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Experimental Validation of a Multi Model PI Controller for a Non Linear Hybrid System in LabVIEW

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Abstract

In this paper a real time Single Spherical Tank Liquid Level System (SSTLLS) has been chosen for investigation. This paper describes the design and development of a Multi Model PI Controller (MMPIC) using classical controller tuning techniques for a single spherical nonlinear tank system. System identification of these different regions of nonlinear process are done using black box modeling, which is identified to be nonlinear and approximated to be a First Order Plus Dead Time (FOPDT) model. A proportional and integral controller is designed using LabVIEW and Chen-Hrones-Reswick (CHR), Zhuang-Atherton (ZA), and Skogestad's Internal Model Controller (SIMC) tuning methods are implemented in real time. The paper provides the details about the data acquisition unit, shows the implementation of the controller and comparision of the results of PI tuning methods used for an MMPI Controller.

***Keywords**: Graphical User Interface (GUI), PI Controller, Chen-Hrones-Reswick (CHR), Zhuang-Atherton (ZA), and Skogestad's Internal Model Controller (SIMC), LabVIEW*

1. Introduction

In common terms, most of the industries have typical problems raised because of the dynamic non linear behavior of the storage tanks. It's only because of the inherent non linearity, most of the chemical process industries are in need of classical control techniques. Hydrometallurgical industries, food process industries, concrete mixing industries and waste water treatment industries have been actively using the spherical tanks as an integral process element. Due to its changing cross section and non linearity, a spherical tank provides a challenging problem for the level control.

Liquid level control systems have always pulled the attention of industry for its very important manipulated parameter of level, which finds many applications in various fields. An accurate knowledge of an adequate model is often not easily available. An insufficiency in this aspect of model design can always lead to a failure in some non linear region with higher non linearity. The evidence that many researchers are working in the nonlinear models and their controlling strategies [1],[2], which in turn explain about the process dynamics around a larger operating region than the corresponding linear models have been gaining great popularity [3].The non linear models are obtained from first principle and further from the parameters which appear within such models that are obtained from the data of the process. However the conventional methods for developing such models are still in search. Once the model has been developed, the need for the controller design comes in to picture to maintain the process under steady state. Proportional Integral Derivative (PID) controller is the name that is widely heard as a part of the process control industry. Despite much advancement in control theory which has been recently seen, PID controllers are still extensively used in the process industry. Conventional PID controllers are simple, inexpensive in cost [4], easy to design and robust provided the system is linear. The PID controller operates with three parameters, which can be easily tuned by trial and error, or by using different tuning strategies and rules available in literature such as Zieglar Nichols [5], Zhuang and Atherton [6].These rules have their bases laid on open-loop stable first or second order plus dead time process models. There are many other methods and approaches which have periodically evolved to improvise the performance of PID tuning, The software and technology have been assisting the mankind to design and implement more sophisticated control algorithms. Despite all the effort, industries emphasize more on robust and transparent process control structure that uses simple controllers which makes PID controller the most widely implemented controller.

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SSTLLS has been a model for quite a many experiments performed in the near past. Nithya et al [7] have designed a model based controller for a spherical tank, which gave a comparison between IMC and PI controller using MATLAB. Naresh Nandola et al [8] have studied and mathematically designed a predictive controller for non linear hybrid system. A gain scheduled PI controller was designed using a simulation on MATLAB for a second order non linear system by Dinesh Kumar et al [9] which gave information about servo tracking for different set points. A fractional order PID controller was designed for liquid level in spherical tank using MATLAB, which compared the performance of fractional order PID with classical PI controller by Sundaravadivu et al [10]. Kalyan Chakravarthi et al have implemented a classical and gain scheduled PI controllers for a single and dual spherical tank systems in real time using LabVIEW [11],[12]. An adaptive fuzzy PID controller has been implemented for controlling level process [13]. A Fuzzy Immune PID Control was also implemented on a hydraulic system ,which was optimized by PSO algorithm [14].

