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Development of an Adaptive PID Controller for a Nonlinear Process

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Abstract

It is a crucial task to control the head of cone shaped tanks which is widely used in many industries like food manufacturing industries, petroleum industries and hydrometallurgical industries. The nonlinearity due to the tapered bottom area of the tank makes the level control in the conical tank the toughest task. The conventional controllers will not give a clear solution for this case. Obtaining the equilibrium conditioning by balancing the inflow rate and the out flow rate is the normal level control problem. Different shapes of the tanks implies different equilibrium and operating regimes. The entire system can be divided in to low middle and high regimes in order to consider the system as piece wise linear and varying controller parameters are required at these points. This work deals with development of a suitable controller for such process. This work start with the development of conventional three mode controller and further it is enhanced with Internal Model Controller and the Adaptive technique. The controllers developed are simulated in SIMULINK environment.

Keywords: Adaptive Controller, ID Controller, Conical Tank,IMC Controller, Nonlinear System

NOMENCLATURE

SLNO	SYMBOLS	SPECIFICATION
1	q	Flow rate(LPH)
2	A	Cross sectional area of conical tank(cm^2)
3	V	Volume of conical tank(cm^3)
4	δ	Density of water
5	τ	Time constant
6	t_d	Delay time
7	$\tilde{d}(s)$& $d(s)$	Disturbance & estimated disturbance
8	$q(s)$	Internal model controller
9	$g_p(s)$& $\widetilde{g_p}(s)$	Process& process model
10	$r(s)$& $\tilde{r}(s)$	Set point & Modified set point
11	$u(s)$	Manipulated input
12	$y(s)$& $\tilde{y}(s)$	Measured process output& Model output

I. INTRODUCTION

Based on the mathematical equation characterized the system it can be classified under the category of Linear or Nonlinear [1-3]. There are many procedures are available to find the nonlinear model of the system and the nature of nonlinearity subjected to the system. The nonlinearity may influence ambiguities and constrains on the control and the input side of the system .So the people working on these process claims that designing the controller for such process is challenging [14] .

The process variables need to be controlled in process industries are such as flow rate, level, pressure, temperature and concentration. The control of liquid level is of great importance in chemical industries. If the level is raised to high then the reaction equilibrium cause damage to the equipment or spillage of valuable material. There will be adverse consequences if the level is down to low [14].The nonlinearities present in the liquid flow line and the shape of the tank introduce the nonlinearities in the system is the basic crises in process industries [5]. The tanks in cylindrical or cubical shapes used in the laboratory are termed as linear , but they provides poor drainage due to their flat base. For the purpose where complete drainage is required like water treatment plants, Food and beverages plants, Metallurgical plants ,Concrete mixing plants the conical bottom tank, is preferred. The conical shaped tank suffered by its nonlinearity behavior especially which is more experienced in the bottom portion of the tank due to the nonlinear variation in the shape and area of cross section. But improved drainage efficiency made the industry to prefer the fully conical shape tank.

This work tries to develop a suitable controller for the conical tank process. The head of the conical tank should be maintained at the desired value by manipulating the inflow rate .To achieve this various controllers are designed and compared here. The three mode Proportional plus Integral plus Derivative Controller has been developed and it is enhanced with Internal Model Controller and Adaptive controller for the parameter variation problem. The experimental results shows the advantage of Adaptive technique over the conventional controller and the IMC technique. This paper is organized as Process description in the section I, and the next two sections explains the setup and the mathematical description of the system and the controller development, Section four explains the simulation and the conclusion is in section Five

II. PROPOSED WORK

II.1 Experimental Setup

The hardware part consists of a cone shaped tank with sensors, converters, controllers, and control valve is as shown in Figure 1. The level is sensed by the differential pressure sensor which give the proportional head and pressure relationship is placed at the bottom of the tank. The output of the DPT is given to the controller and the control signal is communicated to the actuator through E/P converter to manipulate the stem position of the control valve.

