Analysis of Transient Response for Coupled Tank System via Conventional and Particle Swarm Optimization (PSO) Techniques

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Abstract—**This paper investigates the implementation of conventional and Particle Swarm Optimization (PSO) techniques to obtain optimal parameters of controller. In this research, the transient responses of the Coupled Tank System (CTS) are analyzed with the various conventional and meta-heuristic techniques which are Trial and Error, Auto-Tuning, Ziegler-Nichols (ZN), Cohen-Coon (CC), standard PSO and Priority-based Fitness PSO (PFPSO) to tune the PID controller parameters. The purpose of this research is to maintain the liquid at the specific or required height in the tank. Simulation is conducted within Matlab environment to verify the performance of the system in terms of Settling Time (T_s), Steady State Error (SSE) and Overshoot (OS). It has been demonstrated that implementation of meta-heuristic techniques are potential approach to control the desired liquid level and improve the system performances.**

Keyword-Computational Intelligence, Coupled Tank System, Particle Swarm Optimization, Priority-based Fitness, PID controller

I. INTRODUCTION

In chemical process industries, liquid is an agent that needs to be supplied in the tank. For the Coupled Tank System (CTS), it has two tanks (Tank 1 and Tank 2) as shown in Fig. 1. Liquid will be stored up in Tank 1 and transferred it to the Tank 2 as per requirement. The liquid must be maintained at a specific height [1]. If the level cannot be maintained as requirement, it can bring losses to the company or industries. In order to overcome this issue, a control mechanism is required. Based on the previous research, many controllers had been implemented to CTS. However, despite the advent of many control theories and techniques, PID control is still one of the most widely used control algorithms in industries [2].
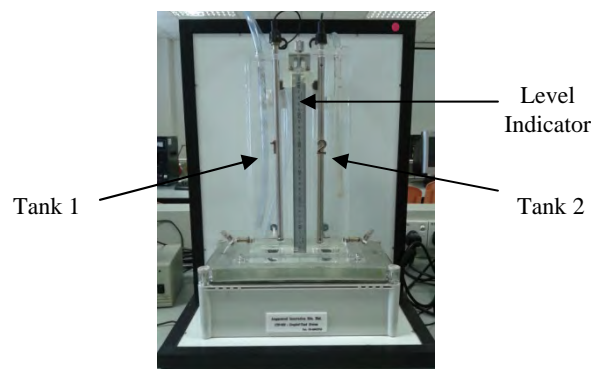

Fig. 1. Coupled tank CTS-001

The parameter of the PID controller can be tuned by conventional or meta-heuristic approach. The purpose of this various tuning techniques is to find the optimal of PID controller parameters. According to Vanuvamalai, Proportional-Integrator (PI) controller is designed using Ziegler-Nichols (ZN) technique for CTS. Even though response of Z-N tuning has high overshoot, it gave faster response with shorter settling time. The rise time is also reduced with good set point tracking characteristics [3]. Yacoub et al. proposed the Simulated Annealing (SA) as the tuning method for PI controller. The result is compared with the Genetic Algorithm (GA) and best performances are evaluated based on Settling Time (T_S) and Rise Time (T_R) [4]. Ramli et al. [5] proposed to upgrade the PI control to hybrid PI-NN (Neural Network) which is compared to the PID-NN controller in terms

of disturbance rejection and control performance measures for common input changes. Based on the control performance, hybrid PI-NN response faster than PID-NN and the T_S is much shorter. The system become more robust and has a small Steady State Error (SSE). However, the problem occurred in presence of disturbance.

Furthermore, Jutarut et al. [6] had done a research of the PID controller design for CTS process using Characteristic Ratio Assignment (CRA). CRA is satisfied with the specification of performance of the system. It is very convenient as a fast adjustment damping ratio and high speed response. Indirectly the overshoot is decreased by using CRA and lead to fast T_S response. Then, development of Genetic Algorithm (GA) is used to tune the parameters of the PID controller to overcome the weaknesses occurs in the nonlinear situation [7]. The PID parameters can be obtained due to GA can be tuned by itself and not just approximated model of the system. Through this method, the Overshoot (OS) of the system is decreased as well as the T_S. In other word, the system was response faster than the original system.

