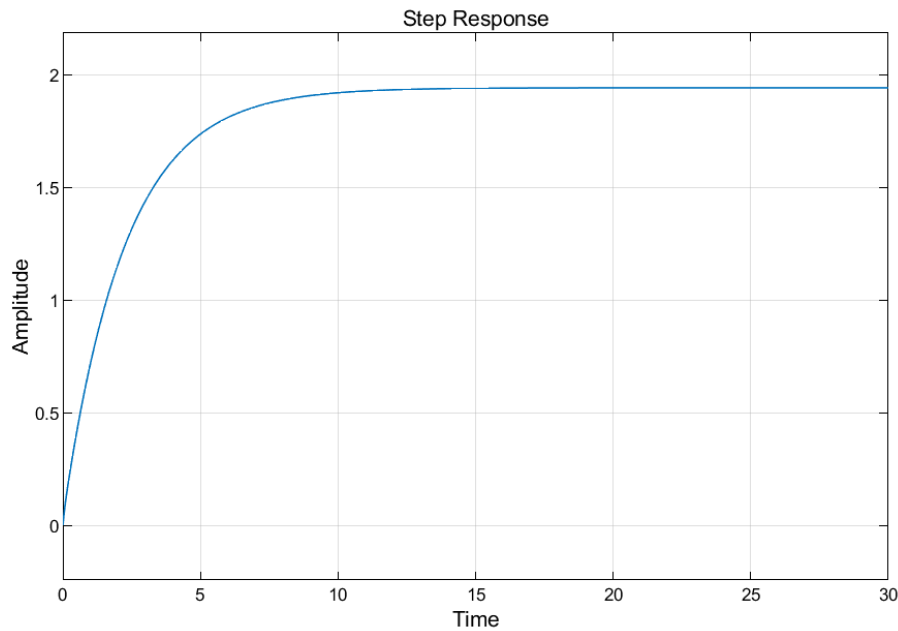


Figure 2.5 : The transfer function index response obtained by linearization

The final value that this function converges to differs from the target value; the discrepancy between the target value and the final result manifests as a static error.

To ensure zero steady-state error and minimize the time required for the transition from the transient state to the steady state while maintaining system stability, control techniques that can deliver the desired performance must be used.

2.10. Conclusion

This chapter focuses on applying core chemical engineering concepts to model a Continuous Stirred Tank Reactor (CSTR) using nonlinear state equations. These equations have been linearized around a stable equilibrium to simplify the analysis. The open-loop simulation of the CSTR indicates a clear need for implementing control measures to effectively follow set points and control the transient behavior. Upcoming chapters will explore a variety of control strategies, tailored to address the critical attributes of the system under review.

Chapter 3 : Adaptive Control

3.1.Introduction

Adaptive control represents a significant advancement in the field of control systems, offering a robust solution for managing complex, dynamic, and nonlinear processes. Unlike traditional controllers with fixed parameters, adaptive controllers possess the unique ability to adjust their parameters in real-time, responding to changes in system dynamics and external conditions. This adaptability ensures optimal performance even in the face of uncertainties and variability, which are common in industrial environments.

The necessity for adaptive control arises from the limitations of conventional control strategies, which often struggle to maintain desired performance levels when confronted with processes that exhibit time-varying behaviors or nonlinear characteristics. By continuously monitoring system outputs and making necessary adjustments, adaptive controllers can maintain stability, improve accuracy, and enhance overall efficiency. [5]

In this chapter, we will explore the principles of adaptive control, examining its theoretical foundations, practical implementations, and diverse applications. We will delve into various adaptive control techniques, such as model reference adaptive control (MRAC) and self-tuning regulators (STR), highlighting their strengths and limitations. Through this exploration, we aim to provide a comprehensive understanding of how adaptive control can be effectively employed to meet the stringent performance requirements of modern industrial processes.

There is 2 different types of adaptive control :

- **Direct Adaptive Control** involves adjusting the controller parameters directly based on the observed error between the system output and the desired output. This method does not explicitly identify the system parameters but focuses on updating the control law directly to achieve the desired performance.

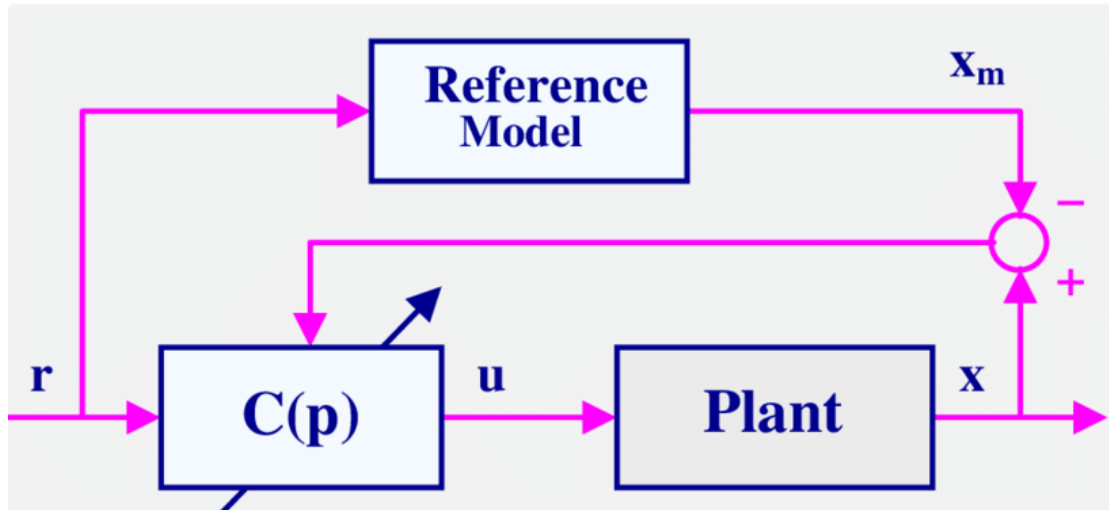


Figure 3.1 : Block diagram of the direct Adaptive control

- **Indirect Adaptive Control** involves two main steps: first, it identifies or estimates the parameters of the system model in real-time, and then it uses these estimated parameters to adjust the controller parameters. This method relies on continuously updating the system model and then adapting the control law based on this model.

In this chapter, we present the study and implementation of an indirect adaptive control system. Specifically, we focus on the development of an indirect self-tuning regulator.

In indirect adaptive control, the controller parameters are updated based on an estimated model of the system. Several models can be used for this purpose, each with its own characteristics and applications. Here are some of the different models commonly used in indirect adaptive control:

- **ARX (AutoRegressive with eXogenous inputs) Model:** Simple and easy to estimate. Suitable for systems where the relationship between input and output is straightforward and noise can be assumed to be white (uncorrelated).