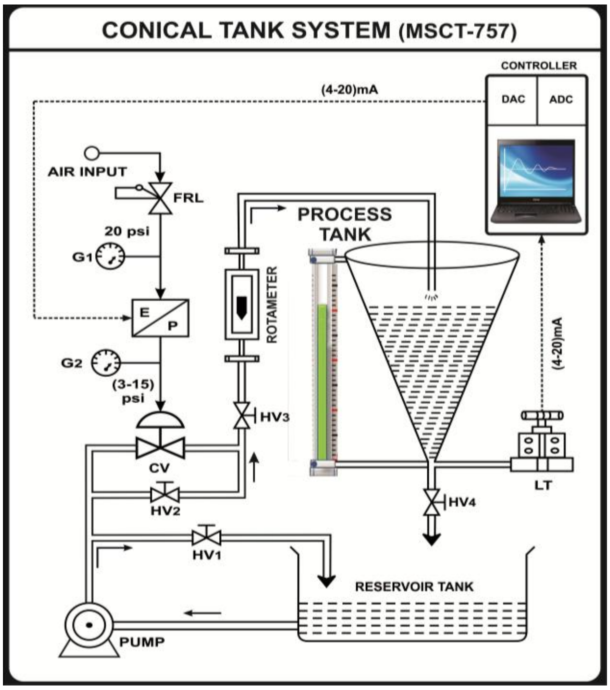

Figure 1: Experimental Setup

The specifications of the system are given in the Table1.

Table 1: Tank Specifications

PARAMETER	SPECIFICATION
Height, H	70cm
Top diameter, D	35.2cm
Bottom diameter, d	4cm
Control valve constant, K	2
Body of tank	Stainless steel
DPT	Capacitive type, Range: Input:2.5-250 mbar, Output 4-20 mA
Pump	½ HP,Centrifugal
Control Valve	Pneumatic actuated , Air to open, Input: 3-15PSI
Rota meter	Range 0-460 LPH

II.2 Mathematical Modelling

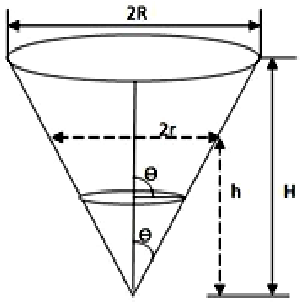

Figure 2: Tank cross section

Figure 2 shows the cross sectional viwe of the process tank [11]. The level (head) h to be controlled.

The accumulated rate is

$$\frac{dV}{dt} = \frac{1}{3}\frac{dh}{dt}\{A + 2\Pi(\frac{R}{H}h)^2\} \tag{1}$$

The Mass balance equation of the tank is

$$F_{in} - F_{out} = \frac{1}{3}\frac{dh}{dt}\{A + 2\Pi(\frac{R}{H})^2 h^2\} \tag{2}$$

Out flow in term of , V_e

$$F_{out} = a_e V_e \tag{3}$$

The balance Eqn of mass,

$$\frac{dm_e}{dt} = 0 = q(u_1 - u_2) + q(\frac{(v_1 - v_2)^2}{2}) + qg(z_1 - z_2) + q(\frac{p_1 - p_2}{\delta}) \tag{4}$$

$$0 = q(0) + q(-\frac{v_2^{\,2}}{2}) + qg(0) + q(\frac{p_1 - p_2}{\delta}) \tag{5}$$

Finally,

$$\frac{dy}{dt} = -2\alpha F_{is} h_s^{-3} Y + \alpha h_s^{-2} U + \frac{3}{2} \beta h_s^{-\frac{5}{2}} Y \tag{6}$$

$$\tau(\frac{dy}{dt}) + y = CU \tag{7}$$

$$C = \frac{2\alpha}{\beta} h_s^{\frac{1}{2}} \quad \& \quad \tau = \frac{2}{\beta} h_s^{\frac{5}{2}} \tag{8}$$

The solution of the equation with the parameter substitution from Table 1, implies the model of the system as follows

Model 1 =3.18462.81s+1 $\frac{3.184}{62.81s+1}$

&

Model 2 =4.472355.28s+1 $\frac{4.472}{355.28s+1}$

III. CONTROLLER DESIGN

III.1 *PID Controller*

The Proportional- Integral -Derivative controllers (PID) are commonly used controllers in the industry to maintain the set value of the plant. The PID controller require proper tuning for good performance. The parameters of the controller can be set by the set of rules defined by the researchers, and the practitioners. The procedures like open loop and closed loop tuning are widely used in industry. Here the controller parameters are set by Ziegler-Nichols open loop tuning method [6].The structure of the controller developed is based on the equation

$$Y(t) = Kp\, e_p + Kp\ Ki \int e(t) + Kp\ Kd \frac{d}{dt} e(t) \tag{11}$$

By step test the open loop response of the system obtained is shown in Fig3.

