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Design and Simulation of Internal Model Controller for a Real Time Nonlinear Process

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Abstract

Background/Objectives: PID controllers are one of the first solutions often considered in the control of process industries. It has always been very difficult to treat the level anomalies n the real time processes. Particularly the non linear systems and processes have been a challenge in relation with their dynamics and flow properties. **Methods/Statistical analysis:** Dual Spherical Tank Liquid Level System (DSTLLS) has the characteristics of nonlinearity due to the dynamic behaviour and area of cross section of tank. One of the major problems in process industries is to control of liquid level for Second Order System Plus Delay (SOSPD) system because the presence of time delay in the system can lead to destabilization of the system. This simulation aims at portraying the performance of the designed Internal Model Control (IMC) PID Controller. Using the black box modelling technique the SOSPD is mathematically modelled experimentally, assuming the system to be a Single Input Single Output (SISO) model. **Findings:** The aim of this paper is to design a PID controller using IMC tuning method for a (DSTLLS) whose modelling has been done in real time. This simulation briefly explains about stabilizing problem for SOSPD system using an IMC PID controller. The designed controller performance is analysed in terms of performance indices like Integral Squared Error (ISE) and Integral Absolute Error (IAE) and time domain specifications like Rise time, Settling time and Peak time. **Conclusion:** The validation of the performance of the designed controller is performed under MATLAB environment. There can different controllers which can be also experimented on the same mathematical model for different configurations of the system, namely MISO and MIMO.

Keywords: Internal Model Control (IMC), MATLAB, Non Linear Systems, SISO, Spherical Tank Systems

1. Introduction

The main challenging task for all process industries is to control liquid level, flow and pressure in the spherical tank. Based on the considered real time setup model can be classified as nonlinear and linear models. For linear models PI controllers are widely used to reduce complexity. But most of the industries working on nonlinear delay dominated systems to control the liquid flow. PID controllers are the preferred solutions always used in process control applications but in practical conventional PID controllers cannot give feasible solution. In this paper, an attempt was made to design efficient model based IMC PID controller for DSTLLS.

The Internal Model Controller (IMC) is being extensively used for process control applications. This paper explains about model based controller like IMC which exhibits several advantages when designing for controlling applications. The model considered for real time modeling is SOSPD. Due to the nonlinearity problem in SOSPD model controller provides a complete analytical solution by proper system modeling.

The system chosen for modeling is nonlinear system so the total height of the tank is divided into three regions. Lower region of the tank exhibits high nonlinearity due to the presence of less area of cross section. The nonlinearity of the tank is increases by varying area of tank. Liquid level controlling for such systems are difficult.

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PI controllers always exhibits high peak overshoot for nonlinear systems which is not feasible. IMC PID controller reduces the peak overshoot and will give high rise time. IMC Controllers are widely recognized in process industries due to having only single tuning parameter (λ). Tuning parameter (λ) is always depends on the time constant and delay time. The value of tuning parameter (λ) is approximately equal to the value of time constant in closed loop response.

Generally IMC tuning controller is used to approximate dead time which is essential need for delay dominated systems. IMC controller provides different tuning techniques to control the level of water in highly nonlinear systems. Usually Proportional Integral (PI) controllers required to meeting the optimal response in linear systems and PID controllers are required to meet desired response in nonlinear systems. Nonlinear systems are the delay dominated systems with unstable characteristics. Unstable processes can be easily tuned by using IMC tuning methods.

The organization of the paper is as follows: section 2, literature survey for IMC controller design section 3, explains about the system description and technical specifications of real time hardware setup. Section 4 gives brief details about designing of controller and the process that is used for modeling of process parameters. Section 4 gives simulation results obtained.

The five different PID tuning rules for SOSPD system which is having large damping coefficient (ξ) and dominated delay[1]. Internal Model based Controller (IMC) for a heat exchanger system has been designed and the results obtained are compared with the fuzzy a PID controller with respect to performance indices[2]. The implementation of an IMC controller which is based on the fractional order PID controller is also performed[3]. In[4] the performance of a model based controller for spherical tank process in real time is validated. In[5] a gain scheduled PID controller for nonlinear delay dominated systems has been designed and implemented. In[6] an IMC based PID controller were implemented for the controlling of level in the conical tank system[6]. In[7] IMC and IMC based PID controller structure were explained for both first order and second order systems. In[8] a modified IMC structure was proposed for unstable processes with large time delays. In[9] fractional PID controllers with the tuning rules of Ziegler–Nichols-type based controller were designed. In[10] a set of tuning rules for fractional order and integer order PID controllers were derived for the first order plus dead time system.

