

# CHAPTER 2

# Chapter 2. Literature Review

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## 2.1 Introduction

In view of the general objectives of present work as outlined in Chapter 1, the state of the art on design and tuning of conventional and model based PID controllers is presented in the following sections:

## 2.2 Control of Multiple Input Multiple Output (MIMO) Processes

The control studies on complex Multiple Input Multiple Output (MIMO) systems such as distillation columns may well be studied with the help of representative mathematical models (Wood & Berry, 1973) (Bezzo & Barolo, 2005). However, the laboratory-scale Quadruple-Tank Process (QTP) has come up as a cost effective, representative and safe alternative for experimental study of various Multiple Input Multiple Output (MIMO) control strategies (Johansson et al., 1999; Johansson, 2002; Johansson, 2000). Even though, the modeling aspects of Quadruple-Tank Process (QTP) has been studied by (Azam & Jørgensen, 2016; Bequette, 2003; Bequette, 1998; Jayaprakash et al., 2014), the in-depth study on process identification of Quadruple-Tank Process (QTP) based on experimental data is not adequately available in literature. The Quadruple-Tank Process (QTP) can be operated to exhibit minimum and non-minimum phase behaviour, by experimentally changing the location of transmission zeros of the system (Dormido & Esquembre, 2003; Kumar et al., 2014). The design of suitable controllers for Multiple Input Multiple Output (MIMO) non-minimum phase systems is a challenging task. The conventional PID controllers are ineffective because of the control loop interactions, inverse response and stability issues (Abdullah & Zribi, 2012; Changela & Kumar, 2013; Kureel et al., 2017). Various advanced control strategies have therefore been developed

(Shah & Patel, 2019; Shukla & Pati, 2019). Model based controller design techniques have therefore come up as better alternative to deal with the drawbacks of conventional PID design methods. . The design of Internal Model Control (IMC) based PID controllers are effective in case of Single Input Single Output (SISO) non-minimum phase systems since they provide a desired closed loop response by appropriately tuning the filter parameters (Chekari et al., 2019; Mute et al., 2016). However, in case of Multiple Input Multiple Output (MIMO) non-minimum phase systems, suitable decoupling techniques have to be used in combination with the Internal Model Control (IMC) based PID controllers in order to negate the effect of interactions among the control loops (Atchaya & Deepa, 2016; Effendi Ak et al., 2017; Ramadevi & Vijayan, 2014). Controller tuning is however important in all design strategies.

### **2.3 Control of Single Input Single Output (SISO) Stable Processes**

The level control in conical process vessels has been studied by several workers. (Ziegler & Nichols, 1993) developed the PID Controller tuning method for open and closed loop systems and utilized it for the level control in a conical tank. (Hägglund & Johan Åström, 1991) developed the auto tuning method for the (PID) Controller, using dominant pole design technique. (Tan et al., 2002) proposed closed-loop automatic tuning of PID controller for nonlinear systems. (Madhuranthakam et al., 2008) studied the optimal tuning of (PID) controller parameters for First order plus dead time (FOPTD) and Second order plus dead time (SOPTD) systems. Apart from using simple PID control and modified PID control to experimental and real situations many model predictive control and fuzzy control techniques have also been studied and published. (Venkatesan, 2015) developed the design procedure and obtained simulation results for an internal model control system for a Real Time Nonlinear Process. (AngelineVijula et al., 2014) proposed

a model based controller design for the nonlinear conical tank system. (Yadav et al., 2016) introduced optimal actuation of PI controller using a predictive technique for level control of nonlinear process. (Rivera et al., 1986) introduced design procedure of internal model control system to establish PID rules using a well described approach. (Parrish & Brosilow, 1988) developed the nonlinear inferential control (NLIC) method for efficient control of nonlinear systems. (Bhuvaneswari et al., 2009) proposed model reference adaptive control based on neural network for level control of nonlinear process. (Nithya et al., 2010) developed design of a soft computing based controller for level control of nonlinear conical tank process. (Tamilselvan & Aarthy, 2017) proposed online tuning of fuzzy logic controller using Kalman algorithm. (Srinivasan et al., 2016) developed the technique for level control of conical tank system using fuzzy based model predictive controller (FMPC). (Ramanathan et al., 2018) developed a smart controller for level control of nonlinear conical tank system using reinforcement learning algorithm and eliminated the drawbacks of PID and fuzzy controllers. (Dinesh et al., 2015) proposed level control of nonlinear conical tank using PID controller and fuzzy logic algorithm.