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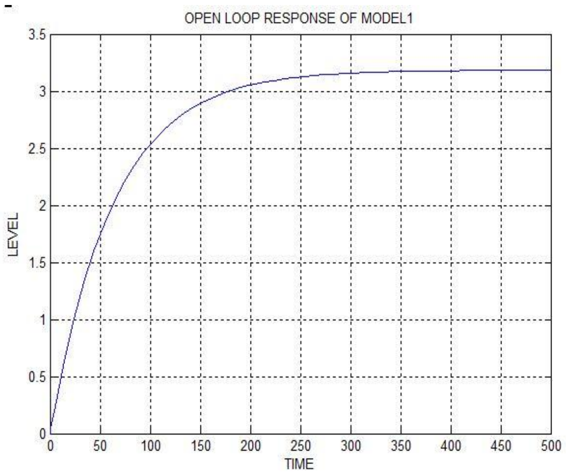

Figure 3: Open loop response

The open loop test of process identification gives the parameters such as,

The maximum output (final value) for the unity input, K=3.184

28.3% of final value = 0.901

The time taken to the response at 0.901= T_1

63.2% of final value = 2.012

Time taken to reach the response at 2.012= T_2

The Time Constant $\tau = (T_2 - T_1)*1.5$

Delay Time, $t_d = T_2 - \tau$

Repeat the procedure for the second model. The PID parameters obtained are listed in Table 2.

Table 2: PID Controller Parameters from Openloop Curve

Model	**PID**		
	K_p	**K_i**	**K_d**
Model 1	27.002	11.236	9.7518
Model 2	335.187	429.05	38.829

III.2 *INTERNAL MODEL BASED PID TUNING*

Internal Model Control (IMC) is a model based approach, and the controller action is not smooth if it is used as an individual controller alone. The combination of IMC with PID controller provides a better response than IMC. In model based controllers if the plant and the model are same, then there is no error occurs. But due to the disturbance and model uncertainty, the error occurs and it is reduced with the help of the adjusting the tuning parameters of the internal model controller. In IMC design the effect of filter tuned parameter "λ" which is selected by trial and error method is used to reduce the errors. The block diagram of IMC structure is shown in Figure 4.

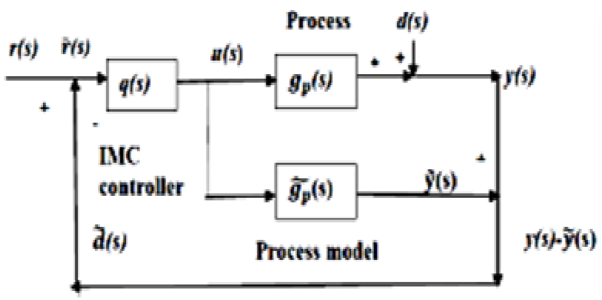

Figure 4: The IMC structure

From the block diagram the transfer function of the plant is $g_p(s)$ and $\widetilde{g_p}(s)$ is a process model, $q(s)$ is the model of the controller and the model of the disturbances is d(s). The following are the steps to design an Internal Model Control (IMC) system [13]:

Step1: Factorization

The transfer function is factorized into invertible and non-invertible parts. The factor containing poles and zeros or time delays become the position of poles depends on the process model is leading to internal stability [14]. So this is the non-invertible part which has to be removed from the transfer function. Mathematically, it is given as

$$\widetilde{g_p}(s) = \widetilde{g_{p+}}(s)\widetilde{g_{p-}}(s) \tag{12}$$

Where

$\widetilde{g_{p+}}(s)$ – Noninvertible part

$\widetilde{g_{p-}}(s)$ - invertible part

Step2: Ideal IMC controller.

The ideal IMC is the inverse of the inverted portion of the process model, $\widetilde{g_{p+}}(s)$.

$$\tilde{q}(s) = \widetilde{g_{p+}}^{-1}(s) \tag{13}$$

Step3: Adding filter

The filter is added to the controller for making the system at least semi-proper because a system is not stable. A transfer function is known as proper if the order of the denominator is greater than the order of the numerator, and for exactly of the same order the transfer function is known as semi-proper [14].

$$q(s) = \tilde{q}(s f(s) = \widetilde{g_{p+}}^{-1}(s) f(s) \tag{14}$$

Where, $$f(s) = \frac{1}{\lambda S+1} \tag{15}$$

Step4: Adjust the filter tuning parameter.

Tune the filter parameter λ to vary the speed of response of closed loop system.

The Equivalent Feedback Form to IMC

The equivalent feedback form to IMC is shown in figure 5.