The explanation for particle swarm optimization technique based design for PI controller for non-linear process in a real-time environment was given[11]. In[12] a decentralized PID controller for nonlinear system was designed and its performance obtained from interacting two tanks. In[13] a skogestad PID controller was modelled and implemented for interacting spherical tank system. In[14] a PI controller for a second order delay system was designed by optimizing tuning parameter. In[15] all stabilizing PID gains were computed for a second-order delay system. In [16] the explanation about comparative study of controllers for an interacting nonlinear Multi Input Multi Output (MIMO) System with variable area was elaborated. In[17], the tuning rules using the Ziegler-Nichols method for PI controller were derived and implemented. The Lab VIEW based tuning method to design PI controller for a real time non linear process was designed and implemented in[18]. The process modelling and implementation of real time gain scheduled controller for higher order real time nonlinear system was performed[19]. In[20] the Lab VIEW based optimally tuned PI controller for a real time non linear process have been designed and implemented.

2. Process Description

2.1 Real Time Setup

The hardware needed for implementing the above model based controller consists of DSTLLS as shown in Figure 1. The two tanks are connected with a manually operable valve as shown in Figure 1. Flow is regulated through the pneumatic control valves into the tank. The position of pneumatic control valves can be controlled by applying air to them. This system is having a proper dynamic

Figure 1. Real Time Hardware Setup of DSTLLS.

Table 1. Technical Specification of Hardware Setup

Hardware parts	Description
Spherical Tank	Material: Stainless Steel Diameter: 45cm
Differential Pressure Transmitter	Type: Capacitance Range: (2.5 to 250)Mbar Output: 4 to 20 mA Make: ABB
Control valve	Size: 1/4",Pnematic Actuated Type: Air to close Input(3-15)PSI 0.2-1 Kg/cm2
Air Regulator	Size ¼" BSP Range: (0-2.2) BAR
Pump	Centrifugal 0.5 HP
I/P Converter	Input: 4-20 mA Output: (3-15)PSI
Pressure Gauge	Range: (0-30) PSI Range: (0-100) PSI

nonlinear characteristics and designing of controller for this type of systems is a challenging task. The process contains two spherical tanks named as tank1and tank 2 whose heights are H (45cm) and radius R (22.5cm). The input flow to the tank 2 is represented as Fin1. Differential Pressure Transmitters are used for measuring liquid height in the spherical tank. These values are transmitted in the output current range of 4–20mA to the interfacing unit of the PC. Technical Specifications of the above mentioned real time setup is mentioned in Table 1.

3. Design Implementation

3.1 Mathematical Modeling

The Dual Spherical Tank Liquid Level system (DSTLLS) is modeled with the obtained experimental data. Due to the usage of two interacting systems the model obtained is highly nonlinear and delay dominated system. A linear system can be modeled by using direct derivations to get optimal response. In case of nonlinear systems certain approximations has to be used.

Methods used for nonlinear approximations:

- Pade's series approximation
- Taylor's series approximation
- Maclaurin series approximation

Pade's approximation method is used for delay dominated systems for approximating time delay. The modeled transfer function is in the structure of

$$G_P(S) = \frac{K_p e^{-Ds}}{\tau^2 s^2 + 2\xi\tau s + 1} \tag{1}$$

Where K_p = Process gain
τ = Process time constant
ξ = Damping coefficient
D = Time delay

Second order system plus delay systems are widely used in dynamics as they include over damped, critically damped, under damped systems. Depend on the type of the system based on ξ SOSPD process is modelled into FOPDT process. The closed loop equation[1] is approximated to First Order Plus Dead Time (FOPDT) system by approximating time delay component using modified Pade's approximation. The obtained approximated FOPDT model from SOSPD in the form of

$$G_m(S) = \frac{K_m e^{-D_m s}}{\tau_m s + 1} \tag{2}$$

By applying the IMC-PID control algorithm to the FOPDT process to calculate the process parameters.

$$K_p = \frac{2\tau_m + D_m}{2K_p(\lambda + D_m)} \tag{3}$$

$$\tau_i = \tau_m + 0.5D_m \tag{4}$$

$$\tau_D = \frac{\tau_m D_m}{2\tau_m + D_m} \tag{5}$$

$$K_i = K_p \cdot \frac{1}{\tau_i} \tag{6}$$

$$K_d = K_p \cdot \tau_D \tag{7}$$

Due to the nonlinear behaviour of the system it is divided into three regions. Lower region in the range of 0–12 cm, middle region in the range of 13–25 and higher region from 26–45. For each region modelling is performed based on the IMC PID tuning rules. The modelled transfer function from the lower region from the experimental data is shown below.

