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Performance Evaluation of Stable and Unstable Biochemical Reactor Process

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Abstract ***- Bioreactor control has become an active area of research in recent years.This paper deals with the operation, mathematical modeling and IMC based design of a biochemical reactor. The dynamic behaviour was studied by changing the main operating parameters – dilution rate and its disturbance rejection for a step input change using autotuning of the controller is determined. We have found that the regimes strongly depend on the operating conditions. The bioreactor model was implemented in Matlab Simulink and the results of simulation for a stable and unstable processes are presented comparatively. Transient response characteristics for the processes are evaluated and discussed.***

Index Terms—Biochemical reactor, autotuning of PID controller, stable operating point, mathematical modelling, Transient response

I. INTRODUCTION

Bioreactor is a device or system that supports a biologically active environment. It is a vessel in which a chemical process is carried out which involves organisms or biochemically active substances derived from such organisms. This process can either be aerobic or anaerobic. These bioreactors are commonly cylindrical, ranging in size from liters to cubic meters, and are often made of stainless steel. A (2×2) bioreactor process having two states namely biomass (x_1,g/L) and substrate concentrations (x_2 g/L) are controlled by dilution rate ($D=F/V$ (hr^{-1})) and feed substrate concentration (x_{2f} ,g/L) at the various operating points of the bio-process. The parameters like specific growth rate (μ), yield constant(Y) & saturation rate constant (k_1, k_m) of the kinetic models are either inadequately determined or vary from time to time regarding the process operation. The aforesaid parameters have been considered as disturbance to the process. The disturbance rejection has given a consideration in selecting suitable control configuration for the continuous bioreactors. The primary aim of a continuous bioreactor is to avoid wash out condition which ceases reaction. This may be done either by controlling cell mass or substrate concentrations. Bioreactor control has been an active area of research over a decade or so. For optimization of cell mass growth and product formation continuous mode of operation of bioreactors are desirable but not the traditional fed batch bioreactors[1].Bioreactors operated under continuous steady state conditions are a versatile tool for characterization of micro organism growth kinetics and stoichiometry [2]and[3]. IMC (Internal model control) strategy integrates the plant model and its inverse in a feedback control loop.
NN based IMC scheme is used, especially for disturbance rejection problem. Application of NN based controllers in chemical processes have gained huge momentum as a result of focused R&D activities taken up by several researchers[4].In recent works, for a MIMO bioreactor in which the closed loop insensivity for the parameter variations, a variable structure controller was designed[5]. Control of bioreactors is implemented using analog and digital controllers[6]. The paper is organized as follows: Section 2 explains mathematical modelling of a bio-reactor. In Section 3 stable and unstable operating points are analyzed. Section 4 describes the IMC based design approach of PID controller and its simulation results. Concluding remarks are given in Section 5 followed by references.

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II. MATHEMATICAL MODELLING OF A REACTOR

A typical control and instrumentation diagram of the bioreactor with biomass concentration as the measured output is shown in figure1.A (2×2) bioreactor process having two states namely biomass (x_1,g/L) and substrate concentrations (x_2 g/L) are controlled by dilution rate (D=F/V (hr^{-1})) and feed
substrate concentration (x_{2f} g/L) at the various operating points of the bio-process.The parameters like specific growth rate (μ), yield constant(Y) & saturation rate constant (k_1, k_m) of the kinetic models are either inadequately determined or vary from time to time regarding the process operation. The aforesaid parameters have been considered as disturbance to the process. The disturbance rejection has given a consideration in selecting suitable control configuration for the continuous bioreactors

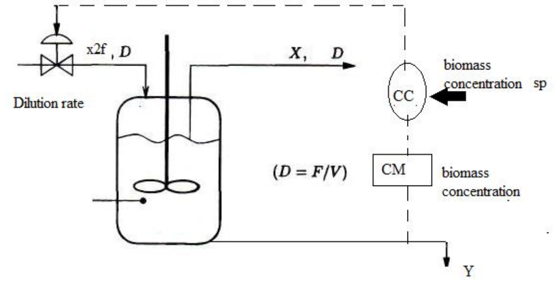

Figure 1 Schematic diagram of a continuous bioreactor

The modelling equations of a bioreactor are given in equations (1),(2).

$$\frac{dx_1}{dt} = (\mu - D)x_1 \quad (1)$$

$$\frac{dx_2}{dt} = \frac{D(x_{2f} - x_2) - \mu x_1}{Y} \quad (2)$$

Where the state variables are x_1,the biomass concentration and x_2 ,the substrate concentration. The manipulated input is D,dilution rate and the disturbance input is x_{2f},substrate feed concentration.

There are 2 possible solutions given by equations 3&4, which represents specific growth .They are monod and substrate inhibition.

$$\frac{dx_2}{dt} = \frac{\mu_{\max} x_2}{K_m + x_2} \quad (3)$$

$$\mu = \frac{\mu_{\max} x_2}{K_m + x_2 + K_1 x_2^{\,2}} \quad (4)$$

III. DYNAMIC BEHAVIOR OF A REACTOR

Table 1 shows the parameters to find the steady state conditions for the model shown by equations 1&2.The steady state dilution rate is D=0.3 $hr^{-1}$and the feed substrate concentration is 4.0 g/litre.