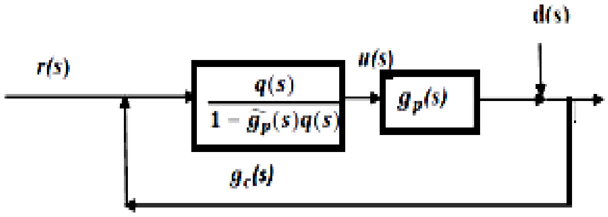

Figure 5: The equivalent feedback form to IMC

The standard IMC approach cannot be used for the unstable system. So the feedback form and filter parameters are used for those cases. To acquire the controller parameters, the obtained IMC controller transfer function is compared with the general equation of PID controller. The standard feedback controller is a function of the internal model $\widetilde{g_p}(s)$ and internal model controller $q(s)$ shown in the equation below.

$$g_c(s) = \frac{q(s)}{1-\widetilde{g_p}(s)q(s)} \tag{16}$$

Now find the PID equivalent

$$g_c(s) = \frac{q(s)}{1-\widetilde{g_p}(s)q(s)} = \frac{\tilde{q}(s)f(s)}{1-\widetilde{g_p}(s)\tilde{q}(s)f(s)} \tag{17}$$

$$= \frac{\tilde{q}(s)f(s)}{1-\widetilde{g_p}-(s)\widetilde{g_p}+(s)\widetilde{g_p}\text{-}(s)^{-1}f(s)} \tag{18}$$

$$= \frac{\tilde{q}(s)f(s)}{1-\widetilde{g_p}+(s)\,f(s)} \tag{19}$$

It is compared with conventional PID as

$$PID(s) = K_c(1 + \frac{1}{T_i s} + sT_d) \tag{20}$$

$$K_c = \frac{\tau+\frac{\theta}{2}}{K(\lambda+\frac{\theta}{2})} \tag{21}$$

$$T_i = \frac{\theta}{2} + \tau \tag{22}$$

$$T_d = \frac{\frac{\theta}{2}+\tau}{2(\frac{\theta}{2}+\tau)} \tag{23}$$

The process discussed above does not consider time delay in any region, so the $'\theta'$ terms can be canceled.

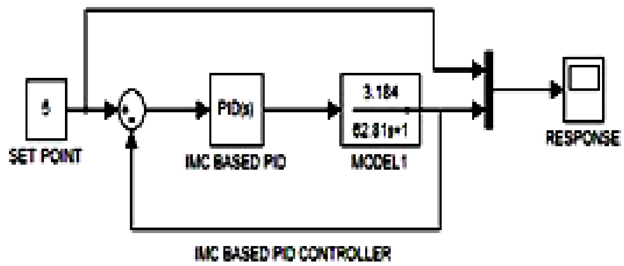

Figure 6: IMC- Based PID Controller system

Fig 6 shows the block diagram , of the IMC based PID controller. In this controller different filter parameters are used for the observation of the output. The below responses shows that the changes of the response depend on the filter parameter λ.