2. Experimental Process Description

The laboratory set up for this system basically consists of two spherical interacting tanks which are connected with a manually operable valve between them. Both the tanks have an inflow and outflow of water which is being pumped by the motor, which continuously feeds in the water from the water reservoir. The flow is regulated in to the tanks through the pneumatic control valves, whose position can be controlled by applying air to them.

Figure 1. Real time experimental set up of the process

Figure 2. Interfaced NI-DAQmx 6211 Data Acquisition Module Card

A compressor so as to apply pressure to close and open the pneumatic valves was used. There is also provision given to manually measure the flow rate in both the tanks using rotameter. The level in the tanks are being measured by a differential pressure transmitter which has a typical output current range of 4-20mA.This differential pressure transmitter is interfaced to the computer connected through the NI-DAQmx 6211 data acquisition card which can support 16 analog inputs and 2 analog output channels with a voltage ranging between ±10 Volts. The sampling rate of the acquisition card module is 250Ks/S with 16 bit resolution. The graphical program written in LabVIEW is then linked to the set up through the acquisition module. Figure 1 shows the real time experimental setup of the process.The process of operation starts when pneumatic control valve is closed by applying the air to adjust the flow of water pumped to the tank. This paper talks only about a single spherical tank liquid level system (SSTLLS), so we shall use only the spherical tank one for our usage throughout the experiment. The level of the water in tank is measured by the differential pressure transmitter and is transmitted in the form of current range of 4-20mA to the interfacing NI-DAQmx 6211 data acquisition module card to the Personal Computer (PC). After computing the control algorithm in the PC, control signal is transmitted to the I/P converter which passes the pressure to the pneumatic valve proportional to the current provided to it. The pneumatic valve is actuated by the signal provided by I/P converter which in turn regulates the flow of water in to the tank. Figure 2 shows the interfaced NI-DAQmx 6211 data acquisition card.

3. System Identification and Controller Design

3.1. Mathematical Modeling of SSTLLS

The SSTLLS is a system which is non linear in nature by virtue of its varying diameter. The dynamics of this non linearity can be described by the first order differential equation.

$$\frac{dV}{dt} = q_1 - q_2 \tag{1}$$

Where, V is the volume of the tank, q_1 is the Inlet flow rate and, q_2 is the Outlet flow rate. The volume V of the spherical tank is given by,

$$V = \frac{4}{3}\pi h^3 \tag{2}$$

Where h is the height of the tank in cm.

On application of the steady state values, and by solving the equations 1 and 2, the non linear spherical tank can be linearized to the following model,

$$\frac{H(S)}{Q1(S)} = \frac{Rt}{\tau s+1} \tag{3}$$

Where, $\tau = 4\pi R_t h_S$ and $Rt = \frac{2hs}{Q2s}$

The system identification of SSTLLS is derived using the black box modeling. Under constant inflow and constant outflow rates of water, the tank is allowed to fill from (0-45) cm. Each sample is acquired by NI-DAQmx 6211 from the differential pressure transmitter through USB port in the range of (4-20) mA and the data is transferred to the PC.This data is further scaled in terms of level in cm.Employing the open loop method, for a given change in the input variable; the output response of the system is recorded. Ziegler and Nichols [5] have obtained the time constant and time delay of a FOPDT model by constructing a tangent to the experimental open loop step response at its point of inflection. The intersection of the tangent with the time axis provides the estimate of time delay. The time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain. Cheng and Hung [15] have also proposed tangent and point of inflection methods for estimating FOPDT model parameters. The major disadvantage of all these methods is the difficulty in locating the point of inflection in practice and may not be accurate. Prabhu and Chidambaram [16] have obtained the parameters of the first order plus time delay model from the reaction curve obtained by solving the nonlinear differential equations model of a distillation column. Sundaresan and Krishnaswamy [17] have obtained the parameters of FOPDT transfer function model by collecting the open loop input-output response of the process and that of the model to meet at two points which describe the two parameters τ_p and θ. The proposed times t_1 and t_2, are estimated from a step response curve. The proposed times t_1 and t_2, are estimated from a step response curve. This time corresponds to the 35.3% and 85.3% response times. The time constant and time delay are calculated as follows.

