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Research Article

Design and Implementation of Adaptive Model Based Gain Scheduled Controller for a Real Time Non Linear System in LabVIEW

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Abstract: The aim of this study is to design and implement an Adaptive Model Based Gain Scheduled (AMBGS) Controller using classical controller tuning techniques for a Single Spherical Nonlinear Tank System (SSTLLS). A varying range of development in the control mechanisms have been evidently seen in the last two decades. The control of level has always been a topic of discussion in the process control scenario. In this study a real time SSTLLS has been chosen for investigation. System identification of these different regions of nonlinear process is done using black box model, 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 Skogestad's and Ziegler Nichols (ZN) tuning methods are implemented. The paper will provide details about the data acquisition unit, shows the implementation of the controller and compare the results of PI tuning methods used for an AMBGS Controller.

Keywords: Graphical User Interface (GUI), LabVIEW, PI controller, skogestad's method, Single Spherical Tank Liquid Level System (SSTLLS), Z-N method

INTRODUCTION

In common terms, most of the industries have typical problems raised because of the dynamic non linear behavior. 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 (Biegler and Rawlings, 1991; Kravaris and Arkun, 1991), which in turn explained about the process dynamics around a larger operating region than the corresponding linear models have been gaining great popularity (Raich *et al*., 1991). The non linear models are obtained from first principles 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, then 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 (Mann *et al*., 1999), 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 ZN (Ziegler and Nicolas, 1942; Zhuang and Atherton, 1993; Sung *et al*., 1996). 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, For instance the Aström-Hägglund phase margin method (Astrom and Hagglund, 1984), the refined ZN method by Cohen and Coon (1953) as well as Hang *et al*. (1991), the Internal Model Control (IMC) design method (Garcia and Morari, 2000; Rivera *et al*.,

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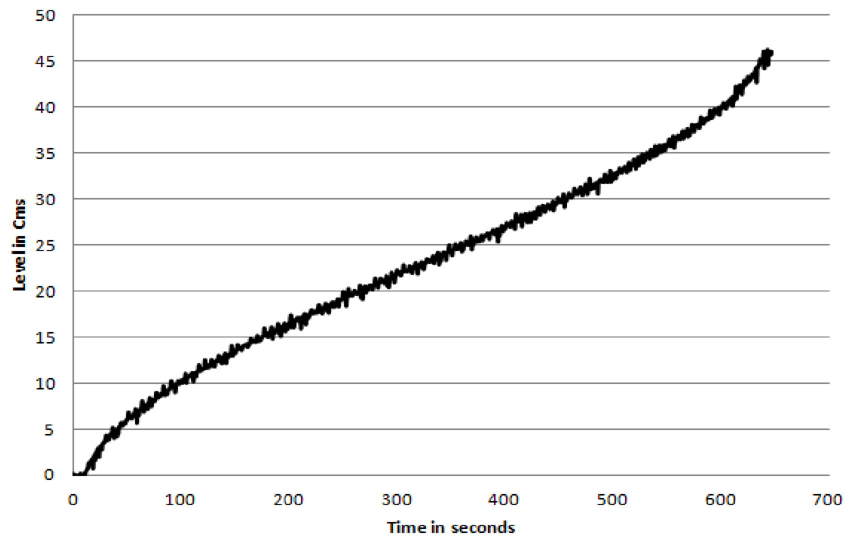

Fig. 1: S-shaped open loop input-output response curve

1986), gain and phase margin design methods (Astrom and Hagglund, 1996).

Depaor and O'Malley (1989) and so on. 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.

SSTLLS has been a model for quite a many experiments performed in the near past. Nithya *et al*. (2008) have designed a model based controller for a spherical tank, which gave a comparison between IMC and PI controller using MATLAB. Nandola and Bharatiya (2008) have studied and mathematically designed a predictive controller for non linear hybrid system. A model reference adaptive controller has been designed and simulated by Krishna *et al*. (2012) for a spherical tank. A gain scheduled PI controller was designed using a simulation on MATLAB for a second order non linear system by DineshKumar and Meenakshipriya (2012) 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 and Saravanan, 2012). Kalyan Chakravarthi and Venkatesan (2014) and Kalyan Chakravarthi *et al*. (2014) have implemented a classical and gain scheduled PI controllers for a single and dual spherical tank systems in real time using LabVIEW. Soni *et al*. (2014) have simulated and studied the performance of multi model PI controller for SSTLLS using MATLAB.

