Optimal PIDA Controller Design for Three-Tank Liquid-Level Control System with Model Uncertainty by Cuckoo Search

T. Jitwang, A. Nawikavatan and D. Puangdownreong

***Abstract*—**In industrial applications, the three-tank (3-tank) liquid-level control commonly exists under the PID control loop. However, the PIDA could provide better responses than the PID for higher order plant. In this paper, an optimal PIDA controller design for 3-tank liquid-level control system with model uncertainty by cuckoo search (CS) is proposed. The CS, one of the most powerful population-based metaheuristic optimization search techniques, is conducted to optimize the PIDA's parameters based on modern optimization context. The CS-based PIDA design framework can be considered as the constrained optimization problem. Model uncertainty is occurred due to aging and environmental effects. As results, it was found that the PIDA controller designed by the CS provides the very satisfactory responses of the 3-tank liquid-level controlled system with model uncertainty superior to the PID controller.

***Keywords*—**PIDA controller, Cuckoo search, Three-tank liquid-level system, Model uncertainty

I. Introduction

THE liquid-level control in tanks containing different chemicals or mixtures is very important in many industrial applications, for example, filtration, dairy, effluent treatment, waste water treatment plant, food processing, nuclear power generation plants, pharmaceutical industries, water purification systems, industrial chemical processing and spray coating as well as boilers [1],[2]. Liquid-level control is commonly large lag, time varying and complex system. The main objective of such the control systems is to fill the tank as quickly and smoothly as possible. The three-tank (3-tank) system relates to liquid-level control generally existing in industrial surge tanks. The 3-tank liquid-level control is classified as process control. It can be considered as non-interaction and interaction. The later one, however, is more complicate than the former one. By literatures, it was found that in process control applications more than 95% of the controllers are the proportional-integral-derivative (PID) controller [3],[4]. Well-known analytical methods for designing the PID controller for process control are Ziegler-Nichols (ZN) method [5] and Cohen-Coon (CC) method [6].

In 1996, the proportional–integral–derivative– accelerated (PIDA) controller was firstly proposed by Jung and Dorf [7]. The PIDA controller, possessing three arbitrary zeros and one pole at origin, can provide faster and smoother responses for the higher-order plants than the PID controller. In addition, modern optimization search techniques called "metaheuristics" have been widely applied to design the PIDA controller, for instance, the PIDA controller designed by the genetic algorithm (GA) [8], particle swarm optimization (PSO) [9],[10], current search (CuS) [11], firefly algorithm (FA) [12] and bat algorithm (BA) [13].

Firstly proposed by Yang and Deb in 2009 [14], the cuckoo search is one of the most efficient population-based metaheuristic optimization search techniques. It was proved for the global convergent property [15] and successfully applied to many real-world engineering problems. The state-of-the-art and its applications of the CS have been reviewed and reported [16]. For our previous work, the cuckoo search (CS) which is one of the most popular metaheuristic optimization search techniques was conducted to design an optimal PIDA controller for non-interaction 3-tank liquid-level control system [17].

In this paper, design of an optimal PIDA controller for an interaction 3-tank liquid-level control system with model uncertainty by the CS is proposed. Such the model uncertainty is assumed to be occurred due to aging and environmental effects regarded as the perturbation. This paper consists of five sections. After an introduction is presented in section I, the rest of the paper is outlined as follows. The PIDA control loop and the 3-tank liquid-level system model are described in section II. Problem formulation consisting of CS-based PIDA design optimization framework and CS algorithms is given in section III. Results and discussions are illustrated in section IV, while conclusions are provided in section V.