$$\tau_p = 0.67(t_2 - t_1) \tag{4}$$

$$\theta = 1.3t_1 - 0.29t_2 \tag{5}$$

At a constant inlet and outlet flow rates, the system reaches the steady state. After that a step increment is given by changing the flow rate and various values of the same are taken and recorded till the system becomes stable again. We obtain the model of the plant experimentally for a given unit-step input. If the plant involves neither integrators nor dominant complex-conjugate poles, then such a unit step response curve may look S-shaped curve.Such step response curve may be generated experimentally or from a dynamic simulation of the plant. The S-shaped curve may be characterized by two constants, delay time L and time constant τ. The experimental data are approximated to be an FOPDT model.

3.2. Design of PI Controller

The derivation of transfer function model will now pave the way to the controller design which shall be used to maintain the system to the optimal set point. This can be only obtained by properly selecting the tuning parameters K_p and K_i for a PI controller.
The conventional FOPDT model is given by,

$$G(s) = \frac{Ke^{-\theta s}}{\tau s+1} \tag{7}$$

Table 1 gives the transfer functions designed for different regions of SSTLLS. It can be noticed that the delay exponentially increases as the degree of non linearity increases. The transfer function models are derived for five different regions across the varying diameter of SSTLLS.

By implementing the rules of PI tuning by the methods ZA, CHR and SIMC methods to get the following parameters for the transfer function specified in Table 1.The parameters of K_p and K_i for different regions of non linearity are derived and given in Table 2.

Table 1. Transfer function models for different regions of SSTLLS

Region of Operation	Transfer Function
0-9	$G(s) = \frac{9e^{(-[illegible])}}{1+91.12s}$
9-18	$G(s) = \frac{18e^{(-[illegible])}}{1+ 142.04s}$
18-27	$G(s) = \frac{11.26e^{(-[illegible])}}{1+125.61s}$
27-36	$G(s) = \frac{10e^{(-[illegible])}}{1+78.866s}$
36-45	$G(s) = \frac{11.26e^{(-[illegible])}}{1+27.808s}$

4. Results and Discussions

The CHR, ZA and SIMC based MMPI controllers which were designed and are implemented using the graphical programming code which is written on LabVIEW. These controllers were applied to SSTLLS and the performance of them was compared under different condition and regions of operation.

Table 2. CHR, ZA and SIMC tuned K_p and K_i parameters for different regions of non linearity

Tuning Method	Regions (cm)	Kp	Ki
CHR	0-9	0.12661	0.0009520856
	9-18	0.03359	0.0000961000
	18-27	0.04123	0.0000757815
	27-36	0.04055	0.0000625104
	36-45	0.03333	0.0000483407
ZA	0-9	0.056	0.0006145404
	9-18	0.0135	0.0000950400
	18-27	0.0107	0.000087265016
	27-36	0.00565	0.000077012199
	36-45	0.00172	0.000061859370
SIMC	0-9	0.11390	0.00124993
	9-18	0.01789	0.00012500
	18-27	0.01210	0.000098682869
	27-36	0.00599	0.000081646561
	36-45	0.001757	0.000063190073

4.1. Changes in the Load

The CHR, ZA and SIMC tuned controllers have been used to control the level of SSTLLS while applying a load change of 7.5% for a set of set points. Initially to test the response of the tank in its non linear region, a set point of 4.5 cm was fed to the program and the readings were recorded. Similar method was employed for the set points of 2.25, and 9 cm respectively. While applying a set point of 2.25 from 4.5 cm, we are intending to observe the negative set point tracking performance.

