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Internal model controller based PID with fractional filter design for a nonlinear process

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ABSTRACT

In this paper, an Internal model Controller (IMC) based PID with fractional filter for a first order plus time delay process is proposed. The structure of the controller has two parts, one is integer PID controller part cascaded with fractional filter. The proposed controller has two tuning factors λ, filter time constant and a, fractional order of the filter. In this work, the two factors are decided in order to obtain low Integral Time Absolute Error (ITAE). The effectiveness of the proposed controller is studied by considering a non linear (hopper tank) process. The experimental set up is fabricated in the laboratory and then data driven model is developed from the experimental data. The non linear process model is linearised using piecewise linearization and two linear regions are obtained. At each operating point, linear first order plus dead time model is obtained and the controller is designed for the same. To show the practical applicability, the proposed controller is implemented for the proposed experimental laboratory prototype.

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1. INTRODUCTION

Most of the process industries like chemical industry, pharmaceutical industry, paper industry have non-linear process tanks namely conical tank, spherical tank and hopper tanks for storage or used in any processing stage. The parameters involved in such cases are flow, level, temperature and pressure, of these one of the major parameter to be considered for control is level in non-linear tanks. The Proportional-Integral-Derivative control (PID) is the extensively utilized control in process industries. The PID controller involves three parameters i.e. Kp, Ki and Kd. There are many analytical [1, 2], Soft computing techniques [3] and optimization techniques are used by the researchers to design the PID. Model based control was introduced and lead to the development of IMC based PID control [4].

Recently, the fractional calculus appealingly turns out to be progressively well known in scholarly world and industry. It has been gain attention in the field of control theory and other engineering applications. The improvement in the numerical and computational investigation expanded the researcher’s eagerness to enhance the controller performance using fractional calculus theory. Eventhough, the integer order controller, especially PI/PID controller dominates the industry, in future the fractional order controller will be widely accepted in the industry, because of its robustness and its flexibility of adjustment in phase and gain characteristics. Nevertheless, many empowering results have been revealed the superiority of the fractional order in model and control applications.

The development of fractional calculus in the control field lead to design of non-integer PID controller [5-9] and non-integer models [10, 11]. Tuning of fractional controllers for FOPDT systems using analytical methods [12], non-linear systems [13], time delay systems [14, 15], optimization techniques [16-18] are reported in literatures. The Flexibility of FOPID controller is increased by the additional parameters such as fractional order derivative and integrator, but it also increases the complexity of the controller tuning. Many researchers attempted to develop a simplified method for tuning FOPID controller. The IMC based controller strategy provides the additional information of controllers which reduces the tuning efforts. IMC based tuning of FOPID using analytical method attracted few researchers due to its simplified structure [19]. Instead of tuning five parameters in the FOPID controller, the IMC based FOPID controller design procedure reduce the controller tuning parameter into two such as filter time constant and order of filter [20]. Ranganayakulu R et. al (2017) proposed a direct synthesis method for designing IMC based fractional order Controller for the second order system with frequency domain tuning approach [21]. Fractional filter based on IMC is discussed along with the robustness analysis and using optimization technique, the filter and reduction of model for Load frequency control of single area non-reheated thermal power system modeled was done [22].

Tavakoli-Kakhki and M. Haeri in (2010) reported IMC based fractional order PI and PID controller structure. The analytical controller tuning is proposed for the reduced order fractional order model [23]. Pachauri N et. al proposed modified fractional order IMC based PID controller for nonlinear Bioreactor temperature control application, where the controller tuning parameter such as proportional gain and fractional order filter are tuned using water cycle optimization algorithm [24]. Heydarpoor, S. and Tabatabaei, M., presented the practical applicability of fractional order PI and fractional order IMC based controller for DC motor velocity control application [25]. Bettayeb M, and Mansouri R, a Proposed a IMC based fractional order PID controller for the integer order model. The controller resulted in integer order PID controller with simple fractional filter [26].

Problem Statement: The integer order control like PI and PID is as yet ruled in the industries with consistent control performance. Recently, the fractional calculus based controller got broad attention and interest from the research and industry community due its promising performance. There has been potential literature is available to proving that fractional order controller outperforms than integer order control. However, there is very few tuning methods are presented compared to PI/PID controller. Few researchers attempted Internal Model Controller (IMC) based Fractional order controller where the PI and PID controllers are casted with the fractional order filter. The problem taken for this research work is very clear that the challenges in the designing IMC based controller for time delay process has to be simplified.

