Design of Adaptive Controller for a Non-Linear Process

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ABSTRACT
Measurement of level, temperature, pressure and flow parameters are very vital in all process industries. The model for such system is identified and validated. Real-time industrial processes are subjected to variation in parameters and parameter perturbations, which sometimes makes the system unstable. Determination of tuning of the PI (Proportional + Integral) parameters continues to be important as these parameters have a great influence on the stability and performance of the control system. Most of the processes are complex and nonlinear in nature resulting into their poor performance when controlled by traditional tuned PI controllers. The need for improved performance of the process has led to the development of optimal controllers. So the control engineers are on look for automatic tuning procedures. In this work the considered non-linear process is spherical tank level process and adaptive controller is gain scheduling controller. This work proposes a Gain Scheduling Controller (GSC). For a spherical tank level process, in the case of Gain Scheduling PI controllers, the plant under consideration is assumed to be governed by a set of PI controllers with the objective to obtain good tracking behavior across the operating envelope of the plant. The PI gains are allowed to vary within a predetermined range. In the case of nonlinear plant, where the nonlinearity is the function of plant output, one strategy for achieving the desired objective is to choose the proportional (K_P) and integral gains (K_I) as function of the plant. The objective of the work is to design the adaptive controller for a spherical tank level process.

Keywords
Spherical tank, PID, Gain Scheduling Controller (GSC).

1. INTRODUCTION
As PID is regarded as the standard control structures of the classical control theory and Adaptive controllers have positioned themselves as a counterpart of classical PID Controllers on the same dominant role at the knowledge rich spectrum. PID controllers are designed for linear systems. However, the presence of nonlinear effects limits their performances. Adaptive controllers are successfully applied to non-linear system because of their knowledge based nonlinear structural characteristics.

Chemical process faces many challenging control problems due to their nonlinear dynamic behavior, uncertain and time varying parameters, constraints on manipulated variable, interaction between manipulated and controlled variables, unmeasured and frequent disturbances, dead time on input and measurements [1]. Because of the inherent nonlinearity, most of the chemical process industries are in need of advanced control techniques. Spherical tanks find wide application in gas plants and process industries. Control of a level in a spherical tank is important, because the change in shape gives rise to the nonlinearity. The most basic and pervasive control algorithm used in feedback control is PID control algorithm [2]. The Adaptive Gain Scheduling Controller is well suited for the level control of spherical tank system for which conventional controller is not giving satisfactory result.

The adaptive control is a dynamic system with online parameter estimation. The basic idea behind adaptive control lies in the estimation of uncertain Plant/controller parameters online, while using systems measured data. The estimated parameters are used in the computation of the control input. The research in adaptive control started in 1950's. The objective of adaptive control is to maintain consistent performance of a system in the presence of uncertainty and variations in plant parameters. A gain scheduling system can be shown to be a non-linear, which is useful for designing the controller for a nonlinear process [4]. In many situations, it is known how the dynamics of the process changes with the operating conditions of the process. One source for the change in dynamics may be non-linearity that are known. It is then possible to change the parameters of the controller by monitoring the operating conditions of the process. This idea is called "Gain Scheduling", since the scheme was originally used to accommodate changes in process gain only [5]. Gain scheduling is a nonlinear feedback of special type. It has a linear controller whose parameters are changed as a function of operating conditions in a preprogrammed way. Gain scheduling is easy to implement in control system.

2. PROCESS DESCRIPTION
Spherical tank finds wide applications in process industries. The spherical shape prevents the accumulation of solids on the bottom of the tank. For the proposed investigation a highly non-linear spherical tank setup is considered. Control of level in the tank is a challenging problem due to its constantly changing cross section. Because of the inherent non-linearity, there is a need of advanced intelligent control techniques. The dependence of discharge flow on the square root of the static head creates another nonlinearity and negative feedback. The model of spherical tank at various operating regions are obtained and detailed in the following section (30%, 50% & 70%). The Digital PI controller parameters are obtained from Synthesis tuning method. The Adaptive Gain Scheduling Controller is designed performance indices like Integral Square Error (ISE) and Integral Absolute Error (IAE) were computed.