Therefore, the PID controller is chosen due to simple structure and easy to work with meta-heuristic techniques [8]-[11]. Three parameters of PID controller (K_P, K_I and K_D) will be tuned using Trial and Error, Auto-Tuning, Ziegler-Nichols (ZN), Cohen-Coon (CC), standard PSO and Priority-based Fitness PSO (PFPSO).

II. Modeling of Coupled Tank System

It is vital to understand the mathematics modeling of CTS. In this system, the model is derived and the linearization process is done according to manual of CTS [12]. Based on Fig. 2, H_1 and H_2 are the fluid level in Tank 1 and Tank 2. It is measured with respect to the corresponding outlet. Considering a simple mass balance, the rate of change of fluid volume in each tank equals the net flow of fluid into the tank.
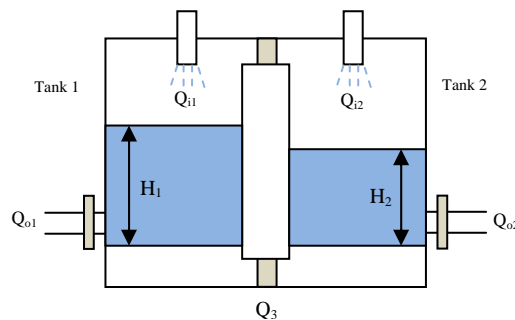

Fig. 2. Schematic model of CTS

The equation for Tank 1 and Tank 2 are:

$$A_1 \frac{dH_1}{dt} = Q_{i1} - Q_{o1} - Q_3 \tag{1}$$

$$A_2 \frac{dH_2}{dt} = Q_{i2} - Q_{o2} + Q_3 \tag{2}$$

where:

H_1, H_2	=	Height of fluid in Tank 1 and 2 respectively
A_1, A_2	=	Cross-sectional area of Tank 1 and 2 respectively
Q_3	=	Flow rate of fluid between Tanks
Q_{i1}, Q_{i2}	=	Pump flow rate into Tank 1 and 2 respectively
Q_{o1}, Q_{o2}	=	Flow rate of fluid out of Tank 1 and 2 respectively

Each outlet drain can be modeled as a simple orifice. Bernoulli's equation for steady, non-viscous, incompressible shows that the outlet flow in each tank is proportional to the square root of the head of water in the tank. Similarly, the flow between the tanks is proportional to the square root of the head differential. Thus:

$$Q_{o1} = \alpha_1 \sqrt{H_1} \tag{3}$$

$$Q_{o2} = \alpha_2 \sqrt{H_2} \tag{4}$$

$$Q_3 = \alpha_3 \sqrt{H_1 - H_2} \tag{5}$$

where α_1, α_2 and α_3 are proportionality constants which is depend on the coefficients of discharge, the cross sectional area of each orifice and the gravitational constant. By substitute equation (3), (4) and (5) into equation (1) and (2), the nonlinear state equations which describe the system dynamics of the CTS apparatus are:

$$A_1 \frac{dH_1}{dt} = Q_{i1} - \alpha_1 \sqrt{H_1} - \alpha_3 \sqrt{H_1 - H_2} \tag{6}$$

$$A_2 \frac{dH_2}{dt} = Q_{i2} - \alpha_2 \sqrt{H_2} + \alpha_3 \sqrt{H_1 - H_2} \tag{7}$$

In the second order configuration, h_2 is the process variable and q_1 is the manipulated variable and assume that q_2 is zero. The block diagram of the second order system can be simplified as shown in Fig. 3.
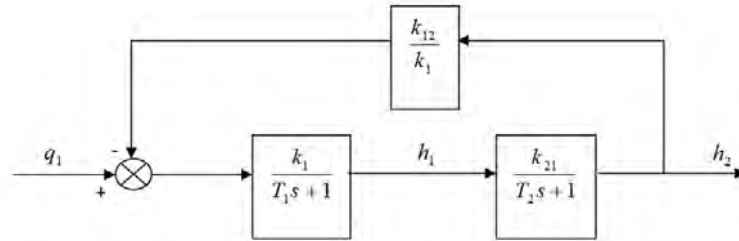

Fig. 3. Block diagram of second order system

The transfer function for the plant can be obtained by substituting all the parameter which was provided from the [8], [10] and [12]. The provided parameters are shown in Table I.