II. PIDA Control Loop

A. PIDA Controller

The feedback PIDA control loop is represented by the block diagram as shown in Fig. 1, where $G_p(s)$ is the 3-tank

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system model and $G_c(s)$ is the PIDA controller. The PIDA controller receives the error signal $E(s)$ and produces the control signal $U(s)$ to control the output response $C(s)$ and regulate the external disturbance signal $D(s)$ referring to the reference input $R(s)$. The s-domain transfer function of the PIDA controller is stated in (1), where K_p is proportional gain, K_i is integral gain, K_d is derivative gain and K_a is accelerated gain. In (1), a, b, c and d, e are zeros and poles of the PIDA controller, respectively. Since a, b, c << d, e, the poles d, e can be neglected [7]. Therefore, the PIDA transfer function in (1) can be rewritten as expressed in (2). Referring to (2), it can be observed that the PIDA controller possesses three arbitrary zeros and one pole at origin.

$$G_c(s)\big|_{PIDA} = K_p + \frac{K_i}{s} + \frac{K_d s}{(s+d)} + \frac{K_a s^2}{(s+d)(s+e)} = \frac{K(s+a)(s+b)(s+c)}{s(s+d)(s+e)} \quad (1)$$

$$G_c(s)\big|_{PIDA} = \frac{K_a s^3 + K_d s^2 + K_p s + K_i}{s} \quad (2)$$

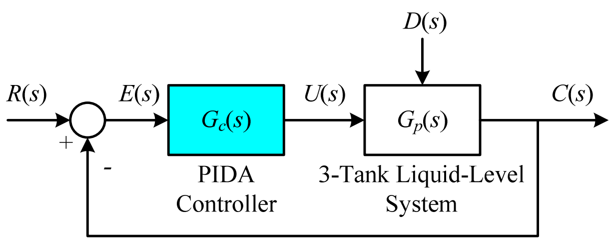

Fig. 1 PIDA feedback control loop

B. Liquid-Level Model with Interaction

According to the magnitude of the Reynolds number, systems involving fluid flow can be divided into laminar and turbulent forms [18],[19]. If the Reynolds number (R_N) is less than about 2000, the flow is laminar. If the R_N is in interval about 2,000 to 4,000, the flow is transition state. If the R_N is greater than about 4,000, the flow is turbulent as shown in Fig. 2.

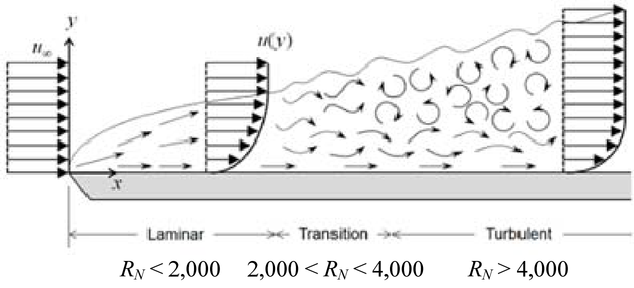

Fig. 2 laminar and turbulent flows

The schematic diagram of an interaction 3-tank liquid-level system consisting of three first-order processes connected in series can be represented in Fig. 3, where...

- $\overline{Q}$ is steady-state flow rate,
- $\overline{H}_j$ is steady-state liquid level of Tank-j, where $j = 1, 2, 3$,
- R_j is valve resistance of Tank-j,
- C_j is capacitance (or cross-sectional area) of Tank-j,
- $h_j(t)$ is liquid level of Tank-j,
- $q_i(t)$ is liquid inflow rate into Tank-1,
- $q_k(t)$ is liquid inflow rate into Tank-k, where $k = 1, 2$, and
- $q_o(t)$ is liquid outflow rate from Tank-3.

