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Liquid Level Control of Four-Tank System Based on Active Disturbance Rejection Technology

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ABSTRACT

In this paper, considering the disturbance in the four-tank system, the new active disturbance rejection control strategies are proposed to resolve the disturbance problem. In the first place, two forms with nonlinear function and linearized active disturbance rejection control are designed by using active disturbance rejection technology and the dynamic model of four-tank system. Among them, the linearized active disturbance rejection control can still arrange transition process for reference input, observe the order states of the system and compensate disturbance. Finally, the simulation and experimental results show that the proposed control strategy compared with the classical proportional integral differential method, active disturbance rejection control strategy can not only achieve good position control and disturbance suppression effect, but also show excellent effect in target tracking on the four-tank system.

1. Introduction

In the process of industrial production, whether it is heavy industry or light industry, chemical industry or food industry, multi-tank system has been widely used. From the perspective of control, the multi-tank system is complex, multi-variable and nonlinear, which is one of the important fields of the application of nonlinear control theory. The level control of multi-tank system is faced with a challenge of high nonlinearity, large inertia, strong coupling and large time delay [1], all of which affect the stability of the control system. The multi-tank system is greatly affected by the unknown disturbance and the uncertainty of parameters, which makes the control task more complex, and the precise control of multi-variables is very difficult. Originally, the classic four-tank control system proposed by Johansson became a very popular benchmark for adopting different control strategies for multivariable processes [2]. Therefore, it is great significance to study and solve the multivariable control problem of four-tank system for industrial production.

At present, the control strategy of the multiple tank system mainly concentrates on the following aspects, such as proportion integration differentiation (PID) control [3–5], predictive control [6–9], fuzzy control [10,11], backstepping control [12,13], and sliding mode control [14–16]. In addition to the above, there are some other methods used for the multi-tank system. Scheme [17] used embedded model control strategy to reject disturbance. The main advantage of this method was that it avoided common multivariable model identification and used simple single input single output structure, thus reduced the workload of model maintenance. Purposed to the stability of physical and chemical nonlinear processes, a non-feedback passivation stage control method based on tracking error was proposed [18,19]. Taken the four-tank process as an example, this paper proposed a method based on nominal error updating model: by comparing the measured output of the system with the corresponding nominal output [20]. The paper of [21] presented the design and implementation of a robust decentralized proportion integration controller based on a predefined transfer function model. The stability performance of the controller was verified by considering the uncertainty of input and output. In [22], a multiagent system-based liquid level control program was developed. In practice, more and more attention has been paid to the influence of external disturbance on non-linear systems and the disturbance rejection. A smooth switching control strategy [23] was proposed to solve the problems of serious chattering of sliding mode and slow transient response of backstepping control strategy for four-tank system in process control.

In recent years, some scholars have proposed the idea of active disturbance rejection control (ADRC) for nonlinear systems with multi-input multi-output (MIMO) and highly coupled states, and it has been verified in some fields. In order to solve the problem that the existing bandwidth tuning methods cannot determine the appropriate controller parameters to achieve the desired system performance, a

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method was proposed to decompose the ADRC into controller and prefilter in frequency domain [24]. The authors of [25], in order to achieve high performance operation of 5-DOF bearingless permanent magnet synchronous motor, a decoupling control strategy combined fuzzy neural network inverse system with ADRC was proposed. For multi area interconnected power system [26,27], excessive load change will lead to system instability. Therefore, active disturbance rejection controller was used to keep the load within the rated range, and Q-learning algorithm was used to select the parameters of the controller. In [28], a bandwidth parameterized ADRC synchronization control method was proposed, which extracts Laplacian matrix from defined adjacent cross coupling error and embeds it into the controller. The authors of [29], purposed to improve the robustness of floating interleaved direct current boost converter and deal with the uncertainty of switching fault, an adaptive active disturbance rejection control method was proposed. Compared with the traditional ADRC, the performance of the proposed controller is significantly improved, and no additional sensors were needed. To solve the problem that the outer loop, speed loop, PI regulator cannot achieve optimal control between the speed dynamic response and torque tracking error compensation, a model predictive torque control [30,31] method based on active disturbance rejection was proposed. The extended state observer [32, 33] was used to deal with the real-time estimation of the total uncertainty. Aimed at the problem of trajectory tracking [34,35] and obstacle avoidance of quadrotor aircraft, an active disturbance rejection control method based on swarm intelligence was proposed. An event-triggered ADRC strategy [36] based on sampled data was proposed for perturbation systems in network environment by using the techniques of disturbance/uncertainty estimation and attenuation. From the above research content, it can be seen that the control strategy related to ADRC has achieved good results in dealing with parameter uncertainty, internal and external interference in power electronics, aircraft, energy and other related fields, and has good tracking performance. Currently, the research and application of ADRC method in the field of strong nonlinear process control is less, so the ADRC method for liquid level control of four-tank system proposed in this paper has strong research and practical value. In the paper of [37], the problem of state and parameter estimation of nonlinear systems was studied by using extended gitaniz Kalman filter.

In order to reduce the influence of interference and unmeasurable parameters, an adaptive L_2 interference attenuation technology [38] was integrated. Under the effect of leakage delay, the design of L_2-L_∞ state estimation for delayed neural network of quadruple-tank liquid level system was considered, and a L_2-L_∞ state estimation criterion based on linear matrix inequalities was proposed [39]. For any steady state feedback gain [40], a 2-DOF MIMO proportional integral derivative controller was designed based on non-iterative linear matrix inequality. The applicability and accuracy of the proposed decentralized control method for nonlinear systems were verified by simulation. In [41], a port-controlled Hamiltonian method based on disturbance observer was proposed for a four-tank liquid level system. The set operation was simplified to a simple matrix representation of the region topology set, which was used to constrain the state/output estimation provided by the interval observer [36,42–44] method. The above contents are some control strategies proposed recently for the disturbance, fault detection, target tracking and other problems in nonlinear MIMO systems, which are worth learning and reference, and can accumulate energy for future research work.

The main contributions of this paper are summarized as follows.

(1) The two forms with nonlinear function and linearized active disturbance rejection control(LADRC) are considered by using active disturbance rejection technology and the dynamic model of four-tank system.

(2) The linearized active disturbance rejection control can still arrange transition process for reference input, states of observation system and disturbance compensation.

