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DIRECT DIGITAL CONTROL OF BIOREACTOR SYSTEMS

P. MUTHAMILSELVI and T. KARUNANITHI

Department of Chemical Engineering, SRM University, KANCHEEPURAM (T.N.) INDIA

ABSTRACT

Control of bioreactors has achieved importance in the recent years. They are difficult to control, which may be attributed to its nonlinear dynamic behavior. The model parameters of the bioreactor also vary in an unpredictable manner. The complexity of the biochemical processes inhibits the accurate modeling and also the lack of suitable sensors makes the process stability difficult to characterize. This paper is mainly concerned in controlling the bioreactors using analog and digital controllers. The bioreactor system is unstable. This unstable system was stabilized and digital controller such as dead-beat and dahlin controllers were implemented. Then the unstable system was considered as it is and various PID controller-tuning methods were studied. The performance of the proposed control strategy is simulated using SIMLINK ver 2.0 in the MATLAB platform and TUTSIM. This methodology can be implemented without any difficulties, and does not show any overshoot and it is quite robust.

Key words: Bioreactor, Digital controller, Unstable system, Nonlinear, stability.

INTRODUCTION

The efficient control of bioreactor system is becoming more and more important due to the recent significant development in biotechnology, computer science and knowledge engineering. An engineer is always interested in consistently providing large quantities of product of interest over long periods of time. The best way to achieve this goal will be to grow the cells in a bioreactor where the cellular activity can be controlled efficiently. In this regard, significant work is needed to optimize the design and operation of bioreactors to make production more efficient and more economical. The ability to control bioprocesses at their optimal states accurately and automatically is now of considerable interest to many bioindustries since it can enable them to reduce their production cost and increase the yield while at the same time maintaining the quality of metabolic products. It should be noted, however that the control system design of bioreactors is not straight forward due to the lack of accurate mathematical models which can describe the cell growth and metabolite production, the time varying and non-linear nature of the system for batch and fed batch operation, the lack of reliable online sensors which can detect the important state variables, the slow responses of the process in particular for cell and metabolite concentration. The use of computer control has attracted great attention recently since many bioprocesses prevent us from applying the conventional controller. The technological developments in a computer control application in which digital computers are

For correspondence; E-mail: muthamilselvi_p@rediffmail.com

used as control elements resulting high speed of computations with storage capacity providing cost effective process. The features of this computerized bioreactor system includes the flexibility to handle various modes of reactor operation for different organisms, the ability to monitor and control the experimental conditions efficiently and accurately and ease of operation. Designing controllers for such systems is an arduous task. Currently (Direct Digital Control) DDC of process is the major research area and there is not much of work in this. It is challenge task to design a controller for bioreactor system, which is highly complex when compared to conventional chemical processes. Presently there is no serious attempt to design digital control system for bioreactors. Currently the bioreactors are fully automated and hence Direct Digital Control strategy has become essential. Keeping this in mind the following objectives have been proposed for this project. To design a Direct Digital Control (DDC) using Dead-beat algorithm for bioreactor system. To design a Direct Digital Control (DDC) using Dahlin algorithm for bioreactor System. To design a conventional Proportional-Integral-Derivative (PID) controller. To compare the performance of bioreactor for all the above three control system.

Process description

Fermenter model

Many models have been proposed for fermentation processes. *Structured models* attempt to describe the individual organisms in detail but are usually mathematically too complex to be useful for controller design. Significantly simpler *unstructured models* can be obtained by assuming that the fermenter culture consists of a single, homogeneously growing organism. These models usually consist of a few nonlinear ordinary differential equations and are particularly well-suited to the nonlinear control strategies.

A schematic of a continuous fermenter is shown in Figure. 1. We assume that the fermenter has a constant volume, its contents are well mixed, and the feed is sterile. The dilution rate D and the feed substrate concentration S_f are available as manipulated inputs. The effluent cell-mass or biomass concentrations X, substrate concentration S, are the process state variables.

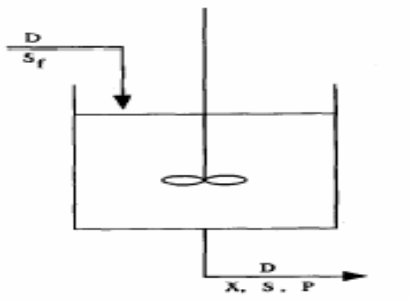

Fig. 1: Continuous fermenter

Mathematical Equation

A Chemostat is a very popular mode of operating a continuous biological reactor. In this

open-loop mode, the flow rate of nutrient to the bioreactor is held constant so that the dilution rate is less than the maximum specific growth rate. The medium contains excess of all but one nutrient. A steady state results when the specific growth rate of microorganism balances exactly with the dilution rate. The steady state is said to be asymptotically stable if the reactor returns to its steady state after small perturbations. However the attainment and maintenance of the desires steady state may be difficult.