- **ARMAX (AutoRegressive Moving Average with eXogenous inputs) Model:** More flexible than ARX, as it can handle systems with colored (correlated) noise. Provides a better fit for real-world data where noise is often not white.
- **ARIMAX (AutoRegressive Integrated Moving Average with eXogenous inputs) Model:** Suitable for systems where the data shows trends or other forms of non-stationarity that can be addressed through differencing
- **BJ (Box-Jenkins) Model:** Separates the dynamics of the system and the noise model. Provides a comprehensive modeling approach suitable for complex systems with significant noise dynamics.
- **NARX (Nonlinear AutoRegressive with eXogenous inputs) Model:** Extends the ARX model to handle nonlinear relationships between inputs and outputs. Suitable for systems with significant nonlinear dynamics.
- **State-Space Models:** Provides a comprehensive framework for modeling and control, especially for multi-input multi-output (MIMO) systems. Can handle both linear and nonlinear dynamics.

In our project on adaptive control for a Continuous Stirred Tank Reactor (CSTR), the ARX (AutoRegressive with eXogenous inputs) model was chosen due to its simplicity, computational efficiency, and suitability for linear approximations of the system dynamics. The ARX model allows for straightforward parameter estimation using the Recursive Least Squares (RLS) algorithm, enabling real-time adaptation essential for managing disturbances and process changes. Its ease of implementation and integration with tools like MATLAB and Simulink makes it a practical choice, ensuring effective and efficient control of the CSTR, maintaining stability and optimal performance.

3.2. Structure of indirect self-adjusting regulators

The block diagram shown in Figure 3.2 outlines how these regulators operate. It includes two loops:

- The primary loop, which represents the conventional control loop.
- An additional loop overlaid on the primary one, comprising a process identification block and a regulator parameter calculation block.

The closed-loop adaptive controller can be viewed as a combination of two algorithms:

- the first is the one used for identification in the closed-loop of the model parameters using a parameter adaptive algorithm. (Process identification)
- the second is used for online adjustment of the controller coefficients at each sampling time by using minimum-degree pole placement method (Updating controller settings)

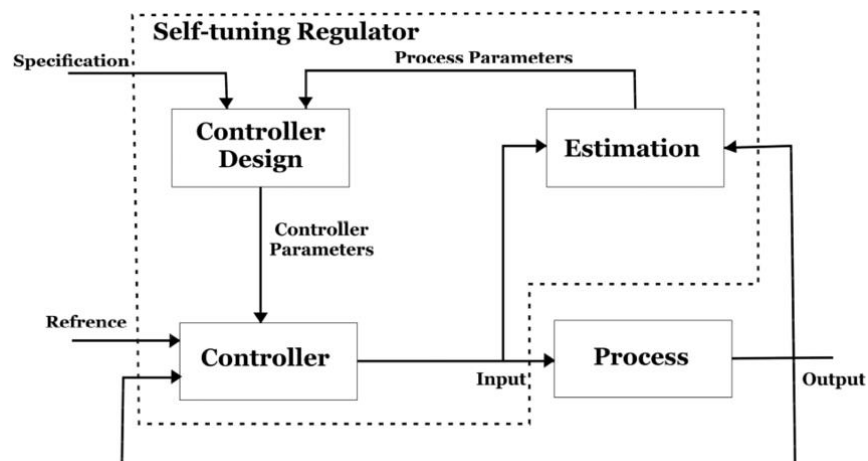


Figure 3.2 : Block diagram of the Indirect Self-Adjusting regulator

Once the process parameters have been identified, they are then passed to the regulator parameter calculation block. Based on the received parameters and specifications

outlined in the requirements (such as speed, damping, etc.), this block automatically updates the new regulator parameters and sends them back, enabling an update of the regulator. This cycle repeats throughout the operation of the control loop.

3.3. Process identification

Process identification refers to the technique or process of determining the mathematical model or parameters that describe the behavior of a dynamic system. This involves analyzing input-output data from the system to extract information about its dynamics, characteristics, and response to stimuli. Process identification aims to create a model that accurately represents the system's behavior under different conditions, allowing for better control and prediction of its performance. This technique is commonly used in control engineering, system analysis, and optimization to improve system understanding and design more effective control strategies. [12]

Many effective identification algorithms with suitable recursive formulations have been developed. The principle of estimating parameters for sampled models is illustrated in Figure (3.2), where command and response represent, respectively, the input and output of the system .

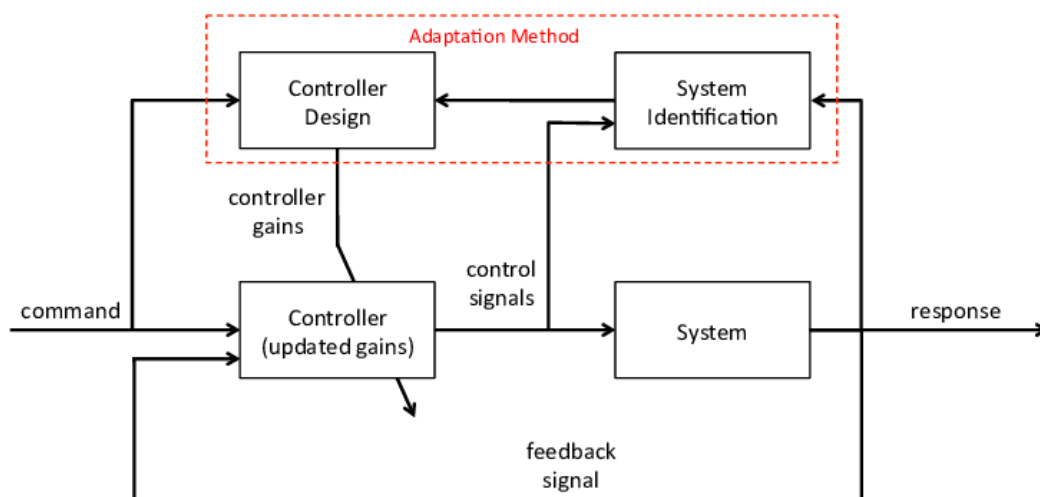


Figure 3.3 : principle of pattern identification

An algorithm called parametric adaptation (AAP) adjusts model parameters during each sampling step to minimize errors. This algorithm operates in a recursive manner, where the new parameter estimate is derived from the previous estimate plus a correction term based on recent measurements. In essence, the AAP structure is defined as follows:

$$\begin{aligned} & \text{(Updated parameter estimate)} = \text{(Previous estimate)} + \text{(Adaptation gain)} \\ & * \text{(Measurement function)} * \text{(Prediction error function)} \end{aligned}$$

Recursive identification offers the advantage of continuously improving model estimations as the process progresses.

3.3.1. Process model

We assume that the system is represented by a sampled model with one input and one output. The system's input will be denoted by $u(k)$ and the system's output by $y(k)$.

$$\frac{B(Z^{-1})}{A(Z^{-1})} = \frac{y(k)}{u(k)} \quad (3.1)$$

where :

$$A(Z^{-1}) = 1 + a_1 z^{-1} + \dots + a_n z^{-n}$$

$$B(Z^{-1}) = b_0 + b_1 z^{-1} + \dots + b_m z^{-m}$$

3.3.2. Recursive Least Squares algorithm (RLS)

RLS algorithm is a powerful method used for parameter estimation in adaptive control and signal processing. It is particularly well-suited for systems where parameters change over time. The RLS algorithm updates estimates of parameters recursively as new data becomes available, providing an efficient way to track these changes in real-time.