Table 3. Comparison of Time Domain Analysis for Servo Response for different regions

Parameter	Set Point (cm)	Tuning Method		
		CHR	ZA	SIMC
Peak Time (sec)	4.5	62.203	53.453	26.64063
	9	126.406	128.906	159.9844
	22.5	76.796	84.89063	104.7031
	27	168.484	162.437	204.1406
	40.5	105.75	85.5	28.04688
	45	156.156	146.25	123.289
Rise Time (sec)	4.5	55.9828	48.1078	23.97656
	9	113.765	116.0156	143.9859
	22.5	69.117	104.6109	94.2327
	27	151.635	146.193	183.726
	40.5	95.175	76.95	25.2421
	45	140.540	131.625	110.7
Settling Time (sec)	4.5	28.953	21.0	17.10937
	9	36.4531	37.0468	6.2969
	22.5	35.546	15.90627	1.5938
	27	20.95	39.1563	9.1563
	40.5	51.0	1.34375	4.4531
	45	17.098	8.8438	1.1406

The similar process of observing the negative set point tracking is also adopted. At all the levels, a disturbance is added to the system to observe its performance. Similarly the set points are changed for the regions of 18-27 cm and 36-45 cm in the SSTLLS. Figures 3(a), 3(b), 3(c), 3(d), 3(e), 3(f), 3(g), 3(h), 3(i) demonstrate the regulatory performance under the influence of external disturbance of tuned MMPI controller in the regions of 0-9 cm, 18-27 cm and 36-45 cm for CHR, ZA and SIMC tuned MMPI controllers respectively. The performance indices of the regulatory response can be seen in Table 5.The designed controllers were able to compensate the effect of the load changes.It can be noticed from Table 5, that the ISE and IAE values for SIMC method are relatively lesser than the ZA and CHR method in the regions 0-9 cm and 36-45 cm of SSTLLS, where the degree of non linearity is very high.At the same time it can be seen that, in all the other regions of operation ZA tuned MMPI controller shows an efficient disturbance rejection and provides relatively lesser ISE and IAE values across the regions 9-18 cm, 18-27 cm, 27-36 cm.

4.2. Variation of the Set Point

The CHR, ZA and SIMC MMPI controllers were run for all different regions of SSTLLS which are modeled in the Table 1. Figure 4(a), Figure 4(b) and Figure 4(c) display the comparison results of servo responses obtained for different regions viz.;0-9 cm,18-27 cm and 36-45 cm respectively. The set points chosen for this analysis are 4.5, 9, 22.5, 27, 40.5 and 45 cm. The level varies for both the controllers and their changes are seen in Figure 4(a), Figure 4(b) and Figure 4(c).It can be observed that the level very swiftly oscillates for CHR and ZA method in comparision to SIMC in most non linear regions towards the curvature of the spherical tanks.It is seen that in the regions with highest degree of non linearity, SIMC tuned MMPI controller tracks the set point in a very less time when compared to that of CHR and ZA tuned controllers. Table 3 gives the time domain specifications of the present system. It is evident from Table 3 that the rise time and settling time for different set points for SIMC tuned MMPI controller is relatively less in the non linear regions when compared with CHR and ZA tuned controllers. Table 4 deals with the performance indices like ISE and IAE for the different set points in the entire region of operation. It can be observed that ISE and IAE values for the

SIMC method in non linear region of 4.5cm and 40cm are less when compared to that CHR and ZA method. If keenly observed, SIMC tuned controller performs better than that of other two methods with respect to ISE and IAE calculations. It can be inferred that for faster time response in non linear regions SIMC method of tuning proves to be the best method. But if the emphasize is more on the error reduction in the system, ZA method gives a best of its performance in almost all the regions of operations. It can be very well seen that extreme non linear regions 0-9cm and 36-45cm have a very less IAE and ISE, thus proving the efficiency of SIMC tuning method over the ZA and CHR method.