Only two variables are chosen to describe the various and complex reaction occurring in the reactor vessel. These are

(i) Biomass concentration and (ii) The limiting substrate concentration

The simplest way to model cell growth will be to consider an unstructured, unsegregated model for cell growth. For this kind of model -

$$r_x = \frac{dX}{dt} = \mu X \qquad \ldots(1)$$

Based on biological data μ(S), the specific growth rate is often defined by a classical function. The specific growth rate μ(S) is related to the concentration of a single inhibitory and growth-limiting substrate, it is represented by Haldane law

$$\mu = \frac{\mu_m S}{K_m + S + K_1 S^2} \qquad \ldots(2)$$

A cell balance on the reactor can be written as -

$$F\mathrm{X} - F\mathrm{X}_f + V\frac{dX}{dt} = r_x \qquad \ldots(3)$$

Dilution rate D is defined as ratio of $\frac{F}{V}$. In terms of dilution rate -

$$D\left(X - X_f\right) + \frac{dX}{dt} = r_x \qquad \ldots(4)$$

Combining equation (1) and (4) -

For a sterile feed $X_f = 0$

$$\frac{d\mathrm{X}}{dt} = \left(\mu - D\right)X \qquad \ldots(5)$$

Including equation (2) in (5) -

Equation (2) may be -

$$\frac{dX}{dt} = \left(\frac{\mu_{\max} S}{K_m + S + K_1 S^2} - D \right) X \quad \ldots(6)$$

A balance on the substrate yields the following equation -

$$FS - FS_f + V \frac{dS}{dt} = r_s V \quad \ldots(7)$$

A yield parameter ($Y_{X/S}$) is defined that relates the amount of cell mass-produced per amount of substrate consumed, and mathematically represented as -

$Y_{x/s}$ = mass of cells produced /mass of substrate consumed = $\frac{r_x}{(-r_s)}$

Equation (7) becomes -

$$\frac{dS}{dt} = D(S_f - S) - \frac{\mu_{\max} S}{K_m + S + K_1 S^2} \frac{X}{Y_{X/S}} \quad \ldots(8)$$

Equation (6) and (8) are coupled by the nonlinear growth rate function μ (S) x, which is the main source of nonlinearity and uncertainty in this simple model.

Kinetic coefficients and feed substrate concentration representative of *candida utilis* yeast grown with sodium acetate as a carbon sources were summarized by Agarwal and Lim[1].

The system parameters are :

Y - 0.4g/g, S_f - 4 g/L, μ_{max} - 0.53 h^{-1}, K*m* - 0.12g/L, K_1 - 0.4545 g/L, D - 0.3 1/h.

Multiple steady states

The steady state equations are

$$\left(\frac{\mu_m S}{K_m + S + K_1 S^2} - D \right) = 0 \quad \ldots(9)$$

$$D(S_f - S) - \left(\frac{\mu_{\max} S}{K_m + S + K_1 S^2} \right) \left(\frac{X}{Y_{X/S}} \right) = 0 \quad \ldots(10)$$

The steady -state solution of above equation gives the following multiple steady states solutions.

Case 1 : x 0 = [0; 4]

Case 2 : x 0 = [0.995; 1.512]

Case 3 : [1.530163; 0.174593]

Methodology

Design strategy is carried out in two different ways

(i) Digital control system is used only for stable system. The unstable System is stabilized and then the Direct Digital control strategy such as Dead-beat and Dahlin controller can be adopted.

(ii) For the conventional PID control system designs are carried out for both unstable and stabilized system

Linearization of equation -

$$\frac{dX}{dt} = \left(\frac{\mu_{\max} S}{K_m + S + K_1 S^2} - D \right) X \qquad \ldots(11)$$

$$\frac{dS}{dt} = D\left(S_f - S\right) - \frac{\mu_{\max} S}{K_m + S + K_1 S^2} \frac{X}{Y_{X/S}} \qquad \ldots(12)$$

around the operating point (0.9951,1.5122) and Laplace transformation of the resulting equations gives the transfer function relating the output variable deviation and manipulated variable deviation in laplace domain -

$$\frac{\Delta X}{\Delta D} = \frac{K_p \left(\tau_o S + 1\right)}{\left(\tau_o S + 1\right)\left(\tau S - 1\right)} \qquad \ldots(13)$$

$$\tau_o = \frac{1}{\overline{D}} \; ; \quad \tau = \frac{Y_{x/S}}{\overline{X}\overline{\varepsilon}} \; ; \quad K_p = -\frac{Y_{X/S}}{\overline{\varepsilon}} \; ; \quad \overline{\varepsilon} = -\frac{\overline{\partial \mu}}{\partial S}$$

where - denotes that the terms are to be evaluated at the steady state condition. The stable pole gets cancelled with the stable zeros to give -

$$\frac{\Delta X}{\Delta D} = \frac{K_p}{\tau S - 1} \qquad \ldots(14)$$

Considering a measurement delay of L units we get the transfer function as -

$$\frac{\Delta X}{\Delta D} = \frac{K_p e^{-s}}{\tau S - 1} \qquad \ldots(15)$$

We get transfer function for a given condition -

$$G_S = \frac{-5.86e^{-s}}{5.89S - 1} \quad \ldots(16)$$

We first stabilize the unstable process by using a proportional controller. The controller gain K_C for an unstable first order plus time delay system is calculated from the expression given by De Paor and O'Malley[2].

