# Adaptive Control of a Bioreaactor Using Gain Scheduling

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**ABSTRACT**
Bioreactor is the heart of many biotechnological systems that are used for agricultural, environmental, industrial and medical applications. The aimed of this work was to use linearized technique for adaptive control of a bioreactor using gain scheduling.The characteristics of the system without control shows the continuous instability of the system; but in the presence of adaptive control at different characteristic gain schedule conditions and linearization of the closed loop system, the system stability was achieved at a shorter time of 0.571 seconds with an overshoot of 0.201 %. The characteristic parameters were found to be $K_p$= 95, $K_I$= 6, $K_D$ = 5 and gain = 5.A step response to the system was used for perturbation. Bode plot, Nichole's plot and Nyquist plot were used to determine thecharacteristic behaviour of the systemto perturbation. Simulation was done using Simulink linear analysis tool. To study the performance and stability of the system, a closed-loop linear system was used. The linearization occurred at the critical operating point of t=34.9sec. The stability, achieved at 0.571 sec, had a delay margin of 0.0261 s, phase margin of $0.209^0$, and "yes" confirmation of the closed loop stability at frequency of 0.14 rad/sec. Also, the positive value of the phase margin of $+0.209^0$ as seen by the Bode plot, indicates good stability of the gain schedule control approach.
**Key Words:**GainScheduling, Bioreactor, Adaptive Control, Stability, Close Loop.

## I. INTRODUCTION

A bioreactor is designed and operated to provide the environment for product formation selected by scientists, bakers, or winemakers. It is the heart of many biotechnological systems that are used for agricultural, environmental, industrial and medical applications (Schaechter & Lederberg, 2004). All the bioreactors are of great importance due the generation of products in this equipment, which are the heart of the bioprocesses (Cinar et al, 2003). In some cases, the bioreactor may be applied for biomass production (e.g. single cell protein, Baker´s yeast, animal cells, microalgae); for metabolite formation (e.g. organic acids, ethanol, antibiotic, aromatic compounds, pigments); to transformation of substrates (e.g. steroids) or even for production of an active cell molecule (e.g. enzymes). The system that is based on the mammalian or plant cells culture iscalled tissue cultures, while those based on the dispersed non-tissue-culture forming culture of the micro-organisms (bacteria, yeast, fungi) are loosely referred to as "microbial" reactors (bioreactor, fermenter). In the enzyme reactors, no live cells are used for the transformation of the substrate. Most often, these reactors employ immobilized enzymes where the solid supports are used to entrap (internally) or attach (externally) the enzyme (biocatalyst) so that it can be repeatedly used to economize the enzyme consumption (Bhattacharyya et al., 2008).

### 1.1 Concept of Gain Scheduling

Gain scheduling is an efficient approach to control of nonlinear systems, the main motivation is in a possibility to transform a complex nonlinear control problem to a computationally tractable one (Hypiusová & Rosinova, 2019). Gain scheduling control scheme is often adopted for a linear parameter varying model of the controlled system to simplify the controller design procedure. (Hypiusová & Rosinova, 2019). Gainscheduling is also a control technique where process dynamics can be associated to the value of some process variables related, in this case, to the operating point, so that the controller parameters can be computed from these variables. (Gallego et al. 2010).It is often possible to find measurable variables that correlate well with the changes in

process dynamics.  It is also possible to reduce the effects of parameter variation simply by changing the controller parameters as a function of the auxiliary variables gain (Karl &Wittenmark, 1994). This approach is called gain scheduling as thescheme was originally used to measure the gain and then change the controller to compensate for thechanges in process gain

### 1.2 Adaptive System

An adaptive system is one that can modify its parameters or behaviour in response to the changes in the dynamics of the process and the character of the disturbances. Adaptive Control is a technique with adjustable parameters and a gain schedule mechanism for adjusting the parameters. The controller becomes non-linear because of the parameter adjustment mechanism. An adaptive control system can be thought of having two loops. One loop is a normal feedback with the process and the controller.   The other is the parameter adjustment loop (Karl andWittenmark, 1994). An adaptive control system provides a means of continuously monitoring the system's performance in relationto the optimum condition and a means of automatically modifyingthe system parameters  to approach this optimum.

The criterion for adaptation is improved performance. Performance quality is evaluated by considering the speed of process recovery from a disturbance or set-point change with constraints on processovershoot. Mathematically, this amounts to evaluating the closed loop Eigen values of the system, linearized about an operating point (Bakke, 1994). Depending on the manner in which, adaptation is performed, there are different types of adaptive schemes. A nonlinear level control example is used to illustrate the theory and utility of adaptive technique.