Table 1: parameters used for modelling of a bioreactor

s.no	Parameter value
1	μ_{max}=0.5 hr^{-1}
2	k_m =0.12 g/litre
3	k_1=0.4545Litre/g
4	Y=0.4

Table 2: Operating conditions of bioreactor

s.no	Steady state	Biomass concentration	Substrate concentration	stability
1	Equilibrium 1	X_{1s}=0	X_{2s}=4.0	stable
2	Equilibrium 2	X_{1s}=0.995	X_{2s}=1.5122	unstable
3	Equilibrium 3	X_{1s}=1.53	X_{2s}=0.175	stable

Table 2 shows the operating conditions for a dilution rate of 0.3hr^{-1}.Steady state condition 1 is a washout case since no reaction was occurred.

IV. STATE SPACE MODEL OF A REACTOR

The state space model matrices are

$$A= \begin{bmatrix} \mu - D_s & x_{1s}\mu_s' \\ \dfrac{-\mu_s}{Y} & -Dx - \dfrac{\mu_s x_{1s}}{Y} \end{bmatrix}$$

$$B= \frac{x_{1s}}{x_{2f} - x_{2s}}$$

$$\mu_s' = \frac{\partial \mu}{\partial x_{2s}} = \frac{\mu_{\max} K_m}{(K_m + x_{2s})^2}$$

A Stable operating point

The following initial condition is used for Simulation X(0)= $\begin{bmatrix} 1.53 \\ 0.175 \end{bmatrix}$ .The state space model for the corresponding to stable operating point is

$$A= \begin{bmatrix} 0 & 0.9056 \\ -0.7500 & -2.564 \end{bmatrix}, \quad B= \begin{bmatrix} -1.5301 \\ 3.8255 \end{bmatrix}$$

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

Eigen values are determined for the above matrix and its values are -0.3,-2.264hr^{-1}.so the system is stable. The transfer function relating the dilution rate to the biomass concentration is determined using Matlab and is given in equation (5).

$$Gp(s)= \frac{-1.5302S - 0.4590}{S^2 + 2.564S + 0.6792} \quad (5)$$

After the pole zero cancellation, the process transfer function will be Gp(s)= $\frac{-0.6758}{0.4417S + 1}$ .The process is controlled at this operating point.

B Unstable operating point

The steady state used by the initial condition given by the equation is x(0)= $\begin{bmatrix} -0.995 \\ 1.5122 \end{bmatrix}$

At this point the state space model is

$$A= \begin{bmatrix} 0 & -0.0679 \\ -0.7500 & -0.1302 \end{bmatrix}$$

$$B= \begin{bmatrix} -0.9951 \\ 2.4878 \end{bmatrix}$$

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

D=0

Eigen values are determined for the above matrix and its values are -0.3, 0.169836hr^{-1}.so the system is unstable. The transfer function given by equation (6) relating the dilution rate to the biomass concentration is determined using Matlab

$$Gp(s)= \frac{0.9951S - 0.2985}{S^2 + 0.1302S - 0.0509} \quad (6)$$

After the pole zero cancellation, the process transfer function is given in equation (7).

$$Gp(s)= \frac{5.8644}{-5.888S + 1} \quad (7)$$

V.DESIGN OF CONTROLLER FOR A STABLE PROCESS AND ITS SIMULATION ANALYSIS

A. Auto tuning method of PID controller

The PID controller parameters are determined using auto tuning method, from which Kc=-2.2742, Ki=-8.148.For the actual bioreactor system, both dilution rate and substrate concentration have great impacts on the output (yield).

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In this study the simulation result of output responses of a process with a dilution rate of D = 0.3 h^{-1} is presented in figure 3.Figure 4 shows the output response for disturbance rejection held at 4th instant.For different values of D the time reponse is obtained and is shown in figure 5.

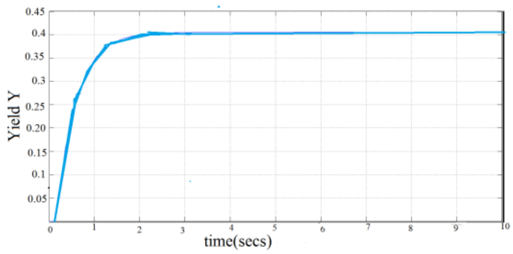

Figure 3 Step input response of the bioreactor with dilution rateof D = 0.3 h–1 bounded between 0 and -0.6 for an yield of 0.4

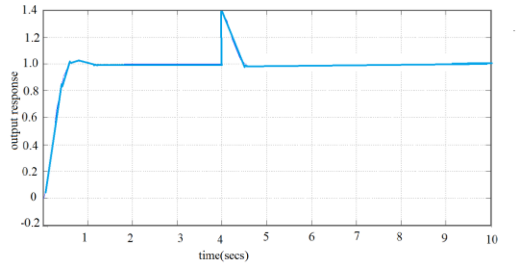

Figure 4 Step input response of the bioreactor with dilution rate of D = 0.3 h–1 bounded between 0 and -0.6

