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Design and Implementation of Non Linear System Using Gain Scheduled PI Controller

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Abstract

This paper presents modeling and control of highly non linear system using gain scheduled PI controller. Interacting spherical two tank system (ISTTS) is considered as non linear system, where the aim is to control the liquid level of tank. Control of liquid level in interacting spherical two tank system is highly challenging due to variation in the area of cross section of ISTTS with change in shape. Transfer function for ISTTS is derived and with the relationship between ISTTS parameters and PI parameters, gain scheduled PI controller is implemented. Performance is highlighted by calculating performance indices.

Keywords: Gain scheduled PI control, Interacting spherical two tank system, Non linear system, Performance indices

1. Introduction

A system whose performance cannot be described by equations of the first degree is nonlinear system. Most economic and social processes are nonlinear where mathematical analysis is unable to provide general solutions. Generally, nonlinear problems are difficult to solve and are much less understandable than linear problems. Many industries use conventional tank system such as cylindrical tanks, cylindrical tanks with conical bottom for their processing. The major problem in process industries is the control of fluid levels in storage tanks, chemical blending and reaction vessels. The rate of change of flow from one tank to another as well as the level of fluid is two important operational factors. Petrochemical industries, paper making industries, water treatment industries, etc need the control of liquid level and flow.

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Comparing with conventional tanks and conical tank system spherical tanks have greater advantages such as inexpensive and efficient washing, reduced product losses and intensified production. An attempt has been made to develop gain scheduled PI controller for liquid level control in interacting spherical two tank system (ISTTS), which would provide a platform to replace the existing tank system and hence reduce wastage of materials.

2. Process Description

2.1. Mathematical modeling of ISTTS

The process contains two spherical tanks, TANK1, TANK2 are two identical spherical tanks whose height is H (30 cm) and radius is R (15 cm). These two tanks are interconnected through restriction MV_{12} as shown in the Fig. 1. F_{IN1} and F_{IN2} are the two input flows to TANK1 and TANK2 respectively. F_{OUT2} is the output flow of the TANK2 which flows through restriction R2 to sumph1, h2 are the liquid heights of the TANK1 and TANK2 respectively. These liquid heights are measured by Differential Pressure transmitters and are transmitted in the form of 4 – 20 mA current signals to interfacing unit of the PC. Here liquid level h2 in TANK2 will be controlled.

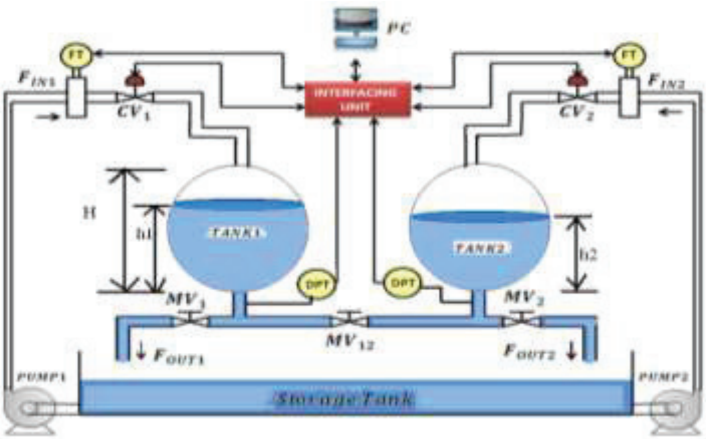

Fig. 1. Liquid level control of interacting spherical two tank system

The input flows F_{IN1} and F_{IN2} can be measured by Magnetic Flow transmitters and are transmitted in the form of 4 – 20 mA current signals to interfacing unit. After implementing the concerned advanced control scheme in the PC, the control signal will be produced in the form of 4 – 20 mA current signals and are transmitted to respective SMART control valves to produce required flow to the TANK1 and TANK2. In this work ISTTS is considered as SISO process in which level h2 in tank 2 is considered as measured variable F_{IN1} as manipulated variable.

