Adaptive Control Design For A MIMO Chemical Reactor

S. Sundari, Alamelu Nachiappan

Abstract

This paper deals with the operation, mathematical modeling and controller design for the jacketed continuous stirred tank reactor. Controller is designed to control the reactant mixture temperature within the reactor. The scheme is simulated using Matlab and the performance of adaptive controller is compared with the conventional PID controller. The simulation results show that the adaptive controller is best suited for CSTR.

Keywords-*MIT rule, CSTR, Mathematical modelling, adaptation law, model reference adaptive control, adaptation gain*.

Introduction

There are several types of stirred reactors used in chemical or biochemical industry. Continuous Stirred Tank Reactors (CSTR) are common used because of their technological paramers. This paper describes the existing techniques of the Continuous Stirred Tank Reactor (CSTR) with the mathematical model of the system, followed by the existing techniques for the implementation of Model reference adaptive controller (MRAC) using MIT rule for the CSTR temperature process .

The Continuous Stirred-Tank Reactor used in this work represents typical nonlinear plant described mathematically by the set of two nonlinear ordinary differential equations (ODE) and has two stable and one unstable steady-state which could lead to very unstable or unoptimal output responses with the use of conventional control methods[1]. One way to overcome this inconvenience is the use of the adaptive control (Åström and Wittenmark 1989) [2],which adopts parameters of the controller to the actual state of the system via recursive identification of the External Linear Model (ELM) as a linear representation of the originally nonlinear system .The results of the adaptive control on this concrete mathematical model can be found for example in [3]. The temperature control of reactor has quite remarkably improved by using the Model Predictive Controller [4]. RathikaraniDuraisamy proposed an adaptive optimization scheme for controlling air flow process with satisfactory transient performance[5]. The automatic tuning of PI controller has been investigated using MRAC concept and AMIT rule. Rahul Upadhyay [6] proposed an analysis of CSTR temperature control with adaptive Controller using Lyapunov rule and PID Controller. Indirect adaptive control based pole placement and adaptive general predict control (GPC) was analyzed in [7]. In [8], a class of nonlinear PID controllers was presented using a nonlinear generalized predictive control approach to a set nonlinear systems. Rajesh singla proposed an application of adaptive control with various types of command inputs in a process plant (CSTR)[9]. The multiple model and neural based adaptive multi- loop PID controller is proposed for a CSTR process[10]. The two controllers designed use the same control law and differ only in the calculation of controller parameters. The NN Adaptive-PID has good set point tracking and disturbance rejection is better than MM Adaptive-PID. An on-line adaptive control for non-linear processes under influence of external disturbance is proposed .An intelligent design of PID controller for a continuous stirred tank reactor was proposed[12] which presents various control methods to control the CSTR temperature control process such as Fuzzy logic PID controller.This paper includes the following parts: section 2 provides an overview of model reference adaptive control. In section 3 mathematical modelling of a chemical reactor is developed. Section 4 and section 5 describes in detail the design and simulation of both non-adaptive and adaptive controller and comparison of performance of adaptive controller and non-adaptive (conventional) controller.Section 6 represents the performance of expanded adaptive controller.

2. Model Reference Adaptive Control (MRAC)

Model reference adaptive controller (MRAC) is a controller used to force the actual process to behave like a model process. MRAC systems adapt the parameters of a normal control system to achieve this match between model and process.

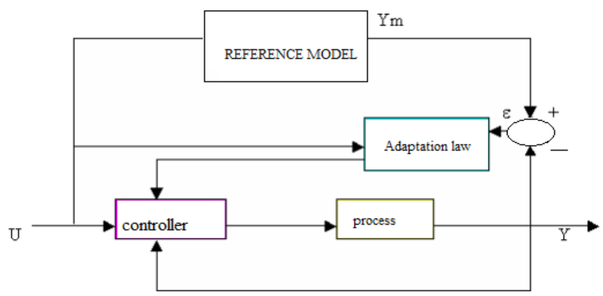

Figure 1 : Basic model reference adaptive control structure

The standard implementation of MRAC based systems is shown in figure 1. The reference model defines the desired performance characteristics of the process being controlled. The adaptation law uses the error between the process and the model output, the process output and input signal to vary the parameters of the control system. These parameters are varied so as to minimize the error between the process and the reference model.