In this work, the linearized mathematical model of an interaction 3-tank liquid-level system is formulated by setting $q_i(t)$ as input variable and $q_o(t)$ as output variable, respectively. Referring to Fig. 3, linear differential equations of Tank-1, Tank-2 and Tank-3 are performed as stated in (3) – (5), respectively. The transfer function of an interaction 3-tank liquid-level system is then formulated in (6).

$$\left.\begin{aligned} q_i(t) - q_1(t) &= C_1\frac{dh_1(t)}{dt} \\ q_1(t) &= \frac{h_1(t) - h_2(t)}{R_1} \end{aligned}\right\} \quad (3)$$

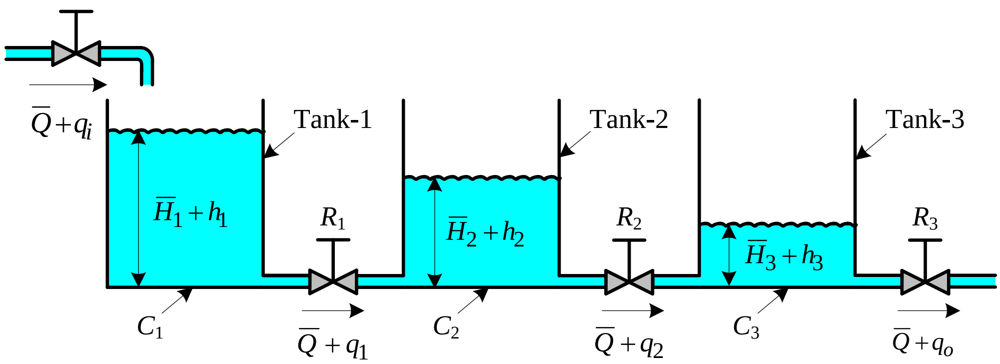

Fig. 3 schematic diagram of interaction 3-tank liquid-level system

$$\left.\begin{aligned} q_1(t)-q_2(t)&=C_2\frac{dh_2(t)}{dt}\\ q_2(t)&=\frac{h_2(t)-h_3(t)}{R_2}\end{aligned}\right\} \quad (4)$$

$$\left.\begin{aligned} q_2(t)-q_o(t)&=C_3\frac{dh_3(t)}{dt}\\ q_o(t)&=\frac{h_3(t)}{R_3}\end{aligned}\right\} \quad (5)$$

$$G_p(s)=\frac{Q_o(s)}{Q_i(s)}=\frac{1}{a_2s^3+a_1s^2+a_0s+1} \quad (6)$$

…where
$a_0=R_1C_1+R_2C_2+R_3C_3+R_2C_1+R_3C_2+R_3C_1$,
$a_1=R_1R_2C_1C_2+R_1R_3C_1C_2+R_1R_3C_1C_3$
$+R_2R_3C_1C_3+R_2R_3C_2C_3$ and
$a_2=R_1R_2R_3C_1C_2C_3$.

III. Problem Formulation

A. CS-Based PIDA Controller Design

According to modern optimization framework, application of the CS to design the optimal PIDA controller for an interaction 3-tank liquid-level system can be represented by the block diagram in Fig. 4. The objective function J is set as the sum-squared error between the referent inflow rate $R(s)$ and the actual outflow rate $C(s)$ as stated in (7). In order to be minimized, J will be fed to the CS by searching for the appropriate values of the PIDA parameters, i.e. K_p, K_i, K_d and K_a subject to inequality constraint functions set by the desired response specifications as stated in (8).

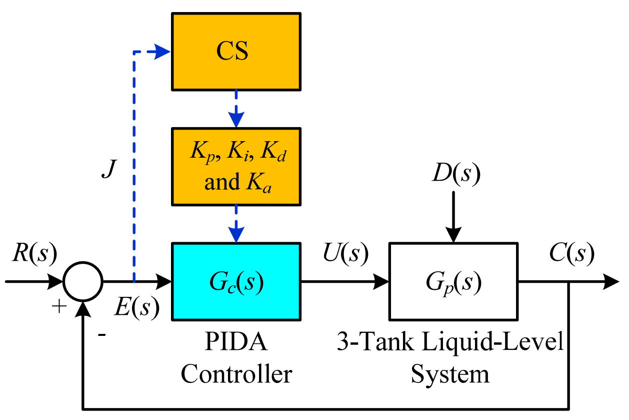

Fig. 4 CS-based PIDA design framework

$$\textbf{Min } J(x)=\sum_{i=1}^{N}[r_i-c_i]^2 \quad (7)$$

$$\textbf{Subject to } \quad g_j(x)\le 0, \quad j=1,2,\ldots \quad (8)$$

Referring to (6), the $G_p(s)$ is considered as the nominal plant model. However, with aging and environmental effects, the nominal plant model can be varied. This is called model uncertainty. Based on the robust control theory [20],[21], the uncertainty term $\Delta(s)$ may be added into $G_p(s)$ as stated in (9). The plant model $\tilde{G}_p(s)$ in (9) will be used as the plant $G_p(s)$ in Fig. 4.

