International Journal of Soft Computing and Engineering (IJSCE)
ISSN: 2231-2307, Volume-4 Issue-2, May 2014

Performance Analysis of CSTR using Adaptive Control

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Abstract— In industry nowadays the control of chemical process is important task. Mostly all the chemical processes are highly nonlinear in nature and this causes instability of process. This paper presents the performance evaluation on the application of model reference adaptive control with various types of command inputs in a process plant. In the design of model reference adaptive control (MRAC) scheme, adaption law have been developed based on MIT and Lyapunov rule. This paper deals with basic simulation studies of the Continuous Stirred Tank Reactor (CSTR). The mathematical model is developed from material balances. Numerical mathematics is used for steady-state analysis and dynamic analysis which is usually represented by a set of differential equations.A simulation is carried out using Mat Lab and Simulink to control the process system using the adaptive control algorithm. It is also concluded that the adaptive controller will be superior to the conventional controller even without parameters change in the process. In a real world situation, these parameters could be estimated by using simulations or real execution of the system. It may be possible to improve the performance of the adaptive controller by further modifying the adaptation law or by incorporating parameter identification into the control.

Index Termss— Process control – CSTR ; Adaptive controller; MIT rule,Lyapunov Rule

I. INTRODUCTION

In common sense, 'to adapt 'means to change behavior to conform to new circumstances.Intuitively, an adaptive controller is thus a controller that can modify its behavior in response to the changing dynamics of the process and the character of the disturbances. The core element of all the approaches is that they have the ability to adapt the controller to accommodate changes in the process. This permits the controller to maintain a required level of performance in spite of any noise or fluctuation in the process. An adaptive system has maximum application when the plant undergoes transitions or exhibits non-linear behavior and when the structure of the plant is not known. Adaptive is called a control system, which can adjust its parameter automatically in such a way as to compensate for variations in the characteristics of the process it control. [1] An adaptive control system can be thought of as having two loops. One loop is normal feedback loop with the adjustment loop. The parameter adjustment loop is slower than the normal feedback loop [3].

II. MODEL REFERENCE ADAPTIVE CONTROL

Model reference adaptive system is an important adaptive controller .It may be regarded as an adaptive servo system in which the desired performance is expressed in terms of a reference model, which gives the desired response to a command signal as shown in figure1 the system has an ordinary feedback loop composed of the process and the controller and another feedback loop that changes the controller parameters. The parameters are changed on the basis of feedback from error, which is the difference between the output of system and the output of reference model [2]. The ordinary feedback loop is called the inner loop and the parameter adjustment loop is called the outer loop. The mechanism for adjusting the parameters in a model reference adaptive system can be obtained in two ways by using a gradient method or by applying Lyapunov's stability theory [3].MRAC is composed of four parts: a plant containing unknown parameters, a reference model for compactly specifying the desired output of control system, a feedback control law containing adjustable parameters [3].

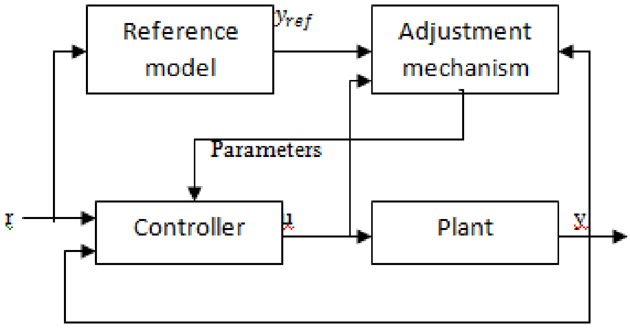

Fig. 1. Model Reference Adaptive Control

A. MIT RULE

The MIT rule is the original approach to MRAC.The name is derived from the fact that it was developed at the instrumentation laboratory at MIT.