There are various types of RLS algorithms:

- Standard RLS
- Exponentially Weighted RLS (EW-RLS)
- Sliding Window RLS (SW-RLS)
- Constrained RLS (CRLS)
- Adaptive Forgetting Factor RLS
- Extended RLS (ERLS)
- Fast RLS
- Regularized RLS

In our project, we used the Exponentially Weighted RLS (EW-RLS) method. Here are the reasons why this choice is appropriate:

- **Adaptability to Time-Varying Systems:** The EW-RLS method includes a forgetting factor, which allows the algorithm to give more weight to recent data and less to older data. This feature makes it suitable for systems like the CSTR where process dynamics can change over time.
- **Real-Time Parameter Estimation:** EW-RLS can efficiently update parameter estimates in real-time, which is crucial for adaptive control applications where timely adjustments are needed to maintain optimal performance.
- **Balancing Responsiveness and Stability:** By adjusting the forgetting factor, the EW-RLS method provides a good balance between being responsive to changes and maintaining stability in the parameter estimates.

Our model is governed by equation (3.1), which in the time domain takes the form

$$y(k) = -\sum_{i=1}^n a_i y(k-i) + \sum_{i=0}^m b_i u(k-d-i) \quad (3.2)$$

$$y(k) = \varphi^T(k-1)\vartheta(k)$$

where :

$$\varphi(k-1) = [-y(k-1) - y(k-2) - \dots - y(k-n), u(k-d) + \dots + u(k-d-m)]^T$$

$$\vartheta(k) = [a_0, a_1, a_2, \dots, a_n, b_0, b_1, b_2, \dots, b_m]^T$$

φ : regression vector

ϑ : vector of parameters

$$N_k(\vartheta) = \frac{1}{2} \sum_{i=1}^k [y(i) - \vartheta^T(i)\varphi(i-1)]^2 \quad (3.3)$$

The minimum criterion to minimize N is obtained by playing with parameters that cancel out its derivative in the parametric space, such as $\frac{dN_k(\vartheta)}{d\vartheta} = 0$

We get :

$$\vartheta(k) = [\sum_{i=1}^k \varphi(i-1)\varphi(i-1)^T]^{-1} [\sum_{i=1}^k \varphi(i-1)y(i)] \quad (3.4)$$

$$= P(k) \sum_{i=1}^k \varphi(i-1)y(i)$$

With :

$$P(k) = \left[\sum_{i=1}^k \varphi(i-1)\varphi(i-1)^T \right]^{-1}$$

Where $p(k)$ represents the variance matrix of the estimation error. [13]

Using the matrix inversion theorem yields the recursive relation of $p(k)$:

$$P(k) = P(k-1) - \frac{p(k-1)\varphi(k-1)\varphi^T(k-1)P(k-1)}{1+\varphi^T(k-1)P(k-1)\varphi(k-1)} \quad (3.5)$$

So using 3.5 we can get :

$$\vartheta(k) = \vartheta(k-1) + P(k)\varphi(k-1) \frac{y(k)-\varphi^T(k-1)\vartheta(k-1)}{1+\varphi^T(k-1)P(k-1)\varphi(k-1)} \quad (3.6)$$

3.3.3. Pseudo-Random Binary Sequence (PRBS)

Pseudo-Random Binary Sequence (PRBS) signals are often used as inputs in system identification and adaptive filtering algorithms like Recursive Least Squares (RLS) for several important reasons:

- Rich Frequency Content : PRBS signals have a flat frequency spectrum similar to white noise, meaning they contain a wide range of frequencies. This makes them ideal for exciting all the modes of the system under test, ensuring that the system's response can be observed across its entire frequency range.
- Deterministic and Repeatable : Although PRBS signals appear random, they are actually deterministic and can be exactly reproduced. This is useful for experiments and testing because the same input signal can be used repeatedly to verify results and compare different algorithms or configurations.
- Good Autocorrelation Properties : PRBS signals have an autocorrelation function that closely resembles that of white noise. This property helps in simplifying the analysis and improving the performance of adaptive algorithms by minimizing the correlation between successive input samples.

- Efficient Generation : PRBS signals can be generated efficiently using simple shift registers with feedback, which makes them computationally inexpensive to produce.
- Wide Dynamic Range : The binary nature of PRBS signals (usually +1 and -1 or 0 and 1) ensures a wide dynamic range, which helps in testing the system's response over a wide range of operating conditions.
- Improved Convergence : In the context of the RLS algorithm, the use of PRBS signals can lead to faster convergence. This is because the RLS algorithm benefits from the rich excitation provided by the PRBS, allowing it to quickly adapt to and identify the underlying system dynamics.

Using PRBS signals as input to the RLS algorithm helps in effectively identifying the system parameters, ensuring the adaptive filter has sufficient information to adjust its coefficients accurately and efficiently.

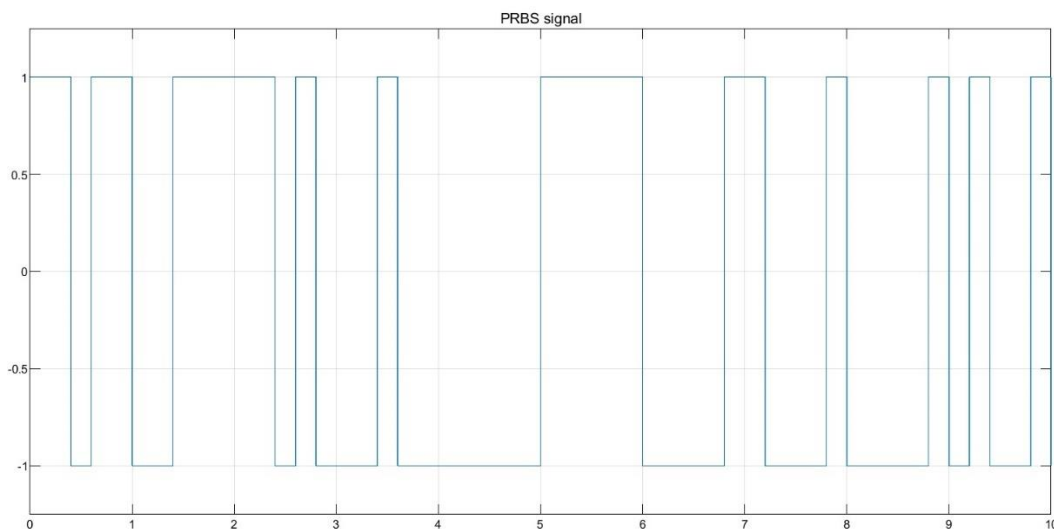


Figure 3.4 : PRBS signal used in simulation

3.3.4. Adapting RLS algorithm to be used on CSTR reactor

In the previous RLS calculations it was assumed that the system parameters remain constant. However, in our case, the control is adaptive and applied to a chemical reactor. It is important to consider the scenario where the parameters change over time. The parameters of the CSTR reactor change continuously over time, but slowly. To address this situation, a relatively simple practical approach can be used, which involves replacing criterion (3.3) with:

$$N_k(\vartheta) = \frac{1}{2} \sum_{i=1}^k \lambda^{k-i} [y(i) - \vartheta^T(i)\varphi(i-1)]^2 \quad (3.7)$$

$$0 < \lambda \leq 1$$

λ : known as the forgetting factor, causes the highest weight to be assigned to the most recent prediction error, with the weight decreasing from point k onwards. A smaller forgetting factor leads to quicker loss of the information contained in the observation vector. [1]