3. MATHEMATICAL MODELING

It is a simple exothermic reaction occurred in the reactor, this is cooled by a coolant that flows in the jacket around the reactor.CSTR process is shown in figure 2.

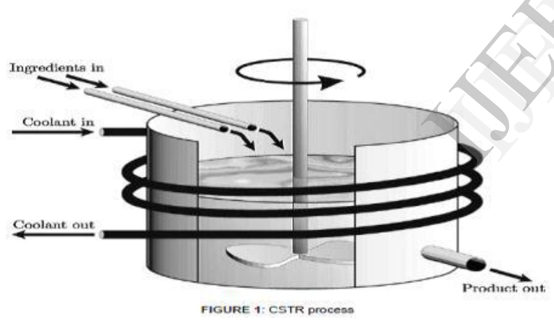

Figure 2 Jacketed Continuous Stirred Tank Reactor

The dynamics of the reacting mixture depends on the mass of the reactants and energy of reactants within the reactor. The reactor material balance equation is

$d/dt(V\rho) = F_{in}\,\rho - F_{out}\,\rho$ [1]

Where V is the reactor's volume, ρ is the density of reactants,F_{in} is flow rate of reactant and F_{out} is the flow rate of product. The flow rates are assumed constant. Consider a simple reaction A →B. The balance on component A is

$V d/dt(C_A) = FC_{AF} - FC_A - V{*}r_A$ (2)

Where C_A is the concentration of reactant within the reactor and r_A is the rate of reaction per unit volume.

The Arrhenius expression is used for the rate of reaction $r_A = K_0 {*} e^{(-E/RT)} {*} C_A$

Where K_0 is the frequency factor, E is the activation energy, R is the ideal gas constant, and T is the reactor temperature.The reactor energy balance assume constant volume, heat capacity Cp and density and neglect the changes in the kinetic and potential energy is

$V\rho\, Cp\, d/dt\,(T) = F\rho Cp\,(Tf - T) + (-\Delta H)\, V{*}r_A - UA\,(T - Tj)$ (3)

Where –ΔH is the heat of reaction, U is the heat transfer co- efficient, A is the heat transfer area, T_f is the reactant temperature, and T_j is the coolant temperature in the jacket . The steady state solution is obtained by equating the derivatives of reactant concentration ,reactor temperature set equal to zero, that is

$d\,C_A/dt = 0 = F/V(C_{Af} - C_A) - r_{A*}\,C_A$ (4)

$dT/dt = 0 = F/V(T_f - T) + (-\Delta H/\rho C_P) K_0 \exp^{(-E/RT)} C_A) - UA/V\rho C_P(T - T_j)$ (5)

To solve these equations, all parameters and variables except for two (C_A and T) must be Specified

Table 1: Reactor Parameter's value

Reactor parameters	Values
F/V,hr-1	**1**
Ko,hr-1	$16.96{*}10^{12}$
(-ΔH),kcal/kmol	5960
E,kcal/kmol	11843
ΔCp,kcal/m^{3}°C	500
T_{jf},°c Caf,kmol/m3	25
UA/V,kcal/m3'c.hr	150
Tj◦C	25

3.1Linearization of Dynamic Equation

Let the state and input variables be defined in deviation variable form:

The stability of the non-linear equation can be determined by finding the following state space form:

X' = AX + BU

And determine the eigen values of the A (state space) matrix. Let the state and input variables be defined in deviation variable form

$$X = \begin{bmatrix} C_A - C_{AS} \\ T - T_S \end{bmatrix}$$

$$U=\begin{bmatrix} F-F_S \\ T_j-T_{js} \end{bmatrix}$$

A=

$$\begin{bmatrix} -\frac{F}{V}-K_0\exp\left(-\frac{E}{RT_s}\right) & -K_0\exp\left(-\frac{E}{RT_s}\right)\left(\frac{E}{RT_s^2}\right)*C_{AS} \\ \left(-\frac{\Delta H}{\rho C_p}\right)*K_0\exp\left(-\frac{E}{RT_s}\right) & -\frac{F}{V}-\frac{UA}{V\rho C_p}*\left(-\frac{\Delta H}{\rho C_p}\right)*K_0\exp\left(-\frac{E}{RT_s}\right)\left(\frac{E}{RT_s^2}\right)*C_{AS} \end{bmatrix}$$

3.2 Stability Analysis

The stability of particular operating point is determined by finding the A-matrix for that particular operating point and finding the Eigen values of the A-matrix.

Substituting the reactor parameter values ,we get

$$A=\begin{bmatrix} -1.567 & -0.0829 \\ 1.868 & -0.3115 \end{bmatrix}$$

λ=eig(A)=-0.8882,-0.5800

Both of the Eigen values are negative, indicating that the point is stable.

$$B=\begin{bmatrix} C_A-C_{AS} & 0 \\ T-T_S & UA/V\rho Cp \end{bmatrix}$$

$$C=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$D=\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

3.3 Derivation of transfer function

Transfer functions for concentration of the reactant to flow rate and jacket temperature and the temperature of the reactant to flow rate and jacket temperature are determined using matlab and are given by the equations 6,7 8 and 9 respectively.

Transfer function relating C_A to F

$$H_{11}=\frac{1.4364S+1.5393}{S^2+1.4682S+0.5152} \quad (6)$$

Transfer function relating C_A to T_j

$$H_{12}=\frac{-0.0249}{S^2+1.4682S+0.5152} \quad (7)$$

Transfer function relating T to F

$$H_{21}=\frac{-13.171-12.5517}{S^2+1.4682S+0.5152} \quad (8)$$

Transfer function relating T to T_j

$$H_{22}=\frac{0.3S+0.34}{S^2+1.4682S+0.5152} \quad (9)$$

3.4 Design of Decouplers

Let

$Y_1 = C_A$,

Y_2 = T,

m_1=F, feed flow rate,

m_2 =Tj, jacket temperature

Input output relation for Concentration control system and Temperature control system are given by equations (10)& (11) respectively.

$$Y_1=\frac{1.4364S+1.5393}{S^2+1.4682S+0.5152}m_1+\frac{-0.0249}{S^2+1.4682S+0.5152}m_2 \quad (10)$$

$$Y_2=\frac{-13.171S-12.5517}{S2+1.4682S+0.5152}m_1+\frac{0.3S+0.347}{S2+1.4682S+0.5152}m_2 \quad (11)$$

Coupling requires finding of the Relative Gain Array matrix:

$$\lambda_{11}=\frac{(\Delta y1/\Delta m1)_{\text{at m2 =const}}}{(\Delta y1/\Delta m1)_{\text{at y2 =const}}}$$

=3.0635/1.33=2.3

Relative Gain Array matrix

$$\lambda=\begin{bmatrix} 2.3 & -1.3 \\ -1.3 & 2.3 \end{bmatrix}$$

The diagonal elements are negative, so the system is unstable. In order to eliminate the interaction, a decoupler D_1(s) & D_2(s) must be designed for the two systems and are given by the equations (12)& (13) respectively.

To cancel the effect of jacket temperature (m2) on the outlet concentration (Y1)

$$D_1(s)=\frac{-H_{12}}{H_{11}}=\frac{-0.0249}{1.4364s+1.5393} \quad (12)$$

To cancel the effect of feed flow rate (m_1) on the reactor temperature (Y_2):

$$D_2(s)=\frac{-H_{21}}{H_{22}}=\frac{13.171s+12.5517}{0.3s+0.347} \quad (13)$$

Where H_{11} & H_{12} are given by equations (6)&(7) respectively and H_{21}& H_{22} are given by equations (8)&(9) respectively. The complete block diagram of the process with two decouplers is shown in figure 3&its equivalent representation of the process for Concentration and temperature control is shown in figure 4&5 respectively.