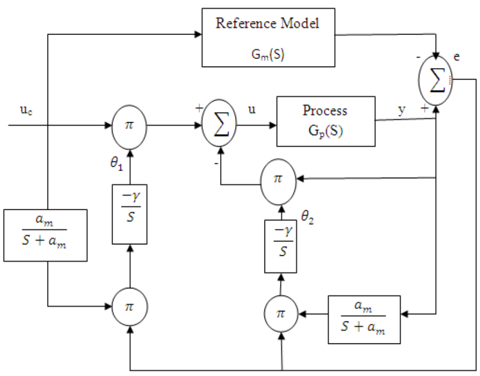

Fig.2 Block diagram of MRAS Based on MIT Rule

Here, we have considered a closed loop control system in which the controller has one adjustable parameter θ the

Manuscript Received on April, 2014.
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desired closed loop response is specified by a model whose output is y_m.Let e be the error between the output y of closed loop system and the output y_m of the model. The convergence of the modeling error to zero for any given uc is assured when y exactly follows the output of the model (ym),
The modeling error e is given by equation (2.1)

$$e = y - y_m \qquad (3.1)$$

One possibility is to adjust the parameter in such a way that the loss function is

$$J(\theta) = \frac{1}{2}\, e^2(\theta) \qquad (3.2)$$

To find out how to update the parameter theta, an equation needs to be formed for the change in theta. If the goal is to minimize this cost related to the error, it is sensible to move in the direction of the negative gradient of *J*. This change in *J* is assumed to be proportional to the change in *theta*. Thus, the derivative of *theta* is equal to the negative change in *J*. The result for the cost function chosen above is:

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} \qquad (3.3)$$

$$= -\gamma\, e \frac{\partial e}{\partial \theta}$$

This relationship between the change in theta and the cost function is known as the MIT rule. The MIT rule is central to adaptive nature of the controller. The partial derivative term $\frac{\partial e}{\partial \theta}$ is called the sensitivity derivative of the system. This shows how the error is dependent on the adjustable parameter, θ. There are many alternatives to choose the loss function *F*, like it can be taken as mode of error also. Similarly dθ/dt can also have different relations for different applications [1,2,3,8,9].

B. Lyapunov's Stability Theory

The Lyapunov's stability theory can be used to describe the algorithms for adjusting parameters in Model Reference Adaptive control system.

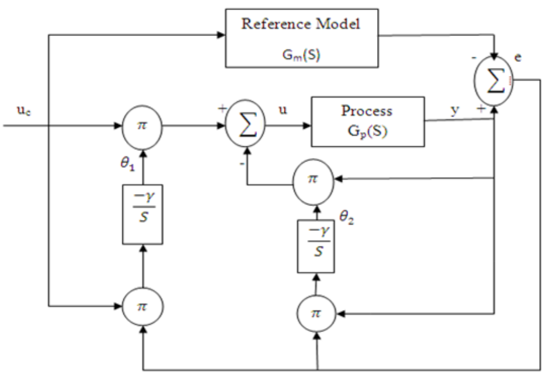

Fig.3 Block diagram of MRAS Based on Lyapunov Rule

In order to derive an updating law using Lyapunov theory, the following Lyapunov function is defined as:

$$V = \frac{1}{2}\gamma e^2 + \frac{1}{2b}(b\theta_1 - b_m)^2 + \frac{1}{2b}(b\theta_2 + a - ba_m)^2$$

The time derivative of V can be found as

$$\dot{V} = \gamma e\dot{e} + \dot{\theta}_1(b\theta_1 - b_m) + \dot{\theta}_2(b\theta_2 + a - ba_m)$$

And its negative definiteness would guarantee that the tracking error converge to zero along the system trajectories [2, 3, 6, 12].

III. DEVELOPMENT OF MATHEMATICAL MODELLING

A perfectly mixed continuously stirred tank reactor (CSTR) as shown in figure 2 with first order exothermic irreversible reaction A → B is considered. In this a fluid stream is continuously fed to the reactor and other fluid stream is continuously removed from the reactor. A jacket surrounding the reactor has in feed and exit streams. The jacket is assumed to be perfectly mixed and a t lower temperature than the reactor. Energy passes through the reactor walls into jacket removing the heat generated by reaction [1].