3.4. Updating controller settings

We will now present the pole placement method (RST controller). Unlike many other controllers, this sort of control sets the disturbance rejection law (regulation) separately from the reference signal tracking law. As a result, this controller is described as having independent tracking and regulation. The goal of this strategy is to provide the closed-loop system with behavior specified by a model transfer function, namely the denominator of this transfer function, which essentially characterizes the system's dynamic behavior. The model transfer function is typically defined in terms of the variable z^{-1} , $H_m(z^{-1}) = \frac{B_m(z^{-1})}{A_m(z^{-1})}$ and its usually of the second order. [14]

3.4.1. RST controller

Assuming the polynomials $A(z^{-1})$ and $B(z^{-1})$ in equation (3.1) are coprime, the structure in figure (3.3) represents the pole placement controller (RST). This controller can be used with both stable and unstable systems. [15]

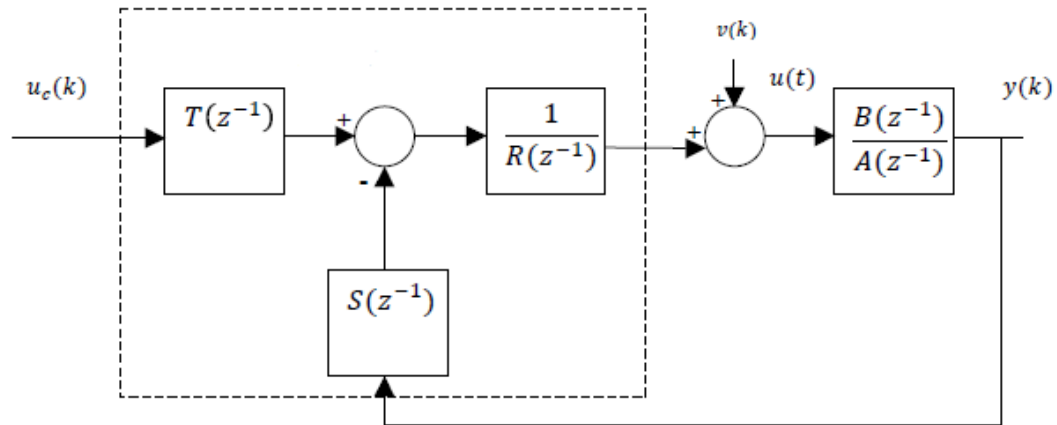


Figure 3.5 : Control Using RST Regulator

The control law of the regulator is expressed as :

$$u(k) = \frac{T(z^{-1})}{R(z^{-1})} u_c(k) - \frac{S(z^{-1})}{R(z^{-1})} y(k) \quad (3.8)$$

$u_c(k)$: the reference

R, S and T : are polynomials in z^{-1}

this control law consists of two distinct parts:

- Regulation part : is the opposite reaction guaranteed by the transfer operator.

$\frac{S(z^{-1})}{R(z^{-1})}$ As follows:

$$y(k) = \frac{BT}{AR+BS} u_c(k) + \frac{BR}{AR+BS} v(k) \quad (3.9)$$

- Setpoint part : This represents the part of the reference filtering, It can be expressed as:

$$u(k) = \frac{AT}{AR+BS} u_c(k) + \frac{BS}{AR+BS} v(k) \quad (3.10)$$

the closed-loop characteristic polynomial is :

$$AR + BS = Ac$$

- **Diophantine equation**

Solving the Diophantine equation is a crucial aspect of the adaptive pole-placement regulator. By solving this equation, we obtain the values of R and S , To achieve this, we implement the following MATLAB function to solve our equation : [16]

```
function [R, S, Acheck] = dioph_mtx(A, B, Ac)    % Solves AR + BS = Ac for R & S.
da = length(A) - 1;                          % da = deg(A) etc.
db = length(B) - 1;                          % pad with zeros
Ac = [Ac, zeros(1, da + db - length(Ac) + 1)]; % Convert to full length
dt = length(Ac) - 1;
dg = da - 1;
df = dt - da;                                % assuming for RAB to be square
B = [zeros(1, df - db + 1), B];              % pad with leading zeros
Rac = [convmtx(A, df + 1); convmtx(B, dg + 1)]; % Construct RAB = [RA; RB]
RS = Ac / Rac;                               % [R, S] = Ac * RAB^(-1)
R = RS(1:df + 1);
S = RS(df + 2:df + dg + 2);                  % Note R & S are row vectors.
Acheck = polyadd(conv(A, R), conv(B, S));     % Verify solution
Return
```

Now, in order to calculate the polynomial T , we need to introduce additional conditions.

To consider the polynomial Ac and integrate a reference model $\frac{B_m}{A_m}$ into T , the polynomial A_m must be a divisor of Ac . [17]

the zeros of the process, which are the zeros of B , are also the zeros of the closed-loop transfer function, unless there are common roots between Ac and B .

Unstable and lightly damped zeros cannot be eliminated, so we factorize the polynomial as follows: [17]

$$B = B^+ B^- \quad (3.11)$$

B^+ : is a polynomial containing all the stable zeros, which can therefore be eliminated.

B^- : is a polynomial containing all the other zeros.

Finally, the polynome Ac is factorized as follows :

$$Ac = A_m B^+ A_0 \quad (3.12)$$

B^+ must be a divisor of R so we set it as:

$$R = R' B^+ \quad (3.13)$$

the simplified Diophantine equation that provides R' and S :

$$AR' + B^- S = A_m A_0 \quad (3.14)$$

the expression for the closed-loop output :

$$y(k) = \frac{B^- T}{A_m A_0} u_c(k) \quad (3.15)$$

For us to have the same output as specified by the reference model $\frac{B_m}{A_m}$ it is necessary that:

$$\frac{B^- T}{A_m A_0} = \frac{B_m}{A_m} \rightarrow B^- T = A_0 B_m \quad (3.16)$$

From the equation, we deduce that B^- must divide B_m . Therefore, we set:

$$B_m = B^- B'_m$$

We obtain the polynomial T :

$$T = A_0 B^+ B_m = \frac{A_0 B_m}{B^-} \quad (3.17)$$

In summary, the polynomials B, T and A_c are chosen such that they have the common factor $A_0 B^+$. Mathematically, the closed-loop transfer function simplifies with the polynomials A_0 and B^+ to achieve the reference model $\frac{B_m}{A_m}$.

