Proceedings of the 7th International Conference on Communication and Electronics Systems (ICCES 2022)
DVD Part Number: CFP22AWO-DVD; ISBN: 978-1-6654-9633-9

System Identification and Control System Design for Bioreactor Process

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Abstract-
A control system can't be simulated using the conventional tuning methods without the availability of mathematical model of the plant being controlled. The work done in this paper is grounded on the available raw data pertaining to an industrial biochemical reactor process. Using this data, multiple mathematical models of the plant are identified in MATLAB using system identification toolbox. The fittest model is chosen for control system designing. For this model, CHR and IMC based controllers are designed in MATLAB. Their set-point and disturbance responses are analyzed.

Keywords- System identification: Biochemical reactor; Controller; Set-point; Transfer function model; IMC; PID

I.INTRODUCTION

A stainless steel made cylindrical tank to carry out chemical process in which organisms are involved is called a bioreactor. It is a kind of CSTR (Continuous Stirred Tank Reactor) with industrial waste as input and the biomass as the output. It may have a size of liters to meter cubes. The temperature, oxygen levels, and the pH inside the reactor are to be kept under tight regulation for the efficient growth of organisms like bacteria, animal cells etc. The continuous steering of the contents is performed to keep it homogeneous. The vaccines and antibodies are produced by the use of bioreactors in industries. The waste products such as corn can be transformed to useful product like ethanol by it in industries. Some energy source plays the role of substrate in bioreactor. Substrates may be classified into limiting and in-excess substrates. Limiting substrates have a direct influence on the kinetics of cell growth, whereas this kinetics has no dependence on in-excess substrates [1].

II. LITERATURE SURVEY

Wang Zai-ying et al. designed a fault-tolerant control system for the temperature control of CSTR [2]. Eva Mathew et al. developed a MRAC technique based control system for temperature control of cascaded CSTR [3]. Kishore Bingi et al. developed PID controller for CSTR. For tuning of PID controller, they used the FGS technique [4].

Thiruppathi. K. et al. optimized the CSTR performance by using various tuning methods of PID controller [5]. De-Xin Gao et al. presented a method for the control of output tracking of CSTR process (non-isothermal) [6]. Yuhong Wang et al. presented the hybrid formal verification of MLD based CSTR process [7].

M. Babu Triven and U. V. Ratnakumari compared the performance of MPC with the Adaptive MPC for the control of CSTR [8]. Xi Lian et al. designed Kalman filter based controller for the CSTR [9]. Ling Gao developed transfer function of CSTR with the immobilized biocatalysis [10].

Sana Bzioui and Rafik Channa simplified the CSTR nonlinear model using the Takagi-Sugeno method and carried out tracking control for it using PDC structure [11]. Shi Li et al. proposed MPC approach based on RBF neural net, and applied it to a CSTR (nonlinear) process [12]. De-Xin Gao and Huan Liu presented a designing method of optimal compensator for CSTR system (nonlinear) [13].

Yang Pu and Wang Yu-hong applied the PWA model based explicit MPC technique for the control of a CSTR system [14]. Shuo Wen et al. developed ANFIS based prediction model for the CSTR process [15]. Bhawna Tondon et al. presented the controller design based on H∞ approach for a CSTR [16]. Dr. Akey Sungheetha and Dr. Rajesh Sharma R have done parameter estimation pertaining to sewage treatment [20]. Karuppusamy, P. designed an adaptive estimator for control system (nonlinear) [21].

III. RESEARCH METHODOLOGY

The flowchart to represent the workflow of this paper is shown in Fig.1. The data that is used to identify the mathematical models of the bioreactor plat with dilution rate as input and biomass concentration as output is shown in Fig.2. The schematic of desired control system to be designed in this work is represented in Fig.3.