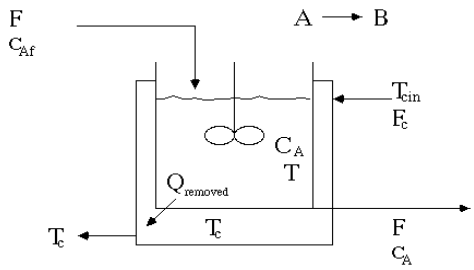

Fig.4 Continuously Stirred Tank Reactor

For simplicity it is assumed that the cooling jacket temperature can be directly manipulated, so that an energy balance around the jacket is not required. We also make the following assumptions
Perfect mixing (product stream values are the same as the bulk reactor fluid)
Constant volume
Constant parameter values

A. Overall Material Balance

The rate of accumulation of material in the reactor= rate of material in by flow = the material out by flow [5].

$$\frac{dV\rho}{dt} = F_{in}\rho_{in} - F_{out}\rho \qquad (1)$$

Assuming a constant amount of material in the reactor($\frac{dV\rho}{dt} = 0$), we find that

$$F_{in}\rho_{in} = F_{out}\rho$$

If we also assume that the density remains constant, then

$$F_{in} = F_{out} = F \qquad (2)$$

$$and\ \frac{dV}{dt} = 0$$

1) *Balance on Component A*

The balance on component A is

$$\frac{dVC_A}{dt} = FC_{Af} - FC_A - rV$$

Where r is the rate of reaction per unit volume.

2) *Energy Balance*

The energy balance is

$$\frac{d(V\rho c_p(T - T_{ref}))}{dt} = F\rho c_p(T_f - T_{ref}) - F\rho c_p(T - T_{ref}) + (-\Delta H)Vr - UA(T - T_j)$$

Where T_{ref} represents an arbitrary reference temperature for enthalpy.

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B. State Variable form of Dynamic Equations

In state variable form equations can be written as

$$f_1(C_A, T) = \frac{dC_A}{dt} = \frac{F}{V}(C_{Af} - C_A) - r \qquad (3)$$

$$f_2(C_A, T) = \frac{dT}{dt} = \frac{F}{V}(T_f - T) + \left(\frac{-\Delta H}{\rho c_p}\right) r - \frac{UA}{V\rho c_p}(T - T_j) \qquad (4)$$

Where it is assumed that the volume is constant. The reaction rate per unit volume (Arrhenius expression) is

r = k_o exp $\left(\frac{-\Delta E}{RT}\right) C_A$

Where it is assumed that the reaction is first-order.

C. Steady-State Solution

The steady-state solution is obtained when $\frac{dC_A}{dt} = 0$ and $\frac{dT}{dt} = 0$, that is

$$f_1(C_A, T) = 0 = \frac{F}{V}(C_{Af} - C_A) - k_o\, \varepsilon\xi\pi\left(\frac{-\Delta E}{RT}\right) C_A \qquad (5)$$

$$f_2(C_A, T) = \frac{dT}{dt} = \frac{F}{V}(T_f - T) + \left(\frac{-\Delta H}{\rho c_p}\right) r - \frac{UA}{V\rho c_p}(T - T_j) \qquad (6)$$

To solve these two equations, all parameters and variables except for two (CA and T) must be specified.[9] Numerical values given in table1 can be use to solve for the steady-state values of CA and T.

D. Guess 1

High concentration (low conversion), Low temperature. Here we consider an initial guess of CA =8 and T = 300 K.

So the steady-state solution for guess is $\begin{bmatrix} C_{As} \\ T_S \end{bmatrix} = \begin{bmatrix} 8.5636 \\ 311.2 \end{bmatrix}$, that is, high concentration (low conversion) and low temperature [1,2,5,7,8].