$$\begin{aligned}\tilde{G}_p(s)&=G_p(s)+\Delta(s)\\ &=\frac{1}{(a_2+\Delta)s^3+(a_1+\Delta)s^2+(a_0+\Delta)s+1}\end{aligned} \quad (9)$$

B. CS Algorithm

Inspired by the behaviour of some cuckoo species associated with the Lévy distribution, the CS algorithms is firstly proposed [14]. Two key parameters of the CS are a number of cuckoos (n) and a fraction p_a denoting the ability of host birds that can find the cuckoos' eggs. In CS algorithms, new solutions $\boldsymbol{x}^{(t+1)}$ for cuckoo i can be generated by Lévy distribution as expressed in (10), where a symbol Lévy(λ) represents the Lévy distribution having an infinite variance with an infinite mean as expressed in (11). The step length s of cuckoo flight can be calculated by (12), where u and v stand for normal distribution as stated in (13). Standard deviations of u and v are also expressed in (14). The CS algorithm is applied for the PIDA controller design application as follows:

$$\boldsymbol{x}_i^{(t+1)}=\boldsymbol{x}_i^{(t)}+\alpha\oplus\text{Lévy}(\lambda) \quad (10)$$

$$\text{Lévy}\approx u=t^{-\lambda}, \quad (1<\lambda\le 3) \quad (11)$$

$$s=\frac{u}{|v|^{1/\beta}} \quad (12)$$

$$u\approx N(0.\sigma_u^2), \quad v\approx N(0.\sigma_v^2) \quad (13)$$

$$\left.\begin{aligned}\sigma_u&=\left\{\frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}}\right\}^{1/\beta}\\ \sigma_v&=1\end{aligned}\right\} \quad (14)$$

Step-1 Perform objective function $J(\boldsymbol{x})$, $\boldsymbol{x}=(K_p, K_i, K_d, K_a)^T$ in (2), initial number of cuckoos (n), fraction p_a and search spaces, randomly generate $\boldsymbol{x}$ as initial solutions and set Max_Gen and Gen = 1.

Step-2 If Gen ≤ Max_Gen, n cuckoo find the new nests by Levy flight and lay their eggs in the random nests according to (10) – (14) to create new solutions $\boldsymbol{x}$*. Otherwise, go to Step-7.

Step-3 If $p_a \le$ `rand`, m (m <= n) cuckoo's egg is found by host birds. m cuckoo find the new nests by Levy flight again and lay their eggs in the random nests according to (10) – (14) to create new solutions $\boldsymbol{x}$*.

Step-4 Evaluate all cuckoos' eggs via $J(\boldsymbol{x})$.
Step-5 If $J(\boldsymbol{x}) < J(\boldsymbol{x}^*)$ in (7) and satisfy to (8), update $\boldsymbol{x} = \boldsymbol{x}^*$.
Step-6 Update Gen = Gen+1, and go back to Step-2.
Step-7 Terminate the search process, and report best solution $\boldsymbol{x}$ found.