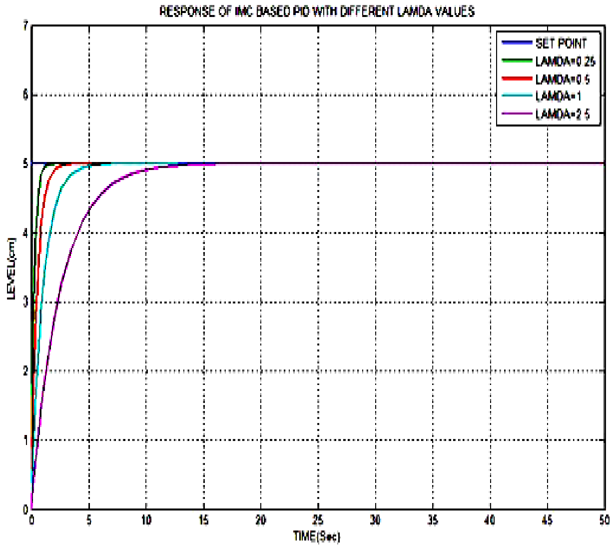

Figure 7: Response of different λ values for model1

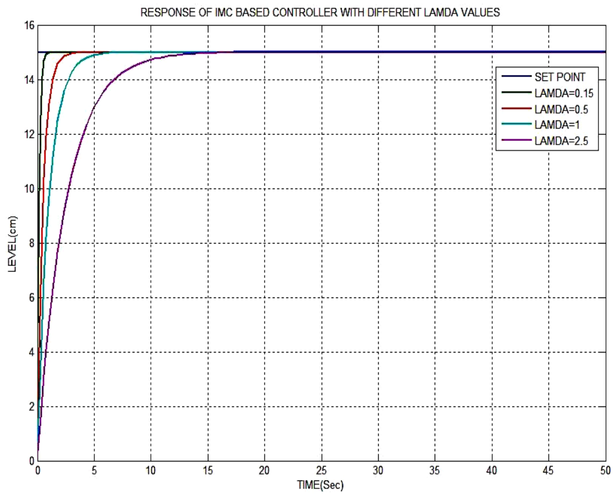

Figure 8: Response of different λ values for model2

Using different λ values 0.25, 0.5, 1, 2.5 the response variation of model 1 and model 2 are as shown in figure 7 & 8. From this observation, for the higher values of filter parameter the settling time increases, and for the lower values of filter parameter the set-point tracking is very fast. So each model λ is set at 0.25.

III. ADAPTIVE CONTROLLER

When and where the process parameters are continuously varying the controller parameters should be able to track the variation and hence the parameters of the controllers should change to nullify the disturbances caused by the variations of process parameters. Such a way the adaptive controllers are designed for the system. The basic classifications are direct, indirect, self-tuning techniques. The most commonly used procedure is by developing a reference model the variation in the actual model is determined. The adaptive mechanism will nullify the deviation in the process model and the reference model. The control parameter and adaptive gain are the factors of the adaptive mechanism. There are different procedures are there to develop an adaptive mechanism [7-10].

The MIT rule, describes about the minimization of the loss function which is quadratic in nature by adjusting the parameter of the controller θ, in order to obtain the desired the desired closed-loop response y_m. The error 'e' be the deviation of plant output y and the model out put, y_m.

$$J(\theta) \;=\; -\frac{1}{2}e^2 \tag{24}$$

$$\frac{d\theta}{dt} = -\,\gamma\frac{dJ}{d\theta} = \;-\gamma e\frac{de}{d\theta} \tag{25}$$

The gradient method gives, $\frac{d\theta}{dt} = -\gamma\frac{\partial e}{\partial\theta} sign\ e$ (26)

Consider a system described by the model

$$\frac{dy}{dt} = -ay + bu \tag{27}$$

$$\frac{dy_m}{dt} = -a_m y_m + b_m u_c \tag{28}$$

$$u(t) = \theta_1 u_c(t) - \theta_2 y(t) \tag{29}$$

The parameters of the controller are, $\theta_1 = \theta_1^{\circ} = \frac{b_m}{b}$ (30)

$$\theta_2 = \theta_2^{\circ} = \frac{a_m - a}{b} \tag{31}$$

So, $\frac{dy}{dt} = \frac{dy_m}{dt}$ (32)

To apply the MIT rule, introduce the error, $e = y - y_m$ finally,

$$e \;= \frac{b\theta_1}{p + a + b\theta_2}u_c - \frac{b_m}{p + a_m}\mathrm{uc} \tag{33}$$

Then the following equation for updating the controller parameters:

$$\frac{d\theta_1}{dt} = -\,\gamma\left(\frac{a_m}{p + a_m}u_c\right)e \tag{34}$$

$$\frac{d\theta_2}{dt} = \gamma\left(\frac{a_m}{p + a_m}y\right)e \tag{35}$$

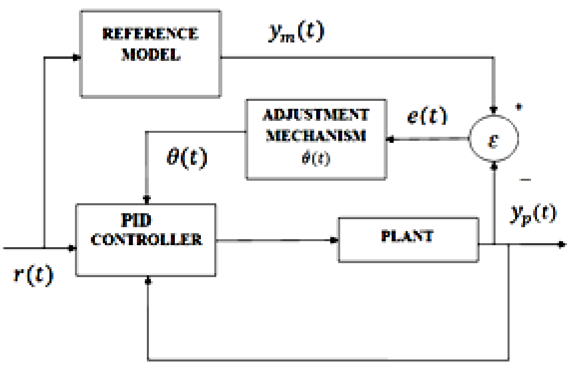

Figure 9: Block diagram of Adaptive PID Controller

Figure 9 shows the proposed structure where the parameters of the PID controller is adjusted on-line automatically based on the parameter variation of the process.

IV. SIMULATION RESULT

The system with nonlinearity is taken to the analysis in order to study the performances of the designed controllers. The system is modeled and simulated. The conventional PID controller is response is compared with the IMC tuned PID and MRAC tuned adaptive PID controllers. In order to study the disturbance rejection and the set point tracking problems the Servo and Regulatory response of the systems are compared for the different controllers.