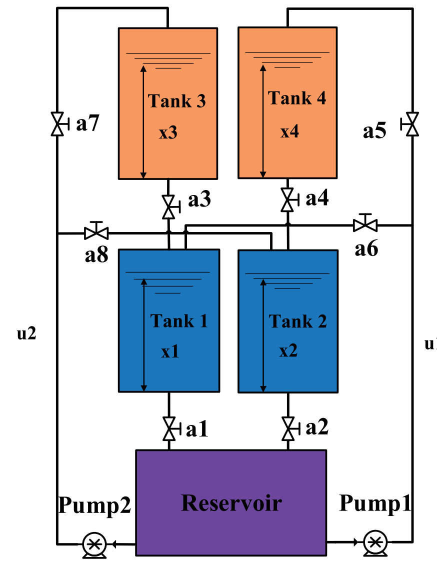


Fig. 1. The four-tank system schematic diagram.

(3) The simulation and experimental results show that the proposed control strategy compared with the classical proportional integral differential method, active disturbance rejection control strategy can not only achieve good position control and disturbance suppression effect, but also show excellent effect in target tracking on the four-tank system.

The remainder of this paper is organized as follows. Section 2 presents four-tank system dynamics model. Controller design is introduced in Section 3. Simulation and experimental results are represented in Section 4. This paper is concluded in Section 5.

2. System description and modeling

As shown in Fig. 1, the system consists of a reservoir, two Pumps, four perforated water tanks of the same area, four level sensors on the top of the tanks, two electric control valves and eight manual control valves. In this experimental setting, Pump 1 feeds into Tank 1 and Tank 4 respectively, and Pump 2 feeds into Tank 2 and Tank 3 respectively. The outflow quantity of Tank 3 and Tank 4 is changed into the input quantity of Tank 1 and Tank 2 respectively, and the outflow of Tank 1 and Tank 2 are discharged into the reservoir again.

According to Bernoulli's law, the dynamic equation of the four-tank system can be written as

$$\frac{d}{dt}[\rho A_i x_i(t)] = \rho q_{in}(t) - \rho q_{out}(t) \tag{1}$$

where, ρ is the liquid density in the tank, A_i is the bottom cross-sectional area of each tank, $x_i(t)$s the level height of the liquid in tank i, $q_{in}(t)$ is the inflow rate of the water tank, $q_{out}(t)$ is the outflow rate of the water tank, $i \in \{1,2,3,4\}$.

The outlet rate of manual regulating valve at the bottom of each tank is

$$q_{out}(t) = a_i\sqrt{2gx_i(t)} \tag{2}$$

where, a_i is the cross-sectional area of the manual regulating valve port, $(i \in \{1,2,\ldots,7,8\})$, g is the acceleration of gravity.

Therefore, the mathematical model of the four-tank system can be expressed as

$$\begin{cases} \dot{x}_1 = -\frac{a_1}{A_1}\sqrt{2gx_1} + \frac{a_3}{A_1}\sqrt{2gx_3} + \frac{a_6}{a_5+a_6}\frac{1}{A_1}u_1 \\ \dot{x}_2 = -\frac{a_2}{A_2}\sqrt{2gx_2} + \frac{a_4}{A_2}\sqrt{2gx_4} + \frac{a_8}{a_7+a_8}\frac{1}{A_2}u_2 \\ \dot{x}_3 = -\frac{a_3}{A_3}\sqrt{2gx_3} + \frac{a_7}{a_7+a_8}\frac{1}{A_3}u_2 \\ \dot{x}_4 = -\frac{a_4}{A_4}\sqrt{2gx_4} + \frac{a_5}{a_5+a_6}\frac{1}{A_4}u_1 \end{cases} \tag{3}$$

where x_1, x_2, x_3 and x_4 are the level height of the four tanks, respectively. u_1 and u_2 are control input(input flow rate) for four-tank system.

3. Controller design of the four-tank system

The control accuracy of the control target will be measured by the tracking error, which is expressed as follows

$$\begin{cases} e_1 = x_1 - x_{1d} \\ e_2 = x_2 - x_{2d} \\ e_3 = x_3 - x_{3d} \\ e_4 = x_4 - x_{4d} \end{cases} \tag{4}$$

where, x_{1d}, x_{2d}, x_{3d} and x_{4d} are the expected value of the liquid level height of the four tanks, respectively. e_1, e_2, e_3 and e_4 are the tracking error value of the liquid level height of the four tanks, respectively.

By taking the first derivative of time from Eq. (4), the rate of change of tracking error can be obtained

$$\begin{cases} \dot{e}_1 = \dot{x}_1 - \dot{x}_{1d} \\ \dot{e}_2 = \dot{x}_2 - \dot{x}_{2d} \\ \dot{e}_3 = \dot{x}_3 - \dot{x}_{3d} \\ \dot{e}_4 = \dot{x}_4 - \dot{x}_{4d} \end{cases} \tag{5}$$

3.1. Determination of expected value

Combine with Eq. (3), the mathematical model of the four-tank system, the expected value $x_d = \begin{bmatrix} x_{1d} & x_{2d} & x_{3d} & x_{4d} \end{bmatrix}^{\mathrm{T}}$. It can be represented by Eq. (5)

$$\begin{cases} a_1\sqrt{2gx_{1d}} = a_3\sqrt{2gx_{3d}} + \frac{a_6}{a_5+a_6}u_{1d} \\ a_2\sqrt{2gx_{2d}} = a_4\sqrt{2gx_{4d}} + \frac{a_8}{a_7+a_8}u_{2d} \\ a_3\sqrt{2gx_{3d}} = \frac{a_7}{a_7+a_8}u_{2d} \\ a_4\sqrt{2gx_{4d}} = \frac{a_5}{a_5+a_6}u_{1d} \end{cases} \tag{6}$$

From Eq. (6), it can be seen that the expected flow and expected value of Pumps 1 and 2 can be determined by electric control valve and manual control valve.

3.2. Design of ADRC controller

ADRC is on the basis of feedback linearization theory of design of a new type of controller, use "observation + compensation" method to nonlinear and uncertainty existing in the processing system, and considering nonlinear system way of feedback, improve the dynamic performance and steady-state performance of the controller reference Han's literature and literature of [26,30,35,45] , the typical structure of ADRC is shown in Fig. 2.