- **Choosing the reference model**

the reference model $\frac{B_m}{A_m}$ guarantees the desired characteristics in the closed-loop system. The numerator B_m of the reference model satisfies $B_m = B^- B^+_m$ indicating that it must contain the zeros of the system to be controlled. It is imperative that all zeros of B are on or outside the unit circle, or they are zeros of B^- to avoid instability One possible choice:

$$B_m = B^- B^+_m \text{ with } B^+_m = \frac{A_m(1)}{B^-(1)}$$

to eliminate all steady-state errors. A_m is monic, typically of degree 2 such as:

$$A_m(z) = 1 + a_1 z^{-1} + a_2 z^{-2}$$

a_1 and a_2 are chosen in such a way as to satisfy the stability, speed, and damping conditions.

$$a_1 = -2 \exp(-\xi \omega_0 T_e) \cos(\omega_0 \sqrt{1 - \xi^2} T_e)$$

$$a_2 = \exp(-\xi \omega_0 T_e)$$

ξ : Damping coefficient : $0.7 \leq \xi \leq 1$

ω_0 : Natural pulsation

T_e : Sampling period.

3.4.2. Regulator causal conditions

To have a causal regulator, a condition is imposed:

$$\begin{cases} \deg S \leq \deg R \\ \deg T \leq \deg R \end{cases} \quad (3.18)$$

When there are no limitations on the degrees of the polynomials, the Diophantine equation can have multiple solutions. Specifically, if R_0 and S_0 represent two specific solutions, then R and S are provided as follows:

$$\begin{cases} R = R_0 + QB \\ S = S_0 - QB \end{cases} \quad (3.19)$$

Where Q is the arbitrarily chosen polynomial of any degree, it is better to seek the solution with the degree smallest possible.

If $\deg A \geq \deg B$ we get :

$$\deg R = \deg A_c - \deg A \quad (3.20)$$

Based on equation (3.18), we can always find a solution S with a typical degree of $\deg A$ which represents the minimal solution to the Diophantine equation. Therefore, the condition $\deg S \leq \deg R$ implies:

$$\deg A_c \geq 2 \deg A - 1 \quad (3.21)$$

$$\deg T \geq \deg A_0 + \deg B_m \quad (3.22)$$

Chapter 4 : Simulation Results

4.1. Building Recursive Least Squares algorithm (RLS)

Using the previously described RLS algorithm, we develop the following model in MATLAB/Simulink :

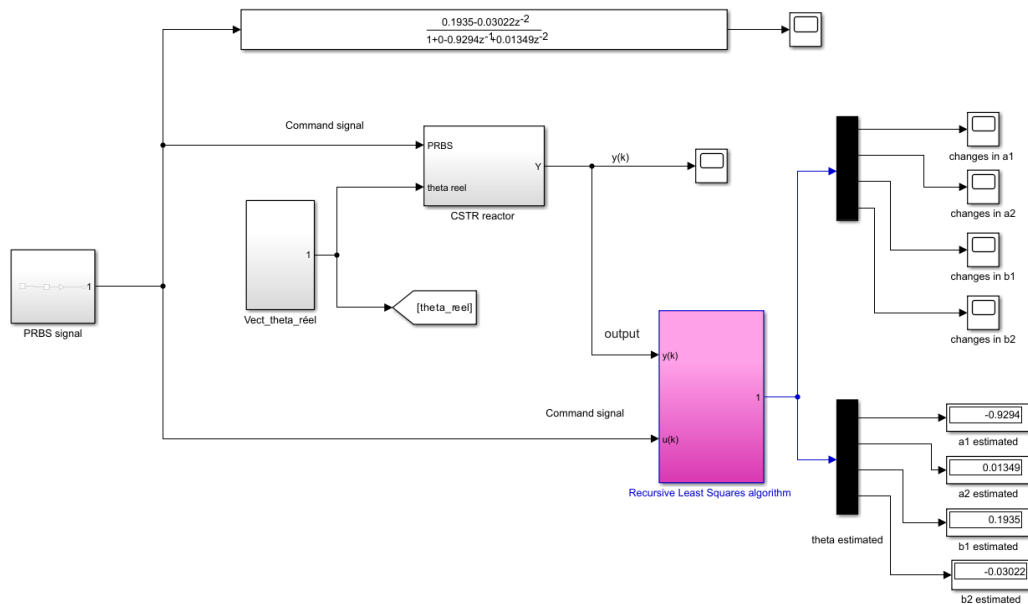


Figure 4.1 : Implementation of RLS to estimate model coefficients.

After running the simulation, we observe that the estimated values calculated by our RLS model ($a_1 = -0.9295$; $a_2 = 0.01349$; $b_1 = 0.1935$; $b_2 = -0.03022$) are within acceptable margins of the real values. The figure 4:2 illustrates the adjustments made to our four parameters to achieve accurate estimation.

