Comparative Study of Controllers for a Variable Area MIMO Interacting NonLinear System

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Abstract—Most of the industrial processes are basically Multi Input Multi Output (MIMO) system. In this paper a new combination of Spherical Conical Interacting Tank System (SCITS) which is a variable area nonlinear MIMO system is considered for study and various control algorithms based on Ziegler Nichol's tuning method, Hagglund Astrom Robust tuning method, Fractional Order (FO) control and Passivity Based Control (PBC) are used and compared for the level control of spherical tank system and conical tank system connected with interaction. Transfer function matrix of the system is obtained experimentally from the open loop response of the system. The designed controllers are tested for servo and regulatory operations. The controllers are compared in terms of time domain specification and performance index criterion. From the analysis of the simulation results, it is seen that FO controller gives improved performance when compared to conventional Integer Order (IO) controller and overall Passivity Based Controller (PBCr) gives improved performance comparatively for spherical conical interacting MIMO system.

Keyword-Spherical-Conical interacting system, MIMO system, Fractional Order Control, Passivity Based Control, PI controller

I. INTRODUCTION

Most of the available papers in the literature are mainly focussed about the control of liquid level in a spherical tank system [1]-[3] and conical tank system [4] separately as a Single Input Single Output System (SISO). Some works have been done on the study of Two Tank Conical Interacting System (TTCIS) [5] and Two Tank Spherical Interacting System (TTSIS) [6]. In this paper a new combination of spherical conical tank system connected with interaction between them is taken for study, the entire system becomes Multi Input Multi Output (MIMO) system. Spherical Conical Interacting Tank System (SCITS) is a variable area highly nonlinear system. Conical tank is nonlinear, spherical tank is more nonlinear and the combination together with the interaction becomes highly nonlinear system and thus becomes a challenging control problem for designing controllers.

Level control is used in various applications like boilers, waste treatment plants, reactors, tank farms etc. Conical tanks are used in various applications like petrochemical, paper making, cement, food process and water treatment industries. The unique feature of spherical tank is it is certified to operate with partial filling to any level because of its slosh suppression feature. This feature of the spherical tank allows it to be used as containment system for floating LNG (Liquified Natural Gas) production units.

Lot of research works have been done using Fractional Order (FO) control and Passivity Based Control (PBC). FO Proportional Integral Derivative (PID) controller firstly proposed by podlubny, is a generalization of PID controller, involving an integer of order and a differentiation of order [7]. FO controllers are used in many applications and have obtained better results compared to Integer Order (IO) controllers [8]-[13]. PBC is a generic name given to a family of controller design techniques that achieves system stabilization via the route of passivation that is rendering the closed loop system passive with a desired storage function that usually qualifies as a Lyapunov function for the stability analysis [14]. Passivity theory has been applied to electrical systems, mechanical systems and electromechanical systems [15], chemical processes [16] with good results.

II. SCITS EXPERIMENTAL SETUP

The experimental setup of the spherical-conical interacting coupled tank system is shown in Fig. 1. It consists of a spherical tank, conical tank, interaction between the tanks using a manually adjustable valve, two pumps, two rotameters for inflow measurement to spherical tank and conical tank, two Differential Pressure Transmitter (DPT) for level measurement in both the tanks separately, I/V converter, interface to PC using USB based DAQ, V/I converter, I/P converter, and a compressor to operate pneumatic control valve.

The objective is to control the level of the spherical tank system h_1 and conical tank system h_2 by varying the inflow to the spherical tank F_{in1} and conical tank system F_{in2}. Thus h_1 and h_2 are the controlled variables and F_{in1} and F_{in2} are the manipulated variables. The pump adjusts the flow of water to the spherical tank and conical tank from the reservoir. The level of water in the tank is measured using DPT and the current output (4-20) mA from the DPT is converted to (0-5) V using I/V converter. This voltage is interfaced with computer using USB based DAQ. The control signal from the PC is transmitted through DAQ in the form of (0-5)V. The output voltage signal (0-5)V from the DAQ is given to a voltage to current converter (V/I) (4-20)mA which in turn is given to a current to pressure (I/P) converter which converts it to corresponding 3-15 psi of compressed air; further given as input to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow rate of water in the spherical tank and conical tank to maintain its level. The inflow rate is thus adjusted by changing the stem position of the control valve from fully open to fully close. The technical details of the experimental setup are given in Table I.