Therefore, the concrete realization form of ADRC controller for four-tank system can be designed as follows

Track differentiator (TD)

$$\begin{cases} e_{11} = z_{11} - x_{1d} + z_{14} - x_{4d} \\ \dot{z}_{11} = -r_1 fal(e_{11}, \alpha_1, \delta_1) \\ \dot{z}_{14} = -r_4 fal(e_{11}, \alpha_1, \delta_1) \end{cases} \tag{7}$$

$$\begin{cases} e_{21} = z_{12} - x_{2d} + z_{13} - x_{3d} \\ \dot{z}_{12} = -r_2 fal(e_{21}, \alpha_2, \delta_2) \\ \dot{z}_{13} = -r_3 fal(e_{21}, \alpha_2, \delta_2) \end{cases} \tag{8}$$

Extended state observer (ESO)

$$\begin{cases} e_{12} = z_1 - x_1 + z_4 - x_4 \\ \dot{z}_1 = z_5 - \beta_{11} fal(e_{12}, \alpha_1, \delta_1) + b_1 u_1 \\ \dot{z}_4 = z_7 - \beta_{41} fal(e_{12}, \alpha_1, \delta_1) + b_4 u_1 \\ \dot{z}_5 = -\beta_{12} e_{12} \\ \dot{z}_7 = -\beta_{42} e_{12} \end{cases} \tag{9}$$

$$\begin{cases} e_{22} = z_2 - x_2 + z_3 - x_3 \\ \dot{z}_2 = z_6 - \beta_{11} fal(e_{22}, \alpha_2, \delta_2) + b_2 u_2 \\ \dot{z}_3 = z_8 - \beta_{31} fal(e_{22}, \alpha_2, \delta_2) + b_3 u_2 \\ \dot{z}_6 = -\beta_{22} e_{22} \\ \dot{z}_8 = -\beta_{32} e_{22} \end{cases} \tag{10}$$

Nonlinear state error feedback control law (NLSEF)

$$\begin{cases} e_{13} = z_{11} - z_1 + z_{14} - z_4 \\ u_{01} = \beta_{13} fal(e_{13}, \alpha_1, \delta_1) + \beta_{43} fal(e_{13}, \alpha_1, \delta_1) \\ u_1 = u_{01} - \frac{z_5}{b_1} - \frac{z_7}{b_4} \end{cases} \tag{11}$$

$$\begin{cases} e_{23} = z_{12} - z_2 + z_{13} - z_3 \\ u_{02} = \beta_{23} fal(e_{23}, \alpha_2, \delta_2) + \beta_{33} fal(e_{23}, \alpha_2, \delta_2) \\ u_2 = u_{02} - \frac{z_6}{b_2} - \frac{z_8}{b_3} \end{cases} \tag{12}$$

In Eqs. (7) to (12), r_1, r_2, r_3 and r_4 are the control gains, z_{11}, z_{12}, z_{13} and z_{14} are the liquid level output values of TD scheduling transition process, z_1, z_2, z_3 and z_4 are the liquid level output values observed by ESO, z_5, z_6, z_7 and z_8 are the system disturbances observed by ESO, e_{11} and e_{21} are the liquid level errors of TD scheduling transition process, e_{12} and e_{22} are the liquid level errors observed by ESO, e_{13} and e_{23} are the system disturbance errors observed by ESO, β_{11}, β_{12}, β_{31}, β_{32}, β_{21}, β_{22}, β_{41}, β_{42}, β_{13}, β_{43}, β_{23} and β_{33} are the corresponding adjustable gains, u_{01} and u_{02} are the control output signals by nonlinear feedback control law, u_1 and u_2 are the control signals after disturbance compensation, b_1, b_2, b_3 and b_4 are the compensation factors that determines the degree of compensation and the adjustable parameter.

In the above TD, ESO and NLSEF, nonlinear functions $fal()$ are used. And the $fal()$ specific expression can be written as

$$fal(e, \alpha, \delta) = \begin{cases} \frac{e}{\delta^{1-\alpha}}, |e| \le \delta \\ sign(e)|e|^{\alpha}, |e| > \delta \end{cases} \tag{13}$$

where, $sign(e)$ is a sign function, α is a nonlinear factor, δ is the filter factor, when $\alpha < 1$, $fal(e, \alpha, \delta)$ has the characteristic of "large error and small gain, small error and large gain".

3.3. Design of LADRC controller

In the simulation and actual application, the parameter adjustment is always the important factors influencing the ADRC's control performance because of the existence of the nonlinear function and its carrying two parameters, and as a result of the existence of its own parameters to carry, takes up a large amount of CPU clock cycle, makes the system run slow cat on cannot deny its excellent control performance for the convenience of the ADRC's parameter setting and simplifying the structure, consider adopting direct error instead of nonlinear function.

The concrete realization form of LADRC based on four-tank system can be expressed as follows

Track differentiator (TD)

$$\begin{cases} e_{11} = z_{11} - x_{1d} + z_{14} - x_{4d} \\ \dot{z}_{11} = -r_1 e_{11} \\ \dot{z}_{14} = -r_4 e_{11} \end{cases} \tag{14}$$

$$\begin{cases} e_{21} = z_{12} - x_{2d} + z_{13} - x_{3d} \\ \dot{z}_{12} = -r_2 e_{21} \\ \dot{z}_{13} = -r_3 e_{21} \end{cases} \tag{15}$$

Extended state observer (ESO)

$$\begin{cases} e_{12} = z_1 - x_1 + z_4 - x_4 \\ \dot{z}_1 = z_5 - \beta_{11} e_{12} + b_1 u_1 \\ \dot{z}_4 = z_7 - \beta_{41} e_{12} + b_4 u_1 \\ \dot{z}_5 = -\beta_{12} e_{12} \\ \dot{z}_7 = -\beta_{42} e_{12} \end{cases} \tag{16}$$

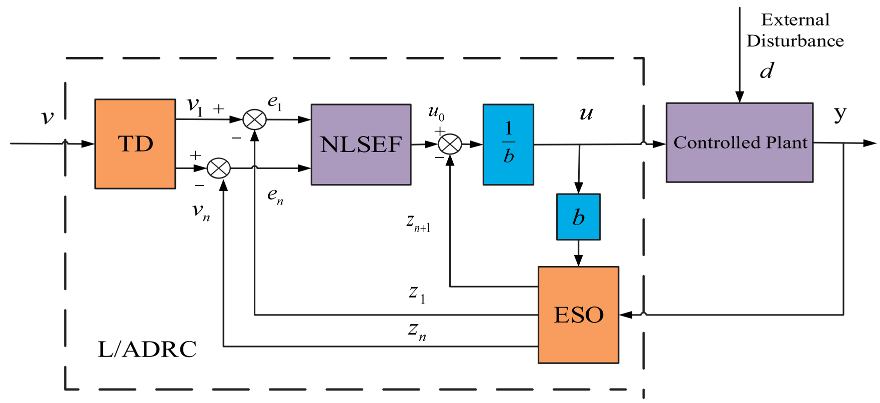


Fig. 2. The typical ADRC structure diagram.