IV. Results and Discussions

To design the optimal PIDA controller for an interaction 3-tank liquid-level system, the CS algorithms were coded by MATLAB version 2017b (License No.#40637337) run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM. Based on the preliminary studies of Yang and Deb [14], number of cuckoos n = 40 and fraction p_a = 0.2 are set according to their recommendations. The parameters of the nominal plant model $G_p(s)$ in (6) are set as $R_1 = R_2 = 1.0$ m/m^3/sec., $R_3 = 0.5$ m/m^3/sec., $C_1 = C_2 = C_3 = 1.0$ m^2 [22],[23]. The nominal plant model $G_p(s)$ in (6) can be rewritten as given in (15). Model uncertainty $\Delta(s)$ = ±10% of each lumped parameter of the nominal plant model is assumed as stated in (16). Search spaces and constraint functions are then performed as shown in (17), where t_r is rise time, M_p is percent maximum overshoot, t_s is settling time and E_{ss} is steady-state error, respectively. The maximum generation Max_Gen = 100 is then set as the termination criteria (TC). 50 trials are conducted to find the best parameters of the PIDA controller for an interaction 3-tank liquid-level system. For comparison with the PID controller, K_a in (2) will be set as zero.

$$G_p(s) = \frac{1}{0.5s^3 + 3s^2 + 4.5s + 1} \tag{15}$$

$$\tilde{G}_p(s) = \frac{1}{(0.5\pm\Delta)s^3 + (3\pm\Delta)s^2 + (4.5\pm\Delta)s + 1} \tag{16}$$

$$\textbf{Subject to} \quad \left.\begin{aligned} & t_r \le 2.5 \text{ sec.}, \\ & M_p \le 20.0\,\%, \\ & t_s \le 15.0 \text{ sec.}, \\ & E_{ss} \le 0.01\,\%, \\ & 0 < K_p \le 30, \\ & 0 < K_i \le 5.0, \\ & 0 < K_d \le 10, \\ & 0 < K_a < 5.0, \\ & [G_p(s) - \Delta(s)] \le G_p(s) \le [G_p(s) + \Delta(s)] \end{aligned}\right\} \tag{17}$$

When the search process stopped, the CS can successfully provide the optimal PID and PIDA controllers for an interaction 3-tank liquid-level system as shown in (18) and (19), respectively.