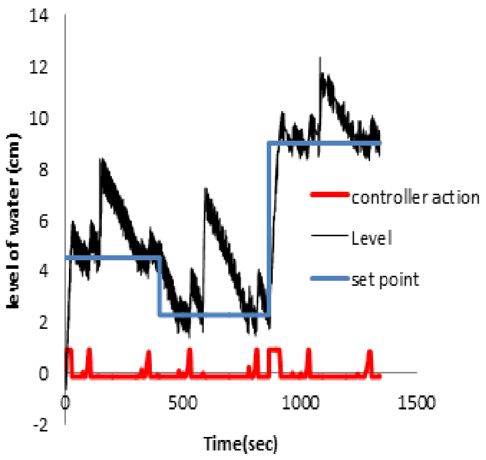

Figure 3(a). ZA tuned MMPI Controller's Regulatory Response for region 0-9cm

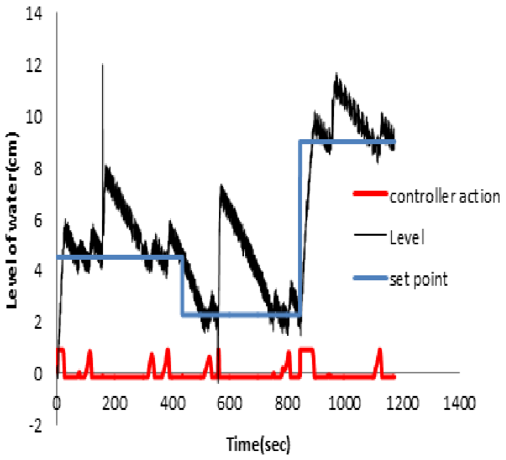

Figure 3(b). SIMC tuned MMPI Controller's Regulatory Response for region 0-9cm

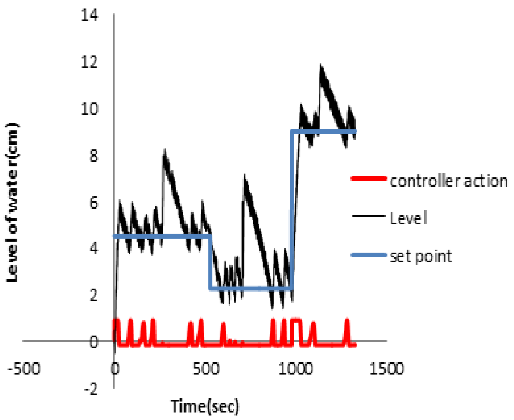

Figure 3(c).CHR tuned MMPI Controller's Regulatory Response for region 0-9cm

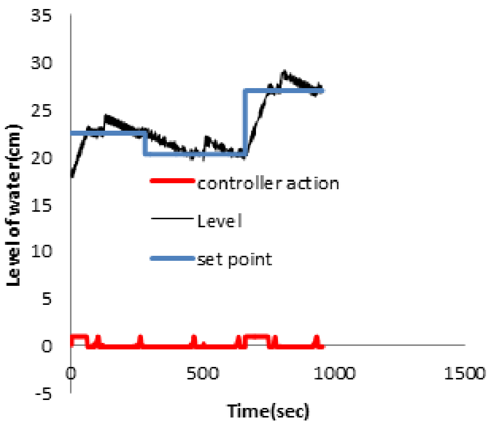

Figure 3(d). ZA tuned MMPI Controller's Regulatory Response for region 18-27cm

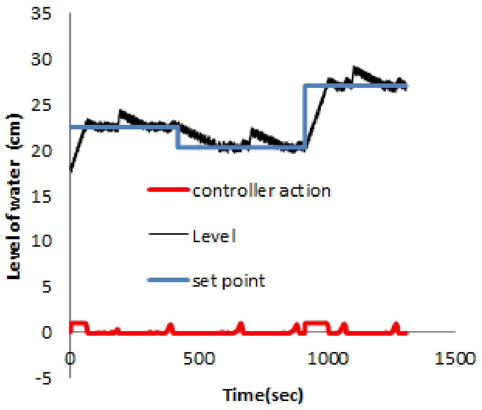

Figure 3(e). SIMC tuned MMPI Controller’s Regulatory Response for region 18-27cm

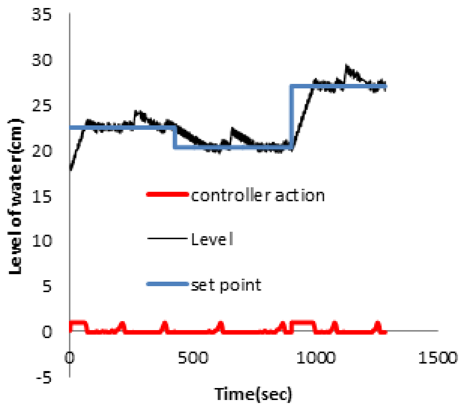

Figure 3(f). CHR tuned MMPI controller’s Regulatory Response for region 18-27cm

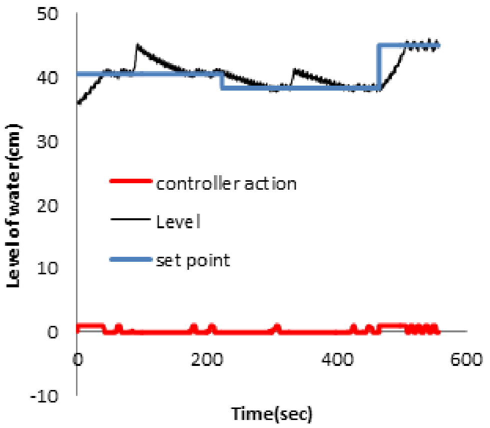