TABLE I
Parameters of CTS

Parameters	Value	Unit
H_1	17	cm
H_2	15	cm
α_1	10.78	$cm^{3/2}$/sec
α_2	11.03	$cm^{3/2}$/sec
α_3	11.03	$cm^{3/2}$/sec
A_1	32	cm^2
A_2	32	cm^2

Therefore, the actual transfer function of the plant with the completed value is:

$$G_p(s) = \frac{h_2(s)}{q_1(s)} = \frac{0.0361}{36.9406 s^2 + 12.1565 s + 0.4514} \tag{8}$$

Thus, PID controller is implemented for this CTS as shown in Fig. 4.

III. TUNING TECHNIQUES

Tuning method is very important in control system. The performance of the system can be affected due to the value of parameters in the PID controller. The performance of the system can be generally improved by proper tuning but it also can be worsen the performance with poor tuning techniques. In this research, six techniques are implemented to obtain the optimal parameters for PID controllers, namely Trial and Error, Auto-Tuning, Ziegler-Nichols (ZN), Cohen-Coon (CC), standard PSO and Priority-based Fitness PSO (PFPSO).

A. Trial and Error

Try and Error is one of the method and easiest way to obtain the value of PID parameters. In this method, no mathematical is required. However, the optimal value of the parameter is not guaranteed. The value of K_I and K_D need to be set first as zero before increasing the value of K_P. This will takes a lot of time and experience skill to obtain the optimal result.

B. Auto-Tuning

Auto-Tuning is one of an interactive tuning method that provided by Matlab software. It is easy to find the parameter of PID controller based on desired performances of the system.

C. Ziegler-Nichols (ZN)

ZN is a tuning method that is widely used of tuning PID controller. It is developed by John G. Ziegler and Nanthaniel B. Nichols in 1940s [13]. Through this method, K_I and K_D parameter are also need to be set first to zero. Then K_P is increased until it reaches the ultimate gain, K_U at which the output of the loop starts to oscillate in the oscillation period, T_U.

D. Cohen-Coon (CC)

CC tuning method is the second popular after the ZN tuning method. The method was published by Cohen and Coon in 1953 [14]. This method is more flexible that ZN tuning method in the wider variety of processes. ZN method work well only on the processes where the dead time is less than half the length of the time response compared to the CC method where the dead time is less than two times the length of the time constant.

E. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) was introduced in 1995 by Kennedy and Eberhart [15]. The basic PSO is developed based on behaviors of fish schooling and bird flocking in order to search and move to the food with certain speed and position. It has two important equations and updated according to P_{BEST} and G_{BEST}.

F. Priority-based Fitness Particle Swarm Optimization (PFPSO)

The different between PSO and PFPSO is the value of P_{BEST} and G_{BEST} are updated according to the priority: Ts, SSE and OS. It means that Ts is set as highest priority, followed by SSE and OS. Based on [16]-[18], the transient response specification of the system can be prioritized according to the needs and circumstances.

IV. RESULTS AND DISCUSSION

The plant of the system is obtained based on equation (8). The input voltage that has been injected to the system is 1 Volt. For this research, the desired level is 1 cm. The control structure with PID controller of the CTS is shown in Fig. 4.
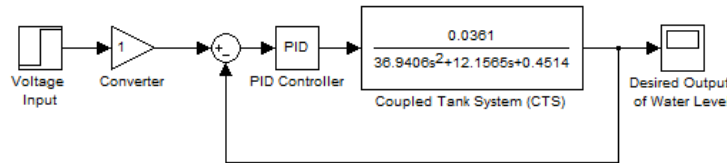

Fig. 4. Control structure of CTS with PID controller parameters

The Simulation exercises are conducted with Intel Core i5-2450M Processor, 2.5GHz, 6GB RAM, Microsoft Window 7 and MATLAB as a simulation platform. Table II shows the optimal value of PID parameters (K_P, K_I and K_D). All the techniques may provide positive values of PID controller parameter except Auto-Tuning. Using Auto-Tuning technique, the value of parameters is uncontrollable for positive and negative value. It depends on how we tune an interactive slide that provided by Matlab.