(Keerthana & Gnanasoundharam, 2016) carried out a comparative study of PI controller, model reference adaptive controller and fuzzy logic controller for a coupled tank system. (Betancor-Martín et al., 2013) developed Takagi-Sugeno fuzzy model for direct inverse control of conical tank system.

#### **2.4 Control of Single Input Single Output (SISO) Unstable Processes**

Several online control tuning methods are available for systems that are unstable. (Kavdia & Chidambaram, 1996) proposed identification of model parameters for a first order process which is unstable and transfer function for time delay using step response data with proportional controller in a closed loop system. They observed that the method gave

less overshoot as well as less settling time. Using the model reference, internal model control and synthesis method, a precise design formula (Jacob & Chidambaram, 1996) had been developed for feedback controllers. (Ajbar & Gamal, 1997) scrutinized bifurcation and stability characteristics of bioreactor using an unstructured model with cell recycle and Substrate Inhibition Kinetics. Step-Change in the PI or PID controller is used for calculating parameters for first order system. Further it is also used in computing time delay transfer function model (Ananth & Chidambaram, 1999). In case of nonlinear process, (Hu & Rangaiah, 1999) suggested AdIMC and its application on fermenter process. Further improvements were made on tuning of PID controllers by (Pramod & Chidambaram, 2000) by optimizing it using step as well as pulse responses. (Cheres, 2006) demonstrated the practical implications of the PID controller involving parameter estimation by reaction curve method as well as by least-squares algorithm for a closed loop arrangement. (Santosh & Chidambaram, 2016) proposed design of parallel cascade controllers for unstable processes in closed loop configuration. Parameter estimation using the discrete indirect estimation for the discrete-time adaptive control and its applications for continuous stirred tank bioreactor are discussed by (Roux et al., 1994). (Raja et al., 2007) developed Adaptive Model Predictive Control for the variation in dissolved oxygen (DO) which represents nonlinear time varying system. (Zhao & Skogestad, 1994) presented a complete analysis of five different control schemes on the basis of disturbance rejection and observed that using feed substrate concentration as the manipulating variable in Substrate-Limited growth scheme. Similar kind of analysis was performed by (Agrawal & Lim, 1984) by checking local controllability, stability criteria and steady state gains. A direct synthesis method was used by (Vinopraba et al., 2013) for the designing of proportional integral controller with fractional order. (Pimentel et al., 2015) proposed feedback strategy to control fed batch bioreactor by Observer based

robust controller by maintaining the by-product concentration at minimum level. (Muthamilselvi & Karunamithi, 2010) studied the performance of digital control used for stabilizing the biochemical process in comparison to other PID controllers. In order to achieve Maximum Production Rate, (Srinivasan & Karunanithi, 2010) gave design of a proportional integral controller on the basis of Monod Kinetics and evaluated its performance in a closed loop configuration. (Saddoud et al., 2010) developed a mathematical model for enzymatic reaction for substrate as well as product inhibition in two interconnected CSTRs. (Ramaswamy et al., 2005) implemented model predictive parameter on nonlinear continuous bioreactor. They investigated its effect based on predictor horizon which is considered an important parameter for MPC controller. (Pachauri et al., 2017a) proposed temperature control in bioreactor using novel control algorithm that combines Internal Model Control (IMC) -PID and fractional mathematics. They further modified it by introducing an additional control loop having proportional gain for reducing offset. (Imtiaz et al., 2014) presented the usage of PID algorithm for control of temperature, pH and Dissolved Oxygen. Their PID controller was based on NARX model whose parameters were tuned using the famous Levenberg-Marquardt algorithm (Ikonen & Najim, 2001). They observed improvement in the response and delay time as well as reduced the residual error. For detection of fault in the model, (Acosta Díaz et al., 2016) developed model based diagnosis in a nonlinear bioreactor. Performance analysis on exergy parameter was done for a continuous stirred bioreactor intended for fermentation of acetate and ethanol from syngas through famous Wood-Ljungdahl pathway by Mortaza. (Shaikh & Jamal, 2006) developed a generalized mathematical model to analyse the steady state behaviour of gas-liquid reactors which were agitated mechanically in non-isothermal conditions. The gas absorption is taken into account with inter-phase mass transfer reaction effects considering various parameters.