Figure 3(g). ZA tuned MMPI Controller’s Regulatory Response for region 36-45cm

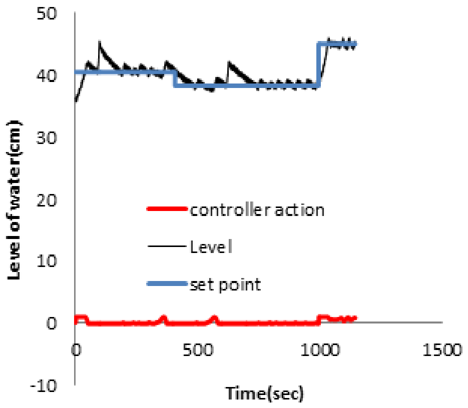

Figure 3(h). SIMC tuned MMPI Controller’s Regulatory Response for region 36-45cm

Table 4. Comparison of performance indices of servo response for different regions

Set Point (cm)	Tuning Method	ISE	IAE
4.5	CHR	139.8357	226.4972
	ZA	647.3612	512.4809
	SIMC	136.6747	222.5321
9	CHR	268.7596	315.4242
	ZA	26.27826	82.10396
	SIMC	274.0812	320.6738
22.5	CHR	124.1946	211.2895
	ZA	70.75993	149.6571
	SIMC	140.9391	228.0648
27	CHR	129.8721	211.7776
	ZA	99.09449	178.9191
	SIMC	170.9055	245.9187
40.5	CHR	1228.188	668.8206
	ZA	171.2032	243.3611
	SIMC	1423.315	720.9027
45	CHR	57.54179	106.1665
	ZA	51.49448	96.66933
	SIMC	40.24258	85.69754