Fig. 1. Experimental setup of SCITS

TABLE I
Technical Specifications

PART NAME	DETAILS
Conical tank & Spherical tank	Stainless Steel, Diameter: 48cm, height:48cm.
Differential pressure transmitter	Type: Capacitance type, Range: 2.5-250 mbar, Output: 4 – 20 mA
Pump	Centrifugal: 0.5HP
Control valve	Size ¼”pneumatic actuated, Type: Air to close, Input: 3 – 15 psi
Rota meter	Range: 44-440 LPH
I/P converter	Input: 4-20 mA, Output: 0.2-1 bar
Pressure gauge	Range: 0-30 psi
Air regulator Size00	¼” BSP, Range: 0-2.2 bar

A. *System Identification*

The transfer function matrix of a 2-by-2 system is represented as below.

$$\begin{bmatrix} h_1(s) \\ h_2(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \tag{1}$$

where h_1 and h_2 are outputs, u_1 and u_2 are the inputs, G_{ij} is assumed to be first order with dead time system given by

$$G_{ij} = \frac{K_{ij}}{\tau_{ij} s + 1} e^{\theta_{ij}} \tag{2}$$

The transfer function $G_{11}(s)$, $G_{21}(s)$, $G_{12}(s)$ and $G_{22}(s)$ are calculated experimentally from the open loop response of the process for the setpoint of h_1=17cm and h_2 =15cm. By keeping constant inflow to the tank and outflow from the tank, the water level h_1 and h_2 in both the tanks reaches the initial steady state after some time. After both the tank level reaches the initial steady state, step change is given in tank 1 (i.e. spherical tank) and water level with respect to time is recorded in both the tanks. The response recorded with tank 1 is used for calculating G_{11} and the response recorded with tank 2 is used to find $G_{21.}$ Similarly the process is allowed to reach the initial steady state again by maintaining the same constant inflow and outflow given before. This time the step change is given in tank 2 (i.e. conical tank) and the water level with respect to time is recorded again. The response recorded with tank 2 this time is used to calculate G_{22} and response recorded with tank 1 is used to calculate G_{12}. The open loop responses for G_{11}, G_{21}, G_{22} and G_{12} are in Fig. 2. The parameters namely gain, time constant and delay are calculated from the open loop response. The gain is calculated as the ratio of change in process output to the change in process input. Time constant and delay are calculated using the two point method [17]. The parameters obtained for the 2-by-2 spherical conical interacting system is given below in Table II.