Earlier research of **Ahmed andDorrah (2018)**shows that closed-loop nonlinear system can be linearized by the Simulink linear analysis tool at critical operating point (time) and the stability can be studied.The purpose of their paper is to control the trajectory of the nonlinear missile model in the pitch channel by using Fractional PID controller (FPID) and Gain Schedule. In their work, FPID and GSFPID with nonlinear missile model are designed where their parameters are tuned by Simulink design optimization in the MATLAB toolbox. Within the simulation results, the optimization method gives the optimal parameters that achieve the best tracking with step unit reference signal. The GSFPID controller compensates the restrictions that represent physical limits of

actuators in the pitch channel. **Yilmaz et al. (2019)**also reported from their paper on "gain-scheduling"control strategy for Z-source inverter used in traction motors. They introduced an iterative reduction-based heuristic algorithms (IRHA) for optimization of controller parameters. Since it is difficult to implement a stabilizable optimization with the conventional heuristic algorithm, optimum design can be achieved via creating stable sets by employing IRHA. In this optimization method, they created a new reduced subset at the end of each iteration, thereby reducing computational complexity.

**Gallego et al. (2019)** in their work investigated "Gain-scheduling model predictive control of a Fresnel collector field"located at the Escuela Superior de Ingenieros de Sevilla. In their work, simulation results were provided showing the effectiveness of the proposed strategy. Furthermore, two real tests are presented. These tests show that the proposed controller successfully tracks the desired set-points and efficiently rejects the multiple disturbances affecting the solar field. Hence, a gain-schedule linearizes the plant, thereby eliminating the disturbances in the system.

**Yarmohammed et al. (2019)**presents a novel method for designing a common gain-scheduled controller covering both partial- and full-load operating conditions that directly leads to a smooth transition between different operation regions.

**Kumar et al. (2019)** investigated the Temperature control of fermentation bioreactor for ethanol production using IMC-PID controller a nonlinear bioreactor   process   model. The temperature of the bioreactor was successfully controlled by proposed  controllerin both set-point and disturbance change.  Hence, the non-linearity of this system needs adoption of a linearization control scheme which fully adopts gain-schedule approach.
In this work, adaptive method and linearization technique to simulate a gain scheduling controller for the control of a bioreactor were applied.

## II.    METHODOLOGY
**The bioreactor model**
 Figure 1 is a schematic diagram of the unstructured bioreactor whose model was developed and used in this work.
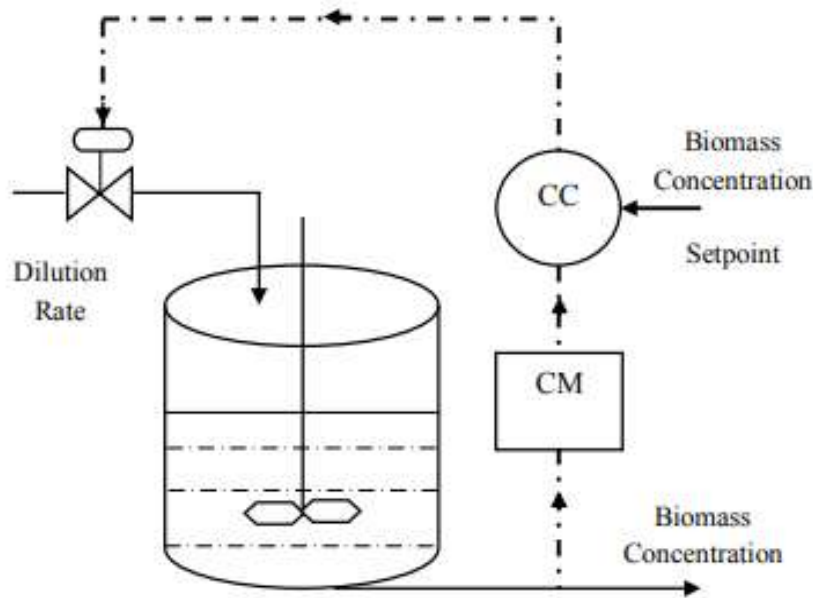
Figure 1: Biochemical Reactor

The simplest way to model cell growth is to consider an unstructured, unsegregated model for cell growth. For this kind of model rate of cell growth is given by

$$r_x = \frac{dX}{dt} = \mu X$$

(1)

The specific growth rate $\mu(S)$ is related to the concentration of a single inhibitory and growth-limiting substrate, given by Haldane's law

$$\mu = \frac{\mu_m S}{K_m + S + K_1 S^2}$$

(2)