Contribution: The main contribution of this paper is that the model based fractional order controller is designed. In this work, a simple IMC based PID with fractional filter is proposed for first order plus dead time process and is employed for the linearized model of non-linear hopper tank process. A simple IMC (Internal model Controller) based PID is proposed for a first order plus time delay process. The proposed controller has two parts, one is integer PID controller part cascaded with fractional filter. The proposed controller has two tuning factors λ, filter time constant and α, fractional order of the filter. The tuning guidelines have been given in straight forward way for the proposed controller. Addition to that, the real time laboratory prototype is developed with hopper tank. This experimental setup will help student community to understand the nonlinear dynamics of real time systems. The proposed controller is implemented in the real time to show the practical applicability.

Highlights:

a. Firstly, the control of hopper tank process is difficult since it is a combination of cylindrical and conical structure. Very few researchers worked in control of hopper tank process.
b. Secondly, though Batteyeb *et al* designed IMC based PID with fractional filter, the design procedure which we followed is different which resulted in a structure as shown in (17) and good closed loop performance will result if proper control parameters are chosen.
c. The proposed IMC based Fractional order Controller is implemented in the proposed laboratory experimental setup.

2. PROCESS DESCRIPTION

The set up consists of a pump, reservoir, process tank (Hopper tank), rotameter, orifice plate, control valve, DPT, air regulator, data acquisition card and personal computer. The setup is shown in Figure 1. The water from the reservoir is discharged through the pump and the process tank viarotameter and control valve. The differential pressure transmitter senses the differential pressure developed across the orifice plate and gives an output current range of 4 - 20 mA to the data acquisition system. The personal computer acts as error detector and controller. According to the error signal, corresponding manipulated input signal is given to the control valve through current to pressure converter which controlsthe input flow of the liquid to the level system. The detailed technical description of the process set up is given in Table 1. The schematic closed loop experimental setup is shown in Figure 2.

The laboratory setup is interfaced to personnel computer using ADuC841 micro controller based data acquisition (DAQ) card of transmitter is 4 - 20 mA current signals, which is converted into 0 to 5V range for interfacing with ADuC841. Data are generated in the single hopper tank by determining open loop response of the system set at manual mode. It is taken from the level process setup by setting the control valve opening as 75% and 90%. Process variable readings are obtained for each time interval. The input – output characteristics for different operating regions are shown in Figure 3.

Figure 1. Process setup

Table 1.Technical description

Component	Specification
Differential Pressure Transmitter	Source - Rose mount. Built-in sensor - Piezo-electric Input - (0-4000) mm H_2O Output -(4-20) mA at $24V_{dc}$/2wire system
Orifice plate	Upstream distance - 25 ×D Down stream distance - 5 × D Tapping - Flange type.
Rotameter	Range - (10-100) Litre / Hour, Body -Acrylic End connection -1/4 (F) BSP
Pneumatic Control Valve	Type - Globe valve Flow rate - (500/1000) Litre / Hour Characteristics - Equal 5% Valve action - Air to open
Level Transmitter	Type - Dual RF capacitance Input range - (0-300) mm Measuring range - (0-250) mm Output - (4-20) mA at $24V_{dc}$/2-wire system
Electro-pneumatic converter	Input pneumatic signal - 20psi constant Input current signal -(4-20) mA at 24V DC Output pneumatic pressure - (3-15) psi
Pump	Voltage - 230V AC, 50Hz. Discharge - 1200 LPH
Process tank	Body Material –Acrylic Dimension - 250 × 120mm
Reservoir tank	Capacity - 15 liter, Body- MS material
Air regulator	Input - 10.6 Kg/cm^2 Output - 2.1 Kg /cm^2 Special feature - Air regulator cum filter
Flow meter	Input - (0-100) Liter/hour Output - (4-20) mA at 24 V_{dc} / 3 wire system Medium - Water