(López Pérez et al., 2015) proposed a controller with the aim of regulating the behaviour of continuous bioreactor in dynamic condition for biogenic production of hydrogen. (Zhao & Skogestad, 1995) suggested modeling with cross flow filtration for a continuous biochemical reactor. The modeling of non-isothermal CSTR dynamics by using components methods based on linear and nonlinear principal were examined by (Kurtanek, 1999) and further analysed for their ability to calculate multiple steady states and usage for adaptive on-line process control. (Hinken et al., 2014) suggested modeling of an Up flow Anaerobic Sludge Blanket reactor used for the treatment of synthetic substrate and wastewater containing starch using ADM1. (Namjoshi & Ramkrishna, 2001) proposed a strategy based on a combinatorics approach for the bifurcation analysis of cybernetic models used for computing all probable consequences of competition amongst diverse enzyme systems. The analysis of the model was done for certain ranges of bifurcation parameters and the results show that multiple stable steady states existed. (Horsthemke et al., 2004) studied the arrays of diffusively coupled reactors and the consequence of the network structure on the instability induced due to diffusion. (Chung & Stephanopoulos, 1996) followed the concept of steady state multiplicity to estimate the physiological multiplicity and population heterogeneity linked to two experimentally described systems – a biological system using bacteriophage 2 and the other using E.coli lactose operon as its nutrient. In earlier work (Ye et al., 2014) proposed nonlinear analysis of hybrid system in order to describe the fed-batch conversion to 1, 3-propanediol from glycerol with substrate open loop inputs and pH logic control. Their recent work in 2014 focuses on its optimal control. (Nelson & Balakrishnan, 2016) studied quadratic autocatalysis in an extended CSTR. (Jang et al., 2013) introduced a parameter in the back-stepping design technique for preventing the control system from functioning at a particular point in a biochemical reactor. (Schaum et al., 2012) projected

the saturated Proportional Integral (PI) control of continuous biochemical reactors using Haldane kinetics. In 2012 they proposed feedback control with saturated linearized output for three-state continuous bioreactors class through inhibited kinetics. The experiments done by (Ertunc et al., 2009) showed that the self-tuning Dissolved Oxygen (DO) concentration control by using the set profile which has five step changes performed 90% better than the performance of the same control strategy which utilized the constant set value of DO concentration. (Seer & Nandong, 2017) investigated the stabilization of a second order unstable process by PID controller using the necessary and sufficient criteria of the of Routh-Hurwitz stability analysis. (Tabis et al., 2014) recommended stabilization of unstable steady states of a Biochemical CSTR with kinetics of predator-prey system by employing continuous P or PI controllers. (Dochain, 2003) presented a review of the state and parameter estimation methods for chemical as well as biochemical processes. (Kiss et al., 2002) studied the multiple steady state behaviour of six reaction systems in polymer reactors. (Baltzis & Wu, 1994) calculated the competition dynamics amongst three microbial populations within a spatially heterogeneous network of four interconnected biochemical reactors. (Yuan et al., 2015) studied the multiple steady state behaviour and stability analysis for various operating conditions. The bifurcation analysis of cybernetic models done by (Namjoshi et al., 2003) indicated the steady state behaviour under optimum operating conditions of biochemical reactor. The study by (Volcke et al., 2010) examines the steady state behaviour of biological conversion systems by common kinetics, which performs two successive reactions by two groups of microbes. (Švandová et al., 2005) presented the work which discusses the connection between software tools primarily intended for mathematical modeling, simulation as well as investigation of chemical reactors and the general method for hazard identification in the HAZOP study. A sample kinetic model of glycolysis by bacteria has been framed and a minimal set of