A cell balance on the reactor can be written as

$$FX - FX_f + V\frac{dX}{dt} = r_x$$

(3)

Dilution rate D is the ratio of V/F. This is used to simplify Equation 3.3 to obtain

$$D(X - X_f) + \frac{dX}{dt} = r_x$$

(4)

Equations (1) and (4) can be combined
For a sterile feed $X_f = 0$

$$\frac{dX}{dt} = (\mu - D)X$$

(5)

Equation (3.2) is substituted in (3.5) to obtain

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

(6)

A balance on the substrate yields the following equation:

$$FS - FS_f + V\frac{dS}{dt} = r_s V$$

(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:

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

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

(8)

Laplace transformation of the resulting equation gives the transfer function relating the output variable deviation and manipulated variable deviation in Laplace domain:

$$\frac{\Delta X}{\Delta D} = \frac{K_p(\tau_o S + 1)}{(\tau_o S + 1)(\tau S - 1)}$$

(9)

Where:

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

Simplifying Eqn. (3.9), we have:

$$\frac{\Delta X}{\Delta D} = \frac{K_p}{\tau S - 1}$$

(10)

We now Introduce a measurement delay of L units to obtain the transfer function of Equation 11;

$$\frac{\Delta X}{\Delta D} = \frac{K_p e^{-s}}{\tau S - 1}$$

(11)

Where x is biomass (cell) concentration, D is the dilution rate. For substrate inhibition model, the following parameters from the work of (Rajinikanth & Latha, 2010) were used: μ max = 0.53 hr. $Y_{x/s}$ = 0.4, $K_c$ = 0.11319, and $X_\varepsilon$ = 0.06826. The steady state dilution rate is Ds = 0.3 h$^{-1}$ (the residence time is 3.33 h) and the feed substrate concentration is $x_{2fs}$ = 4.0 g/l. The dilution rate is taken as the manipulated variable in order to control the cell mass concentration at the unstable steady state. A delay of 1h was assumed as in (Rajinikanth and Latha, 2010).
Where:

$$K_p = \frac{Y_{X/S}}{K_c(Y_{X/S} - 1)}$$

(12)

$$K_p = \frac{0.4}{0.11319(0.4 - 1)} = -5.89$$

And

$$\tau = \frac{Y_{X/S}}{X_\varepsilon}$$

(13)

$$\tau = \frac{0.4}{0.06826} = 5.86$$

The local linearized first order plus time delay transfer function model for the unstable bioreactor is:

$$\frac{\Delta X(s)}{\Delta D(s)} = \frac{K \exp^{-ds}}{(\tau s - 1)} = \frac{-5.89 \exp^{-1s}}{(5.86s - 1)}$$

(14)

### 2.1 GAIN SCHEDULING CONTROL

It is often possible to find measurable variables that correlate well with the changes in process dynamics. It is then possible to reduce the effects of parameter variation simply by changing the controller parameters as a function of the auxiliary variables. This approach, called gain scheduling, measures the process gain changes, i.e. schedule the controller to compensate for the changes in process gain. A block diagram of a system with gain scheduling is shown in Figure 2 ( Astrom & Bjorl, 2001).
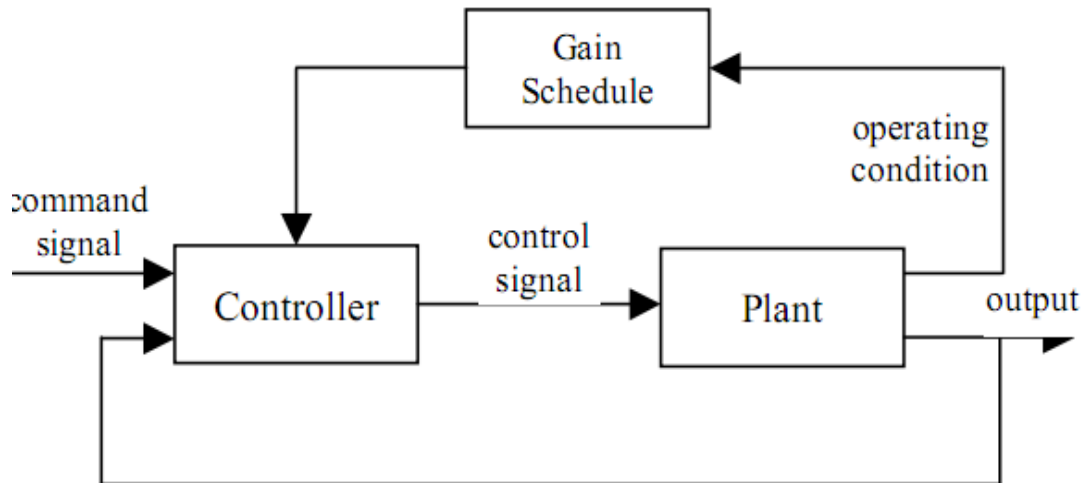