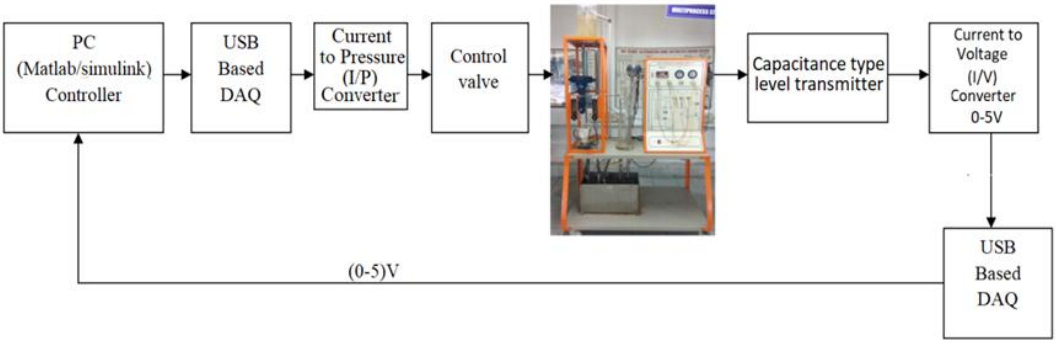

Figure 2. Closed loop experimental setup

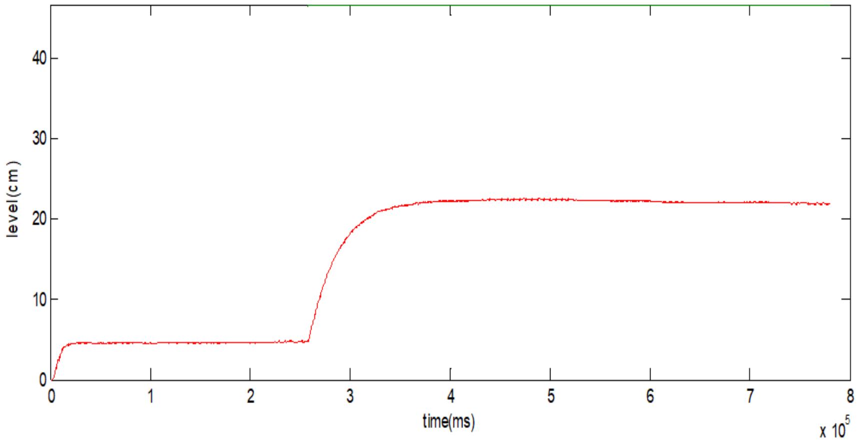

Figure 3. I/O Characteristics

The First Order PlusDead Time (FOPDT) transfer function model for the different operating region is obtained using process reaction curve method. From the Figure 2, the transfer function is obtained around the operating region are given below:

Transfer function for the 1st operating range (0 – 10) cm is obtained as (1):

$$G_1(s) = \frac{4.556}{92.73s+1}e^{-30s} \tag{1}$$

Transfer function for the 2nd operating range (10 – 25) cm is obtained as (2):

$$G_2(s) = \frac{17.86}{136s+1}e^{-13s} \tag{2}$$

3. CONTROLLER DESIGN

The conventional feedback control system is designed, and controller settings are obtained from analytical expression which is the resultant of IMC method with assumed process models. If the parameters are specified steadily, these two methods produce similar controllers. An advantage of the IMC approach is that, it can reject the disturbances faster than the PID control and it provides a tradeoff among performance and robustness.

The IMC control scheme is illustrated in the Figure 4. The approximated model ($G_m(s)$) response y_m, is obtained by applying the manipulated controller output ‘u’. The difference between process model (G(s)) output y and approximated model output ($y_m(s)$) is given as a feedback signal to the IMC controller. Mostly, the model output y and approximated model output will not be equal because of the modeling and approximation error, also due to the external disturbance.

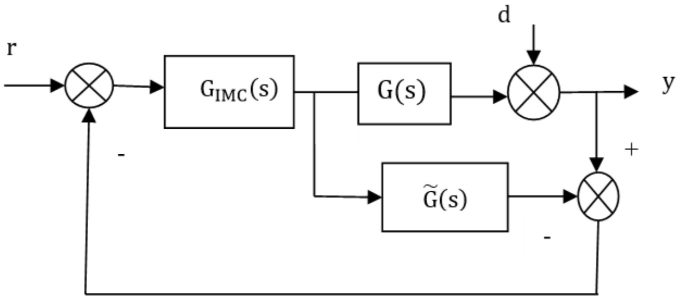

Figure 4. General internal model control structure

The feedback closed loop control system is shown in the Figure 5. The diagrams shown in Figure 4 and Figure 5 are equal if the controller $G_c(s)$ and $G_{IMC}(s)$ satisfies the relation:

$$G_c(s) = \frac{G_{IMC}(s)}{1 - G_{IMC}(s)\tilde{G}(s)} \tag{3}$$

Thus, it can be concluded that any IMC controller, $G_{IMC}(s)$ is comparable to a standard feedback controller $G_c(s)$, and vice versa.