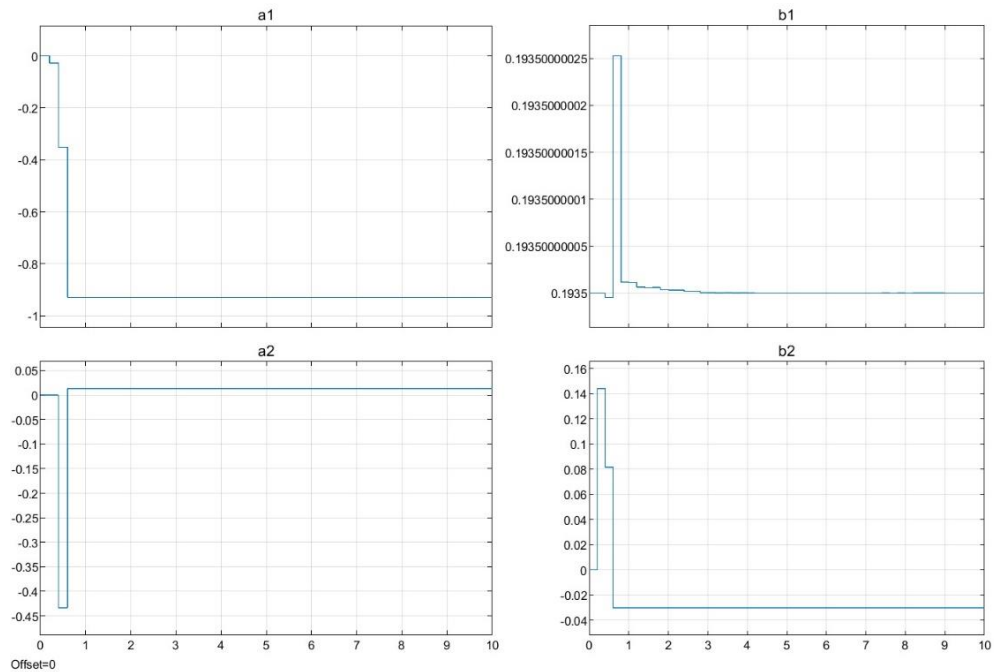


Figure 4.2 : Estimated parameters

4.2.Final model of the Self-tuning Controller For the Regulation of CSTR reactor

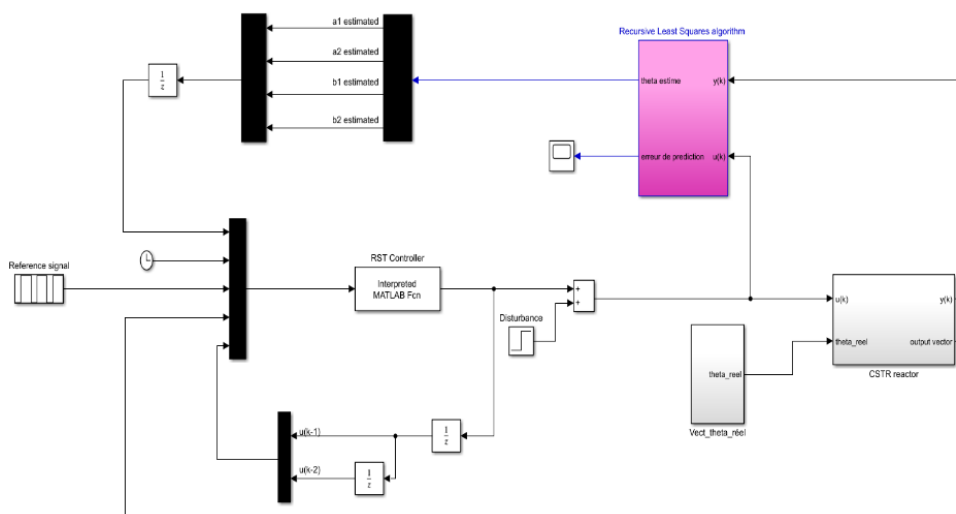


Figure 4.3 : Diagram of indirect adaptive control implemented in Matlab/Simulink

To run the simulation of our complete model, we need to implement the following function in MATLAB, which represents the RST adaptive control function.

```
function output = Reg_RST(input)

global Ts u_prec na mb

theta=input(1:na+mb) ; %input 1
y=input(na+mb+1:na+mb+na+1); %input 2
consigne=input(na+mb+na+1+1); %input 3
u_prec=input(na+mb+na+1+1+1:na+mb+na+1+mb+1); %input 4
temps1=input(na+mb+na+1+mb+1+1); %input 5
col1= round(temps1/Ts);
%desired characteristic equation%
A1 =-0.99; A2=0; A3=0; A4=0; %A5=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
a1=theta(1);
a2=theta(2);
b1=theta(3);
b2=theta(4);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if col1<=na
    teta=ones(na+mb,1)/100;
    %-----
    % Denominator
    a1=teta(1,1);
    a2=teta(2,1);
    a3=0;%teta(3,1);
    %-----
    % Numerator
    b1=teta(3,1);
    b2=teta(4,1);
    b3=0;
end
a3=0;
b3=0;
%-----
k1=A1+1-a1;k2=A2-a2+a1;k3=A3-a3+a2;k4=A4+a3;
h1=a1-1;h2=a2-a1;h3=a3-a2;h3=a3-a2;
N0=k4-h3*k1-b3*(k2-h1*k1)/b1-b2*(k3-(h2*k1+b2*(k2-h1*k1)/b1))/b1;
D0=-h3*b1-b3*(b2-b1*h1)/b1-b2*(-h2*b1+b3-b2*(b2-b1*h1)/b1)/b1;
s0=N0/D0;
gamma=k1-b1*s0;
s1=(k2-h1*gamma-b2*s0)/b1;
s2=(k3-h2*gamma-b3*s0-b2*s1)/b1;
alpha0=-(s1+2*s2)/(1+gamma);
beta=-alpha0-s1-s2;
alpha1=s0-alpha0-beta;
%calculation of the control law
%=====
u=(1-gamma)*u_prec(1)+gamma*u_prec(2)+alpha1*consigne-s0*y(1)-s1*y(2)-s2*y(3);

output(1)=u;
```

4.2.1. CSTR response to adaptive control :

After running our simulation with a disturbance equal to 0 we get the following responses :

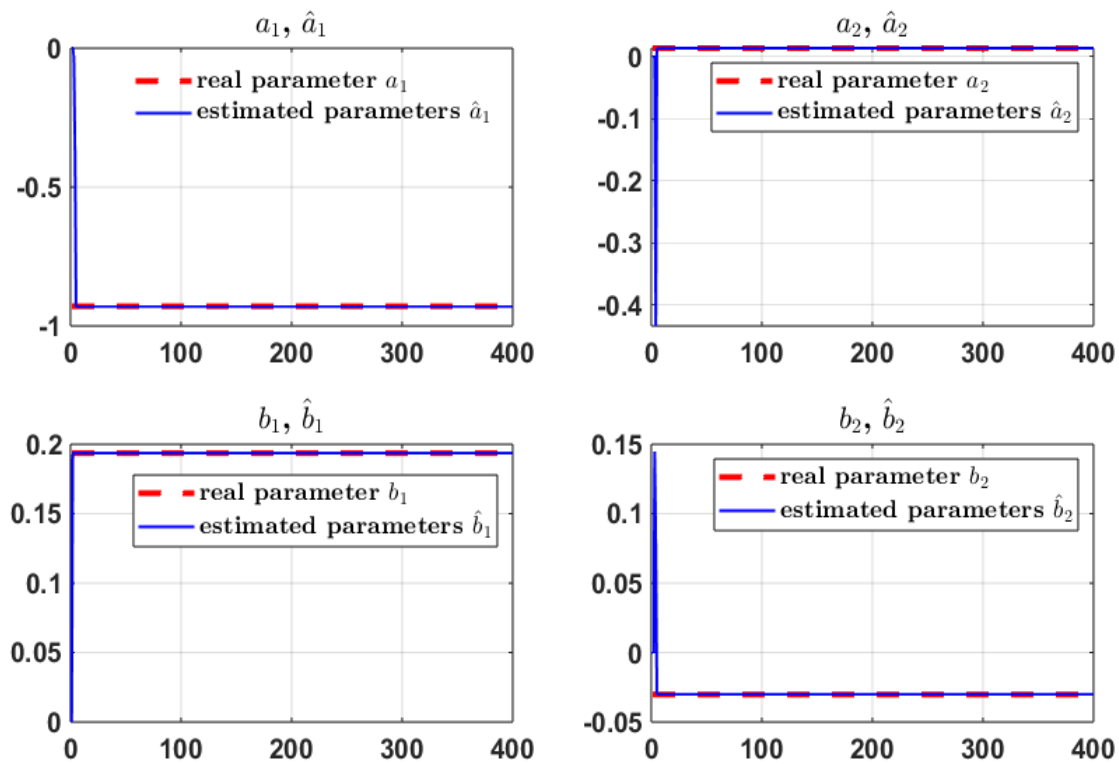


Figure 4.4 : Evolution of estimated parameters vs real parameters

- **Results interpretation**

The estimated parameters converge closely and smoothly to the real parameters. There is minimal deviation, indicating that the adaptive control system works accurately in a disturbance-free environment.