$$G_c(s)\big|_{PID} = 5.02 + \frac{0.89}{s} + 0.99s \tag{18}$$

$$G_c(s)\big|_{PIDA} = 25.03 + \frac{3.04}{s} + 9.98s + 3.01s^2 \tag{19}$$

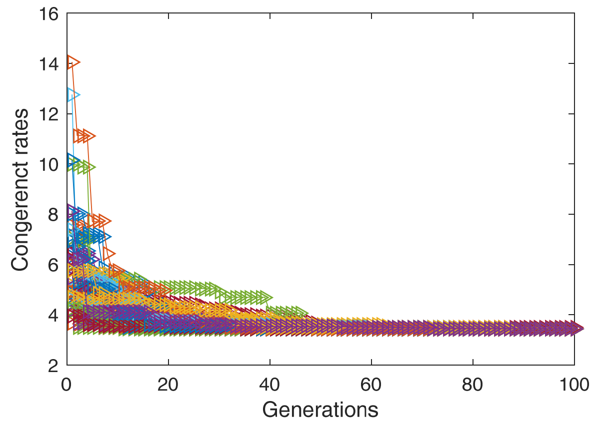

Fig. 5 convergent rates over 50 trials

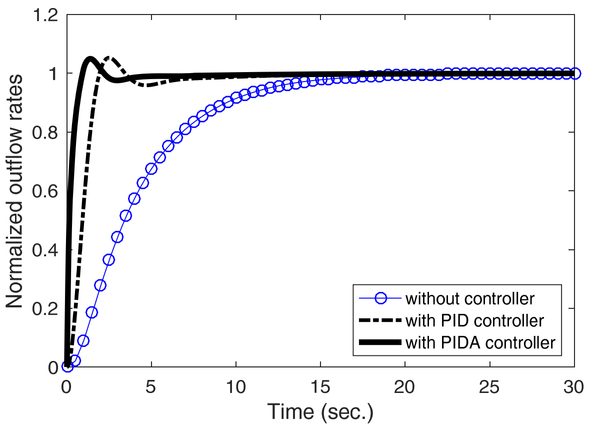

Fig. 6 step responses of 3-tank liquid-level system

The convergent rates of the objective functions in (7) associated with inequality constraint functions in (17) proceeded by the CS over 50 trials are depicted in Fig. 5. Without model uncertainty, the step responses of an interaction 3-tank liquid-level system without controller, with PID controller and with PIDA controller designed by the CS are depicted in Fig. 6. From Fig. 6, the step response of an interaction 3-tank liquid-level system without controller provides t_r = 15.24 sec., t_s = 18.67 sec., without M_p and E_{ss}. With the PID controller, the step response of an interaction 3-tank liquid-level system yields t_r = 1.92 sec., t_s = 8.36 sec., M_p = 6.42% and without E_{ss}. Finally, the step response of an interaction 3-tank liquid-level system with the PIDA controller provided t_r = 0.97 sec., t_s = 4.76 sec., M_p = 6.41% and without E_{ss}. This can be observed that the PIDA controller designed by the CS can provide very satisfactory response of an interaction 3-tank liquid-level system superior to the PID controller.

In case with model uncertainty, 500 variations of each lumped parameter of the nominal plant model in (16) within $\Delta(s)$ = ±10% are randomly generated to simulate the perturbation due to aging and environmental effects. The step

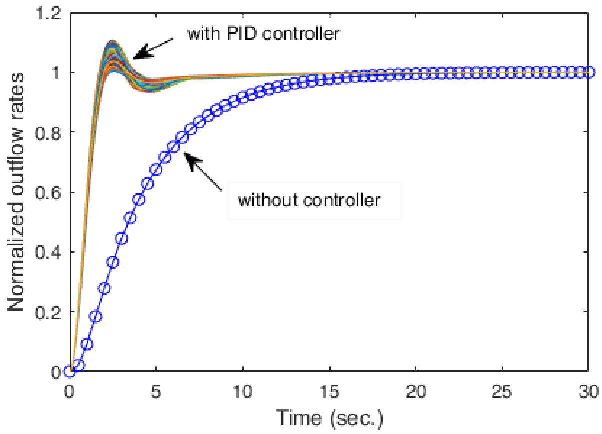

Fig. 7 step responses of 3-tank liquid-level system controlled by PID with model uncertainty

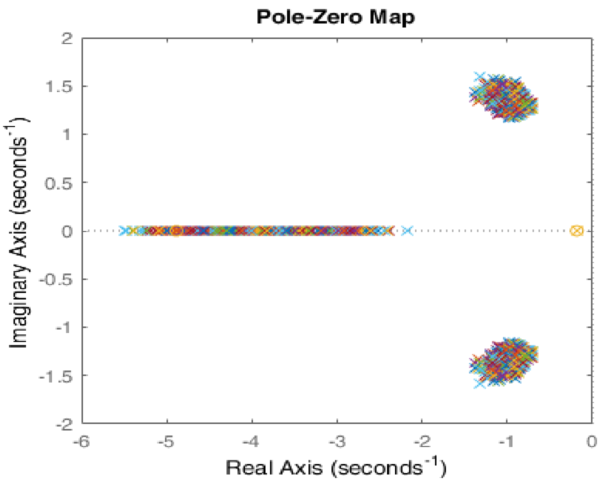

Fig. 8 pole-zero plots of 3-tank liquid-level system controlled by PID with model uncertainty