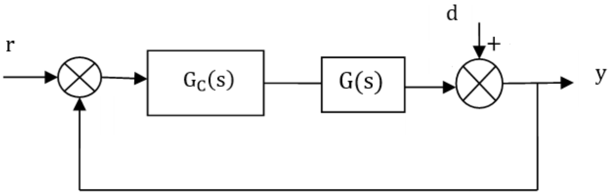

Figure 5.Conventional feedback control

The PID controller $G_c(s)$ is given as,

$$G_c(s) = k_p(1 + \frac{1}{\tau_i s} + \tau_d s) \tag{4}$$

Where, K_p is a Proportional gain, τ_i is the Integral time constant and τ_d is the derivative time constant.
Proposed IMC – PID Controller with Fractional Filter Design
Consider the FOPDT model (5),

$$G(s) = \tilde{G}(s) = \frac{ke^{-\theta s}}{\tau_p s + 1} \tag{5}$$

where, k = Process gain, τ_p = Time constant, θ = dead time
The fractional IMC filter (6) considered is

$$f(s) = \frac{1}{\lambda s^a + 1} \tag{6}$$

where, λ = filter time constant and a = fractional order of the filter time constant

$$\tilde{G}(s) = \tilde{G}_-(s)\tilde{G}_+(s) \tag{7}$$

Where, $\tilde{G}_-(s)$ is the invertible part of the model and $\tilde{G}_+(s)$ is the non- invertible part of the model.

$$\tilde{G}_{-}(s) = \frac{k}{\tau_p s + 1} \tag{8}$$

$$\tilde{G}_{+}(s) = e^{-\theta s} \tag{9}$$

$$G_{IMC}(s) = \frac{f(s)}{\tilde{G}_{-}(s)} \tag{10}$$

Substitute (6) & (8), we get

$$G_{IMC}(s) = \frac{1}{\lambda s^a + 1}\frac{\tau_p s + 1}{k} \tag{11}$$

The controller $G_c(s)$ is derived by substituting (11) & (5) in (3), we get

$$e^{-\theta s} = \frac{1 - 0.5\theta s}{1 + 0.5\theta s} \tag{15}$$

$$G_c(s) = \frac{\tau_p s + 1}{k\left[(\lambda s^a + 1) - \frac{1 - 0.5\theta s}{1 + 0.5\theta s}\right]} \tag{16}$$

Finally, the IMC-PID controller with fractional filter is obtained by substituting (15) in (14), we get

$$G_c(s) = \frac{1}{0.5\theta\lambda s^a + \lambda s^{a-1} + \theta}\left\{\frac{\tau + 0.5\theta}{k}\left[1 + \frac{1}{(\tau + 0.5\theta)s} + \left(\frac{0.5\theta\tau}{\tau + 0.5\theta}\right)s\right]\right\} \tag{17}$$

Thus the proposed controller has the structure,

$$G_c(s) = H(s)\left[k_c\left(1 + \frac{1}{\tau_i s} + \tau_d s\right)\right] \tag{18}$$

Comparing (18) with (17), we have

Filter transfer function, $H(s) = \frac{1}{0.5\theta\lambda s^a + \lambda s^{a-1} + \theta}$

$K_c = \frac{\tau + 0.5\theta}{k}$; $\tau_i = \tau + 0.5\theta$; $\tau_d = \frac{0.5\theta\tau}{\tau + 0.5\theta}$

Using the same procedure as above, IMC based PID controller with integer filter (i.e.$f(s) = \frac{1}{\lambda s + 1}$) is obtained as given in (19),

$$G_c(s) = \frac{1}{\left(\frac{0.5\theta\lambda}{\lambda + \theta}\right)s + 1}\left\{\frac{(0.5\theta + \tau)}{k(\lambda + \theta)}[1 + \frac{1}{(0.5\theta + \tau)s} + \frac{0.5\theta\tau s}{(0.5\theta + \tau)}]\right\} \tag{19}$$