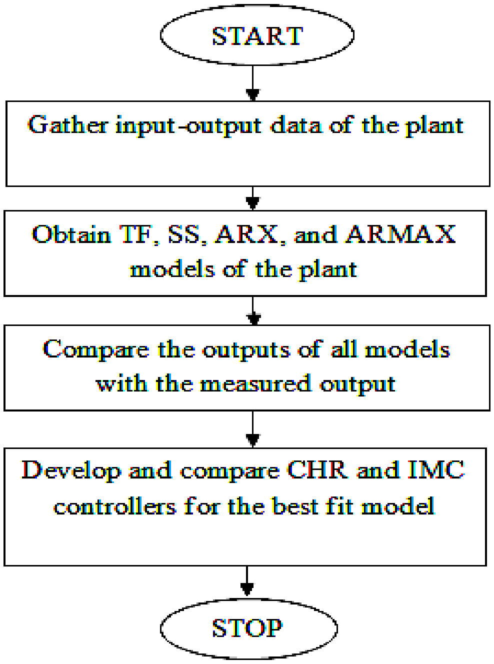

Fig.1. Methodology

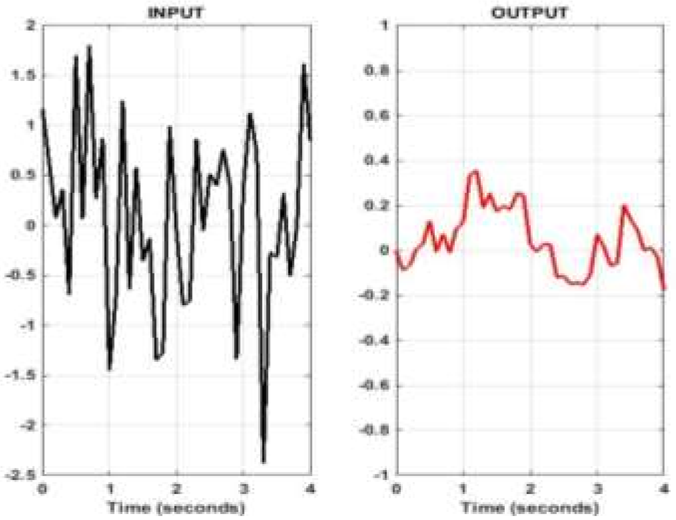

Fig.2. Input-Output data of bioreactor plant

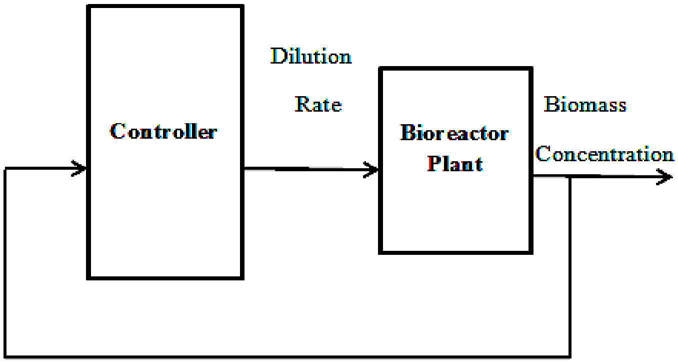

Fig. 3 Visualization of desired control system

IV. SYSTEM IDENTIFICATION

Now, the system identification toolbox of MATLAB is used to identify Transfer Function model (TF), the state space (SS) model, Autoregressive with Exogenous Variable (ARX) model, and Autoregressive Moving Average with Exogenous Variable (ARMAX) model. Following are the identified models:

Transfer Function model:

$$T(s) = \frac{-0.2192\ s + 0.06542}{s^2 + 0.467\ s + 0.1122} \qquad (1)$$

State Space model:

Assuming u, y be input and output respectively, and x and e be state vector and noise respectively,

$$\frac{dx}{dt} = Ax + Bu + K\,e \quad (2)$$

$$y = Cx + Du + e \quad (3)$$

$$A = \begin{bmatrix} -0.5553 & -0.1052 \\ 1.497 & -0.7326 \end{bmatrix}$$

$$B = \begin{bmatrix} -1.464 \\ -24.15 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.2825 & 0.006294 \end{bmatrix}$$

$$D = [0]$$

$$K = \begin{bmatrix} 1.655 \\ -1.41 \end{bmatrix}$$

Autoregressive with Exogenous Variable Model:

$$Ly = Mu + e \quad (4)$$

$$L = 1 - 1.715\,z^{-1} + 0.7675\,z^{-2} \quad (5)$$

$$M = -1.582 * 10^{-14}\,z^{-1} + 0.0298\,z^{-2} \quad (6)$$

$n_1 = 2$, $n_2 = 2$, $n_3 = 1$ (7)

Here n_1 symbolizes No. of poles, n_2 the No. of zeros plus 1, and n_3 the time delay.

Autoregressive Moving Average with Exogenous Variable Model:

$$Ly = Mu + Se \quad (8)$$

$$L = 1 - 1.337\,z^{-1} + 0.376\,z^{-2} \quad (9)$$

$$M = 0.06952\,z^{-1} - 0.04598\,z^{-2} \quad (10)$$

$$S = 1 + 1.023\,z^{-1} + 0.3665\,z^{-2} \quad (11)$$

$n_1 = 2$, $n_2 = 2$, $k = 2$, $n_3 = 1$

Here k is symbolizing the No. of considered past samples of error. Now, the simulated models' fitness is estimated by observing their output for step input.