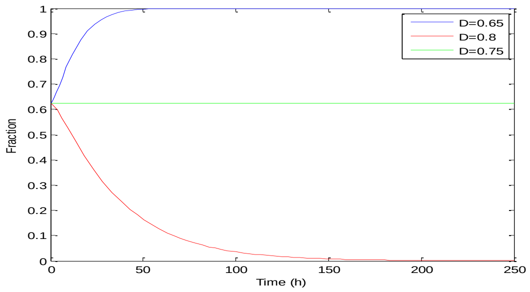

Figure 5 Simulink responses of the bioreactor for various values of dilution rate D

B. IMC based PID controller design and simulation analysis for a stable process

For a stable I order process of the form $G_p(s) = \frac{K_P}{\tau_P S+1}$ (where Kp is the process gain and τ_p is the process time constant),with no delay has the following PI tuning parameters $K_c=\frac{\tau_P}{K_P\lambda}$ and $\tau_i=\tau_p$,where K_c is the proportional gain and τ_i is the integral time constant.

For a bioreactor process $Gp(s) = \frac{-0.6758}{0.4417S+1}$, the tuning parameters for different values of λ are calculated .PI controller is tuned using those values and its step input responses are shown in figure 6.

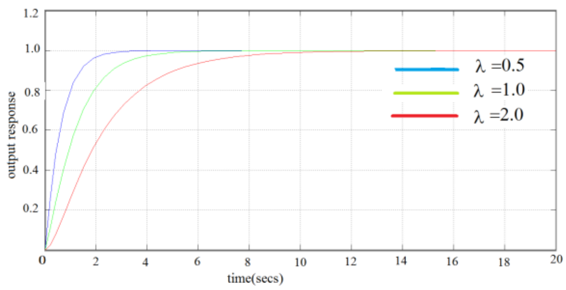

Figure 6: Step input response of the bioreactor with dilution rate of D = 0.3 h^{-1} for different values of λ(=0.5,1and 2)

Analyzing the results of the simulation, the effect of the change in the value of λ (the tuning parameter), has a major impact on the output response. The controller performance is analyzed in terms of rise time, peak time, overshoot, settling time and ISE and it is given in Table 3.It is observed that the response has no overshoot and the remaining parameters are increasing with the increase of λ for a stable process.

C. IMC based PID controller design and simulation analysis for an unstable process

Considering the unstable process of the form

$$Gp(s)=\frac{K_P}{-\tau_P S+1}$$ is tuned based on IMC design

Analysis and it has $\gamma=\lambda(\frac{\lambda}{\tau_P}+2)$, $K_c=\frac{-(\lambda+2\tau_P)}{K_p\lambda}$

$\tau_i=\gamma=\lambda(\frac{\lambda}{\tau_P}+2)$

Consider an unstable process

$$Gp(s)=\frac{5.8644}{-5.888S+1}$$ of a Bioreactor.

PI controller is tuned based on IMC design analysis and its tuning parameters are calculated using the formulae given above for different values of λ. Its step input responses are shown in figure 7.

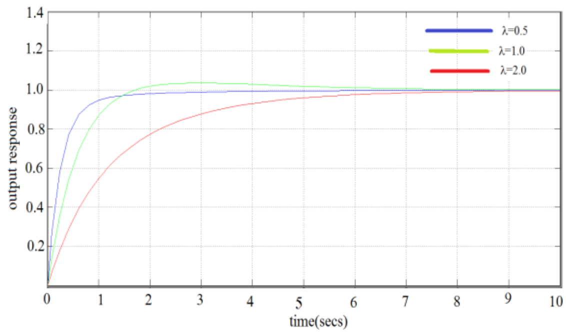

Figure 7: Step input response of the bioreactor with dilution rate of D = 0.3 h^{-1} for different values of λ=0.5,1.0and 2.0

Based on the analysis, it is observed that as λ Increases, the settling time,rise time and also overshoot increases.The response is faster for small values of λ than for larger values and it is given in Table 3.

Table 3 Performance Analysis of Bio-Reactor

Process/	Stable process			Unstable process		
parameters	λ=0.5	λ=1.0	λ=2.0	λ=0.5	λ=1.0	λ=2.0
Rise time	1.1	2.2	4.4	0.496	0.764	1.57
Settling time	1.96	3.92	7.83	4.57	5.9	11.4
%overshoot	0	0	0	2.91	9.59	7.65
Peak time	1	1	1	1.03	1.1	1.08
ISE	0.3092	0.6552	1	0.1365	0.2607	0.6401

VI. CONCLUSION

The performance of the tuning scheme is studied for maximum biomass production rate by simulating the non-linear model equations of the bioreactor for various values of D.

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Controller is tuned using auto tuning and its output responses are shown for both set point tracking and disturbance rejection. IMC Based PID design procedure is applied for controlling both stable and unstable continuous bioreactor and its simulation results for various λ are plotted. The performance of the control strategy is analyzed in terms of transient parameters and tabulated.Output response is sluggish as λ increases. The methodology developed can be implemented without any difficulties.

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