TABLE II
Parameters of PID controller for CTS

Techniques		Value of PID Controller Parameters		
		K_P	K_I	K_D
Conventional	Trial and Error	15.0000	1.0000	8.0000
	Auto-Tuning	53.4000	1.5400	-2.9800
	ZN	168.0000	35.0000	201.6000
	CC	235.8800	33.9200	203.2100
Meta-heuristic	PSO	250.9928	4.3478	171.6427
	PFPSO	250.9641	4.6859	250.8701

Fig. 5 shows the transient responses for CTS by using conventional tuning method. According to Fig. 5, CC method provides better performance than Trial and Error, Auto-Tuning and ZN for conventional techniques. Even though the percentage of overshoot for the system is higher than Try and Error and Auto-Tuning method, the system is able to stabilize the system and achieved the desired water level in shorter time (23.59 sec). Table III summarize all the performance of CTS that obtained using six techniques tuning method.
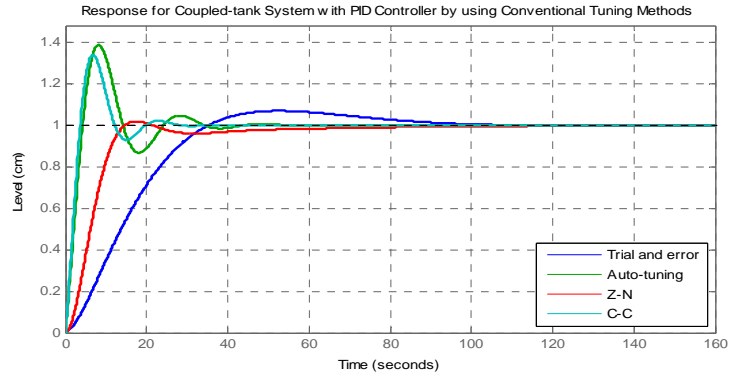
Fig. 5. Performance of CTS by using Conventional Tuning Methods

TABLE III
Performance of Transient Response for CTS

	Techniques	Transient Responses		
		TS (sec)	OS (%)	SSE (cm)
Conventional	Trial and Error	84.4000	6.8600	0.0000
	Auto-Tuning	53.3000	1.8100	0.0000
	ZN	32.1000	38.5000	0.0000
	CC	23.5900	33.7000	0.0000
Meta-heuristic	PSO	17.7519	16.1877	0.0000
	PFPSO	11.5396	11.3344	0.0000

Once meta-heuristic approach is implemented to the PID controller for CTS, it provided more optimal value of PID controller parameters as shown in Table II. Fig. 6 shows that both of the optimization method (PSO and PFPSO) can improve the transient response of the system compared to conventional techniques. However, implementation of PFPSO may provide fastest time to stabilize the system with the smallest OS to achieve the desired water level compared to standard PSO.
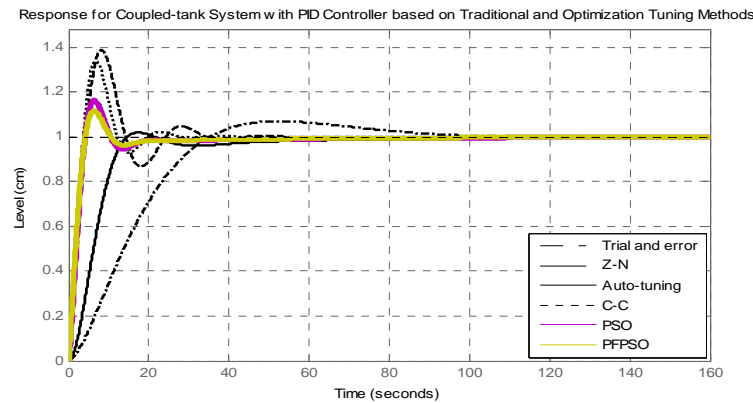

Fig. 6. Performance of CTS by using Meta-Heuristic Methods

V. CONCLUSION

Based on the comparison that has been presented between conventional and meta-heuristic techniques, it shows that PSO and PFPSO are able to improve the performance of CTS. However, PSO and PFPSO might not be the best meta-heuristic tuning method in order to obtain the optimal value of PID controller parameters and provide best performance for transient response of CTS. Further research with other optimization technique and controller implementation is required to compare and improve the performance of the system.

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