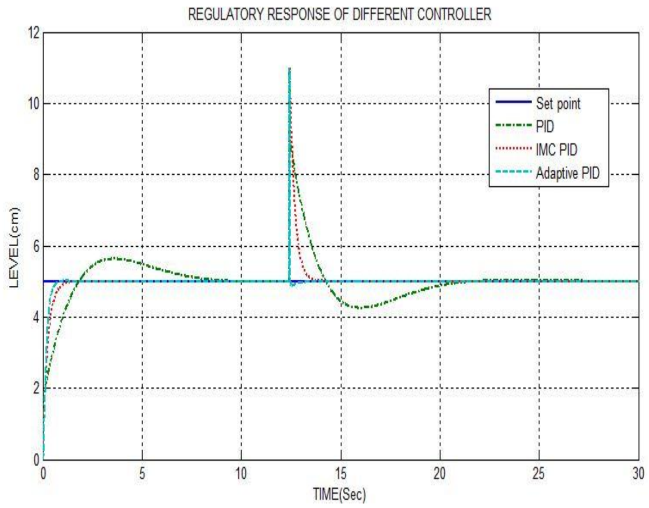

Figure10: Regulatory Response of Model1 at set point 5cm

The regulatory response is obtained, by allowing the system to the steady state and once the system reaches the steady state, apply a disturbance at t=12.8sec and observed. Figure 10 shows that the system settles at t=21sec has good disturbance rejection.

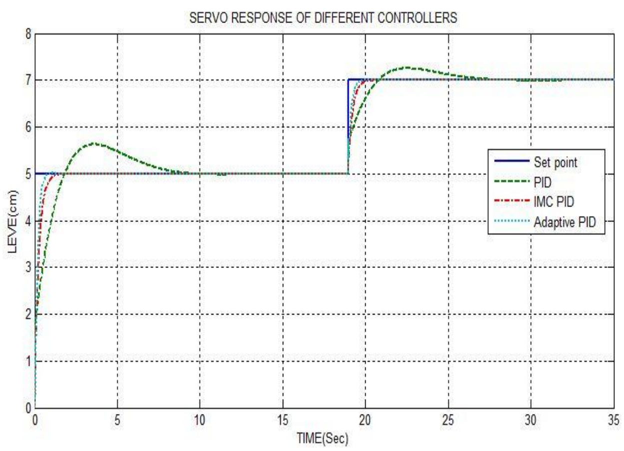

Figure11: Servo Response of Model1

On the other hand the servo response is obtained by creating the variation in the set point as shown in Figure 11.

The performance measure of the controller are tabulated in the Table 3 and Table 4.The time domain specification and the error criterion of the controllers are observed in order to compare the performance of the controllers.

Table 3: Error Specification for Model 1 at Set Point 5cm Model2 at Set Point 15cm

Model	Controller	ISE	IAE	ITAE
1 (Set Point=5cm)	PID	6.15	4.894	12.73
	IMC BASED PID	3.125	1.252	0.3285
	ADAPTIVE PID	3.006	0.9763	0.1585
2 (Set Point=15cm)	PID	18.01	4.79	4.094
	IMC BASED PID	16.83	2.25	2.6
	ADAPTIVE PID	16.81	1.992	0.2631

From the comparison table it shows that the MRAC base adaptive PID controller has low steady state and integral error and good time domain specification in terms of peak overshoot, settling time, rise time and delay time

Table 4: Comparison of Performance Indices of Model1 at Set Point 5cm And Model2 At Set Point 15cm

Model	Controller	Settling Time (Sec)	Delay Time (Sec)	Rise Time (Sec)
1 (Set Point=5cm)	PID	9.33	0.3012	1.51
	IMC BASED PID	1.52	0.1785	0.7571
	ADAPTIVE PID	0.4299	0.1584	0.796
2 (Set Point=15cm)	PID	3.31	0.1915	1.5136
	IMC BASED PID	0.976	0.1059	0.4537
	ADAPTIVE PID	0.915	0.0935	0.3431

V. CONCLUSION

This paper discussed about the design of a suitable controller for the nonlinear conical tank. The system is modeled analyzed and simulated. The conventional PID controller is developed by the open loop process identification technique and the parameters are obtained. The PID controller is then designed using IMC technique and further enhanced design is developed using adaptive technique. The MRAC based PID is finally developed .The performance of the controllers are evaluated by their servo and regulatory responses. Based on the response and the performance indices it is clearly noted that the adaptive PID controller gives the better response than the conventional PID controller and IMC tuned PID controller.

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