$$\begin{cases} e_{22} = z_2 - x_2 + z_3 - x_3 \\ \dot{z}_2 = z_6 - \beta_{21}e_{22} + b_2u_2 \\ \dot{z}_3 = z_8 - \beta_{31}e_{22} + b_3u_2 \\ \dot{z}_6 = -\beta_{22}e_{22} \\ \dot{z}_8 = -\beta_{32}e_{22} \end{cases} \tag{17}$$

Nonlinear state error feedback control law (NLSEF)

$$\begin{cases} e_{13} = z_{11} - z_1 + z_{14} - z_4 \\ u_{01} = \beta_{13}e_{13} + \beta_{43}e_{13} \\ u_1 = u_{01} - \frac{z_5}{b_1} - \frac{z_7}{b_4} \end{cases} \tag{18}$$

$$\begin{cases} e_{23} = z_{12} - z_2 + z_{13} - z_3 \\ u_{02} = \beta_{23}e_{23} + \beta_{33}e_{23} \\ u_2 = u_{02} - \frac{z_6}{b_2} - \frac{z_8}{b_3} \end{cases} \tag{19}$$

3.4. PID controller

PID controller is composed of three parts: proportional link, integral link and differential link.

The PID controller [46] can be described as follows

$$\begin{cases} u_1 = k_{p1}(e_1 + e_4) + k_{i1}\int(e_1 + e_4)dt + k_{d1}(\dot{e}_1 + \dot{e}_4) \\ u_2 = k_{p2}(e_2 + e_3) + k_{i2}\int(e_2 + e_3)dt + k_{d2}(\dot{e}_2 + \dot{e}_3) \end{cases} \tag{20}$$

where, k_{p1} and k_{p2} are proportionality coefficient, k_{i1} and k_{i2} are integral coefficient, k_{d1} and k_{d2} are differential coefficient.

By substituting Eqs. (3) and (4) into Eq. (20), the final expression of PID controller for four-tank system can be calculated

$$\begin{cases} u_1 = k_{p1}(x_1 - x_{1d} + x_4 - x_{4d}) + k_{i1}\int(x_1 - x_{1d} + x_4 - x_{4d})dt \\ +k_{d1}(\dot{x}_1 - \dot{x}_{1d} + \dot{x}_4 - \dot{x}_{4d}) \\ u_2 = k_{p2}(x_2 - x_{2d} + x_3 - x_{3d}) + k_{i2}\int(x_2 - x_{2d} + x_3 - x_{3d})dt \\ +k_{d2}(\dot{x}_2 - \dot{x}_{2d} + \dot{x}_3 - \dot{x}_{3d}) \end{cases} \tag{21}$$

4. Simulation and experimental results

In this paper, the trial and error method is used to determine the parameters of the proposed control strategy and PID control method for optimal tuning. The specific tuning process is illustrated in Fig. 3. Since there is no unified theory on the proof of Lyapunov stability of active disturbance rejection control strategy and PID control method, this paper does not give it at present. If you want to know the detailed proof, please refer to reference [45–50].

4.1. Simulation results and analysis

Simulation verification is carried out in the Simulink environment of Matlab software. First, the structural parameters of the four-tank system are given as Table 1.

Table 1
Adjustable parameters of the system model.

Parameters	Value	Unit	Parameters	Value	Unit
a_1	0.42	cm^2	a_7	0.2	cm^2
a_2	0.38	cm^2	a_8	0.2	cm^2
a_3	0.2	cm^2	A_1	196	cm^2
a_4	0.2	cm^2	A_2	196	cm^2
a_5	0.2	cm^2	A_3	196	cm^2
a_6	0.2	cm^2	A_4	196	cm^2

Table 2
The PID controller parameters.

Parameters	Value	Parameters	Value
k_{p1}	20	k_{p2}	20
k_{i1}	1	k_{i2}	1
k_{d1}	0.1	k_{d2}	0.1

Table 3
The L/ADRC controller parameters.

Parameters	Value	Parameters	Value	Parameters	Value
β_{11}	0.01	β_{13}	2000	r_1	0.2
β_{21}	0.01	β_{23}	2000	r_2	0.2
β_{31}	0.01	β_{33}	2000	r_3	0.2
β_{41}	0.01	β_{43}	2000	r_4	0.2
β_{12}	8000	b_1	8	α_1	0.75
β_{22}	8000	b_2	8	δ_1	0.1
β_{32}	8000	b_3	8	α_2	0.75
β_{42}	8000	b_4	8	δ_2	0.1

The expected value of each tank level are $x_{1d} = 16$ cm, $x_{2d} = 20$ cm in the four-tank system.

In this section, the proposed controller is simulated and its controller adjustable parameters are shown as Tables 2 and 3.

For the three controllers mentioned above, when the simulation time is 1000 s, the simulated external disturbances are injected into Tank 1 and Tank 2 in the four-tank system respectively.

As shown in Fig. 4:(a),(b), when PID control algorithm is adopted, the liquid level response curves of Tank 1 and Tank 2 rise slowly, and the rising time is $t_r = 200$ s and $t_r = 200$ s respectively. Using ADRC control algorithm, the liquid level response curves of Tank 1 and Tank 2 rise faster, and the rising time is $t_r = 15$ s and $t_r = 15$ s respectively. Using LADRC control algorithm, the liquid level response curves of Tank 1 and Tank 2 also rise rapidly, and the rising time is $t_r = 25$ s and $t_r = 25$ s respectively. From the above data, the response curve of PID control algorithm is longer than ADRC and LADRC control algorithm. Compared with LADRC control algorithm, ADRC control algorithm has 40% faster response speed when all adjustable parameters are almost the same.