Figure 2: Block Diagram of a System with Gain Scheduling

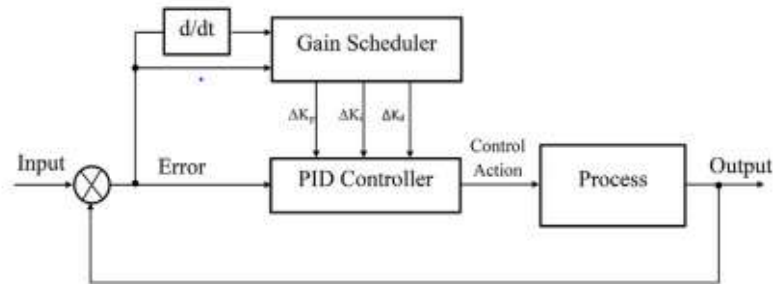In the SIMULINK environment, the block diagram can be presented as shown in Figure 3:

Figure 3: Schematic Diagram of aGain Scheduled PID Controller.

The system can be viewed as having two loops. There is an inner loop consisting of the process and the controllerand an outerloopthat adjusts the controller parameters based onoperating conditions. Gain scheduling can be regarded as a mapping from processparameters to controller parameters. It can be implemented as a function, or a lookup table. Gain scheduling can thus be viewed as a feedback control system in which the feedback gainsare adjusted by using feedforward compensation. ( Astrom & Bjorl, 2001).Gain Scheduling is a special case of adaptive control, in which the controller parameters are modified to compensate for the changes in process gain.

- Since the gain schedule is viewed as a form of feedback control system, the closed loop system is first simulated to convergence
- Linearizing the non-linear (second order) bioreactor model plant at different conditions to obtain linear models that describes plant behaviour in the vicinity of the operating point that a linear model corresponds to. Hence, this linearization was done in the MATLAB SIMULINK environment, thereby observing the behaviour and stability of the process via the step response plot, Bode plot, Nyquist plot and Nichols plot obtained during the simulation.

**2.2 Design of the Gain Schedule:**

## III. RESULTS AND DISCUSSION

**3.1 Simulation Results**

**Table 1: Results of the Open Loop System and Linearized System**

| Characteristics | Open loop bioreactor system | I/O: Step to Transfer Fcn. |
|---|---|---|
| Rise time (sec) | 3.86 | 328 |
| Settling time (sec) | 6.88 | 345 |
| Peak amplitude | >= 0.65 at time > 16 sec | $6 \times 10^{26}$ |
| Overshoot (%) | 0.00 | 89 |
| Final value | 0.65 | $6 \times 10^{26}$ |

**Table 2: Maximum Stability Results as depicted by each Plot**

| Plot | Phase margin (deg) | Delay margin (sec) | At frequency (rad/sec) | Closed loop stable |
|---|---|---|---|---|
| Bode | 0.209 | 0.0261 | 0.14 | Yes |
| Nyquist | 0.209 | 0.0261 | 0.14 | Yes |
| Nichole | 0.209 | 0.0261 | 0.14 | Yes |

**Table 3: Tuning Parameters and Characteristics Performance of Gain-Schedule Controller**

| Tuning Parameters | Characteristics | | | |
|---|---|---|---|---|
| $K_P = 5$, $K_I = 1$, $K_D = 3$, | Rise time (sec) | Settling time (sec) | Peak amplitude | Overshoot (%) |
| | 1.09 | 13.3 | 0.533 | 6.52 |
| $K_P = 6$, $K_I = 2$, $K_D = 5$ | Rise time (sec) | Settling time (sec) | Peak amplitude | Overshoot (%) |