Where, Filter transfer function, $H(s) = \frac{1}{\left(\frac{0.5\theta\lambda}{\lambda + \theta}\right)s + 1}$; $K_c = \frac{(0.5\theta + \tau)}{k(\lambda + \theta)}$; $\tau_i = \tau + 0.5\theta$; $\tau_d = \frac{0.5\theta\tau}{\tau + 0.5\theta}$

4. RESULTS AND ANALYSIS

4.1. Simulation study

The IMC based PID controller and IMC based PID with fractional filter (Proposed method) is designed for the two linear regions of the hopper tank process. The proposed method is compared with Bettayeb *et al* [26]. The controller settings for region 1 obtained using the (19), Bettayeb *et al* method and by (17) respectively are tabulated in Table 2.

For region 1: The transfer function for region 1 is given by $G_1(s)$,

$$G_1\ (s) = \frac{4.556}{92.73s+1} e^{-30s}$$

Table 2. Controller settings for region 1

Controller	k_p	k_i	k_d	Filter transfer function
IMC based PID	0.706	107.73	12.91	$\frac{1}{1+18.5s}$
IMC based PID with fractional filter (Bettayeb *et al*) [26]	1.576	107.73	12.91	$\frac{1}{1+1.76s^{0.11}}$
IMC based PID with fractional filter (Proposed method)	23.65	107.73	12.91	$\frac{1}{228s^{1.02}+15.2s^{0.02}+30}$

The filter transfer function for the IMC based PID with fractional filter (Bettayeb *et al*) is designed by choosing $\alpha = 0.11$ and$\tau_c = 1.76$ (where, $\omega_c = 0.028$). For the proposed method, the λ value is chosen to be 15.2 and a as 1.02 respectively. The closed loop step response of the process for the 1st operating range is shown in Figure 6. The set value is given to be 5 cm and it is observed that the proposed controller has minimum overshoot and settling time. Figure 7 & Figure 8 shows the closed loop response of the process for variations in time constant and gain respectively in order to analyse the controller robustness.