Based on the IMC PID tuning rules proposed[1] controller designed. Process parameters are obtained to design IMC PID controller. The nonlinear system obtained in lower region is an over damped system based on ξ. The parameters gain, time constant and delay time are calculated for over damped system to model it to FOPDT process shown in Table 2.

Table 2. Parameters for nonlinear systems

(a) Parameters	(b) Gain (K_m)	Time Constant (τ_m)	Dead time (D_m)
Critical damped	K_p	K_p	K_p
Over damped	$1.641\ \tau$	$0.828 + 0.812\left(\frac{\tau_{p2}}{\tau_{p1}}\right) + 0.172e^{-6.9}\tau_{p1}$	$2\ \xi\ \tau$
Under damped	$0.505\ \tau + D$	$1.116\ \tau_{P1}\ \tau_{P2} + D$	$\frac{\tau}{2\xi} + D$

$$Tf_1 = \frac{19.09e^{-(7703.142s)}}{3.328 \times 10^6 s^2 + 3650s + 1} \quad (8)$$

IMC PID control algorithm applied on the FOPDT process to calculate process parameters. After approximating delay time using Pade's approximation obtained model is in the form of FOPDT.

$$Tf_1 = \frac{19.09e^{-(923.82459s)}}{2.043682489s + 1} \quad (9)$$

By applying the rules of IMC PID tuning process parameters are calculated from[3–7] for lower region.

Modelling is done for middle region from the taken experimental data which is in the form of

$$Tf_2 = \frac{48.56e^{-(26460.844s)}}{1.323 \times 10^7 s^2 + 7274s + 1} \quad (10)$$

The above closed loop equation is an under damped system. The parameters are calculated from the Table 2 to convert it to FOPDT from SOSPD process. The calculated FOPDT system is in the form of

$$Tf_2 = \frac{48.56e^{-(28279.67923s)}}{7274s + 1} \quad (11)$$

The below shown mathematical model obtained for higher region.

$$Tf_3 = \frac{101.6e^{-(51967.069s)}}{2.084 \times 10^7 s^2 + 9005s + 1} \quad (12)$$

The SOSPD system is converted into FOPDT through Pade's approximation. FOPDT model obtained in the higher region is in the form of

Table 3. Tuned Parameters for different regions

Region	K_p	K_i	K_d
Lower	0.02104608	0.0000453622	0.0428220
Middle	0.01247473	0.0000005825	59.9176
Higher	0.00524326	0.0000001450	35.452755

$$Tf_3 = \frac{101.6e^{-(51967.069s)}}{9005s + 1} \quad (13)$$

Tuned parameters from the above mathematical modeling are shown in below Table 3.

4. Results

4.1 Performance Analysis

To test efficiency and performance of controller MATLAB and SIMULINK are being used. In each region a sequence of step input is given to test the effectiveness of the controller. The results were observed at lower middle and upper non linear regions by giving different operating points to analyze the performance and effectiveness of the controller. Figure 2 shows the step response of IMC controller in the lower region. Figure 3 shows the step response of IMC Controller at the operating point of 22 cm i.e. in middle region.

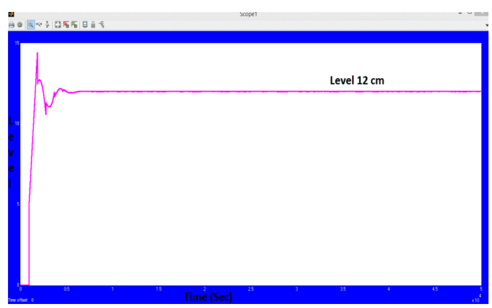

Figure 2. Step response of IMC controller at 12 cm.

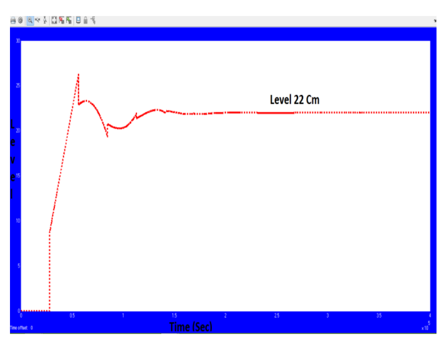

Figure 3. Step response of IMC controller at 22 cm.