| | 1.13 | 9.11 | 0.529 | 5.78 |
|---|---|---|---|---|
| $K_{P=7}, K_I = 3, K_D = 6$ | Rise time (sec) | Settling time (sec) | Peak amplitude | Overshoot (%) |
| | 1.07 | 7.6 | 0.526 | 5.3 |
| $K_P = 8, K_I = 4, K_D = 7$ | Rise time (sec) | Settling time (sec) | Peak amplitude | Overshoot (%) |
| | 1.03 | 6.85 | 0.524 | 6.85 |
| $K_{P=9}, K_I = 5, K_D = 8$ | Rise time (sec) | Settling time (sec) | Peak amplitude | Overshoot (%) |
| | 0.995 | 9.13 | 0.522 | 4.44 |
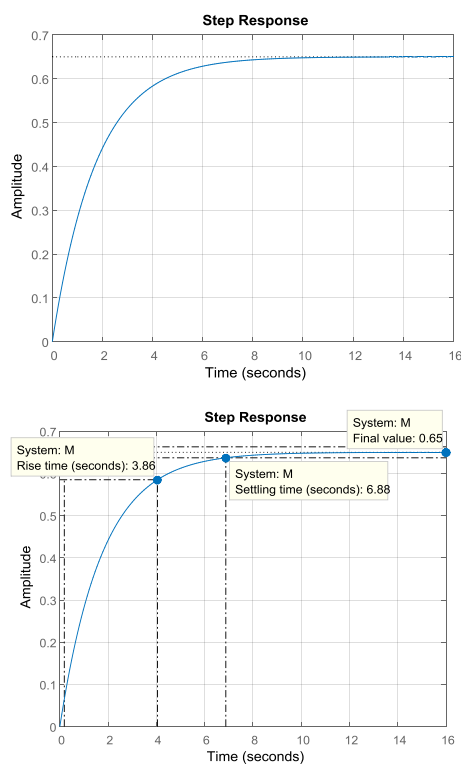




Figure 4:Open Loop Step Response for the Bioreactor System for Waste Water Treatment
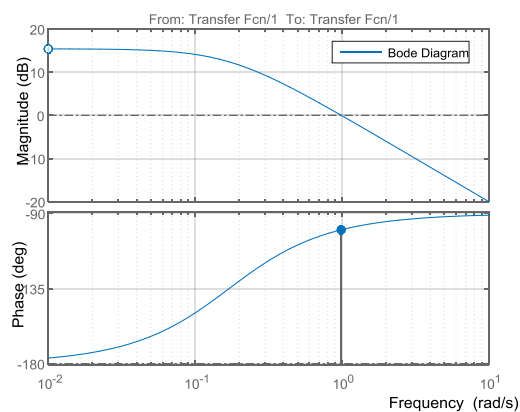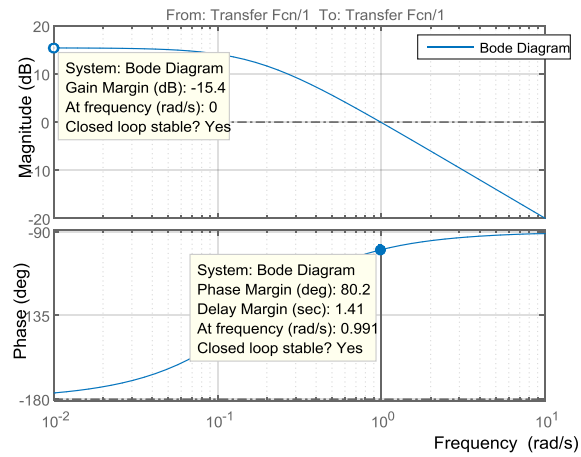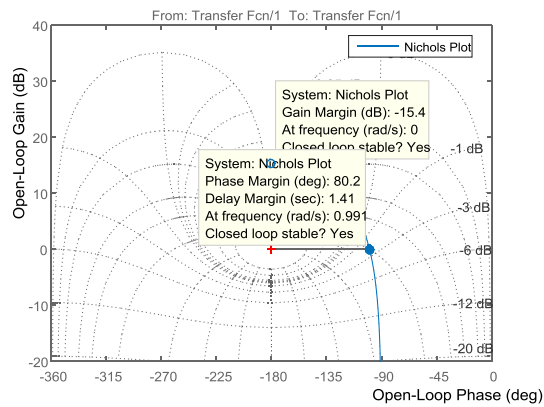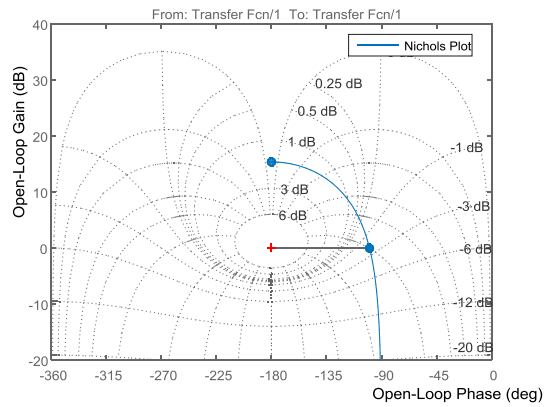
Figure 5: Bode Diagram
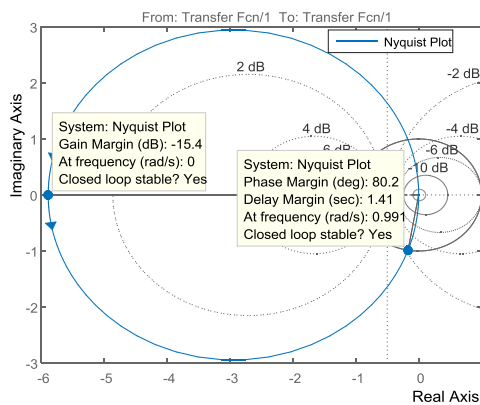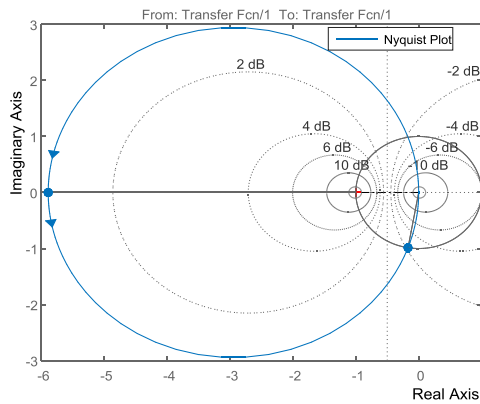