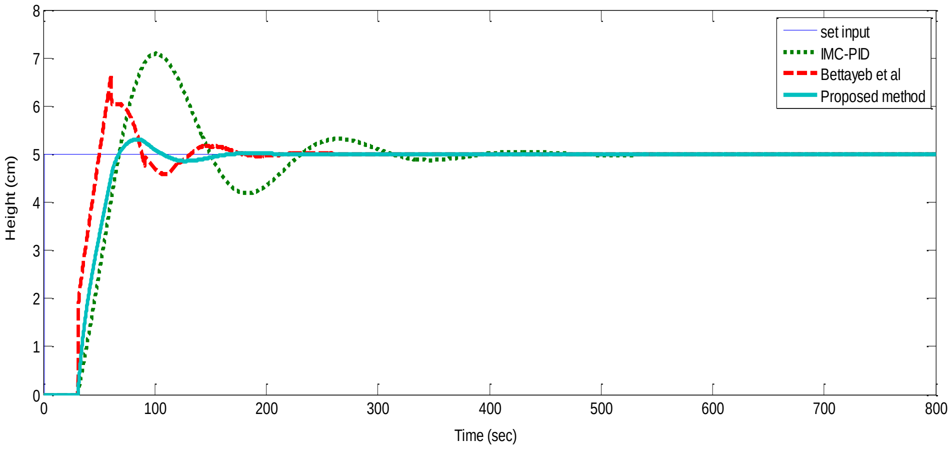

Figure 6. Closed loop step response for region 1

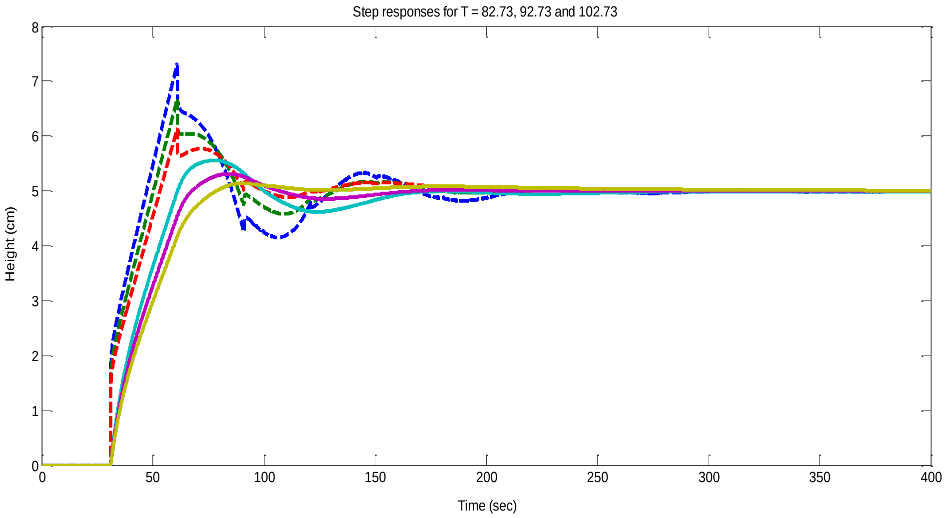

Figure 7. Closed loop response with variations in time constant, T

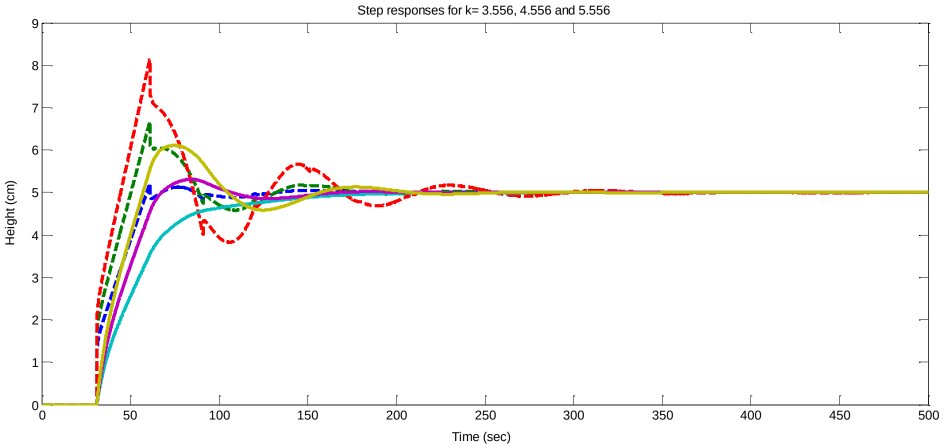

Figure 8. Closed loop response with variations in gain, K

The setpoint tracking performance of the proposed controller for region 1 is verified by changing the set values and its response is shown in Figure 9. The proposed controller can able to track the set point changes efficiently than the other controllers.

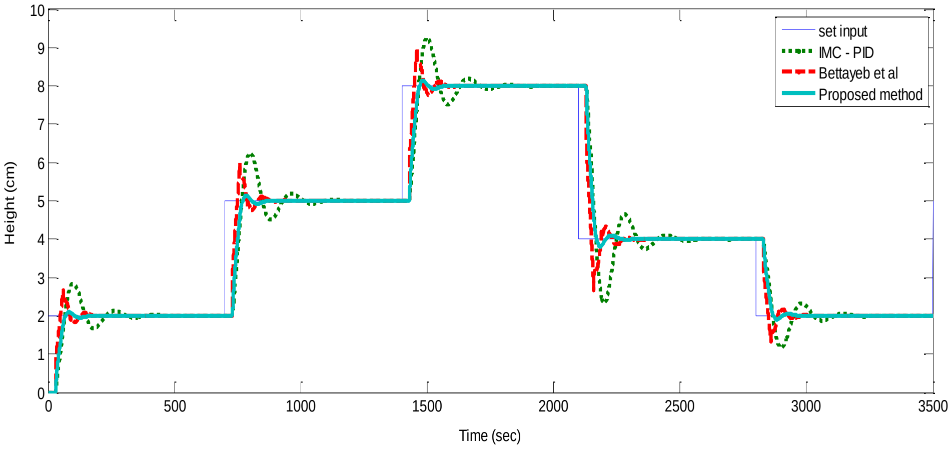

Figure 9. Closed loop response for region 1 with set point tracking

For region 2: The transfer function for region 2,

$$G_2(s) = \frac{17.86}{136s+1} e^{-13s}$$

The controller settings found for region 2 using the (19), Bettayeb *et al* method and by (17) are tabulated in Table 3.