The step response comparison of all simulated models with the measured output is displayed in Fig.4. The resultant error curves are shown in Fig.5. The Table I is revealing the fitness of identified models. The best fitness of 89.95 % is exhibited by Transfer Function model. State Space model is 50.53 % fit; ARX and ARMAX models are respectively 81.61 % and 50.07 % fit.

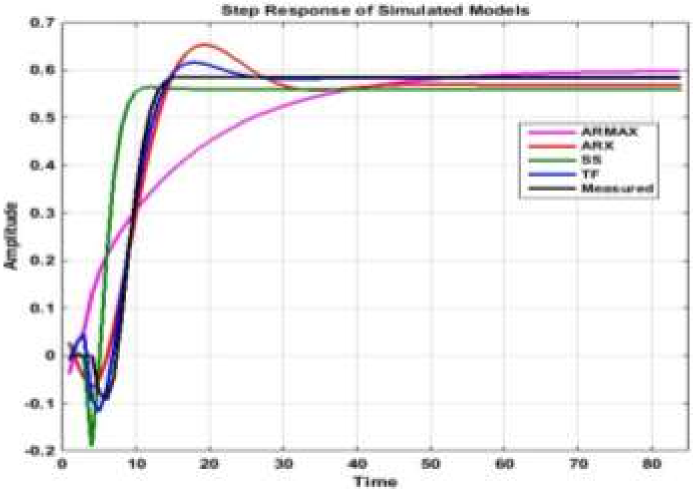

Fig.4 Set-point response of simulated models

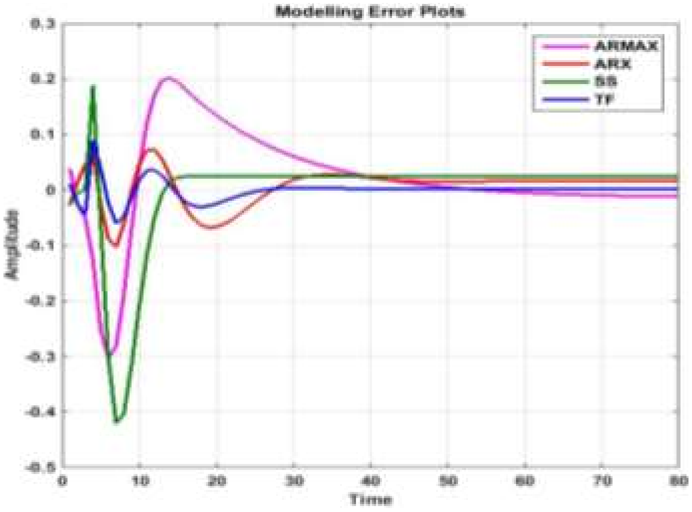

Fig.5 Modeling error plots

TABLE I. Fitness of simulated models

Model	**% Fit**
TF	89.95 %
SS	50.53 %
ARX	81.61 %
ARMAX	50.07 %

V. CONTROL SYSTEM SIMULATION

The identified fittest model is the Transfer Function model as displayed in equation (1). The various open loop curves shown in Fig.6 and Fig.7 are revealing that the considered plant is stable. The control system will be now simulated with this Transfer Function model.