Mathematical Modeling of liquid level system is derived using conservation principle on Total Mass Balance (George Stephanopoulos, 1990). According to which;

$$\frac{\text{accumulation of total mass}}{\text{time}} = \frac{\text{input of total mass}}{\text{time}} - \frac{\text{output of total mass}}{\text{time}}$$

for ISTTS the mathematical model is derived to be

$$\frac{\mathbf{dh1}}{\mathbf{dt}} = \mathbf{0.75}\{\frac{\mathbf{Fin}-\boldsymbol{\beta}_{\mathbf{12}}(\sqrt{\mathbf{h1}}-\mathbf{h2})-\mathbf{1.33\ h1}\frac{\mathbf{dA}}{\mathbf{dt}}}{\mathbf{A}}\} \qquad (1)$$

$$\frac{\mathbf{dh2}}{\mathbf{dt}} = \mathbf{0.75}\{\frac{\boldsymbol{\beta}_{\mathbf{12}}(\sqrt{\mathbf{h1}}-\mathbf{h2})-\boldsymbol{\beta}_{\mathbf{2}}\sqrt{\mathbf{h2}}-\mathbf{1.33\ h2}\frac{\mathbf{dA}}{\mathbf{dt}}}{\mathbf{A}}\} \qquad (2)$$

Where,

ρ	=	density
F_{IN}	=	Volumetric flow rate for inlet stream
F_{OUT}	=	Volumetric flow rate for outlet stream
A	=	Area of the spherical tank with respect to change in flow
h1, h2	=	Height of spherical tank 1 and 2
dh/dt	=	Change in height of liquid level

2.2. Modeling Parameters

In order to develop simulink model for the process based on equations analytical values are needed and is tabulated as modeling parameters as shown in table 1.

Table 1. Modeling Parameters

Parameters	Description	Value
D	Diameter of spherical tank	30 cm
R	Radius of Spherical tank in centre	15 cm
H	Height of spherical tank	30 cm
F_{IN1}	Maximum Inflow to tank1	107.85 cm^3/sec
β12	Valve co-efficient of MV_{12}	78.28 cm^2/sec
β2	Valve co-efficient of MV_{12}	19.69 cm^2/sec

With the help of MATLAB simulink model is created and non linear response is obtained as shown in Fig. 2.

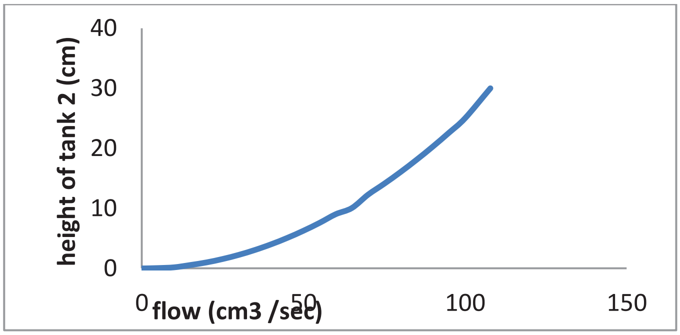

Fig. 2. Process steady state input-output characteristics

The process parameters are obtained using the process reaction curve method in various operating regions. Using these parameters of the operating regions and controller tuning methods, it is proposed to design Gain scheduled PI controller for the control of the level process that is discussed next.

3. Gain Scheduled PI Control

Gain scheduling problem has been interest of may researchers and has been concern both theoretically and practically. The popular engineering method for system controlling concerns a widely varying dynamics domain. In this paper a gain scheduling scheme for liquid level control in ISTTS modeled by standard second order model. For different operating conditions it is important to know the range over which proportional and integral gain could vary. Proportional and integral gains are allowed to vary within predetermined range depending on operating point. This scheme is implemented as a set of equations which are derived below

.

$$\frac{\partial h2}{\partial Fin1} = \frac{R2}{\tau1\tau2s^2 + [\tau1+\tau2+A(h1)R2]s+1} \quad (3)$$

The above differential equation represents the general transfer function of second order non linear system. Parametric values are obtained from the Simulink model to get the transfer function of proposed ISTTS as shown in table 2.