This study endeavors to design a system using the process reaction curve method which is also known as first principle method. We obtain model of the plant experimentally for a given unit-step input. If the plant involves neither integrator (s) nor dominant complex-conjugate poles, then such a unit step response curve may look S-shaped curve as shown in Fig. 1. 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.

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. 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 is being measured by a differential pressure transmitter which has a typical output current range of 4-20 mA. 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 250 Ks/S with 16 bit resolution. The graphical program written in LabVIEW is then linked to the set up through the acquisition module. Figure 2 shows the real time experimental setup of the process.

Fig. 2: Real time experimental set up of the process

Fig. 3: Interfaced NI-DAQmx 6211 data acquisition module card

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 study 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 4-20 mA 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 3 shows the interfaced NI-DAQmx 6211 data acquisition card. Table 1 shows the technical specifications of the interacting two tank spherical tank liquid level system setup. A Graphical User Interface of the SSTLLS, which is designed by using LabVIEW, can also be seen in Fig. 4.

Table 1: Technical specifications of the experimental setup

Part name	Details
Spherical tank	Material: Stainless steel
	Diameter: 45 cm
Storage tank	Material: Stainless steel
	Volume: 100 L
Differential pressure	Type: Capacitance
transmitter	Range: (2.5 to 250) mBAR
	Output: (4 to 20) mA
	Make: ABB
Pump	Centrifugal 0.5 HP
Control valve	Size: 1/4”, Pnematic actuated
	Type: Air to close
	Input (3-15) PSI 0.2-1 kg/cm2
Rotometer	Range: (0-440) LPH
Air regulator	Size 1/4” BSP
	Range: (0-2.2) BAR
I/P Converter	Input: 4-20 mA
	Output: (3-15) PSI
Pressure gauge	Range: (0-30) PSI
	Range: (0-100) PSI

System identification and controller design:

Mathematical modeling of SSTLLS: The SSTLLS is a system which is non linear in nature by virtue of its

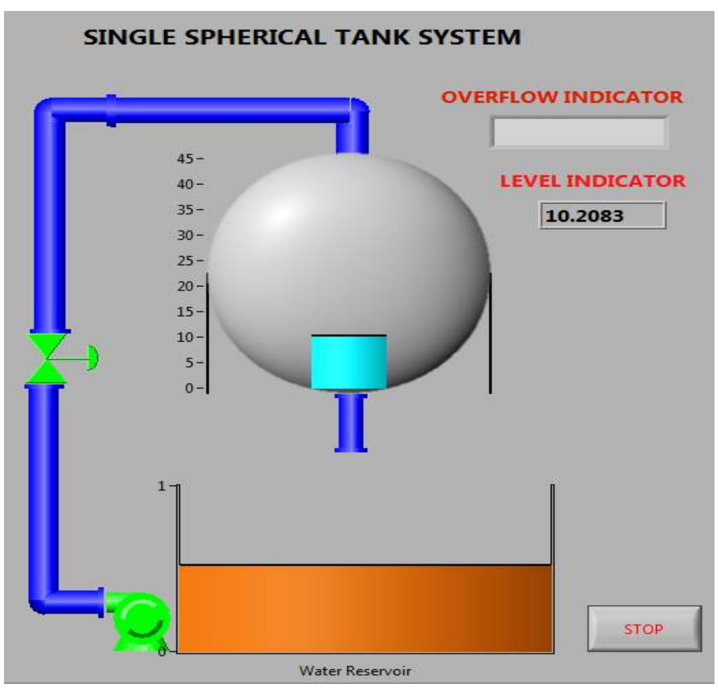

Fig. 4: Graphical user interface for the SSTLLS designed in LabVIEW

varying diameter. The dynamics of this non linearity can be described by the first order differential equation:

$$\frac{dV}{dt} = q_1 - q_2 \quad (1)$$

where,
V = The volume of the tank
q_1 = The Inlet flow rate
q_2 = The Outlet flow rate

The volume V of the spherical tank is given by:

$$V = \frac{4}{3}\pi h^3 \quad (2)$$

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:

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

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 Nicolas (1942) 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 (1985) 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 (1991) 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 (1978) 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. Th e 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:

$$\tau_p = 0.67(t_2 - t_1) \quad (4)$$

$$\theta = 1.3t_1 - 0.29t_2 \quad (5)$$

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 as shown in the Fig. 1. The experimental data are approximated to be an FOPDT model.