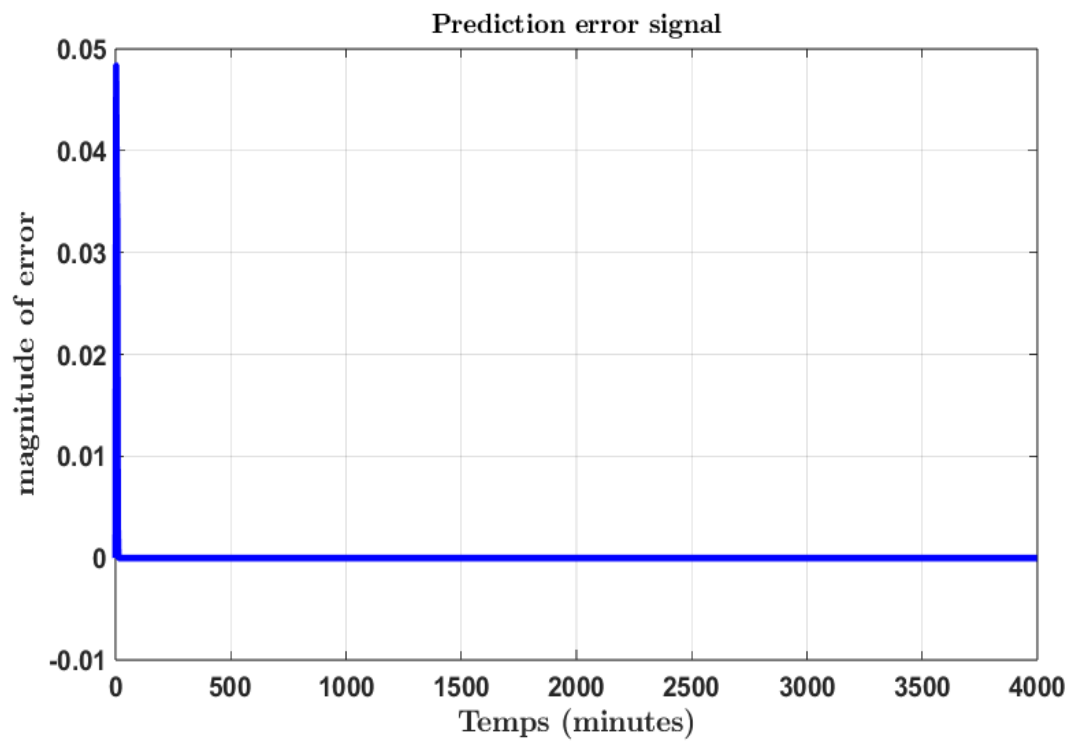


Figure 4.5 : prediction error signal

- **Results interpretation**

The error signal remains nearly zero, showing that the model's predictions are highly accurate.

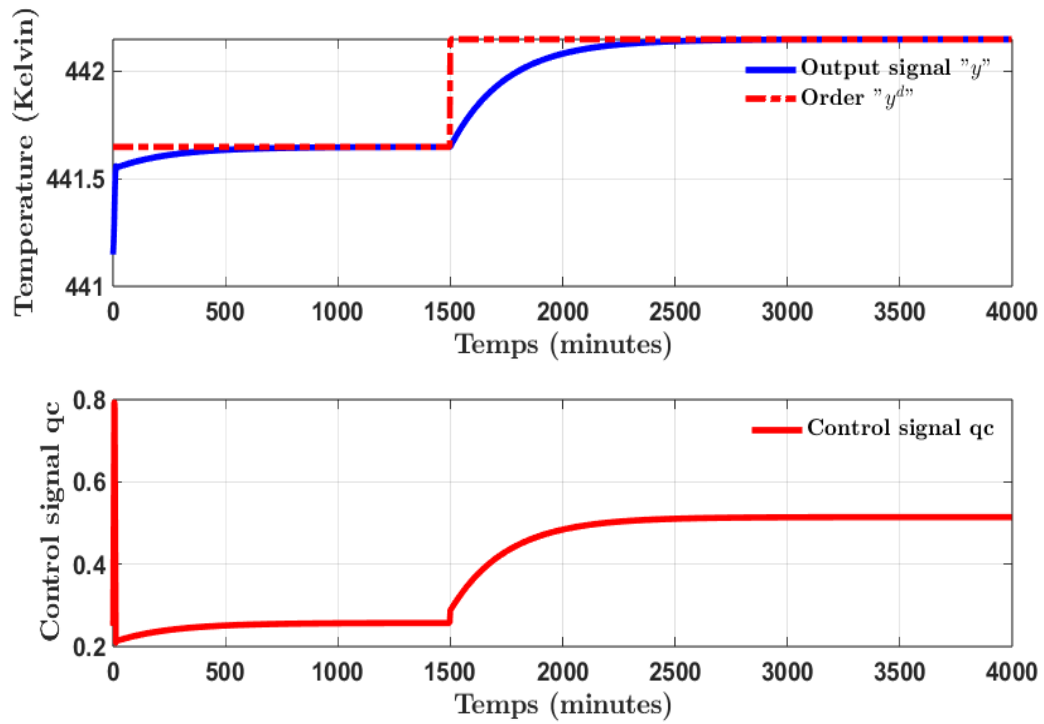


Figure 4.6 : CSTR response with RST controller (without disturbance and no noise)

- **Results interpretation**

The RST controller maintains the reactor temperature at the desired setpoint with minimal adjustment needed in the control signal q_c

4.2.2. CSTR response to adaptive control with noise and disturbances

Adding both noise and disturbances to our system simulation ensures comprehensive evaluation and robustness of the control system under real-world conditions. This approach tests the system's ability to maintain performance despite various perturbations, enhancing confidence in its reliability. It also aids in accurate system identification, fine-tuning control parameters, and evaluating fault detection capabilities, ensuring resilience and compliance with industry standards. Ultimately, this thorough testing process helps develop a robust and high-performance control system capable of handling complex industrial processes.



Figure 4.7 : Evolution of estimated parameters over time vs reel parameters with noise and disturbances

- **Results interpretation**

The estimated parameters still converge to the real parameters but show more fluctuations around the convergence points. This indicates that the adaptive control system is still functional but is affected by the added disturbances and noise.