Table 2. Parameters from Matlab/Simulink model to find transfer function

Parameters	Value
Fin	107.85
β1	78.28
β2	19.69
h1	31.9
h2	30
Θ	0.2
C1	0.3627
R1	0.03522
C2	0.09128
R2	0.5564
τ1	63.85
τ2	1048.2575

On substituting the values from table II in equation 3, transfer function of ISTTS is obtained as given below.

$$\frac{\partial h2}{\partial Fin1} = \frac{0.5564}{66931.25s^2 + [2120.87]s+1} \quad (4)$$

Ravi et al (2011) have discussed on the relationship between ISTTS and PI controller for interacting conical two tank system. The relation has been used by changing the area of conical tank with spherical tank and deployed to find the gain values.

Proportional gain:

$$Kp = \frac{A(h1)(\tau1+ \tau2)}{\tau1\ \tau2} \quad (5)$$

Integral gain:

$$\mathbf{Ti = \tau 1 + \tau 2} \qquad \mathbf{(6)}$$

The above equations are used to calculate the gain values of PI controller and is implemented in simulink model.

4. Design Implementation of Gain Scheduled PI controller (GSPIC)

The PI controller design parameters are obtained from equations (5), (6) and tuned for three operating points 5, 15 and 25. Tracking cases are obtained for +10%, -10%, +15%, -15% for the three operating regions.

GSPIC is designed and simulated in MATLAB. Positive step changes and negative step changes in set point are given with 30cm as the reference point and changes are given in the order of 5cm, 15cm and 25cm in the increasing and decreasing direction. The closed loop response of the PI controlled level process system is studied by introducing step variations in level and the responses plotted with the PI controller are compared with Integral Absolute Error (IAE), Integral Square Error (ISE), the details of which are given in next session.

5. Results and Discussion

5.1. Performance Analysis

A non linear system, interacting spherical two tank system whose time constant and gain are functions of process variable is considered for testing the performance of Gain Scheduled PI controller. The reaction curve is obtained for fixed magnitude of inflow rate at various operating points. The second order model is computed from relating the general transfer function with parameters obtained from Simulink model. In the following sections, the performance of PI controller is summarized. Closed loop simulated transient responses of ISTTS model with analytical PI controller tuning rules for set point tracking are shown in Fig. 3, 4 and 5. The performance measures corresponding to the tracking cases are reported in table 3.

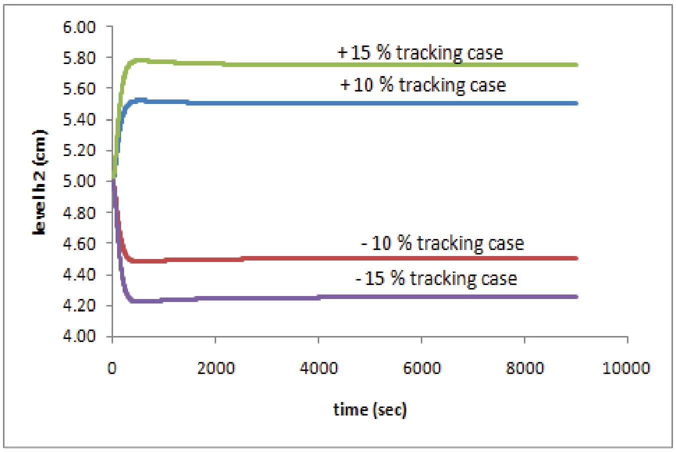

Fig. 3. Servo Response of gain scheduled PI controller for set point tracking of ± 10% and ± 15% at operating point of 5 cm