TABLE I. REACTOR PARAMETERS

Reactor Parameter	Description	Values
F/V(hr-1)	Flow rate*reactor volume of tank	1
K_o (hr-1)	Exponential factor	$15e^{12}$
ΔH (BTU/lbmol)	Heat of reaction	40000
E(BTU/lbmol)	Activation energy	33500
ρC_P (BTU/ ft^3)	Density*heat capacity	54.65
Tf(˚C)	Feed temperature	70
C_{Af}(lbmol/ft^3)	Concentration of feed stream	10
$\frac{UA}{V}$	Overall heat transfer coefficient/reactor volume	122.1
Tj(˚C)	Jacket temperature	60

E. Linearization of Dynamic Equations

The stability of the nonlinear equations can be determined by finding the following state-space form
X(dot)=AX+BU
and determining the eigenvalues of the A (state-space) matrix.
The nonlinear dynamic state equations are

$$f_1(C_A, T) = \frac{dC_A}{dt} = -\frac{F}{V}C_A - kC_A + \frac{F}{V}C_{Af} \qquad (7)$$

$$f_2(C_A, T) = \frac{dT}{dt} = \left(\frac{-\Delta H}{\rho c_p}\right) kC_A - \frac{F}{V}T - \frac{UA}{V\rho c_p}T + \frac{UA}{V\rho c_p}T_j + \frac{F}{V}T_f \qquad (8)$$

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

$$x = \begin{bmatrix} C_A - C_{As} \\ T - T_s \end{bmatrix}$$

$$u = \begin{bmatrix} T_j - T_{js} \\ C_{Af} - C_{Afs} \\ T_f - T_{fs} \end{bmatrix}$$

F. Stability Analysis

Performing the linearization, we obtain the following elements for **A**

$$A = \begin{bmatrix} -7.3929 & -.014674 \\ 2622.9 & 4.7534 \end{bmatrix}$$

$$B = [0; 1.5]$$

The stability characteristics are determined by the eigen values of **A**, which are obtained by solving det $(\lambda I - \mathbf{A}) = 0$.
In Mat Lab command we can write

≫A= [7.3929 –.014674; 2622.9 4.7534]

≫ LAMBDA = eig(A)

≫ $LAMBDA = -1.3134$,–1.3567

Both of the eigen values are negative, indicating that operating point is stable [8, 10].

IV. ADAPTION LAW

The adaption law attempts to find a set of parameters that minimize the error between the plant and the model outputs. To do this the parameters of the controller are inclemently adjusted until the error has reduced to zero. A number of adaption laws have been developed to date. The two main types are the gradient and the lyapunov approach and we have used both approaches [6, 11, 12].

V. ADAPTIVE CONTROL DESIGN AND SIMULATION

In order to implementation of a basic adaptive controller using Simulink, the first step is to define the plant that is to be controlled. The simplified transfer function model of the process given as [1]:

$$G_p(S) = \frac{1.5S + 11.0850}{S^2 + 2.6366S + 3.3503}$$

The next step is to define the model that the plant must be matched to. To determine this model we must first define the characteristics that we want the system to have. Firstly we will select the model to be a second order model of the form:

$$G_m(S) = \frac{\omega^2}{S^2 + 2\xi\omega S + \omega^2}$$

We must then determine the damping ratio ξ and the natural frequency $\omega$to give the required performance characteristics. For the concentration control a maximum overshoot (Mp) of 5%and a settling time (Ts) of less than3 seconds is selected. We can use the following mentioned equations to determine the damping ratio and natural frequency of the system.

$$\xi = \frac{\ln Mp/100}{-\pi}\sqrt{\frac{1}{1+[\frac{\frac{lnMp}{100}}{-\pi}]^2}}$$

$$\omega = \frac{3}{\xi Ts}$$

Based upon formula we get ξ=0.713 and ω_n=2.134rad/s. The transfer function for the model is therefore.

$$G_m(S) = \frac{4.76}{S^2 + 3.1S + 4.76}$$

We need to develop a standard controller to compare with the adaptive controller. Controller setting is done using Ziegler-Nicholas technique and the best controller parameters are found to be $K_c = 10, T_I = 1 \; and \; T_d = 1$

After obtaining the transfer function of process and the transfer function of reference model a Mat Lab Simulink diagram is obtained by applying the MIT and Lyapunov rule [1, 2, 11, 12].