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:

$$G(s) = \frac{K.e^{-\theta s}}{\tau s+1} \quad (6)$$

Table 2 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.

Table 2: Transfer function models for different regions of SSTLLS

Region of operation	Transfer function
0-9	$G(s) = \frac{9e^{(-88.88*s)}}{1+91.12s}$
9-18	$G(s) = \frac{18e^{(-440.995*s)}}{1+\ 142.04s}$
18-27	$G(s) = \frac{11.25e^{(-896.835*s)}}{1+122.61s}$
27-36	$G(s) = \frac{10e^{(-1224.16*s)}}{1+73.365s}$
36-45	$G(s) = \frac{11.25e^{(-1404.51*s)}}{1+27.805s}$

Table 3: Skogestad's and ZN tuned K_p and K_i parameters for different regions of non-linearity

Region		Skogestad's method	ZN method
0-9	K_p	0.056955600	0.10250000000000
	K_i	0.000625062	0.00038460800000
9-18	K_p	0.008940000	0.01610000000000
	K_i	0.000062940	0.00001210000000
18-27	K_p	0.006070000	0.01090000000000
	K_i	0.000049506	0.00000405129150
27-36	K_p	0.002990000	0.00539400000000
	K_i	0.000040755	0.00000146883420
36-45	K_p	0.000878000	0.00158100000000
	K_i	0.000031577	0.00000037468620

By implementing the rules of PI tuning by the methods ZN method and Skogestad's Method to get the following parameters for the transfer function specified in Table 2. The parameters of K_p and K_i for different regions of non linearity are derived as in Table 3.

RESULTS AND DISCUSSION

The ZN and Skogestad's based AMBGS PI controllers which were designed are implemented using the graphical programming code which is written on LabVIEW. Both the controllers were applied to SSTLLS and the performance of the both was compared under different conditions.

Variation off the set point: The Skogestad's and Ziegler Nichols AMBGS controllers were run for all different regions of SSTLLS which are modeled in the Table 2. Figure 5a to c display the comparison results of servo responses obtained for different regions viz.; 0-9,

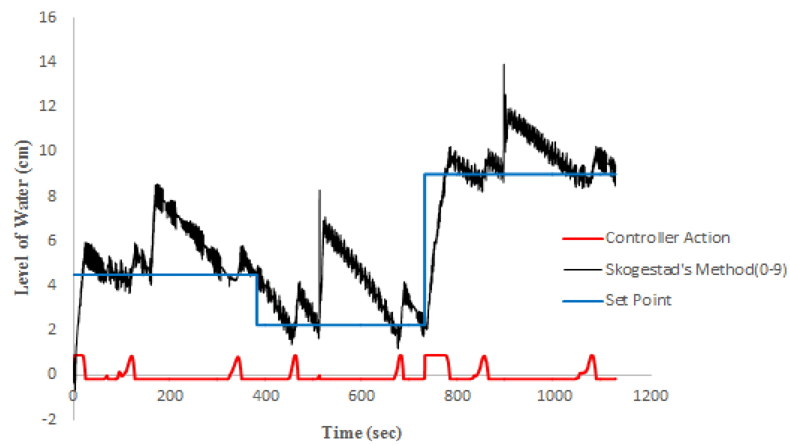

Fig. 5a: Skogestad's tuned AMBGS controller's regulatory response for region 0-9

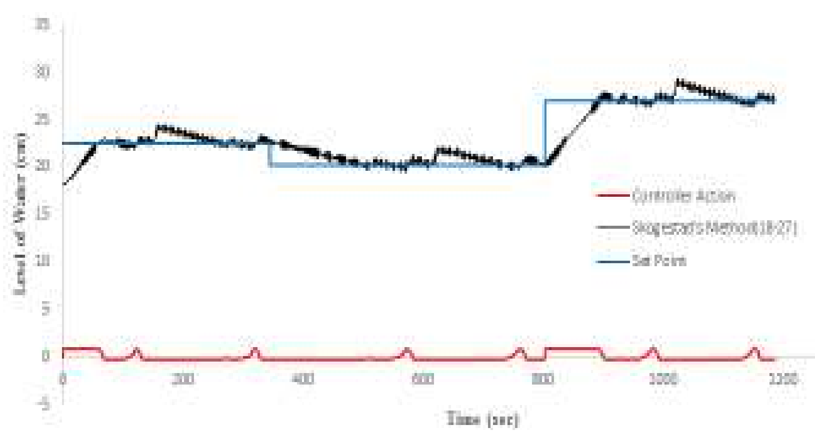

Fig. 5b: Skogestad's tuned AMBGS controller's regulatory response for region 18-27