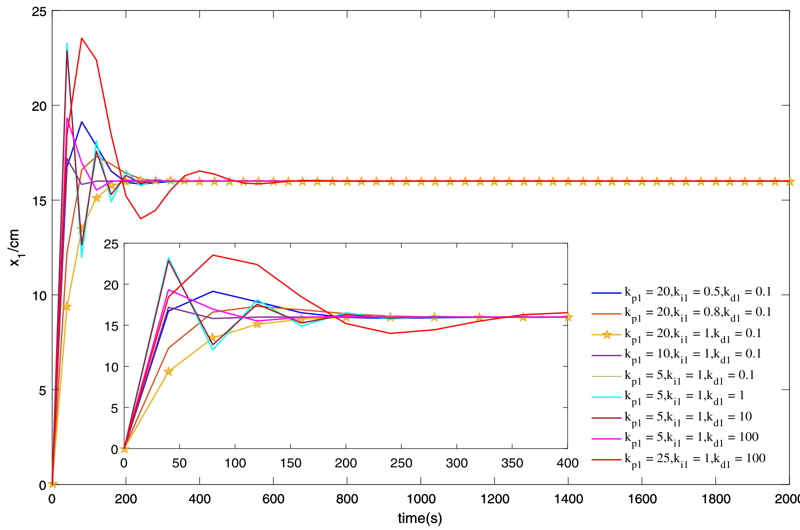
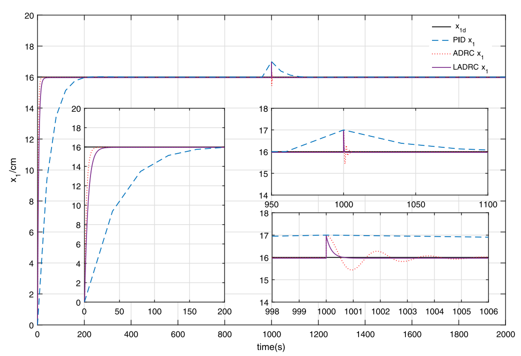
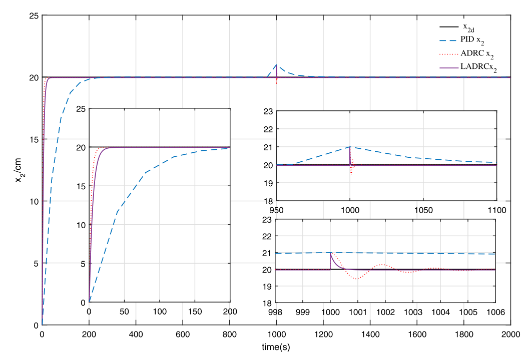


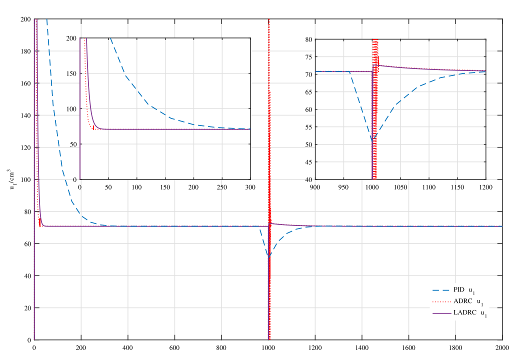
Fig. 3. The optimal tuning process of PID parameters.



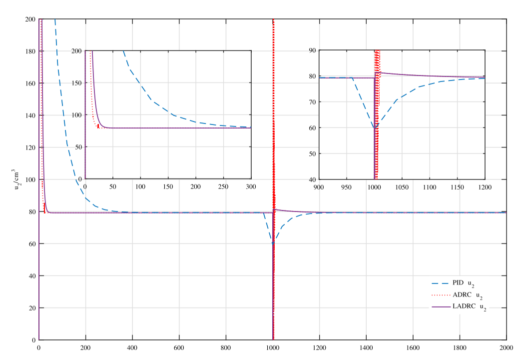
(a) The liquid level response curves of Tank 1.



(b) The liquid level response curves of Tank 2.



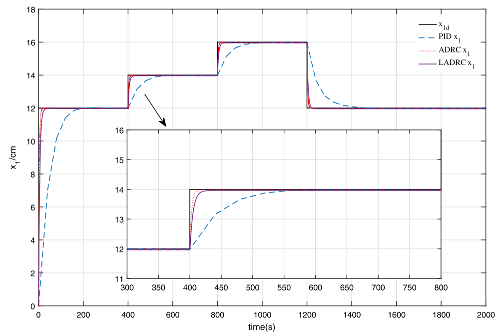
(c) The control input response curves of u_1.



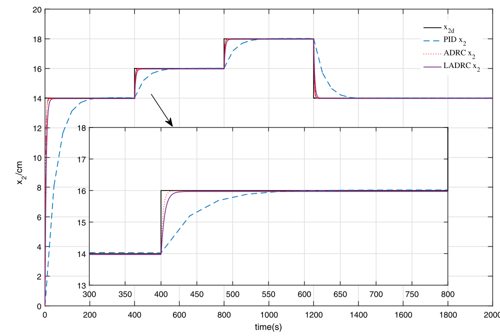
(d) The control input response curves of u_2.

Fig. 4. Response curves of liquid level disturbance compensation control.

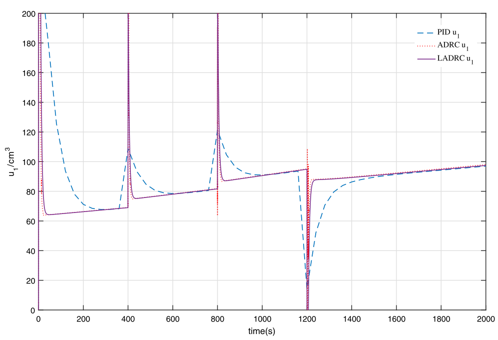
The three control methods show good stability performance when there is no external disturbances. However, after injecting the simulated external disturbances, the three control methods have different suppression effects on the disturbances. In Fig. 4, the liquid level response curves and control input curves of Tank 1 and Tank 2 show that when PID control method is adopted, the time range of the liquid level curve of Tank 1 and Tank 2 affected by disturbances is 950–1150 s, about 200 s, and the disturbance amplitude is large. When ADRC control method is used, the time range of the liquid level curves of Tank 1 and Tank 2 are affected by the disturbances in the range of 1000–1005 s, which is about 5 s. The disturbance amplitude is small, but there is slight oscillation in the recovery stage. When LADRC control method is employed, the liquid level curves of Tank 1 and Tank 2 are affected by disturbances, the time range is 1000–1001 s, about 1 s, and there is no oscillation. The above results show that, compared with ADRC and LADRC control methods, PID has poor disturbance suppression ability and long adjustment recovery time. In addition, compared with LADRC control method, the ADRC control method has a slight oscillation phenomenon when all adjustable parameters are almost the same, which can be recovered to the desired level within 10 s, while the LADRC control method not only has no oscillation, but also recovers to the stable value within 1 s. A comparison of average computation time



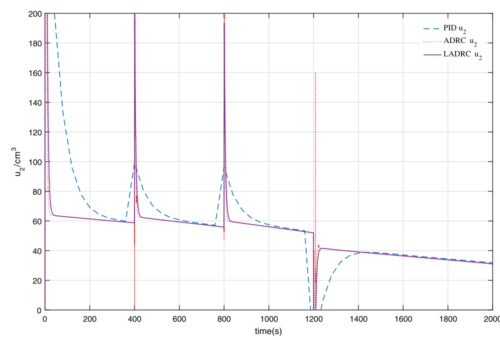
(a) The liquid level tracking response curves of Tank 1.