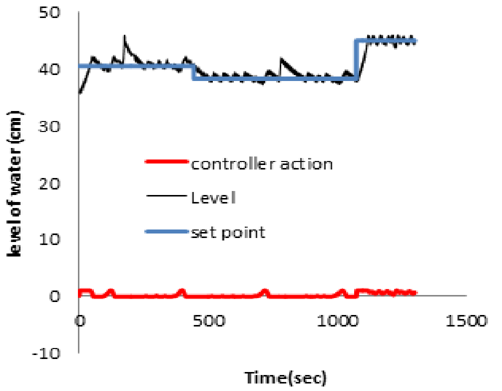

Figure 3(i). CHR tuned MMPI controller's Regulatory Response for region 36-45cm

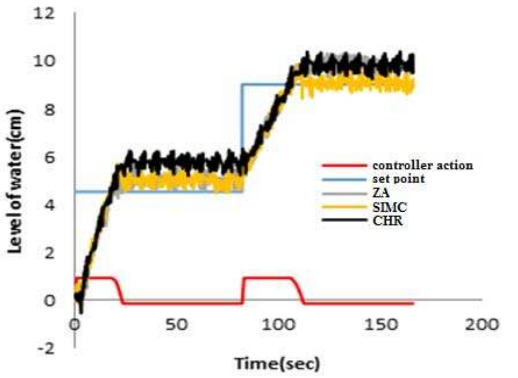

Figure 4(a).Servo Responses of CHR, ZA and SIMC tuned MMPI controllers for region 0-9cm

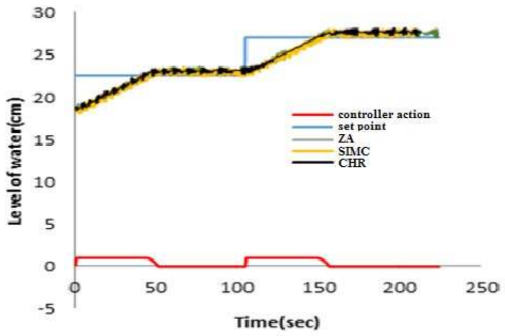

Figure 4(b). Servo Responses of CHR,ZA and SIMC tuned MMPI controllers for region 18-27cm

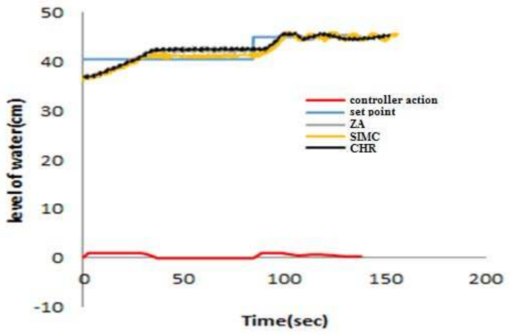

Figure 4(c).Servo Responses of CHR, ZA and SIMC tuned MMPI controllers for region 36-45cm

Table 5. Comparison of performance Indices of regulatory response in different regions

Set Point (cm)	Tuning Method	ISE	IAE
4.5	CHR	5702.741	2598.228
	ZA	5440.887	2574.304
	SIMC	5134.143	2567.652
9	CHR	3029.299	1852.831
	ZA	1979.908	1476.096
	SIMC	2231.789	1553.274
22.5	CHR	2959.168	1942.761
	ZA	885.3459	865.7407
	SIMC	1414.623	1098.509
27	CHR	1156.216	1121.716
	ZA	965.0554	998.3812
	SIMC	1121.784	1055.477
40.5	CHR	1332.551	1013.717
	ZA	3011.964	1270.751
	SIMC	1056.572	1082.533
45	CHR	250.7785	456.9153
	ZA	3289.437	1747.069
	SIMC	107.6896	217.542

4. Conclusion

In this study, a CHR, ZA and SIMC methods based MMPI Controller were designed for a SSTLLS process. The model identification and MMPI controller design were done using an NI-

DAQmx 6211 data acquisition card and LabVIEW. Graphical programming was used to implement the whole experiment. The experimental results evidently prove that the influence of set point and load changes are smooth for SIMC method of tuning in non linear regions. It can be also seen that minimum overshoot, faster settling time and rise time are obtained. It has a better capability of compensating all the load changes. In the regions of lesser degree of non linearity ZA method proves to be relatively effective for it provides smaller values of ISE,IAE and all the time indices. The ISE and IAE values justify that relatively a minimum error is seen in SIMC way of tuning the MMPI PI controller than ZA and CHR methods for both servo and regulatory responses..It can be concluded that SIMC method based MMPI PI controller can be implemented in extreme non linear regions on real time SSTLLS using NI-DAQmx 6211 data acquisition module and LabVIEW in real time.

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