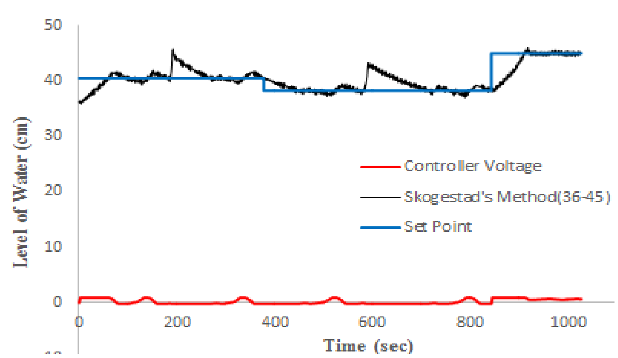

Fig. 5c: Skogestad's tuned AMBGS controller's regulatory response for region 36-45

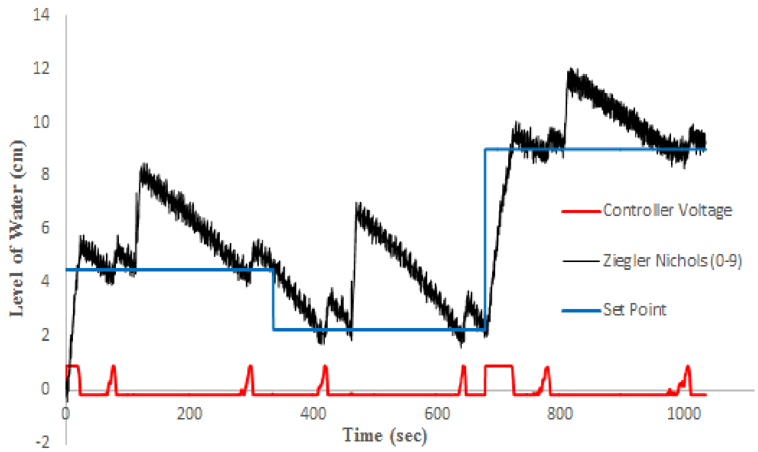

Fig. 5d: Ziegler Nichols tuned AMBGS controller's regulatory response for region 0-9

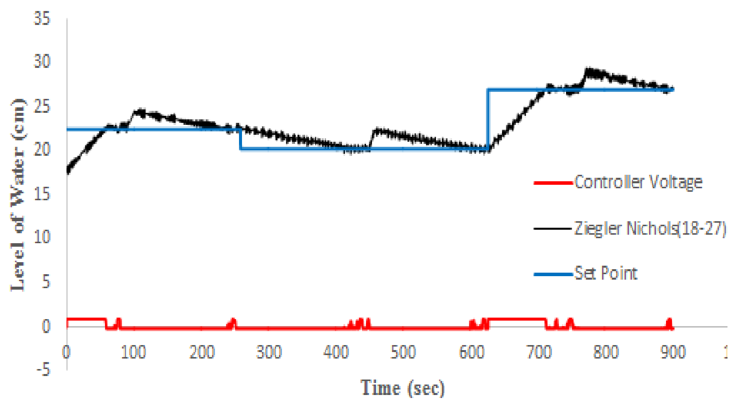

Fig. 5e: Ziegler Nichols tuned AMBGS controller's regulatory response for region 18-27cm