Figure 6: Nyquist plot
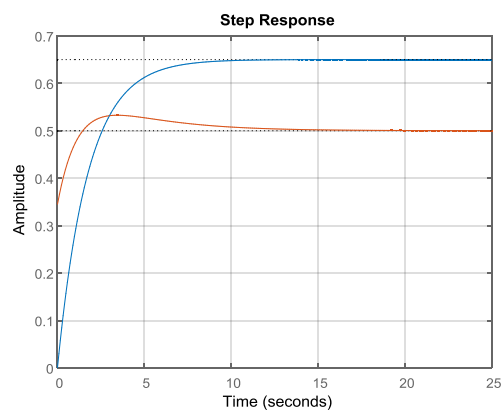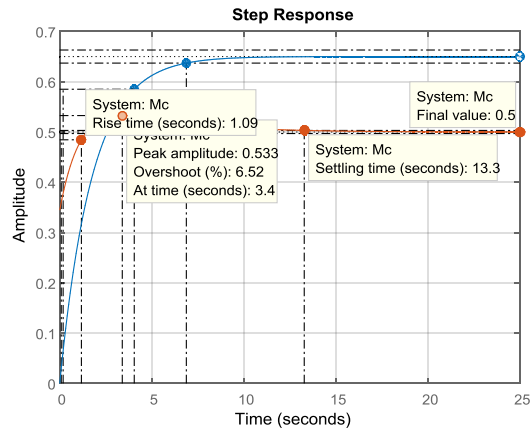
Figure 7: Nichol plot

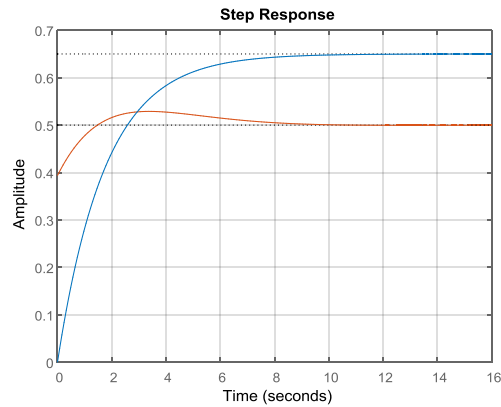Figure 8: Characteristic Response for kp = 5, ki = 1, kd = 3, gain = 1