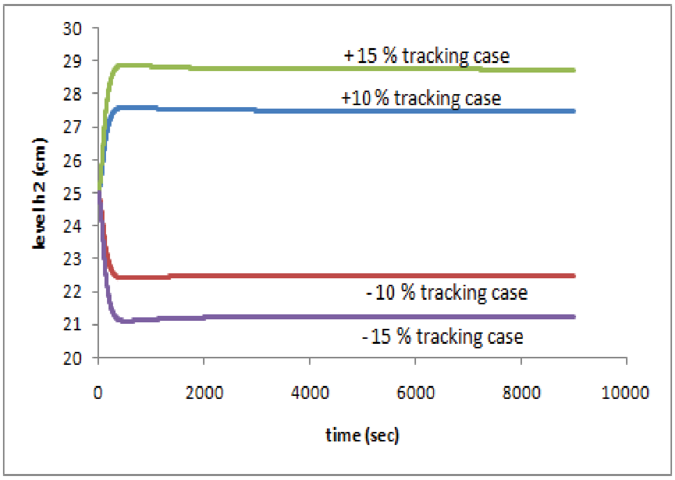

Fig. 4. Servo Response of gain scheduled PI controller for set point tracking of ± 10% and ± 15% at operating point of 25 cm

5.2. Robustness Test

The performance analysis of ISTTS model using analytical PI controller tuning rules illustrated above cannot be completed without a robustness test. The robustness of ISTTS model using GSAC tuning rules are investigated at another critical operating point of level 15 cm for the same set point tracking cases.

Closed loop simulated transient responses of ISTTS model with gain scheduled PI controller tuning rules for set point tracking of ± 10% and ± 15% at the operating point level 25 cm are shown in 5. The performance measures corresponding to tracking cases are reported in table 3.

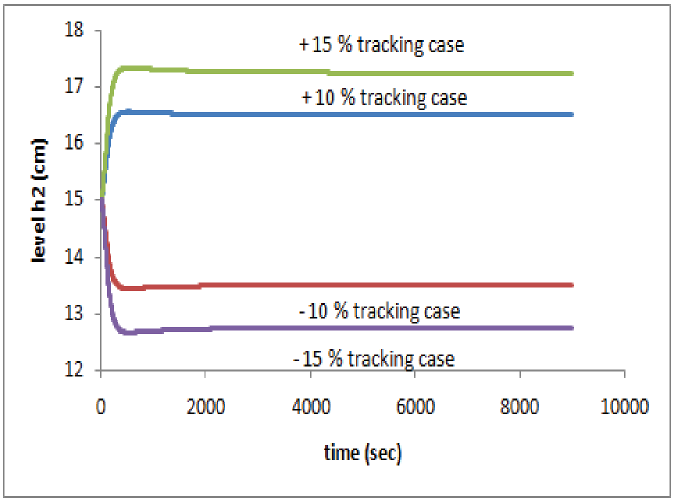

Fig. 5. Servo Response of gain scheduled PI controller for set point tracking of ± 10% and ± 15% at operating point of 15 cm

Table 3. Performance measures

Region	Error	ISE	IAE
5+10%	16.5863	9.8094	41.7114
5-10%	-16.5963	9.8103	41.7065
5+15%	24.8819	22.0715	62.566
5-15%	-24.8920	22.0728	62.5610
15+10%	49.7588	256.1976	125.1345
15-10%	-49.7890	88.2927	125.1197
15+15%	74.6458	198.6439	187.698
15-15%	-74.6579	198.6557	187.6832
25+10%	82.9314	245.2358	208.5574
25-10%	-82.9816	245.2576	208.5574
25+15%	124.4096	551.7887	312.83
25-15%	-124.4599	551.8214	312.8053

6. Conclusion

ISTTS is considered as non linear system for testing gain scheduled PI controller. This control scheme was taken into consideration for achieving good controller performance measures. The simulation for ISTTS was tested at different operating regions. The simulation was carried out using MATLAB to ensure that controller perfectly regulates the desired output level as per the requirement.

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