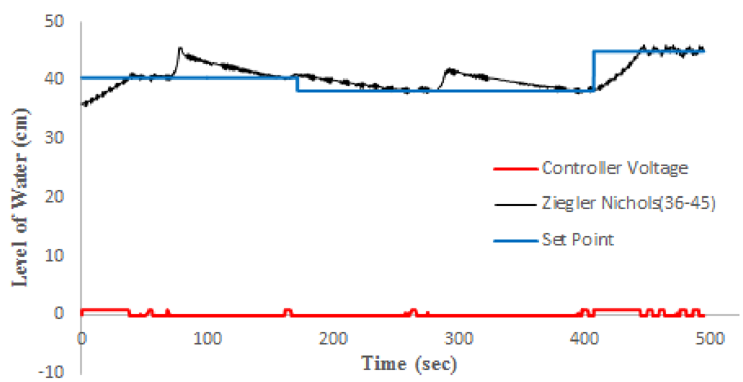

Fig. 5f: ZN tuned AMBGS controller's regulatory response for region 36-45cm

18-27 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 Fig. 5d to f. It can be very clearly observed that the level very swiftly oscillates for the ZN method and oscillation is not very much seen in the Skogestad's method. It can be also observed that the Skogestad's PI based controller tracks the set point in a very less time when compared to that of ZN method. Table 4 gives the time domain specifications of the present system. It is evident form Table 4 that the rise time and settling time for different set points for Skogestad's method are relatively low in comparison with ZN method in the regions with higher degree of non linearity. But the peak time also follows the same pattern of variation for the non linear regions but in contrary it exhibits a higher value in the mid region of the SSTLLS.

Table 4: Comparison of time domain analysis for servo response for different regions of non linearity

Specifications (sec)	Set point (cm)	ZN method	Skogestad's method
Peak time	4.50	37.01563	34.01563
	9.00	57.75000	41.39063
	22.5	70.18750	54.75000
	27.0	55.79685	60.90625
	40.5	43.20313	35.09375
	45.0	18.74998	21.59378
Rise time	4.50	33.31407	30.61407
	9.00	51.97500	37.25156
	22.5	63.16875	49.27500
	27.0	50.21717	54.81563
	40.5	38.88282	31.58438
	45.0	16.87498	14.43440
Settling time	4.50	45.00000	48.00000
	9.00	26.54688	42.90625
	22.5	34.65625	50.09375
	27.0	56.25003	51.14063
	40.5	41.25000	34.95315
	45.0	34.95315	32.10935

Table 5: Comparison of performance indices of servo response for different regions of non linearity

Set point (cm)	Tuning method	ISE	IAE
4.50	ZN	731.013275	546.646215
	Skogestad's	434.549900	419.359200
9.00	ZN	384.898498	379.560200
	Skogestad's	161.137200	242.389000
22.5	ZN	147.409560	226.858124
	Skogestad's	46.3787923	118.084073
27.0	ZN	231.382060	306.347949
	Skogestad's	53.0996220	124.850342
40.5	ZN	635.316800	483.714900
	Skogestad's	85.1496000	163.769200
45.0	ZN	85.1496000	163.769200
	Skogestad's	41.7786500	79.6388100

From Table 5 it can be seen that IAE and ISE values are also very less than 50% at all the set points chosen, for the Skogestad's method in comparison to ZN method. 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 Skogestad's tuning method over the ZN method.

Table 6: Comparison of performance Indices of regulatory response in different regions of non linearity

Set point (cm)	Tuning method	ISE	IAE
4.50	ZN	5702.741	2598.228
	Skogestad's	5440.887	2574.304
9.00	ZN	3029.299	1852.831
	Skogestad's	2959.168	1942.761
22.5	ZN	1414.623	1098.509
	Skogestad's	965.0554	998.3812
27.0	ZN	1332.551	1013.717
	Skogestad's	1056.572	1082.533
40.5	ZN	3289.437	1747.069
	Skogestad's	2979.306	1164.927
45.0	ZN	71.81188	131.5720
	Skogestad's	50.12255	150.8350

Changes in the load: The Skogestad's and ZN 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. 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 and 36-45 cm in the SSTLLS. Figure 6a to c, demonstrate the regulatory performance under the influence of external disturbance of skogestad's tuned AMBGS controller in the regions of 0-9, 18-27 and 36-45 cm respectively. ZN tuned AMBGS controller's regulatory performance can be seen in Fig. 6a to c in the same regions mentionedearlier. The performance indices of the regulatory response can be seen in Table 6.The designed controllers were able to compensate the effect of the load changes. It can be noticed from Table 6, that the ISE and IAE values for Skogestad's method are relatively lesser than the ZN method.