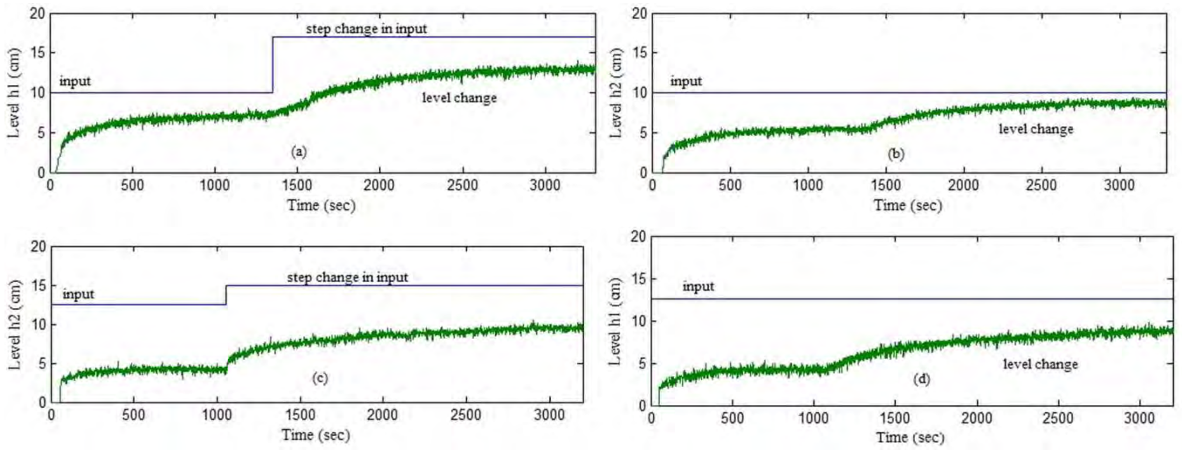

Fig. 2. a. Open loop response of tank 1 showing initial steady state and final steady state by giving step change in tank 1, used to calculate G_{11}

b. Open loop response of tank 2 showing initial steady state and final steady state due to step change given in tank 1, used to calculate G_{21}

c. Open loop response of tank 2 showing initial steady state and final steady state by giving step change in tank 2, used to calculate G_{22}

d. Open loop response of tank 1 showing initial steady state and final steady state due to step change given in tank 2, used to calculate G_{12}

TABLE II

Parameters of Transfer Function Matrix of 2-by-2 Spherical Conical Interacting System for the Operating Point of h_1=17 cm and h_2 =15 cm

	K	τ **(seconds)**	θ **(seconds)**
$G_{11}(s)$	0.9	1935	535
$G_{12}(s)$	1.85	1380	380
$G_{21}(s)$	0.4	1350	350
$G_{22}(s)$	2.3	1590	440

RGA matrix is computed for the 2-by-2 spherical conical interacting system and is given by

$$\lambda = \begin{bmatrix} 1.55639 & -0.55639 \\ -0.55639 & 1.55639 \end{bmatrix} \tag{3}$$

Using Equation (3), the input output pairing is identified as F_{in1}-h_1 and F_{in2}-h_2 where F_{in1} is the input flow to the spherical tank and h_1 is the water level in the spherical tank, F_{in2} is the input flow to the conical tank and h_2 is the water level in the conical tank.

III. CONTROLLER DESIGN

A. PI (Proportional Integral) Controller Design

As a classical candidate for comparison studies the Ziegler Nichols method is chosen [18]. The PI controller parameters are tuned by using ZN method of tuning based on ultimate gain and ultimate period. The PI tuning parameters for ZN method are K_{c11}=2.835, T_{i11}=1689 for G_{C1} and K_{C22}=1.3 and T_{i22}=1509 for G_{C2} for MIMO spherical conical interacting system where G_{c1} and G_{c2} are decentralized PI controllers. The PI controller parameters are also tuned using Hagglund Astrom Robust tuning rules [19]. These tuning rules give improved performance compared to ZN tuning rules [20]. The PI tuning parameters for Hagglund-Astrom Robust tuning method are K_{c11}=1.28, T_{i11}=1142 for G_{C1} and K_{C22}=0.5008 and T_{i22}=939.4 for G_{C2}.

B. FO-PI (Fractional Order Proportional Integral) Controller Design

The FO-PI controller is simply an extension of Integer Order (IO) PI controller with an additional term α being added to the controller's integral term. The FO-PI controller in frequency domain is simply written as [21]

$$C(s) = K_p + \frac{K_i}{s^{\alpha}} \tag{4}$$

where K_p and K_i are the proportional and integral gain values of the fractional controller and α is the non integer order of the fractional integrator. Tuning the gains K_p, K_i and non integer order α is discussed in [22]. The tuning rules developed in [22] are restated as

$$K_p = \frac{0.2978}{K(\tau + 0.000307)} \tag{5}$$

$$K_i = \frac{K_p(\tau^2 - 3.402\tau + 2.405)}{0.8578T} \tag{6}$$

$$\alpha = \begin{cases} 0.7 & if \quad \tau < 0.1 \\ 0.9 & if \quad 0.1 \le \tau < 0.4 \\ 1.0 & if \quad 0.4 \le \tau < 0.6 \\ 1.1 & if \quad \tau \ge 0.6 \end{cases} \tag{7}$$

and the relative delay τ is given by

$$\tau = \frac{L}{L+T}. \tag{8}$$

where L corresponds to the time delay and T corresponds to the time constant of the system. The FO-PI controller parameters obtained are K_{c11}=1.523, T_{i11}=1384, α_{11}=0.9 for G_{c11} and K_{C22}=0.58, T_{i22}=828, α_{22}=0.9 for G_{c22}.