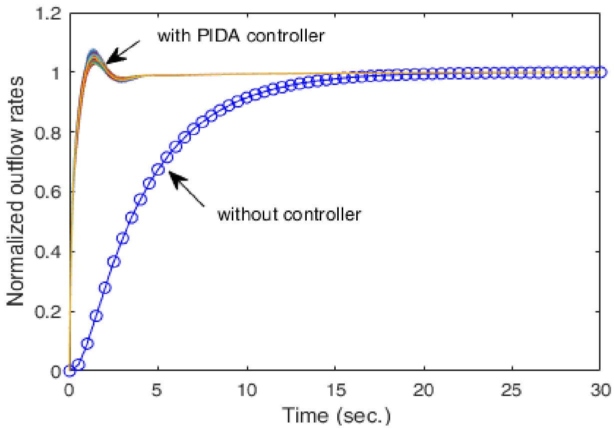

Fig. 9 step responses of 3-tank liquid-level system controlled by PIDA with model uncertainty

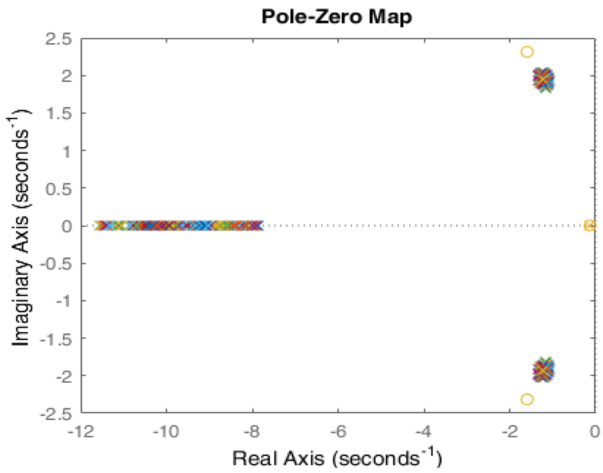

Fig. 10 pole-zero plots of 3-tank liquid-level system controlled by PIDA with model uncertainty

responses of an interaction 3-tank liquid-level system with the PID controller in (18) are plotted in Fig. 7. It was found that all system responses with the PID controller in (18) satisfy to inequality constraint functions in (17). This means that the system with the PID controller is robust performance. Regarding to robust control theory [20],[21], if the system is robust performance, the system is also robust stability. This can be proved by the pole-zero plots in Fig. 8.

By using the PIDA controller in (19) with model uncertainty, 500 variations of each lumped parameter of the nominal plant model in (16) within $\Delta(s) = \pm 10\%$ are randomly generated to simulate the perturbation. The step responses of an interaction 3-tank liquid-level system with the PIDA controller are depicted in Fig. 9. It was found that all system responses the PIDA in (19) satisfy to inequality constraint functions in (17). The system with the PIDA controller is robust performance and robust stability which is proved by the pole-zero plots in Fig. 10.

In comparison between Fig. 7 and Fig. 9 when model uncertainty is presented within $\Delta(s) = \pm 10\%$, the deviation of the step responses of the system with PID controller is greater than those with PIDA controller. Once considering the differences between Fig. 8 and Fig. 10, it can be observed that the deviation of pole-zero locations of the system with PID controller is greater than those with PIDA controller. This can be concluded that the PIDA controller designed by the CS provides the very satisfactory responses of an interaction 3-tank liquid-level system with model uncertainty better than the PID controller.

V. Conclusions

The optimal PIDA controller design for an interaction 3-tank liquid-level control system with model uncertainty by cuckoo search (CS) has been proposed in this paper. As one of the most efficient population-based metaheuristic optimization search techniques, the CS has been outperformed both PSO and GA in minimum finding of many benchmarking optimization functions. In this work, the CS has been applied to optimize the PID's and PIDA's parameters based on modern optimization context. As results, it was found that the PIDA controller designed by the CS could provide the better responses of the 3-tank liquid-level controlled system than the PID. With model uncertainty within ±10% of each lumped parameter of the nominal plant model of 3-tank liquid-level system, the PID and PIDA designed by the CS could provide the responses satisfying to inequality constraint functions. The robust performance of this controlled system has been performed, and the robust stability of this system has been also investigated. From simulation results with model uncertainty, it can be concluded that the PIDA controller designed by the CS could provide the very satisfactory responses of an interaction 3-tank liquid-level system superior to the PID controller, significantly.

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