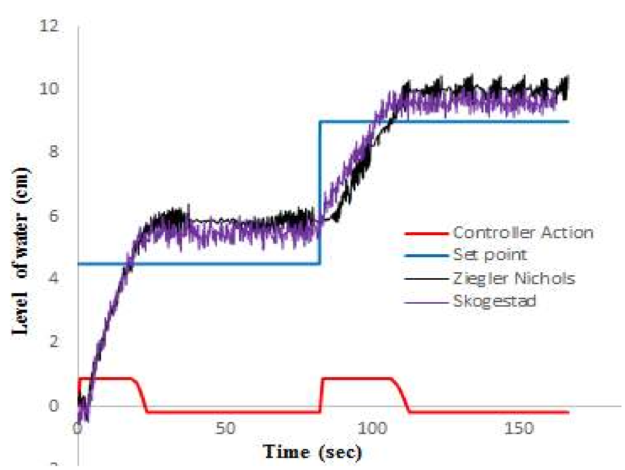

Fig. 6a: Servo response comparison of Skogestad's and ZN tuned AMBGS controllers for region 0-9cm

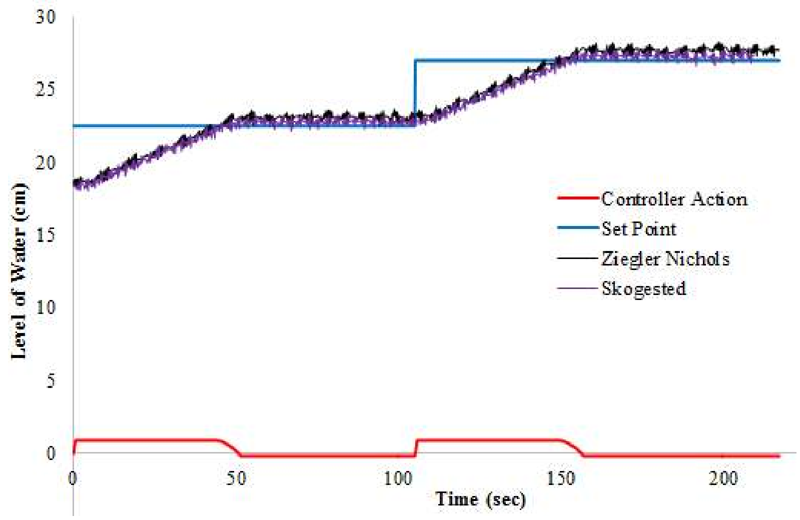

Fig. 6b: Servo response comparison of Skogestad's and ZN tuned AMBGS controllers for region 18-27cm

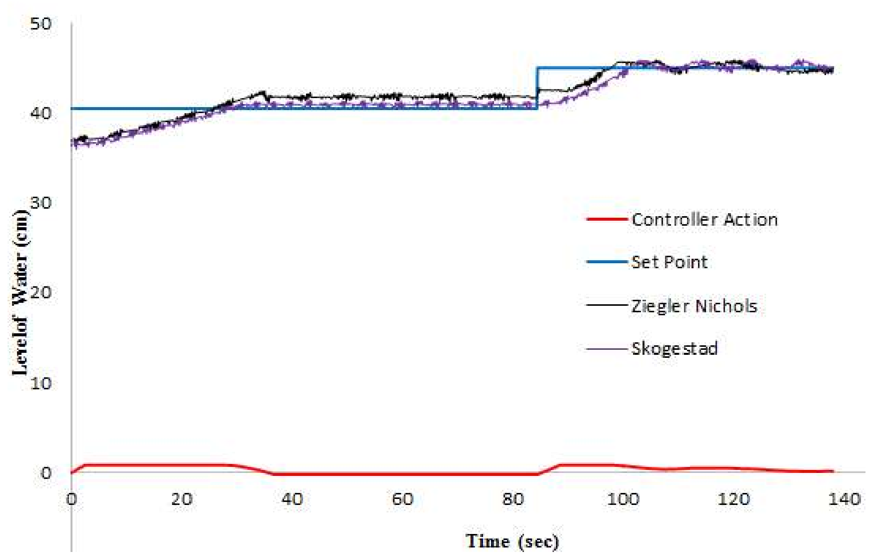

Fig. 6c: Servo response comparison of Skogestad's and ZN tuned AMBGS controllers for region 36-45cm

CONCLUSION

In this study, a Skogestad's and ZN method based Controller were designed for a SSTLLS process. The model identification and AMBGS 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 Skogestad's method of tuning. It can be also seen that minimum overshoot, faster settling time and rise time. It has a better capability of compensating all the load changes. The ISE and IAE values justify that relatively a minimum error is seen in Skogestad's way of tuning the AMBGS PI controller than ZN method for both servo and regulatory responses. It can be concluded that Skogestad's method based AMBGS PI controller can be implemented on real time SSTLLS using NI-DAQmx 6211 data acquisition module and LabVIEW.

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