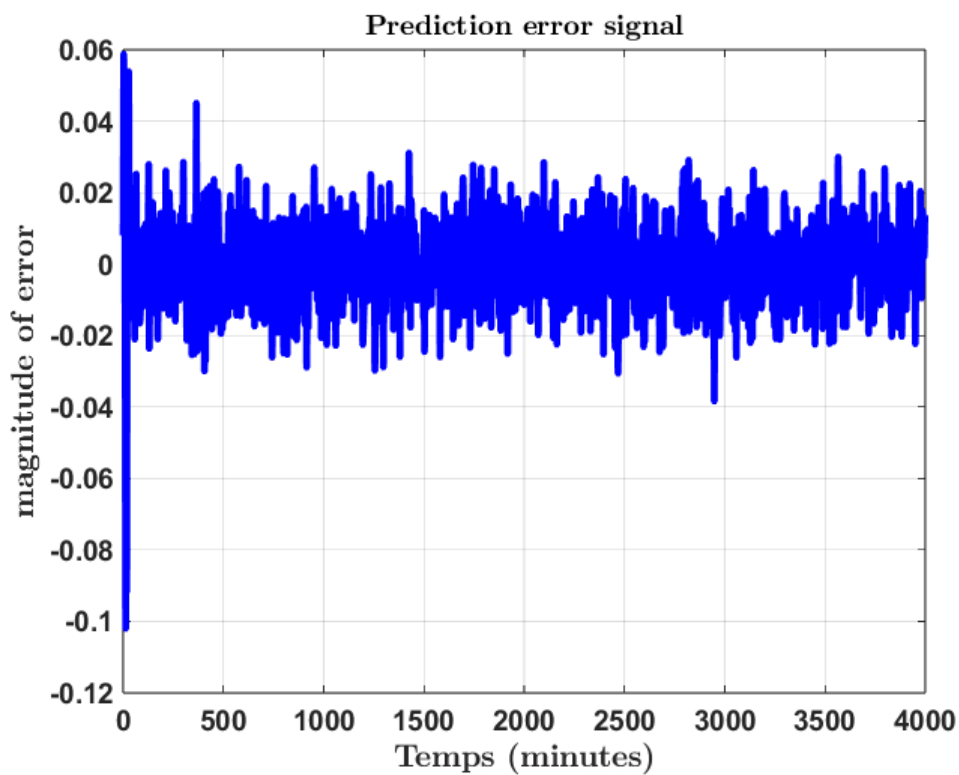


Figure 4.8 : Prediction error signal with disturbance and noise

- **Results interpretation**

The error signal exhibits significant fluctuations. The magnitude of the error increases compared to the no-disturbance case, reflecting the impact of external disturbances and noise on the system.

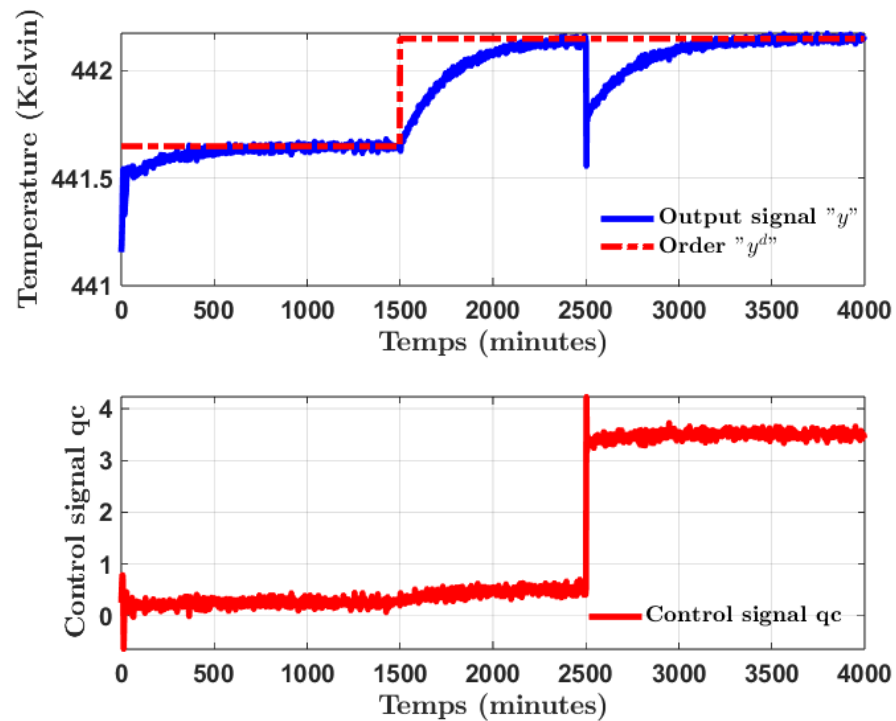


Figure 4.9 : CSTR response with RST controller with disturbance and noise

- **Results interpretation**

The reactor temperature shows more variability, and the control signal q_c adjusts more frequently and significantly to counteract the disturbances and maintain the desired temperature. The control signal's increased variability indicates the controller's active role in mitigating the effects of disturbances and noise.

4.2.3. *Commentary on Results with Disturbance and Noise*

➤ **Robustness of the Adaptive Control :**

The adaptive control system shows robustness as it continues to function and maintain control over the system despite the disturbances and noise. The estimated parameters, while more variable, still converge close to the true values.

➤ **Increased Prediction Error :**

The prediction error signal's increased fluctuations indicate that disturbances and noise introduce unpredictability into the system. However, the error remains within a manageable range, suggesting that the control system can handle these external factors effectively.

➤ **Control Effort :**

The variability in the control signal q_c reflects the system's response to disturbances. The controller actively compensates for these changes, which is a positive sign that the adaptive control can dynamically adjust to maintain system performance.

➤ **System Stability :**

Despite the added noise and disturbances, the system remains stable. The temperature control, while showing more variability, does not exhibit instability or runaway behavior. This stability is crucial for practical applications where disturbances are common.

• **Conclusion**

The introduction of disturbances and noise tests the adaptive control system's resilience. Our results show that the system remains functional, albeit with more variability in parameters and error signals. The control system effectively adapts and maintains the

desired reactor temperature, demonstrating its robustness and reliability under less ideal conditions. This analysis highlights the strength of our adaptive control implementation in a realistic, disturbance-prone environment .

General Conclusion

General Conclusion

Our project on applying adaptive control to a Continuous Stirred Tank Reactor (CSTR) has showcased the remarkable efficacy of adaptive control strategies in effectively managing intricate chemical processes. Through the development of a detailed MATLAB simulation model, we accurately mirrored the dynamic behavior of the reactor and successfully validated the adaptive control system's capability to estimate parameters and uphold the desired temperature setpoint with remarkable precision and minimal error. The incorporation of the Recursive Least Squares (RLS) algorithm and the RST controller facilitated swift real-time adjustments, ensuring that the system adeptly adapted to fluctuating conditions.

Furthermore, even when subjected to disturbances and noise, our system consistently maintained stability and high performance, underscoring its robustness and resilience in the face of heightened prediction error and variability. This comprehensive analysis underscores the inherent strength of adaptive control mechanisms in ensuring control and stability within environments prone to disturbances, positioning it as a dependable and indispensable solution for managing CSTR Reactors effectively.

Moreover, our project sheds light on the potential for adaptive control to enhance not just control and stability but also efficiency in chemical processes. The adaptability of the system allows for optimization in real-time, leading to improved resource utilization, reduced energy consumption, and minimized waste production. These factors are crucial in modern industrial settings, where sustainability and cost-effectiveness are paramount concerns.

Additionally, the successful implementation of adaptive control in a CSTR Reactor opens doors for its application across a wide range of dynamic systems in various industries, from chemical manufacturing to energy production and beyond. Its ability to

learn and adapt to changing conditions makes it a versatile and scalable solution with promising implications for the future of process automation and optimization.

In conclusion, our project not only demonstrates the effectiveness of adaptive control in managing CSTR Reactors but also highlights its broader potential to revolutionize control systems across diverse industrial sectors, paving the way for more efficient, reliable, and sustainable processes.

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