2.1 Experimental setup of spherical tank system
A real time experimental setup for highly nonlinear spherical tank is constructed. The process control system is interfaced

using VMAT-01 module to the Personal Computer (PC). The laboratory set up for this system is shown in Figure 1. It consists of a spherical tank, a water reservoir, pump, rotameter, a differential pressure transmitter, an electro pneumatic converter (I/P converter), a pneumatic control valve, an interfacing VMAT-01 module and a Personal Computer (PC). The differential pressure transmitter output is interfaced with computer using VMAT-01 module in the RS-232 port of the PC.

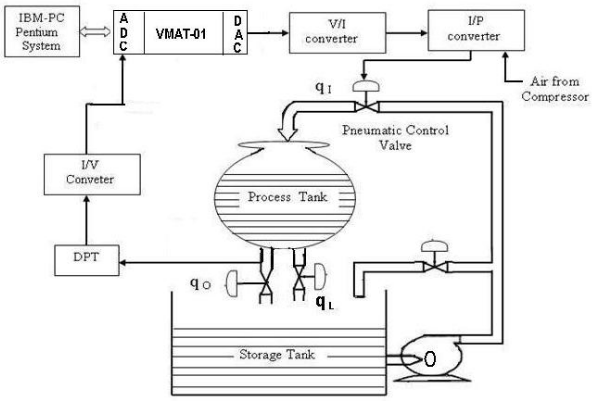

Fig 1: Laboratory Setup for Liquid Level Control of Spherical Tank

Fig 2: Real time Experimental Setup for a Spherical Tank

This module supports 1 analog input and 1 analog output channels with the voltage range of ±5 volt and two Pulse Width Modulation (PWM). The sampling rate of the module is 0.1 sec and baud rate is 38,400 bytes per sec with 8-bit resolution. The model is developed using Simulink block set in MATLAB software and is then linked via this VMAT-01 module with the sampling time of 0.1second. Figure 2, shows the real time experimental setup of a spherical tank. The pneumatic control valve is air to close, adjusts the flow of the water pumped to the spherical tank from the water reservoir. The level of the water in the tank is measured by means of the differential pressure transmitter and is transmitted in the form of (4-20) mA to the interfacing VMAT-01 module to the Personal Computer (PC). After computing the control algorithm in the PC control signal is transmitted to the I/P converter in the form of current signal (4-20) mA, which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water in and out of the tank. There is a continuous flow of water in and out of the tank. Table 1 shows the various technical specifications of experimental setup.

2.2 Mathematical modeling of spherical tank system

Figure 3 shows the schematic diagram of spherical tank level system, in which the control input f_{in} is being the in- flow rate (m3/s) and the output x is the fluid level (m) in the spherical tank.

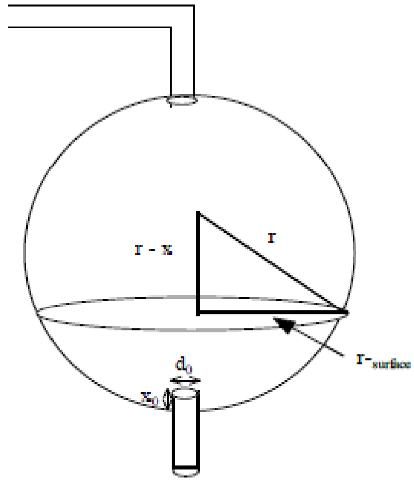

Fig 3: Schematic diagram of Spherical Tank Level System

Let, r, d_0 and x_0 be the radius of spherical tank, thickness (diameter) of pipe and initial level. Assume ‘r surface’ is radius on the surface of the fluid which varies with respect to the level of fluid in the tank. The dynamic model of the spherical tank is given as [2]

$$\frac{\partial}{\partial t}\left[\int_0^{x_1} A(x)\,\partial x\right] = f_{in}(t) - a\sqrt{2g(x - x_0)} \qquad (1)$$

where A(x) is the area of the cross section of tank (i.e.) $A(x) = \pi(2rx - x^2)$

a is the cross sectional area of the pipe (i.e.)

$$a = \pi\left(\frac{d_0}{2}\right)^2$$

Rewrite the equation (1) at time, $t + \partial t$

$$A(x)\,\partial x = f_{in}\,\partial t - a\sqrt{2g(x - x_0)}\;\partial t \qquad (2)$$

Combine equation (1) and (2)

$$\frac{\partial x}{\partial t} = \frac{f_{in}\,\partial t - \frac{\pi d_0^2}{4}\sqrt{2g(x - x_0)}}{\pi(2rx - x^2)} \qquad (3)$$

By applying $\lim_{d \to 0}$ in above equation we have, $\frac{\partial x}{\partial t} = \frac{dx}{dt}$

Therefore

$$\frac{dx}{dt} = \frac{f_{in}\,\partial t - \frac{\pi d_0^2}{4}\sqrt{2g(x - x_0)}}{\pi(2rx - x^2)}$$

$\frac{dx}{dt}$ Represent the dynamic model of the spherical tank level process.