(b) The liquid level tracking response curves of Tank 2.



(c) The control input response curves of u_1.



(d) The control input response curves of u_2.

Fig. 5. Response curves of liquid level tracking control.

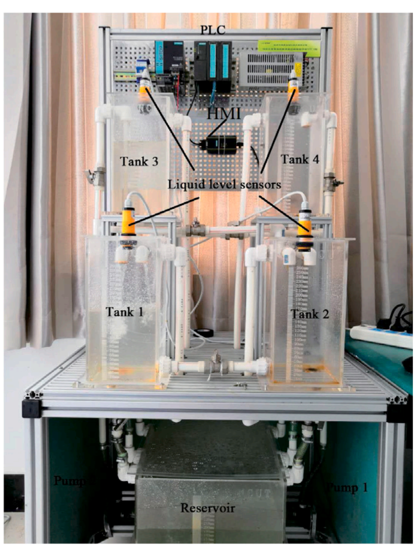


Fig. 6. The four-tank system experimental equipment.

for resolving dynamic response and disturbance rejection problems of PID, ADRC and LADRC are presented in Table 4.

In order to show the trajectory tracking performance of the control strategy, we use the form of three step up and one step down. As shown in Fig. 5, the liquid level curves of Tank 1 and Tank 2 are from $0 \rightarrow 12 \rightarrow 14 \rightarrow 16 \rightarrow 12$ and $0 \rightarrow 14 \rightarrow 16 \rightarrow 18 \rightarrow 14$, respectively. Simulation results show that compared with PID control algorithm, L/ADRC control strategy can track the desired position in a short time, while PID control strategy takes a long time.

Table 4
Simulation study of liquid level: average computation time.

Algorithm/Performances	Rising time (s)	Disturbance rejection adjusting-time (s)
PID	200	250
ADRC	1	10
LADRC	1	1

The above simulation results show that, compared with PID control algorithm, L/ADRC control algorithm has shorter dynamic response time and faster tracking speed, which is 8–13 times of PID control algorithm. Moreover, after disturbance, the system has less influence and faster recovery time.

4.2. Experimental results and analysis

Fig. 6 is shown as the four-tank complex control system innovation experiment platform diagram experiment device. It including a typical process control object-four tank system, on the basis of the typical industrial process object, constructed with programmable logic controller (PLC) and Matlab/simulink as operation platform, and feedback control system. PLC part selects the Siemens company's S7 300 CPU Module, expanded the dedicated analog input module to collect the actual level of four-tank system, extends the analog output module for feed water pump to provide actual analog voltage value through the OPC communication technology required for the Matlab/HMl with PLC industrial control system integration and SIMATIC Windows Control Center (WinCC) system, the researchers simply by Matlab/Simulink operation can complete the design of controller for real-time control. Thus, making some advanced technology and advanced control method of system identification can be easily applied in four system on the controlled object.

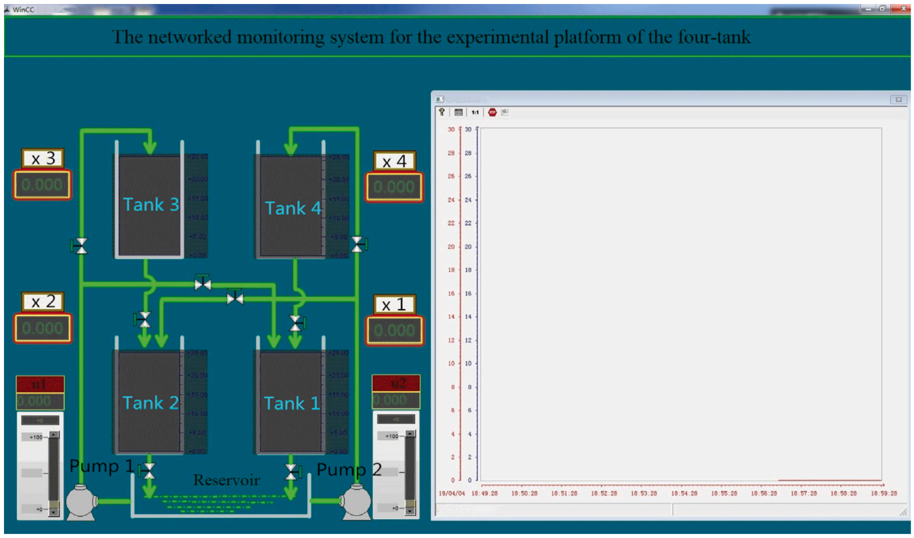


Fig. 7. Wincc liquid level monitoring interface.

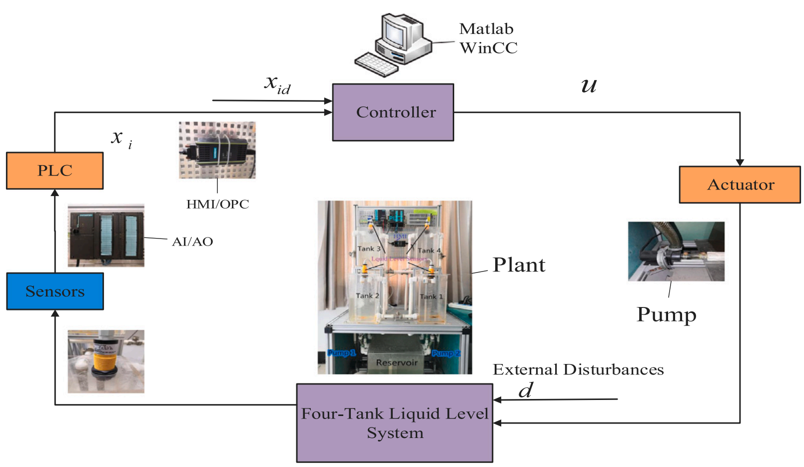


Fig. 8. The closed-loop feedback control for four-tank liquid level system.