$$K_{c,i} = \frac{(\tau / L)^{0.5}}{K} \quad \ldots(17)$$

The closed loop transfer function

$$G_i = \frac{G_c G_p}{1 + G_c G_p} \quad \ldots(18)$$

$$G_i = K_{c,i} \quad \ldots(19)$$

$$G_p = \frac{Ke^{-Ls}}{\tau S - 1} \quad \ldots(20)$$

On approximating exp (-Ls) by (1-Ls) in the denominator of the closed loop stabilized transfer function of the system, we get a first order plus time delay transfer function.

$$G_i = \frac{K' \exp^{(-LS)}}{\tau S + 1} \quad \ldots(21)$$

where

$$K' = \frac{Kk_{c,i}}{(Kk_{c,i} - 1)} \quad \tau' = \frac{(\tau - Kk_{c,i}L)}{Kk_{c,i} - 1}$$

Using above formula, the transfer function is found -

$$G(S) = \frac{1.7e^{-S}}{2.4S + 1} \quad \ldots(22)$$

For the purpose of controller design, the dynamics of the processes are described by first order plus time delay models.

Digitalcontrolalgorithm

Step 1 : Take the material balance of chemo stat

Step 2 : Linearise the nonlinear equation around unstable equilibrium point

Step 3 : It is give unstable transfer function

Step 4 : Stablize the unstable transfer function and get stable transfer function

Step 5 : Multiply the process transfer unction by the transfer function of ZOH

Step 6 : Take the Z transfer form

Step 7 : Substitute in the digital controller equation

Step 8 : Invert the equation to give the algorithm, to compute the controller output.

Step 9 : Implement the controller output by using Z blocks in TUTSIM.

Step 10 : Analysis the response.

Conventional controller

For stabilize system

Ziegler and Nichols have developed PID tuning methods back in the early forties based on open loop tests (less known than for example the Cohen-Coon formulas) and also based on a closed loop test, which is maybe their most widely known achievement.

The open loop method allows calculating PID parameters from the process parameters. The procedure:

Step 1: Make an open loop plant test (e.g. a step test)

Step 2: Determine the process parameters: Process gain, dead time, time constant

Step 3: Calculate the parameters according formulas:

For unstable system

Various methods of PID controller setting is found out for the unstable transfer function and the performance of the bioreactor is compared.

Simulation

Before implementing any algorithm on real time process, it is advisable to study the process by simulation. The effect of controller parameter, robustness is found out by simulation. The ringing is also essential parameter for direct digital controller.The conventional PID controller tuning is also implemented by using MATLAB software. One of these simulation programs to be discussed here is TUTSIM.TUTSIM is a computer simulation program that provides a numerical and graphic representation of linear or piecewise linear systems. It can also handle nonlinear functions. A problem is solved by constructing. A TUTSIM model consisting

of interconnected blocks that matches the block diagram of the control system. The block diagram for the model resembles an analog computer diagram, but all the computations are done numerically by the digital computer. Once a TUTSIM model has been created, it is very easy to change its structure and parameters. TUTSIM also provides 'Z' blocks for use in sampled –data system. The use of this software is similar to the use of the analog computer in that computing blocks are selected and connected to one another in a manner similar to the connecting of analog computing elements by wires.

RESULTS AND DISCUSSION

Digital controller

Dead-beat controller

Rise time = 3 sec,

Settling time = 3 sec,

There is no decay ratio and overshoot.

Dahlin controller

Rise time = 6.9 sec,

Setting time = 7 .2 sec

There is no decay ratio and overshoot.

Conventional controller

Stabilize system

$$G(S) = \frac{1.7e^{-s}}{2.4S + 1}$$

For stabilize system,

The controller performance is analyzed in terms of rise time, decay ratio, overshoot, settling time. The direct digital controller gives no overshoot, decay ratio. The settling time is also lesser compared to conventional controller. The direct digital control gives the best performance when compared to that of Ziegler and Nichols method.

For unstable system, the controller performance is analyzed in terms of integral of the square error (ISE). Padama See et al.[3] and Chidambaram[4] methods give lesser value compared to linearised model and De Paor O'Malley. So Padama See & Chidambaram are significantly better than the method proposed by De Paor & O'Malley and Linearised model.

Table 1: Performance crieteria for stabilize system

Parameter	*Values*
Rise time	2.8 sec
Decay ratio	0.3725
Overshoot	0.51
Settling time	13 sec

Unstable system

ISE values for unstable system (K_p = -5.89; τ = 5.86) using PID controller

Table 2: Performance criteria for unstable system

Method	**ISE**
PC	2.711
LM	16.82
DM	80.51

Where PC (Padma Sree & Chidambaram), LM (Linearised Model) and DM (De Paor & O'Malley).

CONCLUSION

The digital controllers are highly accurate fast and flexible, and use of time-sharing concept of digital computer results in economical cost and space. The digital components are less affected by noise, nonlinearities and transmission errors of noisy channel. The methodology developed can be implemented without any difficulties. The closed loop response will not show any overshoot and the setting time also will be less. Also the control system is robust.

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