The performance of the IMC controller is tested using a DSTLLS nonlinear system at various operating points. Figure 2 shows the step response for given input for IMC controller at the operating point of 12cm. The performance of IMC controller is analyzed by below shown Figure 2 and Figure 3 demonstrates the step response for IMC controller in the middle region at the operating point of 22cm. Figure 4 shows the response of IMC controller for the given step input in the higher region at the operating point of 39cm. Figure 5 illustrates the response along with the behavior of the IMC controller in all three regions according to the given operating point.

The observation from the results obtained is IMC controller exhibits quite high peak overshoot and fast settling time in lower region compare to the other regions due to the presence of nonlinearity at the bottom of tank. In case of middle region IMC controller settling time is less and peak overshoot is also less when compare with the results of lower region. So IMC controller exhibits better performance with respect to time indices even in the presence of nonlinearity.

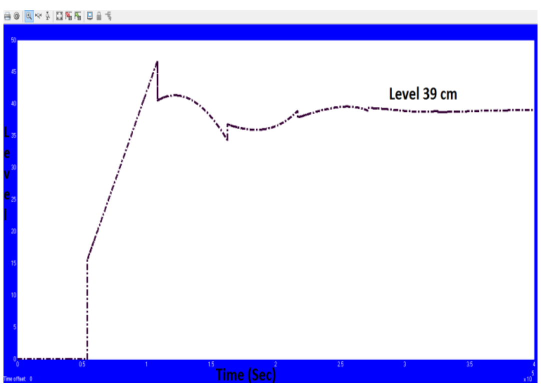

Figure 4. Step response of IMC controller at 39 cm.

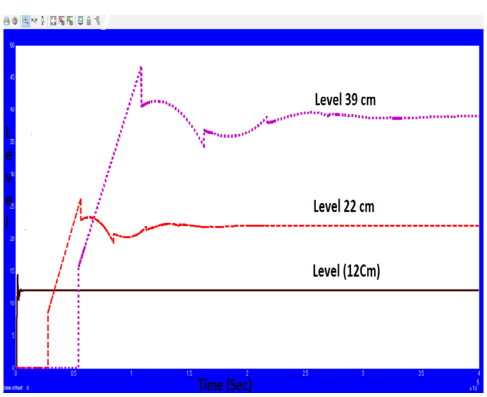

Figure 5. Step response of IMC controller in three regions.

The performance of IMC controller for all regions at different operating points shown in Figure 5. The derived nonlinear system mainly depends on the value of ξ . The value of ξ mainly depends on τ. Depends on the value of ξ nonlinear system can be classified as either under damped or over damped system. By comparing the results obtained if $\xi < 1$ this system exhibits better performance. By the simulation results we observe that if $\xi > 1$ this exhibits more peak overshoot and more settling time which is not required for better controlling action.

5. Conclusion

In this study, we compared the results obtained for IMC controller for all three regions with respect to performance and time indices. The effectiveness is also tested by giving step sequence as input among the all three regions designed IMC controller in higher region reduces the settling time and percentage overshoot.

In Table 4 displays Performance Indices values tabulated for lower region at operating point of 12 cm. Finally by comparing the time indices and ISE and IAE values performance of IMC controller is better in higher region when compare to the lower region. The peak time and the values of ISE and IAE are quite high in lower region due to nonlinearity behaviour of real time spherical tank. The simulation results are obtained through Matlab Simulink for the real time SOSPD system. The results obtained are shown in tabular columns. Table 4 demonstrates values of performance indices for IMC controller at the operating point of 12cm. Table 5 demonstrates values of performance indices IMC controller at the operating point of 22cm. Table 6 shows the values of performance indices and time specifications for designed IMC controller in higher region. By comparing all these values obtained for all three regions higher region has the fast settling time with less square error.

Table 4. Performance Indices of IMC controller in lower region

Region	Set Point (cms)	Specifications	IMC
		ISE	1793.77
		IAE	1180.99
Lower Region	12	Peak Time (sec)	134.5
		Rise Time (sec)	121.05
		Settling Time (sec)	27.05

Table 5. Performance Indices of IMC controller in middle region

Region	Set Point (cms)	Specifications	IMC
		ISE	1441.79
		IAE	1019.637
Middle Region	22	Peak Time (sec)	739.0781
		Rise Time (sec)	665.1
		Settling Time (sec)	16.985

Table 6. Performance Indices of IMC controller in Upper region

Region	Set Point (cms)	Specifications	IMC
		ISE	501.6964
		IAE	615.2921
Upper Region	39	Peak Time (sec)	1607.203
		Rise Time (sec)	1446.3
		Settling Time (sec)	11.938

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