C. Passivity Based Controller (PBCr) Design

Passivity concept has been used in nonlinear control theory since 1970 [23]. A passive system is one which can store and dissipate the energy supplied from the environment without generating its own. In other words the stored energy cannot become more then the energy supplied to the system. This feature is related to the stability property which is the main criteria for designing any controller.

The PBCr equation is simple and easy to obtain from the First Order Plus Dead Time (FOPDT) model of the system. The FOPDT model of the process with Taylor series approximation is given by

$$\frac{X_1(s)}{U(s)} = \frac{K}{(\tau s + 1)(\theta s + 1)} \tag{9}$$

where X(s) is the Laplace transform of the controlled variable and U(s) is the Laplace transform of the manipulated variable. The model of the above process can be written in state variable [24] as

$$\begin{cases} \dot{x}_1 = (x_2 - x_1)D - A \\ \dot{x}_2 = \frac{-x_2}{\tau} + B + CU \\ y = x_1 \end{cases} \tag{10}$$

where $A = \frac{1}{t_o}(\overline{x_2} - \overline{x_1})$

$$B = \frac{x_2}{\tau} \qquad C = \frac{K}{\tau} \qquad D = \frac{1}{t_o}$$

where x_2 is an auxiliary variable and x_1 and x_2 are always positive for all times $x(t) \geq 0$. Following the passivation procedure [25], the state dependent input coordinate transformation is given by

$$U = \frac{1}{C} W\left(\frac{x_1}{x_2} - x_1 D - B\right) \tag{11}$$

where W is the new input variable used to make the system passive. Substituting equation (11) in (10), the system model becomes

$$\begin{cases} \dot{x}_1 = (x_2 - x_1)D - A \\ \dot{x}_2 = \frac{-x_2}{\tau} - x_1 D + W\frac{x_1}{x_2} \\ y = x_1 \end{cases} \tag{12}$$

This system is a passive system relating the new input W with the output variable x_1 and can be represented in canonical form as in [26]. After converting the system into passive system, storage function given below is used for designing the PBCr and the derivative of the storage function is obtained.

$$S_d(x, x_d) = \frac{1}{2}(x - x_d)^T (x - x_d) \tag{13}$$

where x_d is an auxiliary state vector which satisfies the following state equation representation

$$\dot{x_d} = -Rx_d - Jx_d + R_{d1}(x - x_d) + MW \tag{14}$$

where R, J and M are the matrices in the canonical form [26]. Substituting R, J and M matrices the following state equation is obtained

$$\begin{cases} \dot{x}_{1d} = -\left(D + \frac{A}{x_1}\right) x_{1d} + Dx_{2d} + R_1(x_1 - x_{1d}) \\ \dot{x}_{2d} = -\frac{x_{2d}}{\tau} - Dx_{1d} + R_2(x_2 - x_{2d}) + \frac{x_1}{x_2} W \end{cases} \tag{15}$$

In the above equation x_{2d} is set to $\overline{x_2}$ in the range $0 < \overline{x_2} < \overline{x_1}$ and W is obtained given by (16)

$$W = \frac{x_2}{x_1}\left(\frac{\overline{x_2}}{\tau} + Dx_{1d} - R_2(x_2 - \overline{x_2})\right) \tag{16}$$

Substituting W in the equation (12) and adding integral term the final controller expression is obtained given by

$$\begin{cases} U = \frac{1}{C}\left[-D(x_1 - x_{1d}) - R_2 \int (x_1 - x_{1d})dt - R_2(x_2 - \bar{x}_2)\right] + \bar{u} \\ \dot{x}_{1d} = -\left(D + \frac{A}{x_1}\right) x_{1d} + D\bar{x}_2 + R_1(x_1 - x_{1d}) \end{cases} \tag{17}$$

The same procedure is extended to MIMO system and the PBC parameters are set to $R_1 = 0.15$, $R_2 = 0.12$ and $R_3 = 0.005$ for G_{c1} and $R_1 = 0.15$, $R_2 = 0.15$ and $R_3 = 0.009$ for G_{c2} in the case of MIMO spherical conical interacting system.