3. ESTIMATION OF PROCESS PARAMETERS

Consider the first order system represented by the following transfer function

$$y(s) = \frac{k_p}{\tau s+1} u(s) \tag{5}$$

in the above equation, y(s) the measured output is in deviation variable form. The process parameters, τ and K_p can be estimated by performing a single step test on process input. The process gain is found as simply the long term change in process output divided by the change in process input. There are several ways to estimate time constant for this model. Synthesis method for estimating the process parameters are shown in Figure 4.

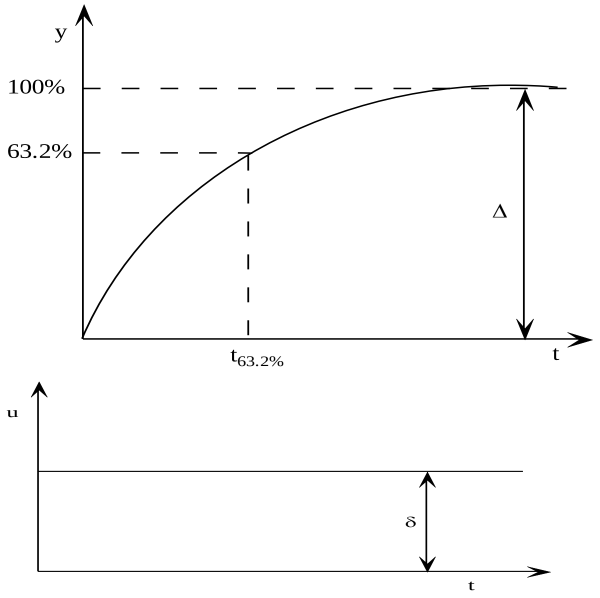

Fig 4: Synthesis Method for Estimating Process Parameters

$$K_p = \frac{\Delta}{\delta} = \frac{\text{Change in process output}}{\text{Change in process input}} \tag{6}$$

Time constant can be estimated from the equation given below.

$$\tau = t_{63.2\%} \tag{7}$$

The proposed work is to find the three different models at various operating regions. Three operating regions are 20-39%, 40-59% and 60-75%. The obtained parameters are reported in table 1.

Table 1. Process Gain, Time Constant at Different Operating Regions

Operating region	K_p	τ(sec)	Transfer function
20-39%(1st region)	0.906	122.587	$\frac{0.906}{122.587s+1}$
40-59%(2nd region)	1.29	237.573	$\frac{1.29}{237.573s+1}$
60-75%(3rd region)	1.596	254.025	$\frac{1.596}{254.025s+1}$

3.1 Synthesis tuning

If a mathematical model of the plant can be obtained, then it is possible to apply different design techniques to define controller parameters. On the other hand if the system is complicated and getting the mathematical model is difficult, then experimental approaches must be used to tune the PID parameters [6]. Synthesis tuning is based on the transient response characteristics of the systems and determined the values of PID controller. In synthesis tuning proposed, tuning parameters for a process that has been identified as first order based on open loop step response. Their recommended tuning parameters are shown in Table 2.

Table 2. PI parameters using synthesis method

Operating region	K_C	K_I
20-39%(1st region)	2.1038	0.0172
40-59% (2nd region)	1.7752	0.0075
60-75% (3rd region)	1.6265	0.0064

4. DESIGN OF GAIN SCHEDULING CONTROLLER

In the case of Gain Scheduling Controller, the plant under consideration is assumed to be governed by a set of PI controllers with the objective to obtain good tracking behavior across the operating envelope of the plant. In the case of non-linear plant, where the nonlinearity is the function of plant output, one strategy for achieving the designed objective is to choose the Proportional (K_P) and Integral (K_I) gain as function of the plant output. Inflow level (set point) is scheduled to select specific gains of the controller [8]. For each linearized operating range, PI controller is tuned in offline and the parameters are stored in a lookup table.