The driver of the water pump has a double closed loop adjustment function, and the speed adjustment method adopted by this device is 1–5 V analog speed adjustment, which the corresponding analog digital signal range is 0–100. Considering that input saturation may occur in the start-up and operation stage of the experimental system, we add a limiter to the output end of the controller to ensure the normal operation of the system and reduce the impact of input exceeding the limit on the system. As shown in Fig. 7, WinCC of Siemens is used as the upper computer state monitoring software in this system. WinCC is a process visualization system that can effectively control automated processes. It can be easily combined with standard and user programs to establish human-machine interface and accurately meet actual needs. The PLC adopts the industrial Ethernet communication method and connects a network cable to the computer through the PROFINET interface. This computer is used as the upper computer. The above software is installed, the compiled program is downloaded to the CPU of PLC. The system establishes communication, so that the collected real-time liquid level value and the control quantity for the pump can be embedded in the Simulink environment, and finally a closed-loop feedback four-tank system (Fig. 8) for liquid level control is constructed on Simulink.

The experimental controller parameters are given as Tables 5 and 6.

In the experiment, a certain amount of water is injected into Tank 1 and Tank 2 at the same time, which is regarded as external disturbance.

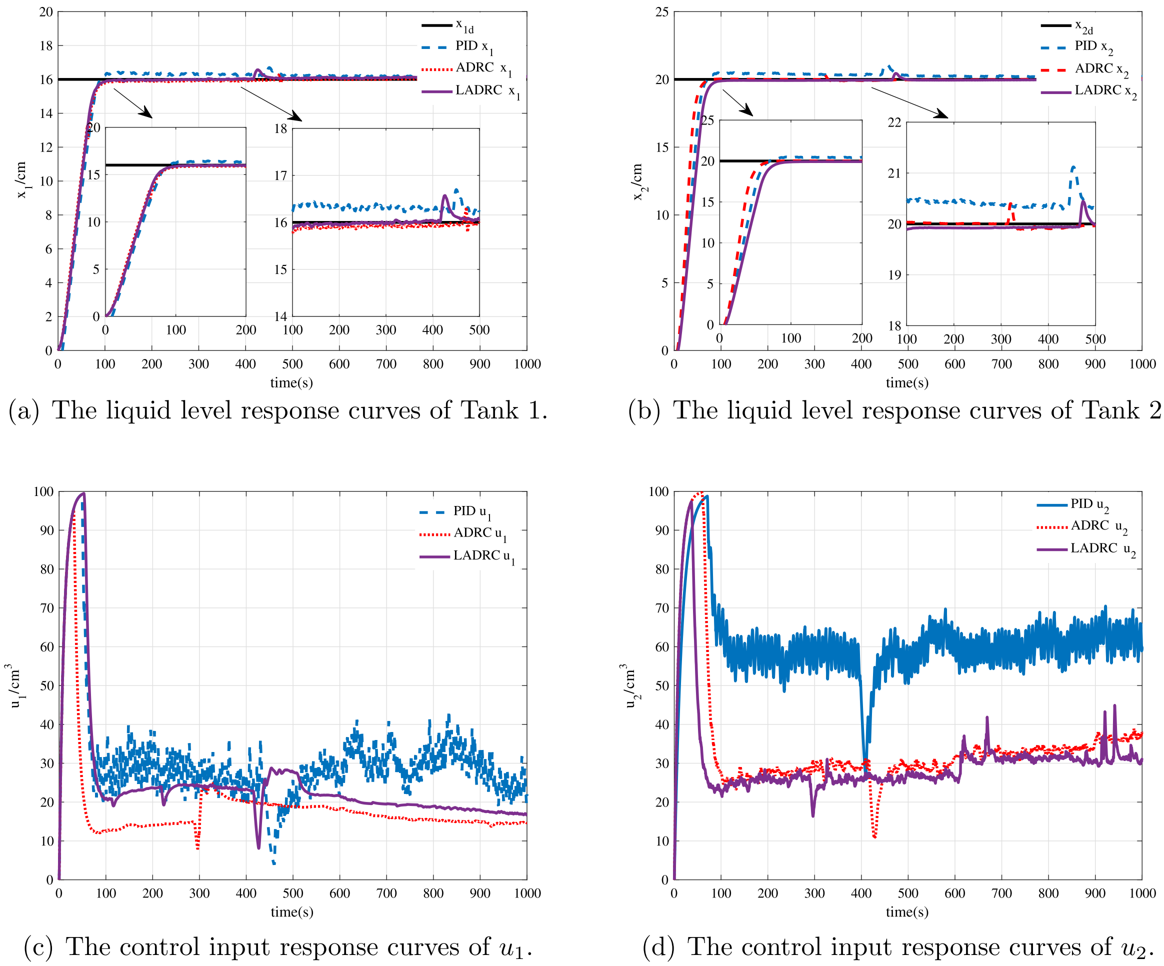
Table 5
PID controller parameters.

Parameters	Value	Parameters	Value
k_{p1}	500	k_{p2}	500
k_{i1}	10	k_{i2}	10
k_{d1}	0.1	k_{d2}	0.1

Table 6
The L/ADRC controller parameters.

Parameters	Value	Parameters	Value	Parameters	Value
β_{11}	200	β_{13}	400	r_1	2
β_{21}	200	β_{23}	400	r_2	2
β_{31}	200	β_{33}	400	r_3	2
β_{41}	200	β_{43}	400	r_4	2
β_{12}	400	b_1	8	α_1	0.75
β_{22}	400	b_2	8	δ_1	0.1
β_{32}	400	b_3	8	α_2	0.75
β_{42}	400	b_4	8	δ_2	0.1

Due to different control strategies, the time of water injection will be different. Moreover, the three control strategies have no obvious difference in the dynamic response phase of the actual experimental process, and all of them can reach the steady-state stage. As shown in Fig. 9, the liquid level of PID control algorithm is affected by



(a) The liquid level response curves of Tank 1. (b) The liquid level response curves of Tank 2.

(c) The control input response curves of u_1. (d) The control input response curves of u_2.

Fig. 9. Response curves of liquid level disturbance compensation control.