IV. SIMULATION RESULTS

Simulations are performed using Matlab simulink to validate the performance of the designed controllers. The effectiveness of the controllers are tested by giving sequence of step changes in case of servo response and load disturbance in case of regulatory response and the results are compared. The comparison of closed loop response of ZN tuned PI controller, Hagglund Astrom Robust tuning based PI controller, FO-PI controller and PBCr are shown in Fig. 3 and Fig. 4 for the level h_1 and h_2 corresponding to the operating point of h_1 =17 cm and h_2 = 15 cm level for SCITS. Performance analysis of closed loop response including time domain specification such as percentage peak overshoot, settling time and performance index criterion such as normalised Integral Square Error (ISE) and Integral Absolute Error (IAE) values are given in Table III.

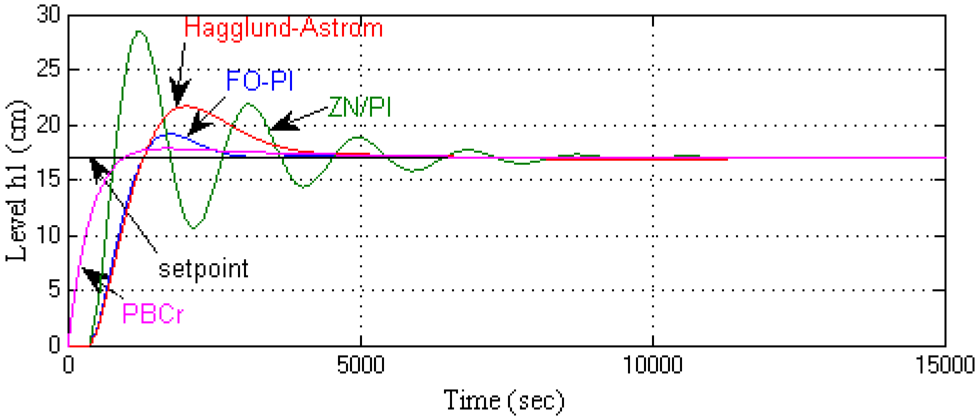

Fig. 3. Combined controller response for level h_1 of the SCITS

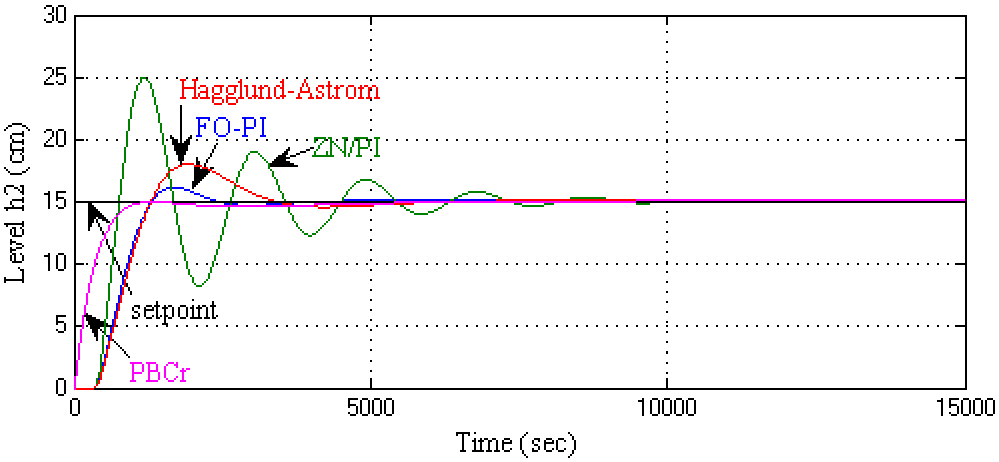

Fig. 4. Combined controller response for level h_2 of the SCITS

TABLE III
Performance Analysis of Closed Loop Response of MIMO System of Level h_1 for the Setpoint of 17cm Level and Level h2 for the Setpoint of 15cm Level