There are several methods to schedule the gains of PI controller [3]. In this work, a scheduling interval is defined around each set of controller gains (K_p and K_I). The controller parameters are kept constant as long as the scheduling value is within the interval. When the scheduling values changes from one interval to another the controller parameters are selected accordingly [9].

However, these analyses are made under the assumption that the mathematical models of the nonlinear plant under consideration are known for various linearized operating ranges. This type of multiple model approach is introduced to control the process throughout its operating range [7]. Since the number of available model is finite and the environment is generally infinite a supervisor is included along with the controller. This supervisor selects a particular controller corresponding to the value of set point. Thus, safe control is concerned ensuring the stability of the closed loop. The change in the range of scheduling variable is fixed. If a particular controller is selected for a specific range, it is kept in the loop as long as the deviation is within the specified range. The chosen nonlinear plant is linearized at specific operating regions. For bump less change over the output from the present controller starts from the last value of the manipulated variable (output of the previous controller) [3].

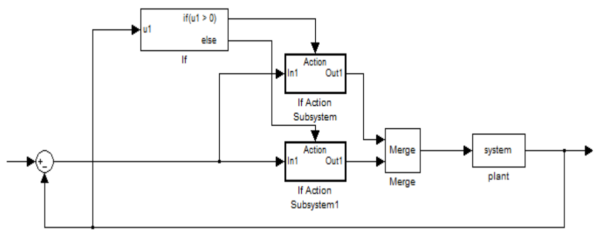

Fig 5: Block diagram of Gain Scheduling Controller

5. RESULTS AND DISCUSSION

The Gain Scheduling Controller is designed and applied to control of spherical tank liquid level system. The servo responses of PI controller are shown in figure 6, 7, and 8. Figure 9, 10 and 11 shows the regulatory responses of PI controller. Figure 12 shows the servo response of GSC. Figure 13 shows the regulatory response of GSC.

It is observed that in GSC follows the smooth tracking towards the given set point. The performance indices were shown in Table 3.

The Gain Scheduling Controller is used to control the spherical level system while applying a load change of 5% is recorded. Gain Scheduling Controller returns to the given set point immediate.