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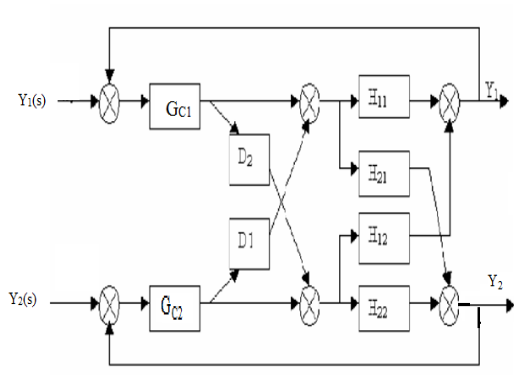
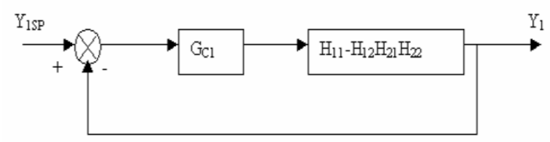
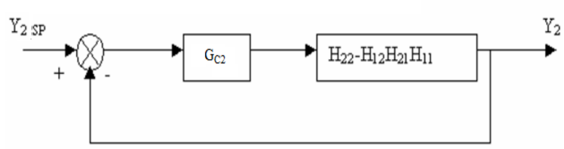


Figure. 3. Block Diagram of the Process with Two Decouplers



Figuer4. Equivalent Representation for concentration control system



Figuer 5 . Equivalent Representation for temperature control system

4. Non-Adaptive Control Analysis

Simulink model is designed using PID controller for concentration and temperature control system and its transfer functions are given by the equations 14&15 respectively**.** The conventional PID controller is implemented based on the auto tuning method.

(i)Concentration control system

The simplified transfer function model of the process is given by

$$G_{p1}(s)=\frac{1.44s^5+5.78s^4+9s^3+6.88s^2+2.53s+0.31}{s^6+4.44s^5+7.94s^4+8.42s^3+4.1s^2+1.19s+0.14} \quad (14)$$

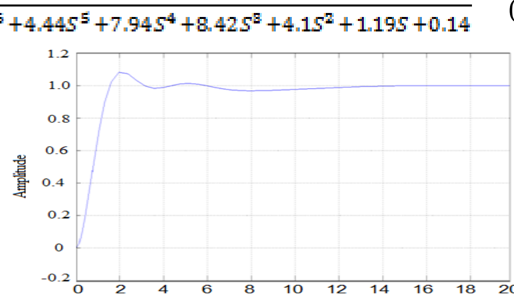


Figure 5: Step Input Response of Concentration Control

(i) Temperature control system

The simplified transfer function model of the process is given by

$$G_{p2}(s)=\frac{0.3s^5+1.18s^4+1.96s^3+1.54s^2+0.62s+0.095}{s^6+4.41s^5+7.94s^4+8.42s^3+4.1s^2+1.19s+0.14} \quad (15)$$

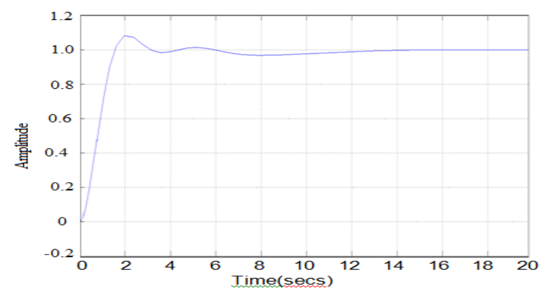


Figure 6: Step Input Response of Temperature Control System

The step input response of Concentration control system and temperature control system is shown in figure 5&6respectively.It was observed that the response has large settling time and overshoot for both Concentration and temperature control system,which is not desirable.