Type of controller	**Level output of tank 1 h_1**				**Level output of tank 2 h_2**			
	M_p %	**T_s(sec)**	**ISE**	**IAE**	**M_p %**	**T_s(sec)**	**ISE**	**IAE**
ZN/ PI	68	9000	17.17	1.9	67	10000	13.25	1.698
Hagglund-Astrom robust tuning/PI	27.4	7200	15.49	1.54	19.33	7200	10.76	1.14
Fractional Order PI (FO-PI)	12.4	3000	13.55	1.11	7.33	3500	9.89	0.89
Passiviy based controller (PBCr)	4.8	6000	3.56	0.52	-	6000	2.597	0.41

Combined servo response of controllers for both the tanks are shown in Fig. 5 and 6 for level h_1 and h_2 and combined regulatory response of controllers for level h_1 and h_2 are shown in Fig. 7 and 8. Performance analysis of servo and regulatory response indicating normalised ISE and IAE is given in Table IV.

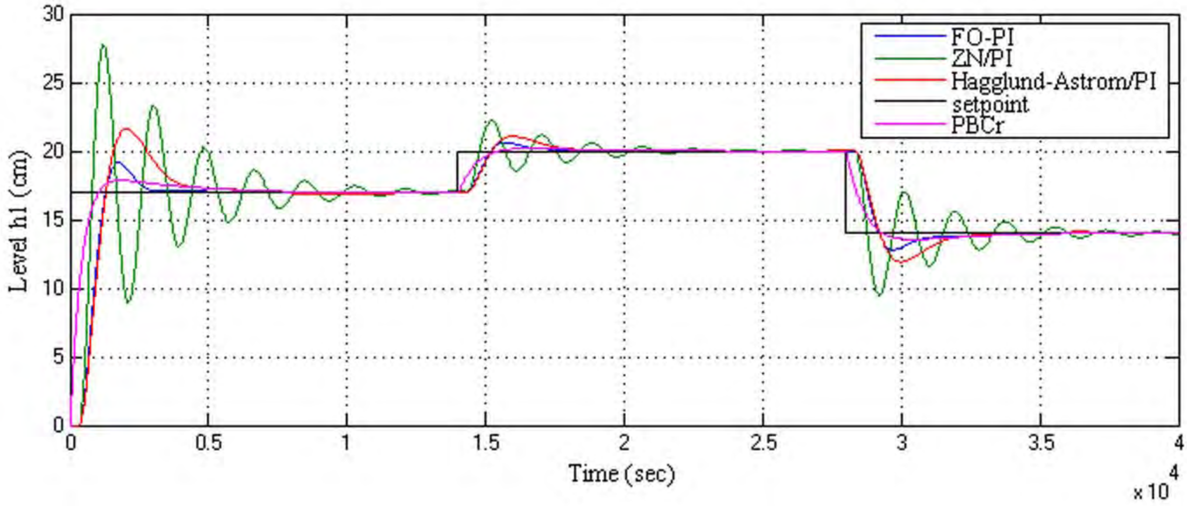

Fig. 5. Combined servo response of controllers for change in setpoint of +17.6 % and -30% at 14000 and 28000 sec for level h_1