Table 3. Controller settings for region 2

Controller	K_p	τ_i	τ_d	Filter transfer function
IMC based PID	0.532	142.5	6.203	$\frac{1}{1+8.5s}$
IMC based PID with fractional filter(Bettayeb *et al*) [26]	1.23	142.5	6.203	$\frac{1}{1+2.05s^{0.11}}$
IMC based PID with fractional filter(Proposed method)	7.97	142.5	6.203	$\frac{1}{42.25s^{1.02}+6.5s^{0.02}+13}$

The filter transfer function for the IMC based PID with fractional filter is designed by choosing α=0.11and τ_c = 2.05 (where, ω_c = 0.052). For the proposed method, the λ value is chosen to be 6.5 and a as 1.02 respectively. The setpoint tracking behaviour of the designed controller is shown in Figure 10 and it is evident that the proposed method has the ability to adapt to set point changes faster than the other methods.

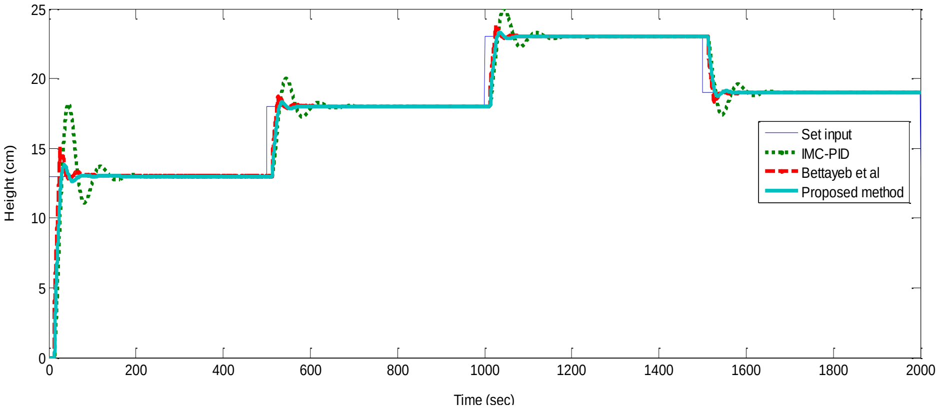

Figure 10. Closed loop step response for region 2 with set point tracking

4.2. Real time implementation of the proposed controller

Using the concept of fractional calculus, a toolbox has been developed by AlekseiTepliakov named as FOMCON [27]. The tool is developed for designing fractional model and controller. Fractional integrator, fractional differentiator, fractional order transfer function and fractional PID controller are available as simulink block set in FOMCON toolbox. The real time interfacing between the transmitter (capacitive type level transmitter) & controller (Personal computer) is done using the DAQ card. The DAQ card and Matlab are operated in same windows/2000/XP platform.

Figure 11 shows the real time implementation of PID controller with fractional filter using Matlab/simulink. The "Query instrument block" is used to acquire input from the level transmitter as digital bit of data in which the sampling time and interacting information are selected with its block itself. The controller output is sent to the DAQ card through the "To instrument block". The output from DAQ card is used to actuate the final control element (Control valve). The real time implementation of proposed controller with Matlab/ Simulink real time query instrument tool box. The real time implementation of proposed controller is shown in the Figure 12.

The time domain performance indices are calculated for the IMC based PID with integer filter and for fractional filter (Bettayeb *et al* and proposed method) and tabulated in Table 4. It is observed from the tabulated results in Table 4 is that, the IMC based PID controller with fractional filter has less overshoot and fast settling time compared with the other.