Figure 9: Characteristic Response for kp = 6, ki = 2, kd = 5, gain = 2
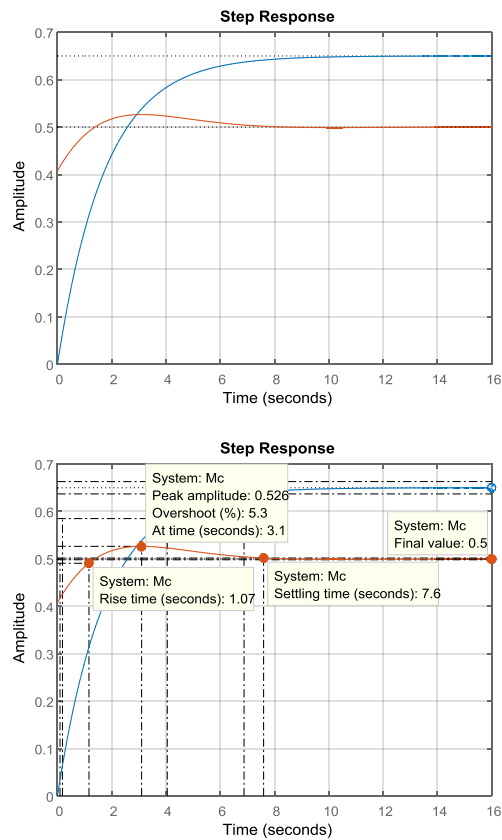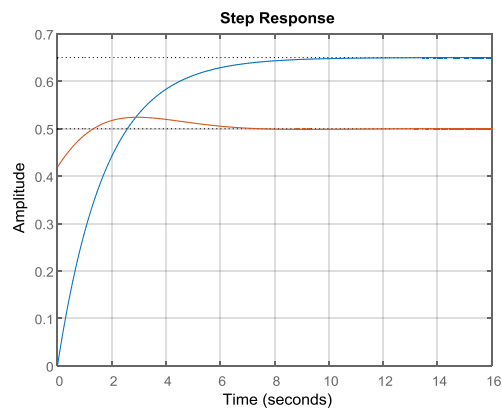
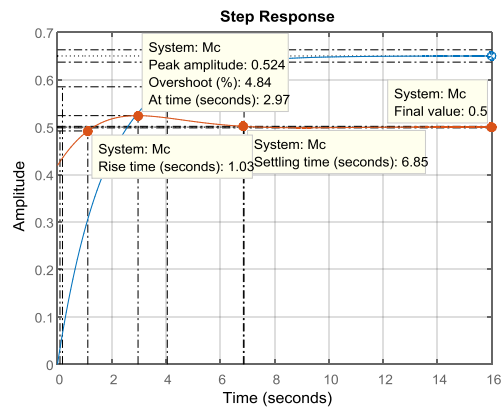Figure 10: Characteristic Response for kp = 7, ki = 3, kd = 6, gain = 3

Figure 11: Characteristic Response for kp = 8, ki = 4, kd = 7, gain = 4
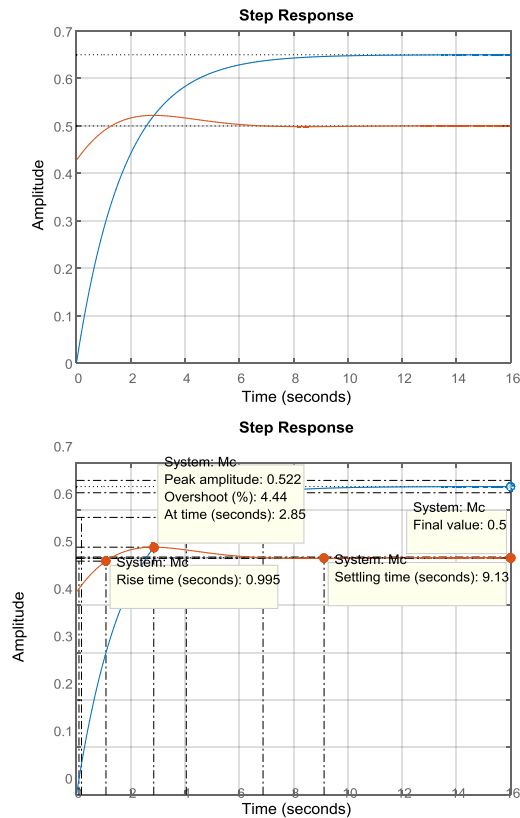


Figure 12: Characteristic Response for kp = 9, ki = 5, kd = 8, gain = 5

Table 1 shows the characteristics of the open loop system and linearized system. This shows the continuous instability of the system until a time of 6.88 seconds and overshoot of 10.00 % were achieved, but the presence of the gain schedule approach which used the effect of linearization of the closed loop system, the system stability was achieved at a shorter time. Table 2 is the maximum stability results shown by Bode plot, Nyquist plot and Nichole plot. These properties and results were also shown on the Bode plot, Nyquist plot and Nichole plot which are represented in Figure 5, Figure 6 and Figure 7, respectively. Within the control parameter of these plots, they all

show same phase margin of $0.209^o$, same delay margin 0.0261 sec, at frequency of 0.14 rad/sec. The "Yes" statement of the closed loop stability indicates better control strength achieved by the linearization of the plant with the gain-schedule approach.