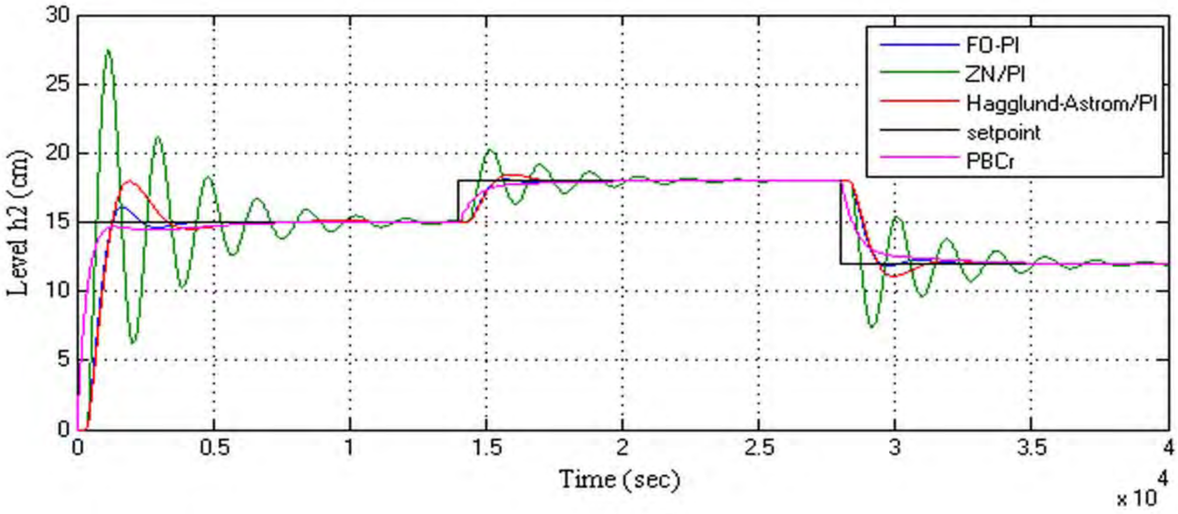

Fig. 6. Combined servo response of controllers for change in setpoint of +20% and -33.33% at 14000 and 28000 sec for level h_2

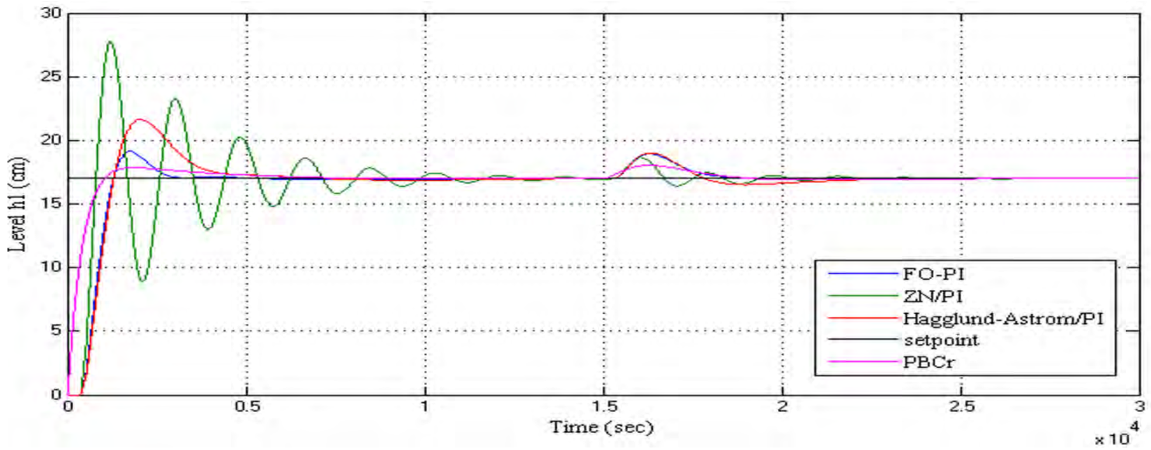

Fig. 7. Combined regulatory response of controllers for load change of +11.76% applied at 14000 secs