G. MIT Rule

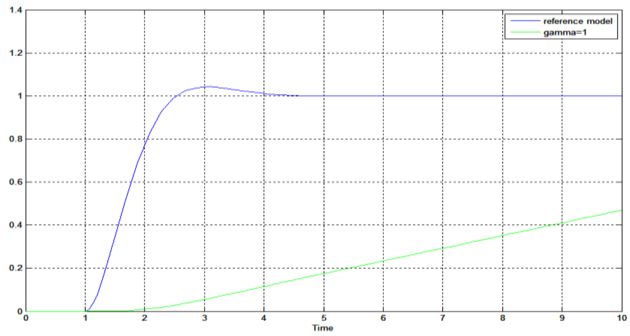

Fig.5 Output of CSTR with MIT Rule when gamma=1

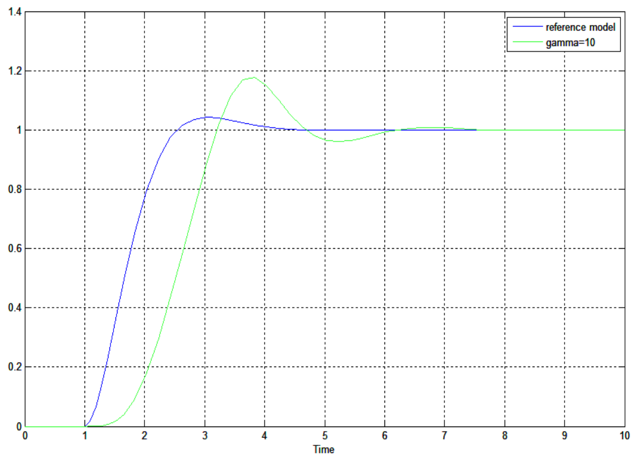

Fig.6 Output of CSTR with MIT Rule when gamma=10

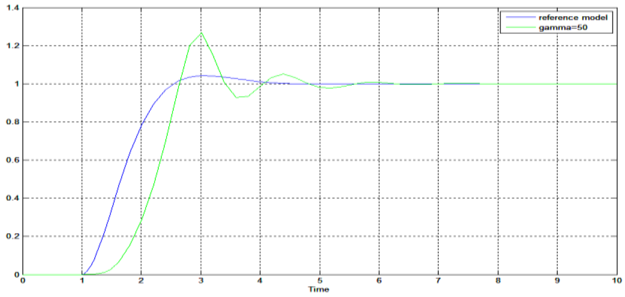

Fig.7 Output of CSTR with MIT Rule when gamma=50

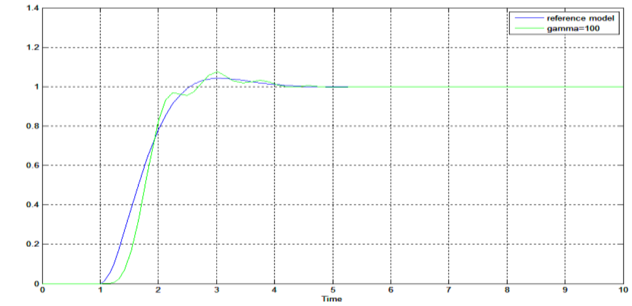

Fig.8 Output of CSTR with MIT Rule when gamma=100

H. Lyapunov Rule

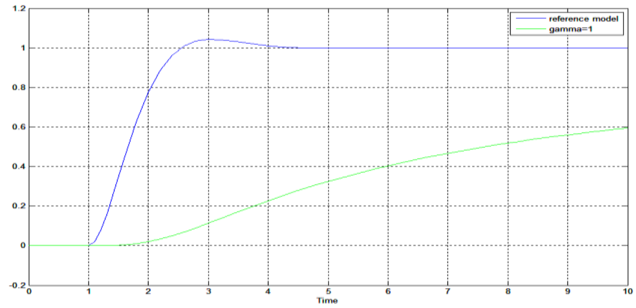

Fig.9 Output of CSTR with Lyapunov Rule when gamma=1

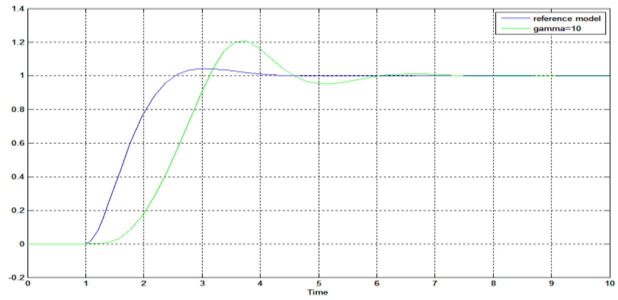

Fig.10 Output of CSTR with Lyapunov Rule when gamma=10

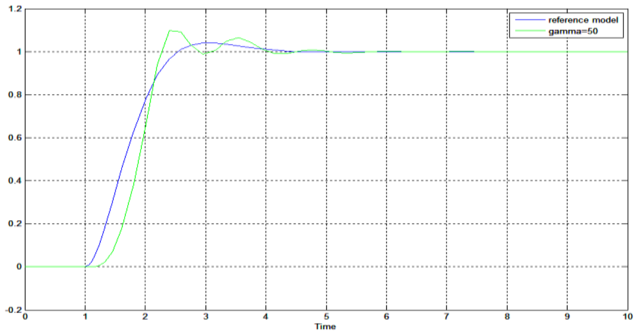

Fig.11 Output of CSTR with Lyapunov Rule when gamma=50

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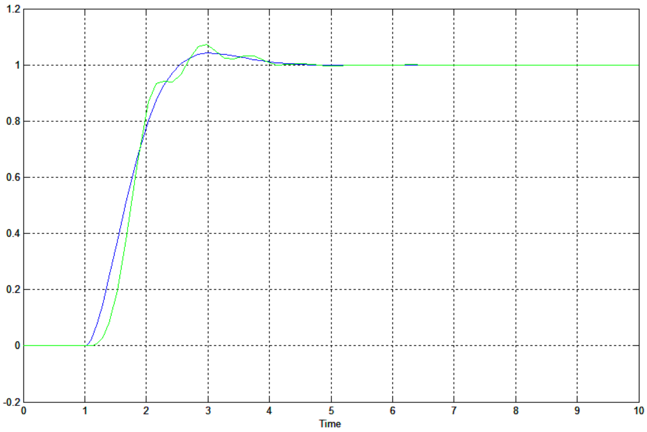

Fig.12 Output of CSTR with Lyapunov Rule when gamma=100

VI. CONCLUSION

A comparative analysis has been shown in Table II by using MIT and Lyapunov rules of MRAC.

TABLE II. COMPARISON RESULTS

Performance specification	MIT Rule				Lyapunov Rule			
	γ = 1	γ = 10	γ = 50	γ = 100	γ = 1	γ = 10	γ = 50	γ = 100
Rise time (sec.)	-	3.275	2.658	2.785	-	3.15	2.3	2.6
Peak time (sec.)	-	3.83	3.0	3.017	-	3.8	2.4	3
Maximum Overshoot (%)	-	17.83	26.74	7.5	-	20.34	9.65	7.3
Settling time (sec.)	-	7.0	6.25	4.5	-	6.4	4	3.9
ISE	5.023	.4052	.2147	.0204	3.156	.3799	.0464	.01412

The proposed adaptive controller is tested by using MatLab Simulink program and a comparison study has been made between MIT and Lyapunov rule. To resolve the problem of large convergence time and large overshoot with conventional controller, the controller is redesigned by modifying the adaption law and the results shows a significant improvement in the performance of adaptive controller. It is clear from table II that by increasing the adaption gains in both MIT and Lyapunov a very significant control parameters can be obtained, further by using Lyapunov better results are obtained as compared to MIT rule. The simulation shows that very good conversion can be achieved and at the same time. The temperature inside the reactor does not violate the safety concentrations, even when there are large disturbances in the feed concentrations. The proposed process control system increases the safety of operations by reducing the impact from external disturbances. This will decrease the risk of unnecessary shutdowns of the process operation and also reduce the power consumption in industrial interactive thermal process by effective recycling of heat. In future this interactive thermal process can be tested with other intelligent controller.

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