During gain-scheduling simulation process, $K_P$, $K_I$, $K_D$ and gain tuning parameters were varied and the resulted is presented in Tables 3. These parameters are gotten during the simulation process by tuning until a stable process is achieved; at this point the tuning parameters were recorded.The plots which show the dynamics and transient behaviours of the varied tuning parameters, $K_P$, $K_I$, $K_D$and gain are shown in Figure 9 – 12. Variations in the characteristics of the system were observed as the system stability increased with increase in these parameters. Lower rise time, and settling time were achieved as the tuning parameters increased (Sree, Srinivas, & Cidambaram, 2004). Hence, there is a linear relationship between the tuning parameters and the system stability.

**3.2 Discussion of Results**

Table 1 shows the characteristics of the open loop system and linearized system. Stability of the system was achievedin a time of 6.88 seconds and overshoot was 10.0 %.Using gain schedule with linearization of the closed loop system, the system stability was achieved in a time of 6.85 seconds and overshoot of 21 %. Figures 4 and 5 are the open loop transfer function for the system without control. The two figures indicate the unstable dynamic responses of the process. The characteristics of the plant system, without control shows the system has peak amplitude of 0.65, overshoot of 10.00 % at 16 seconds, settling time of 6.88 seconds, rising time of 3.86 seconds. The nonlinear closed-loop bioreactor system was linearized using the Simulink linear analysis tool box. The Bode plot is simply a plot of magnitude and phase of the transfer function as frequency varies. The Bode magnitude plot measures the system input/ output ratio in special units called decibels. The Bode phase plot measures the phase shift in degrees. The Nyquist plot is the representation of the vector response of the feedback control system (especially an amplifier) showing the relationship between the feedback and the gain. The Nichol plot is similar to the Nyquist plot, but shows gain on logarithmic scale versus phase on a linear scale (degrees), with an axis origin at the point. The advantage of the Nichol's chart is the ease by which gain and phase margins can be determined graphically.

The plots; were used to study the performance and stability of the closed-loop linear system. The linearization occurs at the critical operating point at t=34.9 secs. This point marks separation between boost and sustained phases. Figure 6 depicts the step unit response for the closed-loop linear system. Modification was done to this work as critical point of t = 0.65 secs was used for the linearization of the process in order to achieve a better linearized plant, faster settling time and rise time; hence providing a better stability. These results are comparable to earlier study byReginikanth& Letha (2010) on identification and control of unstable biochemical reactor. The earlier study of Gallego et al. (2019) gives good insight on how the gain-schedule control scheme eliminates the disturbance. This process approach was adopted in this work, and the results shows close agreement with the earlier findings of Gallego et al. (2019) as the system is linearized, thereby eliminating the disturbances and brings the system to stability within a shorter time. The control scheme shows that stability and good performance of the closed-loop system is analytically guaranteed. Numerical studies reveal the superiority of the presented method. It eliminates errors, disturbances as well as linearizing the plant to gain stability within shorter time.

Adaptive gain schedule controller gives the best tracking and performance. Figure 5 represents the Bode diagram for the closed-loop linear system.

The closed-loop linear system with gain schedule approach is stable due to the following reasons:

- The root locus in Nyquist diagram did not encircle the point $-1+j\theta$ and is far from it as shown in Figure 8.
- The phase margin in the Bode diagram is positive as seen in Figure 5.
- The indication of the "closed loop stability" in the plots
- All poles of a linear system have negative real parts (i.e. all poles on the left-hand side in S-plane as shown in Figure 5.).

These properties obtained from the linearized (gain scheduled) system are in agreementwith the earlier findings of (Muthamilselvi & Kancheepuram, 2010) on Direct Digital Control of Bioreactor Systems. The step response of the closed loop stability conforms with the early findings of Agrawal & Lim (1984) on Control Schemes for Continuous Bioreactors.

## IV. CONCLUSION

This workfocused on adaptive control of a bioreactor using gain scheduling and MIT rule. The adaptive control block with MIT rule was applied in this work. The simulation was carried out using MATLAB Simulink, while the gain was varied. The adaptive-gain scheduling approach, gave the system response with time-delay at every value of process gain as shown in Tables 4.2, and stability of the system at 0.571 sec, with the plots indicating a delay margin (sec) of 0.0261, phase margin of $0.209^{o}$, "yes" confirmation of the closed loop stability at frequency of 0.14 rad/sec as shown in Table 2. Also, the positive value of the phase margin of $+0.209^{o}$ as seen in the Bode plot, indicates good stability ofthe gain schedule control approach on the system as pointed out by Ahmed and Dorrah (2018). The simulation results also Shows that the adopted gain scheduling model efficiently eliminates the disturbances.

Finally, the linearization time, t = 6.85secs gave a stable system because all the poles are on the left-hand side in S-plane and it has positive delay margin and peak gain of $0.209^{o}$ and 15.40dB respectively.

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