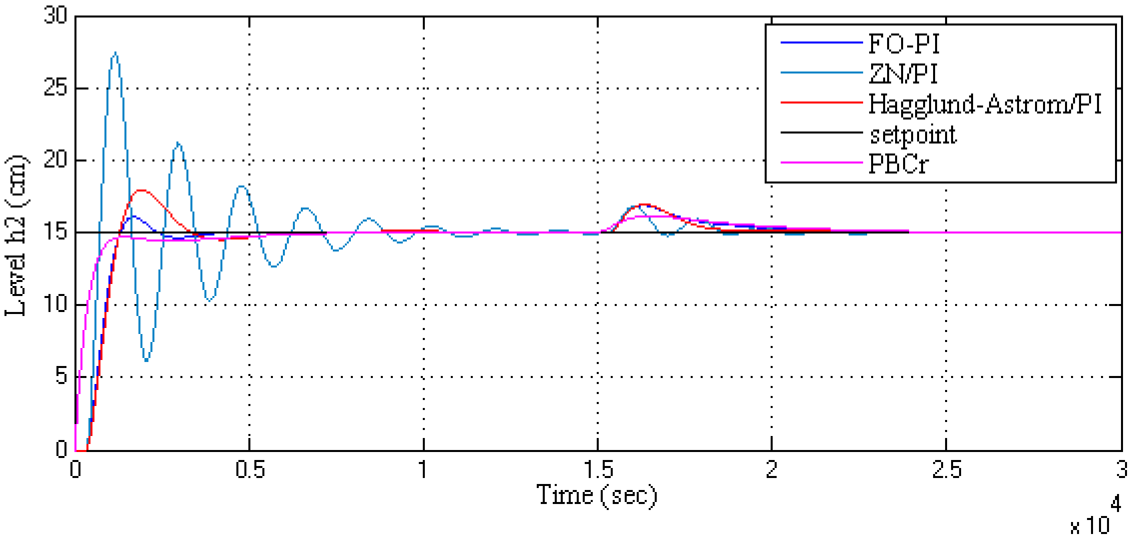

Fig. 8. Combined regulatory response of controllers for load change of +13.33% applied at 14000 secs

TABLE IV
Performance Analysis of Servo Response and Regulatory Response of Level h_1 and h_2 of MIMO System

Type of controller	**Servo Response**				**Regulatory Response**			
	h_1		**h_2**		**h_1**		**h_2**	
	ISE	**IAE**	**ISE**	**IAE**	**ISE**	**IAE**	**ISE**	**IAE**
ZN/ PI	8.07	1.31	7.69	1.33	9.25	1.21	8.72	1.23
Hagglund-Astrom robust tuning/PI	6.76	0.92	4.84	0.68	7.90	0.92	5.53	0.70
Fractional Order PI (FO-PI)	5.875	0.667	4.47	0.539	6.92	0.667	5.12	0.597
Passiviy based controller (PBCr)	1.74	0.369	1.44	0.372	1.94	0.367	1.51	0.392

From the closed loop response shown in Fig. 3 and 4 and the quantitative analysis given in Table III, it is seen that for both the tank levels h_1 and h_2, the percentage peak overshoot has been decreasing from ZN tuned PI controller to PBCr. Thus ZN/PI controller has the highest overshoot and PBCr has the lowest overshoot. While comparing settling time for both the tank levels from Table III it is clear that ZN/PI controller has the highest settling time and FO-PI controller has the lowest settling time. Finally comparing ISE and IAE values, PBCr has the least ISE and IAE values among all the four controllers designed. This is also evident from the servo and regulatory response analysis given in Table IV.

V. CONCLUSION

In this paper, four controllers namely ZN tuned PI controller, Hagglund-Astrom robust tuning PI controller, FO-PI controller and PBCr are discussed and tested for the level control of a new combination of SCITS which is a variable area interacting nonlinear system. The effectiveness of the controller is also tested for servo and regulatory operations. Among the four controllers FO-PI controller reduces the settling time to a greater extent where as PBCr reduces the percentage overshoot. Finally comparing the performance index criterion values, ISE and IAE values seems to less for FO-PI controller compared to ZN/PI controller and Hagglund Astrom robust tuning PI controller and more when compared with PBCr for both the tank levels h_1 and h_2 which is also evident from the servo and regulatory response analysis. Thus concluded that FO-PI controller performs better than conventional IO PI controller and of the four controllers PBCr performs best level control for the SCITS comparatively.

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