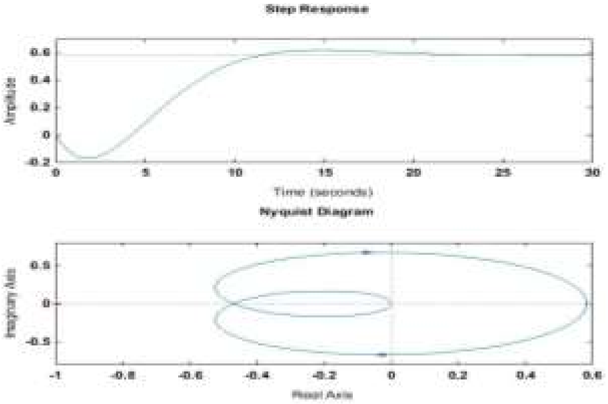

Fig.6 Step response and Nyquist diagram for bioreactor transfer function model

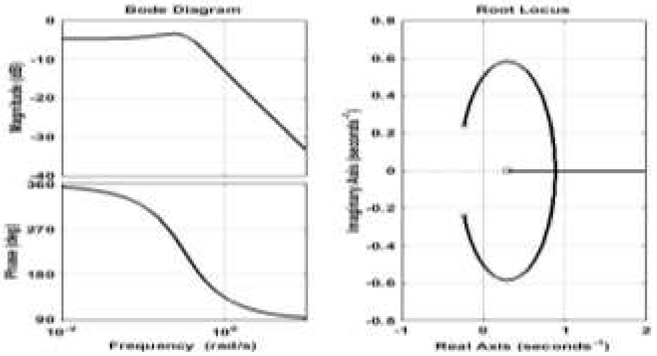

Fig.7 Bode and root locus diagrams of bioreactor transfer function model

Considering the process model being regulated is of the form given in equation (12), the Chien- Hrones- Reswick (CHR) based rules are summarized in the Table II [17]. The notation λ is defined in equation (13).

$$G(s) = \frac{Ke^{-\alpha s}}{\beta s+1} \quad (12)$$

$$\lambda = \frac{K\alpha}{\beta} \quad (13)$$

TABLE II. CHR TUNING RULES

Controller	**K_P**	**T_I**	**T_D**
P	0.3/λ	------	------
PI	0.35/λ	1.2β	------
PID	0.6/λ	β	0.5

PID control system based on CHR method using MATLAB comes up with following values of tuning parameters:

$K_P = 1.292$; $K_I = 0.128$; $K_D = 2.3$

This PID controller is represented by equation (14).

$$C_{CHR}(s) = 1.292 + \frac{0.128}{s} + 2.3\,s \quad (14)$$

Now another controller design technique i.e Internal Model Control (IMC) is used for controller design. Fig.8 is depicting the architecture of IMC control system [18,19]. Here, $G_m(s)$ is the internal model of that plant G(s). Assuming $G_{inv}(s)$ and $G_{non}(s)$ be invertible & non-invertible factors of $G_m(s)$ [18],

$$G_m(s) = G_{inv}(s) * G_{non}(s)$$

The IMC controller is determined using equation (15)

$$C_{IMC}(s) = G_{inv}(s) * Z(s) \quad (15)$$

Here Z(s) is the IMC filter (a low pass filter).

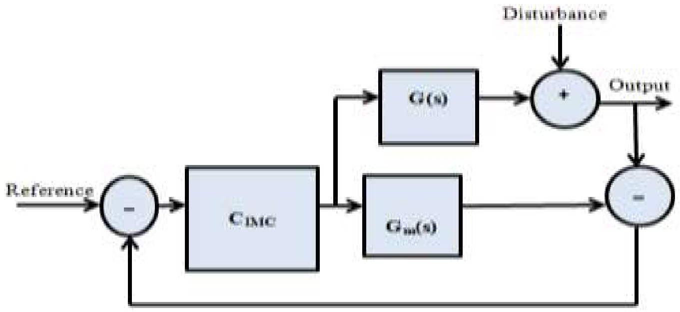

Fig.8 IMC control system architecture

Equation (16) is representing the developed IMC controller using the MATLAB.

$$C_{IMC}(s) = \frac{4.6476(s^2+0.467\ s+0.1122)}{s(s+2.336)} \quad (16)$$

VI. PERFORMANCE COMPARISON

Fig.9 is depicting the MATLAB Simulink model of the developed CHR and IMC control systems. On execution it returns the comparison of set-point responses of the two control systems as displayed in Fig.10. It is clearly showing that the set-point response is greatly upgraded by the IMC controller which is reducing the settling time to a great extent. Fig.11 is revealing the disturbance rejection responses of the developed controllers indicating very clearly that the disturbance is more quickly rejected by the IMC control system as compared to the CHR control system. As shown in Table III, the settling time of CHR controller is very high i.e 50.5 seconds whereas that of IMC controller is very much reduced i.e 15.4 seconds. The disturbance rejection time also is very large in case of CHR controller i.e 70 seconds which is reduced to only 20 seconds in case of IMC controller.