Table 7
Experimental study of liquid level: steady-state error.

Performances/Algorithm	PID	ADRC	LADRC
Steady-state error (cm)	0.45	0.15	0.1

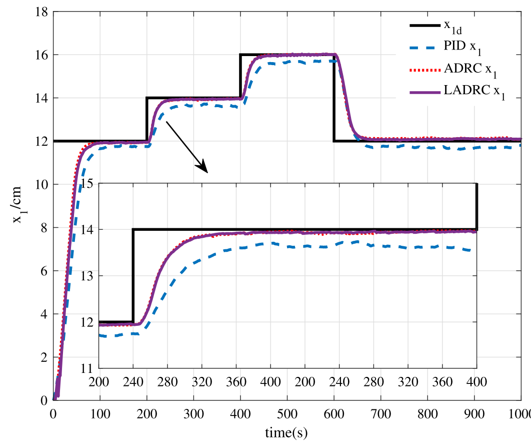
the disturbance for a long time, the disturbance amplitude is large, and there is obvious steady-state error all the time, and the error is $e_{ss} = 0.45$ cm. When the liquid level controlled by ADRC and LADRC is disturbed, the recovery time is short, the disturbance amplitude is small, and the steady-state error is small, and the error is $e_{ss} = 0.15$ cm and $e_{ss} = 0.1$ cm respectively. As shown in Fig. 9:(c),(d), the fluctuation range of the control input curves with L/ADRC control strategy is very small, while the control input curves by using PID method has a large fluctuation range and fluctuates frequently. Compared with LADRC control strategy, ADRC control strategy has faster dynamic response, but LADRC control strategy has smaller steady-state error of liquid level curves. A comparison of steady-state error for resolving accuracy control and disturbance rejection problems of PID, ADRC and LADRC are presented in Table 7.

As shown in Fig. 10, in order to show the trajectory tracking performance of the control strategy, we also use the form of three step up and one step down. It can be clearly seen from the figure that the tracking speed of liquid level curves with L/ADRC control strategy is very fast, the tracking accuracy is very high, and the steady-state error is almost zero. The tracking speed of the liquid level curves by using PID algorithm is still very slow, the tracking accuracy is low, and there has been a steady-state error of the size of $e_{ss} = 0.35$ cm. It can be seen from Fig. 10: (c),(d), that the control input curves value of L/ADRC control strategy is lower than that of PID method, which shows that the L/ADRC control strategy consumes less energy when reaching the same control objectives.

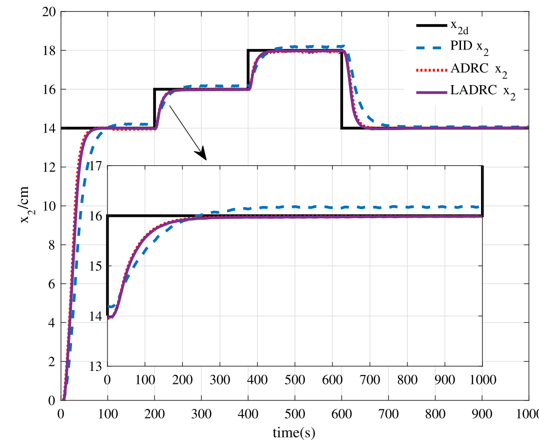
The above experiment results show that, compared with PID method, the L/ADRC control method has better precise control performance, higher position tracking accuracy and stronger disturbance suppression ability, which fully verifies the effectiveness of L/ADRC control strategy.

5. Conclusions

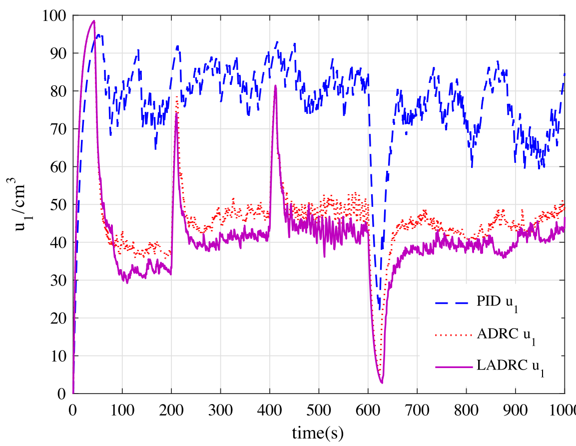
A new L/ADRC strategy is proposed for the influence of disturbance on the four-tank system. Two kinds of control strategies, ADRC with nonlinear function and linearized ADRC are designed based on ADRC technology. The applicability of classical PID controller to four-tank system is considered. A large number of simulation and experimental results demonstrated to validate the linearized ADRC controller can still meet the requirements of the reference input arrangement of the transition process, the observation system states of each order and disturbance compensation. Compared with the linearized ADRC strategy, the ADRC strategy with nonlinear function has the obvious advantage of short response time in the dynamic phase, and the latter has the advantage of better disturbance suppression in the steady-state phase. The L/ADRC control strategy proposed in this paper shows that the dynamic response curves of position control and tracking control and the disturbance suppression performance of steady-state phase are superior to PID control strategy. In conclusion, the L/ADRC strategy



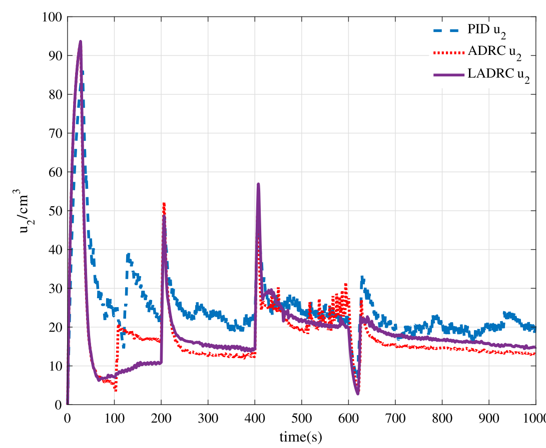
(a) The liquid level tracking response curves of Tank 1.



(b) The liquid level tracking response curves of Tank 2.



(c) The control input response curves of u_1.



(d) The control input response curves of u_2.

Fig. 10. Response curves of liquid level tracking control.

can effectively weaken and eliminate the influence of disturbance on the system, and realize the precise position control and tracking control of the liquid level, which fully shows its good dynamic and steady-state performance. Therefore, the control strategy proposed in this paper has a wide range of engineering application prospects.

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