assumptions has been hypothesized that allows the devising of a rough mathematical model by (Hatzimanikatis & Bailey, 1997). The work by (Sankar Rao & Chidambaram, 2015) use subspace-based identification method for transfer function model identification for an unstable bioreactor. (Villa-Gomez et al., 2014) used the values obtained through the sulphide response analysis of sulphide control in sulphate reducing biochemical reactors by means of a pS electrode, for calculating the parameters of a PID controller. (Gómez-Pérez & Espinosa, 2017) suggested that continuous bioreactors operating in series with recirculation can be modelled as a system of linear equations and the singular value decomposition can be used for analysis. A mathematical model of a three-phase fluidized bed biofilm reactor for aerobic processes was presented by (Skoneczny et al., 2017). They also showed how the growth of biofilm is related with the boundaries of fluidized bed. (Pachauri et al., 2017b) presented the control scheme using inferential predictions which was founded on ADALINE soft sensor for fermentation process control. PID and 2-DOF-PID were used by means of ADALINE and retrained ADALINE which in turn resulted in RAN2PID inferential controller. Control of CSTR has been widely studied by researchers of past. (Pinheiro & Kershenbaum, 1999) studied the applicability of Model Predictive Control (MPC) to a pilot scale unstable CSTR. (Biagiola & Figueroa, 2004) studied the application of state estimator based nonlinear MPC for CSTR control. (Czeczot, 2006) proposed the Balance – based Adaptive control (B-BAC) method for temperature control of a non-isothermal CSTR and compared the results with that of the conventional Proportional Integral (PI) controller.

(Bakošová et al., 2009) developed PI controller for a CSTR with parametric uncertainty. From the closed loop feedback system, a set of Kharitonov polynomials were developed for both the numerator and the denominator of the transfer function. The controller parameters were calculated using these equations for all the three steady state operation of

the reactor. The parameters were found by plotting the stability boundary plane. These parameters were chosen from the stable region in the plot. The designed controllers were verified by simulations in the MATLAB and SIMULINK environment. The designed PI controllers were able to stabilize the reactor in all the operating points represented by the two stable steady states and an unstable steady state. The controllers show excellent performance in both servo and regulatory situations. However, knowledge of the process model is required to design such a controller.

(Subramanian et al., 2015) proposed the design of an adaptive multi-stage output feedback NMPC using the Extended Kalman Filter (EKF) for a CSTR with time varying uncertainties. The adaptive scheme was compared with to the conventional multi-stage NMPC. The adaptive MSOF showed better performance than the MSOF. The application of such control methodology requires the design of a state estimator whose performance determines the efficiency of the designed controller.

It has already been established that despite the advancement in control techniques and the availability of advanced control methodologies, the chemical industry prefers the use of linear control techniques due to its wide availability (Shamsuzzoha, 2013; Wang et al., 2016). PID controller is the most used controller in chemical plants. Hence, the tuning rules available for estimating the parameters of the controller are of paramount importance.

(Kumar & Singh, 2016) used three variants of the CSTR Process transfer functions and implemented the PI control for stable steady state operation to compare the closed loop performance of three different tunings methods based on the performance indices (ISE, IAE, ITAE). The mathematical model of the CSTR was linearized and converted to Laplace domain function to study the response of the linearized model of the CSTR. The

resulting transfer function was further reduced to a First Order Plus time Delay (FOPTD) form using model reduction techniques. The PID parameters were obtained using Skogestad Internal Model Control (SIMC) method and a computational optimization method. Simulation results were generated using SIMULINK. They concluded that the nonlinear model of the CSTR gave better results in terms of the performance indices. Also, it was observed that the SIMC provided better values of PI control parameters.

(Nikita & Chidambaram, 2016a) developed a continuous cycling method of tuning PID parameters for unstable systems with two unstable poles. The controller parameters were determined by solving the gain and phase angle criteria using a proportional controller. The resulting transfer function is incorporated along with the PID transfer function. The new system is again analysed using the same criteria to get the controller settings. The proposed method is compared with Ziegler-Nichols (Z-N) tuning technique and it is observed that the proposed method shows improved robustness and better control.

(Padma Sree et al., 2004) suggested a simple PID tuning method for stable and unstable first order time delay process and compared the resulting controller with modified Ziegler-Nichols (Z-N) and Internal Model Control (IMC) method for servo problems. The method is based on the equating the coefficients of corresponding powers of 's' in the numerator and denominator of the transfer function to the closed loop response of a servo problem. The Internal Model Control (IMC) method gave better results than the proposed method for servo problems with small time delay. However, for larger time delay, the proposed method gave best performance. The robustness of the designed controllers is also evaluated using the stability boundary condition by forming the Kharitonov's equations. The proposed method performed better than the Internal Model Control (IMC) method for unstable systems. But these results are restricted only to first order plus time delay (FOPTD) systems.