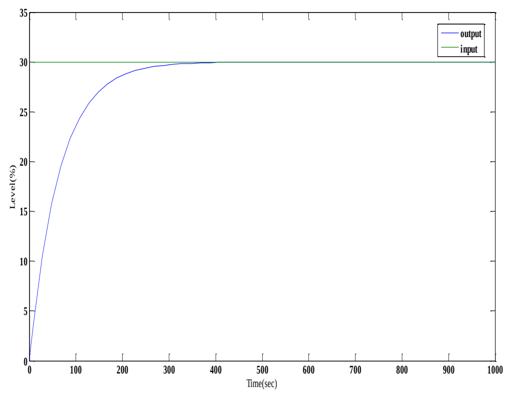

Fig 6: Servo response of PI controller for set point 30 %

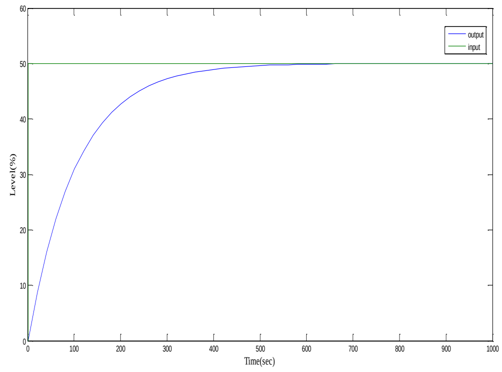

Fig 7: Servo response of PI controller for set point 50 %

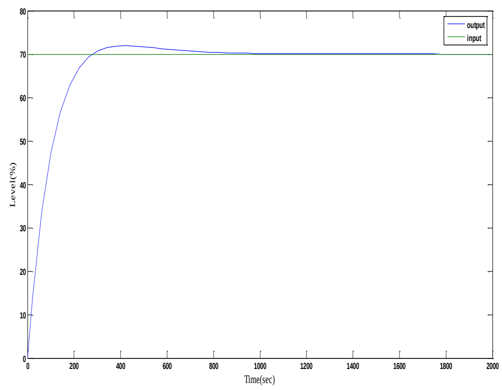

Fig 8: Servo response of PI controller for a set point 70 %

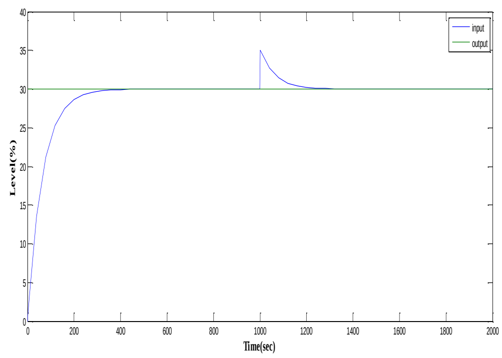

Fig 9: Regulatory response of PI controller for a set point 30 %

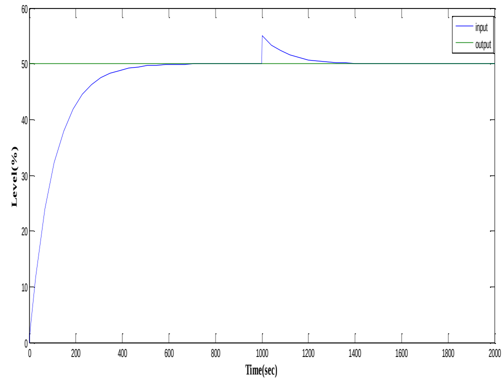

Fig 10: Regulatory response of PI controller for set point 50 %

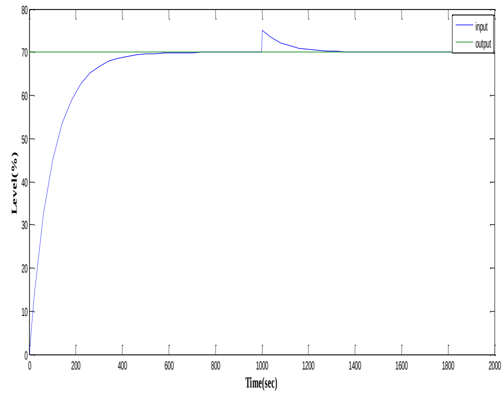

Fig 11: Regulatory response of PI controller for set point 70 %

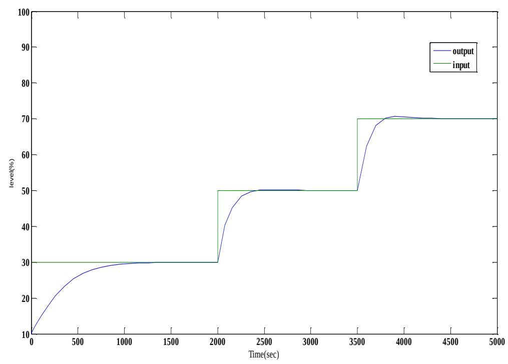

Fig 12: Servo response of Gain Scheduling Controller for set point 30%, 50% and 70 %

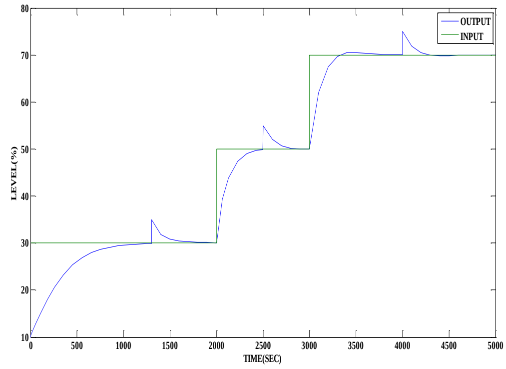

Fig 13: Regulatory response of Gain Scheduling controller for set point 30%, 50% and 70 %

Table 3 Performance indices

OPERATING POINT	GSC	
	ISE	IAE
30%	264.2	299.1
50%	1283	511.3
70%	1154	443.7

6. CONCLUSION

For non-linear processes, Gain Scheduling Controller is designed. Its performance is tested in Simulink for a Spherical tank level process. Simulink results prove that the response is smooth for both servo and regulatory changes for Gain Scheduling Controller. The performance indices IAE and ISE values were computed. It is concluded that for a nonlinear system the Gain Scheduling Controller performs well. The developed approach will go a long way in exploring innovative applications to meet state of art requirements.

7. REFERENCES

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