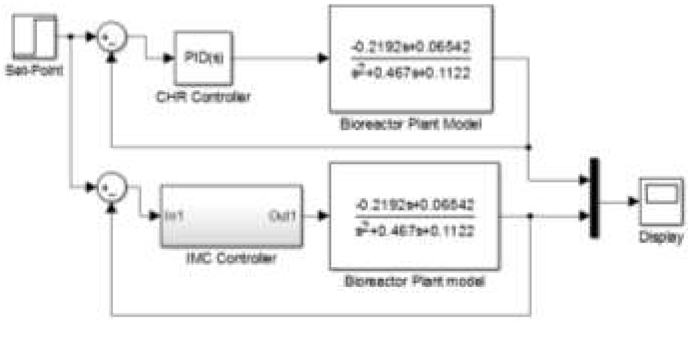

Fig. 9 Simulink model of IMC and CHR controllers

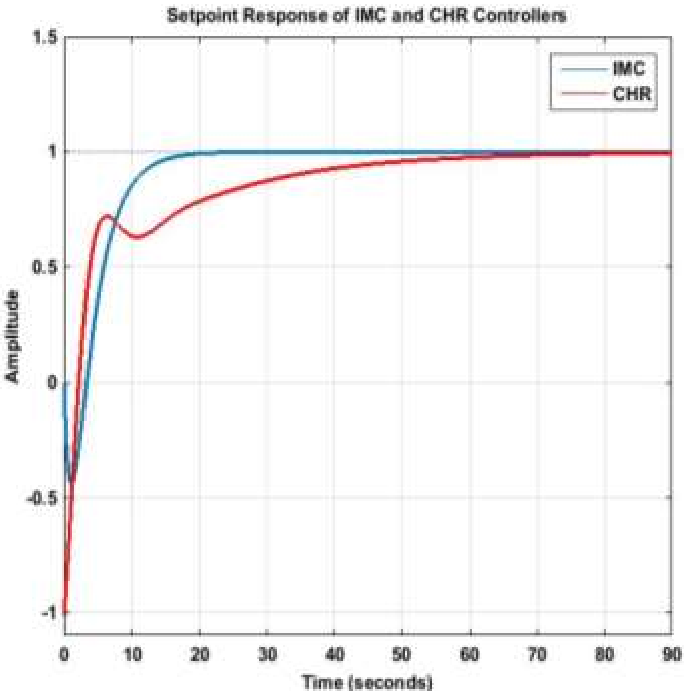

Fig.10 Set-point response of IMC and CHR controllers

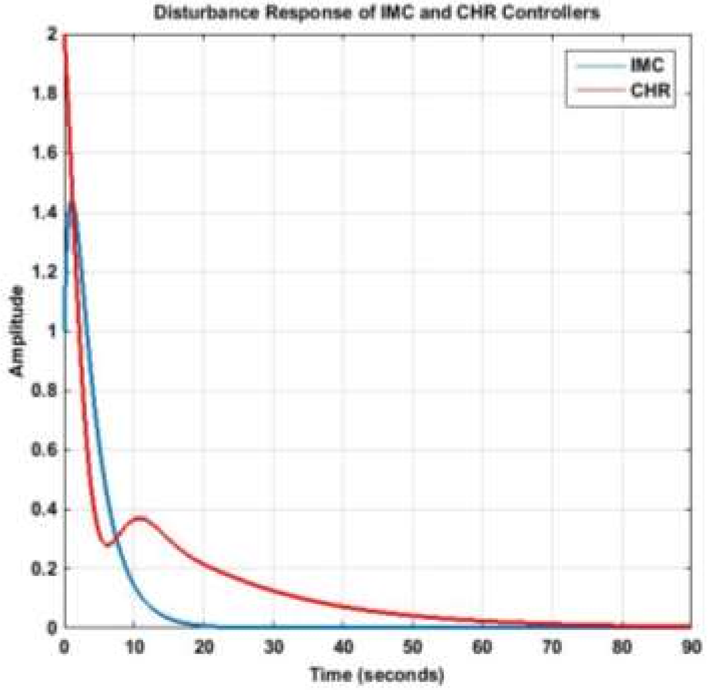

Fig.11 Disturbance response of IMC and CHR controllers

TABLE III. Comparison of IMC and CHR control systems

Controller	Settling Time (seconds)	Disturbance Rejection Time (seconds)
CHR	50.5	70
IMC	15.4	20

VII. CONCLUSION

The present paper is demonstrating the method of identifying the mathematical model of any dynamic system with known input-output data, and hence simulating the control system with the identified plant model. The process that is considered as a case study in this work is the biochemical reactor. Using MATLAB, multiple models of this process are identified. It has been observed that the transfer function model is most promising to represent this process. Then CHR method based PID controller, and IMC control system are developed for this model using MATLAB. It is found that the IMC controller improves the control performance significantly.

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