(Wang et al., 2016) proposed an Internal Model Control (IMC) based PID tuning method for unstable systems with time delay. They considered six different transfer functions with integrating response along with time delay. They reduced undesirable overshoot by using set-point weighting. The resulting controller had only one tuning parameter  $\lambda$ , which could be estimated from the process time constants. The tuning parameter  $\lambda$  is selected by analysing the maximum sensitivity function (Ms) of the resulting closed loop.

(Ghousiya Begum et al., 2016) proposed an Internal Model Control (IMC) based PID tuning method for cascade systems for integrating systems with time delay. Integrating systems are also unstable as they are non-self-regulating systems. They used the Internal Model Control (IMC) tuning method to establish the PID control parameters. A set point filter was also developed for each case to reduce overshoot. The Maximum sensitivity (Ms) was used to obtain the tuning parameter  $\lambda$ . They concluded that their proposed method performed better as compared to the method suggested by (Lee et al., 1998).

(Panda, 2009b) obtained PID controller parameters based on the Internal Model Control (IMC) method. He used the Laurent series expansion for the resulting controller to obtain the controller parameters in parallel form PID and reported simulation results for various unstable and integrating systems. He obtained faster responses than other conventional methods and concluded that the method could be implemented for low order open loop unstable processes with time delay. (Kumar & Padma Sree, 2016) proposed IMC based PID controllers for a range of integrating systems with dead time.

(Anusha & Rao, 2012a) developed a PID control based on the Internal Model Control (IMC) for a magnetic levitation system which is a nonlinear and unstable system. They reported that the Internal Model Control (IMC) based tuning method used for the model performed satisfactorily with elimination of overshoot by using a set point filter. The

closed loop system resulted in a damped response having short settling time and perfect set point tracking capabilities.

(Anusha & Rao, 2012b) designed PID controllers using the IMC method and  $H_2$  minimisation for second order unstable systems with time delay and RHP zeroes. The tuning parameter  $\lambda$  was selected by using a plot between the Maximum Sensitivity (MS) and  $\lambda$ . They compared the controller performance with the method proposed by (Panda, 2009a). They reported that the proposed method provided superior performance for disturbance rejection problems. (Krishna et al., 2012) determined PID parameters for different operating conditions for an unstable CSTR using the IMC method and the stability analysis of method of (Nikita & Chidambaram, 2016b) Their CSTR transfer function model relates the reactor temperature to jacket temperature. They compared the responses of their proposed Internal Model Control (IMC) method with a controller designed using the direct synthesis method. They concluded that the proposed Internal Model Control (IMC) method performs better than the direct synthesis method.

(Kumar & Padma Sree, 2016) developed Internal Model Control (IMC) based PID controllers for various integrating systems with time delay. They also considered two transfer functions developed for jacketed CSTR with unstable poles. These were reduced to lower order model with time delay and integrator dynamics using model reduction techniques. Internal Model Control (IMC) based PID controller were developed for each of these systems. They reported that their method yielded fast response and satisfactory performance as compared to other reported methods.

## **2.5 Specific Objectives of the Present Work**

Based on the review of the literature, following specific objectives are set for the present work:

1. Development of a suitable mathematical model, process identification and design of Internal Model Control (IMC) based PID control system for Two Input Two Output (TITO) non-minimum phase nonlinear process and experimental validation on a laboratory scale experimental Quadruple Tank Process (QTP) setup.
2. Development of a suitable mathematical model, process identification and design of Internal Model Control (IMC) based PID control system for Single Input Single Output (SISO) stable nonlinear process and experimental validation on a laboratory scale experimental annular conical tank liquid level process setup.
3. Development of a suitable mathematical model and design of Internal Model Control (IMC) based PID control system for Single Input Single Output (SISO) unstable nonlinear process utilizing the data generated from steady-state and dynamic simulation of a continuous bioreactor and a non-adiabatic jacketed CSTR.