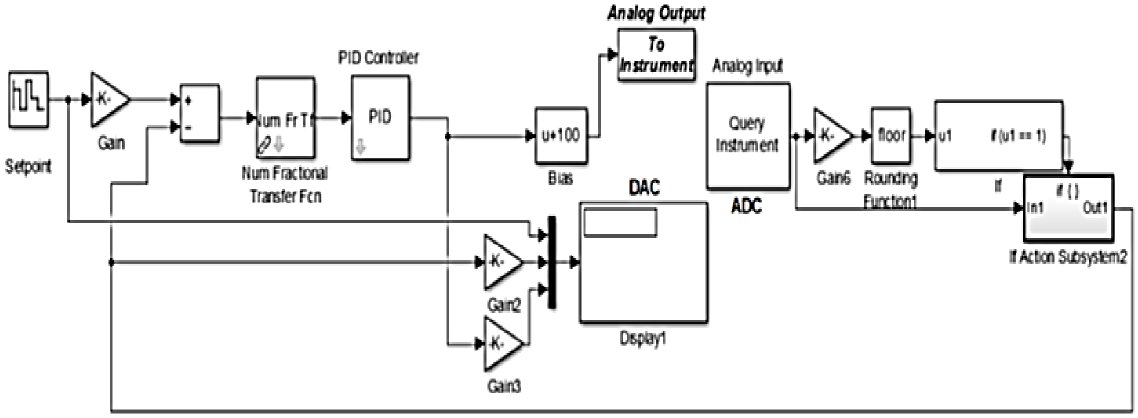

Figure 11. Real time implementation of PID controller with fractional filter using Matlab/Simulink

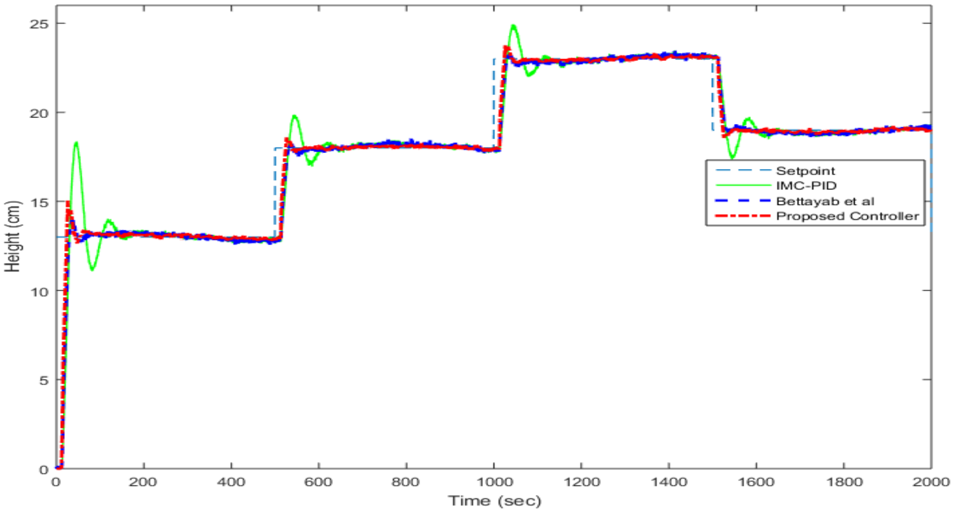

Figure 12. Real time implementation of proposed controller.

Table 4. Time domain performance indices

Controller	Region 1					Region 2				
	PO	Settling time, (ts)	ITAE	ISE	$ITAE_{sp}$	PO	Settling time, (ts)	ITAE	ISE	$ITAE_{sp}$
IMC based PID	7.09	634.5	$3.386x10^4$	1272	$1.79x10^6$	19.5	250.3	$1.79x10^4$	4349	$5.225x10^5$
IMC based PID with fractional filter (Bettayeb *et al*) [19]	6.65	305.7	7982	845.3	$9.45x10^5$	15.72	240.2	4018	2886	$2.87x10^5$
IMC based PID with fractional filter (Proposed method)	5.3	216.7	6883	960.9	$9.20x10^5$	14.82	138.8	3846	3279	$2.68x10^5$

5. CONCLUSION

A simple IMC based PID controller with fractional filter for a FOPDT process is proposed. The proposed design is applied to the non-linear hopper tank process modeled linearized as FOPDT process. The simulation result shows the effectiveness of the designed controller. The performance indices of the proposed controllerare compared with IMC based PID with fractional filter (Bettayeb *et al*) and IMC based PID and results are tabulated. From the tabulation, it is clear that the proposed controller has minimum overshoot, settling time and improved robustness. The proposed controller is implemented practically with the laboratory hopper tank prototype inorder to control the level of the tank.

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