5. Adaptive control design and simulation

In this section the model reference adaptive control is designed and implemented in simulink. The performance of an adaptive control to a conventional controller is compared. The modification of model reference adaptive controller is done to adapt faster and better accommodate variations in the parameters. The model that the plant is designed to have the following characteristics.

(i) Concentration control

For the concentration control a maximum overshoot (Mp) of 5% and a settling time (T_s) of less than 4 seconds are selected. The following equation is used to determine the required damping ratio and natural frequency of the system.

$$\xi=\left[\ln\left(\frac{\%M.P}{-\pi}\right)\right]*\sqrt{\frac{1}{1+[\ln(\%Mp/-\pi)]^2}}$$

ξ=0.68 and ω_n=2.1986 rad/s. The transfer function for the model is therefore

$$G_m(s)=\frac{4.834}{s^2+1.3s+4.834} \quad (16)$$

(ii) Temperature control

A reference model (second order) with a maximum overshoot (Mp) of 2.5% and settling time(Ts) of 1 second is chosen.

The transfer function for the model is therefore

$$G_m(s)=\frac{15.54}{s^2+6s+15.54} \quad (17)$$

This has improved the overshoot to below 10% and the settling time is now less than 2 seconds. Conventional controller has large overshoot and settling time.By increasing the adaptation gain the system becomes unstable .

6. Expanded adaptive control

The controller parameters are initialized to a value closer to their final value ,the performance of the adaptive controller will be improved. Table 2 shows the comparative overview of different transient domain parameters like overshoot, rise time and settling time of PID and adaptive controller. Comparing the Figure 7 and Figure 8,the adaptive controller has less settling time with no overshoot and rise time compared to conventional controller.

Table 2: Transient domain parameters of controllers

criterion	Concentration control		Temperature control	
	PID controller	Adaptive controller	PID controller	Adaptive controller
Rise time (sec)	1.03	0	1.04	0
Settling time (sec)	10.6	3.5	9.33	1.5
Overshoot(%)	8.51	0	8.28	0

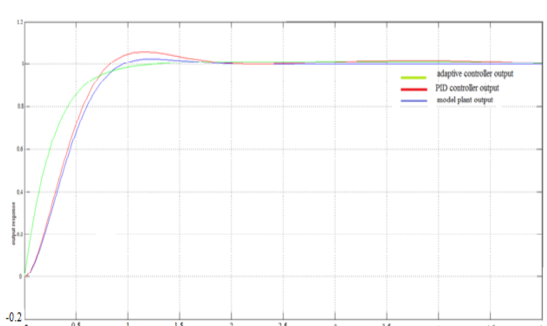


Figure 7: Comparison of Adaptive controller and PID controller with a step input for concentration control

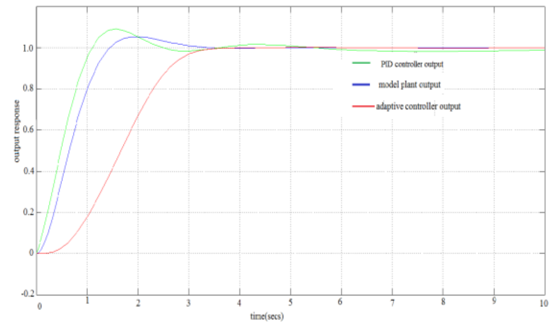


Figure 8: Comparison of Adaptive controller and PID controller with a step input for temperature control

7. Conclusion

This paper describes the behavior of a system controlled by model reference adaptive control scheme using MIT rule. The effect of adaptation gain is viewed on the time response characteristic of the second order system. The paper demonstrated that while the adaptive controller exhibits superior performance and the PID controller has the convergence time of typically large (greater than 10 seconds) and there is large overshoot. Increasing the adaptation rate improves the performance of the adaptive controller at the cost of increased oscillation.It is possible to significantly improve the performance of an adaptive controller simply by initializing the controller parameters to a value close to their final value.Proposed adaptive controller has good results of control and fulfilled the maximum control requirements such as stability,reference signal tracking and disturbance rejection.

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